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MMS 95-0051

ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA—1991 AND 1994 PHASES:

SOUND PROPAGATION AND WHALE RESPONSES TO PLAYBACKS OF ICEBREAKER NOISE

by

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PROJECT ORGANIZATION

The 1991 and 1994 phases of this contract were conducted by LGL Ltd., environmental research associates, assisted by subcontractor Greeneridge Sciences Inc. **LGL** organized the project as a whole, and conducted the biological aspects of the work. M. Smultea, now of Foster Wheeler Environmental Corp., and B. Würsig of the Marine Mammal Research Program, Texas A & M University, worked with LGL on the biological components. **Greeneridge** was responsible for the physical acoustics components. **BBN Systems & Technologies Corp.** assisted with physical acoustics modeling in 1989. The affiliations of the senior authors (in boldface) and co-authors are as follows:

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Another major contributor to the fieldwork in 1989-91 and 1994 was Kenneth Toovak Sr. of Barrow.

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EXECUTIVE SUMMARY

Previous studies of the reactions of bowhead whales to noise from oil industry operations have been conducted during late summer or early autumn, in open water or at most light ice conditions. Concern has arisen about potential effects of man-made noise in the leads through which bowheads migrate in spring.

Objectives

General Objectives

In response to this concern, the Minerals Management Service funded the present experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives were

1. To quantify sound transmission loss and ambient noise within nearshore leads off northern Alaska in spring, emphasizing propagation of underwater sounds produced by production platforms and icebreakers.
2. To quantify the short term behavioral responses of spring-migrating bowhead whales and, if possible, white whales to sounds from production platforms and icebreakers.
3. To assist and coordinate with other studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.
4. To analyze the data in order to test hypotheses concerning the effects of oil industry noises on the movement patterns and behavior of bowhead and white whales.

Specific 1991/94 Objectives

The present report deals primarily with data collected in the springs of 1991 and 1994, the third and fourth years of the project. However, many parts of the report also take account of data collected in 1989 and 1990. In 1989-90, data were obtained on ambient noise, acoustic transmission loss, activities of undisturbed bowhead and white whales during spring migration, reactions of both species to playbacks of recorded continuous low-frequency sound from a drilling operation on the *Karluk* grounded ice pad, and reactions of both species to aircraft overflights. The 1989-90 results were reported in two previous LGL reports to MMS, OCS Studies MMS 90-0017 and 91-0037 (Richardson et al. 1990a, 1991a).

The specific objectives of the 1991 and 1994 phases of this project were similar to those in 1989-90, with the main exception being that the top priority work involved playbacks of variable icebreaker sounds to bowheads. When possible, reactions of white whales as well as bowheads were to be determined. Because of poor weather and ice conditions in 1991, and the low number of whales observable during playbacks in that year, few data on reactions to playbacks of icebreaker sounds were acquired in 1991. Hence, the highest priority for subsequent fieldwork was to continue studying reactions of bowheads to icebreaker noise playbacks. Fieldwork was not possible in 1992 or 1993 because of concern about potential interference with the ice-based bowhead census at Barrow in 1992 and 1993. Fieldwork resumed in 1994.

Because of the possible effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components adequately, indirect methods of addressing the importance of low-frequency components were again identified as one of the specific objectives in 1991/94 (see item 5, below).

The specific objectives for 1991/94 were as follows:

1. To record sounds from the SSDC caisson while it was drilling during winter conditions, including infrasonic components, and to analyze those sounds to determine their levels, spectral characteristics, and attenuation properties.
2. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.
3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of *(a)* test tones at selected frequencies, and *(b)* continuous industrial sounds. Infrasonic components cannot be projected.
4. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of variable icebreaker sounds. Infrasonic components cannot be projected.
5. To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, *(a)* to measure ambient noise at infrasonic frequencies, and *(b)* to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990). Also, based on the winter recordings of SSDC sounds (specific objective 1), we were *(c)* to determine the frequencies, levels and attenuation of the infrasonic components of drilling caisson sound.
6. To measure, on an opportunistic basis, the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights (supplementing limited data from 1989-90).
7. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowhead and white whales along their spring migration corridor in the western Beaufort Sea.
8. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.
9. To analyze the data to test hypotheses concerning the effects of the icebreaker sounds and helicopter overflights mentioned in (4) and (6) on *(a)* the movement patterns and *(b)* the

behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

Significant progress has been made toward meeting all nine objectives during the four spring seasons. Several objectives—2, 3, 5a, 7 and 8—can be considered "achieved". Some data on the responsiveness of spring-migrating bowheads and white whales to playbacks of steady drilling noise and variable icebreaker noise were obtained, along with some data on responsiveness to actual aircraft overflights (objectives 4, 6 and 9). However, better quantification of whale responses to these activities than achieved in this study would be desirable. Similarly, objectives 1 and 5b,c were partially met, but additional data would be helpful.

Approach and Procedures

No oil production facilities have yet been constructed in or near the spring lead systems off northern Alaska, so a study of the effects of such facilities on whales must be done by simulation methods. The underwater sound playback method was used. Two types of playbacks were conducted: ▸ In 1989-90, playbacks of steady low-frequency noise recorded near the *Karluk* drilling operation on a grounded ice pad. ▸ In 1991/94, playbacks of variable and broader-bandwidth sound from the icebreaking supply ship *Robert Lemeur* recorded while it was managing ice.

The study had to be conducted such that it did not interfere, and was not perceived to interfere, with either subsistence whaling or the spring bowhead census. Barrow is the northeasternmost community with spring whaling, and the bowhead census is also done just north of Barrow. After consultation with the Barrow Whaling Captains' Association, Alaska Eskimo Whaling Commission, and North Slope Borough Dept of Wildlife Management, it was agreed that the most suitable location for playbacks in 1989 was about 60+ km (32+ n.mi.) NE or ENE of Pt. Barrow. In 1990-91 and 1994, it was agreed that the work could be done as close as 15 n.mi. (28 km) beyond the northeasternmost whaling camp.

The field crew consisted of two teams. *(1)* A helicopter-supported crew deployed one or two underwater sound projectors from ice pans or, on some dates in 1991/94, the landfast ice edge. They projected recorded drilling platform sound or icebreaker sound into leads. When whales came within visible range of the projector site, the ice-based crew documented whale movements and behavior, using a surveyor's theodolite to measure the successive bearings and distances of whales from the projector(s). In addition, this crew measured the rate of attenuation of projected underwater sounds with increasing distance from the projector(s). *(2)* A second crew, in a Twin Otter aircraft, located whales and suitable projector sites, documented behavior of whales as they swam toward and past the projector(s), and (in 1989, 1991 and 1994) obtained known-scale vertical photos of bowheads to identify and measure them. The aircraft crew also used naval sonobuoys to monitor underwater sounds near whales.

Whale observations obtained by the two crews were complementary. Ice-based observers obtained detailed data on the paths and speeds of some whales that passed within 1-1½ km (0.54-0.8 n.mi.) of the projector, and observed whales even when there were low clouds. Aerial observers could observe whales at any distance from the projector site, could follow them for longer distances, and had a much better vantagepoint for viewing details of behavior. However, aerial observations were only useful when the cloud ceiling was at least 460 m (1500 ft) above sea level, as bowheads sometimes react to an observation aircraft circling at lower altitudes. Low cloud frequently interfered with behavioral observations in 1989 and especially 1991, but did so less commonly in 1990 or 1994. In 1994, strong winds often hindered behavioral observations from both the ice and the aircraft.

Sample Sizes

The ice-based crew worked from the ice on 33 days from 27 April to 30 May in 1989-90, and on 26 days from 28 April to 26 May in 1991/94. They conducted successful transmission loss tests on eight days in 1989-90 and five days in 1991/94. They projected industrial sounds into the water for several hours on each of 19 days in 1989-90 (drilling noise) and 13 days in 1991/94 (icebreaker noise).

The aircraft-based crew conducted reconnaissance surveys on 46 dates from 29 April to 30 May in 1989-90, and on 45 dates from 27 April to 26 May in 1991/94. The aerial crew conducted 46 behavior observation sessions on 22 days in 1989-90, and 30 sessions on 15 days in 1991/94. Behavioral observations totaled 72.4 h in 1989-90, 4.1 h in 1991 (limited by prevailing low cloud), and 36.2 h in 1991. Of these 112.7 h of systematic aerial observations over four spring seasons, 72.1 h involved presumably undisturbed bowheads (control data) and 40.6 h involved potentially disturbed bowheads.

Bowheads were observed in waters ensonified by the projected industrial sounds on 10 days with *Karluk* drilling noise in 1989-90 and on 7 days with icebreaker noise in 1991/94. **Total numbers of bowheads observed near the operating projector(s) during playbacks were ~221 in 1989-90 and 93 in 1991/94.** Bowheads were also observed near the ice camp under quiet "control" conditions at other times during most playback dates, and on a few additional days as well, in 1989-90 (~204 bowheads) and 1991/94 (~229 bowheads). White whales were seen near the operating projector(s) on five days in 1989-90 (~219 exposed to playbacks of *Karluk* drilling sounds) and on three days in 1991/94 (~46 exposed to playbacks of *Robert Lemeur* icebreaker sounds). In 1989-90, observation time near the ice camps totalled 74 h during drilling noise playbacks, plus 119 h of "control" observations near the ice camps. In 1991/94, observation time there totalled 40 h during the icebreaker playbacks, plus 101 h of "control" observations.

Physical Acoustics

Ambient Noise

Ambient noise levels measured in 1991 were similar to those during 1989-90, with median levels in the 20-1000 Hz band being 89-92 dB re 1 μPa, just above the 87 dB level computed for Knudsen's sea state zero extrapolated down to 20 Hz. In 1994, the corresponding measured median level was notably higher, 97 dB. This is ~2 dB less than the computed level for Knudsen's sea state two. The 1994 measurements were made in higher average wind speeds than prevailed in 1989-91. Wind speed has a dominant influence on underwater noise levels. Compared to the Wenz spectrum level ranges at 32 and 1000 Hz, the 1991/94 levels during this project were about mid-range. Compared to Chukchi shallow water measurements at those frequencies from May 1977, the 1991/94 levels were 7 dB re 1 $\mu Pa^2/Hz$ higher at 32 Hz and 18 dB higher at 1000 Hz.

Overall, the measurements from the western Beaufort Sea in spring fit well into the range of ambient noise measurements taken around the world.

Transmission Loss Tests

Transmission loss measurements were conducted 14 times during the four field seasons. The best results came from 1/3-octave hyperbolic frequency modulated "sweeps" and from samples of broadband *Karluk* drilling sounds. Tests with tones and clusters of tones gave more variable results. Icebreaker sounds, although broadband, varied too much in level over the duration of transmission to give consistent results. Assuming that bottom acoustic properties did not vary significantly over the region where the transmission loss tests were conducted, a basic model for sound transmission loss was developed. The validity of the assumption was ascertained by plotting, for each test frequency, transmission loss minus 20log(water depth) vs. range, normalized by twice the depth. Agreement among tests was generally within about ±4 dB (s.e.) for frequencies 50-1000 Hz and within about ±6 dB for higher frequencies to 5000 Hz. The model is thus frequency and depth dependent. All sources and receivers were at depth 18 m, and a frequency-dependent Lloyd's Mirror component is included in the model for frequencies <50 Hz. For example, the transmission loss at 10 Hz will be 28 dB greater than at 50 Hz due to the Lloyd's Mirror effect.

Comparison of received levels at sonobuoys during playbacks with model predictions for those ranges and water depths showed that the broadband measured levels generally agreed with the predicted broadband levels within the ±4 dB spread expected. As expected, exceptions occurred when the distance was so great that the predicted levels were less than the measured ambient noise. Model estimates of received level in the strongest 1/3-octave band may be underestimated by a few decibels.

Transmission loss at the 13 May 1990 playback site was less than that expected based on the transmission loss tests. The 13 May 1990 site was in water shallower (27 m) than that where any transmission loss test was done. The observed results from 13 May 1990 can be accounted for if there was subsea permafrost close to that playback site. Received levels of man-made noise from a source in such an area would be higher than levels predicted by the propagation model developed from the 14 transmission loss tests.

Comparison of transmission loss in the western Beaufort Sea (this project) with U.S. Navy-sponsored measurements in the Chukchi Sea (Greene 1981) suggests that the two areas are similar.

Playback Tests

In 1991/94, recorded underwater noise from an actual icebreaker (*Robert Lemeur*) operating in heavy ice was transmitted repetitively to simulate an icebreaker operating at the playback test sites. How did the playbacks compare with the original icebreaker?

Over the 40-6300 Hz range, the median source levels of the icebreaker playbacks on various days were 20-44 dB lower than the median source level of the actual icebreaker. Thus, at any distance from the source, the median level of the simulated icebreaker sound was 20-44 dB lower than would be expected if the actual icebreaker were operating there. A given received level would be found much farther from the actual icebreaker than from the projectors.

The overall median playback source level in the frequency range 40-6300 Hz was 34 dB less than the actual icebreaker source level (0.04% of the acoustic power). The median deviation from a flat frequency response across the 40-6300 Hz range was ±10 dB. The differences in source level at frequencies below 40 Hz increased with decreasing frequency to a median difference of 63 dB at 20 Hz. Considering the 1/3-octave bands centered at 20-6300 Hz (i.e. the 18-7100 Hz band), 45% of the acoustic power emitted by the icebreaker was below 45 Hz. Because of the more rapid attenuation of the lowest sound frequencies with increasing distance, the percentage of power below 45 Hz is estimated to diminish to 18% at range 50-100 m from the icebreaker, 17% at 1000 m, and 6.5% at 10,000 m. In comparison, <1% of the acoustic power emitted by the projectors during icebreaker playbacks was below 45 Hz.

Because of the differences between the actual icebreaker sound and the projected sound, and because of the variable levels at different times during playbacks, it was necessary to examine whale behavior in relation to the sound level being received at the whales' locations. A sound exposure model was developed to estimate received levels at whale locations, based on projected level and spectral composition and on the transmission loss model.

Infrasounds

Characteristics of the infrasonic components of ambient noise and drilling caisson noise were studied, along with the possibility that bowhead calls include infrasonic components. This work was done to help assess whether oil-industry sources emit strong infrasounds, how far away these infrasounds might be detectable, and whether bowheads are likely to hear infrasounds.

Infrasonic (<20 Hz) ambient noise was measured in the 1/3-octave bands centered at 10, 12.5 and 16 Hz. Compared to median levels at higher frequencies, the levels in infrasonic bands increased slightly with decreasing frequency in 1991 but decreased markedly with decreasing frequency in 1994. The median and range of 10 Hz spectral density levels agree well with measurements made in the deep Beaufort Sea and shallow Chukchi Sea during May 1977 (Greene 1981) and fit into the range of levels at 10 Hz reported by Wenz (1962). If bowhead calls include infrasonic components at levels comparable to those of the known call components, the expected high rate of attenuation in shallow water would result in masking by the observed levels of ambient infrasonic noise at relatively short ranges. Similarly, industrial noise components at infrasonic frequencies, unless much stronger than industrial noises at sonic frequencies, would be masked by the infrasonic ambient noise at short ranges.

There was no evidence of infrasonic tones (at frequencies <20 Hz) in a brief recording of noise from the SSDC drilling caisson engaged in drilling east of Barrow during winter.

If bowhead calls contain infrasonic components, bowheads probably can hear infrasounds. Infrasonic sound coincident with bowhead calls was studied in 1990 and 1991. In 1990, of 45 calls analyzed, one showed coincidence with an infrasonic transient. In 1991, of 73 calls analyzed, 11 occurred coincidently with infrasonic transients. An array of acoustic sensors would be needed to determine if the source locations of infrasonic and sonic components are coincident, thereby providing stronger evidence of infrasonic calls by bowheads.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area during late April and May of 1989-91 and 1994. In 1989, the migration was often through heavy pack ice conditions. In other years, the ice was less compacted. In 1989-91, even when a broad nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 35+ km (19+ n.mi.) ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead. However, up to 15 May in 1994, the landfast ice edge that far east of Pt. Barrow was farther offshore than normal, and at times bowheads traveled near the landfast ice edge as far as 70 km (38 n.mi.) east of Pt. Barrow. This allowed much of the 1994 playback work to be done from the landfast ice edge 40-70 km east of Pt. Barrow.

Bowheads visible under undisturbed conditions in 1989-94, mainly amidst pack ice and in the main nearshore lead, were engaged predominantly in traveling (migration), sometimes intermixed with socializing. In 1989, when ice conditions were heavy, some resting bowheads were seen in small areas of open water amidst heavy ice. In subsequent years when heavy ice cover was less common, a higher proportion of the whales observed were actively migrating northeast or east. No surface feeding was seen, and apparent water-column or under-ice feeding was rare. A few bowheads were seen surfacing with mud streaming from their bodies and (rarely) from their mouths. Pre-dive flexes and fluke-out dives were seen less commonly in spring than in previous summer/autumn studies. A few bouts of sexual activity were observed during early May. Most mating apparently occurs earlier in the spring.

Bowhead calves and their mothers were seen only in the latter half of May in 1989, 1990 and 1991; only one calf was seen in 1994. In late May, mothers and calves often constituted the majority of the bowheads present in the study area. They did not migrate as strongly or consistently eastward as did other bowheads, especially in 1989 when the ice was heavy. Direct observations and photographic resightings showed that a few mother-calf pairs traveled *west* for at least a few kilometers. Some of these pairs may have been waiting for ice conditions to ameliorate before continuing east. During travel, bowhead calves often "rode" on the backs of their mothers. Dives by calves tended to be short. Heavy ice conditions pose a greater impediment to spring migration of mother-calf pairs than of other bowheads.

Drilling Noise Playbacks

Results of the drilling noise playbacks in 1989-90 were described and summarized in OCS Study MMS 91-0037. Migrating bowheads tolerated exposure to high levels of continuous drilling noise if this was necessary to continue their migration. Bowhead migration was not blocked by projected drilling sounds, and there was no evidence that bowheads avoided the projector by distances exceeding 1 km (0.54 n.mi.). However, local movement patterns and various aspects of the behavior of these whales were affected by the noise exposure, sometimes at distances considerably exceeding the closest points of approach of bowheads to the operating projector. When ice was loose, some migrating bowheads diverted their courses enough to remain a few hundred meters to the side of the projector. Surfacing and respiration behavior, and the occurrence of turns during surfacings, were strongly affected out to 1 km. Turns were unusually frequent out to 2 km (1.1 n.mi), and there was evidence of subtle behavioral effects at distances up to 2-4 km (1.1-2.2 n.mi.).

From a statistical viewpoint, the null hypotheses of no playback effects on migration route and behavior were rejected. However, the demonstrated effects were localized and temporary. We concluded that the effects of the *Karluk* playbacks on distribution and movements were not biologically significant, and that playback effects on behavior probably were not biologically significant either. At distances beyond 100 m (109 yd), the projector used in 1989-90 adequately reproduced the overall 20-1000 Hz level even though sound components below 80 Hz were underrepresented. If bowheads are no more responsive to sound components at 20-80 Hz than to those above 80 Hz, then the playbacks provided a reasonable test of bowhead responsiveness to components of the actual *Karluk* sound above 20 Hz.

Icebreaker Noise Playbacks

Bowheads migrating in the nearshore lead often tolerated exposure to projected icebreaker sounds at received levels up to 20 dB or more above the natural ambient noise levels at corresponding frequencies. Bowheads are believed to be able to hear sounds of this type at levels near ambient. Thus, most of them apparently did not react in a manner that we could detect when they received weak icebreaker sounds.

However, some bowheads that would have come within a few hundred meters of the projectors if they had not turned apparently diverted so as to remain farther away. Diversion was apparently common when bowheads were exposed to levels of projected icebreaker sound more than 20 dB above the natural ambient noise level in the 1/3-octave band of strongest icebreaker noise. However, not all bowheads diverted at that signal-to-noise ratio (S:N), and a minority of them apparently diverted at lower S:N.

Bowhead behavior was significantly correlated with S:N and with received level (RL) of icebreaker sound in the 1/3-octave of strongest icebreaker sound, but not with distance from the projectors. The lack of correlation with distance was no doubt related to the highly variable levels of icebreaker sound at different times. Various measures of behavior were significantly different when S:N (the icebreaker-to-ambient ratio) exceeded 20 dB or, in the case of frequency of turning during surfacings, exceeded 10 dB. Measures of behavior that were significantly correlated with S:N were turning, duration of surfacing, number of blows per surfacing, and two multivariate indices of behavior. With icebreaker noise, turns during surfacings tended to be more common and larger, durations of surfacing longer, and blows per surfacing more numerous.

In general, movements and behavior of migrating bowheads exposed to playbacks of variable icebreaker noise were altered subtly but statistically significantly when S:N (as defined above) exceeded 20 dB, and when RL of icebreaker sound exceeded 100 dB re 1 μPa. Statistical power analyses showed that the possibility of behavioral effects at lower S:N and RL values cannot be excluded. One measure of behavior (frequency of turning) was apparently affected at S:N as low as 10-20 dB, and another measure (duration of surfacings) was apparently affected at RL as low as 90-100 dB re 1 μPa (1/3-octave basis).

The source level of an actual icebreaker is much higher than that of the projectors used in this study (median difference 34 dB over the frequency range 40-6300 Hz). If bowheads react to an actual icebreaker at S:N and RL values similar to those found during this study, they might commonly react at distances up to 10-50 km (5.4-27 n.mi.) from the actual icebreaker, depending on many variables. Predicted reaction distances around an actual icebreaker far exceed those around an actual drillsite like *Karluk* because of (a) the high source levels of icebreakers and (b) the better propagation of sound from an icebreaker operating in water depths 40+ m than from a bottom-founded platform in shallower water.

This study is consistent with previous analyses that predicted highly variable reaction distances even for a single source of man-made noise. Predicted reaction distances depend on

- temporal variations in its source level;
- temporal and geographic variations in propagation loss between source and receiver;
- temporal and geographic variations in ambient noise (and thus signal-to-ambient ratio);
- variations in the response thresholds of individual whales.

Given these factors and the observed reactions to playbacks of icebreaker sound, predicted reaction distances for bowheads around an icebreaker like *Robert Lemeur* vary from as little as ~2 km to as much as 95 km.

One of the main limitations of the study (during all four years) was the inability of a practical sound projector to reproduce the low-frequency components of recorded industrial sounds (see "Playback Tests", p. xvii). Both the *Karluk* rig and the icebreaker *Robert Lemeur* emitted strong sounds down to ~10-20 Hz, and quite likely at even lower frequencies. It is not known whether the underrepresentation of low-frequency (<45 Hz) components during icebreaker playbacks had significant effects on the responses by bowheads. Bowheads presumably can hear sounds extending well below 45 Hz. It is suspected but not confirmed that their hearing extends into the infrasonic range below 20 Hz.

Also, this study was not designed to test the potential reactions of whales to non-acoustic stimuli detected via sight, olfaction, etc. At least in summer/autumn, responses of bowheads to actual dredges and drillships seem consistent with reactions to playbacks of recorded sounds from those same sites (Richardson et al. 1990b, *Mar. Environ. Res.* 29:135-160). This observation gives us some reason for optimism that playbacks provide meaningful results.

Additional limitations of the playbacks included low sample sizes (especially for the 1991/94 icebreaker tests, see p. xvi) and the fact that responses were only evident if they could be seen or inferred based on surface observations. The numbers of bowhead and white whales observed during both playback and control conditions were low percentages of the total Beaufort Sea populations. These samples may or may not have been representative of the overall populations. Also, differences between whale activities and behavior during playback vs. "control" periods represent the incremental reactions when playbacks are added to a background of other activities associated with the research. Thus, the playback results may somewhat understate the differences between truly undisturbed whales vs. those exposed to playbacks.

Nonetheless, the data allow us to conclude that exposure to a single ***playback*** of variable icebreaker sounds can cause statistically but probably not biologically significant effects on the movements and behavior of migrating bowheads visible in the open water of nearshore lead systems during spring migration east of Pt. Barrow. Reaction distances around an ***actual icebreaker*** like *Robert Lemeur* are predicted to be much greater, commonly on the order of 10-50 km. Effects of an actual icebreaker on migrating bowheads, especially mothers and calves, could be biologically significant.

Aircraft Disturbance

The 1989-94 observations show that a minority of spring-migrating bowheads dive or exhibit other short-term behavioral changes in response to a close approach by a turbine-powered helicopter. However, other bowheads show no obvious reaction to single passes—even at altitudes of 150 m (500 ft) or below, and lateral distances ≤250 m (820 ft).

We conclude that, although some bowheads exhibit short-term behavioral reactions, single helicopter overflights at altitudes of 150 m (or below) do not appear to disrupt the distribution, movements or behavior of bowheads visible during spring migration in pack ice or nearshore leads in a biologically significant way. This assessment concerns potential effects of single, straight-line overflights. Repeated passes, circling, or prolonged hovering at low altitude would be more likely than single, straight-line overflights to cause significant disturbance effects.

Spring-migrating bowheads occasionally dive, turn or otherwise react in an obvious manner to low-altitude overflights (altitude ≤182 m or ≤600 ft) by a Twin Otter fixed wing aircraft. A very small percentage (~1.3%) react similarly to overflights at altitude 460 m (1500 ft) if the lateral distance is ≤300 m (≤1000 ft). In spring, migrating bowheads do not react in an obvious manner to a Twin Otter aircraft circling at altitude 460 m and radius 1-1½ km, nor is there any clear evidence of subtle alterations in their behavior within 15 min after circling begins as compared with later observations.

White Whales

Sightings of white whales were more numerous than those of bowheads, and white whales tended to be more widely scattered and slightly farther offshore than bowheads. However, their migration corridors overlapped broadly.

Drilling Noise Playbacks

Results of the drilling noise playbacks in 1989-90 were described and summarized in OCS Study MMS 91-0037. In brief, we observed migrating white whales close to the operating projector on five dates. On four of these dates, at least a few white whales came within ~200 m (655 ft) of the operating projector, including a few within 50-100 m (165-330 ft). White whales migrating toward the projector appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some white whales that came that close continued past without apparent hesitation or turning. Others reacted temporarily to the noise, or perhaps to visual cues, at distances on the order of 200-400 m (655-1310 ft). Some white whales slowed down, milled, or reversed course for several minutes. Then they continued past the projector, in some cases passing within 50-100 m of it.

We saw no evidence that white whales reacted at distances greater than 200-400 m even though projected drilling noise was measurable up to several kilometers away. This was probably related to the poor hearing sensitivity of white whales at low frequencies where the *Karluk* drilling sounds were concentrated. At distances beyond ~200 m, received levels of low-frequency drilling sounds (on a 1/3-octave basis) usually were less than the measured hearing sensitivity of white whales.

The observed reactions may have been to weak artifactual components of the projected sound at frequencies above 2-3 kHz rather than to stronger *Karluk* components at ~63-300 Hz. Although weak, the high-frequency components were potentially audible to white whales at somewhat greater ranges, given the much better hearing of white whales at higher frequencies.

The maximum acoustic reaction distance of white whales near a shallow-water drillsite like *Karluk* is predicted to be similar to that observed in our tests (a few hundred meters). Reaction distances near the actual drillsite might be less than those near the projector if the observed reactions were to the weak high-frequency system noise rather than the drilling noise *per se*. This high-frequency noise would not be present near the actual drillsite. However, minimum reaction distances near an actual drillsite like *Karluk* probably exceed those observed near the projector (15-50 m) because of the higher noise levels and other stimuli present within ~200 m of the actual site relative to those at corresponding distances from the projector site.

We conclude, based on a small sample size, that playbacks of sounds from drilling on a bottom-founded ice platform like *Karluk* have no biologically significant effects on migration routes and spatial distribution of white whales visible while migrating through pack ice and along the seaward side of the nearshore lead east of Point Barrow in spring. Furthermore, we expect that maximum reaction distances of white whales to an actual drillsite like *Karluk* (a few hundred meters) would be similar to those observed during the playback experiments. In drawing these conclusions, we consider that the observed temporary hesitation and minor changes in migration paths exhibited by some white whales within 200-400 m of the noise source were not biologically significant. Our acceptance of the amended null hypothesis is based on a "weight of evidence" approach; available data are not suitable for a statistical test of the hypothesis. Also, the available data are not adequate for a test, statistical or otherwise, of the second hypothesis, concerning effects of *Karluk* drilling noise on subtle aspects of the individual behavior of white whales.

Icebreaker Noise Playbacks

We observed migrating white whales close to the operating projector(s) on three dates in 1991/94. Interpretable data were collected on 17 groups of white whales observed during playbacks on two of these dates. At least six groups appeared to alter their paths in response to playbacks. As in the drilling noise playbacks, however, white whales approached within a few hundreds (and sometimes tens) of meters before showing any response. At these distances received levels at frequencies below 1000 Hz were high, but below the hearing threshold at corresponding frequencies. However, white whales within a few hundred meters of the projectors probably could hear, at least faintly, higher frequency components of the projected sounds, around

5000 Hz. Icebreaker sounds received by six groups of white whales that reacted were estimated as 78-84 dB re 1 μPa in the 1/3-octave band centered at 5000 Hz, or 8-14 dB above ambient in that band. Corresponding levels for 11 groups showing no obvious diversion were generally similar.

If some white whales react to an actual icebreaker at RL near 80 dB re 1 μPa or S:N near 10 dB (both in the 1/3-octave band near 5000 Hz), reactions would be expected to occur at distances on the order of 10 km from an icebreaker like *Robert Lemeur* operating in the present study area in spring.

Because we saw few groups of white whales near the projector(s) during icebreaker playbacks, additional field tests would be needed before formally evaluating their effects on movements of migrating white whales. However, small-scale diversions such as those sometimes seen in 1991/94 are unlikely to be biologically significant. Given the much larger anticipated radius of influence around an actual icebreaker and our small sample size, any conclusions about the effects of icebreaker playbacks on white whales cannot be applied directly to actual icebreaker effects.

Aircraft Disturbance

Opportunistic observations in 1989-94 showed that spring-migrating white whales appeared more responsive to aircraft overflights than were bowheads, often responding to a close approach by a turbine-powered helicopter. Apparent reactions were observed during 31% of overflights. Whales reacted by diving, veering away, or showing other changes in behavior. During overflights, reactions occurred exclusively when the helicopter passed at ≤250 m (820 ft) lateral distance from the white whales, and at altitudes up to 460 m ASL (1500 ft). However, most white whales showed no obvious reaction to single passes at altitudes >150 m ASL. These white whales maintained their headings and continued respiring at the surface when the helicopter operated nearby. Reactions were also noted among half of the 14 groups observed from the ice camp when the helicopter was stationary on the ice with its engines running.

Operations by a Bell 212 helicopter can locally alter the movements of white whales visible in the open water of nearshore lead systems and amidst the pack ice during spring migration near Pt. Barrow. However, these local effects do not cause migration blockage or biologically significant diversion from migration routes in the circumstances studied. Likewise, single overflights at lateral distances <250 m, especially at altitudes ≤150 m ASL, often affect the behavior of the white whales. There is no objective way to assess the biological significance of these behavioral reactions, but they appear brief and probably are not of lasting significance. This assessment concerns potential effects of single, straight-line overflights.

White whale groups were sometimes observed reacting overtly to Twin Otter overflights. Most reactions occurred when the aircraft was at altitudes ≤182 m (600 ft) and lateral distances ≤250 m (820 ft). Direct overflights generated the most pronounced reactions, such as vigorous swimming, abrupt dives, or tail thrashing. In a few cases, white whale responses involved turning directly away from the aircraft. In other cases, white whales responded to overflights by looking up at the aircraft. The number of white whales observed reacting overtly to Twin Otter overflights represented a very small fraction of the total number of white whales observed from the aircraft: 24 of ~760 groups.

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Dr. Thomas Albert	North Slope Borough Dep. Wildl. Manage. (1989-95),
Mr. Mark Fraker	BP Exploration (Alaska) (1989-91),
Ms. Michelle Gilders	BP Exploration (Alaska) (1994-95),
Dr. Roger Green	University of Western Ontario (1990-95),
Mr. Edward Itta	Barrow Whaling Captains Assoc. (1994-95),
Mr. Charles Malme	Hingham, MA (1994-95),
Mr. Allen Milne	Sci. Rev. Board Chairman (1989-91),
Mr. Ron Morris	Nat. Mar. Fish. Serv. (1990-95),
Mr. Thomas Napageak	Alaska Eskimo Whaling Commission (1989-91),
Mr. Burton Rexford	Barrow Whaling Captains' Assoc. (1989-91) and Alaska Eskimo Whaling Commission (1994-95),
Dr. Steven Swartz	Nat. Mar. Fish. Serv. (1989-95; SRB Chairman in 1994-95).

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GLOSSARY

absorption. The process by which sound energy is converted into heat.

acoustic impulse. Integral over time of the initial positive acoustic pressure pulse, measured in pascal-seconds (Pa·s); used in describing sound pulses.

acoustic intensity. Acoustic power crossing a unit area; pressure squared divided by acoustic impedance (ρc, where ρ represents the density of the medium and c the sound speed).

acoustic power. The energy per unit time, measured in watts. The acoustic power is proportional to acoustic pressure squared.

acoustic pressure. Pressure variations around an ambient static pressure (such as the hydrostatic pressure in water at some depth) at acoustic frequencies. These are very small pressures compared to the static pressure or compared to shock or blast wave pressures.

ambient noise. Background noise; noise not of direct interest during a measurement or observation. Excludes sounds produced by the measurement equipment, such as cable flutter.

Argotec 220. A particular type of underwater sound transducer that can project low-frequency sounds. Used in 1994.

ASL. Above sea level.

audiogram. A graphical depiction of auditory thresholds, showing the sound levels that are barely detectable by an animal, in the absence of significant background noise, as a function of frequency.

auditory sensitivity. An animal's hearing sensitivity as a function of frequency.

auditory threshold. The minimum amplitude of sound that can be perceived by an animal in the absence of significant background noise. Auditory threshold varies with frequency and is inversely related to the animal's auditory sensitivity.

bandpass filter. A filter with high-pass and low-pass cutoff frequencies, designed to pass only a desired band of frequencies.

bandwidth. A range of frequencies.

Bell 212. Medium-size helicopter (4500-5100 kg gross weight) with 2-bladed main and tail rotors producing families of tones with fundamental frequencies ~11 and 55 Hz, respectively. Powered by paired turboshaft engines (PT6T), together producing 1100 shp for cruise and a maximum of 1800 shp. Civil equivalent of military Twin Huey UH-1N.

biologically significant. Likely to affect the long-term well-being or reproductive productivity of individuals or of the population.

blow interval. The interval, in seconds, between two successive respirations within the same surfacing by a whale.

CEPA. Closest Estimated Point of Approach. A term used in this study to represent the closest known distance of a whale from the ice camp. It is (a) the interpolated Closest Point of Approach for whales observed both before and after passing the ice camp; and (b) the closest observed distance for whales seen either approaching or moving away from the ice camp, but not both.

CPA. Closest Point of Approach.

critical band. The frequency band within which background noise can affect detection of a sound signal at a particular frequency.

critical ratio. The ratio of power in a barely-audible tone to the spectrum level of background noise at nearby frequencies.

continuous wave. A sound whose waveform continues with time.

crosscorrelation. A measure of the similarity of two waveforms. As a function of time displacement or delay between the two waveforms, useful for determining the travel time difference of a signal received at two spatially separated sensors. Computed for each value of displacement by averaging the product of the two waveforms.

cylindrical spreading. Sound spreading as cylindrical waves. The transmission loss for cylindrical spreading is given by

$$10*\log_{10}(\text{Range}/R_0),$$

where R_0 is a reference range. The received level diminishes by 3 dB when range doubles, and by 10 dB for a tenfold increase in range.

cylindrical wave. A sound wave with cylindrical fronts. For a point source in shallow water, a cylindrical wave forms at distances that are large compared to the water depth because of the way sound reflected from the surface and bottom reinforces the direct wave.

decibel (dB). A logarithmically based relative measure of sound strength. A sound pressure P can be expressed in dB as a sound pressure level of $20*\log_{10}(P/P_{ref})$, where P_{ref} is a reference pressure (usually a standard pressure like 1 microPascal). Note that $20*\log(X)$ is the same as $10*\log(X^2)$, where X^2 is the mean square sound pressure and is proportional to power, intensity or energy.

DIFAR. A type of sonobuoy (AN/SSQ-53B) with the ability to determine the direction of arrival of a sound. Effective at 10-2400 Hz.

DSP. Digital Signal Processor. A microprocessor whose internal design is optimized for the types of repetitive mathematical calculations required during signal analysis.

electrical noise. Noise generated by electronic circuits, as distinct from acoustic noise.

F-40. A particular type of U.S. Navy underwater sound transducer that can project high-frequency sounds, e.g. 1-10 kHz. Used in 1991 with J-13.

faired cable. A cable with many ribbon- or hair-like attachments to reduce strumming in currents.

filter. An instrument or mechanism for restricting or altering the frequency range or spectral shape of a waveform.

fluke-out dive. A dive in which the whale raises its tail flukes above the surface of the water as it dives.

frequency. The rate at which a repetitive event occurs, measured in hertz (cycles per sec.).

GPS. Global Positioning System. A system for determining position (latitude, longitude, altitude) based on reception of signals from several of the GPS satellites that orbit the earth; horizontal accuracy 100 m or better.

hertz (Hz). A measure of frequency corresponding to a cycle per second.

high-pass filter. A filter passing only sounds above a specified frequency, to eliminate lower-frequency sounds.

hydrophone. A transducer for detecting underwater sound pressures; an underwater microphone.

impulse. see "acoustic impulse.

infrasound. Sound energy at frequencies too low to be directly audible to humans; generally taken to be sound at frequencies below 20 Hz.

intensity. See "acoustic intensity".

J-11; J-13. Particular types of U.S. Navy underwater sound projectors. The J-11 is a broadband projector (used in 1994 with or without Argotec 220); the J-13 is a low-frequency projector (used in 1991 with F-40).

Karluk. *Karluk* was a grounded ice platform that was constructed in 6 m of water near Prudhoe Bay, Alaska, during the winter of 1988-89. The *Karluk* ice platform was used as a drill-site during that winter. The underwater sounds projected during playback experiments in the 1989-90 phases of this study were recorded 130 m from *Karluk* while it was drilling during March 1989.

Lemeur. See *Robert Lemeur*.

level. The term "level" is usually applied to sound amplitudes, powers, energies or intensities expressed in dB.

Lloyd's mirror effect. The diminished pressure of a sound from an underwater source when it is received near the water/air boundary (the surface). The reflected sound wave is inverted (out of phase) with respect to the incident sound wave, and their sum at the receiver approaches zero as the receiver approaches the surface.

low-pass filter. A filter passing sounds below a specified frequency.

masking. The obscuring of sounds of interest by stronger interfering sounds.

microbar (μbar). A unit of pressure previously used as a reference pressure in dB level measurements. A μbar is equivalent to 1 dyne/cm^2 and to 0.1 pascal, or 10^5 μPa.

noise. Sounds that are not of particular interest during an acoustic study and that form the background to the sound being studied. Noise can include both natural sounds and man-made sounds.

micropascal (μPa). The usual reference pressure in underwater sound level measurements.

octave band. A frequency band whose upper limit in hertz is twice the lower limit.

one-third octave band. A frequency band whose upper limit in hertz is $2^{1/3}$ times the lower limit. Three ⅓-octave bands span an octave band. Such bands have widths proportional to the center frequency; the center frequency is given by the square root of the product of the upper and lower limit frequencies, and the bandwidth is 23% of the center frequency. There is a standard set of ⅓-octave frequency bands for sound measurements.

pascal. A unit of pressure equal to 1 newton per square meter.

peak level. The sound level (in dB) associated with the maximum amplitude of a sound.

point source. A hypothetical point from which sound is radiated. The concept is useful in describing source levels by a pressure level at unit distance. The concept is an abstraction; to describe a 300 m ship as a point source stretches the imagination, but at a distance of 10 n.mi. the received sound may as well have come from a point source radiator.

power. See "acoustic power".

power density spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where continuously distributed sound (not tones) is the important signal component. Correct units of a power density spectrum are watts/Hz but the usual units in acoustics are μPa^2/Hz, because the power is proportional to the mean square pressure and pressure is the commonly measured quantity.

power spectrum. The result of a frequency spectrum analysis to determine the distribution of power in a signal vs. frequency where tones are the important components of the signal. Correct units of a power spectrum are watts but the usual units in acoustics are μPa^2, because the power is proportional to pressure squared and pressure is the commonly measured quantity.

pre-dive flex. A distinctive concave bending of the back occasionally exhibited by bowheads while they are at the surface but shortly before they are about to dive.

pressure. A physical manifestation of sound. The dimensions of pressure are force per unit area. The commonly used unit of acoustical pressure is the micropascal.

projector. An underwater transducer used to transmit sounds; an underwater loudspeaker.

propagation loss. The loss of sound power with increasing distance from the source. Identical to transmission loss. It is usually expressed in dB referenced to a unit distance like 1 m. Propagation loss includes spreading, absorption and scattering losses.

proportional bandwidth filters. A set of filters whose bandwidths are proportional to the filter center frequencies. One octave and one-third octave filters are examples of proportional bandwidth filters.

pure tone. A sinusoidal waveform, sometimes simply called a tone. There are no harmonic components associated with a pure tone.

reflection. The physical process by which a traveling wave is returned from a boundary. The angle of reflection equals the angle of incidence.

refraction. The physical process by which a sound wave passing through a boundary between two media is bent. If the second medium has a higher sound speed than the first, then the sound rays are bent away from the perpendicular to the boundary; if the second medium has a lower sound speed than the first, then the sound rays are bent toward the perpendicular. Snell's law governs refraction: $c_2 * \sin \theta_1 = c_1 * \sin \theta_2$, where c is the sound speed, subscript 1 refers to the first medium and subscript 2 refers to the second medium, and the angles are measured from the perpendicular to the boundary. Refraction may also occur when the physical properties of a single medium change along the propagation path.

RL. Received Level; the level of sound reaching a location some distance from the sound source (*cf.* source level).

Robert Lemeur. An Arctic Class 3 icebreaking supply ship whose underwater sounds, recorded during icebreaking, were projected during playback tests in 1991 and 1994. The ship has 83 m length overall, 3184 tons gross displacement, with two turbocharged diesel engines of combined power 9600 bhp (7.2 MW). The two four-bladed controllable-pitch propellers are in Kort nozzles.

scattering. The physical process by which sound energy is diverted from following a regular path as a consequence of inhomogeneities in the medium (volume scattering) or roughness at a boundary (boundary scattering).

signal. A sound of interest during an acoustic study.

S:N. Signal-to-Noise ratio; the difference in level, measured in decibels, between a signal of interest (in this study, usually *Karluk* or icebreaker sound) and the background noise at the same location (in this study, usually ambient noise).

sonobuoy. A sound monitoring and transmitting device that includes a hydrophone, amplifier and an FM radio transmitter. Sonobuoys are designed to be dropped into the water from an aircraft. They can also be deployed from the surface. Sounds in the water can be monitored from a remote location via radio receivers.

sound. A form of energy manifested by small pressure and/or particle velocity variations.

sound pressure. The pressure associated with a sound wave.

sound pressure density spectrum. The description of the frequency distribution of sound pressure in which the actual pressure at any frequency is infinitesimal but, integration over any non-zero frequency band results in a non-zero quantity. The correct dimensions of sound pressure density spectrum are pressure squared per unit frequency; a common unit is $\mu Pa^2/Hz$. *cf.* power density spectrum.

sound pressure density spectrum level. The measure, in decibels, of sound pressure density spectrum. A common unit is dB re 1 $\mu Pa^2/Hz$.

sound pressure level (SPL). The measure, in decibels, of sound pressure. The common unit is dB re 1 μPa.

sound pressure spectrum. The description of the frequency distribution of a sound pressure waveform consisting of tones. The dimension is that of pressure; a common unit is the micropascal (μPa).

source level. A description of the strength of an acoustic source in terms of the acoustic pressure expected a hypothetical reference distance away from the source, typically 1 m, assuming that the source is a point source. Source level may be given in units of dB re 1 μPa-m. Source level may vary with frequency (see source spectrum level) but it may be given for some band of frequencies.

source spectrum level. A description in decibels of the strength of an acoustic source as a function of frequency. The description is meaningful for sources of tones. Source spectrum levels are described in decibels referred to a unit pressure at a unit distance, such as dB re 1 μPa-m.

spectrum level. See "sound pressure density spectrum level".

spherical spreading. Sound spreading as spherical waves. The transmission loss for spherical spreading is given by

$$20*\log_{10}(\mathrm{Range}/R_0),$$

where R_0 is a reference range. The received level diminishes by 6 dB when range doubles, and by 20 dB for a tenfold increase in range.

spherical wave. A sound wave whose fronts are spherically shaped. Such a wave forms in free space without reflecting boundaries or refraction. Typically, spherical waves are emitted by point sources and retain their sphericity until the influence of reflected waves or refraction becomes noticeable.

spreading loss. The loss of acoustic pressure with increasing distance from the source due to the spreading wavefronts. There would be no spreading loss with plane waves. Spreading loss is distinct from absorption and scattering losses.

SSDC. Single Steel Drilling Caisson or Steel-Sided Drilling Caisson; this is a mobile bottom-founded drilling platform constructed from part of a supertanker.

surfacing. As defined in this study, a surfacing by a whale is the interval from the arrival of the whale at the surface following one long dive until the start of the next long dive. Periods while the animal is just below the surface between breaths (blow intervals) are not counted as dives. Equivalent to the term "surfacing sequence" used by some authors.

threshold of audibility. The level at which a sound is just detectable. The threshold of audibility depends on the listener and varies with frequency.

third octave. Abbreviation for one-third or ⅓ octave (see above).

time delay. A time difference between related events, such as the time between arrivals of a sound wave at two receivers, or the time between sound transmission and the reception of its reflection.

tone. A sinusoidal waveform, sometimes called a pure tone. There are no harmonics. A tone is distinct from waveforms consisting of components continuously distributed with frequency.

transducer. A device for changing energy in one form (say mechanical) into energy in another form (say electrical). An acoustic transducer might change a pressure waveform into an electrical waveform, or vice versa. Microphones, hydrophones, and loudspeakers are examples of transducers.

transmission loss. The loss of sound power with increasing distance from the source. Identical to propagation loss. It is usually expressed in dB referenced to a unit distance like 1 m. Transmission loss includes spreading, absorption and scattering losses.

Twin Otter (de Havilland). A relatively small (≤5670 kg gross weight) fixed-wing utility aircraft commonly used for offshore aerial surveys. Two PT6A gas turbine engines totalling ~1200 shp turn 3-bladed propellers, producing a family of tones with fundamental frequency about 83 Hz.

VLF Navigation (Very Low Frequency). VLF/Omega navigation systems, based on very long-wavelength radio transmissions, have been widely used for aircraft navigation, especially in remote areas where LORAN was not usable. Accuracy variable, often deteriorating during a flight. Now being replaced by GPS in most applications.

waterfall spectrogram. A graphical depiction of the intensity of sound components at various frequencies over time. Time and frequency are shown on the X and Y axes, and intensity is shown as a third dimension. A waterfall graph may indicate only relative powers.

waveform. The functional form, or shape, of a signal or noise vs. time.

wavelength. The length of a single cycle of a periodic waveform. The wavelength λ, frequency f, and speed of sound c are related by the expression $c = f*\lambda$.

1. INTRODUCTION[1]

The possible effects of underwater noise from offshore oil and gas activities have been a significant concern to Minerals Management Services (MMS), the National Marine Fisheries Service (NMFS), and other agencies for several years. Hence, MMS has funded studies to document the characteristics of oil industry noises and their effects on the behavior of bowhead and gray whales (e.g. Gales 1982; Malme et al. 1984; Richardson et al. 1985b; Miles et al. 1987; Ljungblad et al. 1988). The oil industry has funded related monitoring studies of the reactions of bowhead whales to oil industry operations in the Alaskan Beaufort Sea (e.g. LGL and Greeneridge 1987; Hall et al. 1994). These and other similar studies have been reviewed by Richardson and Malme (1993) for bowheads, and by Richardson et al. (in press) for marine mammals in general.

Prior to this study, all systematic studies of disturbance to bowheads had been done in summer or early autumn when the whales are either in open water or in loose pack ice where their movements are relatively unrestrained by ice. There had been no work on the disturbance reactions of bowheads migrating in leads through areas of heavy ice cover—the normal situation in spring. Also, there had been no systematic scientific study of the suggestion by Inupiat whalers that bowhead whales are especially sensitive to noise in the spring.

The sounds considered in the summer-autumn studies conducted in the Beaufort Sea have been those associated with some of the major offshore exploration activities: aircraft and boat traffic, marine seismic exploration, drillships, and offshore construction. Previous to this project, only a very limited effort had been devoted to the reactions of bowheads to icebreaking, which is a particularly noisy activity (e.g. Greene 1987a; Thiele 1988; reviewed in Greene and Moore in press:117*ff*). Reactions of bowheads to sounds from an oil production platform had not been studied, in part because no production platforms exist in arctic waters deeper than a few meters. Reactions of migrating gray whales to noise from a production platform were studied by Malme et al. (1984), but the type of platform involved was very different from the types likely to be used in the Arctic.

The National Marine Fisheries Service took note of the above situation in its Biological Opinions on lease sales in the Beaufort and Chukchi seas. NMFS believed that development and production activities in spring lead systems used by bowheads might, in certain circumstances, jeopardize the continued existence of the Western Arctic bowhead whale population (Evans 1987; Brennan 1988; Fox 1990). The possibility of significant disturbance in spring lead systems, when bowheads may have few or no optional migration routes, was one of the factors about which NMFS was concerned.

The beluga or white whale is the one other cetacean that migrates through the spring lead systems in a manner similar to the bowhead. The sensitivity of various populations of white whales to several types of human activities and underwater noises has been studied in summer in Alaska, in late spring and summer in the Mackenzie Delta area, and in spring in the eastern

[1] By W.J. Richardson

Canadian High Arctic. There has also been a playback study with captive white whales (Thomas et al. 1990). The sensitivity of the white whales in these situations varied widely. There was great tolerance in some situations. However, white whales exhibited strong avoidance reactions to ships and icebreakers at very great distances during spring in the eastern high arctic (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990). The responsiveness of white whales to underwater noise during the spring migration around western and northern Alaska had not been studied previous to this project.

Bowhead and white whales are both important to subsistence hunters in Alaska. An assessment of the potential effects of industrial activities on subsistence hunting is beyond the scope of this project. However, if industrial sounds affect the availability of these species to subsistence hunters, there could be economic, social, cultural, and political implications.

To answer some of these questions, MMS funded this study. The main objectives were to determine the short-term effects of production platform noise and icebreaker noise on the movements and behavior of bowhead and white whales migrating through open leads and pack ice near Pt. Barrow, Alaska, in spring. A related objective was to determine the characteristics of sound propagation and of natural ambient noise in spring lead systems. These physical acoustic phenomena affect the received levels and prominence of man-made noise. Reactions of whales to helicopter overflights were also to be determined when possible.

This report describes results from 1991 and 1994, the third and fourth years of the study. In 1989-1990, we obtained

- considerable information on physical acoustic phenomena (ambient noise and sound propagation) in spring lead systems,
- considerable data on reactions of bowhead and white whales to playbacks into spring lead systems of continuous sounds from one drilling platform—a rig on a bottom-founded ice pad, and
- limited data on reactions of bowhead and white whales to the Twin Otter fixed wing aircraft and the Bell 212 helicopter (Richardson et al. 1990a, 1991a).

In 1991 and 1994, our highest priority objective was to determine the reactions of bowhead and white whales to a second type of industrial noise, the variable noise from an icebreaker that was actively breaking ice. There were several additional related objectives (see below).

Weather and ice conditions were generally unfavorable for this type of work near Barrow, Alaska, during the spring of 1991. In 1991, we obtained additional information about physical acoustic phenomena and whale movement patterns past Barrow, but results from the playback experiments with icebreaker noise were very limited. Consequently, the Minerals Management Service decided to continue the project for another spring season, and to cancel the requirement for a detailed report on the 1991 data. The additional fieldwork was not possible in 1992 or 1993 because of concern about the potential for interference with bowhead censusing efforts underway in those years. Consequently, the fourth field season was delayed until 1994.

This report was planned and funded to describe results from 1991 and 1994, years 3 and 4 of the study, not as an integrated account of results from all four years of the study. Results from 1989 and 1990 were described in Richardson et al. (1990a, 1991a). However, some sections of the present report do incorporate data from 1989-90 as well as 1991 and 1994. These include the sections on acoustic transmission loss (§4.3), the activities of undisturbed bowheads in the study area during spring (§5.1-5.4), the migration of white whales during spring (§7.1), and the reactions of both species to aircraft (§6.7 and §7.4). These comprise most of the sections for which data were collected in comparable ways during 1989-90 and 1991/94. The top-priority acoustic playback work in 1989-90 involved playback tests of whale reactions to steady low-frequency drilling sounds, whereas the corresponding work in 1991 and 1994 tested reactions to more variable and wider-bandwidth icebreaker sounds. Thus, the 1989-90 and 1991/94 playback data cannot be combined, although the two sets of results can be compared. Sections 6.1-6.6 and 7.2 of this report present the 1991/94 icebreaker playback results, and compare them with the previously-reported 1989-90 drilling noise playbacks.

1.1 Objectives and Rationale

General Objectives

In early 1988, MMS requested proposals for an experimental study of the effects of noise from oil production activities on bowhead and (secondarily) white whales during their spring migrations around Alaska. The overall objectives of the study, as defined by MMS, were

1. "To quantitatively characterize the marine acoustic environment including sound transmission loss and ambient noise within the nearshore leads of the Alaskan Chukchi Sea and Beaufort Sea in the spring.

2. "To quantitatively describe the transmission loss characteristics of underwater sound produced by production platforms and icebreakers in the spring lead study area.

3. "To quantitatively document the short term behavioral response of spring migrating bowhead and, as possible, beluga [white] whales resulting from exposure to the [above] sources (see objective 2) of production sounds.

4. "To assist and coordinate with other MMS sponsored studies and local resource users to maximize collection of needed data and avoid conflict with subsistence whaling activities.

5. "To analyze acquired and synthesized data to test the generalized null hypothesis."

Rationale for Various Study Components

The rationale for studying topics such as sound transmission loss, ambient noise levels, and received sound levels near whales requires some explanation. These data are needed in order to develop quantitative models for predicting the radii of noise detectability and noise responsiveness around the specific types of noise sources that are tested. The basic components and interrelationships of this model are illustrated in Figure 1.1.

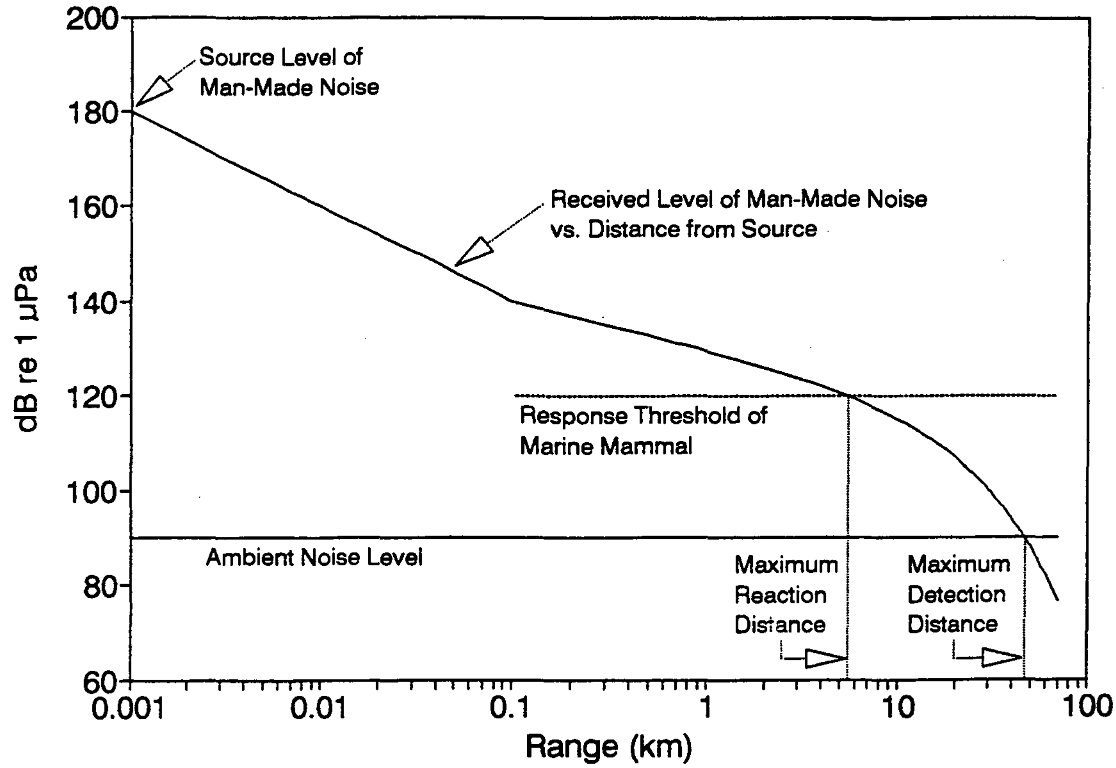

FIGURE 1.1. Components of a simple zone of acoustic influence model. See text for explanation.

The underwater noise received from an industrial source diminishes in level with increasing distance from the source. The rate of transmission loss depends on water depth, bottom conditions, ice conditions, and other factors. Hence, the slope of the received level vs. range curve illustrated in the diagram can vary from place to place and time to time. The transmission loss properties of a particular study area need to be studied during the season of interest to make meaningful predictions of received noise levels as a function of range.

The level of the natural ambient noise has a major influence on the maximum distance to which man-made noise can be detected. Man-made noise is normally detectable by an animal (or hydrophone) if its received level exceeds the level of natural background noise at similar frequencies. The range at which the received level of man-made noise diminishes below the ambient noise level is, to a first approximation, the maximum radius of detectability (Fig. 1.1). Beyond that distance, the man-made noise will be weaker than the natural background noise, and is likely to be undetectable. Closer to the source of man-made noise, the received level of man-made noise will exceed the ambient noise level and the man-made noise is likely to be detectable. Ambient noise levels vary naturally from day to day as a function of wind, waves, ice conditions, calling rates by animals, and other factors. Day-to-day variations of ±10 dB or even ±20 dB are not uncommon. A 10 or 20 dB change in the ambient level has a drastic change on the range at which the received level of man-made noise falls below the ambient noise level, and thus on the radius of detectability of the man-made noise. Hence, it is important to characterize the typical ambient noise levels in the study area and season, the normal range of variation of these ambient noise levels, and the factors affecting ambient noise levels in any particular circumstance.

In most previous studies of the disturbance reactions of marine mammals, it has been found that disturbance responses do not begin until the received level of man-made noise exceeds the minimum detectable level by a substantial margin. This has been the case in studies of bowhead whales, including the 1989-90 phases of this study. Thus, the received level of man-made noise diminishes below the response threshold before it diminishes below the ambient noise level and becomes inaudible (Fig. 1.1). To quantify the responsiveness of bowheads and white whales to man-made noise, it is necessary to determine the response threshold level. This will not be a constant. Whale responsiveness varies considerably. As a minimum, the average response threshold should be determined. If sample size allows, the noise levels to which various percentages of the animals react should also be determined. The lower the response threshold, the greater the distance at which the received level of man-made noise will diminish below that threshold.

One additional component of the zone of acoustic influence model is the source level of the man-made noise. An increase in source level will shift the received level vs. range curve upward by a corresponding amount. This shift will result in an increase in the distances at which the received level diminishes below the response threshold (= maximum reaction distance) and the ambient noise level (= maximum detection distance).

In many cases the source level of the sounds emitted during a playback experiment is less than that of the actual industrial activity being simulated, e.g. due to projector limitations. If the source levels of the projector and the actual industrial activity are known, along with the other components of the model (Fig. 1.1), then it is possible to estimate the maximum reaction and detection distances around the actual industrial site based on the results collected near the projector. This assumes that a given received level of sound from the projector causes the same reaction as the same received level of sound from the actual industrial source. This assumption is discussed as item (3) in §1.3, Assumptions and Limitations.

Thus, by considering the source level of man-made noise, its propagation loss, the ambient noise level, and the response threshold of whales, a meaningful quantitative model of acoustic influence can be developed, given various assumptions. This study aims to collect the types of data needed to quantify, for particular situations, the conceptual model illustrated in Figure 1.1. Section 6.4 of this report develops a preliminary model of this type for reactions of spring-migrating bowheads to playbacks of icebreaker sound (Fig. 6.26, p. 314). Section 6.5 compares it to a similar preliminary model concerning their reactions to steady drilling sound. The model for drilling is based mainly on our 1989-90 work (Richardson et al. 1991a).

<u>Specific 1991 and 1994 Objectives</u>

The specific objectives of the 1989-90 and the 1991/94 phases of this project were similar, except that a different type of industrial sound was to be used during sound playback experiments in 1991/94. Specific objectives in 1989-90 were listed by Richardson et al. (1990a:17, 1991a:5). As in 1989-90, physical acoustic measurements—including data on received sound levels near whales, sound propagation loss, and ambient noise—were necessary to interpret the 1991/94 playback results. Because of concern about the effects of low-frequency industrial sound components on bowheads, and the inability of a practical sound projector to reproduce those components, indirect methods of addressing the importance of low-frequency components were again identified as objectives in 1991/94 (see specific objective 5, below). As a lower priority, the reactions of bowhead and white whales to actual helicopter overflights again were to be determined if opportunities allowed.

The first of the specific objectives for the third and fourth years of the project involved work during the winter, not the spring:

1. To record sounds from the SSDC caisson while it was drilling during winter conditions, including infrasonic components, and to analyze those sounds to determine their levels, spectral characteristics, and attenuation properties.

It had originally been thought that this effort might provide a suitable sound stimulus for use during playbacks in years three and/or four of the study. However, it was later decided that a recording of underwater sounds from the Canmar icebreaker *Robert Lemeur* while it was actively breaking ice would be more appropriate for playbacks in 1991 and subsequently in 1994.[2] The icebreaker sounds used for the 1991/94 playbacks vary widely during the duration of the recording. It was agreed that reactions of whales to these variable sounds, relative to their reactions to the steady *Karluk* drilling platform sounds tested in the 1989-90 playbacks, would be of much interest. Tests of the reactions of whales to icebreaker sounds had been identified by MMS as one of the top priority objectives since the beginning of the project.

Only a few data on reactions of bowheads and white whales to icebreaker sounds were obtained in 1991 (year 3) because of difficult weather and ice conditions. Therefore, specific objectives for the spring work in 1994 (year 4) were essentially unchanged from those in the spring of 1991:

2. To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.

3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of *(a)* test tones at selected frequencies, and *(b)* continuous industrial sounds. Infrasonic components cannot be projected, as discussed on page 10, item (3).

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[2] Winter drilling from the icebound SSDC (Steel-Sided Drilling Caisson), which operated in the Alaskan Beaufort Sea during the winters of 1990-91 and 1991-92, was considered a potentially suitable source of sounds for playbacks. Drilling by the SSDC ceased early in December 1990, before the caisson operator considered it practical for us to make the desired field measurements. Hence, this objective was not met in 1990-91. In the absence of a suitable recording of drilling noise from an icebound caisson, it was decided to use icebreaker sounds as the playback stimulus during the spring of 1991. The SSDC drilled again at another site east of Barrow during the winter of 1991-92, and SSDC sounds were recorded in January 1992. Thereafter, discussions were held with the project's Scientific Review Board, the Barrow Whaling Captains' Association, and the Minerals Management Service to determine whether to use the icebreaker or the SSDC sounds during the fourth spring season of playback work in 1994. It was agreed to continue using the icebreaker sound.

4. To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of variable icebreaker sounds. Infrasonic components cannot be projected.

5. To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, *(a)* to measure ambient noise at infrasonic frequencies, and *(b)* to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990). Also, based on the winter recordings of SSDC sounds (specific objective 1), we were *(c)* to determine the frequencies, levels and attenuation of the infrasonic components of drilling caisson sound.

6. To measure, on an opportunistic basis, the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to actual helicopter overflights (supplementing limited data from 1989-90).

7. To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment of bowhead and white whales along their spring migration corridor in the western Beaufort Sea.

8. To assist and coordinate with other studies and local resource users to maximize collection of needed data and to avoid interference with subsistence whaling and other studies.

9. To analyze the data to test hypotheses concerning the effects of the icebreaker sounds and helicopter overflights mentioned in (4) and (6) on *(a)* the movement patterns and *(b)* the behavior of bowheads and white whales visible along their spring migration corridor in the western Beaufort Sea.

Significant progress has been made toward meeting all nine objectives during the four spring seasons. Several objectives—2, 3, 5a, 7 and 8—can be considered "achieved". Some data on the responsiveness of spring-migrating bowheads and white whales to playbacks of steady drilling noise and variable icebreaker noise were obtained, along with some data on responsiveness to actual aircraft overflights (objectives 4, 6 and 9). However, better quantification of whale responses to these activities than achieved in this study would be desirable. Similarly, objectives 1 and 5b,c were partially met, but additional data would be helpful.

1.2 Null and Alternate Hypotheses

MMS initially indicated that the *primary purpose* of the study was to test the following generalized null hypothesis:

> "Noises associated with offshore oil and gas production activities *will not* significantly alter the migratory movements, spatial distribution, or other overt behavior of bowhead whales during the spring migration in the eastern Chukchi and western Beaufort Seas."

MMS indicated that the *secondary purpose* of this study was to test a similar generalized null hypothesis concerning white whales.

During the planning phase of this study, the hypotheses to be assessed were made more specific by adding more specific wording about four topics: (1) the types of oil and gas activities of concern, (2) the criteria of whale behavior to be considered, (3) the geographic location and environmental circumstances of the tests, and (4) the fact that playback techniques were to be used to simulate the noise from some production activities. Four null hypotheses of a more specific nature were developed for each of the two whale species:

1. Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
2. Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
3. Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
4. Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

MMS indicated that greater emphasis should be placed on hypotheses (1) and (3) relating to effects on migration routes and distribution, than to hypotheses (2) and (4), relating to subtle aspects of the behavior of individual whales. However, we undertook to address hypotheses (2) and (4) as well, at least for bowheads. Difficulties in observing some aspects of the individual behavior of white whales from an aircraft circling at high altitude made it doubtful whether hypotheses (2) and (4) could be assessed for white whales.

Hypotheses 1 and 2 have already been addressed with respect to the effects on ***bowheads*** of playbacks of recorded continuous noise from a bottom-founded platform like *Karluk* (Richardson et al. 1991a:226*ff*, 246*ff*). We concluded that, at least in the circumstances studied,[3] *Karluk* playbacks resulted in statistically significant small-scale changes in migration routes, spatial distribution, and individual behavior. However, there was no evidence of migration blockage, and we concluded that the observed effects were likely to be biologically non-significant. (By biologically non-significant, we mean "Would be unlikely to affect the long-term well-being or reproductive productivity of individuals or of the population.") We have discussed elsewhere the

[3] For whales visible in open water amidst the pack ice and in the seaward side of the nearshore lead system during spring migration east of Pt. Barrow, Alaska.

numerous complications and limitations in applying these 1989-90 results from playback tests with one type of industrial sound to the situation of an actual drilling platform operating in or near a spring lead system (Richardson et al. 1991a:10*ff*, 261*ff*). One purpose of the 1991/94 tests with a second and more variable type of industrial sound was to evaluate the generality of the 1989-90 results. Section 6.6 of this report addresses hypotheses 1 and 2 as regards reactions of spring-migrating bowheads to playbacks of icebreaker noise.

Hypothesis 1 has also already been addressed with respect to the effects on ***white whales*** of playbacks of the *Karluk* sounds (Richardson et al. 1991a:281). We concluded that, in the circumstances studied (see footnote [2]), playbacks of *Karluk* sounds had detectable but biologically non-significant effects on migration routes and spatial distribution of white whales. Again, various complications and limitations apply. Hypothesis 2, concerning effects on individual behavior, could not be tested for *Karluk* drilling sounds vs. white whales. Section 7.3 of this report addresses hypothesis 1 as regards reactions of spring-migrating white whales to playbacks of icebreaker noise.

Hypotheses 3 and 4, relating to effects of helicopter overflights on bowheads and white whales, were not formally tested during the 1989 or 1990 phases of the work. Relevant data were obtained in 1989-90, but this work was given a low priority; the 1989-90 data were opportunistic. Further relevant data of the same types were obtained in 1991 and 1994, and hypotheses 3 and 4 are evaluated in §6.7 and §7.4 of this report for bowheads and white whales, respectively.

1.3 Assumptions and Limitations

A number of assumptions had to be made in designing an experimental field study that would address the general project objectives and the specific 1989-94 objectives. This section lists several assumptions that may need to be made in using the results to predict the reactions of whales to actual oil industry operations. Associated with most of these assumptions are various limitations.

(1) The study area, located NE, ENE and E of Point Barrow, is assumed to be reasonably representative of locations where bowheads and white whales migrating around northern Alaska in spring might encounter oil industry activities.

> ***Limitations***: *(a)* The applicability of the 1989-94 results to the Chukchi Sea is not verified. All 1989-90 data were necessarily obtained in the western Beaufort Sea. However, it is noteworthy that sound propagation conditions in the western Beaufort Sea during spring (this study) are similar to those in the Chukchi Sea during late winter-early spring (Greene 1981)—see §4.3 (p. 115).
>
> *(b)* Water depths at many 1989-94 study locations were greater than those where bottom-founded drilling and production platforms are likely to be constructed. Water depth affects sound propagation.

(2) In order to draw conclusions about *all* whales migrating around northern Alaska in spring, it would be necessary to assume that whales visible in leads and amidst the pack ice (i.e. those studied here) react to underwater noise in about the same way as those that are not visible. The accuracy of this assumption is unknown, so we restrict our discussion (and the title of the report) to whales *visible* during spring migration.

> ***Limitations***: *(a)* Some whales migrate along the open nearshore lead, others through extensive leads and cracks in the pack ice, and others through closed-lead or heavy pack ice conditions. The likelihood of detecting whales differs greatly among these three habitats. Also, once detected, the likelihood of successfully observing them for a prolonged period differs greatly among habitats. Almost all 1989-94 data on reactions to noise were from whales migrating through open pack ice or along an open nearshore lead. We obtained no data on whales migrating through closed lead conditions, and very few data on whales traveling through heavy pack ice (but see 30 April 1989 results—Richardson et al. 1990a:174).
>
> *(b)* Even in open pack ice, some individual whales are likely to behave in ways that make them more visible than other whales. Because observations are concentrated on the area close to the noise source, whales that come close to the source are most likely to be seen. This "observability bias" was a problem in 1989, when heavy ice hindered observations, and 1991, when aerial observations were not possible during playbacks, but it was less of a problem in 1990 and 1994.
>
> *(c)* Because of masking problems, acoustic monitoring and localization methods are not as useful in a noise playback study as in a study of undisturbed whales.
>
> *(d)* Relatively low numbers of whales were observable during playbacks in the area where this study had to be conducted (§1.4, Study Area). Sample sizes during playbacks are shown later in this report, in Tables 2.2, 6.1 and 6.2 (see §2.2 and §6.1).

(3) Underwater playback of recorded underwater sounds from an industrial operation is assumed to be a useful method for evaluating the likely reactions of whales to actual industrial operations of corresponding types.

> ***Limitations***: *(a)* Underwater playback techniques simulate the sounds emitted by an industrial site, but exclude other stimuli to which whales may be sensitive, e.g. sight, smell, effects of physical presence on water flow. This is an advantage in the sense that it allows an assessment of the effects of noise *per se*, but a disadvantage in that the playback does not simulate all aspects of the actual industrial operation.
>
> *(b)* The types of sounds available for use in this study were limited. ▸ It is uncertain how closely the *Karluk* drilling sound and the *Robert Lemeur* icebreaker sound resemble sounds that would emanate from future oil industry activities in or near spring lead systems. To date, neither drilling nor production have been done in or near spring lead systems off northern Alaska, so it has been impossible to record or study the sounds emitted by such an operation. ▸ Also, icebreaker sound is unlikely to be commonly associated with future oil

production activities in or near leads used by migrating whales in spring. ▸ However, the steady, low-frequency drilling sounds and the variable, broader-bandwidth icebreaker sounds used during the playbacks represent a wide range of noise characteristics. Whales may react in a similar way regardless of the specific type of industrial noise used for playbacks, provided that it is continuous (Malme et al. 1984; Richardson et al. 1991b, in press). Nonetheless, any extrapolation of the 1989-94 playback results to situations involving other types of industrial sounds would be speculative.

(c) Sounds emitted during playbacks do not simulate the full range of sounds that an actual industrial site would emit over time. In 1989-90, we repeatedly projected a 3-minute segment of sounds emitted by the *Karluk* drillsite while it was drilling, simulating a continuous drilling operation with no interruptions. There was no attempt to simulate the noise from other activities that occur intermittently on a drillrig. In 1991/94, we repeatedly projected a 14.3-min segment of sounds emitted by one icebreaker operating in a particular type of ice conditions at one site. Icebreaker noise varies somewhat depending on the vessel and the circumstances of operation.

(d) Sounds emitted during playbacks do not simulate the full frequency range of sound and vibration emitted by an industrial site. ▸ Procedures used in 1989-90 provided a reasonable simulation of the components of *Karluk* sound within the 50 to 12,000 Hz band. Procedures used during most playbacks in 1991/94 provided a reasonable simulation of the components of icebreaker sound within the 40 to 6300 Hz bands, and probably up to 12,000 Hz. To the human ear, the projected *Karluk* and icebreaker sounds, as received by hydrophone or sonobuoy 100 m to 1+ km from the projector(s), strongly resembled the original recordings of *Karluk* and icebreaker sounds. ▸ However, the playback systems used in 1989-90 and 1991/94 underrepresented the components at frequencies below, respectively, 80 Hz and 40 Hz, and especially the components below, respectively, 63 Hz and 32 Hz (see Richardson et al. 1991a:88 for 1989-90, and §4.4 for 1991/94). ▸ White whales are not sensitive to these low frequency components unless their levels are very high (§7.2). Hence, the inability to project them was not a problem during playback tests on white whales. However, bowhead whales are expected to be sensitive to these low frequency components. ▸ In summer, bowheads seem at least as sensitive to playbacks of drillship and dredge sounds as to actual drillships and dredges (Richardson et al. 1990b), suggesting that playbacks can provide relevant data.

(e) The rate of change of received sound level with increasing distance (sound gradient) may be steep near a playback site, potentially causing stronger reactions than with shallower gradients (Ellison and Weixel 1994a,b). When the playback source level is less than that of the human activity being simulated, a given received sound level will occur closer to the playback site than to the actual source. The gradient usually diminishes with increasing range. Whales approaching through a steep gradient close to a playback site would be exposed to a more rapidly increasing sound level than would those swimming at the same speed through an equally strong but shallower gradient farther from the actual source. Whales often seem to be more responsive to rapidly changing sound (Richardson et al. in press). If so, a given sound level may have more effect on traveling whales when it comes from a "weak" source nearby (e.g. playback) as compared with a strong source farther away (e.g. icebreaker). If

so, the reaction threshold to the full-scale noise source would be less than that estimated by playbacks simulating that source. Differences in the vertical position of the playback vs. actual sources, and in their acoustic coupling into the bottom, may also affect the propagation and received level of the sound.

(4) It is assumed that the presence of the observers did not bias the results significantly. Three potential problems existed (see below). However, the potential for bias was limited, and comparison of playback vs. control data provided meaningful data.

Limitations: *(a)* Whales are known to react to aircraft overflights in some situations; many of the 1989-90 and 1994 observations were obtained from an aircraft circling above the whales. However, studies in summer and autumn, corroborated in this spring study (§6.7), indicate that an observation aircraft circling over bowheads very rarely causes any overt disturbance reaction provided that it remains at an altitude of at least 460 m (1500 ft) at a low power setting, and avoids passing directly over the whales (Richardson and Malme 1993). Opportunistic observations suggest that white whales also tolerate aircraft at that height (reviewed by Richardson et al. 1991b, in press; this study, §7.4). Given this, and the fact that we excluded behavioral observations from periods when the aircraft was below 460 m, the presence of the aircraft is not considered to be a significant problem.

(b) The projected drillsite noise came from a small camp located on the edge of an ice pan. This camp, including the ice-based personnel, may have been visible to some of the closer whales while they were at the surface. However, reactions to visual cues would be minimized by the small size of the ice-based operation, the limitations of vision through the air-water interface, and the frequent presence of visual obstructions (ice floes) between the camp and the whales. In 1991/94, personnel at the ice camp wore long, white snow-shirts to reduce their visual conspicuousness. Also, interpretation problems arising from any non-acoustic effects that do exist can be minimized by comparing behavior of whales passing the camp when the projector is operating vs. silent.

(c) It was necessary to use a small gasoline-powered generator at the ice camp during playbacks. For consistency, the generator was also operated during most control periods, whether or not it was needed as a power source. The generator emitted underwater noise, which was detectable underwater within a few hundred meters of the campsite during control (quiet) periods in 1989-90. There may have been some short-range responses to acoustic (or non-acoustic) cues from the camp itself during 1989-90. However, these cannot explain the more pronounced responses observed during projection of drilling noise than when the projector was off. In 1991 and 1994, underwater noise from the generator was greatly reduced through use of a suspension system (§4.6).

(5) It is assumed that disturbance of whales is evident by visual observations of their distribution and movements near the noise source, and (for bowheads) visual observations of the details of their individual behaviors. Previous studies have shown that bowhead and white whales often react in visually observable ways when subjected to strong noise from actual or simulated oil industry operations.

Limitations: *(a)* Even the most conspicuous whales are visible for only a fraction of the time—typically less than 20% in migrating bowheads. Whales migrating past a disturbance source are often below the water and invisible when at their closest point of approach. During periods while whales are underwater or under ice, it usually is not possible to observe them directly. However, some aspects of their movements underwater or under ice often can be inferred from their diving and re-surfacing positions, headings, and times. Also, migrating whales occasionally travel at sufficiently shallow depths such that aerial observers can see them below the surface throughout part or all of a dive in open water. This was common on some days in 1990, including the playbacks on 11, 13 and 16 May 1990.

(b) The calling rates of whales could not be compared under playback vs. control conditions. Some other studies of whales have suggested, often based on equivocal evidence, that call rates diminish in the presence of man-made noise. This could not be studied here because the majority of the calls heard in the absence of projected noise would be undetectable due to masking even if they were present during playbacks.

(c) No direct measure of physiological stress is possible during field observations of passing whales. However, in the case of bowheads, surfacing, respiration and diving cycles were monitored quantitatively. These variables may provide indirect and limited indications of stress. These variables could not be observed reliably for white whales, so we had no similar indicator for that species.

(d) No data of any type could be collected on any whales that avoided detection, e.g. by remaining amidst heavy ice. This was not considered to be a significant problem in 1990 or 1994 (see limitation 2b, above).

(e) This study concerns the short-term reactions of migrating whales, mainly to two sources of man-made noise. The long-term consequences with respect to the well-being of individuals and the population are not addressed directly.

(6) To perform meaningful tests of hypotheses about disturbance effects on bowheads and belugas, it is necessary to have adequate data. The lack of a statistically significant disturbance effect does not prove the absence of a disturbance effect. A statistical power analysis will indicate how large a disturbance effect might have occurred without being detectable statistically.

Limitations: Because of logistical constraints, sample sizes for most types of disturbance observations in this study are small. Nonetheless, playbacks of both drilling and icebreaker sound were shown to cause statistically significant effects on bowhead behavior. Thus, the limited sample sizes and limited power are not central issues in determining whether the null hypotheses of "no disturbance effect from playbacks" can be rejected. The limited sample sizes and limited power are, however, an issue in evaluating the threshold distances and threshold sound levels at which disturbance become detectable. Section 6.3 (p. 290-295) includes analyses of the power of this study to detect whether disturbance effects from icebreaker playbacks occurred at various received sound levels and icebreaker-to-ambient ratios.

(7) Evaluations of potential disturbance radius often assume that ambient noise levels and propagation loss rates are average, or are equal to those at a particular date and time. Also, it is often assumed that a given human activity is representative of other activities of the same general type, e.g., that icebreaking by the specific icebreaker whose sounds were used in the 1991 and 1994 playbacks is representative of icebreakers in general.

> ***Limitations***: (a) There is much variability in ambient noise levels and propagation loss rates in leads and below pack ice during spring. Therefore, a given received sound level or signal-to-ambient ratio may occur at widely differing distances from a particular noise source, depending on physical factors such as ice cover, water depth, wind speed, bottom conditions, etc. If marine mammals begin to react at a given received sound level or a given signal-to-ambient ratio, reaction radii are expected to vary drastically depending on these physical factors. This variability is added to the variability in expected reaction radii caused by differences in the responsiveness of different animals. This topic is discussed in §6.4.
>
> (b) There can be differences in the levels and spectral characteristics of the sounds emitted by different human activities of a given class, e.g., different icebreakers. *Robert Lemeur*, the icebreaking supply ship whose sounds were used in the 1991 and 1994 playbacks, is a relatively low-powered icebreaker (9600 bhp or 7.2 MW).

1.4 Study Area

In choosing a study area, it was necessary to compromise between choosing *(a)* an area where many whales would be encountered in situations where playbacks and observations were practical, and *(b)* an area where project activities would not interfere (or be perceived to interfere) with native subsistence whaling or other scientific studies.

Local Concerns

This study could not have been conducted if it had been opposed by local organizations such as the North Slope Borough (NSB), the Alaska Eskimo Whaling Commission (AEWC), or the Barrow Whaling Captains' Association (BWCA). Strong opposition would have occurred if the proposed study site were southwest of the northeasternmost of the spring whaling communities (Barrow). Whalers would have been strongly concerned about a proposed disturbance experiment anywhere "upstream" (south or southwest) of any whaling site. They would have been concerned that such a study might block the passage of some whales, or interfere with the subsequent timing or route of the whale migration past the whaling community. For the same reasons, the study area could not have been near Barrow itself.

In addition, for almost two decades there has been a spring bowhead census near Pt. Barrow in certain years. In 1988, a very intensive census effort was conducted, and in 1989 a scaled-down census effort was planned for late April and May. A minor effort was planned again for 1990 but no work was actually conducted in 1990 or 1991. A full-scale census was attempted in 1992 (unsuccessful due to ice conditions) and again in 1993 (successful). This census at Barrow has been very important to the local people, to U.S. regulatory agencies, and to the International

Whaling Commission. The census and data analysis procedures depend on the consistent migratory behavior of the whales. Disturbance-related changes in swimming speeds, average distance from the ice edge, or whale headings could affect the census results. Also, if background noise levels at acoustic monitoring sites were elevated because industrial sounds were being projected into the water nearby, the range of effective acoustic monitoring (and especially of call localization) would be reduced. Any real or potential interference with the census was unacceptable to a variety of local, national, and international interests.

Given these considerations, the project would not have received local acceptance if the proposed field site were anywhere near or southwest of Barrow. Locations well to the east of Pt. Barrow appeared to be the only locations that might be acceptable to local people and to agencies concerned about the whale census.

Specific Study Locations

As part of the planning process for this study, Miller (1989) reviewed the available information on ice conditions and on whale distribution in the area east and northeast of Pt. Barrow during spring. Results of this review are summarized in Richardson et al. (1990a:2-12). Logistically, the most advantageous location for the study area and ice camp was expected to be along the landfast ice edge where a semi-permanent camp might be established. However, the literature reviewed by Miller (1989) indicated that, in most years, few whales are found along the landfast ice edge more than about 35 km east of Barrow. This was confirmed by our 1989-91 studies, although 1994 was an exception (§5.1). Farther east, most whales in most years move offshore into the seaward side of the nearshore lead or into the pack ice beyond the nearshore lead.

Thus, during most if not all years, the best location for the sound projector would be along the landfast ice edge within 35 km of Pt. Barrow. Given that such a site might be too close to whaling and census areas, LGL recognized from the start of the planning process that the projector might have to be set up on pack ice northeast of Pt. Barrow. However, the whale migration corridor widens as the whales travel east of Pt. Barrow, reducing the numbers of whales expected to pass close to any given site. Also, logistic support becomes more difficult with increasing distance to the east. Dedicated helicopter support was essential for work on the pack ice.

Given the above, it was desirable to work as close to Barrow as possible without causing real or perceived interference to whaling and to the census. The most appropriate distance east of Barrow was determined through an acoustic modeling study (Malme et al. 1989; included as p. 261-284 *in* Richardson et al. 1990a) and consultation with local Barrow organizations, individuals, and scientific investigators.

In ***1989***, to provide convincing "safety" margins and to avoid opposition from the various concerned groups, we selected an area about 60 km (32 n.mi.) NE or ENE of Pt. Barrow as the approximate location for the industrial noise playback experiments. We also undertook not to fly within 10 km of the census or whaling sites (unless these were within 10 km of Barrow's airport). The specific locations of the main ice-based and aerial work in 1989 and subsequent years of the study are mapped later, in §3.2 (Fig. 3.2-3.9) and §5.2 (Fig. 5.19, 5.21).

The 1989 study showed that we could conduct the work without interfering with whaling. Therefore, in ***1990*** and ***1991***, after consultation with the BWCA, AEWC and NSB, it was agreed that we could work closer to Barrow. In 1990, it was agreed that our projector sites would be at least 15 n.mi. (28 km) northeast or east of the northeasternmost whaling camp. At any times when the bowhead census crew was working on the ice, we undertook to keep the projector at least 20 n.mi. (37 km) away. In addition, we again undertook not to fly within 10 km of the whaling or census sites except as necessary to take off or land at Barrow. The reduced distance limit in 1990-91 proved to be very helpful in providing more flexibility in choice of projector sites.

In 1991, spring whaling at Barrow ended in mid-May, and there was no ice-based whale census. During consultations in mid-May, representatives of the BWCA, AEWC and NSB agreed that we could work close to Barrow, where the whale migration corridor seems to be more concentrated and consistent. Starting on 17 May 1991, we began to conduct aerial surveys west and north of Barrow as well as in our usual study area farther to the northeast. On 17 and 18 May, the sound projector was set up on the landfast ice closer to Pt. Barrow than we had worked before. The sound playback results from 17 May were the most valuable playback results obtained in 1991. On other dates in mid- and late May 1991, experimental opportunities were better on the pack ice, and we worked there rather than on the landfast ice. However, we continued to work closer to Barrow than had been possible previously.

In ***1992*** and ***1993***, the Barrow Whaling Captains' Association requested that LGL and MMS not undertake this study in the usual area northeast of Barrow because of the possibility that it might interfere with the full-scale bowhead census efforts planned for those years. In the absence of any logistically-practical alternative study area, this study was deferred from 1992 to 1993 and then again from 1993 to 1994.

In ***1994***, when no census work was planned, the BWCA indicated that it had no objection to resumption of the study in the usual area northeast of Barrow. The agreed-upon guidelines were the same as for 1990 and 1991: projector 15 n.mi. beyond northeasternmost whaling camp; no flying within 5 n.mi. of whaling camps.

In 1994, bowheads migrating through the area up to 15 May often traveled close to the landfast ice edge even in areas as much as 70 km east of Pt. Barrow where, in 1989-91, they tended to be at least a few kilometers north of the landfast ice edge. This difference was related to the fact that, until 15 May in 1994, the landfast ice in the eastern part of the study area extended unusually far offshore (§3.1, Ice and Weather Conditions). This situation allowed us to conduct playback work from the landfast ice edge 40-70 km ENE of Pt. Barrow during the 7-14 May 1994 period. However, because of the precarious nature of the ice there, it was again necessary to go to that area on a daily basis by helicopter rather than to establish a longer-term camp on the landfast ice edge. The landfast ice in that area began to break up on 15 May 1994. Thereafter, the main bowhead migration corridor was far enough north of the new landfast ice edge to require that ice-based work be done from the pack ice, as in previous years.

1.5 Decibel Scales

Sound levels are expressed in decibels in this report. Decibels are logarithmic units. Decibel scales cause considerable confusion and misunderstanding among acousticians and non-acousticians alike, but serve a useful purpose. The range of sound levels perceived by human beings extends from the molecular noise of air molecules colliding on the low side to the roar of jet engines at close range. The ratio of sound pressures thus spanned is about 1,000,000:1. A linear pressure scale to portray such a range of sound pressures would be cumbersome, and sounds at low and intermediate levels (e.g., molecular noise and typewriter noise) would seem very similar on this scale. A logarithmic scale for pressures solves this problem.

Human beings respond to sound pressures on a logarithmic basis as well. The minimum change in sound level perceived by humans is on the order of 1 dB. In the middle of the frequency and intensity ranges for human hearing, a sound pressure increase of 10 dB is perceived by humans as an apparent doubling of loudness. Thus, there is more than one reason for using a logarithmic scale.

A logarithmic scale has to be "anchored" by some reference unit of pressure. The reference unit now used to describe underwater sounds is the micropascal. Thus, decibels on a sound pressure level scale are said to be referred to 1 micropascal, or "dB re 1 μPa". Other reference units are sometimes used, including 20 μPa (=0.0002 μbar) for airborne sounds, and 1 μbar (0.1 Pa) in much of the older underwater acoustics literature. Table 1.1 summarizes the interrelationships of various scales for acoustic measurements, and shows the levels of some airborne and underwater sounds on these measurement scales. More details, including information about decibel scales as used to describe sound pressure spectral density and sound energy, are given in Greene (in press).

TABLE 1.1. Interrelationships of various scales for acoustic measurements; standard reference units are underlined[a]

Pascals	Dynes/ cm^2	Bars	dB re 1 µPa	dB re 1 µbar	dB re 0.0002 µbar	Typical airborne sounds and human thresholds	Typical underwater sounds and marine mammal thresholds
1,000,000	10^7	10	240	140	214		
							2 kg high explosive, 100 m
100,000	1,000,000	1	220	120	194		Beluga echolocation call, 1 m
10,000	100,000	.1	200	100	174		Airgun array, 100 m
						Some military guns	
1,000	10,000	.01	180	80	154		
						Sonic booms	
100	1,000	.001	160	60	134		Large ship, 100 m
10	100	100 µ	140	40	114	Discomfort threshold, 1 kHz	Fin whale call, 100 m
						500 m from jet airliner	
1	10	10 µ	120	20	94		
.1	1	**1 µ**	100	**0**	74	15 m from auto, 55 km/h	Beluga threshold, 1 kHz
						Speech in noise, 1 m	Ambient, SS4, ⅓-OB @ 1 kHz[b]
.01	.1	.1 µ	80	-20	54	Speech in quiet, 1 m	Seal threshold, 1 kHz
.001	.01	.01 µ	60	-40	34		Ambient, SS0, ⅓-OB @ 1 kHz
.0001	.001	.001 µ	40	-60	14		Beluga threshold, 30 kHz
20 µ	200 µ	**.0002 µ**	26	-74	**0**	Open ear threshold, 1 kHz	
10 µ	100 µ	.0001 µ	20	-80	-6	Open ear threshold, 4 kHz	
1 µ	10 µ	.00001 µ	**0**	-100	-26		

[a] From Greene (in press); airborne portions adapted from Kryter (1985:8).
[b] Ambient noise in ⅓-octave band centered at 1 kHz under sea state 4 conditions.

2. METHODS[4]

2.1 Physical Acoustics Methods

The specific 1991 and 1994 field objectives that concerned physical acoustics, in whole or in part, were as follows:

1. ***Ambient Noise***: To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components.

2. ***Transmission Loss***: To measure and model underwater sound transmission loss along the study portion of the spring migration corridor, based on transmissions of (a) test tones at selected frequencies between 20 Hz and 10 kHz, and (b) steady drilling platform sounds (*Karluk*) and variable icebreaking sounds (*Robert Lemeur*).

3. ***Playback Experiments***: To measure the short-term behavioral responses of bowheads and 6(as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of variable icebreaking (*Robert Lemeur*) sounds.

4. ***Infrasonic Sounds***: To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, (a) to measure ambient noise at infrasonic frequencies (less than 20 Hz), and (b) to determine whether bowhead calls contain infrasonic components (supplementing limited data from 1990).

An additional objective associated with the 1991 effort was to obtain and analyze recordings of the SSDC during winter drilling operations east of Pt. Barrow (Appendix H). The sounds associated with the SSDC were considered for use during playback experiments.

This section begins with a general description of the approach and equipment used in the acoustic work. Then there are sections describing specific methods applicable to each of the above objectives. Emphasis is given to acoustical methods applied in 1991 and 1994, but significantly-different procedures used in 1989-90 are mentioned as well. Methods applied in 1989 and 1990 were described in more detail by Richardson et al. (1990a, 1991a).

General Approach and Equipment

Acoustical work in 1991 and 1994 generally followed the methods of 1989-90. The work occurred at two types of places: (1) ice camps located along the edges of ice pans or (less often) the landfast ice edge, and (2) aboard the project's chartered Twin Otter fixed-wing aircraft:

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[4] By W.J. Richardson, C.R. Greene Jr., and W.R. Koski

- The ice-based personnel were transported by helicopter to a suitable place on the ice on a daily basis. Weather and ice conditions permitting, personnel typically remained on the ice for 8 to 12 hours. On most days, the ice-based crew attempted to perform either a transmission loss test or a playback experiment, as well as measuring ambient noise and observing whales.
- The aircraft-based crew dropped sonobuoys to measure sounds received near whales, as well as observing and photographing whales (§2.2, Whale Surveys and Observations).

At a minimum, the ice camps were occupied by an acoustician, two field biologists, and an Eskimo guide from Barrow. A second acoustician was present occasionally in 1991 and frequently in 1994. The biologists observed marine mammals and operated a theodolite to measure azimuth and depression angles to whales and seals. Distances were computed from depression angles and the measured height of the theodolite above the sea. Ice camps were established by flights from Barrow, AK, in a NOAA Bell 212 helicopter dedicated to support the field work.

The major types of equipment used at and near the ice camp for acoustical aspects of the work were as follows:

- sound projector(s) for use in both playbacks and transmission loss tests, with tape recorder and amplifier(s) to play the recorded sounds;
- generator to power this and other equipment;
- hydrophone(s) deployed near the projector(s) to monitor the projected or ambient sounds, and tape recorder to record these sounds;
- monitor sonobuoy deployed ~1 km from the ice camp to monitor sounds received at that distance.

Also, sonobuoys were air-dropped from the project's Twin Otter aircraft to record projected and ambient sounds received near whales. During transmission loss experiments, a hydrophone and tape recorder were taken to various receiving stations to record the sounds received at different distances from the sound projectors. The specific equipment varied from year to year, as summarized in Table 2.1.

Sound Projectors and Signal Source.—To project sounds for transmission loss and playback experiments, a davit installed in the ice about 1 m from the edge of the ice floe supported various sound projectors and one or more monitor hydrophones lowered over the edge. The sound projectors were at depth 18 m (60 ft) except during a transmission loss test on 30 April 1989, when projector depth was 9 m.

In 1989 and 1990, a U.S. Navy model J-11 wideband electrodynamic acoustic transducer served as the sound projector. The J-11 is limited to a maximum sound pressure source level of about 166 dB re 1 μPa-m. It is rated as effective at 20-12,000 Hz, but its output diminishes at frequencies below about 100 Hz, becoming negligible at frequencies below 50 Hz. The J-11 was powered by a Bogen model MT250 amplifier rated at 250 W. The signal source in 1989-90 was an audio cassette recorder (Table 2.1A) with servo-controlled capstan for accurate speed control. Playback frequency response was flat ±5 dB from 20 to 10,000 Hz. Further details are given in Richardson et al. (1990a, 1991a).

TABLE 2.1. Equipment used for acoustic work in each year of the project.

	1989	1990	1991	1994
A. Projectors and Signal Source				
Projector(s)	J-11	J-11	J-13 & F-40	Argotec 220 & J-11
Amplifier(s)	Bogen MT250	Bogen MT250	Bogen MT250	Techron 7560 & Techron 7550
Source tape recorder	Marantz PMD-430 cas.	Sony TC-D5M cas.	Sony TCD-D3 DAT	Sony TCD-D3 DAT
Generator	Honda 2.2 kW	Homelite 2.2 kW EH2500HD	Homelite 2.2 kW EH2500HD	Kubota 5 kW (most days)
B. Sound Monitoring on Ice				
Monitor hydrophone near proj.	ITC 1042	ITC 1042	ITC 1042	ITC 1042
Ambient & TL signals @ depth	ITC 6050C @ 18 m	ITC 6050C @ 18 m	ITC 6050C @ 18 m	ITC 6050C @ 18 m
Infrasonic ambient @ depth		ITC 1032 @ 18 m	ITC 1032 @ 18 m	
Monitor sonobuoy at approx. 1 km range from camp	AN/SSQ-41B @ 9 m or -57A @ 12 m	-41B @ 9 m or -57A @ 14 m	-57A @ 18 m (usually)	-57A @ 18 m
Sonobuoy receiver	L-tronics LS44	Kenwood RZ-1 (mod.)	Kenwood RZ-1 (mod.)	L-tronics LS44
Tape recorders				
Playback monitor @ camp	* & Sony TC-D5M cas.	* & Marantz PMD-430 cas.	* & TEAC RD-101T DAT	* & TEAC RD-101T DAT
Ambient @ camp	Sony TC-D5M cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
TL monitor @ camp	*	* & Marantz PMD-430 cas.	* & Sony TC-D5M cas.	* & Sony TCD-D7 DAT
TL & Amb. @ TL receive sites	Sony TC-D5M cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
C. Sound Monitoring from Twin Otter				
Sonobuoys	AN/SSQ-57A @ 12 m	-57A @ 14 or 18 m or -41B @ 18 m	-57A @ 14 or 18 m or -53B @ 27 m	-57A @ 14 or 18 m or -53B @ 27 m
Sonobuoy receivers	2xRegency MX5000 (modified)	2xRegency MX5000 (modified)	2x Kenwood RZ-1 (mod.)	3x Kenwood RZ-1 (mod.) & 1 ICOM R100 (mod.)
Tape recorder	Marantz PMD-430 cas.	TEAC RD-101T DAT	TEAC RD-101T DAT	TEAC RD-101T DAT
D. Position Finding				
Ice camp	Si-Tex A-310 SatNav	Si-Tex A-310 SatNav	Magellan OEM GPS	Magellan OEM GPS
Bell 212 helicopter	GNS-500 VLF	GNS-500 VLF	GPS & VLF	GPS & VLF
Twin Otter aircraft	GNS-500A VLF	GNS-500A VLF	Wulfsburg GPS/VLF	2xGPS & VLF

* An oscilloscope and voltmeter were used to monitor projector output during each year.

In 1991 a U.S. Navy model J-13 electrodynamic sound projector served to project the low frequency sounds and a model F-40 ceramic spherical transducer was used for frequencies above about 1000 Hz. A crossover network set for 1 kHz was used to divide the sound between low and high frequencies. Each projector was driven separately with signals from one 250-W Bogen model MT250 power amplifier. In use, the J-13/F-40 combination was disappointing, providing source levels on the order of 164-167 dB re 1 μPa-m, about the same as obtained with the J-11 during 1989-90. The signal source in 1991 was a Sony TCD-D3 DAT Walkman, with frequency response flat ±3 dB from 6 Hz to 23 kHz.

In 1994 an Argotec model 220 low frequency projector was obtained, along with two model 219 transducers for mid-range frequencies, and an F-56 for high frequencies. Separate power amplifiers were used for each of the three frequency ranges, and frequency equalizers were used to divide the DAT recorder output signal into three bands for driving the power amplifiers. The model 220, having pistons at each end, required two amplifiers, although their inputs were the same. There were thus four power amplifiers: two 1600-W Techron model 7560 amplifiers for the Argotec 220, and two 350-W Techron model 7550 amplifiers, one for the mid- and one for the high frequencies. The system was designed to provide sound pressure source levels up to 180 dB at the low frequencies and to 170 dB at the higher frequencies. This frequency-related difference in maximum potential source level was acceptable because the playback stimulus sounds were at least 10 dB lower at the mid- and high frequencies than at the lower frequencies.

The 1994 projector system was tested at Argotec and at the Navy's Underwater Sound Reference Detachment, Orlando, FL, before our 1994 field season. However, operational problems with the projectors at the ice camps led to use of only one end of the model 220 for low frequencies (up to 500 Hz) and a J-11 for frequencies from 500 Hz upward. These were powered by two of the Techron amplifiers, one model 7560 and one model 7550. Furthermore, during three playback days in 1994 (3, 9 and 17 May), only the J-11 was operational. Source levels varied from day to day, and typically were comparable to those obtained in previous years (§4.4, Playback Fidelity). The signal source in 1994 was a Sony TCD-D3 DAT Walkman.

Generator.—The sound projectors and other equipment were powered by a small gasoline-engine generator (Table 2.1A). In 1989-90 the generator was placed directly on the ice. In 1991 and 1994, it was suspended by bungee cords from a frame constructed of PVC pipe. The frame stood on the ice, but the bungee cords isolated the generator from the frame and ice. In all years, the generator was placed about 20 m back from the ice edge where the projector was suspended.

Sound Monitoring at Ice Camp.—Whenever the projectors were deployed during any of the four years, an International Transducer Corporation (ITC) model 1042 spherical hydrophone was used to monitor the projected signals. This was secured to the lowering line at a measured position 1.6-3 m above the projector face (1990-94) or was positioned 0.8 m in front of the projector (1989). An ITC model 6050C wideband low-noise hydrophone was also lowered to depth 18 m over the edge of the floe, usually 3-5 m from the sound projector. The hydrophone cable was faired with 15-cm long nylon fibers to minimize cable strum. This hydrophone was used to record ambient noise when the projectors were silent, and during projector operations in 1994 it served as a second monitor of the projected sounds.

During almost all days of ice-based work, a sonobuoy was deployed ~1 km from the ice camp to serve as a far-field monitor of projected sounds (Table 2.1B). This buoy was attached to an ice edge to minimize its drift relative to the ice camp, with the exception of 17 May 1994 when the sonobuoy drifted freely. In 1991 and 1994, sonobuoy position at installation time was determined by the helicopter's GPS navigation system. The buoy radio signal was received at the ice camp with a sonobuoy receiver (Table 2.1B). When the sonobuoy and ice camp were on different ice pans, the distance from ice camp to sonobuoy was, when possible, determined periodically through the day by theodolite readings taken from the ice camp and/or by crosscorrelation of the sounds recorded near the projector and at the sonobuoy. This monitor sonobuoy, along with a hydrophone at the ice camp, provided ambient noise data at times when there was no playback.

To document the sounds being projected during playbacks and transmission loss tests, a tape recorder was used to record the signals from the ITC 1042 monitor hydrophone and, during playbacks, the monitor sonobuoy. During playbacks in 1991 and 1994, we also recorded, on the same recorder, the signals being fed to the projector amplifier(s) and the signals received at the ITC 6050C hydrophone a few meters from the projector(s). Equipment and procedures varied somewhat, depending on the year and whether a playback or a TL test was in progress (Table 2.1B). This acoustic monitoring is described further in later subsections on methods for "Transmission Loss" and "Playback Experiments".

<u>Sound Monitoring Aboard Aircraft</u>.—Acoustics work from the Twin Otter was based on air-dropping sonobuoys at locations near whales or where whales were likely to pass. The aircraft had an antenna, preamplifier, two or four calibrated sonobuoy radio receivers (depending on year), and a TEAC four-channel DAT recorder (1990-94) or a calibrated cassette recorder (1989; Table 2.1C). The sonobuoys were mainly of two types: Sparton AN/SSQ-57A omnidirectional, calibrated wideband (10-20,000 Hz) sonobuoys, and AN/SSQ-53B DIFAR (DIrectional low Frequency and Recording) 10-2400 Hz sonobuoys. Calibrations were extrapolated down to 8 Hz to permit measuring the sound level in 1/3-octave bands centered down to 10 Hz. Hydrophone depth was 18 m for most -57A buoys (a few had been customized for 14-m or, in 1989, 12-m depth for use in shallow areas) and 27 m for the -53B buoys.

Sonobuoy position was determined from the aircraft navigation system (GPS in 1991/94; VLF in 1989-90; Table 2.1D) at launch and impact time, and (when the sonobuoy was visible from the air) by flyovers at later times. Also, we sometimes flew directly from the ice camp to a sonobuoy (or the reverse) to take GPS or VLF readings in quick succession at the two locations. Generally, the signal from the ice camp's monitor sonobuoy located ~1 km from the projector(s) was recorded on one channel of the same recorder that was recording the signals from aircraft-deployed sonobuoys. This allowed us to use crosscorrelation methods to determine relative distances of two sonobuoys from the projector based on differences in arrival times of projected sounds.

The following sections describing specific acoustic tasks include more information about specific equipment and procedures applied during those types of work.

Ambient Noise

Field Procedures.—Ambient noise was recorded from the 6050C hydrophone at the ice camps and, during transmission loss (TL) tests, at TL receiving sites. Standard practice was to record ambient noise before and after projector operation at each ice camp. During TL tests, ambient noise was recorded at the various receiving stations prior to transmission of the test signals. Hydrophone depth was 18 m in all of these cases. Ambient noise was also recorded from the monitor sonobuoy near the ice camp and from sonobuoys deployed and recorded by the aircraft-based crew. Sonobuoy frequency range was 10-2400 Hz for the AN/SSQ-53B DIFAR sonobuoys and 10-20,000 Hz for the AN/SSQ-57A sonobuoys. Sonobuoy hydrophones were at depths ranging from 9 to 27 m (Table 2.1B,C). An ITC model 1032 spherical hydrophone was used in 1990 and 1991 to record infrasonic sounds.

Ambient noise was recorded on a TEAC DAT recorder in 1990-94 and a calibrated cassette recorder in 1989 (Table 2.1B). At the ice camp, the TEAC DAT recorder was sometimes operated as a four-channel recorder in 1990-91, and always in 1994. In 4-channel mode, the frequency range on each channel was 0-10,000 Hz. Analyses were restricted to frequencies up to 8000 Hz (see "Analysis", below). This 8000 Hz upper limit was reasonable because the man-made sounds used in playbacks during 1989-94 diminished severely in level with increasing frequency, and because bowhead calls rarely contained components approaching 8 kHz.

A major component of arctic springtime ambient noise is bearded seal calls. When measuring ambient noise, we avoided sampling the taped data at times when there were prominent bearded seal calls. At times such sounds had to be included; these were times for which an ambient analysis was needed but there was no 8.5-s segment lacking bearded seal sound. At these times the spectrum had higher than usual levels at high frequencies, anywhere from 400 Hz up. Thus, the resulting ambient noise data represent noise levels in the quieter periods between bearded seal calls or, when bearded seal calls were nearly continuous, at times with such calls. When the 1/3-octave ambient noise data were summarized on a percentile basis, the shape of the 100th percentile (maximum) 1/3-octave spectrum may be influenced by the presence of a bearded seal call. However, the 95th percentile spectrum usually does not manifest such calls.

Analysis Procedures.—Segments of ambient recordings were analyzed to characterize the noise on each day of ice camp operation and during TL tests. Analysis methods in 1991 and 1994 were generally the same as in 1989 and 1990. Recorded sounds were analyzed with a computer workstation that included a two-channel 12-bit analog-to-digital converter in 1989-90, and a two-channel 16-bit analog-to-digital converter and digital signal processor (DSP) in 1991/94. The sample frequency was generally $2^{14} = 16,384$ samples/second, permitting useful analyses of sounds up to 8 kHz and determination of levels in 1/3-octave bands centered up to 6300 Hz. System calibrations (hydrophones, amplifiers, sonobuoys, sonobuoy receivers, tape recorders, A/D converter, and processing software) permitted results to be computed in units of pressure (micropascals) and pressure spectral density ($\mu Pa^2/Hz$) at frequencies from 8 to 8000 Hz.

A standard ambient noise analysis was based on an 8.5-s segment of sound (139,264 samples). These data were processed by Fourier transforming 0.5-s blocks (8192 samples/block) to which a Blackman-Harris window had been applied, overlapping blocks by 50%, and averaging the results from the 0.5-s blocks. The resulting spectrum elements were spaced by 2 Hz and the effective bandwidth of each element was 3.4 Hz.

From these narrowband results, we summed the powers to determine the levels in 1/3-octave bands centered at frequencies 10 to 6300 Hz. The 1/3-octave bands centered at 10, 12.5 and 16 Hz constituted the infrasonic components. Levels in several broader bands were also computed from the narrowband spectra or from the 1/3-octave band levels. In the latter case, half of the power in each of the relevant 1/3-octave end-bands was assumed to be within the broadband frequency range. The resulting 1/3-octave and broadband levels were saved in a spreadsheet.

After the 1989 field season, the project's Scientific review Board (SRB) recommended investigating the shorter-term variability of the ambient noise. This would show whether there were short periods of time (briefer than the standard 8.5 s analysis interval) during which the noise level was significantly lower than the measured average level. If so, whales might, at times, be able to hear weak sounds from distant sources—sounds with received levels lower than the longer-term average ambient noise. The characteristics for short-term analyses were

- Sample rate: 2048 samples/second;
- Sample block size: 122,880 samples (1 minute);
- Block sizes for acoustic power computations: 512 and 17,408 samples (0.25 and 8.5 s).

The work was part of the 1990 effort and the results are reported in Richardson et al. (1991a).

Transmission Loss

Field Procedures.—Transmission loss (TL) tests were completed on 13 dates over the four years: on four dates in each of 1989, 1990 and 1991, and on one date in 1994. An additional partial test was done in 1994. Figure 2.1 shows the projector locations and, for each of these, the line along which the receive stations were located.

The bathymetric contours on this and subsequent maps were developed by Paul Dysart, SAIC Applied Ocean Sciences, McLean, VA, based on soundings on National Ocean Service chart 16004, the NOAA bathymetric databases, and soundings taken by us in 1989-94 at our ice camp locations and at many TL receive sites.

During TL measurements, the sound projector system described above and in Table 2.1A projected a sequence of sounds that had been recorded at carefully-chosen levels on a test tape:

- discrete tones (1989-90) or combined tones (1991 and 1994),
- 1/3-octave band tonal sweeps (1989-90) or tone clusters (1991 and 1994),
- steady drilling sounds from *Karluk* (1989-90 and 1994), and
- varying icebreaking sounds from *Robert Lemeur* (1991 and 1994).

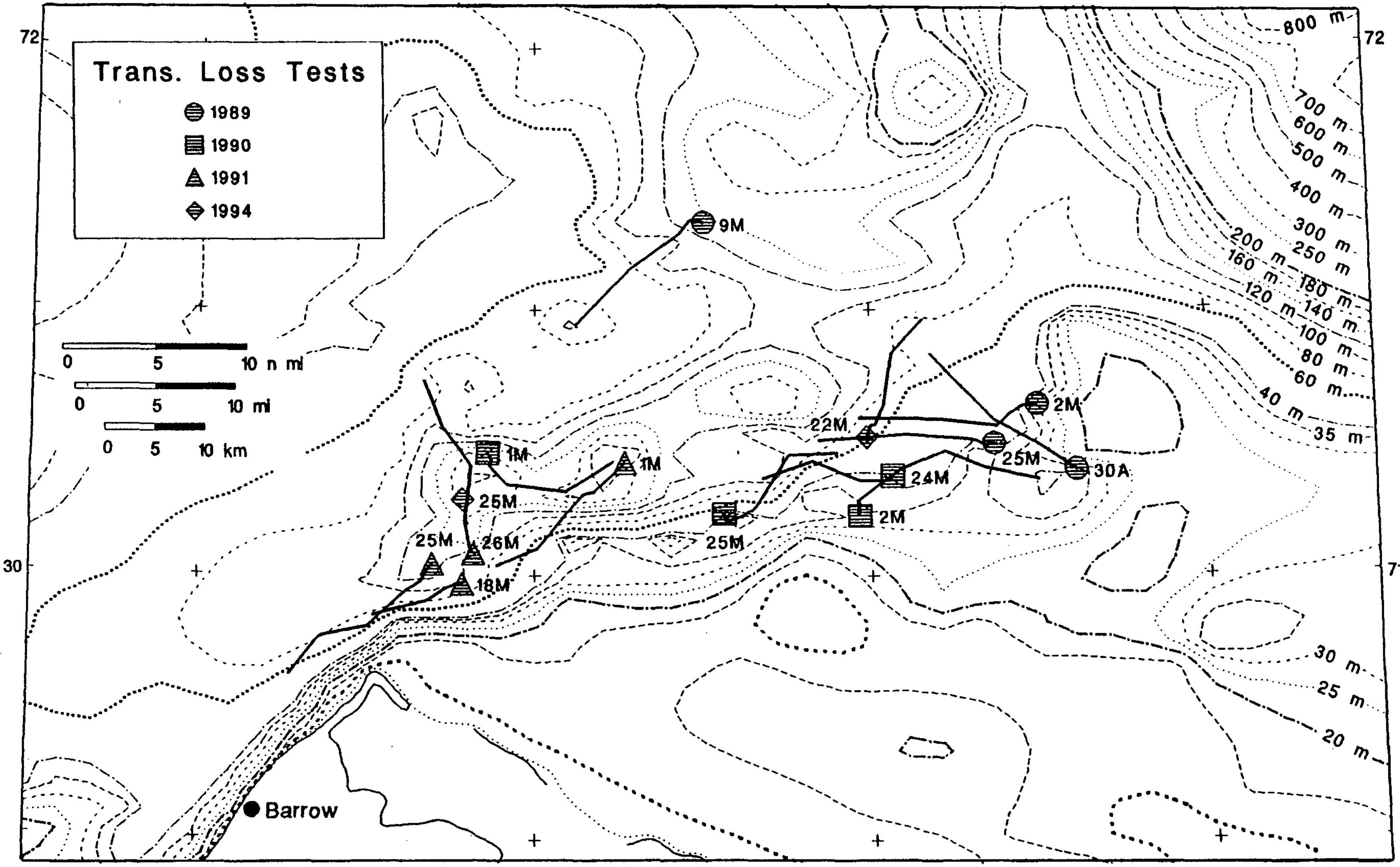


FIGURE 2.1. Projector locations during transmission loss tests and, for each test, the line along which the receive stations were located.

These signals were as follows:

- The discrete tones used in 1989-90 consisted of 10- or 20-s segments of pure tone at the following frequencies: 50, 100, 200, 500, 1000, 2000, 5000 and 10,000 Hz.
- The combined tones used in 1991 and 1994 were combinations of continuous wave (CW) tones at different frequencies, phased to assure that peak levels were not too high. There were three waveforms of this type, containing tones at (a) 20 and 40 Hz, (b) at 50, 100, 200 and 500 Hz, and (c) at 1000, 2000, 5000, and 10,000 Hz. These three waveforms were each transmitted for 30 s.
- The tonal sweeps used in 1989-90 were hyperbolic frequency modulation (HFM) signals synthesized by BBN Systems & Technologies Corp. following Rihaczek (1986). Each 5-s sweep spanned 1/3-octave at a center frequency of 100, 200, 500, 1000, 2000 or 5000 Hz. Each sweep was projected two or four times.
- The tone clusters used in 1991 and 1994 were clusters of narrowly-spaced tones spanning 20 Hz. There were two waveforms of this type: (a) with clusters centered at 150 and 300 Hz, and (b) with clusters centered at 500 and 1000 Hz. Each was transmitted for 30 s.
- The sample of *Karluk* drilling sound used in 1989-90 and 1994 was a 35-s (or longer) segment of the rather steady, low-frequency (mainly 50-350 Hz) drilling sound used during playback experiments in 1989-90. It was recorded in shallow water under ice 130 m from a drillrig on an ice pad east of Prudhoe Bay on 30-31 March 1989, as described in Richardson et al. (1990a:80).
- The sample of icebreaker sounds used in 1991 and 1994 was a 60-s (1991) or 20-s (1994) segment of the icebreaking sounds used during playback experiments in those years. This sound had been recorded 460 m from the icebreaking supply ship *Robert Lemeur* while it was breaking ice in water 35 m deep, as described in Greene (1987a).

At the projector site (base camp), TL test signals were played back with the DAT (1991 and 1994) or cassette (1989-90) recorders listed in Table 2.1A. In 1990-94, another DAT or cassette tape recorder was used to record the monitor hydrophone signal and, in 1994, the projector amplifier input signal. These recordings provided the basis for measuring the projector source levels. During each TL test, the sequence of test sounds was projected several times, twice during the period of recording at each receiving station. The location of the ice camp, which was on drifting pack ice during all but one TL test, was recorded periodically via GPS (1991 and 1994) or a Si-Tex model A-310 satellite navigation receiver (1989-90).

During each TL test, ambient noise and the transmitted sounds were received successively at various distances from 100 m to 18.5 km along or near a single azimuth. Receiving stations were along the edges of ice pans or, during one TL test (18 May 1991), on the landfast ice edge and on drifting floes in the lead. To obtain data at distances 100 m, 200 m and (rarely) 400 m from the projectors, a sled was used to haul the equipment along the ice edge from the base camp. Distance to these sites was determined with a Rolotape distance measuring wheel rolled along the ice. The helicopter provided transportation to the more distant sites at nominal distances 0.5, 1, 2, 5, 7.5 and 10 n.mi. (0.93, 1.85, 3.7, 9.3, 13.9 and 18.5 km). The 10 n.mi. station was skipped if no projected sounds were heard at 7.5 n.mi. Positions of these sites were determined via the helicopter's navigation system (GPS in 1991 and 1994; GNS-500 VLF in 1989-90). In 1989-90, when the less-precise VLF navigation system was used, the helicopter often flew back over the ice camp and noted its apparent VLF position before moving to a new receiving station and noting its VLF position. About 4 h were required to measure the received signals at ~8 ranges, exclusive of the time (4-5 h) needed to set up and remove the projection equipment.

At each receiving station, the transmitted test signals were recorded with an ITC model 6050C hydrophone suspended via faired cable at 18 m depth. Also, ambient noise was recorded at each receiving station before and after the period with test signals. During some tests in 1989-91, ambient noise was recorded at the closer ranges with the generator at the base camp turned off as well as operating. This was done to determine the characteristics and range of detectability of the generator sounds. The received sounds were tape recorded with a battery-powered portable TEAC DAT recorder in two-channel mode (bandwidth 0-20,000 Hz) during 1990-94, and with a calibrated cassette recorder in 1989 (Table 2.1B). Water depths at the ice camp and at most of the more distant receiving stations were measured with an echosounder. An ITC 1032 hydrophone was used to record infrasound at TL receive stations in 1990-91.

Analysis Procedures.—Signal analysis was generally the same as was used for ambient noise analysis (see above). Signal segments 8.5-s long were sampled at 16,384 samples/s. For each receive station, we measured the received level of each projected signal and of the ambient noise level. These signals were analyzed by Fourier transformation of windowed, overlapped blocks 0.5 s long (8192 samples), and the results were averaged. The spectrum resolution was 3.4 Hz on 2-Hz centers. The powers (pressures squared) in the analysis cells spanning each 1/3-octave band were summed to derive the 1/3-octave band levels for the drilling, icebreaker, and ambient sounds received at each station. The tone levels were measured from the appropriate narrowband frequency element, and the sweeps were analyzed by taking the appropriate 1/3-octave band level.

Results were kept separate by type of signal: tones, HFM sweeps, clusters, *Karluk* drilling, and *Robert Lemeur* icebreaking. The variable qualities of the icebreaking sounds, even over the relatively short period of 20 s, and the fact that the received and transmitted signals were not recorded on the same tape recorder, made it impossible to analyze exactly the same transmitted and received segments. Thus, the TL measurements based on the samples of variable icebreaker sounds were less accurate than the measurements based on the steady *Karluk* drilling sounds and the HFM sweeps.

Transmission loss was computed by subtracting the measured received levels from the measured source levels. The resulting data were used directly when the signal + noise level exceeded the ambient noise level in the corresponding frequency band by at least 10 dB. When the signal + noise level exceeded the noise level by 3-10 dB, the combined level was corrected for the noise to calculate the signal level alone. The TL modeling effort based on the resulting data is described in §4.3. This effort resulted in a model that, for the conditions prevailing in our study area in late April and May, predicts transmission loss in relation to frequency, water depth, and distance from source.

Playback Experiments

The acoustical methods used during playback experiments are best described in conjunction with methods for biological observations during playbacks. This material appears in §2.3.

Infrasonic Components of Ambient Noise and Bowhead Calls

Because of concerns about the possibility that bowheads are sensitive to frequencies lower than those that can be reproduced adequately by projectors of practical size, we wanted to obtain information concerning the sources, transmission and reception of sounds at low frequencies, including infrasonic frequencies (<20 Hz). Of the several possible avenues of investigation, two were practical in this study. We measured the infrasonic components of the natural ambient noise, and we undertook a preliminary assessment of bowhead calls to see if they included infrasonic components. *(1)* The levels of ambient noise at infrasonic frequencies are relevant to any attempt to evaluate how far away an infrasonic component of an industrial noise might be audible above the natural background noise at corresponding frequencies. *(2)* If bowhead calls contain infrasonic components, there would be increased reason for believing that bowheads can hear those frequencies.

Infrasonic Ambient Noise.—The standard methods for determining ambient noise also provided data on infrasonic ambient noise. The hydrophone, preamplifier and DAT recorder used for hydrophone-based ambient noise recordings in 1990-94 were calibrated at frequencies from 5 to 20,000 Hz; the response was suitable for recording the infrasonic sounds from 8 to 18 Hz. The sonobuoys, radio receivers and DAT recorders used at the ice camp and on the aircraft in 1990-94 were sufficiently calibrated to be useful at infrasonic frequencies as well. Both the -57A and -53B sonobuoys are sensitive from 10 Hz upward. All ambient noise recordings from 1991 and 1994 that were suitable for measurements at higher frequencies were also suitable for infrasonic noise measurements at 8-18 Hz. The 1/3-octave band levels centered at 10, 12.5 and 16 Hz were determined along with the levels in higher-frequency bands. Those infrasonic band levels were saved in the same spreadsheet with the higher frequency 1/3-octave band levels.

A special hydrophone (ITC model 1032 sphere) was used in 1990-91 to sense infrasonic ambient noises and bowhead calls that might contain infrasonic sounds. The 1032 with a high-impedance preamplifier was essentially flat down to a frequency of 1 or 2 Hz.

Infrasonic Components of Bowhead Calls.—The 1990 results on the question of infrasonic components in bowhead calls were presented in Richardson et al. (1991a:91*ff*). In 1991, narrow-band spectral density analyses were performed on all bowhead calls received on the 6050C hydrophone or sonobuoys and recorded on the TEAC DAT recorder during five dates: 1, 11, 18, 25 and 26 May 1991. Waterfall spectrograms were plotted for the frequency range 6-250 Hz to support a search for call energy at frequencies below 20 Hz. A minority of the calls analyzed in this way included infrasonic energy that may have been associated with the call (§4.5).

Waterfall spectrum analysis was useful in determining whether, at the times when bowheads emitted their known types of calls, there also were infrasonic components that have not previously been recognized. The characteristics for waterfall spectrum analysis were as follows:

- Sample rate: 1024 samples/second.
- Fourier transform blocksize: 1024 samples (1 Hz bin spacing).
- Blackman-Harris minimum 3-term window applied (1.7 Hz bin width).
- 87.5% overlap of transform blocks.
- 1 s of data analyzed and displayed per spectrum displayed.
- Typically, 9.45 s of data were displayed in a waterfall plot showing frequencies 5 to 250 Hz.

2.2 Whale Surveys and Observations

Aerial Reconnaissance and Surveys

General Approach.—Aerial reconnaissance and surveys were necessary to meet specific objective 4, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks of variable icebreaker sounds ...". Aircraft-based work was also important in addressing specific objective 7, "To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment ...".

Aerial reconnaissance of the study area was done daily to locate whale migration corridors, which often changed from day to day. This information was used in selecting the location where the sound projectors were set up each day. Aerial reconnaissance was also a necessary first step in locating and selecting the specific whales to be observed and photographed from the air.

The flight route depended upon ice conditions, and was non-systematic. On most days, the survey route initially followed the south side of the nearshore lead along the landfast ice edge. We generally began surveying about 15 km northeast of Pt. Barrow and flew east along the ice edge for as much as ~75 km. (We did not search that far east on days ▸ when the nearshore lead did not extend that far east, or ▸ when it was apparent that the main bowhead migration corridor was farther offshore, or ▸ when weather deteriorated to the east.) If a suitable projection site was not identified along the landfast ice edge, the north side of the lead was then surveyed. Finally, if a suitable projection site was not found in or adjacent to the nearshore lead, or if the nearshore lead was congested with pack ice, a series of widely-spaced transects was usually flown over the pack ice farther offshore to determine ice conditions there, the locations and orientations of leads and cracks, and the locations of any bowhead or white whale concentrations. When searching for whales in the pack ice, we often followed leads and cracks that seemed likely to provide migration routes for migrating bowheads and white whales.

After a location for the sound projectors had been selected, additional surveys were usually conducted as far as ~20 km west and southwest of the projector site. At the point when it became apparent that further reconnaissance surveys were unnecessary in meeting that day's objectives, the aerial crew

- began to conduct systematic aerial observations of whale behavior if bowheads were found and if clouds either were absent or were above 460 m Above Sea Level (1500 ft ASL); or
- began to photograph bowheads if bowheads were present but low cloud prevented behavioral observations from 460 m ASL; or
- returned to Barrow if no bowheads could be found or if the weather was too marginal for productive or safe flying.

In 1989-91, insofar as possible, we avoided flying low (at <460 m) over the main nearshore lead during midday. At midday, a National Marine Mammal Laboratory (NMML) crew was usually flying low over the leads within the study area, searching for bowheads to photograph. In 1994, the NMML crew was not present so low-level flights were possible at any time.

We avoided flying within 5 n.mi. (9 km) of active whaling camps except when this was unavoidable because of the presence of camps within 5 n.mi. of the approach to Barrow's airport. In 1991, whaling at Barrow ended in mid May. From 17 May onward, we conducted reconnaissance surveys along the landfast ice edge and nearshore lead west and northwest of Barrow as well as in the usual study area farther northeast of Pt. Barrow. In 1994, whaling continued until the end of the our field season, and surveys were restricted to the normal study area east and northeast of Pt. Barrow.

<u>Survey Methods and Data Recording</u>.—We conducted aerial surveys from 28 April through 26 May 1991 and from 27 April through 25 May 1994 in a DHC-6-300 Twin Otter aircraft. (Table 3.2, on p. 62, summarizes aerial efforts in all four years of the project.) In addition to the standard belly fuel tanks, the aircraft had wingtip tanks (1991 only) and an additional tank in the cabin; total aircraft endurance under our typical operating conditions was 9+ or 8+ hours in 1991 and 1994, respectively. Other special equipment included marine VHF radios, VLF/GPS navigation system, radar altimeter with digital display, invertors for 120 V/60 Hz AC power, three bubble windows (right center, left center, left rear), intercom system with voice activated microphones, and ventral camera port.

In 1991, the aircraft was equipped with a Wulfsburg combined VLF/GPS navigation system that operated in GPS mode normally and reverted to the less-precise GNS-VLF mode during the small percentage of the time when GPS was unusable. (The GPS satellite constellation was not yet complete during the 1991 work.) When GPS became usable again after a period of VLF navigation, the GPS automatically updated the VLF system to correct for accumulated errors. When the GPS was usable, position readouts were usually accurate within 0.2 n.mi., based on the readout upon return to a known location at Barrow. As usual, position errors as large as 1 km were common when operating in VLF mode. A microcomputer interfaced to the VLF/GPS system and the radar altimeter automatically recorded aircraft position and altitude at intervals of 10 s or less.

In 1994, the aircraft was equipped with two independent GPS systems in addition to a VLF system. One GPS was part of the aircraft navigation equipment. The second GPS system, a Trimble Pathfinder, was part of a GeoLink data acquisition and mapping system that provided a real-time map display on a portable computer (Dell 25 MHz 386/387), and stored GPS positions at 1-s intervals.

There were a total of 30 offshore flights on 23 different dates from 28 April to 26 May during 1991 (Table 3.2, p. 62). On five of these days, the single flight was terminated within 0.3-1.0 hours because of poor weather offshore. The remaining 25 flights ranged from 1.6 to 5.2 h in duration. Longer flights were not warranted during 1991 because of the low clouds that almost always prevented observations from altitude 460 m. Total flight time during the 30 offshore flights was 75.4 h, of which 55.8 h was spent on reconnaissance.

In 1994, there were 35 flights on 22 dates from 27 April to 25 May. Poor visibility or high winds prevented any useful work during flights conducted on the afternoons of 2 and 18 May. The remaining 33 flights ranged from 1.0 to 7.3 h in duration. Total flight time during the 35 offshore flights was 119.0 h, of which 66.0 h was spent on reconnaissance.

Flight and observation procedures were consistent with those during the 1989-90 phases of this project. During reconnaissance work, the aircraft was flown at ~185-200 km/h groundspeed and, when possible, at 460 m ASL. When the cloud ceiling was lower than 460 m, as it almost always was in 1991 and frequently was in 1994, the maximum possible altitude below the cloud layer was maintained.

Four observers were present during almost all surveys in 1990-94 (three in 1989). During surveys, one observer (right front) was in the co-pilot's seat, two were at bubble windows on the left and right sides of the aircraft two seats behind the pilot's seat, and the fourth was at a rear-left bubble window. When a whale was sighted, the observer(s) notified other members of the crew via the intercom. Most bowheads were circled at least briefly to obtain information on the activity of the whale and to determine whether additional whales were present nearby. White whales were usually not circled, but large groups were sometimes circled to obtain more accurate counts and heading information. For each whale sighting, we recorded on paper and/or a tape recorder the time, location, species, number, general activity, orientation, and percent ice cover. Ice conditions were recorded throughout the survey, particularly whenever a change in ice type or percent cover occurred. Aircraft position and altitude were recorded manually from the GPS or VLF system whenever sightings were made and whenever the aircraft changed course. Position and altitude were also logged automatically throughout each flight, as noted earlier.

All sightings of bowheads and white whales from all years of the project (1989-90 as well as 1991 and 1994) have been transcribed into a standard numerical format, computerized, and mapped in this report.

Aerial Photography of Bowheads

Field Procedures.—Aerial photography of bowheads was one of the lower priorities during this project. However, it was often possible at times when higher priority work was prevented by the low clouds that prevailed during the spring of 1991 and that occurred commonly during other years. Vertical photos of bowheads were obtained in 1991 during 11 flights on 10 dates ranging from 29 April through 26 May, and in 1994 during 12 flights on 10 dates ranging from 30 April to 25 May. Similar work was done during the 1989 phase of this project, when vertical photos were obtained during 9 flights on 8 days (Richardson et al. 1990a). Vertical photography was not possible in 1990.

We used the calibrated vertical photography technique developed by LGL and described by Davis et al. (1983) and Koski et al. (1992). The resulting photos provided data on the individual identities and sizes of many of the whales photographed. These data are relevant to specific objective 7 concerning the movements, behavior and basic biology of bowheads (p. 7). The data are also at least indirectly relevant in certain aspects of the evaluation of playback effects (specific objective 4).

Field procedures were as described by Davis et al. (1983), Richardson et al. (1990a:60*ff*), and Koski et al. (1992). Briefly, the aircraft, flying at an airspeed of ~160 km/h and—cloud ceiling permitting—an altitude of ~137 m (450 ft), passed directly over bowheads. Because of the prevailing low clouds in 1991, some 1991 photographs were taken from lower altitudes. Photographs were taken through the aircraft's ventral camera port with one of two hand-held Pentax medium-format cameras (6x7 cm film size), each with a 105 mm *f*2.4 lens, pointed directly downward. Ektachrome 200 and Fujichrome 400 color positive film were used. Aircraft altitude was recorded from the radar altimeter at the moment the camera shutter fired. In 1989 and 1994, radar altitude was manually recorded by the observers in the rear of the aircraft from a digital display and, independently, in the front of the aircraft from an analog display on the instrument panel. In 1991, the radar altitude was recorded both manually and via the computerized data logger.

On one date in each year, a calibration target of known dimensions was spread out on a flat surface (airport runway in 1989; lagoon ice in 1991 and 1994) and photographed with each of the two cameras from the same altitudes used to photograph whales. Both whale and calibration photographs were most commonly taken from ~137 m, but in 1991 a few photographs were taken from altitudes as low as ~76 m.

When behavioral observations of whales were possible either from the aircraft or by ice-based observers, low-altitude photographic work was avoided until the behavioral observations were completed. In 1989 and 1991, we also did not purposefully photograph bowheads at locations where the NMFS/NMML crew had photographed bowheads on the same date. We supplied NMML with copies of our 1989, 1991 and 1994 photos of identifiable bowheads, and they reciprocated with copies of their relevant 1989 and 1991 photos (NMML did not conduct photography in 1994).

<u>Analysis Procedures</u>.—The procedures used to identify individual whales and to determine their sizes are summarized by Richardson et al. (1990a:62-63); Koski et al. (1992), and Rugh et al. (1992a).

Measurements of the 1991 LGL calibration target as photographed from ~76 m ASL were more variable than those from higher altitudes. Hence, we considered whale lengths determined from photographs taken at <91 m (<300 ft) to be approximate. Such lengths are included in histograms when no "better" measurement was available for the whale in question. However, these approximate lengths will be excluded from analyses that require precise length measurements, e.g. analyses of growth rate.

All LGL and NMML whale images obtained were classified as Grade A (recognizable between years if compared to a photo of similar or better quality), Grade B (recognizable on a different day within the same season if compared to a photo of similar or better quality), or Grade C (not recognizable). The reader is referred to Davis et al. (1983) for a more detailed description of grading of photos for reidentification purposes.

To check for whales photographed more than once within a given year, each LGL image from 1989 was compared to all others acquired by LGL in 1989, and to all images acquired by NMML in 1989 after 11 May. For 1991, each LGL and NMML Grade A and B whale image was compared with all other Grade A and B images acquired within 7 days of that image. The procedure used in 1994 was the same as that in 1991, except that in 1994 there were no NMML photos. The procedure used in 1991 and 1994 assumes that no whale would linger in the Barrow area for more than 7 days during spring migration.

To identify between-year resightings, we also compared all LGL and NMML Grade A images from 1989, 1991 and 1994 with the complete 1981-94 LGL and 1984-91 NMML collection of Grade A photos. (NMML's 1992 photos were not considered.) In these inter-year comparisons, the new Grade A whale images were compared with images in the same file and in "adjacent" files. The adjacent files are those containing whale images with similar characteristics (Rugh et al. 1992a).

Aerial Observations of Behavior

Our standard procedures for aerial observations of focal groups of bowheads (e.g. Richardson et al. 1991a:27*ff*) were applied whenever observations were possible from an altitude of 460 m. Previous studies have indicated that bowheads observed from an aircraft circling at 460 m ASL and at reduced power (~165 km/h) are usually not disturbed by the aircraft (Richardson et al. 1985a,b, 1991; Richardson and Malme 1993). Results from the present study verified this (§6.7).

In 1991, the prevailing low cloud usually prevented useful behavioral observations from the aircraft. We obtained only 4.1 h of systematic behavioral observations; these came from 7 observation sessions on 5 dates (29 April, 4, 6, 20 and 25 May). In 1991, we were never able to obtain aerial observations of bowheads near the operating sound projectors. The few times when the aircraft crew could observe from 460 m ASL near the ice camp were times ▸ when no bowheads were present, or ▸ when the sound projection equipment was still being set up, or ▸ when dangerous ice conditions or encroaching fog forced termination of ice camp and/or aircraft operations before useful data could be obtained.

In 1994, we were able to observe the behavior of bowheads or (rarely) white whales from the Twin Otter circling at 460 m ASL for a total of 36.2 hours during 23 observation sessions on ten different days (Table 3.2, p. 62). Twelve of these sessions on four days (7, 9, 16 and 17 May) were done near the ice camp either during a playback of icebreaker sounds or during the preceding or following control period; five of these 12 sessions were at times while icebreaker sounds were being projected. Numerous bowheads were observed during most playback sessions (see Table 3.8, p. 80-81). However, the high sea states encountered commonly during 1994 resulted in discontinuous and fragmentary observations on most days. When the sea state is high, it is often impossible to detect bowheads when they first surface. This prevents determination of the duration of surfacing, number of blows per surfacing, amount of turning during surfacing, and other variables that require observation of the complete surfacing. Also, with high sea states it is frequently impossible to be sure whether any surfacings have been missed, or to see the distinctive markings that show whether a given whale is the same one observed during a previous surfacing. These problems were unusually common during the 1994 behavioral observation work.

Observation Procedures.—Throughout each observation session, two full-time observers plus (in 1990-94) one part-time observer on the right side of the aircraft dictated standardized behavioral observations and whale position data via the intercom into a single audio recorder and also into the audio channel of a video recorder. The two full-time observers were seated in the co-pilot's seat and the seat two rows behind it. The part-time observer occupied a seat 2-3 rows behind the primary observers. During each surface/dive sequence by bowheads, they described the same behavioral attributes as recorded in our previous studies of bowhead behavior and disturbance reactions (e.g., Würsig et al. 1984, 1985, 1989; Richardson et al. 1985a, 1986, 1990b, 1991a, 1995; Koski and Johnson 1987; Dorsey et al. 1989). These data included times when each focal whale surfaced, blew and dove; its headings and turns; occurrence of pre-dive flexes, fluke-out dives and aerial activities (breaches, tail and flipper slaps, etc.); and occurrence of numerous other behaviors as listed in §5.3, Behavior of Undisturbed Bowheads.

Another observer, also on the right side during behavioral observations, operated a high-resolution 8-mm video camera whenever whales were at the surface. In 1991, this was usually a Sony CCD-V99 with 11-88 mm zoom lens, x1.4 teleconverter, and monochrome viewfinder. In 1994, we usually used a Sony CCD-TR500 with 5.4 to 54 mm lens, x2 teleconverter (on some days), and color LCD viewfinder. Videotaping was through a side window at the rear of the aircraft. In 1991/94, the standard plexiglass window there had been replaced by flat glass. The video camera was usually operated with manual focusing and with high shutter speed (e.g. 1/1000 s) to provide sharp images when viewed in stop-frame mode. Automatic exposure was used when practical, but manual exposure adjustment was necessary when there was much ice within the field of view. The date and time (to the second, synchronized with observers' digital watches) were recorded on each video frame to facilitate analyses. The audio signal recorded on the videotape was taken from the aircraft intercom, and thus included the behavioral, positional, and other data dictated by all personnel on the aircraft. While the focal whale or group of whales was at the surface, the video camera was normally kept tightly framed on those whales. After they dove, a wide-angle view of the area was normally recorded to assist in determining whale position relative to ice features and the ice camp.

Behavioral data were transcribed from audiotape between flights or, in some cases, after the field season. The videotape was then examined for details not noted during the real-time behavioral dictation. The combined data were coded numerically as in our previous work (see

Richardson and Finley 1989:25-28 for details). These records were hand checked and then typed into an IBM-compatible microcomputer for computerized validation and analysis. Statistical analyses of the resulting behavioral data were done with the BMDP program system (BMDP/ Dynamic, release 7.0 for MS-DOS computers—Dixon 1992).

Behavioral Definitions and Criteria.—Most definitions and criteria were the same as in our previous related studies (e.g. Dorsey et al. 1989; Richardson et al. 1995). In particular, a surfacing is again defined as the interval from the first arrival of a whale at the surface after a long ("sounding") dive to the time when the whale descends below the surface for the next long dive. A surfacing usually includes several blows, and is equivalent to a "surfacing sequence" as defined by some other authors. Some studies define the surface time as the interval from the first blow to the last blow of a surfacing sequence. In contrast, we define it as the interval from first arrival of the whale at the surface to the final submergence of the sequence. Bowheads are often visible at the surface for a few seconds after the last blow, and occasionally for a few seconds before the first blow. Therefore, surface times defined on the basis of the first and last blows presumably would average a few seconds shorter than those obtained with our procedure.

There were two changes in procedures in this study (1989-94) relative to our previous projects concerning bowhead behavior in summer and autumn:

- Occasions when the whales's blowholes rose above the surface in the pattern usually associated with a blow, but no blow was seen, were recorded as "presumed blows". Such cases seemed to be more common in spring than in summer or autumn. These cases were treated as actual blows when determining blow intervals and number of blows per surfacing. Ice-based observers noted that these whales were in fact blowing; the invisible blows were audible.
- The primary measure of blow interval in this study is the "median blow interval for a surfacing". In some previous summer/autumn analyses we used mean, not median, blow intervals. The median is less affected by occasional extreme values, or by missed blows.

There can be some doubt as to whether certain brief (<1 min) submergences should be counted as dives or as intervals between two blows within a surfacing sequence. The procedure for handling these cases is important because it has major effects on variables such as duration of surfacing and number of blows per surfacing. One approach is to use "log survivorship analysis" (Fagen and Young 1978) to identify a specific time interval to be used to separate long blow intervals from short dives. We did not use that approach, as no one simple arithmetic criterion is appropriate. Certain blow intervals, e.g. by some whales resting at the surface, are quite long but nonetheless clearly blow intervals and not dives. Conversely, certain dives, e.g. when bowheads are being actively pursued, are quite short but nonetheless clearly dives and not blow intervals. Thus, the longest blow intervals are longer than the shortest dives and no single "duration" criterion is appropriate for all cases.

When viewed from an aircraft, the behavior of bowheads at the start of a sounding dive is usually distinct from that at the start of a submergence between blows. When sounding, a bowhead usually arches its back as it submerges, the flukes are sometimes raised, and the whale typically appears to be diving deeper and/or more steeply. However, bowheads occasionally surface again within ½-1 min after such an apparent sounding dive. In this study, we classified these short submergences as dives if one or more of the usual indicators of a dive were seen: an arch, fluke-out, or steep submergence. If the whale sank out of sight without any of these indicators of a dive, and surfaced again within 1 min, the submergence was classified as a blow interval within a surfacing sequence. Shallow dives during which whales swam close enough to the surface to be visible from above were counted as dives only if they were >1 min in length (>½ min for calves).

Number of Observations.—In this report, when analyzing the behavior of undisturbed bowheads (§5.3, §5.4), we combined results from 1991 and 1994 with those from the 1989-90 phase of the project. Observation procedures in 1989-90 were very similar to those described above for 1991 and 1994 (see Richardson et al. 1990a, 1991a for details). Results from all four years are directly comparable. Over the four years of the study, the numbers of bowhead surfacings and dives for which we have at least partial behavioral data are shown in Table 2.2.

TABLE 2.2. Number of bowhead surfacings and dives for which behavioral data (complete or partial) were obtained via the aerial observation technique.

	1989	1990	1991	1994	Total
Surfacings					
Presumably undisturbed whales	258	558	57	496	1369
Potentially disturbed whales[a]					
Drilling noise playbacks	128	261	-	-	389
Icebreaker noise playbacks	-	-	0	149	149
<30 min after playback	0	27	0	26	53
Aircraft at <460 m ASL	58	2	0	0	60
Other or combination	39	12	0	26	77
Total, undisturbed + disturbed	483	860	57	697	2097
Dives					
Presumably undisturbed whales	157	377	40	325	899
Potentially disturbed whales[a]					
Drilling noise playbacks	105	136	-	-	241
Icebreaker noise playbacks	-	-	0	83	83
<30 min after playback	0	15	0	20	35
Aircraft at <460 m ASL	35	2	0	1	38
Other or combination	36	4	0	22	62
Total, undisturbed + disturbed	333	534	40	451	1358

[a] Includes observations during 30-min or (for aircraft) 15-min post-disturbance periods.

Ice-based Observations

Ice-based observations of bowheads and white whales were obtained to help meet specific objectives 4, 6 and 7 (p. 7). A watch for whales was maintained by 1-4 people (most often 2 or

3) starting within a few minutes of arrival on the ice and continuing until about ½ h before departure. At least one person watched throughout this period, but the number of additional people who were watching for whales tended to be lower early and late in each day's observation period, when equipment was being set up or packed, than during the middle hours. When no whales were present, ringed and bearded seals were observed opportunistically, or the day's plan was changed to conduct a transmission loss test.

Field procedures in 1991 and 1994, primarily involving use of a surveyor's theodolite to observe and locate whales, were very similar to those during 1990 (see Richardson et al. 1991a:29*ff*). In 1991, we used a Lietz/Sokkisha model DT5 digital theodolite with 10 second precision. In 1994, we used a Lietz/Sokkisha model DT5A with 5 second precision. The height of the theodolite was determined each day by taking a gravity-referenced reading from a vertical stadia rod at the projector location. Theodolite readings in degrees, minutes and seconds were referenced to magnetic north and to gravity. Ice ridges on which the theodolite was placed ranged in height from 2.8 to 6.0 m ASL, but were less stable than desired. To control for errors caused by movement of the theodolite base, the horizontal and vertical zeroes were checked every 15-30 min and after tracking episodes, and were reset if off by >1 minute of arc in 1991 or >40 seconds of arc in 1994.

One difference from 1989-90 was that, on most dates, the digital theodolite was interfaced by way of an RS-232 serial interface to a Hewlett Packard 71B "palmtop" computer (1991) or a Tandy 102 "laptop" computer (1994). This allowed direct logging of bearings and depression angles in relation to time. The program also permitted entry of notes about whale behavior and identification. Distances were computed using an iterative equation that included correction for curvature of the earth.[5] Data were stored on diskette and, for backup, printed in real time via a portable ink jet printer. A heating pad designed for a car battery and powered by the generator at the ice camp kept the computer batteries and ink jet printer warm enough to work on the ice. This data logging system allowed for automated and hence quicker collection of theodolite readings, resulting in more detailed tracks of successive animal positions.

Because of the low vantage point from the ice, ice-based observers could not see whales unless they were within ½-2 km, depending on ice conditions, visibility, and perch height. Also, because of the near-horizontal observation angle, whales could not be seen when slightly below the surface, and many aspects of behavior were difficult to observe. The most valuable data obtained from the ice-based observations were data on the closest point of approach (CPA) of whales to the ice camp, and on the paths of the whales passing close to the camp. For whales passing within about 1 km, ice-based observers aided by the theodolite could obtain more precise data on whale CPAs and tracks than could aerial observers. Also, ice-based observers maintained a continuous watch on the area near the ice camp throughout each playback and its associated pre- and post-playback control periods. During much of this time, aerial observations were not possible

[5] The computer program that acquired and processed the theodolite data in 1991 was prepared by F. Cipriano, Dept of Ecology and Evolutionary Biology, University of Arizona. A similar program prepared by A. Frankel, Dept of Oceanography, University of Hawaii, was used in 1994.

near the ice camp because the aerial crew was observing other whales farther away, or was away refueling, or was unable to observe because of low clouds. Thus, the ice-based and aerial observations were complementary to one another.

During each day of ice-based work, ice conditions near the ice camp were documented by taking theodolite readings of ice edges and other prominent ice features visible from camp. These readings were taken about once per hour, and/or immediately after whales were observed. The theodolite-to-projectors distance was also measured each day using a Rolotape measuring wheel.

During 1991 and 1994 all personnel at the ice camp wore long white snow-shirts over their parkas to minimize their visual conspicuousness.

2.3 Playback Experiments

General Playback Approach

The general approach was very similar to that in preceding years of this project, as described by Richardson et al. (1991a:30*ff*). Icebreaker sounds were projected from a mobile ice-based camp established on the landfast or pack ice each day when weather or ice conditions were suitable. The reactions of whales to these sounds were determined by systematic observations of whales approaching, passing, and moving away from the ice camp. Such observations were obtained both when the projectors were operating ("playbacks") and when they were silent ("control"). These types of observations were obtained by observers at the ice camp and, when the cloud ceiling exceeded 460 m, by observers in an observation aircraft, as described in §2.2.

Playback experiments had higher priority than any other project task during all four years of fieldwork. This was particularly so on days when whales were observed migrating through the study area and when weather conditions were suitable for behavioral observations of whales from the circling fixed-wing aircraft. On these occasions, personnel at the ice camp projected sounds, and personnel on the ice and in the aircraft observed whale behavior. On many days, the cloud was too low for aerial observations from 460 m altitude, but horizontal visibility was good. If whales were migrating in the area on these "low-cloud" days, playback experiments were usually attempted, with all observations then being from the ice camp. In either case, the Twin Otter aircraft generally departed Barrow first, conducted a survey for whales and ice conditions, and selected a possible site for the ice camp before the helicopter arrived.

Cloud permitting, the Twin Otter crew then conducted "control" observations of the behavior of undisturbed whales within a few kilometers of the ice camp while the ice-based crew set up the projection equipment and, simultaneously, began ice-based control observations of whales. Weather permitting, both aerial and ice-based observations of whales continued during the subsequent playback period and during a following post-playback "control" period. Often weather conditions changed during the day. Sometimes this forced cancelation of aerial observations but allowed continuation of ice-based work. Occasionally clouds were too low for aerial observation during the pre-playback control period early in the day, but aerial observations became possible later, during and after the playback period.

Playbacks were done with the equipment listed in Table 2.1A (p. 21). The time required to set up the equipment at an ice camp was 1-2 h in 1989-90, 2-3 h in 1991, and 3-4 h in 1994. These are the approximate intervals from first arrival on the ice until everything was ready to project underwater sound. Setup time became longer after 1990 because of the increasingly heavy and elaborate sound projector systems and associated electronics in 1991 and especially 1994. Control observations were collected during the setup process but, especially in 1991 and 1994, conditions on the ice sometimes became untenable before the equipment was ready for a playback or shortly after the playback began.

Meaning of the Term "Control"

Insofar as possible, we obtained control observations near the ice camp under conditions that differed from those during playbacks only by the emission of sound from the projectors. This is the usual definition of "control". This approach is appropriate for determining whether playbacks *per se* had any discernible effects. However, concern has been expressed that this approach might underestimate the actual effects of playbacks if whales observed under control conditions were already somewhat disturbed.

Some whales that approached the ice camp during control conditions probably could hear man-made sounds associated with operation of the generator, intermittent helicopter operations, and the circling Twin Otter observation aircraft. We attempted to minimize exposure of whales to noise from these sources, but it was not possible to eliminate all exposure. Section 4.6 describes the generator noise, and §6.7 and §7.4 describe reactions of spring-migrating bowhead and white whales to aircraft. The few cases of bowheads and belugas reacting to helicopter operations near the ice camp are excluded from our "control" datasets. There was little indication of reactions to our other activities during control periods. However, we cannot exclude the possibility that these activities had subtle effects on some whales observed near the ice camp during control periods.

Strictly speaking, therefore, the differences between whale activities and behavior during playback vs. control periods represent the incremental reactions to playbacks when playbacks are added to a background of other human activities associated with the research. If the whales observed under control conditions were somewhat disturbed, then the differences in whale activities between control and playback conditions might understate the differences between activities of truly undisturbed whales vs. those exposed to playbacks. However, almost all bowhead and white whales observed during control conditions during this study behaved in a manner indistinguishable from that seen, during this and other studies, by ice- or shore-based personnel observing in the absence of any known disturbance. Of the few exceptions, most involved helicopter disturbance, and these cases have been excluded. Therefore, we believe that the playback vs. control comparisons in this study provide a good indication of the differences in whale activities that would occur between playback conditions and otherwise-similar situations with no human activities.

Acoustical Aspects of Playbacks

Playback Stimuli.—During 1989 and 1990, the steady underwater sounds of drilling on an ice pad, as recorded at the *Karluk* site, were projected as the playback stimulus. The collection and characteristics of these sounds were described in Richardson et al. (1990a, p. 44 and 80*ff*).

During 1991 and 1994, the varying sounds of an icebreaker operating in heavy ice were used, as recommended by project personnel and agreed by the Minerals Management Service and the project's Scientific Review Board. In contrast to the steady, low-frequency drilling sound used in the 1989-90 tests, icebreaker sound has significant energy at frequencies up to a few kilohertz, and the source level is quite variable over time. After data on whale reactions to the drilling sound were collected in 1989-90, it was considered important to test the reactions to a more variable sound with broader frequency composition.

The icebreaking sounds used for playback stimulus were recorded on 2 September 1986 from a drifting boat 0.25 n.mi. (460 m) from the icebreaking supply ship *Robert Lemeur* operating in heavy ice near the Corona drillsite ~40 km north of Camden Bay (Greene 1987a). This ship is an Arctic Class 3 icebreaker of 83 m length overall and 3184 tons gross displacement. It has two turbocharged diesel engines of combined power 9600 bhp (7.2 MW). The two four-bladed controllable-pitch propellers are in Kort nozzles. Sounds were recorded continuously for over 14 minutes. The characteristics of these received icebreaker sounds were reported by Greene (1987a) and are further summarized in §4.4 of this report (p. 115*ff*).

Prior to the field season, the taped icebreaker sounds were played back several times to record a 2-h DAT tape of icebreaking sounds, which was itself copied to provide a second 2-h DAT tape. The end time of the 14-min segment was selected such that the levels at the start and end of the segment were closely matched. Thus, there was no sharp change in the sound at 14-min intervals when the segment began to repeat. During playback experiments on the ice, the two tapes were played sequentially, replacing the played-out tape with the alternate quickly to minimize the break in transmission (about 30 s), and then rewinding the first tape while the second one played.

Projector Operations.—Playbacks were done with the equipment listed in Table 2.1A and described in §2.1 under "General Approach and Equipment". Briefly, during 1991 and 1994, a Sony DAT recorder was used to play back the icebreaker sounds. This resulted in accurate speed and frequency reproduction for the playbacks. These sounds were projected into the water by a J-13/F-40 system (1991) or an Argotec 220/J-11 system (1994) suspended at a depth of 18 m. In 1991, we used a 250-W amplifier powered by a 2.2 kW gasoline generator. In 1994, we used a 1600-W amplifier to drive the Argotec 220, only one side of which was operational, and a 350-W amplifier to drive the J-11; these were powered by a 5 kW gasoline generator. In 1991 and 1994, the generators were suspended from a frame via bungee cords to minimize transmission of generator noise and vibration into the water. In both years, the projectors were turned on at a time when no whales were known to be within ½ km of the ice camp, as required by Scientific Research Permit 670/Modification 2, issued by the National Marine Fisheries Service. At the start of most playbacks, the sound level was increased gradually over 1-5 minutes ("ramped up").

In 1991 and 1994, icebreaker playbacks were done for a total of ~40 h distributed over 13 d. This included 7 d when bowheads were seen near the ice camp during the playback, and 3 d when white whales were seen there during the playback (see Table 6.1 in §6.1).

Playback operations in 1989-90 were described by Richardson et al. (1990a, 1991a). Drilling sounds were projected for prolonged periods on 19 d, including 10 d when bowheads were seen near the ice camp during the playback, and 6 d when white whales were seen there during the playback (Table 6.2 in §6.1). Equipment used for playbacks in 1989-90 is summarized in Table 2.1.

Acoustic Monitoring.—During all playback experiments in 1994, a four-channel TEAC DAT recorder was operated continuously to record the following signals: (1) the tape player output signal (the signal being amplified for projection); (2) an ITC 1042 monitor hydrophone within 3 m of the projectors; (3) an ITC 6050C hydrophone about 3-5 m from the projectors; and (4) when available, a sonobuoy installed manually about 1 km from the projector site. Date and time were recorded continuously and automatically, and periodic voice announcements by the operator were recorded on a special fifth memo channel. Amplifier and tape recorder gain settings were noted, along with the exact times of any changes. In 1991, procedures were similar, except that usually only the monitor hydrophone and sonobuoy signals were recorded on the DAT recorder, and these recordings were intermittent during the playback. In 1989-90, the signal from the ITC 1042 monitor hydrophone and the monitor sonobuoy ~1 km away were recorded intermittently on a calibrated audio cassette recorder (Table 2.1B).

When the cloud ceiling was high enough to allow the aerial observation crew to observe from 460 m ASL, personnel on the aircraft dropped sonobuoys (AN/SSQ-57A or AN/SSQ-53B DIFAR) near bowheads to monitor and record the sounds received near the whales. This was done in 1989-90 and 1994. In 1991 the prevailing low cloud made it impractical to conduct aircraft operations near the projector site during playback experiments. The procedures followed when using both manually-deployed and air-dropped sonobuoys are described in §2.1. Because the positions of many buoys relative to the ice camp changed over time, especially when the ice camp was on landfast ice, sonobuoy data were used to determine received levels of projected sounds only when the distance from the ice camp was known through one or more of the following procedures:

- the buoy had just been deployed at a known distance, or
- the buoy's location relative to the camp was more-or-less fixed by ice and was determined when it was first deployed, or
- the buoy's location was variable but known and periodically measurable from the ice camp by theodolite or from the observation aircraft by direct overflight and GPS readout, or
- the buoy's location was variable but measurable by crosscorrelating the sounds received near the projector and at the sonobuoy.

Acoustic Analysis.—In all years, the taped acoustic data, along with notations about gain settings and associated calibration data, allowed us to measure the source level of the projected sounds on an overall and a 1/3-octave basis. These source level analyses were done after each field season for various representative times during each playback test.

To determine the source level of the projected sounds at a given time, an 8.5-s segment of the sound recorded from the ITC 1042 monitor hydrophone was sampled at 16,384 samples/s and analyzed by Fourier transforming windowed, overlapped blocks of 8192 samples, followed by averaging of the various ½-s blocks and application of calibration data. This was the same process that was applied in analyzing ambient noise, signals received during transmission loss tests, and signals received at sonobuoys. From the resulting narrowband spectrum, we determined the levels received at the monitor hydrophone in 1/3-octave bands from 10 to 6300 Hz, and in various broad bands. These data were converted to source levels based on the measured distance of the monitor hydrophone from the projectors, assuming spherical spreading over this distance. Because the icebreaker sounds were variable, repeating after 14 minutes, it was important to determine the time of each source level measurement within the 14.3-min sequence. For each source level measurement, the offset time from the start of the sequence was determined by crosscorrelating the sample segment against the entire 859-s sequence length.

Levels of icebreaker sound received at sonobuoys that had been deployed near the ice camp manually or from the aircraft were determined in a similar manner, taking account of the strongly sloped frequency response of sonobuoys.

The crosscorrelation method could be used to determine the distance between the projector and any hydrophone, including a sonobuoy, when sounds at the two sites were recorded on the same tape recorder. By crosscorrelating the projector input signal or the monitor hydrophone signal with the signal from the monitor sonobuoy, the delay time between the two signals could be determined to an accuracy of about 5 ms. Distance was determined by multiplying the time delay by the speed of sound (about 1435 m/s near the surface under our field conditions). Crosscorrelation was also used occasionally to determine the difference in distances of two sonobuoys from the projector based on differences in arrival times of projected sounds.

Ambient noise levels just before and after the playback period were determined from hydrophone and sonobuoy signals recorded at the ice camp and from sonobuoy signals recorded aboard the project aircraft, as described in §2.1, Physical Acoustics Methods. These data were later used to estimate the signal-to-noise ratio at locations of observed whales, i.e. the difference (in decibels) between the levels of the icebreaker signal and the ambient noise in a corresponding band (§6.1-6.3).

Whale Movements and Behavior During Playbacks

Observation Procedures.—To maximize the power of the observations in assessing the hypotheses, we planned to use whales approaching the sound projectors as their own controls insofar as possible. Our intent was to compare the movement patterns and behavior of the same whales when they were at various distances from the projectors. This approach reduces the complications caused by differences in the natural activities of different individual whales. We planned to begin observing the movements and behavior of whales when they were far enough from the projector system that they could not hear it or, at the least, were not likely to react to it.[6] This required aerial observations, as ice-based observers stationed near the projectors would be unable to see whales more than ½-2 km away, depending on ice conditions and visibility. We then intended to observe whale movements and behavior as they approached and passed the projectors. This would involve both aerial and ice-based observations.

Specific procedures for aerial and ice-based observations of whale movements and behavior are described in §2.2. Near the ice camp, the same ice-based and aerial observation procedures were used during playback and non-playback periods. Also, the aerial observation procedures used for whale observations in the absence of an ice camp were the same as those near the ice camp, with the exception that bearings and distances of whales from the ice camp were not relevant in the latter case.

Because the ice camp and projector system had to be reestablished on the ice each day, the projectors often began operating while whales were already under observation from the aircraft. To minimize observer expectancy biases, during 1991/94 we prevented the two primary behavioral observers in the aircraft from knowing whether the sound projector was operating. A third part-time observer on the aircraft was, unavoidably, often aware of projector status because she was monitoring the signals received by sonobuoys, which detected the projected sound when it was present. The fourth biologist on the aircraft (project director) was in radio communication with the acoustician on the ice, and was aware of projector status. The 3rd and 4th observers did not discuss projector status on the aircraft intercom, and behavioral data were transcribed from audiotape and videotape onto dataforms without knowledge of projector status.

The ice-based observers, because of their proximity to the projector site and their involvement in its deployment and retrieval, occasionally were aware of projector status (on or off). However, most of their data were theodolite readouts, which do not involve subjective judgments. Thus, observer expectancy bias would not be a problem in these data. Furthermore, the ice-based biologists often were unaware of projector status. The generator was operated during both playback and control periods. During control periods as well as playbacks, the tape recorder used to play back the icebreaker (1991/94) or drilling (1989-90) sounds was operated, and those sounds were played over a monitor speaker in the tent at the ice camp. With this procedure, only the acoustician at the camp knew whether sounds were being projected into the water.

<u>Distances and Bearings of Whales from Ice Camp</u>.—When whales were seen by observers at the ice camp, the distances and bearings were determined using a theodolite (§2.2). This was done whether or not the projectors were operating at the time.

When aerial observations were obtained within 10 km of the ice camp, bearings and distances of whales from the camp were determined for each surfacing. Again, this was done whether or not man-made sounds were being projected from the ice camp. (As described above, the primary

[6] Previous studies of bowheads and other baleen whales have shown that they generally show no discernible reaction to steady sounds that are weak but presumably detectable (Richardson and Malme 1993; Richardson et al. in press).

aerial observers did not know when sounds were being projected.) Several types of data were used to determine whale position relative to the ice camp; not all of these were relevant or available at any one time. Types of data used included the following:

- Whale-to-projector bearings were estimated by eye to the nearest 10° by reference to the aircraft's gyrocompass and, on some occasions in 1994, real-time GPS readouts of aircraft-to-camp bearing. These estimates were usually accurate within 10°, and should always be accurate within 20°.
- The distance from the whale to the projector was estimated visually during most whale surfacings. When distance between two points could be determined by some independent means, we compared our visual estimates with the independent determination. For distances of 0.5 to 5 km, visual estimates were usually within 25% of the correct value. In most cases, one or more of the following types of data were available to replace or refine the visual estimate.
- Whales within ½-2 km of the ice camp were often under observation from the ice camp as well as the aircraft. When accurate theodolite data on bearing and distance from the ice camp were available, these data were used in preference to visual estimates by aerial observers.
- In all years, aerial observers frequently dictated onto audiotape the position of the aircraft according to the aircraft's GPS (1991/94) or VLF (1989-90) navigation system as we reached a consistent point on the observation circle (e.g., north of the whale position). Although the focal whale(s) usually were ~1 km from this location, the offset from aircraft to whale was similar from one surfacing to the next, as we attempted to fly circles of consistent radius.
- In 1994, the aircraft's GPS position was logged by computer about once per second. A program was written to compute the centroid positions of successive observation circles and, from those plus ice camp position, the distance and bearing from ice camp to centroid. The focal whales were usually near the centroid.
- When the focal whale(s) were not at the center of the observation circle, whale position relative to the center was often dictated onto audiotape (e.g., "whale is about 400 m north of the center").
- Whale position relative to any nearby distinctive ice features was usually dictated onto audiotape and/or visible on videotape. Locations of ice features relative to the ice camp were determined by vertical photography from high altitude on days when cloud ceiling permitted (see below).
- Whale positions were estimated by eye relative to locations of other whales and locations of the same whale during preceding surfacing(s).
- The aircraft was occasionally (1991/94) or often (1989-90) flown from the location where whales had just dived to the ice camp. By flying directly over these two positions within a short interval, even the less-accurate VLF navigation system used on the aircraft in 1989-90 provided accurate (±0.3 km) data on the whale-to-projector distance and bearing.
- The absolute location of the ice camp was determined using the GPS (1991/94) or VLF (1989-90) navigation systems on the Twin Otter and helicopter, and a separate GPS (1991/94) or Si-Tex model A-310 SatNav receiver (1989-90) at the ice camp. When the ice camp was on pack ice, its position often changed substantially during an experiment due to wind- and current-induced drift of the ice. To account for this, all whale sightings and movements were plotted relative to the sound projector location at the sighting time.

By considering all of these types of data, positions of most whales relative to the ice camp were determined within ±20% distance and ±20° bearing. In the few cases where the uncertainty appeared to be greater, the distance and/or bearing were recorded as unknown. A high proportion of the distance and bearing records are accurate within ±20% and ±20°, and we believe that many are accurate within ±10% and ±10°. Also, relative distances and bearings of the same whale during successive surfacings were determined with greater accuracy than were the absolute distances and bearings. Distance uncertainties of ±10% and ±20% translate into received level uncertainties of only 1 or 2 dB, respectively, if spherical spreading is occurring, and less with cylindrical spreading. Even a 40% error in a distance estimate, which would be rare, translates into no more than a 4 dB error in estimated received level.

Ice Conditions Near Playback Sites

On playback days when clouds were absent or high, we obtained vertical photographs of the area near the ice camp in order to "map" the ice in the area. Whale locations were often identified, in part, relative to ice features described or videotaped by the aerial observers. Thus, vertical photos of the ice were extremely valuable in mapping positions and movements of whales relative to the ice camp.

In 1994, once or twice during each day with coordinated aerial and ice-based work, the project aircraft climbed to an altitude as high as 9000 ft or 2750 m (cloud ceiling permitting). A sequence of vertical photographs was taken through the aircraft's ventral camera port using a 35-mm camera with 17-mm very wide angle lens and/or a video camera with wide angle lens. One photo-mosaic prepared from these vertical photos appears as Plate 6.1 on p. 258. In addition, oblique photos of the ice and leads were sometimes taken with a Polaroid camera; these provided prints onto which notes could be made immediately. In 1991, ice photos were not available at playback sites because low clouds prevented aircraft operations near the ice camp.

During each day of ice-based work, ice conditions near the ice camp were documented by taking theodolite readings for ice edges and other prominent ice features visible from the camp. From these theodolite readings, distances were later calculated.

Sound Levels Received by Whales During Playbacks

Unlike the steady drillrig sounds from *Karluk*, the icebreaker sounds played back in 1991 and 1994 varied considerably with time, corresponding to the phases of heavy icebreaking: ramming ahead, stopping but maintaining full-ahead power, and backing down. Accordingly, the received signal levels near the actual icebreaker and near our projectors varied with time as well as with distance from the projector. Figure 2.2 shows the distribution of 1/3-octave received levels as recorded at distance 460 m from the actual icebreaker at the Corona site. These levels represent the range of recorded levels provided to the projector amplifiers during the playback experiments reported here.

The effective source levels for the actual icebreaker were estimated by using the acoustic transmission loss model developed in the present project for the western Beaufort Sea (see §4.3, Transmission Loss, p. 96*ff*), the water depth at the icebreaker recording site (35 m), and the measured received levels near the Corona site off Camden Bay. We estimated the source level in various broad bands (e.g., 20-1000 Hz; 20-5000 Hz) and in each 1/3-octave band from 20 to 6300 Hz. The underlying assumption for this derivation is that the bottom properties at the Corona drillsite are similar to those in the present study area.

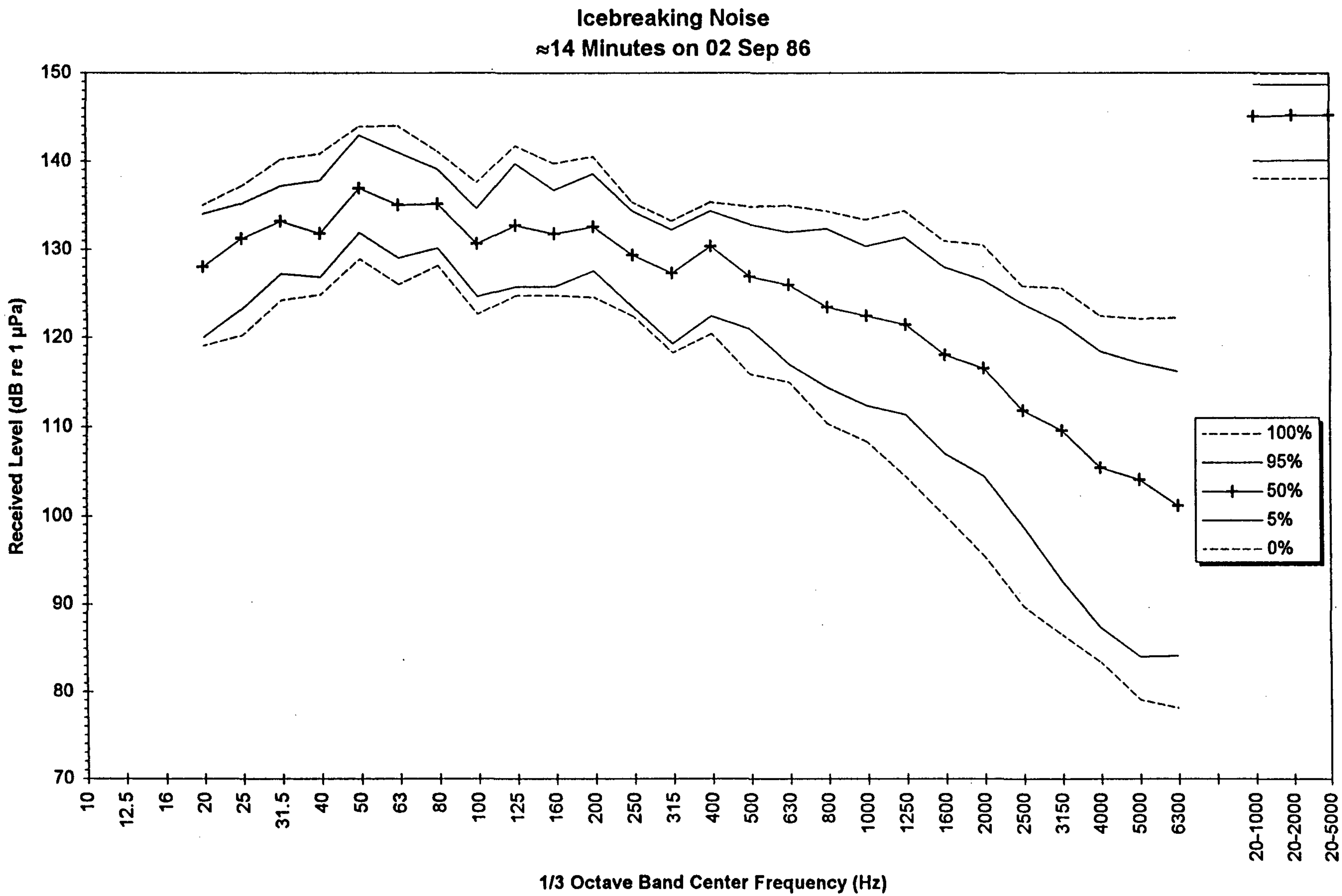


FIGURE 2.2. The distribution of received levels from the icebreaker *Robert Lemeur* operating at range 460 m, by 1/3-octave band center frequency. This distribution was computed from the 14+ minute recording of Greene (1987a:48*ff*).

Figure 4.25 in §4.4 shows the resulting estimates of 1/3-octave effective source levels during the 14-min recording. Figure 4.26 shows the time-variability of the resulting estimated source levels in four bands in relation to changes in ship activity. The results shown in these Figures are important in the discussion of playback fidelity (§4.4).

To interpret our observations of whale behavior, it was necessary to estimate the sound levels to which the observed whales were exposed. Whales under observation at a given distance from the projectors at various times in 1991 and 1994 were subjected to widely varying sound levels because of

- moment-to-moment variability in received levels of the original icebreaker sound at the recording site 460 m from the icebreaker,
- day-to-day variability in projector capabilities, and
- site-to-site variability in sound propagation conditions at different projector locations.

Thus, sound levels received at any specified distance on a given date and time had to be estimated on a statistical basis. We chose to estimate the minimum, median and maximum levels expected for each band within the 64-s period preceding the observation time, and the minimum, median and maximum plus 5th and 95th percentiles expected for each band during the entire 14-min segment of recorded icebreaker sound. Because the 14-minute segment was repeated over and over during prolonged playbacks, the distribution of sound levels at a given distance from the projectors would be the same for one 14-min period as for the next if the projection equipment was not adjusted in the meantime and if the playback did not start or stop within the 14-min period.

Some sonobuoy measurements were available for directly measuring the received levels at specific sites, times and distances from the projector. However, given the variability in the sounds, it was usually essential to rely on a complex source level/transmission loss database and prediction program (which we call the "sound exposure model") to estimate the received level statistics for a given projector location, time, and projector-to-whale distance.

The basic elements of the resulting sound exposure model are as follows:

a. Measurements of the 1/3-octave spectrum of the recorded icebreaker sounds at 8-s intervals throughout the 14+ minute sequence used in the playbacks. This database consists of a series of 109 1/3-octave spectra, each of which represents the average signal characteristics over an 8.5-s interval. This series characterizes the playback levels vs. time. Although not calibrated absolutely, the series spectra are comparable to one another. Given calibrated acoustic pressure source levels for one spectrum in the series (see [c], below), all other series spectra can be adjusted to be calibrated source spectra, thereby characterizing the source levels of the projected icebreaking sounds for any time during the playback until the playback conditions changed.

b. A histogram arrangement of the 109 series spectral elements in "a" above, where the levels for each frequency band are ordered and the corresponding minimum, 5th, 50th, 95th percentiles, and maximum values are identified. Once calibrated for a given playback condition, these values characterize the distribution of playback levels during any 14-min interval until the playback conditions changed.

c. A database of measured projector source levels from selected times during every icebreaker playback experiment when whales were observed, keyed by date, time, and offset time from the beginning of the 14+ minute icebreaking sequence. As a minimum, a new source level measurement was taken whenever there was a change in amplifier setting or other playback conditions. Each of the several measured source level spectra in the database for each day was calculated from an 8.5-s segment of recorded sound, and the offset time of each such segment relative to the start of the 14-min icebreaker sequence was determined (see p. 43 in "Acoustic Analysis"). Knowing the offset time, one can match the source levels with specific elements in the 109 series analyses. Thus, each source level measurement can be used to calibrate all 109 members of the series database. In other words, having measured the projected source level in one 8.5-s segment of the playback, and knowing when during the 14-min sequence this segment occurred, one can determine the projected source level during any 8.5-s segment until the playback conditions changed. The water depth associated with each source level measurement, for use in the transmission loss model, is also stored in this database.

d. A depth-dependent transmission loss model with parameters for the 1/3-octave bands centered at 20-6300 Hz. This model was developed based on the transmission loss data collected during all four years of the present project, as described in §4.3, Transmission Loss. This TL model is specific to the present study area northeast and east of Pt. Barrow under spring (late April and May) conditions.

To use the sound exposure model to estimate the levels of projected icebreaker sound that will reach a given distance from a particular playback site, the user has only to specify one of the playback dates, a time during that playback, and the distance. The program follows a sequence of steps:

1. It searches the source level database ("c" above) to find the closest measurement time preceding the specified time of interest.

2. From the offset time associated with the source level measurement in "1", the program selects the two series spectra in "a" that bracket that time. Interpolating between the two, the program computes a 1/3-octave spectrum corresponding to the exact time of the source level measurement.

3. The program calculates the differences between the measured source level spectrum and the interpolated series spectrum. These differences may be added to any series spectrum, and to the histogram spectra, to derive corresponding calibrated source level spectra.

4. The program selects the eight consecutive spectra from "a" that characterize the 64-s period up to the time of interest specified in "1" above.

5. From these eight spectra, the program calculates the minimum, median and maximum levels in each 1/3-octave spectral band for the 64-s period up to the time of interest.

6. Applying the differences from "3" to the minimum, median and maximum values in "5", the program calculates the range of source levels for each 1/3 octave band for the 64-s period immediately preceding the specified time of interest.

7. Applying the differences from "3" to the 14-min minimum, 5%, 50%, 95% and maximum 1/3-octave band levels in "b" above, the program calculates the calibrated source level distribution, by 1/3-octave band, for the full 14-min playback cycle and for all following times, including the specified time of interest, up to the time of some change in projector operation.

8. The program applies the transmission loss model mentioned in "d" to the source levels computed in "6" and "7" above to obtain the expected ranges of received levels at the specified distance for both the 64-s period preceding the time of interest and the entire 14-minute playback duration.

9. The program also calculates the expected received broadband levels for the 20-1000 Hz, 20-2000 Hz, and 20-5000 Hz bands.

The 1/3 octave band spectra from "8" and the broadband received levels from "9" constitute the output of the sound exposure model program. If the specified time of interest occurred within 64 s after some change in projector operation, such as turning it on or adjusting the transmitted power, the 64-s results are reported as "discontinuity". Similarly, if the specified time of interest occurred sooner than 14 min after a change in projector operation, the 14-minute results are reported as "discontinuity".

To validate the sound exposure model, we used it to estimate the expected received levels of projected icebreaker sounds at times and distances where sonobuoy measurements of actual received levels were obtained during 1991 and 1994. The sonobuoy measurements were not used in developing either the transmission loss model or the sound exposure model. Thus, the sonobuoy measurements provided an independent source of data useful in checking the models. Results of this comparison are described in §4.3 (Fig. 4.21, 4.22). As described there, the sound exposure model provides reasonable estimates of actual received levels.

The sound exposure model has been implemented as a series of 14 interlinked spreadsheets in a MicroSoft Excel version 5 notebook. It can be used either to process single date/time/distance requests entered from the keyboard or, in batch mode, to process a file containing any number of such requests, saving the results to output files for subsequent use in other analyses. The latter capability was used to estimate the received sound levels at times and distances when whales were observed. The resulting estimates of received sound level were subsequently used in analyses of whale movements and behavior relative to received sound levels and relative to the ratio of icebreaker sound to ambient noise (§6.1-6.3).

3. ICE, WEATHER AND FIELD ACTIVITIES[7]

3.1 Ice and Weather Conditions

Ice conditions in 1991 and 1994 were generally similar to the typical conditions described by Marko and Fraker (1981) and Richardson et al. (1990a:28*ff*). A nearshore lead along the landfast ice edge extended from the Chukchi Sea, around Point Barrow, and ENE into our study area during most of each field season. However, within the more easterly part of the study area, the landfast ice extended farther offshore in 1994 than in 1991 (Plate 3.2 vs. 3.1). In both 1991 and 1994, the offshore pack ice and the landfast ice at the floe edge were thinner than normal. Therefore, on several days we could not find suitable and safe sites for the projector system even though extensive areas of open water were found along the migration corridor being used by whales.

In 1991, low cloud prevented aerial observations from altitude 460 m ASL on most days. In 1994, low cloud was less common and fog was unusually infrequent, but stronger-than-normal winds made aerial observations difficult during most days with ceilings >460 m.

Because this report takes account of some acoustic and biological data from 1989-90 as well as 1991 and 1994, weather and ice conditions encountered during all four field seasons are briefly described and compared below. More details concerning conditions in 1989 and 1990 are given in Richardson et al. (1990a, 1991a).

Ice and Weather in 1989

Very heavy sea ice conditions prevailed in the Barrow area from late April through mid-to-late May 1989. When the study was initiated in late April, the overall ice cover was 98 to >99% and no major leads were present. The few open water areas consisted of small holes among pans plus narrow cracks and leads that tended to be oriented NW to SE. From 7 to 11 May slightly colder temperatures (Fig. 3.1A) and calm winds resulted in freezing of virtually all open water in the study area. On 12 May moderate NNE winds shifted the offshore pack ice, forming several minor leads oriented SW to NE. The overall ice cover decreased to 95% on that date, and ranged from 85-95% until 20 May, when a "nearshore" lead 1-6 km wide formed along the landfast ice edge, extending well east of Barrow. This lead, shown in Richardson et al. (1990a:Plate 2), remained open for the remainder of the 1989 study period.

Ice conditions during much of the 1989 season were worse than normal for conducting bowhead whale studies, and at times when ice conditions were better, the weather usually was not good. The weather was clear in late April and early May in 1989, but little open water was present so whales could not be studied effectively. Unusually cold weather from 5 to 8 May 1989 froze existing open water areas and consolidated the offshore pack ice, making observations even more difficult. From 10 to 26 May 1989, low ceilings, snow and fog prevented aerial observations from

[7] By G.W. Miller, W.R. Koski and W.J. Richardson, with R. Elliott and N. Patenaude

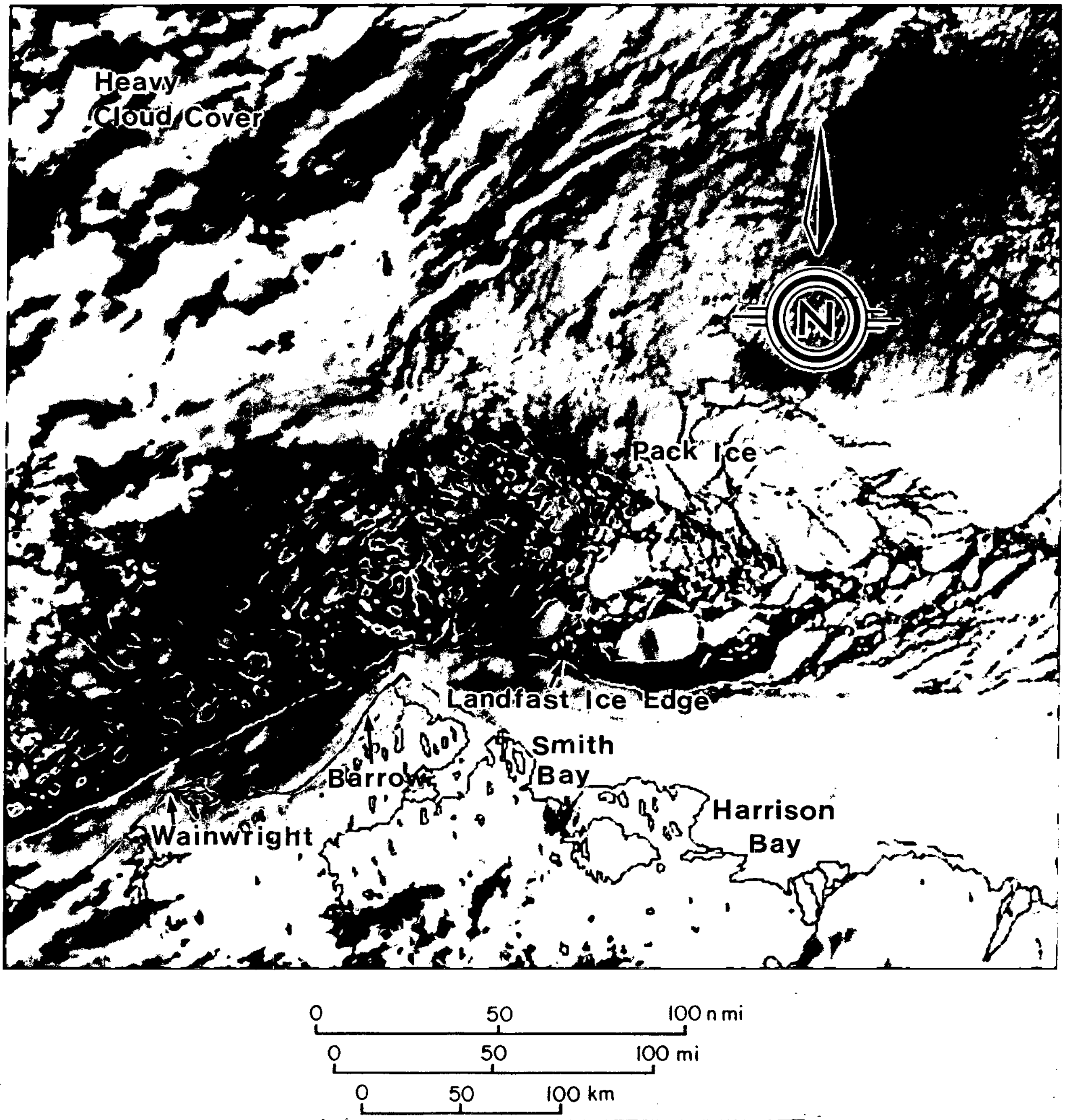


PLATE 3.1. NOAA satellite imagery of the Beaufort Sea, 4 May 1991, showing a well-developed nearshore lead and extensive offshore pack ice.

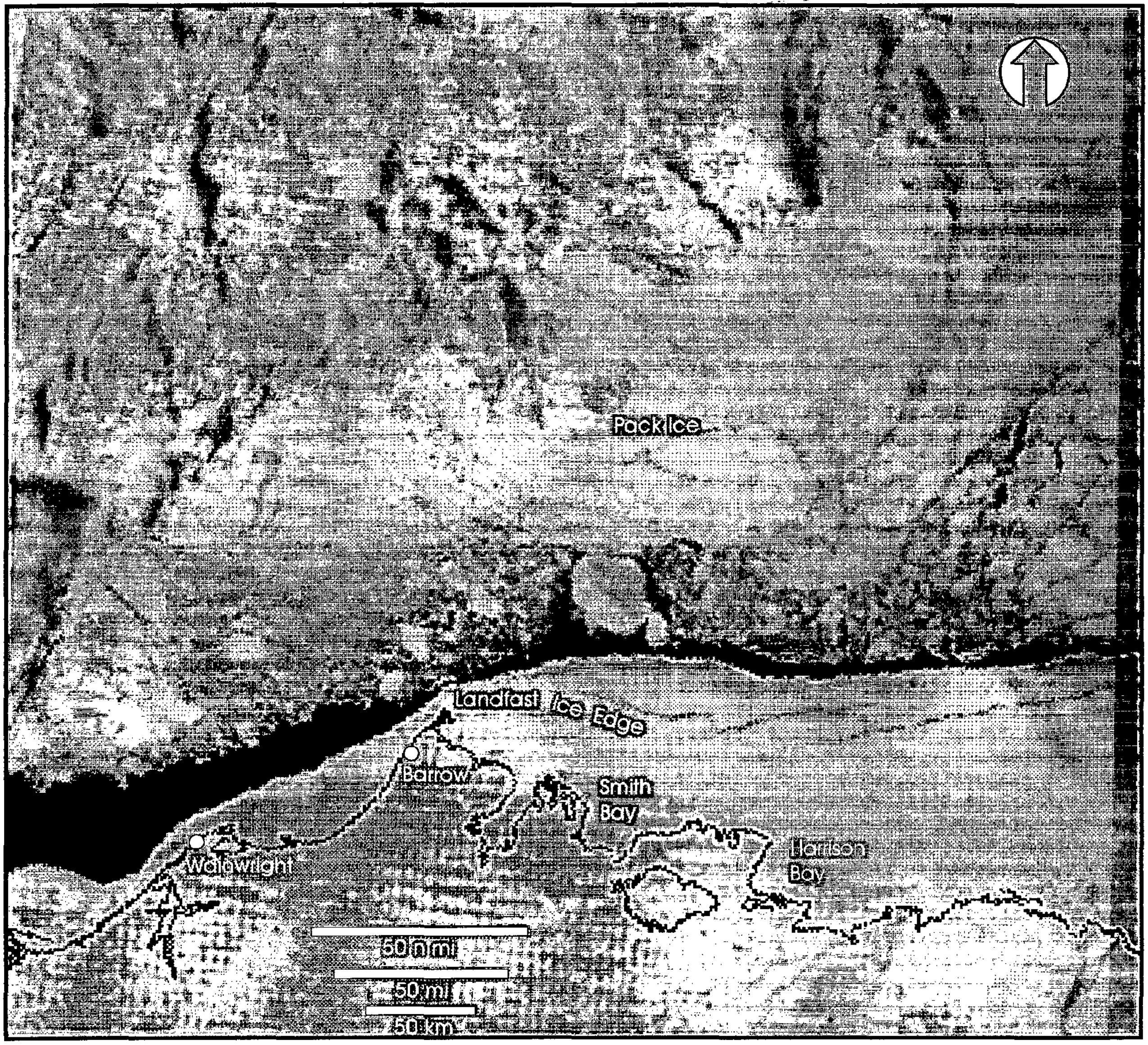
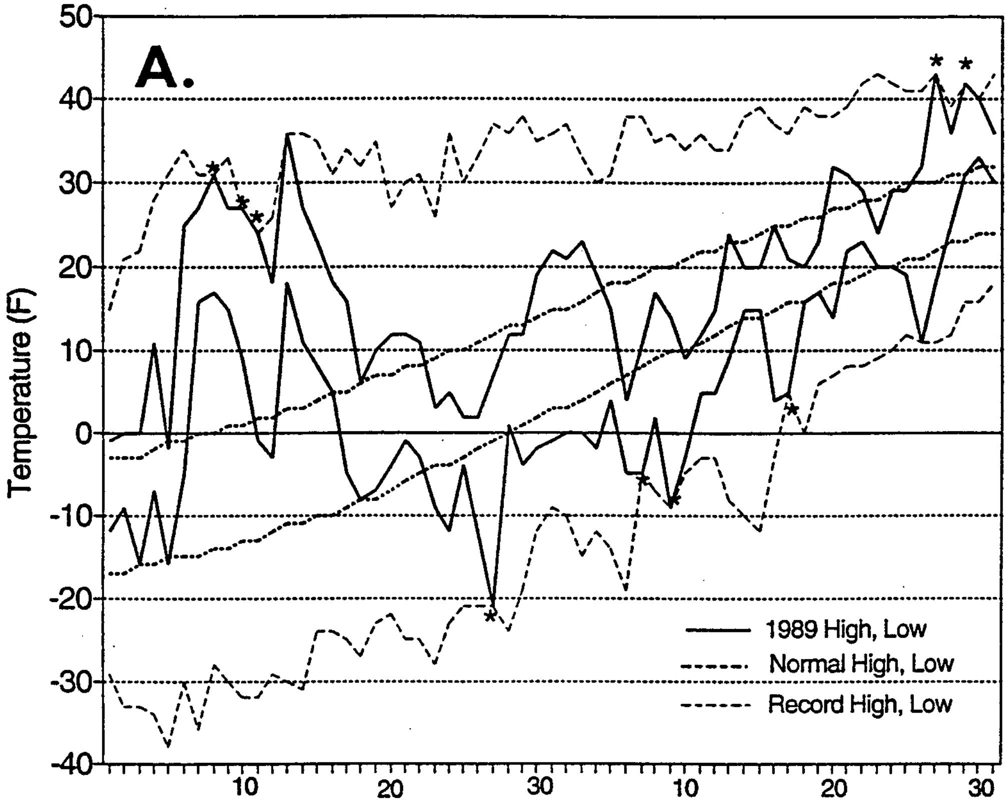


PLATE 3.2. NOAA satellite imagery of the Beaufort Sea, 16 May 1994, showing the recently-formed nearshore lead and offshore pack ice conditions, including the much wider former nearshore lead. Note the formatión of cracks in the landfast ice east of Pt. Barrow.



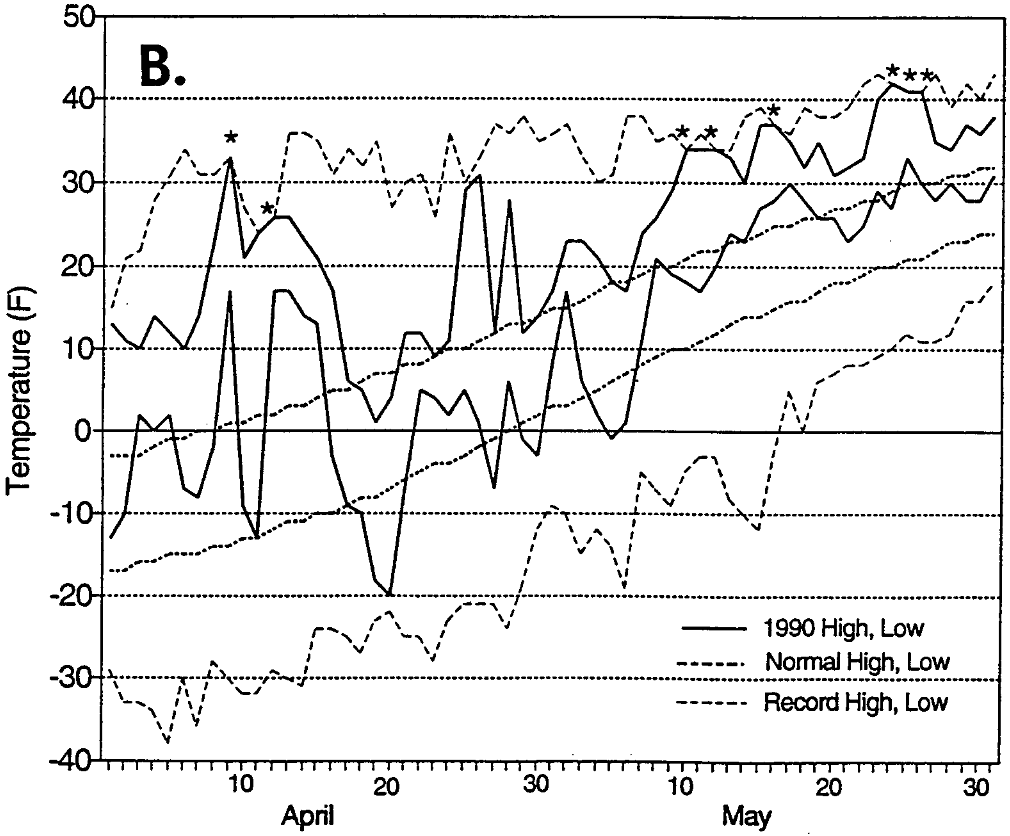


FIGURE 3.1. Daily Barrow weather in April and May of 1989-91 and 1994. Normal and record high and low temperatures are based on data from 1961-90. Asterisks indicate temperatures that set (1989-90) or exceeded (1991, 1994) those record temperatures.

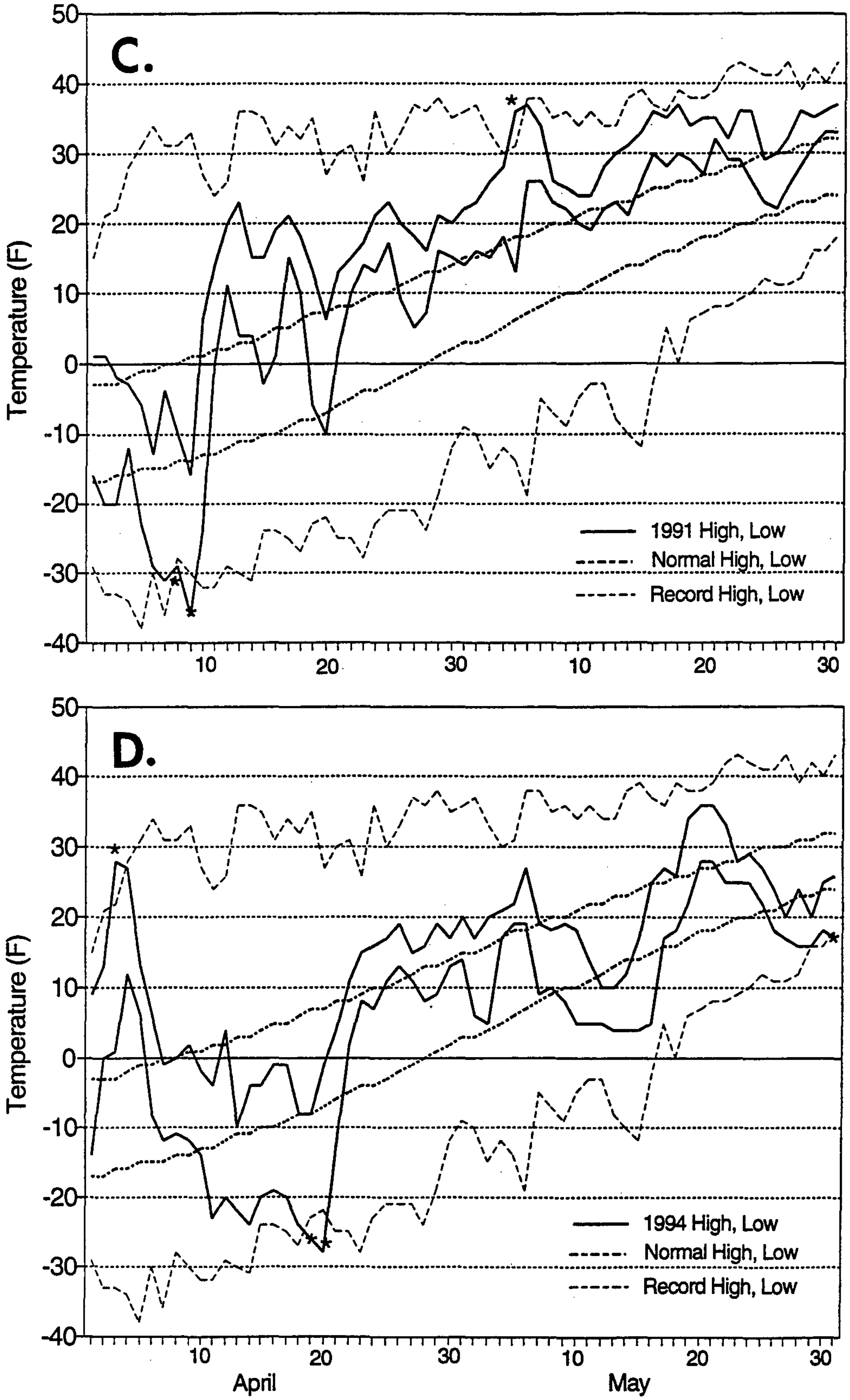


FIGURE 3.1. (continued).

altitude 460 m ASL most of the time. Observing conditions were ideal on 27-30 May 1989, but most bowheads had already migrated past Barrow by that time.

Ice and Weather in 1990

Ice conditions in 1990 were more similar to those in typical years. When the study was started in late April, there was a narrow nearshore lead along the landfast ice edge ENE of Barrow. Little open water was present amidst the offshore pack ice north and NE of Barrow. The lead started to widen at Barrow on 7 May, and was several kilometers wide by 10 May. This major lead extended across much of our study area. The pack ice north of the lead was generally heavy, but there were localized corridors of less-dense pack ice, especially in the first few kilometers north of the main nearshore lead.

The main nearshore lead and pack ice farther offshore, shown for 19 May 1990 in Plates 1 and 2 of Richardson et al. (1991a), remained more or less unchanged until 20 May when strong winds moved the ice. The lead near Barrow widened but the lead became choked with ice ~40 km ENE of Barrow. During the final few days of the 1990 study, strong winds altered the lead and pack ice conditions almost daily. The lead along the landfast ice edge was reduced to 1 km wide by 25 May, and secondary leads developed in the offshore pack ice north of Barrow.

Weather conditions near Barrow during the spring of 1990 were much more amenable to aerial observations of whale behavior than they had been in 1989. During the last few days of April and the first six days of May, temperatures were near normal (Fig. 3.1B). However, during the remainder of May temperatures were consistently above normal, and record high temperatures were recorded or equaled on several days (Fig. 3.1B). The overall average temperature at Barrow in May 1990 was 7 F° above normal (Table 3.1). Although fog was common, especially in the mornings, ceilings often were high enough to permit aerial observations of behavior from the desired 460 m ASL altitude.

TABLE 3.1. Weather conditions recorded at Barrow, Alaska, during April and May 1989-91 and 1994 in comparison to long-term average conditions from Brower et al. (1977).

	Average Wind Speed (mph)		Average Sky Cover (tenths)		Average Temperature (degrees F)	
Year	April	May	April	May	April	May
1989[a]	12.8	10.3	7.1	7.7	6.0	17.4
1990[a]	12.5	14.0	6.1	8.3	7.5	26.5
1991[a]	11.5	13.6	6.8	9.4	3.3	28.0
1994[a]	10.6	15.9	6.7	7.8	-0.1	18.6
1948-1974 Average	11.5	11.6	-	-	-2.2	19.4

[a] Data from National Climatic Data Center, Asheville, NC.

Ice and Weather in 1991

When the 1991 field season began in late April, ice conditions near Barrow were more open than during typical years. A wide nearshore lead was present along the landfast ice from southwest to northeast of Barrow (Plate 3.1). The ice within this lead was primarily newly-frozen ice with a few large pans of old ice. This broad lead extended far to the east. The ice cover was in particular contrast with that in 1989, when there was nearly total ice cover, largely by thick multi-year ice.

A period of strong easterly winds on 6-10 May forced pack ice against the landfast ice, ground many of the ice pans into brash ice, and closed the lead N and NE of Barrow. When the wind subsided, a wide lead remained west and southwest of Barrow, but the lead was closed to the north and northeast. However, irregular openings were present along the landfast ice edge in that area. The prevalence of brash, small pans, and generally thin, unstable ice, and the small sizes of open water areas near the landfast ice edge, made it difficult to locate safe and suitable locations for the projector system. On several occasions, we began setting up the equipment along the edge of a pan bordering open water but, before projection could begin, loose ice moved toward the equipment and forced its retrieval from the water.

During mid-to-late May 1991, a narrow discontinuous lead was present along the landfast ice edge north and northeast of Barrow. The lead consisted of a series of small to large openings in the pack ice along the landfast ice edge. West and northwest of Barrow the lead remained open and was several kilometers wide. The ice along the northern margin of the lead was primarily unstable new ice.

Temperatures during the 1991 field season tended to be well above normal (Fig. 3.1C; Table 3.1). Low cloud was more frequent than normal. Although the cloud ceiling was high enough to allow low-altitude VFR flights on most days, days with clear skies or high clouds were very infrequent. This greatly curtailed our ability to obtain systematic aerial observations of whale movements and behavior from an altitude of 460 m. In 1991, it was rarely possible to climb that high without losing sight of the sea; on most occasions the cloud ceiling was at or below 305 m (1000 ft). The average sky cover at Barrow (in tenths) was 9.4 for May 1991; this was the highest monthly average sky cover recorded during April or May of any of the four years of this study (Table 3.1).

Ice and Weather in 1994

Only small areas of open water were present in our study area during late April and early May, 1994. Ice, primarily first-year ice, covered from 97 to 99% of the sea, and the only areas that could be used by migrating whales consisted of small open areas between pans of ice, cracks, and narrow discontinuous leads. These areas were often covered with thin layers of new ice.

By 3 May, the pack ice in the study area began to loosen and by 4 May there was a major (in places 2-3 km wide) continuous lead along the landfast ice edge extending east to 75 km east of Pt. Barrow. The landfast ice edge continued ENE across the entire study area rather than curving to the ESE in the more easterly areas. The lead along this ice edge remained open until 10 May, when the effects of several days of strong east winds pushed pack ice against the landfast ice (Plate 3.3). For the next few days, the nearshore lead along the landfast ice edge was variously open or choked with pack ice.

By the evening of 15 May, the outer 2.5 km of the landfast ice broke free along a 75 km extent, forming an inner lead along the new landfast ice edge and an outer lead along the former landfast ice edge (now drifting; Plates 3.2, 3.4. Ice conditions changed from day to day for the remainder of the study period (through 25 May) as winds (frequently in the moderate to strong range) and currents shifted the pack ice (Plate 3.5).

Temperatures during the 1994 field season fluctuated from above normal in late April and early May to below normal in mid-May, and back to above normal around 20 May (Fig. 3.1D). The proportion of days with clear skies or ceilings suitable for VFR aviation was similar to 1989 and 1990 and was much higher than in 1991. However, on many days in 1994, thin ice, high winds, and the resulting shifting of pack ice made it difficult to find stable pack ice on which to establish ice camps. On most days when aerial observations were possible near an ice camp, high sea states associated with the high winds made it difficult to observe whale behavior. The average wind speed at Barrow during May 1994 was 15.9 miles per hour; this was the highest average wind speed recorded during the four years of the study (Table 3.1) and was well above the May average for 1948-74 (Table 3.1; Brower et al. 1977).

3.2 Summary of Field Activities

This report deals primarily with results from fieldwork in 1991 and 1994. The first priority of this fieldwork was to study the effects of playbacks of icebreaker noise on the distribution, movements and behavior of bowhead whales and (as possible) white whales during their spring migration near Barrow. An important component of this assessment was to obtain data on distribution, movements and behavior of presumably undisturbed whales for comparison with the experimental data. Data on ambient noise and sound propagation in the study area were also needed for interpretation of playback results. Data on ambient noise, sound propagation, whale movements and whale behavior during all four years of study are relevant as a basis for interpreting the 1991 and 1994 playback results. Therefore, several types of data from 1989-90 are integrated into this report.

We present here a summary of project activities during 1989 and 1990, and then a more detailed account of the previously-unreported activities during 1991 and 1994. More detailed information about the activities in 1989 and 1990 is given by Richardson et al. (1990a:67*ff*, 1991a: 34*ff*). Table 3.2 summarizes the amount of effort of various types in the four years of the study. Table A-1 in Appendix A summarizes the observation effort near the ice camp, and the number of whales seen there, under control, playback and other conditions on each date with ice-based work during all four years of study.

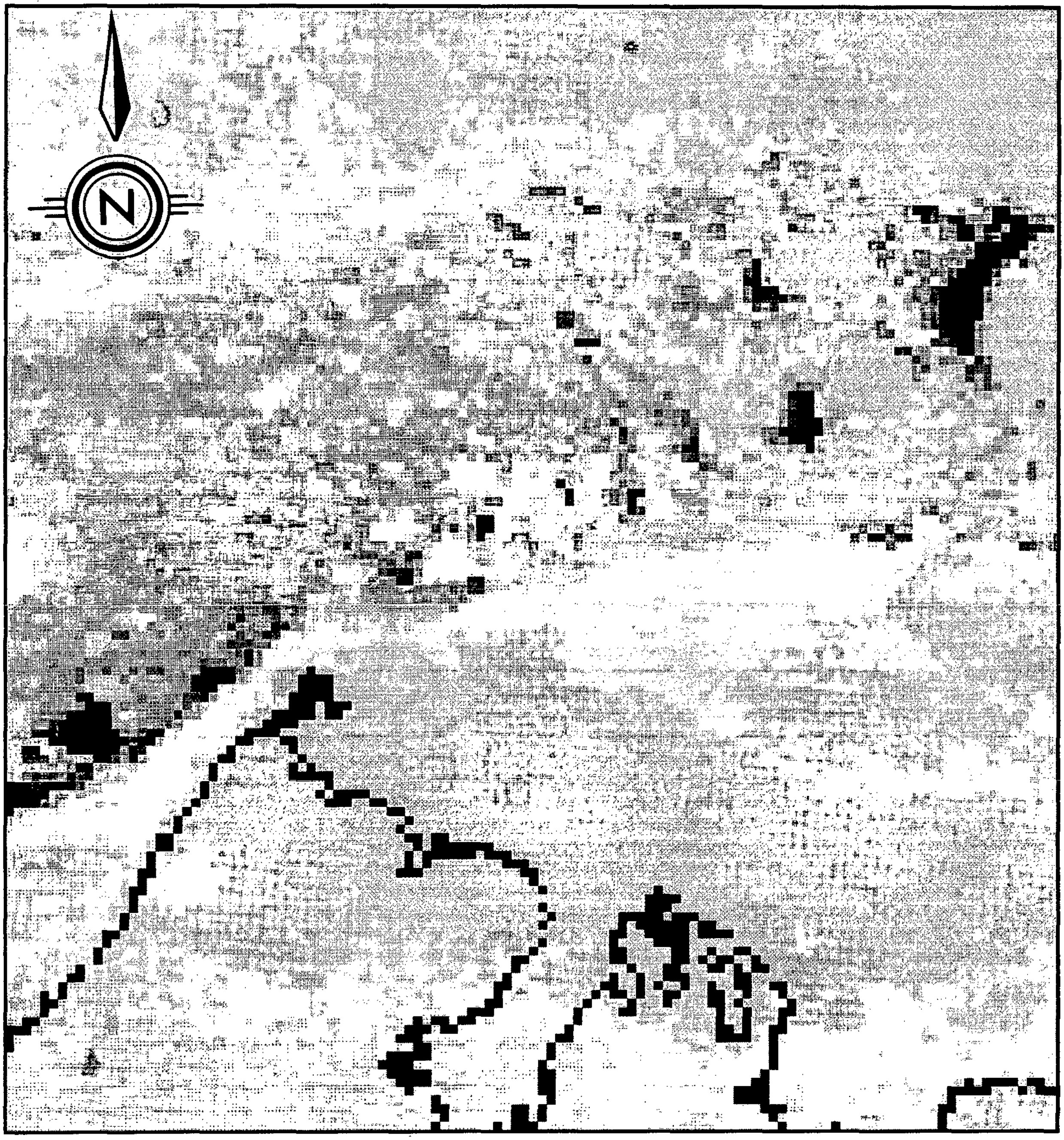


PLATE 3.3. NOAA satellite imagery of the study area, 11 May 1994, showing the ice-choked nearshore lead and offshore pack ice conditions.

PLATE 3.4. NOAA satellite imagery of the study area, 16 May 1994, showing the recently-formed nearshore lead and offshore pack ice conditions, including the much wider former nearshore lead. Note the formation of cracks in the landfast ice east of Pt. Barrow.

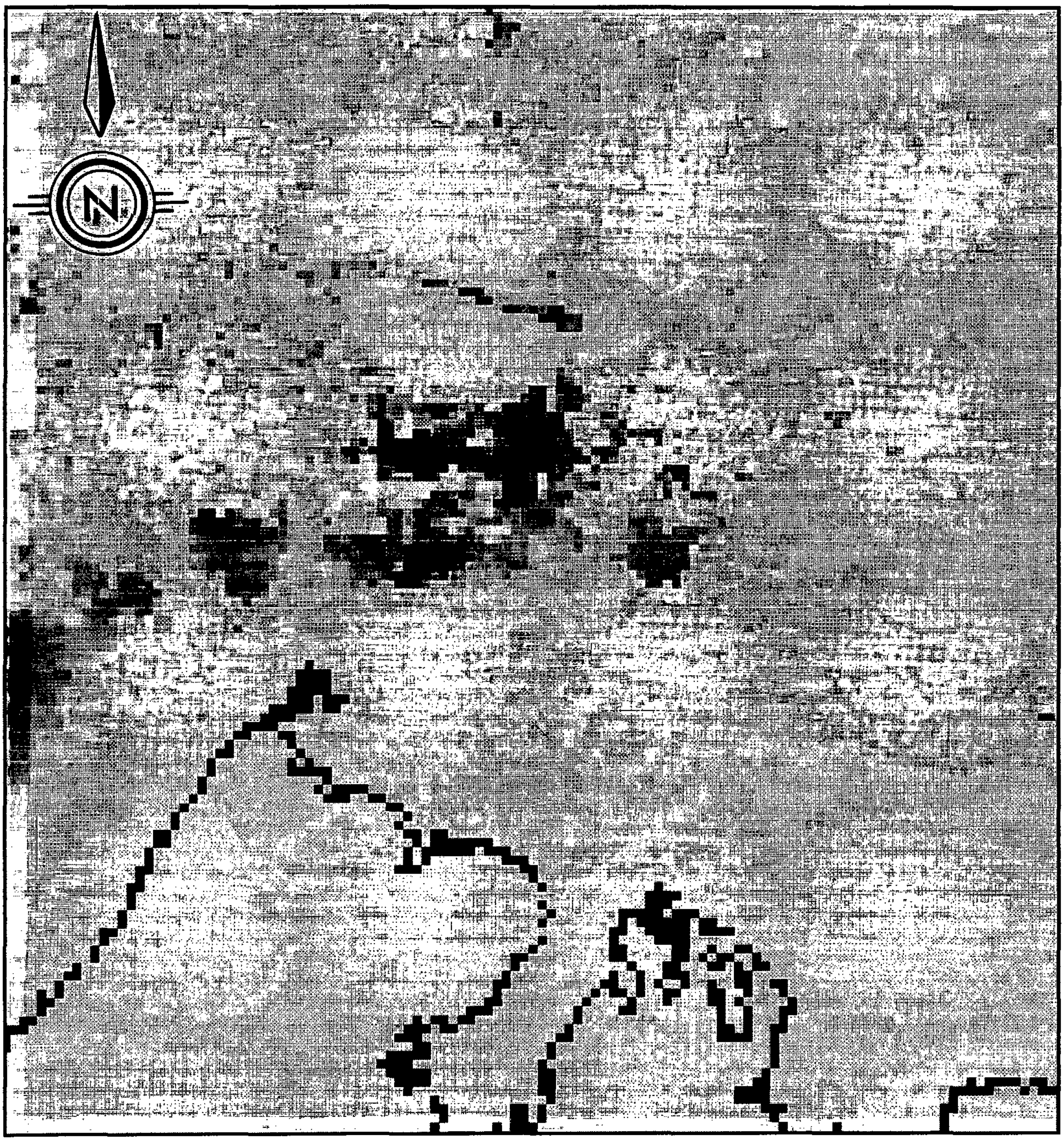


PLATE 3.5. NOAA satellite imagery of the study area, 20 May 1994, showing the nearshore lead and offshore pack ice conditions.

TABLE 3.2. Summary of observation effort of various types during each year of the study.

	1989	1990	1991	1994	Total
A. Ice-Based Work					
First date	29 Apr	27 Apr	28 Apr	28 Apr	27 Apr
Last date	30 May	26 May	26 May	25 May	30 May
Total Days	17	16	13	13	59
Projector(s)	J-11	J-11	J-13 + F-40	A220 + J-11	
Playback Days-Total	11	8	6	7	32
With bowheads during plbk [a]	4	6	1	6	17
With white whales " [a]	5	1	2	1	9
Transmission Loss Tests	4	4	4	1.5	13.5
Obs. hours - Control	64.9	45.8	35.4	59.3	205.4
" " - Playback	43.3	30.7	12.7	27.2	113.9
" " - Other	13.2	4.8	13.4	14.1	45.5
B. Aerial Work					
First date	1 May	29 Apr	28 Apr	27 Apr	27 Apr
Last date	30 May	26 May	26 May	25 May	30 May
# days with flights	24	22	23	22	91
# " " >1 h	24	20	18	21	83
# flights offshore	28	37	30	35	130
# " " >1 h	28	34	25	33	120
Flight hours offshore - Total	88.4	98.8	75.4	119.0	381.6
" " - recon.	57.8	52.0	55.8	66.0	231.6
" " - behav. obs.	25.6	46.8	4.1	36.2	112.7
" " - photog.	5.0	0	15.5	16.8	37.3
Behav. obs. - days	10	12	5	10	37
" " - sessions	17	29	7	23	76
" " - undisturbed hours	12.3	31.6	4.1	24.1	72.1
" " - other hours	13.3	15.2	0	12.1	40.6
Photo Sessions					
# Days	8	0	10	10	28
# Sessions	10	0	13	15	38
# Flights	9	0	11	12	32
C. Combined Ice-based and Aerial Observation near Ice-Camps [b]					
Hours - Control	65.4	53.3	35.4	65.2	219.3
- Playback	43.3	30.7	12.7	27.2	113.9
- Other	15.0	4.8	13.4	14.3	47.5
Bowheads - Control	16	188	18	211	433
- Playback	21	200	9	84	314
- Other	16	43	7	57	123
White Whales - Control	132	277	165	26	600
- Playback	170	49	14	32	265
- Other	19	42	70	6	137

[a] Counting whales seen near camp by aerial as well as ice-based observers.
[b] From Appendix A, Table A-1.

Fieldwork in 1989 and 1990

The 1989 study provided only a limited amount of playback data, but provided considerable baseline information on ambient noise, sound propagation, whale movement patterns, and whale behavior. In 1989 the ice-based crew was able to work on the ice on 17 days (Table 3.3, Fig. 3.2). They completed transmission loss experiments on four days, and obtained ambient noise data on most days when they were on the ice. They projected continuous drilling noise into the water on 11 days, but bowheads were seen near the ice camp on only four of these days: on 1 d by the ice crew only, 1 d by the aircraft crew only, and 2 d by both crews (Table 3.3). White whales were seen near the operating projector on five days: 2 d by the ice crew only, 1 d by the aircraft crew only, and 2 d by both crews. Behavior of bowheads was observed from the circling Twin Otter aircraft during 17 observation sessions on 10 days (Table 3.3, Fig. 3.3). Aerial observations of the behavior of bowheads exposed to drilling noise playbacks were obtained on three days. Vertical photography of bowheads was done on 8 days.

The 1990 field study was highly successful, largely because of the large numbers of bowheads that passed the sound projector during control and experimental periods on a few of the days. The ice-based crew was able to work on the ice on 16 days (Table 3.4, Fig. 3.4). Transmission loss experiments were completed on four days, and ambient noise data were collected on most days. Bowheads were seen from the ice on eight days (Table 3.4). Continuous drilling noise was projected into the water on eight days and bowheads were seen from the ice while sounds were being projected on six of these days. Aerial observations of bowhead behavior were done on 29 occasions during 12 days (Table 3.4, Fig. 3.5). Aerial observations were conducted near the projector site during both control and playback periods on five playback days. Data on behavior of undisturbed bowheads were obtained on seven additional days at locations near the ice camp (2 days) or elsewhere (5 days). No vertical photography of bowheads was possible in 1990.

Fieldwork in 1991

The 1991 field study provided data on ambient noise, sound propagation, and whale movement patterns in the study area, but obtained few data on whale reactions to icebreaker sound or on behavior of undisturbed whales. The ice-based crew was able to work on the ice on 13 days, and icebreaker noise was projected into the water, at least briefly, on six of these days (Table 3.5). Bowheads were seen from the ice camp on eight days, but on only one day were they seen while icebreaker sounds were projected (Table 3.5). Deteriorating ice conditions forced premature termination of ice-based operations on some days. Because of prevailing low cloud, the aerial crew was not able to obtain behavioral observations near the ice camp on any day in 1991, and obtained brief observations elsewhere on only five days. In general, persistently low ceilings and unstable ice conditions limited the useful work that could be done in 1991. However, vertical photography of bowheads, which can be done under low cloud, was possible on 10 days, and the planned number of transmission loss tests (4) were also completed. The one successful playback test with bowheads in 1991 was done on the first day when it was possible to set up the projector system on the landfast ice edge close to Pt. Barrow. All previous playbacks in 1989-91 had been from pack ice farther east or northeast.

TABLE 3.3. Daily activities by the aerial and ice-based crews in 1989[a]. See Richardson et al. (1990a:68*ff*) for more details.

	Aerial Crew					Ice-based Crew		
	Aerial	Behav. Near Camp		Other	Photo-	Control		
Date	Survey	Control	Playback	Behavior	graphy	Obs.	Playback	TL Test
29 April						O [a]		[O] [b]
30 April						O		B
1 May	O [a]							
2 May	W					O		O
3 May	BW			B	B	O	O	
5 May	W							
6 May	BW			B		O	O	
7 May	BW			B		O	O	
8 May	W							
9 May	W					O		O
12 May	BW			B [c]				
13 May	BW							
14 May	BW	BW	BW		B	W	BW	
15 May	BW				B			
16 May	W					BW	O	
17 May	BW					W [d]		
18 May	BW				B			
19 May						O	BW	
20 May	O							
21 May	W					W	O	
23 May	BW	B	BW			BW	BW	
24 May	BW			B [c]				
25 May	BW				B	O		O
27 May	BW	B	B	B	B	O	W	
28 May	BW			B	B	O [e]	O	
29 May	BW		[W] [f]	BW	B	W	O	
30 May	O							

[a] O indicates that no whales were seen, B indicates that bowheads were seen, and W indicates that white whales were seen; blanks mean "no work of this type on this date".

[b] Incomplete transmission loss test.

[c] During this session whales were subjected to potential aircraft disturbance.

[d] A helicopter overflight experiment was conducted on this date.

[e] Measurements of underwater noise from helicopter and Twin Otter overflights were obtained.

[f] White whales were seen near the ice camp during the survey but were not observed systematically.

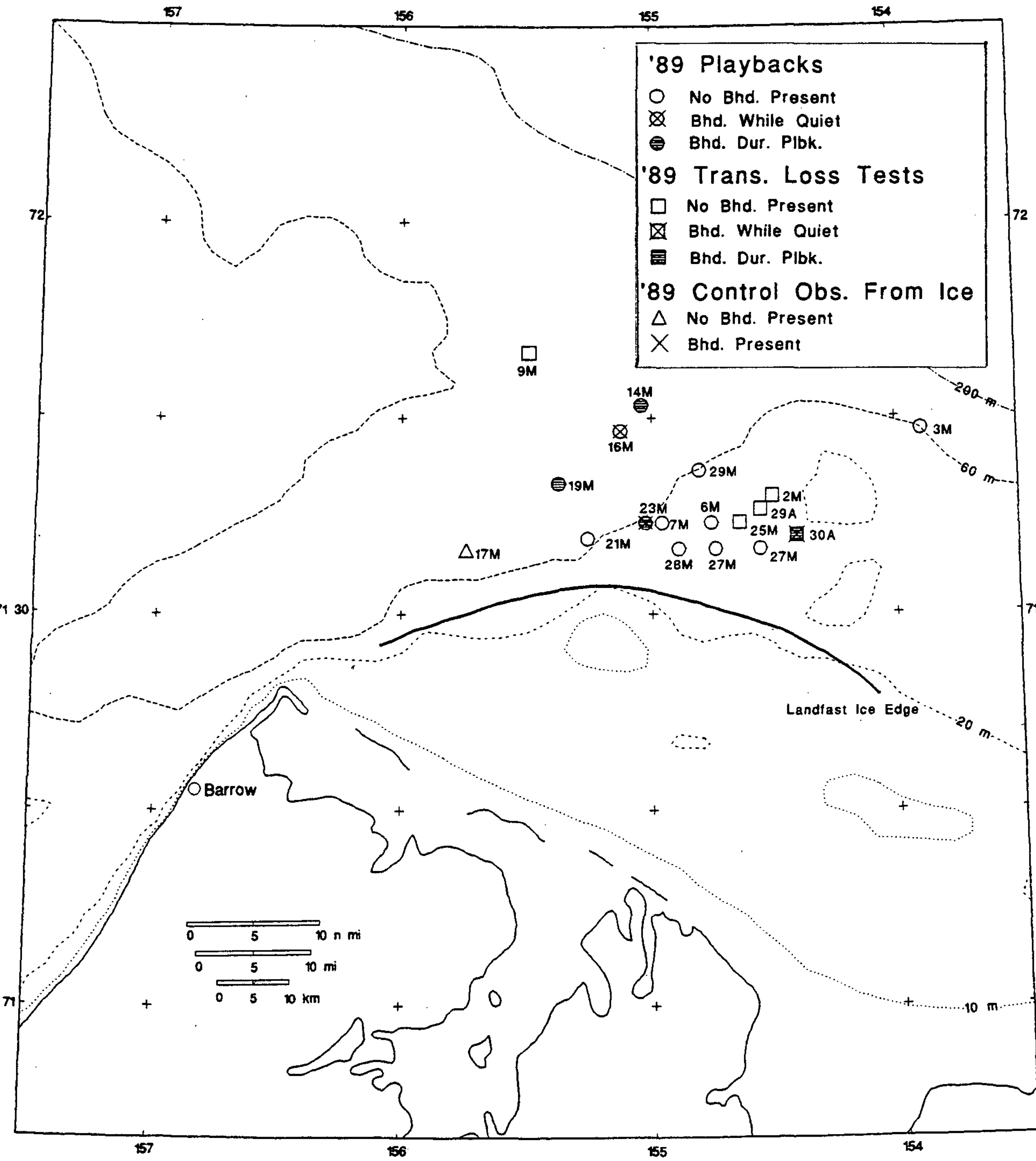


FIGURE 3.2. Locations where ice-based crews projected drilling sounds, conducted transmission loss tests, and made control observations, 29 April to 29 May 1989. X and solid symbols represent days when bowheads were observed. Locations on the pack ice are approximate because of ice drift during the course of each day's work.

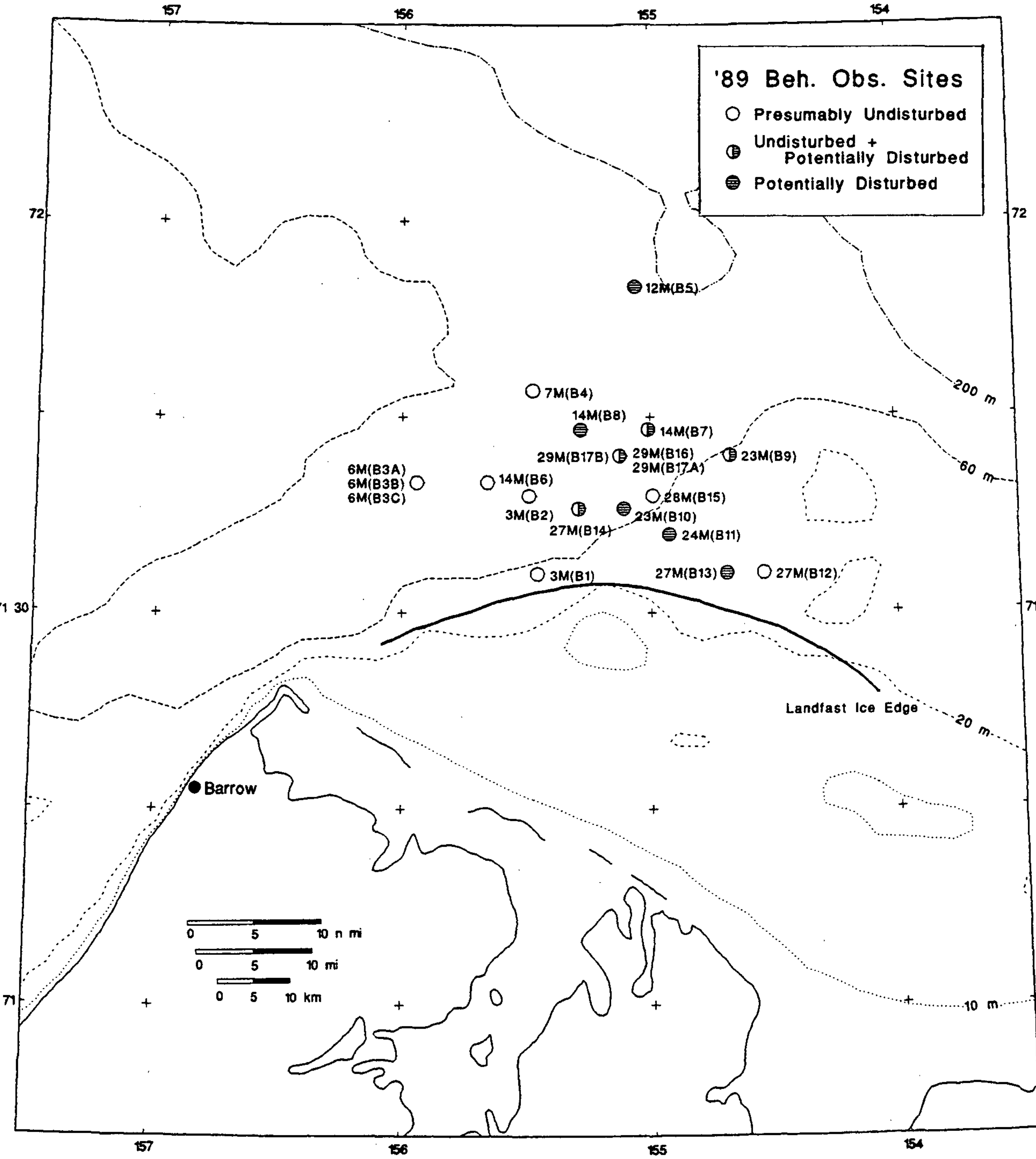


FIGURE 3.3. Locations where behavior of bowhead whales was observed by the aerial crew, 3-29 May 1989. Annotations represent the date in May (M) and, in parentheses, the behavioral observation session number (B1-B17). On other dates, behavioral observations were prevented by low clouds that precluded observations from altitude 460 m ASL.

TABLE 3.4. Daily activities by the aerial and ice-based crews in 1990[a]. See Richardson et al. (1991a: 35*ff*) for more details.

	Aerial Crew					Ice-based Crew		
	Aerial	Behav. Near Camp		Other	Photo-	Control		
Date	Survey	Control	Playback	Behavior	graphy	Obs.	Playback	TL Test
27 April						O		
29 April	B[a]	B				B		
30 April	O					O		[O][b]
1 May	O					O		O
2 May	W					O		O
3 May	O							
4 May	O					O	O	
5 May	B	B				O	O	
6 May	O							
9 May	B			B		B	B	
10 May	BW	BW	B			BW	B	
11 May	BW	B[c]	B			BW	B	
12 May	BW			B				
13 May	BW	B	B			B	B	
16 May	BW	B	B			B	B	
17 May	BW							
19 May	BW					BW		
21 May	BW	BW	B			BW	BW	
22 May	O							
23 May	B			B				
24 May	BW			B		O		O
25 May	BW			B		O		O
26 May	BW							

[a] O indicates that no whales were seen, B indicates that bowheads were seen, and W indicates that white whales were seen; blanks mean "no work of this type on this date".

[b] Incomplete transmission loss test.

[c] Helicopter overflight experiment on this date.

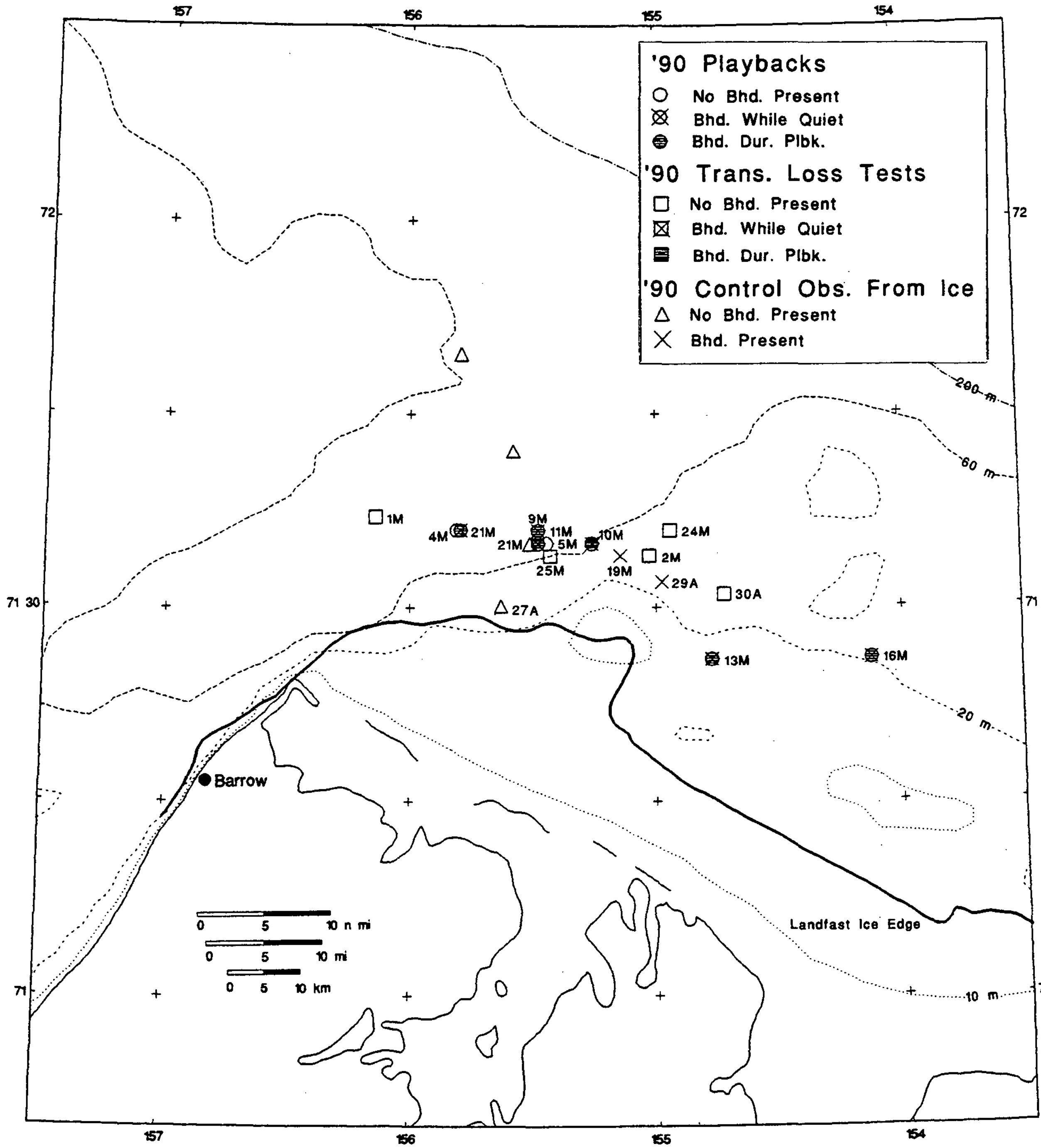


FIGURE 3.4. Locations where ice-based crews projected drilling sounds, conducted transmission loss tests, and made control observations, 27 April to 25 May 1990. X and solid symbols represent days when bowheads were observed. Locations on the pack ice are approximate because of ice drift during the course of each day's work.

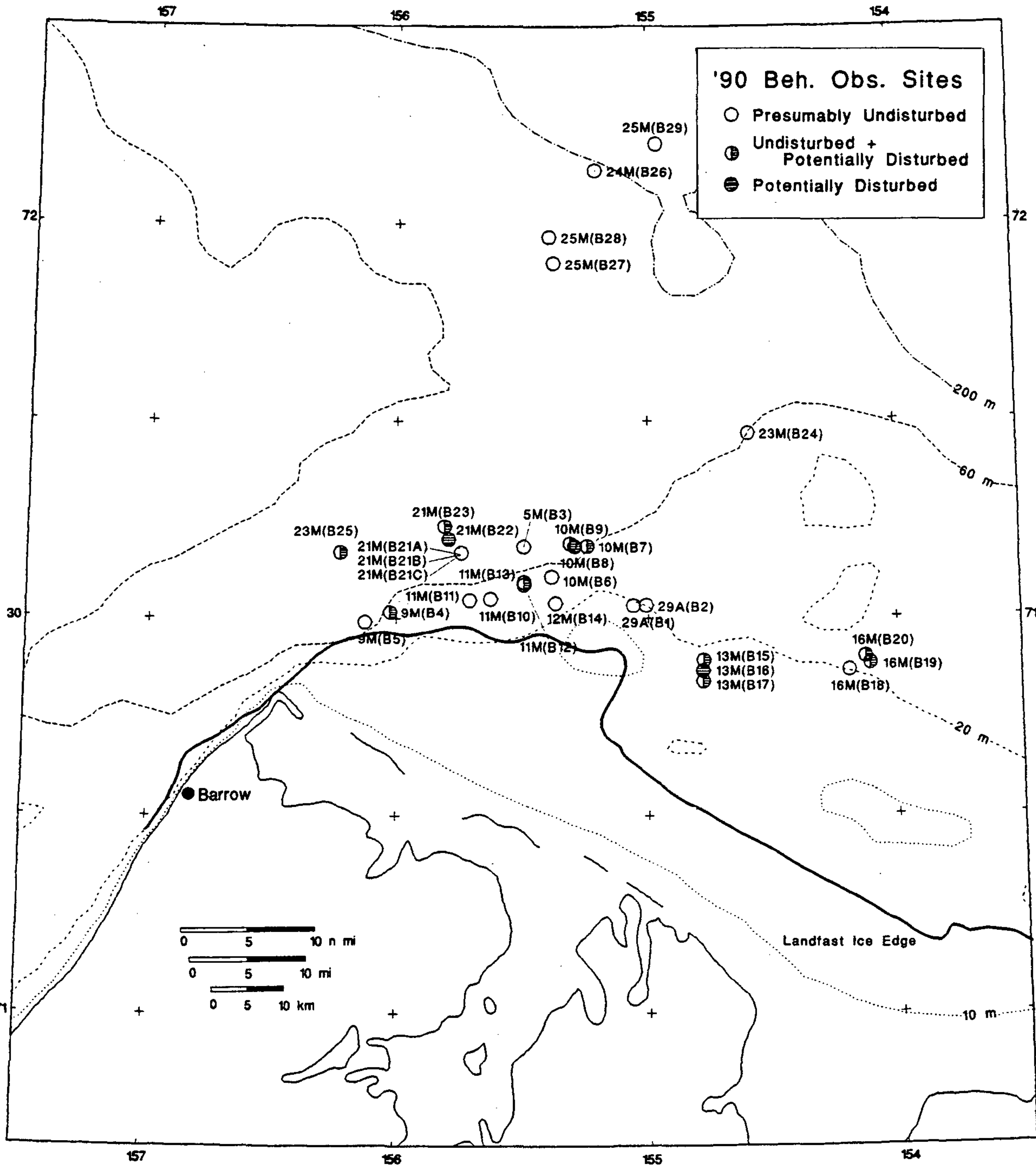


FIGURE 3.5. Locations where behavior of bowhead whales was observed by the aerial crew, 29 April-25 May 1990. Annotations represent the date in April (A) or May (M) and, in parentheses, the behavioral observation session number (B1-B29). On other dates, behavioral observations were prevented by low clouds that precluded observations from altitude 460 m ASL.

TABLE 3.5. Daily activities by the aerial and ice-based crews in 1991[a]. See Appendix A, Table A-2, for more details.

	Aerial Crew					Ice-based Crew		
	Aerial	Behav. Near Camp		Other	Photo-	Control		
Date	Survey	Control	Playback	Behavior	graphy	Obs.	Playback	TL Test
28 April	W[a]					B		
29 April	B			B	B			
1 May	BW				B	O		O
2 May	O							
3 May	BW					B		
4 May	BW			BW				
5 May	BW					W	O	
6 May	BW			B		O		
7 May	B							
8 May	BW				B			
10 May	BW				B			
11 May	BW				B	BW	W	
12 May	BW							
13 May	O							
16 May	BW							
17 May	BW				B	BW	BW	
18 May	BW				B	B	O	O
20 May	BW			B		O		
21 May	W							
22 May	BW				B	O	O[b]	
23 May	BW					O	O	
25 May	BW			B	B	B[c]		O
26 May	BW				B	B		O

[a] O indicates that no whales were seen, B indicates that bowheads were seen, and W indicates that white whales were seen; blanks mean "no work of this type on this date".

[b] One bowhead was seen shortly after a distorted playback ended and before an undistorted playback started.

[c] One bowhead was seen as the helicopter landed. None were seen during presumably undisturbed conditions.

Ice-based work was possible on 13 days in the period 28 April through 26 May 1991. The 13 locations are mapped in Figure 3.6. Bowheads were seen by the ice-based crew on 8 of these days (Table 3.5):

1. During 4 of 13 days, only "control" observations were obtained; the projectors did not operate (Table 3.5; no playback and no TL test). On three of these days deteriorating ice and/or weather conditions forced the crew off the ice before the playback could begin (3, 6 and 20 May). On one day equipment problems prevented a playback (28 April). Bowheads were seen from the ice during two of these 4 "control" days (28 April, 3 May). White whales were not seen from the ice on "control" days.

2. During 6 of 13 days, icebreaker sounds were projected for prolonged periods (Table 3.5). Bowheads were seen from the ice during four of these six days (11, 17, 18, and 22 May). On the 11th and 18th, bowheads were seen only during the periods of "control" observations before and after icebreaker sounds were projected. On 22 May, a bowhead was seen shortly after distorted icebreaker sounds ended. Bowheads were seen during the actual playback period only on 17 May. White whales were seen from the ice on 3 of 6 days with playbacks (5, 11 and 17 May). They were seen during the actual playback period on 11 and 17 May, and during the control periods on 5, 11 and 17 May.

3. During 4 of the 13 days, transmission loss tests were conducted. (On one of these 4 days—18 May—there also was a prolonged playback.) Bowheads were seen within 5 km of the projector site on three of these 4 days, always while the projectors were silent. However, on one occasion (25 May) the observation was only 11 min after test sounds were projected. White whales were not seen during TL tests.

The aircraft crew conducted 30 flights on 23 different days from 28 April to 26 May 1991. However, on five of these days, poor weather (low ceiling, poor visibility, or high winds) prevented any useful work. The remaining 25 flights ranged from 1.6 to 5.2 hours in duration. Although the aircraft used in 1991 had an endurance of about 9 hours, longer flights were not warranted during 1991 because of the low clouds that almost always prevented observations from altitude 460 m (1500 ft). The ceiling was below 460 m during 18 of the 25 "effective" flights. Total flight time during the 30 offshore flights was 75.4 h.

On five days when it was possible to see the surface from an altitude of 460 m, the aerial crew conducted 7 behavior observation sessions totaling 4.1 h (Fig. 3.7; Table 3.6). Although this work was our top priority, the prevailing low cloud rarely allowed it. Furthermore, of the 7 flights when we could observe from 460 m, the winds were too strong for effective observations during two flights. Bowheads were very scarce (only 1 seen per flight) during two additional flights. Thus, only three of the 1991 flights provided a reasonable prospect for obtaining many behavioral observations. All behavioral observations in 1991 involved presumably undisturbed whales. The aircraft crew did not obtain observations of whales subjected to icebreaker noise because, during our opportunities to project icebreaker noises to whales (Table 3.5), cloud ceilings were too low to permit aerial observations near the projectors (Appendix A, Table A-2).

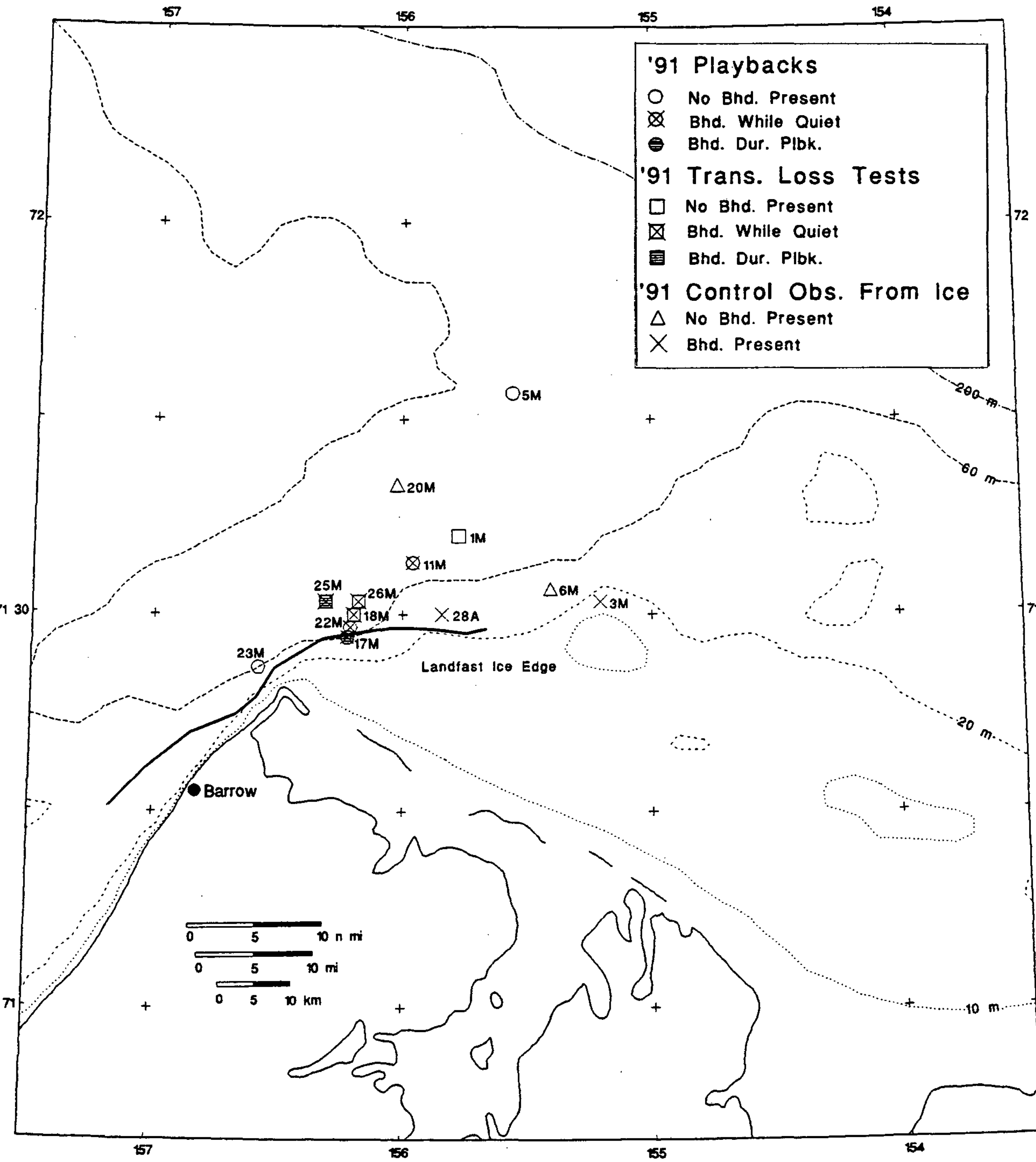


FIGURE 3.6. Locations where ice-based crews projected icebreaker sounds, conducted transmission loss tests, and made control observations, 28 April to 26 May 1991. X and solid symbols represent days when bowheads were observed. Locations on the pack ice are approximate because of ice drift during the course of each day's work.

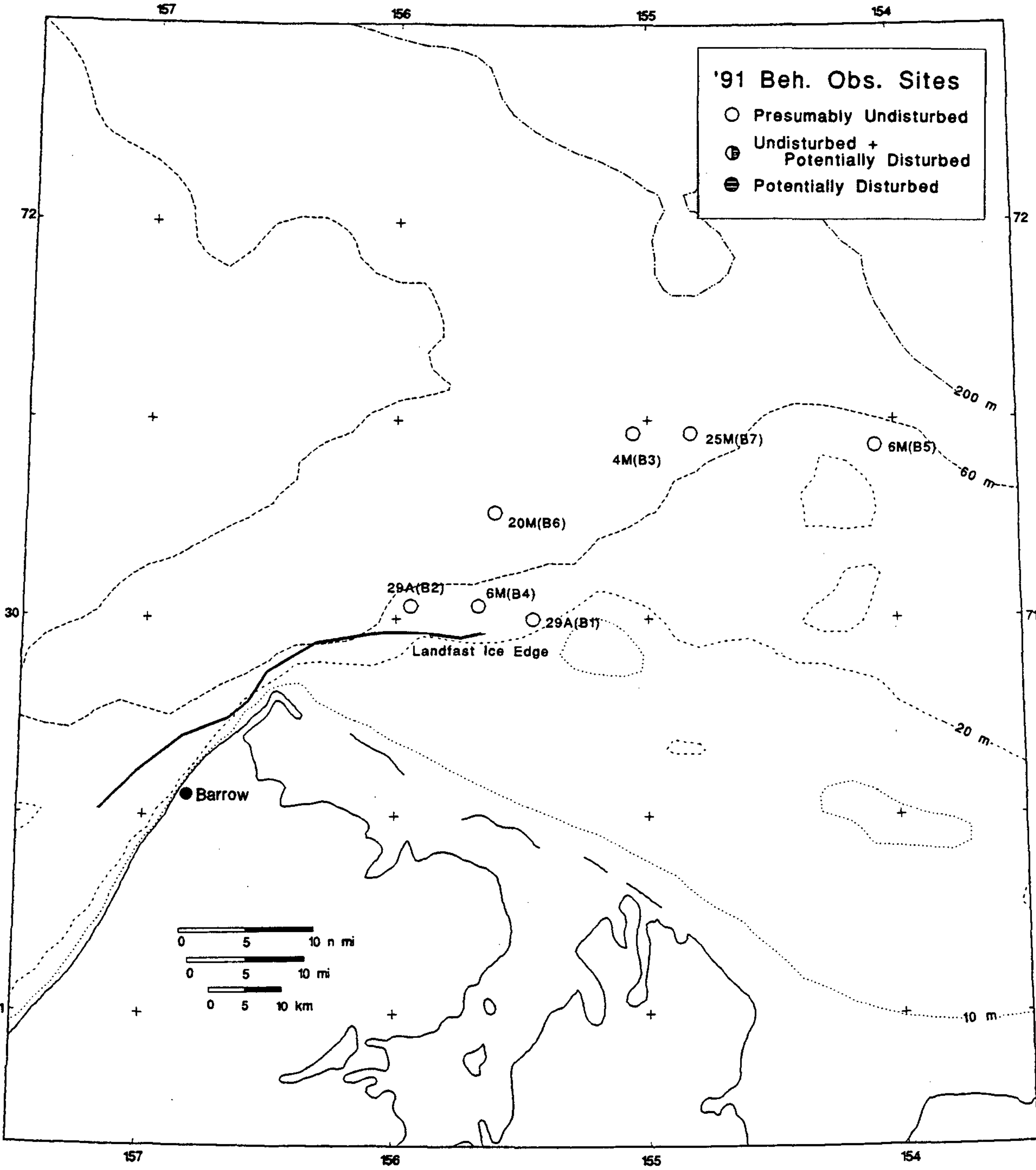


FIGURE 3.7. Locations where behavior of bowhead whales was observed by the aerial crew, 29 April-25 May 1991. Annotations represent the date in April (A) or May (M) and, in parentheses, the behavioral observation session number (B1-B7). On other dates, behavioral observations were prevented by low clouds that precluded observations from altitude 460 m ASL.

TABLE 3.6. Summary of behavioral observation sessions, aerial crew, 1991.

Date	Behav. Obs. Sess.	Location	Obs. Period	No. Bowheads		General Activity	Predom. Orient. °T	Predom. Speed of Travel	Size Classes	Dist-urb-ance	Water Depth (m)	Sea State	% Ice	
				Circle	Area								In Circle	In Area
29 Apr	1	71°30' 155°28'	11:30-12:14	2	2	unknown	various	slow-medium	mother + yearling	none	19	1	50	85
"	2	71°31' 155°57'	13:06-13:13	2	2	travel	070-090	medium	unknown	none	19	1	90	85
4 May	3	71°44' 155°04'	20:52-21:28	1	1	travel?	various	slow	subadult	none	180	1	85	85
6 May	4	71°31' 155°41'	11:20-12:29	2	3+	travel	090-120	medium	unknown	none	19	3-5	35	93
"	5	71°43' 154°05'	14:56-15:24	2	2	social/ travel	various	medium	unknown	none	130	5	65	93
20 May	6	71°38' 155°37'	15:04-15:55	2	2	travel	060-090	medium	mother + calf	none	210	2-3	15	90
25 May	7	71°44' 154°50'	16:12-16:17	4	13	travel	180/230	medium	2 mothers + 2 calves	none	~130	1	1	90

More details about the field activities during 1991 and the ice and weather conditions that affected the fieldwork are given in Appendix A, Table A-2. Numbers of bowheads and white whales sighted near the ice camp each day by the ice-based and aircraft-based crews are summarized in Appendix A, Table A-1.

Because the top-priority behavioral observations were rarely possible, a higher-than-expected proportion of the aerial effort was devoted to vertical photography of bowheads in 1991. A total of 15.5 flight hours were spent on aerial photography during 11 different flights on 10 different days (Table 3.5).

In summary, because of the difficult weather and ice conditions in 1991, we were able to project industrial sounds on fewer occasions in 1991 (6 days) than in 1989 (11 days), 1990 (8 days) or 1994 (7 days). The prevailing low clouds in 1991 had a particularly severe effect on aerial observations of whale behavior: we were able to observe bowheads during only 7 sessions in 1991, as compared to 17, 29 and 23 sessions in 1989, 1990 and 1994, respectively. The low clouds totally prevented systematic aerial observations of bowheads near the operating projectors in 1991. Because of the extensive areas of new ice and brash ice in the study area during 1991, there were far fewer suitable locations for the sound projectors in 1991 than in any other year of the study. Also, on several occasions in 1991, drifting ice encroached on the projector site after it was established, forcing curtailment of ice-based work.

Fieldwork in 1994

The 1994 field study was partly successful, but success was limited by stronger-than-normal winds (Table 3.1), the usual frequency of low ceilings, and sometimes-unstable ice conditions. Large numbers of bowheads were seen migrating along or near the landfast ice edge where additional playback trials could have been conducted with better weather and ice conditions. In 1994, more than 300 bowheads were observed briefly as they passed the ice camp, but—largely due to high sea states—a high proportion of the sightings involved brief observations of single surfacings or partial surfacings. In contrast, during 1990, we obtained lengthy sequences of data for many whales as they approached and passed the projector.

In 1994, ice-based work was possible on 13 days (Table 3.7). Two transmission loss tests were done, one of which was incomplete. Four transmission loss tests had been planned but, given the higher priority assigned to icebreaker noise playback tests, all field days when playbacks were possible were devoted to playbacks. Icebreaker noise was projected into the water for extended periods on seven days. Bowheads were observed by the ice-based observers during six playbacks, and the aircraft-based observers also observed bowheads during four of those playbacks (Table 3.7). Control observations of bowheads were obtained from the ice on 7 days, and by aerial observations near the ice camp on four of those seven days plus three additional days. Overall, aerial observations were obtained on 23 occasions during 10 days. Vertical photography of bowheads was done on 10 days, and vertical video imagery was obtained on one additional day.

The 13 locations where ice-based work was done in 1994 are mapped in Figure 3.8. Bowheads were seen by the ice-based crew on 9 of these days (Table 3.7):

TABLE 3.7. Daily activities by the aerial and ice-based crews in 1994[a]. See Appendix A, Table A-3, for more details.

	Aerial Crew					Ice-based Crew		
	Aerial	Behav. Near Camp		Other	Photo-	Control		
Date	Survey	Control	Playback	Behavior	graphy	Obs.	Playback	TL Test
27 April	BW[a]							
28 April	O					O		
30 April	BW				B			
2 May	W					O		
3 May	BW			BW		B	W	
4 May	BW				B[b]			
5 May	BW				B			
7 May	BW	B	B	B	B	B	B	
8 May	BW				B	B		
9 May	BW	B	B		B	B	B	
10 May	BW			B	B			
11 May	B	B			B	B		
14 May	BW				B	B	B	
15 May	BW			B				
16 May	BW	B	B			O	B	
17 May	BW	B	B			O	B	
18 May	B							
19 May	BW							
20 May	BW	B			B	B	B	
22 May	BW	BW				W		W
24 May	W							
25 May	BW				B	W		O[c]

[a] O indicates that no whales were seen, B indicates that bowheads were seen, and W indicates that white whales were seen; blanks mean "no work of this type on this date".

[b] Only video images were obtained.

[c] Incomplete transmission loss test.

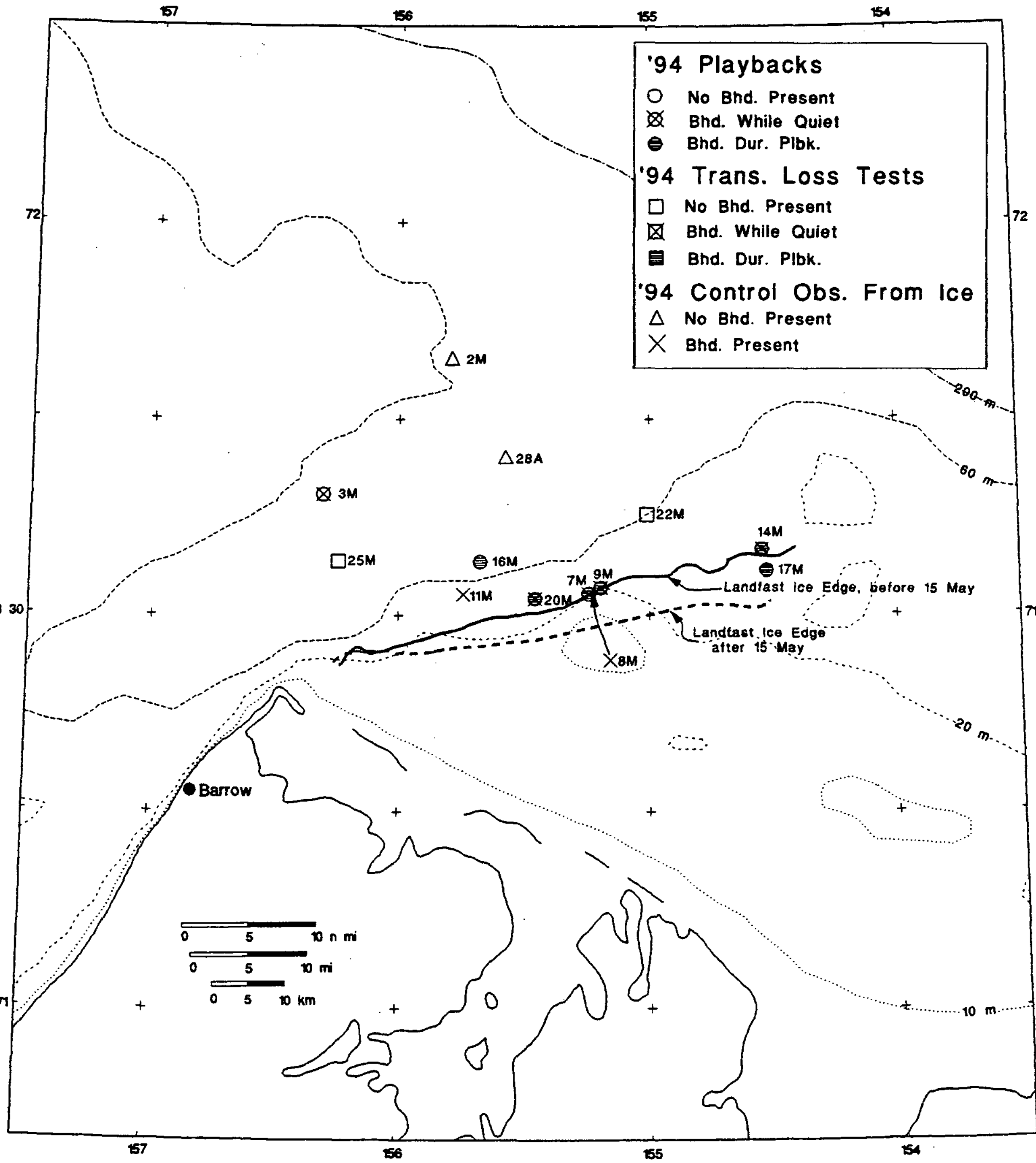


FIGURE 3.8. Locations where ice-based crews projected icebreaker sounds, conducted transmission loss tests, and made control observations, 28 April to 25 May 1994. X and solid symbols represent days when bowheads were observed. Locations on the pack ice are approximate because of ice drift during the course of each day's work.

1. During 4 of 13 days, only control observations were obtained. On two "control" days (28 April and 2 May), tones were projected for brief periods and no whales were seen from the ice. On the other two "control" days, bowheads (but no white whales) were seen from the ice: On 8 May, high winds in the morning delayed ice-based operations, and it was not practical to being playback operations late in the day. On 11 May a large ice pan collided with the pan supporting the camp, forcing the crew to abort operations before the playback could begin.

2. During 7 of 13 days, icebreaker sounds were projected for prolonged periods (Table 3.7). (On four of these days, 3, 7, 14 and 16 May there were also periods when calibration tones were projected.). Bowheads were seen from the ice on all seven of these days: during both control and playback periods on 7, 9, 14 and 20 May; during the control period on 3 May; and during the playback period on 16 and 17 May. White whales were seen from the ice on only 1 day with playbacks (3 May). They were seen only during the playback period on that day.

3. During 2 of 13 days (22 and 25 May), transmission loss tests were conducted. No bowheads were seen by the ice-based crew on these days. White whales were seen both before and during the TL test on 22 May. On 25 May white whales were seen 20 min prior to an incomplete TL test.

The aerial crew conducted a total of 35 flights on 22 different days from 25 April to 25 May 1994 (Table 3.7; Appendix A, Table A-3). Poor visibility or high winds prevented any useful work during brief flights on the afternoon of 2 May, and on 18 May. The remaining 33 flights ranged from 1.0 to 7.3 h in duration. Total flight time during the 35 offshore flights was 119.0 h, with 66.0 h of this being reconnaissance surveys.

The aerial crew conducted behavioral observations on 23 occasions during 10 days (Fig. 3.9; Table 3.8). These observations totaled 36.2 h: 24.1 h under presumably undisturbed conditions and 12.1 h under potentially disturbed conditions, mainly icebreaker noise playbacks.

Vertical photography of bowheads occupied 16.8 flight hours during 12 flights on 10 different days in 1994, excluding a flight and day when only vertical video images were obtained (Table 3.7). As in 1989 and 1991, most vertical photography was done when low clouds prevented aerial observations of bowhead behavior.

<u>Overall Effort over Four Seasons</u>

Table 3.2 summarizes the amount of field effort for the four spring seasons, individually and combined.

Ice-based work was done on a total of 59 days ranging from 27 April to 30 May. Transmission loss tests were completed on 13 days. Underwater playbacks of man-made noise were done on 32 days. Bowhead whales were observed by the ice-based and/or aerial observers during the playback periods on 17 days—10 days during 1989-90 while *Karluk* drilling noise was being projected, and 7 days during 1991 and 1994 while *Robert Lemeur* icebreaker noise was being

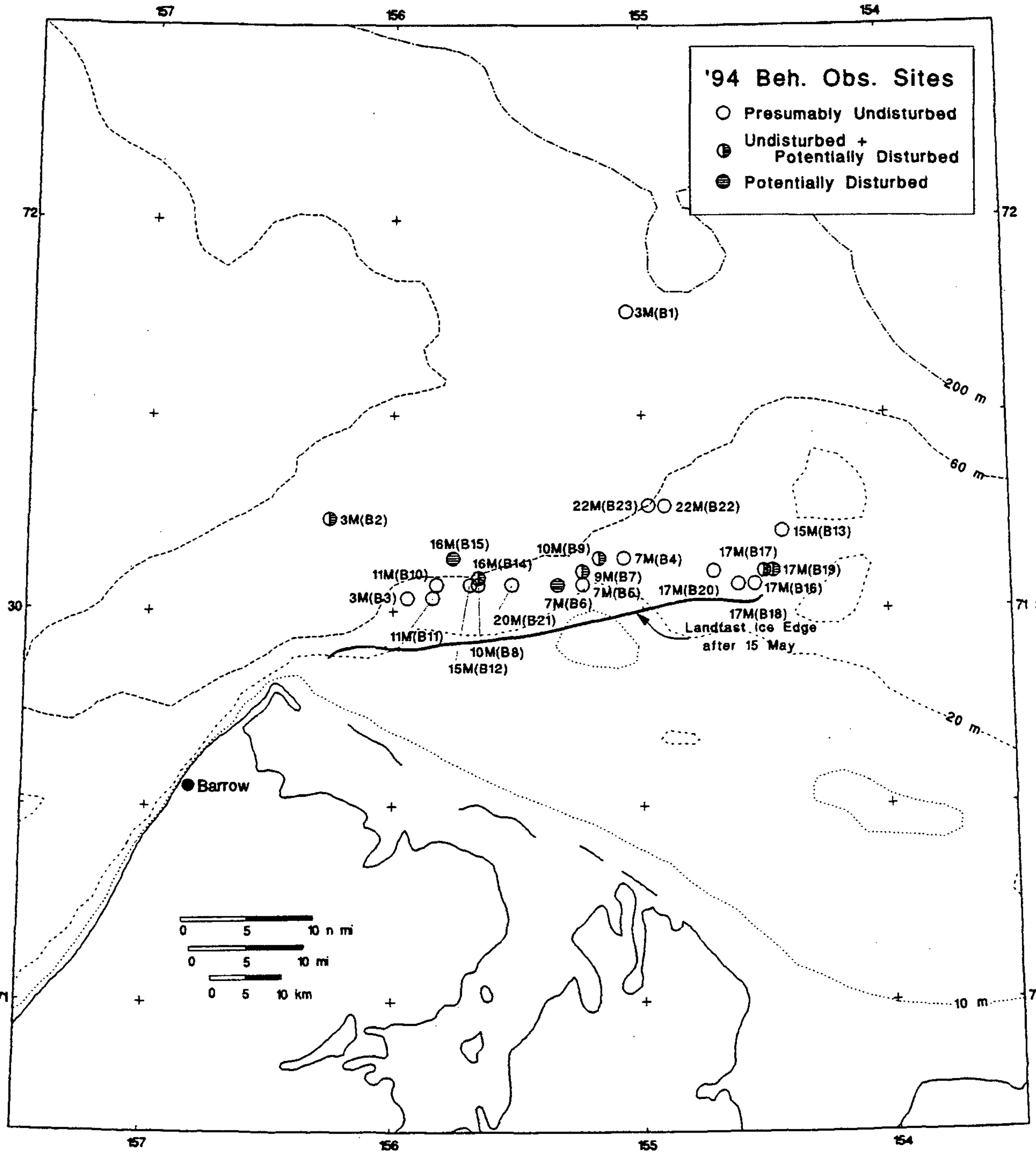


FIGURE 3.9. Locations where behavior of bowhead whales was observed by the aerial crew, 3-25 May 1994. Annotations represent the date in May (M) and, in parentheses, the behavioral observation session number (B1-B23). On other dates, behavioral observations were prevented by low clouds that precluded observations from altitude 460 m ASL.

TABLE 3.8. Summary of behavioral observation sessions, aerial crew, 1994.

Date 1994	Behav. Obs. Sess.	Location	Obs. Period	No. Bowheads Circle	No. Bowheads Area	General Activity	Predom. Orient. °T	Predom. Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice In Circle	% Ice In Area
3 May	1	71°53' 155°04'	10:03-11:05	1	2	Travel	030-060	Slow	Subadult + unknown	None	300	1	80	90
"	2	71°37' 156°16'	11:22-13:46	1	1	Aerial	Various	Medium-slow	Unknown	Hel. til 11:38; none 11:38-12:21; sonobuoy 12:21-12:46; tones 12:32-13:09; post-disturbance til 13:39	140	1	70	95
"	3	71°31' 155°57'	17:50 18:48	4	8	Travel	060-080	Medium	2 Adults, subadult + unknown	None	20	3	60	95
7 May	4	71°34' 155°05'	09:20-10:38	4	10	Travel	060-080	Slow-medium	3 Adults, subadult + unknown	None	37	2	60	95
"	5	71°32' 155°15'	11:03-13:09	9	15+	Travel	050-070	Slow-medium	2 Adults, 2 subadults + unknown	None	37	3	50	90
"	6	71°32' 155°21'	16:14 17:41	3	15+	Travel	060	Slow-medium	2 Adults, subadult + unknown	Icebreaker playback throughout	33	3	20	90
9 May	7	71°33' 155°15'	15:11-19:54	7	35+	Travel/some social, occ. feeding	030-080	Slow	3 Adults, 2 subadults mother, yearling, calf + unknown	Icebreaker playback til 17:30, post-playback til 18:00	37	3-6	30	90
10 May	8	71°32' 155°40'	11:36-12:34	2	9	Travel/ occ. social	030-070	Slow	Adult, 2 subadults + unknown	None	22	3	50	85
"	9	71°34' 155°11'	13:34 14:49	3	6	Travel/ some feed/ occ. rest	040-070[a]	Slow	Adult, 2 subadults + unknown	None to 13:53; then helicopter overflight	27	2	80	85
11 May	10	71°32' 155°50'	08:56-10:14	6	15+	Social/ travel	050-090	Slow-medium	Unknown	None	20	4	60	85
"	11	71°31' 155°51'	10:46-13:21	3	8+	Travel/ occ. social	050-080	Slow-medium	2 Adults, 2 subadults + unknown	None	20	4	60	85
15 May	12	71°32' 155°42'	20:08-20:41	2	5	Travel/ rest	080[a]	Slow	Adult, subadult + unknown	None	22	3	2	80

Continued...

TABLE 3.8. Concluded.

Date 1994	Behav. Obs. Sess.	Location	Obs. Period	No. Bowheads Circle	No. Bowheads Area	General Activity	Predom. Orient. °T	Predom. Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice In Circle	% Ice In Area
15 May	13	71°36' 154°26'	20:54-21:41	3	7	Travel	060-070	Slow-medium	Adult, subadult + unknown	None	37	4	2	80
16 May	14	71°33' 155°40'	12:17-14:21	5	10+	Travel/ occ. social	040-100	Slow-medium	2 Adults + unknown	None to 12:50; then tones to 12:59; then post-playback to 13:02; then icebreaker playback 3:02-end	24	1	20	80
"	15	71°34' 155°46'	14:31-16:22	3	5	Travel/ social	040-090	Slow	1 Adult + unknown	Icebreaker playback throughout	155	1	60	80
17 May	16	71°32' 154°33'	09:41-10:40	5	8+	Travel	060	Slow-medium	Unknown	None	40	5	20	80
"	17	71°33' 154°30'	10:58-12:44	4	8+	Travel/occ. rest, feeding and social	030-070	Slow-medium	Subadult + unknown	None to 11:38, then helicopter overflight	40	3-5	20-70	80
"	18	71°32' 154°37'	13:10-15:05	2	6+	Travel	040-060	Medium	Adult, subadult yearling + unknown	Icebreaker playback throughout	40	4-6	5	80
"	19	71°33' 154°29'	17:10-18:12	2	7	Travel	050-070	Slow-medium	Unknown	Post-playback 17:10-17:32	37	6-7	30	80
17 May	20	71°33' 154°43'	18:37-19:32	2	5	Travel	040-070	Slow	Mother, yearling 2 subadults + unknown	None	43	4	70	80
20 May	21	71°32' 155°32'	09:43-12:18	4	9	Travel/ occ. social.	060	Slow	2 Adults, subadult + unknown	None	40	2	2	80
22 May	22	71°38' 154°55'	09:46-10:40	1	2	Travel	090	Slow	Unknown	None	52	2	2	75
"	23	71°38' 154°59'	10:47-11:33	0[b]	4	Travel	060	Slow	Unknown	None	55	3	2	75

[a] Predominant orientation for traveling whales only.
[b] Observation session 23 was devoted to behavioral observations of white whales.

projected. White whales were observed during the playback periods on 9 days—6 days with drilling noise and 3 days with icebreaker noise.

Aircraft-based work was done on 91 days ranging from 27 April to 30 May (Table 3.2). There were a total of 130 offshore flights totaling 381.6 hours. Of these hours,

- 231.6 h were spent on reconnaissance or ferrying.
- 112.7 h of behavioral observation were distributed over 76 observation sessions on 37 days. This effort included 72.1 h when the whales were presumably undisturbed, i.e. aircraft at ≥460 m ASL and no other known sources of potential disturbance. The remaining 40.6 h of behavioral observations from the aircraft involved whales that were potentially disturbed, usually by playbacks of drilling or icebreaker noise.
- 37.3 h were spent on vertical photography of bowheads. This effort included 38 photo sessions on 28 different days in 1989, 1991 and 1994.

Observations near the ice camp, including both ice-based and/or aerial observations, totaled 380.7 hours: 219.3 h during "control" conditions, 113.9 h during playbacks (74.0 h with drilling noise in 1989-90 and 39.9 h with icebreaker noise in 1991/94), and 47.5 h under other potentially disturbed situations (including the first half hour after playbacks ended).

The number of different bowhead and white whales observed near the ice camp during these periods cannot be determined precisely, as it was not always certain whether a given whale had been seen previously. Our best estimates of the number of different whales observed within several kilometers of the ice camp under control, playback and other conditions were, respectively, 433, 314 and 123 bowheads, and 600, 265 and 137 white whales (Appendix A:Table A-1). Of the whales seen during playback periods, the breakdown between drilling noise playbacks (1989-90) and icebreaker playbacks (1991/94) was 221 vs. 93 for bowheads, and 219 vs. 46 for white whales (Table 3.2).

4. PHYSICAL ACOUSTICS RESULTS[8]

The results of the physical acoustics effort are presented in six subsections: ambient noise, infrasonic ambient noise, transmission loss, fidelity of playback experiments, bowhead call infrasonic components, and generator noise. The results of the winter recording effort at the SSDC are contained in Appendix H.

4.1 Ambient Noise

The ambient noise component of the study responds to specific objective 2, "To measure ambient noise levels and characteristics in leads and cracks along the spring migration corridor of bowhead and white whales in the western Beaufort Sea, including infrasonic components" (p. 6). Ambient noise is an important factor in determining the distances at which whales can detect, may react to, and may show a strong avoidance of, sources of industrial noise.

Methods used to study ambient noise are described in §2.1 (p. 19*ff*). Ambient noise analyses from 1989 and 1990 indicated that there was not much difference in the spread of noise levels measured with sonobuoys compared with ITC model 6050C hydrophones deployed from the ice. However, the presentation of 1991 and 1994 ambient noise measurements continues to distinguish between the two types of sensors. Two kinds of sonobuoys were used: AN/SSQ-57A wideband buoys effective up to 20 kHz and AN/SSQ-53B DIFAR (DIrectional low Frequency Analysis and Recording) sonobuoys with an upper limiting frequency of 2400 Hz. These -53B sonobuoys could not provide measurements in the highest 1/3-octave bands that we examined—2500, 3150, 4000, 5000 and 6300 Hz. Thus, there are not as many measurements at these higher frequencies, and there are not as many measurements for the 20-5000 Hz band as there are in the lower bands. No DIFAR sonobuoys were used for ambient noise measurements in 1991.

Results

Table 4.1 presents the statistical distribution of ambient noise during 1991 for the 1/3-octave bands from 10 to 6300 Hz, plus various broader bands. Tables 4.2 and 4.3 present the corresponding ambient noise data for 1994 and for the combined years 1991/94. The 1991 sonobuoy and hydrophone medians are about the same (Table 4.1A vs. B). The 1994 sonobuoy levels are notably higher than the hydrophone levels at all frequencies up to 4 kHz, probably because the sonobuoys were launched into substantially higher sea states and wind speeds.

Figure 4.1 presents the distribution of 1/3-octave band levels from 10 to 6300 Hz, and levels in broader bands, for the 54 analyses computed for the spring 1991 season. In this and similar figures, bearded seals are responsible for occasional high levels at frequencies >400 Hz, and these elevate the 95th percentile and maximum curves at frequencies >400 Hz. Figure 4.2 presents the 57 analyses for 1994 in the same format, and Figure 4.3 presents the 111 analyses for both years. Higher levels of ambient noise were measured in 1994. The explanation is that more of the field work was done in high wind and sea state conditions in 1994 than in 1991 or earlier years.

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[8] By C.R. Greene Jr. and J.S. Hanna, with R. Blaylock

TABLE 4.1. Ambient noise statistics from the 1991 measurements, by 1/3-octave band and wideband levels, in dB re 1 μPa. *(A)* 47 hydrophone measurements; *(B)* 7 sonobuoy measurements; and *(C)* 54 combined sensor measurements.

A. Spring 1991 Ambient Noise — 47 Hydrophone Samples

	100%	95%	50%	5%	0%
10 Hz	99.9	94.9	79.5	69.0	68.9
12.5 Hz	95.0	91.4	76.1	69.5	68.8
16 Hz	91.3	88.4	76.5	69.7	68.1
20 Hz	87.0	86.0	75.0	69.0	69.0
25 Hz	86.0	85.0	75.0	69.0	67.0
31.5 Hz	87.0	84.0	76.0	69.0	66.0
40 Hz	88.0	83.0	76.0	69.0	65.0
50 Hz	88.0	84.0	76.0	66.0	65.0
63 Hz	88.0	83.0	76.0	67.0	62.0
80 Hz	89.0	84.0	76.0	68.0	60.0
100 Hz	87.0	84.0	76.0	68.0	59.0
125 Hz	90.0	86.0	77.0	68.0	59.0
160 Hz	89.0	87.0	77.0	69.0	60.0
200 Hz	88.0	84.0	76.0	69.0	61.0
250 Hz	87.0	85.0	76.0	67.0	64.0
315 Hz	87.0	86.0	79.0	69.0	67.0
400 Hz	96.0	89.0	81.0	69.0	64.0
500 Hz	98.0	91.0	81.0	66.0	63.0
630 Hz	99.0	88.0	80.0	64.0	61.0
800 Hz	99.0	90.0	81.0	65.0	61.0
1000 Hz	104.0	89.0	76.0	64.0	60.0
1250 Hz	101.0	98.0	74.0	62.0	60.0
1600 Hz	98.0	95.0	74.0	61.0	59.0
2000 Hz	96.0	89.0	73.0	60.0	56.0
2500 Hz	91.0	90.0	71.0	60.0	58.0
3150 Hz	89.0	89.0	70.0	60.0	55.0
4000 Hz	88.0	85.0	67.0	56.0	53.0
5000 Hz	89.0	83.0	66.0	56.0	53.0
6300 Hz	88.0	83.0	65.0	57.0	53.0
20-1000 Hz	102.5	100.8	92.5	84.1	80.3
20-2000 Hz	106.1	103.1	92.6	84.2	80.9
20-5000 Hz	106.2	103.2	92.6	84.2	81.5

B. Spring 1991 Ambient Noise — 7 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	98.3	98.3	78.6	69.7	69.7
12.5 Hz	93.7	93.7	80.4	70.2	70.2
16 Hz	89.4	89.4	81.1	68.3	68.3
20 Hz	86.0	86.0	77.0	60.0	60.0
25 Hz	85.0	85.0	75.0	64.0	64.0
31.5 Hz	84.0	84.0	74.0	68.0	68.0
40 Hz	84.0	84.0	75.0	70.0	70.0
50 Hz	83.0	83.0	74.0	71.0	71.0
63 Hz	83.0	83.0	74.0	70.0	70.0
80 Hz	81.0	81.0	74.0	69.0	69.0
100 Hz	80.0	80.0	73.0	70.0	70.0
125 Hz	80.0	80.0	72.0	69.0	69.0
160 Hz	81.0	81.0	73.0	69.0	69.0
200 Hz	83.0	83.0	74.0	70.0	70.0
250 Hz	90.0	90.0	75.0	68.0	68.0
315 Hz	89.0	89.0	75.0	70.0	70.0
400 Hz	92.0	92.0	78.0	66.0	66.0
500 Hz	91.0	91.0	75.0	65.0	65.0
630 Hz	90.0	90.0	74.0	68.0	68.0
800 Hz	87.0	87.0	73.0	69.0	69.0
1000 Hz	84.0	84.0	75.0	65.0	65.0
1250 Hz	78.0	78.0	74.0	65.0	65.0
1600 Hz	87.0	87.0	71.0	67.0	67.0
2000 Hz	85.0	85.0	69.0	64.0	64.0
2500 Hz	76.0	76.0	69.0	64.0	64.0
3150 Hz	72.0	72.0	68.0	64.0	64.0
4000 Hz	71.0	71.0	68.0	64.0	64.0
5000 Hz	71.0	71.0	67.0	63.0	63.0
6300 Hz	72.0	72.0	67.0	64.0	64.0
20-1000 Hz	97.2	97.2	92.8	82.7	82.7
20-2000 Hz	97.7	97.7	92.9	83.0	83.0
20-5000 Hz	97.9	97.9	93.0	83.2	83.2

C. Spring 1991 Ambient Noise — 47 Hydrophone Samples — 7 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	99.9	95.7	78.6	69.1	68.9
12.5 Hz	95.0	92.5	76.1	69.6	68.8
16 Hz	91.3	89.1	76.5	68.9	68.1
20 Hz	87.0	86.0	75.0	69.0	60.0
25 Hz	86.0	85.0	75.0	69.0	64.0
31.5 Hz	87.0	84.0	76.0	69.0	66.0
40 Hz	88.0	83.0	76.0	69.0	65.0
50 Hz	88.0	83.0	75.0	68.0	65.0
63 Hz	88.0	83.0	76.0	69.0	62.0
80 Hz	89.0	83.0	75.0	68.0	60.0
100 Hz	87.0	82.0	75.0	68.0	59.0
125 Hz	90.0	84.0	76.0	68.0	59.0
160 Hz	89.0	86.0	76.0	69.0	60.0
200 Hz	88.0	84.0	74.0	69.0	61.0
250 Hz	90.0	85.0	76.0	68.0	64.0
315 Hz	89.0	87.0	78.0	69.0	67.0
400 Hz	96.0	89.0	81.0	69.0	64.0
500 Hz	98.0	91.0	80.0	66.0	63.0
630 Hz	99.0	90.0	78.0	67.0	61.0
800 Hz	99.0	88.0	77.0	67.0	61.0
1000 Hz	104.0	88.0	75.0	65.0	60.0
1250 Hz	101.0	97.0	74.0	62.0	60.0
1600 Hz	98.0	94.0	72.0	61.0	59.0
2000 Hz	96.0	89.0	72.0	60.0	56.0
2500 Hz	91.0	88.0	71.0	61.0	58.0
3150 Hz	89.0	87.0	69.0	61.0	55.0
4000 Hz	88.0	83.0	67.0	58.0	53.0
5000 Hz	89.0	83.0	66.0	57.0	53.0
6300 Hz	88.0	82.0	65.0	57.0	53.0
20-1000 Hz	102.5	100.2	92.5	83.3	80.3
20-2000 Hz	106.1	101.7	92.6	83.8	80.9
20-5000 Hz	106.2	102.4	92.6	84.2	81.5

TABLE 4.2. Ambient noise statistics from the 1994 measurements, by 1/3-octave band and wideband levels, in dB re 1 μPa. *(A)* 36 hydrophone measurements; *(B)* 21 sonobuoy measurements; and *(C)* 57 combined sensor measurements.

A. Spring 1994 Ambient Noise
36 Hydrophone Samples

	100%	95%	50%	5%	0%
10 Hz	92.0	89.3	69.4	64.8	63.7
12.5 Hz	87.3	80.2	69.5	62.2	61.7
16 Hz	88.8	87.1	72.8	65.3	64.0
20 Hz	93.2	87.7	74.0	66.4	64.3
25 Hz	96.6	87.8	78.0	67.6	66.8
31.5 Hz	98.2	87.9	80.0	69.2	68.6
40 Hz	96.6	85.5	79.0	69.6	67.2
50 Hz	99.5	87.9	80.9	70.7	69.2
63 Hz	100.5	90.0	80.0	72.3	70.1
80 Hz	95.0	87.0	81.0	71.1	69.6
100 Hz	93.6	91.0	81.2	70.8	69.4
125 Hz	91.7	88.4	82.7	71.1	69.9
160 Hz	91.2	87.3	81.8	73.4	69.9
200 Hz	90.6	89.5	81.0	72.1	67.5
250 Hz	91.1	87.5	80.4	72.7	66.3
315 Hz	95.0	88.7	80.7	73.7	72.1
400 Hz	98.0	90.1	81.2	74.0	72.4
500 Hz	93.0	88.0	81.8	74.8	71.4
630 Hz	98.4	89.0	82.0	75.8	69.1
800 Hz	102.3	91.0	82.2	75.6	70.2
1000 Hz	102.0	91.0	82.0	75.5	66.2
1250 Hz	100.2	88.5	81.5	74.2	65.3
1600 Hz	91.1	88.3	80.8	73.0	64.9
2000 Hz	90.2	87.4	80.2	71.5	65.1
2500 Hz	86.8	86.5	79.5	71.7	65.1
3150 Hz	86.2	85.6	78.3	70.3	64.8
4000 Hz	85.1	83.9	77.3	70.1	64.8
5000 Hz	84.3	83.1	76.4	68.2	64.2
6300 Hz	83.5	82.4	76.1	68.1	64.6
20-1000 Hz	109.0	103.8	94.4	85.2	82.6
20-2000 Hz	109.2	104.1	94.7	86.7	82.8
20-5000 Hz	109.3	104.2	94.9	88.0	83.1

B. Spring 1994 Ambient Noise
21 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	108.4	105.5	88.2	75.3	70.1
12.5 Hz	99.3	98.9	88.0	71.1	64.5
16 Hz	100.0	99.8	88.3	75.0	66.0
20 Hz	102.7	102.0	94.0	74.2	64.1
25 Hz	105.9	105.2	94.7	74.7	65.0
31.5 Hz	105.4	103.8	93.0	76.4	63.2
40 Hz	102.6	101.0	91.0	74.0	63.0
50 Hz	101.9	99.7	90.0	72.5	68.4
63 Hz	100.2	99.1	90.0	70.2	67.9
80 Hz	101.1	100.8	91.0	70.9	68.1
100 Hz	100.4	98.0	89.0	69.2	65.8
125 Hz	100.1	96.9	90.0	71.1	67.5
160 Hz	100.3	97.7	91.0	75.4	71.2
200 Hz	101.1	100.2	91.0	75.2	67.0
250 Hz	99.7	99.0	92.0	70.7	70.1
315 Hz	101.3	99.5	93.0	73.9	67.9
400 Hz	100.7	98.8	93.4	74.7	67.2
500 Hz	102.8	101.1	93.0	73.4	70.3
630 Hz	99.7	99.3	93.0	73.0	72.8
800 Hz	100.6	99.2	92.0	73.0	71.8
1000 Hz	100.0	96.2	91.0	70.9	70.1
1250 Hz	97.6	92.5	90.0	68.1	67.5
1600 Hz	92.9	92.3	88.0	68.4	63.6
2000 Hz	94.1	90.0	86.0	65.0	63.0
2500 Hz	92.3	92.3	83.3	63.6	63.6
3150 Hz	90.3	90.3	80.9	62.8	62.8
4000 Hz	89.7	89.7	76.6	59.8	59.8
5000 Hz	87.5	87.5	74.6	58.3	58.3
6300 Hz	85.9	85.9	75.7	58.1	58.1
20-1000 Hz	112.9	111.1	106.2	87.9	85.9
20-2000 Hz	113.0	111.2	107.2	88.2	86.0
20-5000 Hz	111.0	111.0	98.9	86.1	86.1

C. Spring 1994 Ambient Noise
36 Hydrophone Samples
21 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	108.4	102.9	72.1	64.8	63.7
12.5 Hz	99.3	92.0	73.8	62.5	61.7
16 Hz	100.0	96.4	78.0	65.7	64.0
20 Hz	102.7	101.0	82.0	66.4	64.1
25 Hz	105.9	102.4	83.0	67.6	65.0
31.5 Hz	105.4	101.0	81.5	69.2	63.2
40 Hz	102.6	100.3	81.0	69.6	63.0
50 Hz	101.9	99.0	82.0	70.7	68.4
63 Hz	100.5	99.0	83.0	71.8	67.9
80 Hz	101.1	97.3	82.7	70.9	68.1
100 Hz	100.4	95.0	82.0	70.4	65.8
125 Hz	100.1	94.5	84.0	71.1	67.5
160 Hz	100.3	94.9	83.0	73.4	69.9
200 Hz	101.1	95.2	84.0	72.1	67.0
250 Hz	99.7	97.7	82.3	72.4	66.3
315 Hz	101.3	98.2	84.4	73.7	67.9
400 Hz	100.7	98.0	85.6	74.0	67.2
500 Hz	102.8	97.6	85.6	73.5	70.3
630 Hz	99.7	98.4	84.0	73.0	69.1
800 Hz	102.3	99.2	85.5	73.0	70.2
1000 Hz	102.0	96.2	82.8	70.9	66.2
1250 Hz	100.2	92.3	82.2	68.3	65.3
1600 Hz	92.9	90.9	81.5	68.4	63.6
2000 Hz	94.1	89.6	81.0	66.0	63.0
2500 Hz	92.3	88.3	79.5	65.5	63.6
3150 Hz	90.3	88.3	78.3	65.7	62.8
4000 Hz	89.7	85.9	76.6	65.1	59.8
5000 Hz	87.5	84.3	75.9	64.7	58.3
6300 Hz	85.9	83.5	75.7	65.3	58.1
20-1000 Hz	112.9	110.1	96.8	85.9	82.6
20-2000 Hz	113.0	110.3	97.4	86.7	82.8
20-5000 Hz	111.0	107.7	94.9	86.1	83.1

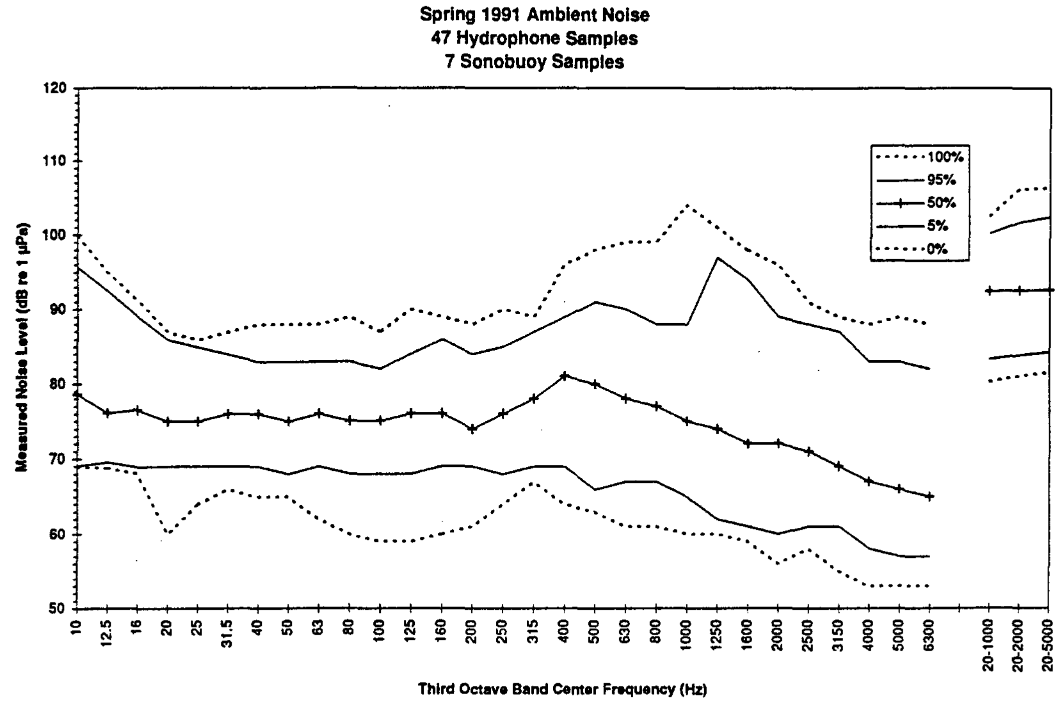


FIGURE 4.1. The distribution of ambient noise levels for the 1991 field season vs. 1/3-octave band center frequency; levels in three broad bands are also shown at right. There were 47 samples from ice-based hydrophone recordings and seven samples from sonobuoys.

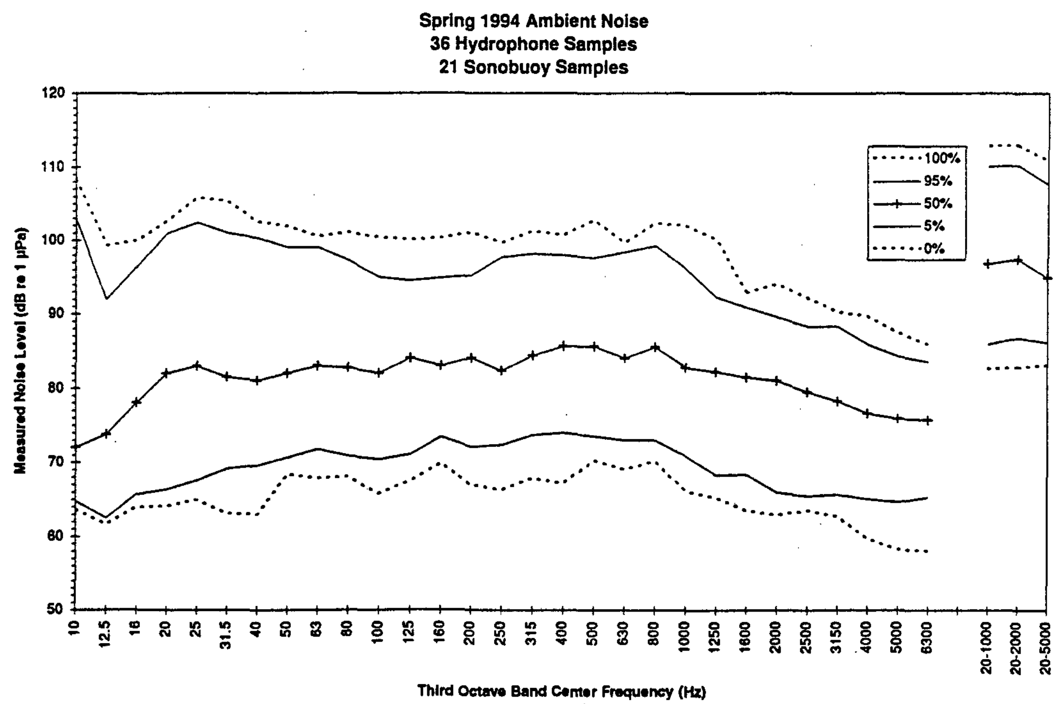


FIGURE 4.2. The distribution of ambient noise levels for the 1994 field season vs. 1/3-octave band center frequency; levels in three broad bands are also shown at right. There were 42 samples from ice-based hydrophone recordings and 21 samples from sonobuoys.

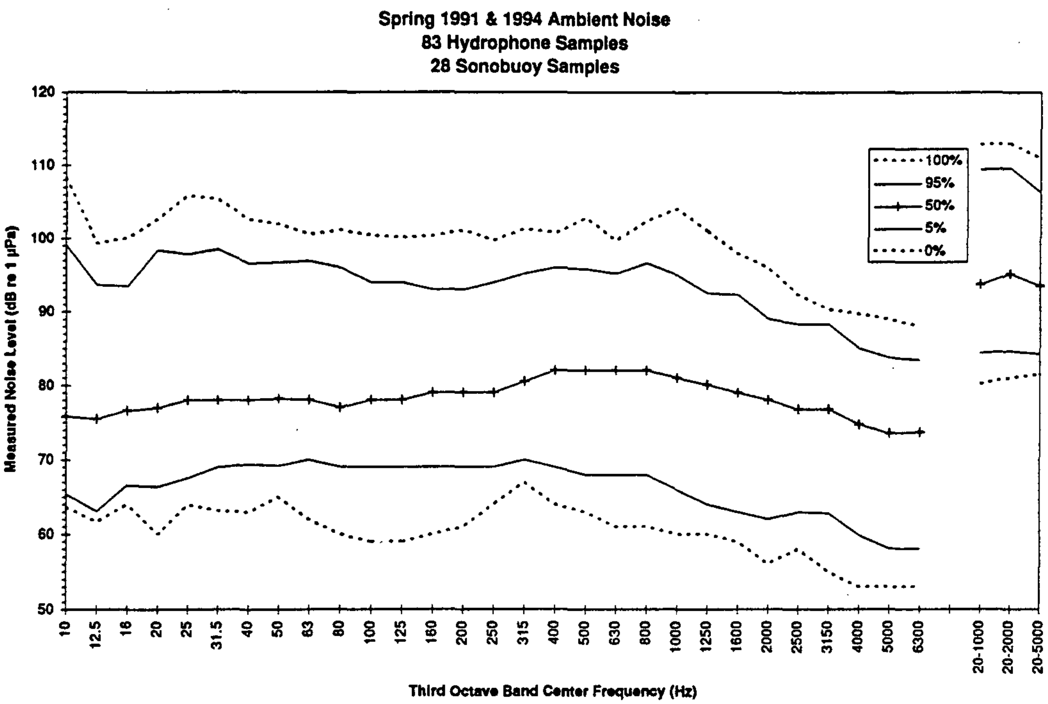


FIGURE 4.3. The distribution of ambient noise levels for the combined 1991 and 1994 field seasons vs. 1/3-octave band center frequency; levels in three broad bands are also shown at right. There were 89 samples from ice-based hydrophone recordings and 28 samples from sonobuoys.

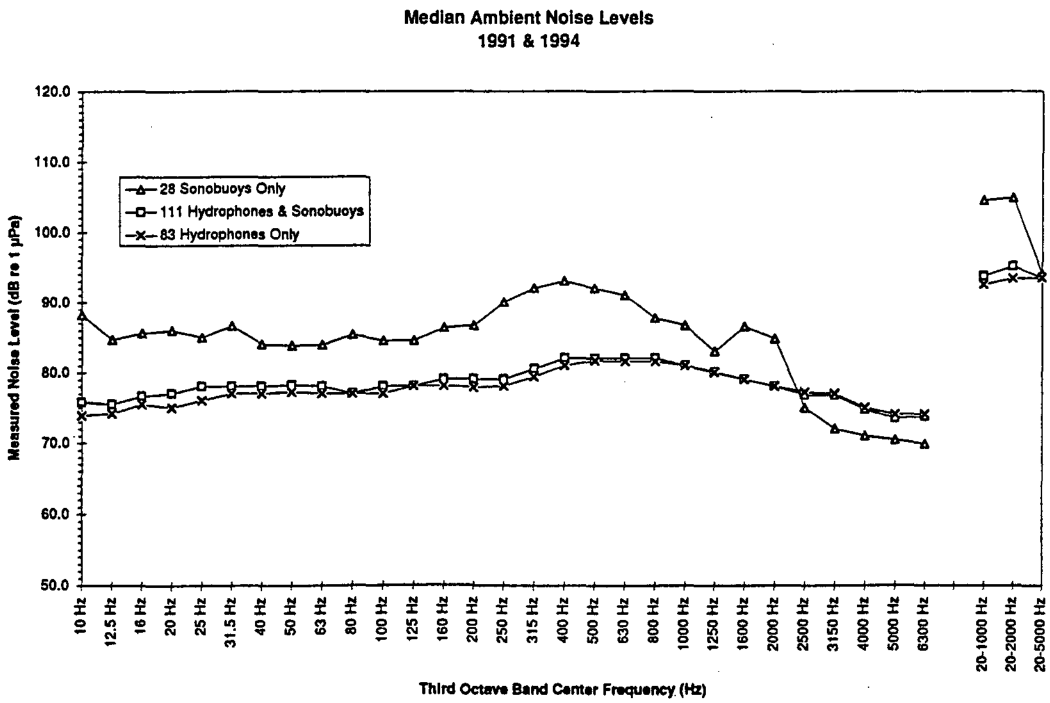


FIGURE 4.4. Median 1/3-octave band spectra for sonobuoys, hydrophones, and the two types of sensors combined, 1991/94.

TABLE 4.3. Ambient noise statistics from the combined 1991/94 measurements, by 1/3-octave band and wideband levels, in dB re 1 μPa. *(A)* 83 hydrophone measurements; *(B)* 28 sonobuoy measurements; and *(C)* 111 combined sensor measurements.

A. Spring 1991 & 1994 Ambient Noise — 83 Hydrophone Samples

	100%	95%	50%	5%	0%
10 Hz	99.9	94.1	73.9	65.3	63.7
12.5 Hz	95.0	89.8	74.2	62.5	61.7
16 Hz	91.3	87.3	75.5	66.6	64.0
20 Hz	93.2	87.0	75.0	67.0	64.3
25 Hz	96.6	86.4	76.0	67.7	66.8
31.5 Hz	98.2	87.0	77.0	69.0	66.0
40 Hz	96.6	85.5	77.0	69.0	65.0
50 Hz	99.5	87.9	77.2	69.0	65.0
63 Hz	100.5	87.9	77.0	69.0	62.0
80 Hz	95.0	87.0	77.0	69.0	60.0
100 Hz	93.6	87.0	77.0	69.0	59.0
125 Hz	91.7	88.0	78.0	68.0	59.0
160 Hz	91.2	87.3	78.0	69.0	60.0
200 Hz	90.6	88.0	77.8	69.0	61.0
250 Hz	91.1	87.0	78.0	69.0	64.0
315 Hz	95.0	87.0	79.4	69.0	67.0
400 Hz	98.0	90.0	81.0	69.0	64.0
500 Hz	98.0	90.0	81.7	68.0	63.0
630 Hz	99.0	89.0	81.6	67.0	61.0
800 Hz	102.3	91.0	81.6	67.0	61.0
1000 Hz	104.0	91.0	81.0	65.0	60.0
1250 Hz	101.0	97.0	80.0	63.0	60.0
1600 Hz	98.0	93.0	79.0	61.0	59.0
2000 Hz	96.0	89.0	78.0	61.0	56.0
2500 Hz	91.0	88.0	77.2	63.0	58.0
3150 Hz	89.0	87.0	77.0	62.0	55.0
4000 Hz	88.0	85.0	75.0	58.0	53.0
5000 Hz	89.0	83.1	74.0	58.0	53.0
6300 Hz	88.0	83.0	74.0	57.0	53.0
20-1000 Hz	109.0	101.8	92.5	84.4	80.3
20-2000 Hz	109.2	104.1	93.4	84.6	80.9
20-5000 Hz	109.3	104.1	93.5	84.8	81.5

B. Spring 1991 & 1994 Ambient Noise — 28 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	108.4	105.5	88.2	70.1	69.7
12.5 Hz	99.3	98.9	84.7	70.2	64.5
16 Hz	100.0	99.8	85.6	68.3	66.0
20 Hz	102.7	102.0	86.0	61.0	60.0
25 Hz	105.9	105.2	85.0	65.0	64.0
31.5 Hz	105.4	103.8	86.6	68.0	63.2
40 Hz	102.6	101.0	84.0	70.0	63.0
50 Hz	101.9	99.7	83.8	71.0	68.4
63 Hz	100.2	99.1	83.9	70.0	67.9
80 Hz	101.1	100.8	85.4	69.0	68.1
100 Hz	100.4	98.0	84.5	69.2	65.8
125 Hz	100.1	96.9	84.5	69.0	67.5
160 Hz	100.3	97.7	86.3	70.0	69.0
200 Hz	101.1	100.2	86.6	70.0	67.0
250 Hz	99.7	99.0	90.0	70.1	68.0
315 Hz	101.3	99.5	92.0	70.0	67.9
400 Hz	100.7	98.8	93.0	67.2	66.0
500 Hz	102.8	101.1	92.0	68.0	65.0
630 Hz	99.7	99.3	91.0	68.0	68.0
800 Hz	100.6	99.2	87.7	71.0	69.0
1000 Hz	100.0	96.2	86.7	69.0	65.0
1250 Hz	97.6	92.5	83.0	67.5	65.0
1600 Hz	92.9	92.3	86.5	67.0	63.6
2000 Hz	94.1	90.0	84.8	64.0	63.0
2500 Hz	92.3	90.5	75.0	64.0	63.6
3150 Hz	90.3	90.1	72.0	64.0	62.8
4000 Hz	89.7	86.7	71.0	64.0	59.8
5000 Hz	87.5	85.0	70.4	63.0	58.3
6300 Hz	85.9	84.6	69.8	64.0	58.1
20-1000 Hz	112.9	111.1	104.5	83.3	82.7
20-2000 Hz	113.0	111.2	104.8	83.8	83.0
20-5000 Hz	111.0	107.7	94.0	84.2	83.2

C. Spring 1991 & 1994 Ambient Noise — 83 Hydrophone Samples — 28 Sonobuoy Samples

	100%	95%	50%	5%	0%
10 Hz	108.4	99.1	75.8	65.4	63.7
12.5 Hz	99.3	93.7	75.5	63.1	61.7
16 Hz	100.0	93.5	76.6	66.6	64.0
20 Hz	102.7	98.4	77.0	66.4	60.0
25 Hz	105.9	97.8	78.0	67.6	64.0
31.5 Hz	105.4	98.5	78.0	69.0	63.2
40 Hz	102.6	96.6	78.0	69.4	63.0
50 Hz	101.9	96.7	78.2	69.2	65.0
63 Hz	100.5	96.9	78.0	70.0	62.0
80 Hz	101.1	96.0	77.0	69.0	60.0
100 Hz	100.4	94.0	78.0	69.0	59.0
125 Hz	100.1	94.0	78.0	69.0	59.0
160 Hz	100.3	93.0	79.0	69.0	60.0
200 Hz	101.1	93.0	79.0	69.0	61.0
250 Hz	99.7	94.0	79.0	69.0	64.0
315 Hz	101.3	95.2	80.5	70.0	67.0
400 Hz	100.7	96.0	82.0	69.0	64.0
500 Hz	102.8	95.8	82.0	68.0	63.0
630 Hz	99.7	95.2	82.0	68.0	61.0
800 Hz	102.3	96.6	82.0	68.0	61.0
1000 Hz	104.0	95.0	81.0	66.0	60.0
1250 Hz	101.0	92.5	80.1	64.0	60.0
1600 Hz	98.0	92.3	79.0	63.0	59.0
2000 Hz	96.0	89.0	78.0	62.0	56.0
2500 Hz	92.3	88.3	76.8	63.0	58.0
3150 Hz	90.3	88.3	76.8	62.8	55.0
4000 Hz	89.7	85.0	74.7	59.8	53.0
5000 Hz	89.0	83.7	73.5	58.0	53.0
6300 Hz	88.0	83.4	73.7	58.0	53.0
20-1000 Hz	112.9	109.4	93.7	84.4	80.3
20-2000 Hz	113.0	109.6	95.1	84.6	80.9
20-5000 Hz	111.0	106.2	93.5	84.2	81.5

Figure 4.4 displays the median 1/3-octave band spectra for the two combined years by sensor type, showing graphically the higher levels for the sonobuoys. The drop in the broadband level for the 20-5000 Hz band, compared to the 20-1000 Hz band, occurs because the DIFAR buoys do not sense sounds at frequencies above 2400 Hz.

Figure 4.5 presents the 20-1000 Hz band levels for each 1991 measurement plotted against the measurement times. The ice camp hydrophone and sonobuoy measurements are differentiated by plotted symbol. Figure 4.6 presents the 20-1000 Hz band levels for each 1994 measurement plotted against the measurement times. Sonobuoy measurement levels on 3 May 94 were 7-17 dB higher than measurement levels with the hydrophone, and sonobuoy levels on 16 and 17 May were also higher than the hydrophone levels. The highest levels recorded for 1994 were obtained from sonobuoys on 3, 11 and 17 May. The 6050C hydrophone cable was faired to prevent strumming, although there may still have been noise from water flow around the sensor. Each sonobuoy hydrophone was suspended by a spring, mass and damper system to decouple surface motion from the sensor, and there should not have been cable strumming.

Discussion

Major environmental influences on ambient noise in the Beaufort Sea during spring include wind and waves, biologics, thermal ice cracking, and ice deformation (ice floe collisions, pressure ridge formation). The effects of wind and waves are well-studied. Biologic noise sources include seals, especially bearded seals, whose calls glissade across frequencies from several kilohertz down to about 400 Hz, and the bowhead and beluga whales. During this project, animal sounds were deliberately excluded from ambient noise analyses if possible. A close animal could raise the sound levels above ambient noise levels expected from storms. Thermal ice cracking is a minor source of sound, especially after the diurnal temperature cycling moderates when the sun no longer sets (after 10 May in Barrow). Ice floe collisions and pressure ridge formation are transient but on-going events occurring at unknown and varying distances from the measurement point and contributing varying amounts of sound.

Short-term variability in ambient noise levels was studied and reported for the 1990 field season (Richardson et al. 1991:55*ff*). The study compared noise levels for 33 recordings, each averaged over one minute, 8.5-s periods, and 0.25-s periods. The result was that shorter averaging often yielded lower noise levels. The implication was that animals with suitably responsive hearing often would be expected to hear weak sound signals during brief periods when the ambient noise was lower than average even if the average ambient noise level over a longer period was high enough to mask the signal. There were 33 different 1-min periods analyzed, or 231 8.5-s periods. Figure 16C in Richardson et al. (1991:61) graphs the difference between the 8.5-s average noise level and the corresponding median 0.25-s average noise level (the median of 8.5/(0.25)=34 separate 0.25-s averages; there were 231 such medians). Almost all differences were positive, and the largest difference was 18 dB. From the Figure, it appears that about half the 231 differences exceeded 2 dB. This 2 dB figure is used in a later discussion of icebreaker signal-to-noise ratios vs. distance (Figure 6.25 in §6.4).

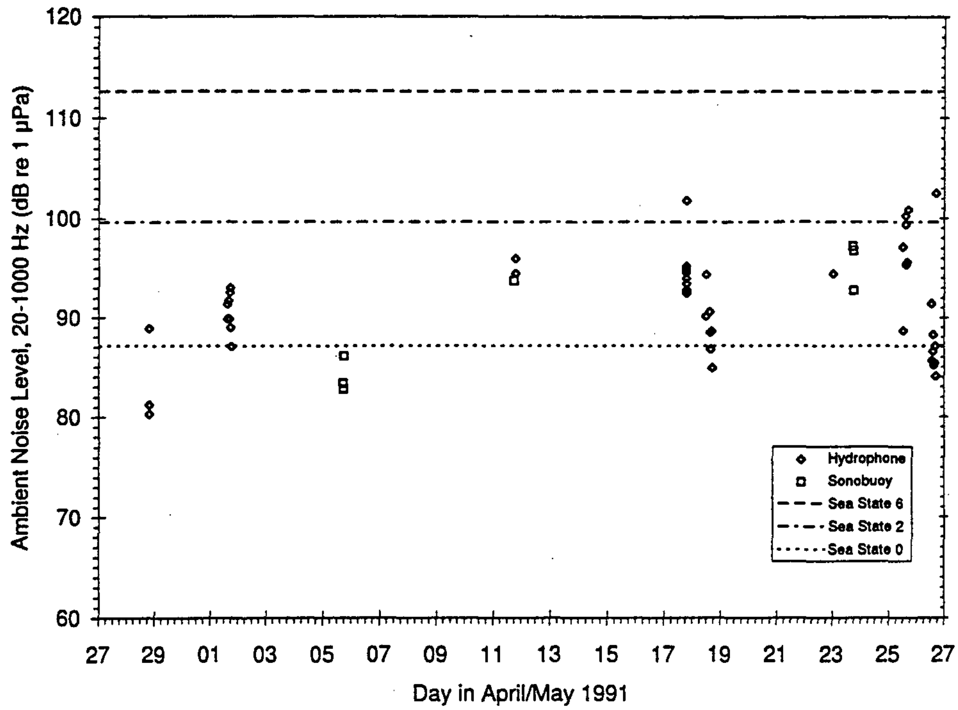


FIGURE 4.5. Ambient noise level, 20-1000 Hz band, vs. recording date and time in 1991.

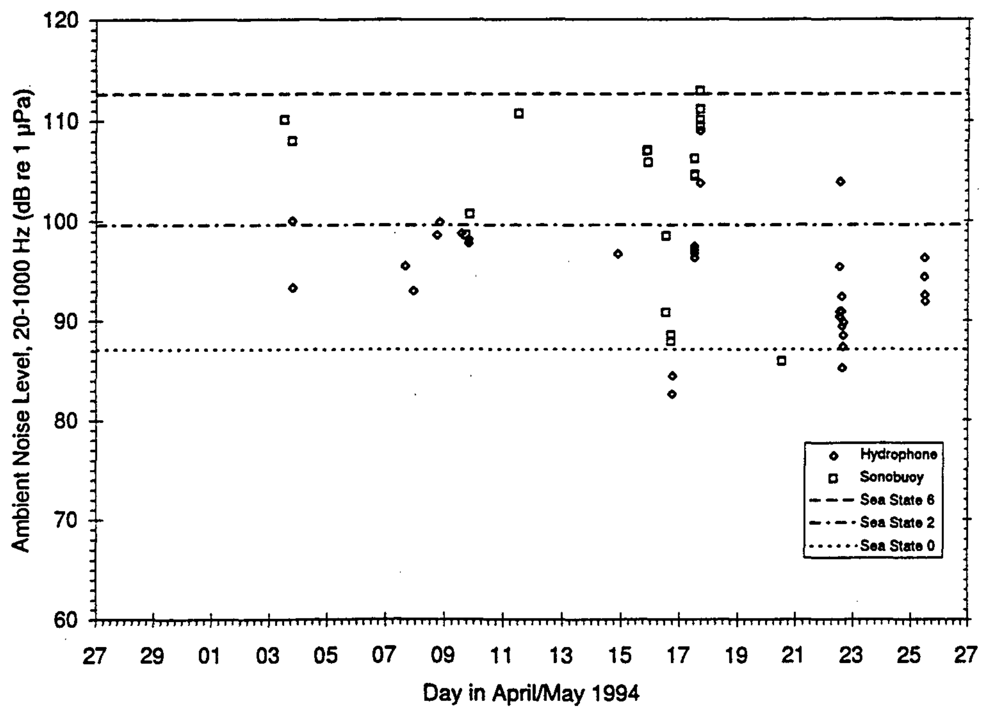


FIGURE 4.6. Ambient noise level, 20-1000 Hz band, vs. recording date and time in 1994.

A key concern about the 1994 ambient noise data arises from the higher levels observed from the sonobuoys than from the ice camp hydrophone. Furthermore, one questions whether there might have been a bias of some kind in the DIFAR sonobuoy measurements. No DIFAR sonobuoys were used in 1991 and the sonobuoy and hydrophone data were comparable for that year.

However, associating the type of sonobuoy with each plotted value in Figure 4.6 reveals that DIFAR buoys were used on 3, 9 and 17 May, while -57A sonobuoys were used on 11, 15, 16 and 20 May. The highest levels, which were observed on 3, 11 and 17 May, came from both types of sonobuoys. The moderate levels observed on 9 May came from a DIFAR buoy and were comparable to the hydrophone levels recorded on that date. Also, the somewhat higher levels observed on 15 May came from a -57A sonobuoy. Thus, there does not appear to be a bias toward higher levels from DIFAR sonobuoys.

An alternative explanation for the high sonobuoy levels is that, in 1994, the sonobuoys were deployed into open water under high sea state conditions. Even when the wind speed was high, the ice camp hydrophone was generally deployed on the lee side of a large ice floe, assuring sea state zero from the area covered by ice and a lower-than-open-water sea state extending away from the floe because of low fetch (the distance the wind has blown over water to create waves).

A simple comparison of ambient noise over the four years of the project field work is possible with the ranges of the 20-1000 Hz broadband levels observed each year (Fig. 4.7). The first three years were roughly comparable, neglecting the extraordinarily low level observed on 2 May 1990. The 1994 levels were higher, corresponding to the higher wind and sea state conditions under which much of the 1994 work was done (§3.1, p. 51).

During 1980-84 summer (August) studies in the Canadian Beaufort Sea, the median ambient noise level was 99 dB re 1 μPa in the 20-1000 Hz band (Greene 1985). This was 10 dB higher than the corresponding median level in spring 1989, 7 dB higher than in 1990 and 1991, but only 2 dB higher than the median level in 1994. These levels are close to the 100 dB level expected for sea state two based on the Knudsen curves extended to low frequencies (Fig. 4.7). Miles et al. (1987) reported ambient noise statistics for six sites in the Alaskan Beaufort Sea measured for brief periods in late summer and early fall (September and October); their levels also corresponded to nominal sea state two value.

Measurements were made during late September 1984 near Seal Island, Alaskan Beaufort Sea (water depth 13 m), while a drillrig on this artificial gravel island was in standby mode (Davis et al. 1985). The median level in the 20-1000 Hz band was close to 93 dB, or 2 dB below the level expected for sea state one and close to the median level for this project in spring 1990 and 1991.

Another comparison is possible with ambient noise data collected from one drifting buoy in the Chukchi Sea (shallow water) and from one in the deep Beaufort Sea during May 1977 (Greene 1981). Acoustic pressure spectral density data were measured every three hours at three frequencies: 10, 32 and 1000 Hz. The 5th, 50th and 95th percentiles of the acoustic pressure spectral densities were obtained at those three frequencies. The percentile values for those same 1/3-octave

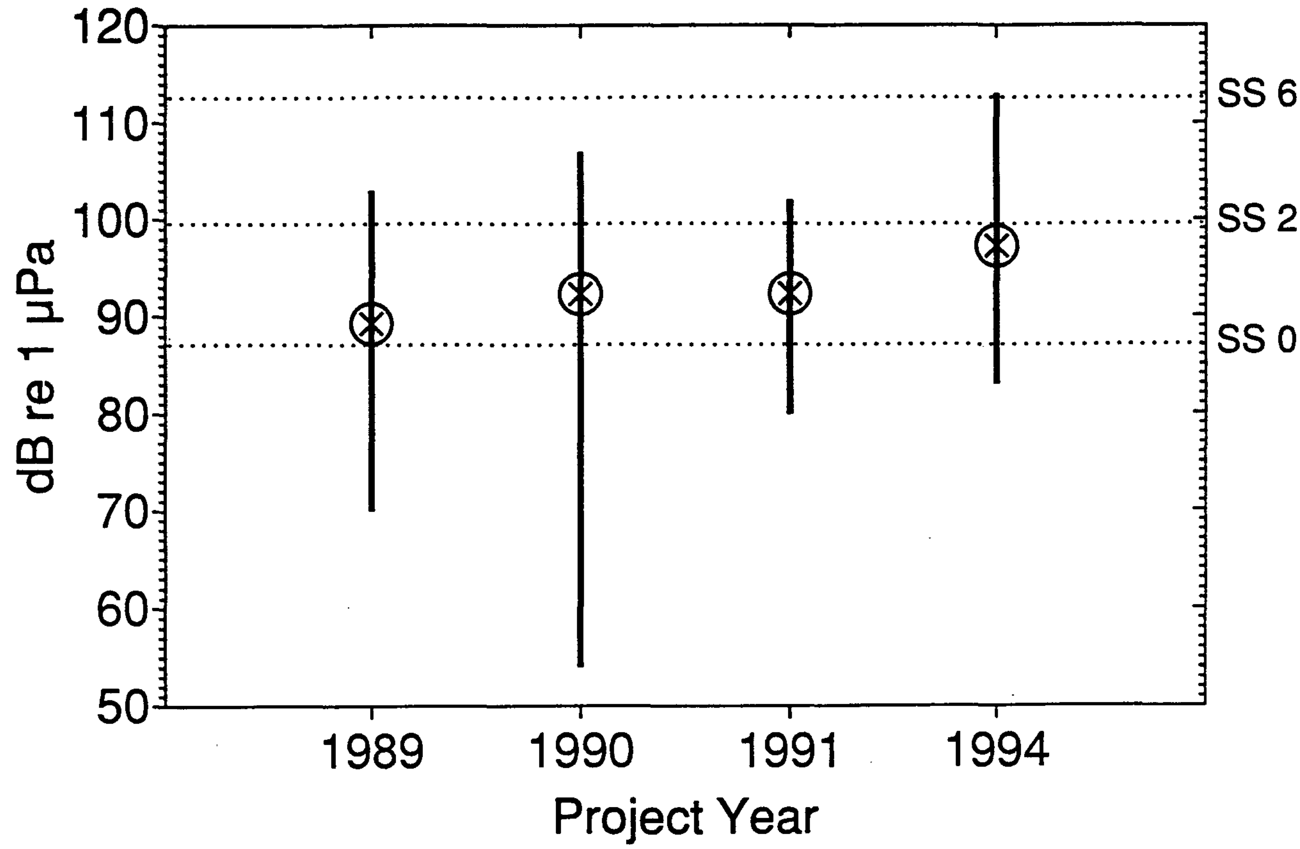


FIGURE 4.7. Minimum, median and maximum ambient noise levels, 20-1000 Hz band, during the four project years. Circled-X symbols mark median levels. Levels for three sea states are extrapolated Knudsen et al. (1948) spectra.

bands from the present project, 1991/94, were adjusted to compute spectral densities. All these data are graphed in Figure 4.8 for comparison. Wenz's limits (maxima and minima) for the three frequencies are also plotted; they show that the project and buoy data fall within the expected range at those frequencies. The wider range of levels from the present project may possibly be explained by the confluence in the project operating area of the generally northeasterly coastal current from the Chukchi Sea with the generally north-northwestward clockwise Beaufort Gyre, leading at times to extraordinary ice deformation and noise.

4.2 Infrasonic Ambient Noise

The infrasonic ambient noise component of the study responds to project objective 5, "To collect some of the data needed to assess the importance of the infrasonic components of industrial noise. Specifically, *(a)* to measure ambient noise at infrasonic frequencies..." (§1.1, p. 7). Such noise would be important in determining the detection radius if infrasonic industrial noises are detectable by bowheads, or if bowhead calls include infrasonic components that are detectable by other bowheads.

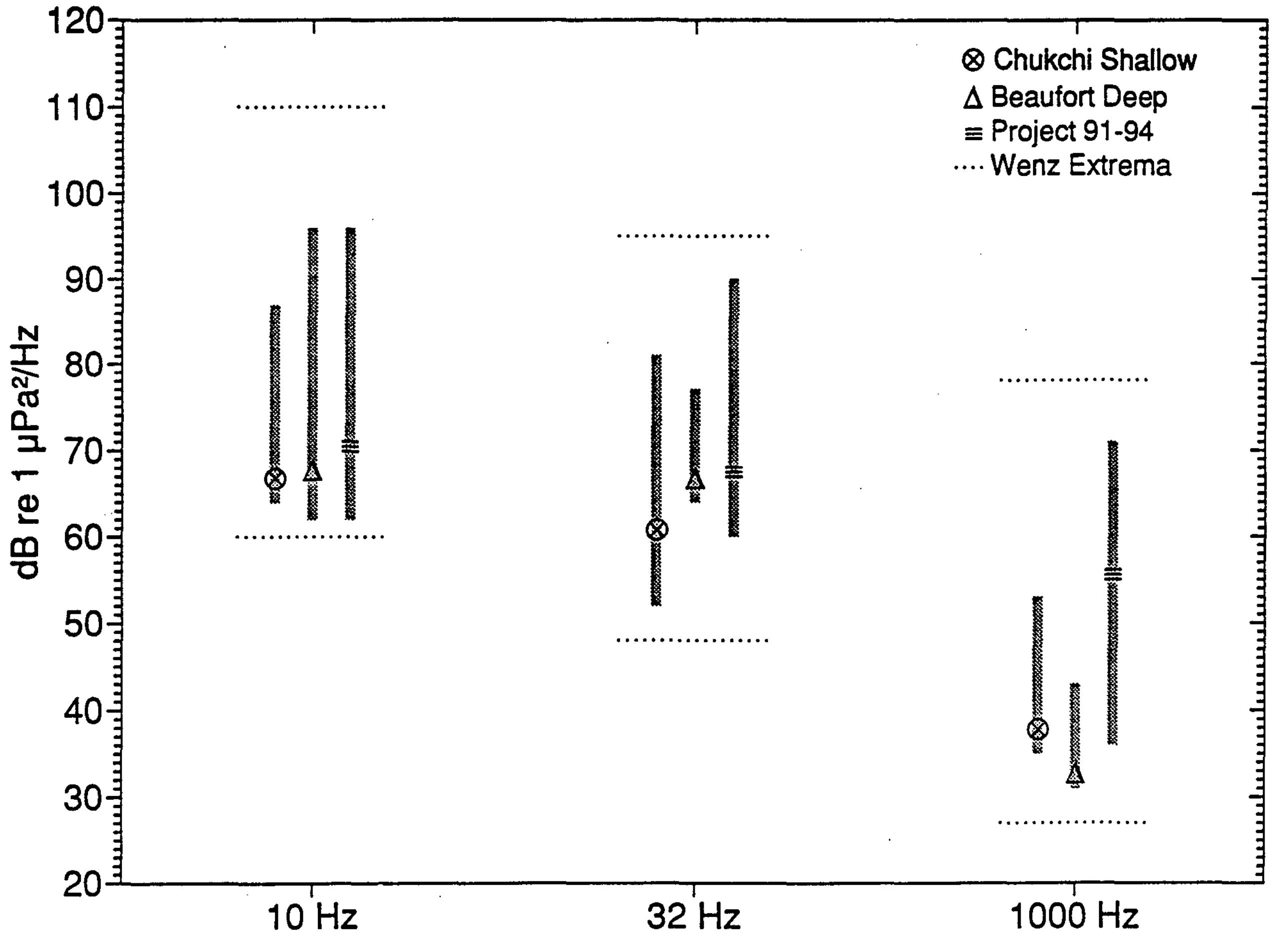


FIGURE 4.8. Comparison of 5th, 50th and 95th percentile ambient noise spectral density levels at 10, 32 and 1000 Hz, based on two data buoys operating in the Chukchi and Beaufort Seas during May 1977 and on the present project (1991/94 phases). The upper and lower limits from Wenz (1962) for those frequencies are also shown.

Results

Figures 4.1-4.3, the percentile distributions for the 1991/94 ambient noise data, include the levels for the 1/3-octave bands centered at 10, 12.5 and 16 Hz. The pattern of levels in these three bands relative to levels at higher frequencies differs for the two years. In 1991, the low and median levels at infrasonic frequencies appear to be extensions of the higher frequency levels, but the 95th percentile and maximum levels increase with decreasing frequency below 20 Hz (Fig. 4.1). In 1994, the low and median levels decrease with decreasing frequency (Fig. 4.2). For the two years combined (Fig. 4.3), the median levels follow the trend established at frequencies up to 400 Hz of decreasing slightly with decreasing frequency.

As seen in Table 4.1C and 4.2C, the median level for the 10 Hz 1/3-octave band was 79 dB re 1 µPa in 1991 and 72 dB re 1 µPa in 1994, or 7 dB lower. At 20 Hz, however, the corresponding levels are 75 and 82 dB, or 7 dB higher in 1994. Generally, the 1994 median levels are higher than the 1991 median levels, except at infrasonic frequencies.

In separate presentations, the sums of the ambient noise mean square pressures in the 10, 12.5 and 16 Hz 1/3-octave bands are graphed against time for 1991 (Fig. 4.9) and for 1994 (Fig. 4.10). These bands span the frequency range 8.9 to 18 Hz. Although the highest levels were measured from sonobuoys on 3, 9 and 16 May 1994, there were high levels in the hydrophone measurements on 18 and 25 May 1991.

Discussion

D'Spain et al. (1991) studied infrasonic energy at frequencies 0.5-20 Hz. They used neutrally buoyant Swallow floats at great depths (e.g., 2960 and 5700 m) in deep water west of California, where there is shipping. At 10 Hz, they show the range of spectral density levels off California to be 75-80 dB re 1 $\mu Pa^2/Hz$, compared with median levels in this project of 71 dB for 1990, 75 dB for 1991, and 68 dB for 1994. Thus, the spring Beaufort Sea measurement results at 10 Hz are comparable to or slightly lower than the results from deep water off California.

What is the likely effect of infrasonic noise on reception of infrasonic bowhead calls, if these exist? Analyses to date suggest the possibility that bowhead calls may sometimes include infrasonic components (§4.5, p. 129). For discussion purposes, let us assume that the levels of any infrasonic components of bowhead calls are similar to the levels of sonic components—that is, the distribution of call energy is approximately flat with frequency, including infrasonic frequencies. Keeping in mind the typically-high transmission loss for infrasonic sounds in shallow water, the infrasonic components of bowhead calls, which are strongly attenuated by propagation losses, are more likely to be masked by ambient noise than are the higher frequency components of bowhead calls, which are less strongly attenuated during propagation. This assessment assumes that ambient noise levels are similar at infrasonic and sonic frequencies, and that—as in other mammals—received sound signals are masked primarily by ambient noise at frequencies similar to those of the signals. It should be noted that this conclusion would not necessarily be true in the deep-water portions of the range of bowhead, where infrasonic sounds might not be attenuated any more rapidly with increasing range than are higher-frequency sounds.

Infrasonic ambient noise also has the potential to mask infrasonic components of industrial noise, when these exist. Icebreakers, other large ships, and some bottom-founded oil-industry platforms are known to emit strong infrasounds (reviewed in Greene and Moore in press). The relatively high levels of ambient noise at infrasonic frequencies will limit the radius around a source of infrasonic sounds within which those sounds will be detectable above the ambient level. In shallow water, which for infrasonic frequencies is water less than 150-300 m deep, infrasonic components of industrial sound will normally be attenuated rapidly by poor sound propagation. However, the infrasonic components will be detectable out to some distance determined by factors affecting the rate of propagation loss (e.g., sound frequency, water depth, bottom materials) and by the ambient noise level. The radius around the source of infrasound within which those sounds would be above the ambient level, and presumably detectable to an animal with infrasonic hearing capability, would need to be assessed on a site-specific basis, taking account of the local sound

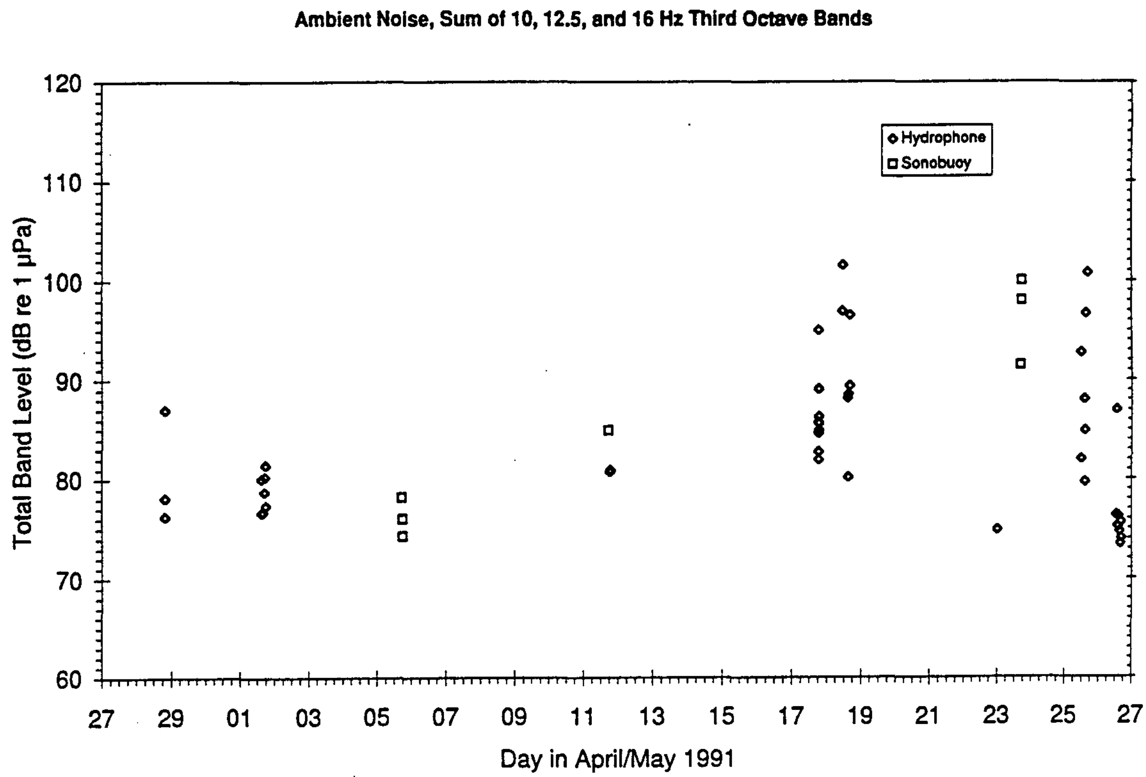


FIGURE 4.9. Infrasonic ambient noise levels, 8.9-18 Hz band, vs. recording date and time in 1991.

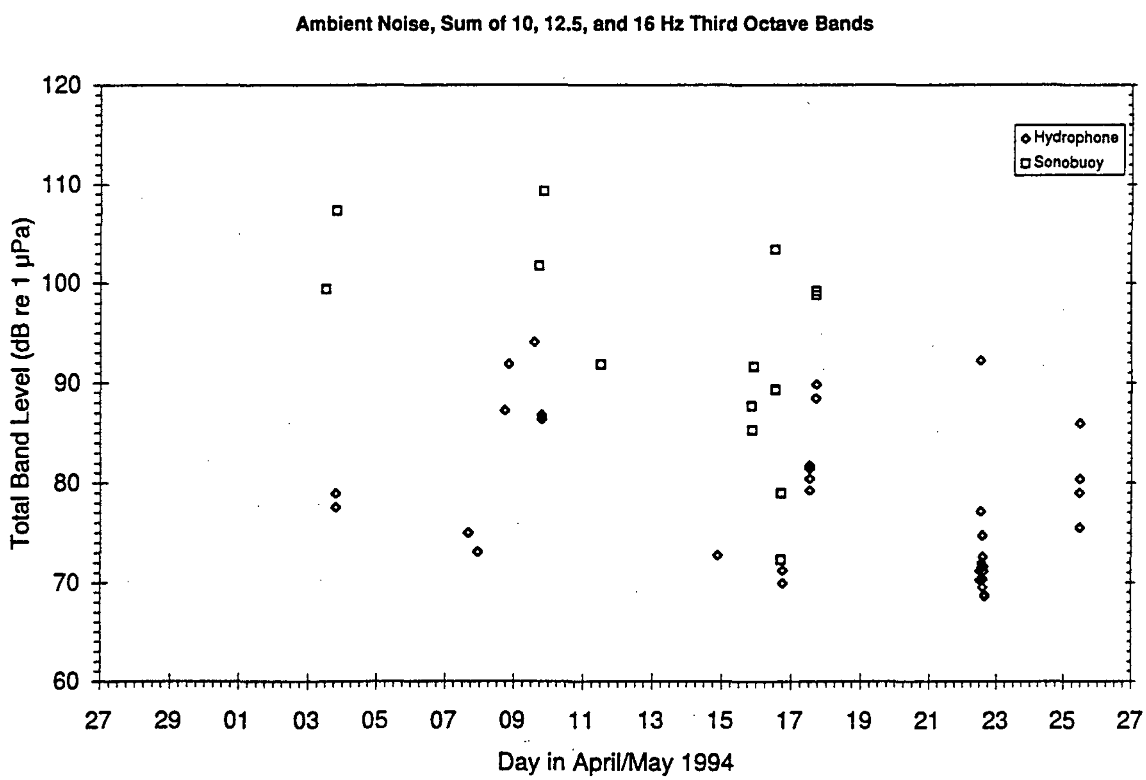


FIGURE 4.10. Infrasonic ambient noise levels, 8.9-18 Hz band, vs. recording date and time in 1994.

propagation conditions as well as the source level of the infrasonic man-made noise and the anticipated levels of infrasonic ambient noise.

4.3 Transmission Loss

The acoustic transmission loss component of the study responds to specific objective 3, "To measure and model transmission loss of underwater sound along...the spring migration corridor, based on playbacks of *(a)* test tones at selected frequencies, and *(b)* continuous industrial sounds. Infrasonic components cannot be projected..." (§1.1, p. 6). Transmission loss, or propagation loss, generally causes the sound level from any source to diminish as distance increases. In shallow water, transmission loss is influenced primarily by the water depth, the sound frequency, and by bottom acoustic properties. Methods used to study transmission loss are described in §2.1.

Summary of 1989-1994 Transmission Loss Data

There were four transmission loss tests during the 1991 phase of the program and two during the 1994 phase. The second 1994 test was aborted after data were collected at ranges 100 and 200 m because an ice floe drifted threateningly toward the projector site. The 1991/94 results are tabulated in Appendix B, Tables B-1 to B-6. Corresponding data from 1989-90 were reported previously, by Richardson et al. (1990a:106*ff*; 1991a:63*ff*). There were four successful transmission loss tests in 1989 and four in 1990.

Figure 2.1 summarizes the locations of the transmission loss tests in all four years, superimposed on newly-derived depth contours for the area. These contours, derived by Paul Dysart, SAIC, take account of depth soundings taken at many of the 1989-94 source and receive stations, and at many of our other ice-camp locations, as well as previously-available soundings. Figures B-15 to B-18 in Appendix B provide additional details regarding receive station locations.

Analysis of 1989-1994 Transmission Loss Data

The propagation data from all four years of measurements near Barrow, AK, collected as part of this project, have been examined for consistency. The amount of ice cover varied from test to test as well as from station to station, but the estimated coverage was always 50% or greater. The one environmental variable that changed significantly from one measurement to the next is the water depth; it ranged from 40 to 180 m and was sometimes not constant along a single measurement track. In examining the data for consistency, a simple model for propagation in an isovelocity channel was used to account for the dependence of propagation on depth. This model allows the depth dependence to be scaled out of the data so all data for a given frequency may be compared. A significant finding of this comparison is that there is consistency in the scaled data, both across years of the test and across source types. This suggests, primarily, that the acoustic bottom conditions are relatively homogeneous over the test area. Data collected with single-frequency tones are reasonably consistent with those from broadband sources, including frequency sweeps and recorded broadband noise from a drilling platform, especially when allowance is made for the frequency averaging of data from the latter sources.

The Propagation Model

In general, a number of environmental variables affect the propagation of sound in the ocean, including water depth, sound speed profile, volume attenuation in the water, and losses induced by interactions with the ocean boundaries. In shallow water, the boundary interactions are usually the dominant influence and the important question concerns how often a propagating path interacts with these boundaries over a given range interval. Both the sound speed profile and the water depth have primary control over the range between interactions. In some shallow water areas, the sound speed does not change significantly with depth, and then the depth itself becomes the important variable. In the analysis below, a simple model for the influence of depth on propagation is used to collapse propagation from a variety of water depths onto a single plot. This same model is then used to make estimates of the received level at the locations of animal sightings during playback experiments.

In a previous report (Hanna 1991) that considered the propagation data from the 1990 test at Barrow, an analysis tool was introduced that scales the propagation data, taken in differing depths of water, to look for consistency in their behavior. In that report, a simple ray-theory model (Hanna 1976) for propagation in an isovelocity channel was used to motivate this approach; the model takes the form

$$I = e^{-\delta R} I_0 \frac{e^{-\alpha\rho}}{\beta\rho^2}(1 - e^{-\beta\rho}) \tag{1}$$

where I is the intensity of the field at some range R (in m) greater than the channel depth D (in m); $e^{-\delta R}$ accounts for the volume attenuation in water (Thorp 1967); $\rho = R/2D$ is the range scaled by the channel depth, D (both in m); $I_0 = \Delta\theta/D^2$ is the intensity at $\rho = 1$; $\Delta\theta$ is the angular aperture of propagating paths to be included; and α and β are parameters related to boundary losses at the channel bottom. Transmission loss is given by $-10\log(I)$.

Thorp (1967) presents an equation for the volume absorption loss term in dB/kyd. That equation is easily converted to dB/km, appropriate to this work. However, the $e^{-\delta R}$ term in Equation (1) is more directly applicable if written as $10^{-\delta' R'}$, where δ' is adapted from Thorp:

$$\delta' = (0.11*F^2)/(1 + F^2) + (44*F^2)/(4100 + F^2) \text{ dB/km},$$

with F being frequency in kHz and $R' = R/1000$ being range in km.

Before proceeding to the application of Equation (1), it is instructive to examine its behavior and develop some intuition for its implications. Consider what generally is expected of propagation in a waveguide. For a point source somewhere in the waveguide, the sound should spread spherically ($1/R^2$, as in free space) until it encounters the boundaries. When this occurs, the sound will reflect from these boundaries and, if they are lossless, the wavefront will eventually spread cylindrically ($1/R$), at ranges large compared with the water depth. If there is some sound loss (from scattering or absorption) when sound reflects from a boundary, the spreading will become asymptotically exponential with range as the propagating field loses some fraction of its intensity with every boundary interaction.

To see if Equation (1) conforms to this expectation, we begin by setting $\delta=0$, which corresponds to negligible volume attenuation, and by setting α and β to zero, which corresponds to no boundary losses. It becomes

$$I=\frac{\Delta\theta}{D^2}\frac{1}{\rho}$$

where the factor $1/D^2$ accounts for the initial spherical spreading and the factor $1/\rho$ accounts for the subsequent cylindrical spreading. For α and β nonzero, and $\beta\rho\gg1$, Equation (1) approaches

$$I=\frac{\Delta\theta}{D^2}\frac{e^{-\alpha\rho}}{\beta\rho^2}$$

which corresponds to the intensity for a single path at the shallowest grazing angle, experiencing its geometrical spherical spreading and suffering a loss at the boundary expressed by the exponential factor. Although β is related to losses at the boundary, it is useful to interpret its reciprocal as the transition range from cylindrical back to spherical spreading as determined by the factor

$$\frac{1-e^{-\beta\rho}}{\beta\rho^2}$$

since for $\beta\rho\ll1$ it behaves like cylindrical spreading and for $\beta\rho\gg1$ it behaves like spherical spreading. So, the model does include all the behaviors that are expected.

As was noted in the previous analysis, this model suggests plotting data in the form

$$\bar{I}=e^{\delta R}D^2 I_{meas} \tag{2}$$

If the region were homogeneous, meaning it had one set of values for α and β, then all data for a particular frequency would be described by the same curve. This idea is used below to review, for consistency, the data from all four years of the tests at Barrow.

Results

In the discussion below, three topics are covered. First, the data collected using the tones are compared to those collected with the wideband sources. Second, the results of scaling the data relative to water depth are presented. Third, values of the model parameters are derived by fitting the model to the scaled data for each frequency band.

Single-Frequency and Frequency-Averaged Data.—Propagation data were collected using a set of single-frequency tones and several broadband waveforms (p. 25*ff* in §2.1). A general expectation, born out by the data, is that the measurements made with the tones show more variability than those using the broadband waveforms. To illustrate what was found to be true across the frequency band from 50 to 1000 Hz, the data at 200 Hz are shown here as examples. Figure 4.11 is a composite plot of all the propagation data for a 200 Hz tone from the 1989, 1990, 1991, and 1994 tests. For comparison, Figure 4.12 presents all the data for propagation, measured using the oil-drilling sounds (*Karluk*), for the 1/3-octave band centered at 200 Hz.

Since the disturbance tests were made using broadband signals (oil-drilling and icebreaker sounds), the frequency-averaged propagation is most appropriate for interpreting those tests. Accordingly, the conclusions below emphasize the frequency-averaged propagation, although data from the tones are shown for comparison.

Scaled Data.—Equation (2) has been used to scale the propagation data, and the next few figures display the results of its application. The data at 200 Hz are used to illustrate the process, and then the data from other frequencies are summarized. Figure 4.13 is the scaled version of Figure 4.11, where the assumed depths for the various tests are summarized in Table 4.4. In this and the following figures, the curve labelled "model" is the result of finding a representative fit to the plotted data using the model described earlier. The fit has been judged visually, rather than by some objective measure, such as least-squares; however, an analysis of the difference between model and data is presented below. The depth was not constant along all the tracks; for those cases where it was not, a representative depth was chosen for the dominant portion of the track.

TABLE 4.4. Depths at TL test sites.

Test	Depth (m)	Test	Depth (m)
1989 #2	40	1991 #1	60
1989 #3	50	1991 #2	100
1989 #4	120	1991 #3	100
1989 #5	50	1991 #4	150
1990 #1	180	1994 #1	70
1990 #2	40	1994 #2	178
1990 #3	75		
1990 #4	75		

Note that some of the variability seen in Figure 4.11 is eliminated by the scaling, suggesting that some is attributable to significant differences in the water depth, rather than just multipath interference that can dominate the variability of single-frequency propagation.

Figure 4.14 contains the scaled data for *Karluk* signals corresponding to Figure 4.12; as with the tone data, the scaling has reduced the variance somewhat. Finally, Figure 4.15 and Figure 4.16 show data from 1/3-octave sweeps before and after the scaling. Again, scaling reduces the variance. Also, the data from *Karluk* and the sweeps are gratifyingly consistent with one another, and with the data from the tones, when allowance is made for the additional variability that is characteristic of single-frequency data.

One-third octave propagation data were also collected using the recorded icebreaker (*Robert Lemeur*) sound; however, these results are not very consistent with the *Karluk* or sweep data. Figure 4.17 shows an example of the scaled icebreaker data for 200 Hz. Comparison of this figure with Figure 4.12, Figure 4.14, and Figure 4.16 illustrates the point. The reason for this disparity

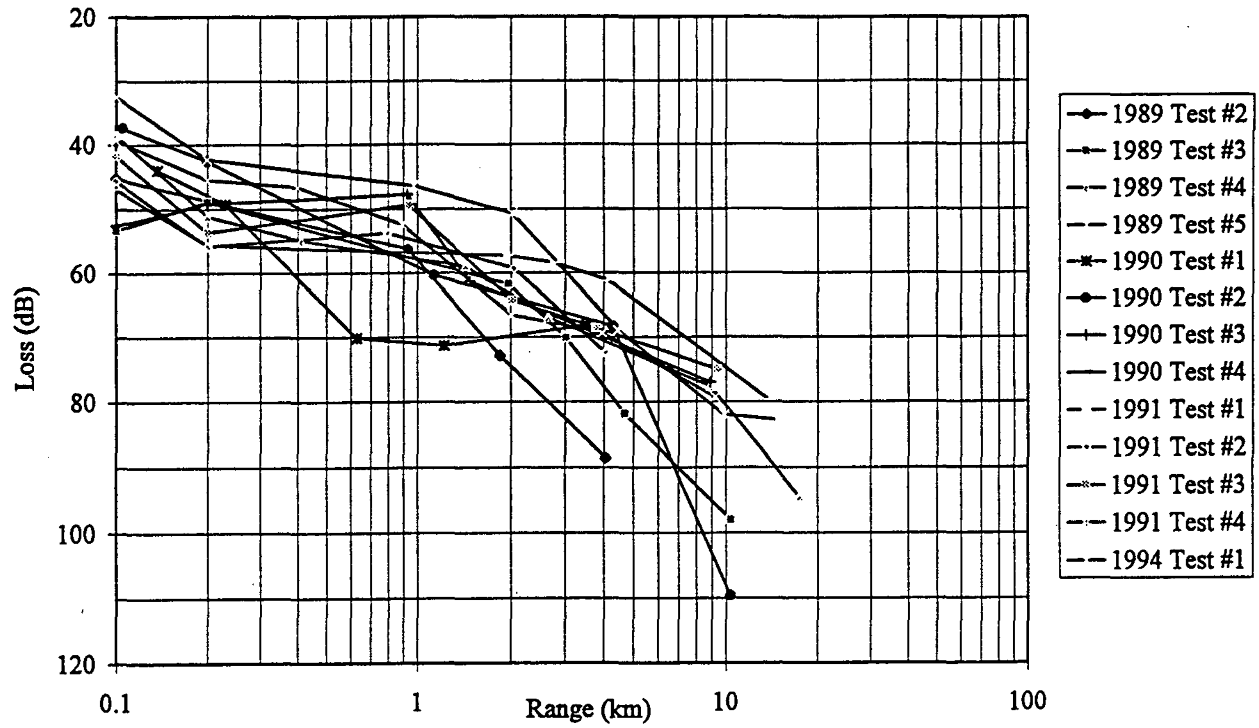


FIGURE 4.11. Transmission loss vs. distance for 200 Hz tones measured during transmission loss experiments, 1989-94.

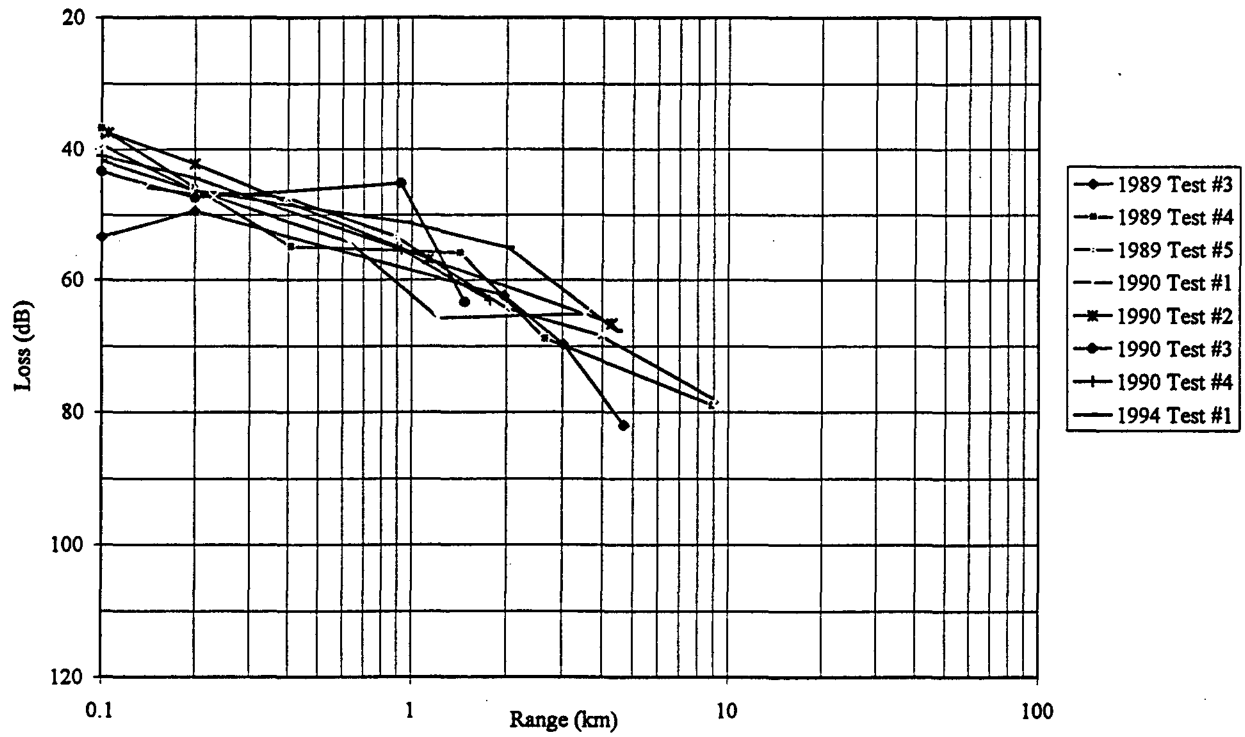


FIGURE 4.12. Transmission loss vs. distance for 200 Hz 1/3-octave band levels of *Karluk* drilling sounds measured during transmission loss experiments, 1989-94.

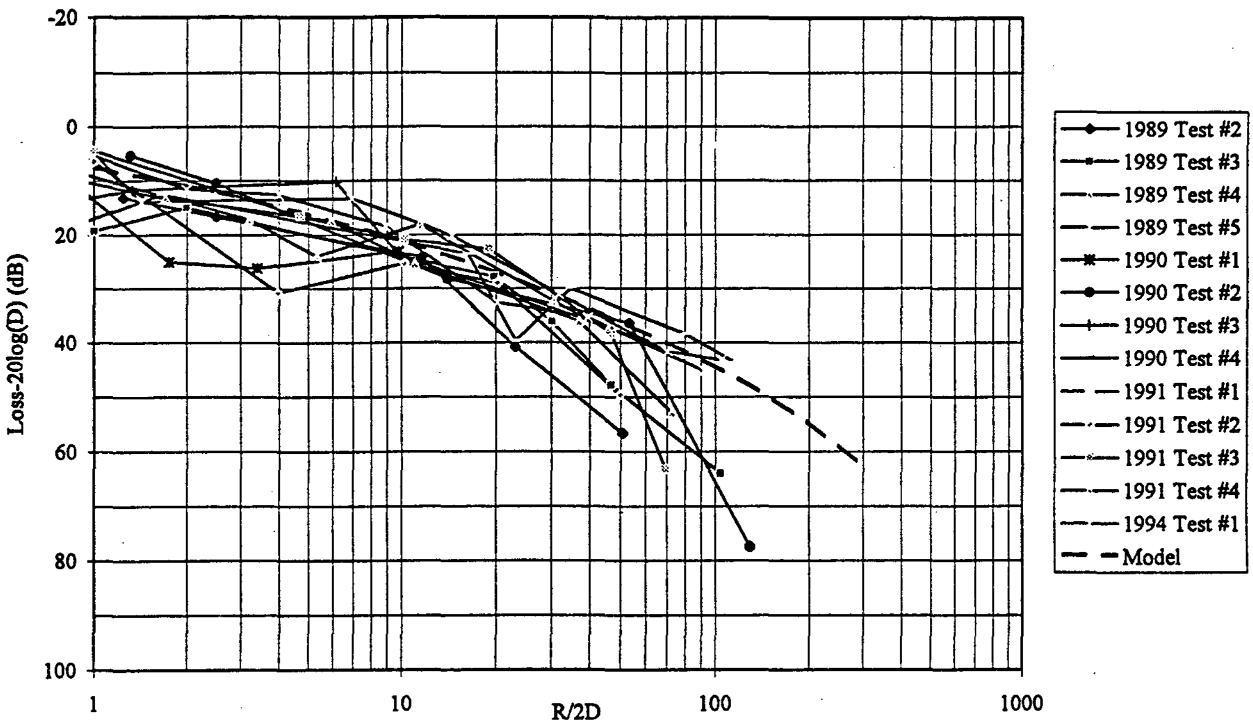


FIGURE 4.13. Transmission loss minus 20 log(Depth) vs. distance scaled by twice the water depth for 200 Hz tones measured during transmission loss experiments, 1989-94 (*cf.* Fig. 4.11).

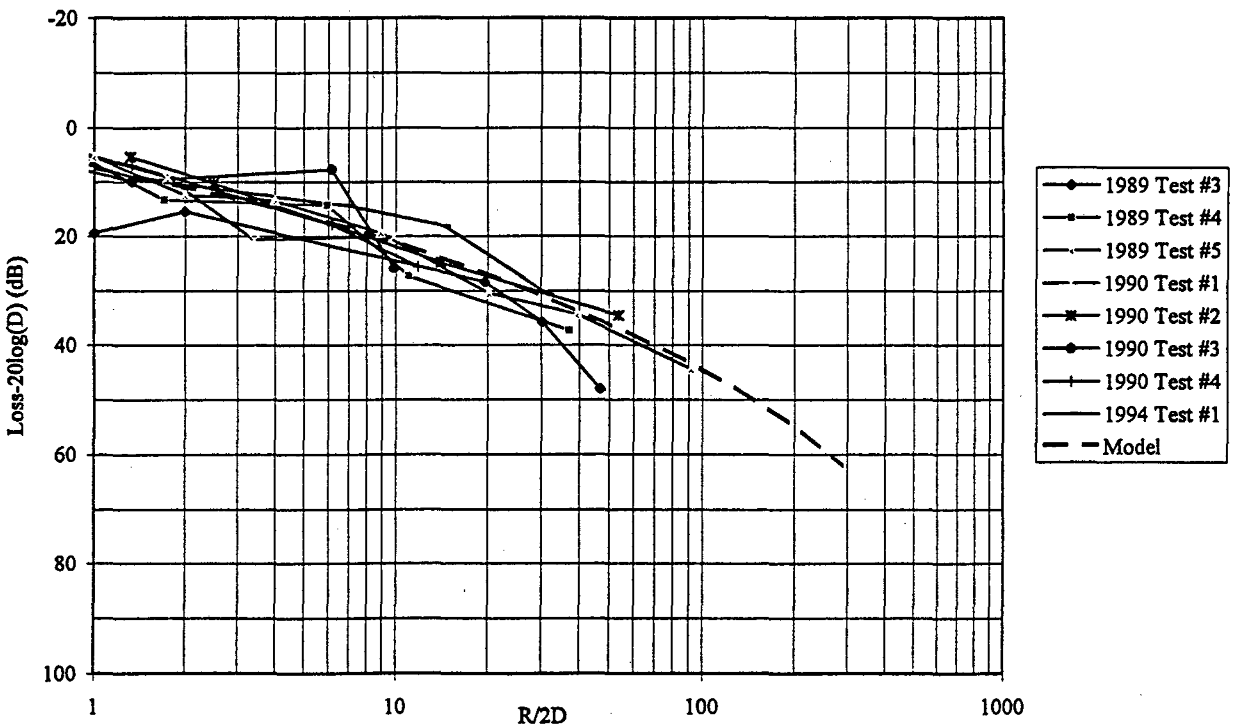


FIGURE 4.14. TL-20log(D) vs. distance scaled by twice the water depth for 200 Hz 1/3-octave band levels of *Karluk* drilling sounds measured during transmission loss experiments, 1989-94 (*cf.* Fig. 4.12).

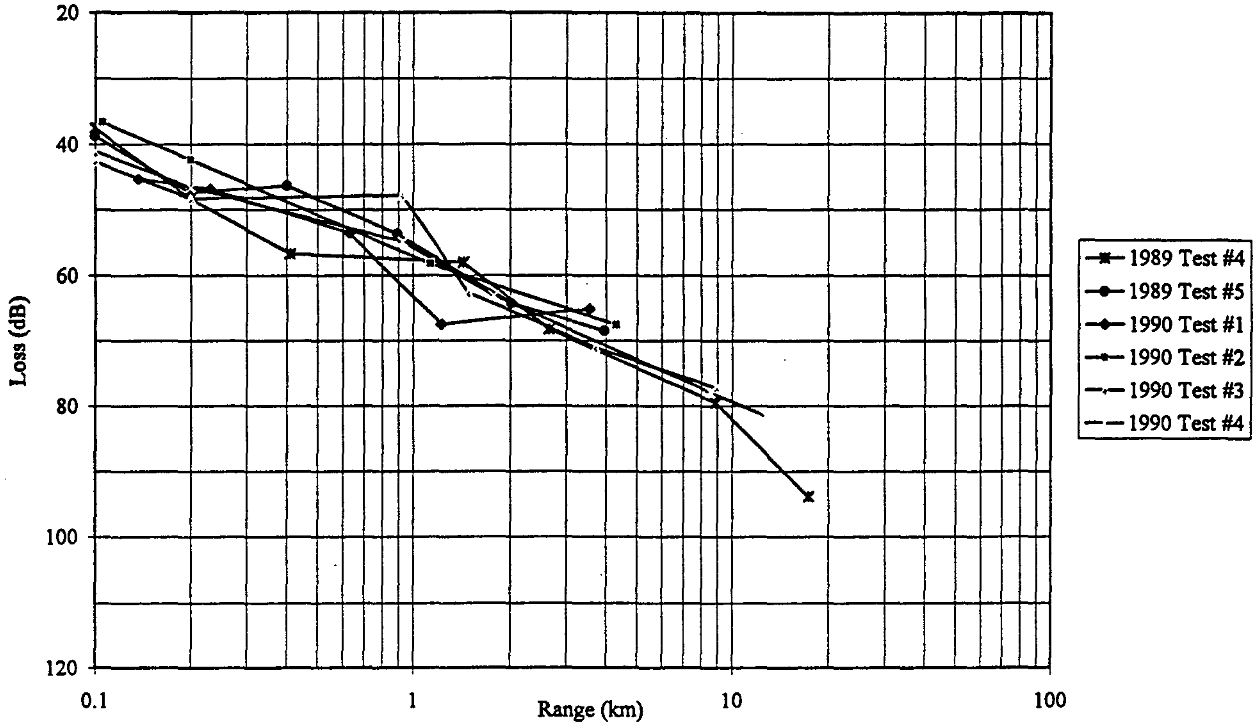


FIGURE 4.15. TL vs. distance for 200 Hz frequency-modulation sweeps measured during transmission loss tests, 1989-90.

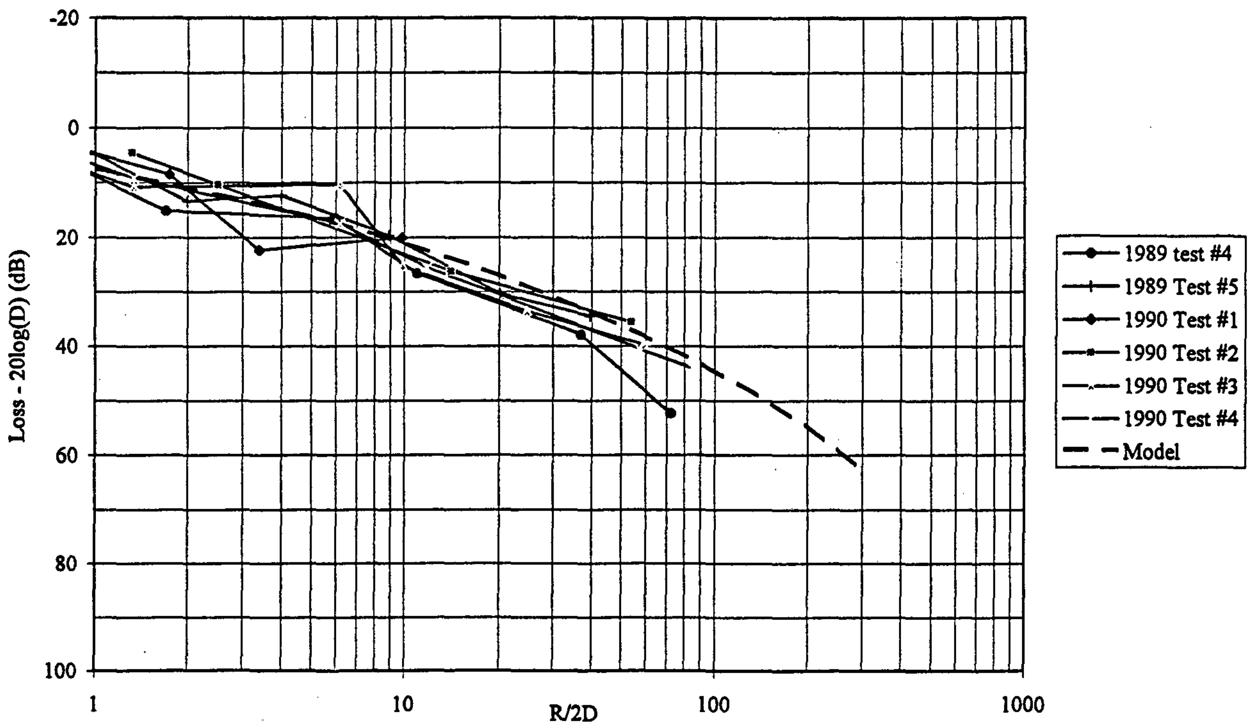


FIGURE 4.16. TL-20log(D) vs. scaled distance for 200 Hz FM sweeps measured during transmission loss tests, 1989-90 (cf. Fig. 4.15).

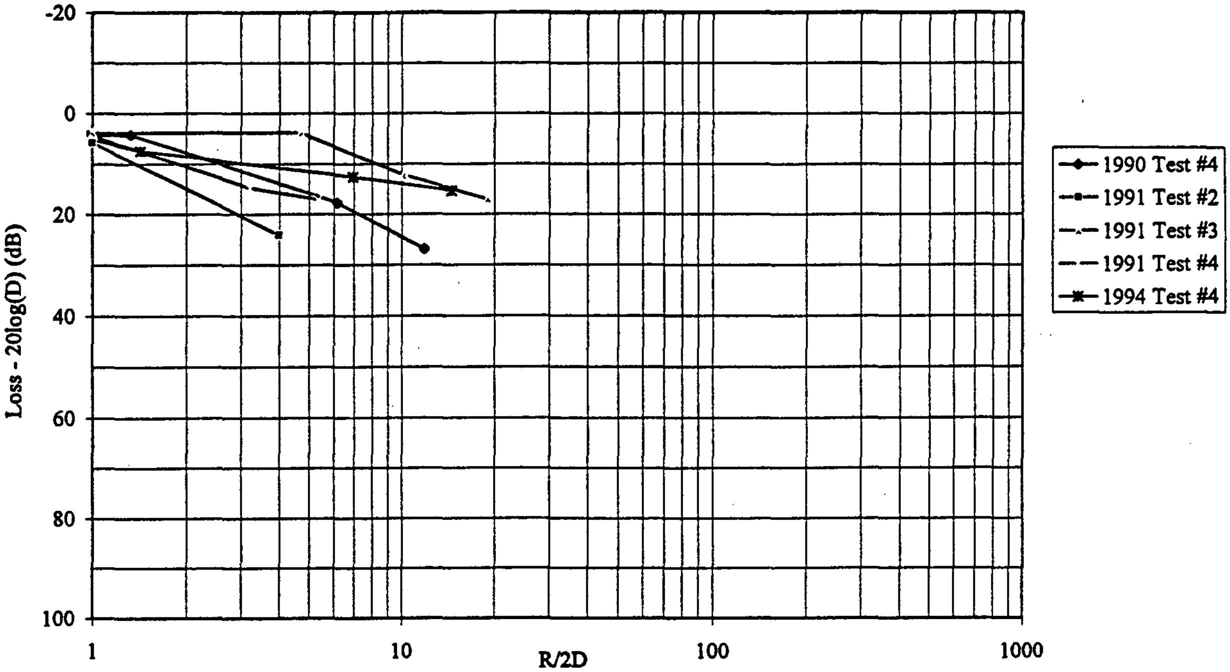


FIGURE 4.17. TL-20log(D) vs. scaled distance for 200 Hz 1/3-octave band levels of icebreaker *Robert Lemeur* sounds projected during transmission loss tests, 1990-94.

is probably related to the substantial time variability of the icebreaker waveform compared with that for the other signals. During the TL tests it was not feasible to record the transmitted and received signals on the same recorder, which would have permitted simultaneous source level/ received level measurements. Time alignment between the projected and received signals was difficult.

Figures B-1 through B-14 (in Appendix B) show the scaled data at 50, 100, 500, 1000, 2000, and 5000 Hz for the tone, *Karluk*, and sweep signals. The *Karluk* data only extended up to about 350 Hz. The tone and sweep data covered all the frequencies shown. The general points made above in connection with the 200 Hz data are seen to hold across the frequency band. The increased variability above 1000 Hz is likely caused by scattering and absorption losses at the water-air or water-ice interfaces. These losses are not explicitly treated in the present model.

One additional propagation mechanism is important at frequencies below 50 Hz for the projected signals. The fact that the ocean surface creates what is called a pressure-release boundary has a profound effect on the propagation when the source, receiver, or both are within about one wavelength of the surface. In general, each path at the source or receiver has a surface-reflected counterpart, and it can be shown (Bannister and Pedersen 1981) that the coherent addition of these paths results in an intensity factor that is well-approximated by the following expression:

$$4\sin^2\left(2\pi\frac{d\sin(\theta)}{\lambda}\right)$$

where d is the depth below the surface of either the source or receiver, θ is the path angle relative to the horizontal, and λ is the wavelength. This factor multiplies the intensity associated with either of the individual paths. When the two are in phase, the argument of the sine is an odd multiple of $\pi/2$, and the factor is 4, which corresponds to a doubling of the single-path pressure. Since this mechanism affects both the source and receiver, the total effect on propagation is a product of two such factors. When the wavelength becomes large compared to the depth, the sine may be approximated by its argument and the total factor becomes

$$16\left(2\pi\frac{d_s\sin(\theta)}{\lambda}\right)^2\left(2\pi\frac{d_r\sin(\theta)}{\lambda}\right)^2$$

Because this factor is inversely proportional to the 4th power of the wavelength, it is likewise proportional to the fourth power of frequency. Consequently, the pressure field decreases with decreasing frequency, source depth, or receiver depth. The diminution of the level resulting from this mechanism is often referred to as the Lloyd's mirror effect. This name arises from optics (Jenkins and White 1957:242) where an interference pattern is observed involving lightpaths from a common source, one arriving directly and the other via one reflection from a mirrored surface.

This frequency behavior may be seen in the data from the 1994 test #1 as shown in Figure 4.18 for a range of 200 m and in Figure 4.19 for a range of 1000 m. In both figures, the data for the tones and *Karluk* signals are plotted and compared with a curve that has a slope given by the fourth power of frequency. (Note that this power law behavior of the intensity results in a straight line when plotted against the logarithm of frequency.) In both cases, it is apparent that the influence of this mechanism becomes important below about 50 Hz, although this frequency would be different for other source or receiver depths. In the model or propagation being used here, this mechanism is included by multiplying Equation (1) by the factor for frequencies below 50 Hz.

<u>Model Parameters</u>.—As mentioned above, the model was used to fit the scaled data as a function of frequency. The parameters were chosen by concentrating on the frequency-averaged data, and then checking the resulting fit against the tone data. The reason for this is that the data from the tones extended to somewhat longer ranges, and their decay rate was significant in picking the parameter α, which controls the asymptotic decay of the model curve. The depth-scaled form of Equation (1) that was used here is

$$\bar{I}=\bar{I}_0\frac{e^{-\alpha\rho}}{\beta\rho^2}(1-e^{-\beta\rho}) \tag{3}$$

where

$$\bar{I}_0=\Delta\theta \;\; if\; f>50\; Hz$$
$$=\Delta\theta\left(\frac{f}{50}\right)^4 \;\; otherwise$$

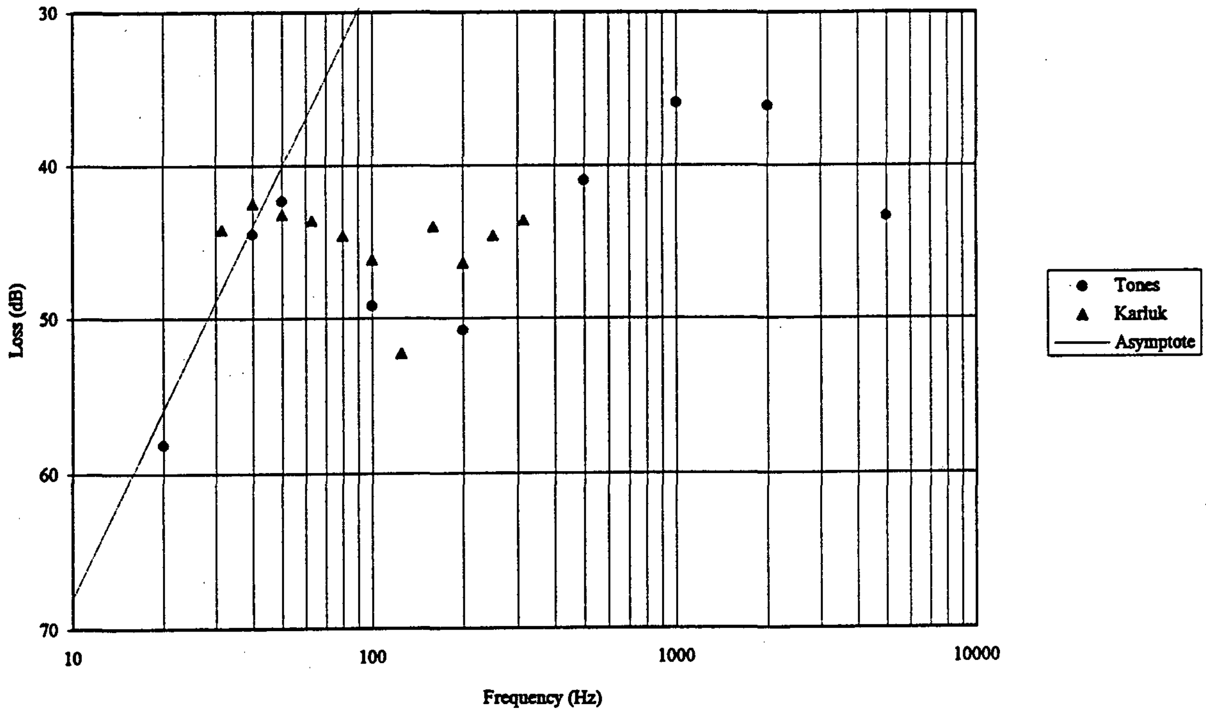


FIGURE 4.18. The Lloyd's mirror factor for the 1994 TL test #1 data at distance 200 m.

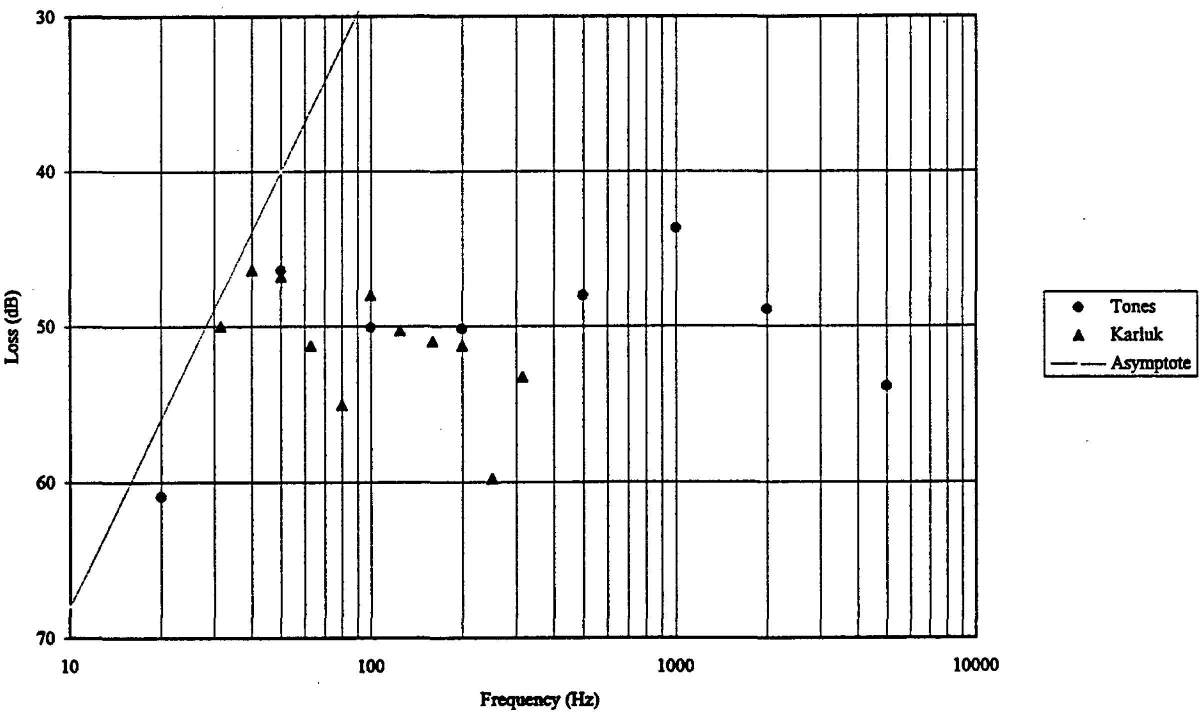


FIGURE 4.19. The Lloyd's mirror factor for the 1994 TL test #1 data at distance 1000 m.

and the last expression accounts for the Lloyd's mirror effect. The parameters that resulted from fitting the data are shown in Table 4.5. The parameters at 20 Hz have been extrapolated from 50 Hz using a comparison with the limited data from the 1994 tests at this frequency, and include the Lloyd's mirror effect described above.

TABLE 4.5. Transmission loss model parameters vs. frequency.

	Frequency (Hz)							
Parameter	20	50	100	200	500	1000	2000	5000
$\Delta\theta$	0.015	0.300	0.200	0.200	0.200	0.200	0.200	0.200
α	0.03	0.02	0.01	0.01	0.035	0.045	0.055	0.065
β	0.20	0.2	0.2	0.2	0.2	0.2	0.2	0.2

The comparisons offered in the preceding figures are useful visual indicators of how well the model represents the data. These can be complemented by estimates of the standard deviation of the differences between the data and the model for the various signal waveforms.

Figure 4.20 shows these standard deviations for the 1/3-octave bands from 50 to 5000 Hz. The larger deviations for the tone data are a quantitative confirmation of the point made above about the greater variability of single-frequency propagation. The similarity between deviations for the *Karluk* and sweep data confirm the consistency of these two band-averaged data sets. For the latter data sets, a deviation of about 4 dB characterizes the model-data comparison over the band from 50 to 1000 Hz. Above 1000 Hz, the deviation grows for the reasons mentioned above having to do with variable surface or ice scattering losses.

To work through an example of a transmission loss computation, take frequency f = 500 Hz, water depth D = 100 m, and distance R = 10,000 m. From Table 4.5, 500 Hz, read $\Delta\theta = 0.2$, α = 0.035, and $\beta = 0.2$. Thus, $\rho = R/(2*D) = 50$ and $I_0 = \Delta\theta/D^2 = 2*10^{-5}$. To obtain transmission loss in decibels, one needs $-10\log(I)$, which means Equation (1) can be factored and the 10log() terms added. The volume absorption loss term is first: 0.25 dB. The $I_0 e^{-\alpha\rho}$ term is next: $3.475*10^{-6}$ or 54.59 dB. The last term is $(1-e^{-\beta\rho})/(\beta\rho^2) = 2.0*10^{-3}$ or 27 dB. Thus, the total transmission loss for a 500 Hz sound traveling 10 km in water 100 m deep is 81.8 dB re 1 m.

Comparison with BBN's Weston-Smith TL Model.—The model in Equation (1) is very similar to one used in earlier analyses of shallow Beaufort Sea propagation by Miles et. al. (1986, p. 96*ff*) as related to marine mammal disturbance. Using the scaled range introduced above and the notation of this report, their equation takes the form

$$I=e^{-\delta R}\left(\frac{\pi}{4b}\right)^{1/2}\frac{e^{-2a\rho}}{D^2\rho^{3/2}}$$

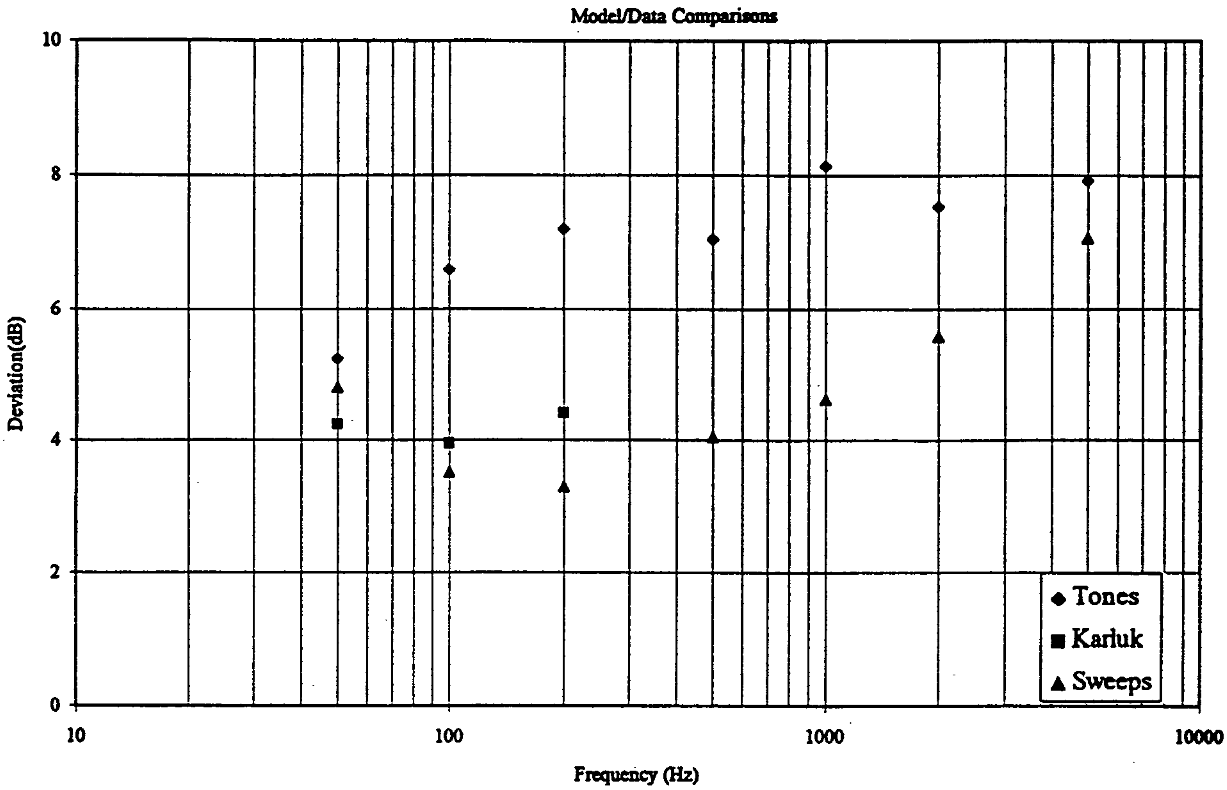


FIGURE 4.20. Standard deviations between the measurements and the model predictions vs. frequency for three types of sounds.

where a and b are parameters related to the boundary losses. This model includes the initial spherical spreading region, followed by a region with geometrical spreading midway between cylindrical and spherical combined with exponential decay. Except for the fact that the model in Equation (1) has geometrical spreading for this latter region that transitions from cylindrical to spherical spreading, the two models are very similar. In fact, in analysis not reported here, it was determined that nearly identical fits to the data could be achieved with either representation by suitable selection of the model parameters. The most important points about the two models are that (1) they both suggest scaling the data according to Equation (2), and (2) for suitable values of the a and b parameters, the two models agree in predicting received levels at ranges long compared to the ranges for which transmission loss experimental data are available.

Comparison of the Propagation Model and Playback Data

The sonobuoy signals received during playback tests were not used in defining the transmission loss model parameters. Thus, they can be used to verify the validity of the model.

The validation methodology was as follows. For times when the received level was measured via sonobuoy, the sound exposure model program described in §2.3 (p. 46*ff*) was run to predict received level statistics. The program incorporates the present propagation model along with a procedure to estimate source level spectrum at any time during a playback experiment (§2.3). The resulting received level estimates for the 20-1000 Hz broad band and for the dominant 1/3-octave band in the 64-s and the 14-min periods preceding the specified time were compared with the measured received levels in those bands. The 14-min estimates actually describe the distribution of levels for all time during which projection continued without interruption or variation in playback amplifier settings.

The results are presented in graphical form in Figures 4.21 (20-1000 Hz) and 4.22 (dominant 1/3-octave band received). Prevailing ambient noise levels measured at times before and after the playback period are included, as some of the predicted received levels are below the noise level and would not be expected to be heard. Some of the other predicted received levels are within a few decibels of the ambient noise level, in which cases the level measured by the sonobuoy, representing both icebreaker and ambient noise, would be expected to be slightly above the level of icebreaker noise predicted by the model. With these exceptions, the measured received levels should, ideally, fall in the minimum-maximum range predicted by the model for the 64-s period adjacent to the recording time; it would be coincidental if the measured levels agreed with the predicted medians. Allowance for the nominal 4 dB standard error in the model predictions increases the allowable range of the difference. At worst, the measured received levels should fall in the range of the predicted 14-min distribution of levels ± the 4 dB allowance. Table 4.6 summarizes the results of the comparison by date and time.

TABLE 4.6. Summary observations comparing the model predictions with the observed received levels at sonobuoys during icebreaker playbacks.

Date	Time	Remarks
17 May 91	14:18:00 14:20:00 16:17:00 16:23:00	The measured sonobuoy levels fall within the model prediction ranges. The playback icebreaker sounds were audible.
3 May 94	17:00:00 19:14:44	The predicted received level ranges are lower than the measured ambient noise. The sonobuoy measurements are in the range of the ambient noise measurements, and the icebreaking sounds were not audible.
9 May 94	16:55:37 17:24:43	The measured sonobuoy levels are generally within the model prediction ranges, but so are the ambient noise levels, and the icebreaking sounds were not audible.
16 May 94	13:17:33 13:20:38 13:55:58 14:42:59 17:07:31 17:08:25	Discontinuities in playback transmission prevented predicting received level ranges for every time, but the sonobuoy received levels are generally within the predicted ranges available, or within 4 dB. The ambient noise was lower, and the icebreaking sounds were audible.
17 May 94	12:50:12 12:51:06 12:53:16	The measured sonobuoy levels are generally in the range of the ambient noise levels and above the predicted ranges, but the icebreaking sounds were audible weakly on the sonobuoys. It appears that the predicted levels may be lower than the levels actually received.

The measured and predicted broadband levels (20-1000 Hz) are generally in good agreement, after discounting the 3 and 17 May 1994 cases when the measured level was largely attributable to ambient noise (Fig. 4.21). However, for the 1/3-octave band of strongest icebreaker sound, the model estimates were a few decibels below the measured levels of playback sound (17 May 1991, 16 May 1994), even after discounting cases in which ambient noise probably dominated the sonobuoy measurements (3, 9 and 17 May 1994).

This validation analysis suggests that the sound exposure model provides reasonable estimates of received sound levels, provided that these estimated levels exceed ambient noise levels prevailing in the corresponding frequency band at the time in question. Model estimates of received levels may be more accurate in the case of broadband levels than for levels in the dominant 1/3-octave band; the latter may be underestimated by a few decibels. Before use, estimates of received levels need to be compared with measured or estimated ambient noise levels to determine whether the received level would be detectable above the ambient.

Sound Propagation on 13 May 1990

An unusually large number of bowhead whales (~105, see Table 6.2 in §6.1) were observed on 13 May 1990 while *Karluk* drilling sounds were projected at a shallow-water site (depth 27 m) in the southeastern part of the study area (see Fig. 3.4 on p. 68). The validity of estimated received levels at this whale location is especially important, given that important results concerning bowhead reactions to steady drilling sounds were obtained there (Richardson et al. 1991a). Preliminary estimates of the received levels of the projected *Karluk* sounds vs. range were included in that report, based on a simpler propagation model.

Here we re-evaluate the 13 May 1990 received level estimates based on the new propagation model. The sonobuoy data for dates in 1990 were converted to propagation loss for these comparisons, and the associated ranges and losses are summarized in Table 4.7. Discussion of the playback levels from which these losses are inferred may be found in Richardson et al. (1991a).

TABLE 4.7. Transmission loss measured via sonobuoys during playback experiments in May 1990.

Date	Range (km) (dB)	TL
9-May-90	0.6	55
10-May-90	1.4	51
11-May-90	3.2	54
13-May-90	3.5	59
13-May-90	1.64	45
13-May-90	2.06	46
13-May-90	2.03	47
13-May-90	5.8	73
16-May-90	0.9	48
16-May-90	4	70
21-May-90	0.4	49
21-May-90	0.9	62

The transmission losses from Table 4.7 are shown in Figure 4.23 where they are compared with the model for 200 Hz propagation, using the scaling algorithm described above. Most of the data are within a standard deviation of the model curve, but the behavior of the data from 13 May 1990 is significantly different from the model. These data are about 15 dB above the model curve at scaled ranges from 30 to 40 (actual ranges 1.6 to 2.2 km), and then increase with range much more rapidly than the model curve. To predict such low propagation losses at the shortest ranges, one must assume much lower boundary losses than are implicit in the model used to fit the TL

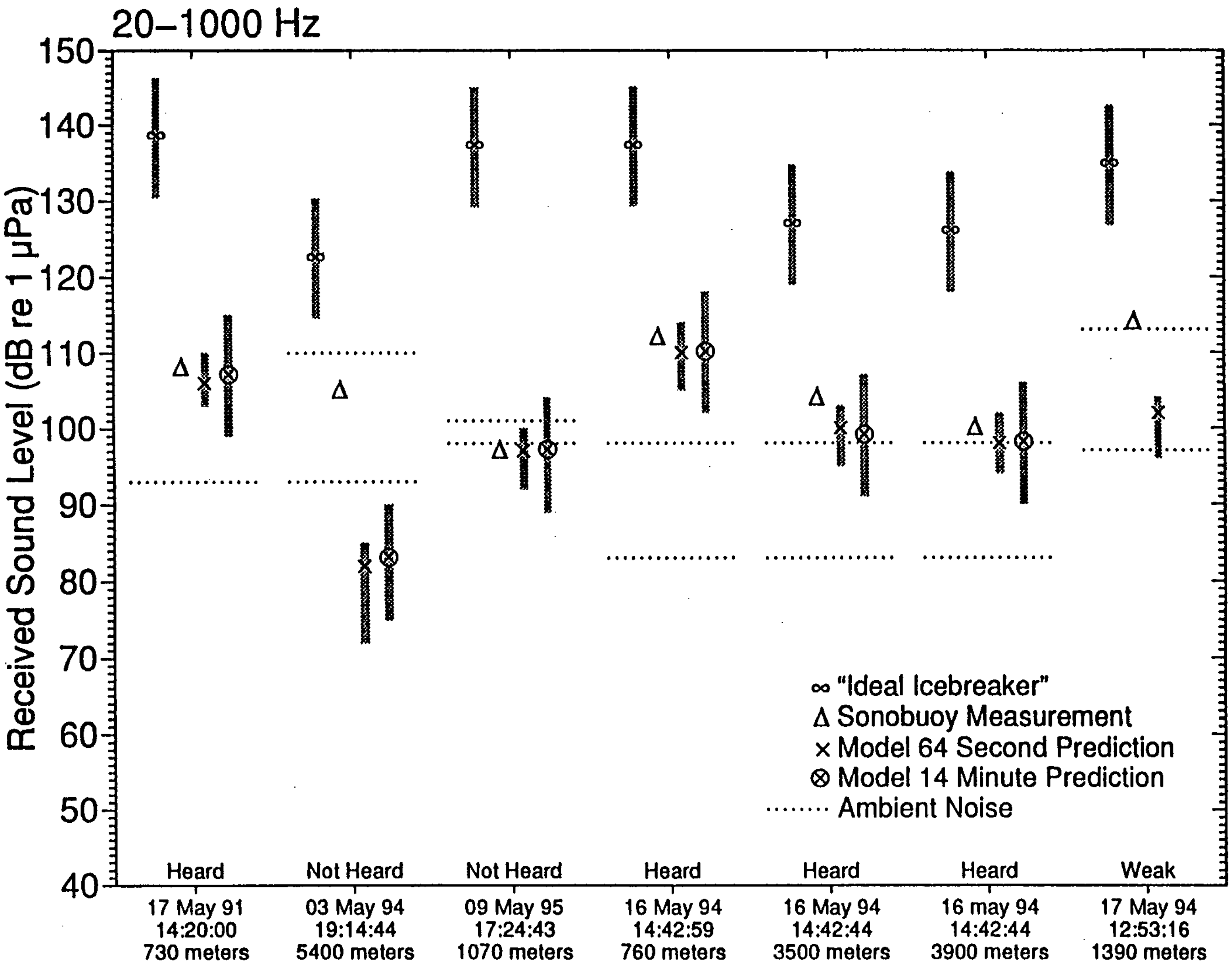


FIGURE 4.21. Measured 20-1000 Hz band levels at sonobuoys (triangles) vs. model predictions of received levels from actual icebreaker and playback source: (a) Actual icebreaker if it, instead of the sound projector, were operating at the site; (b) the 14-min period of icebreaker playback (the full cycle of the playback recording); and (c) the 64-s period of icebreaker playback just before the sonobuoy measurement time. The nominal ambient noise level in the same frequency band for the day, measured with both ice-based hydrophones and sonobuoys, is also plotted as a dashed line.

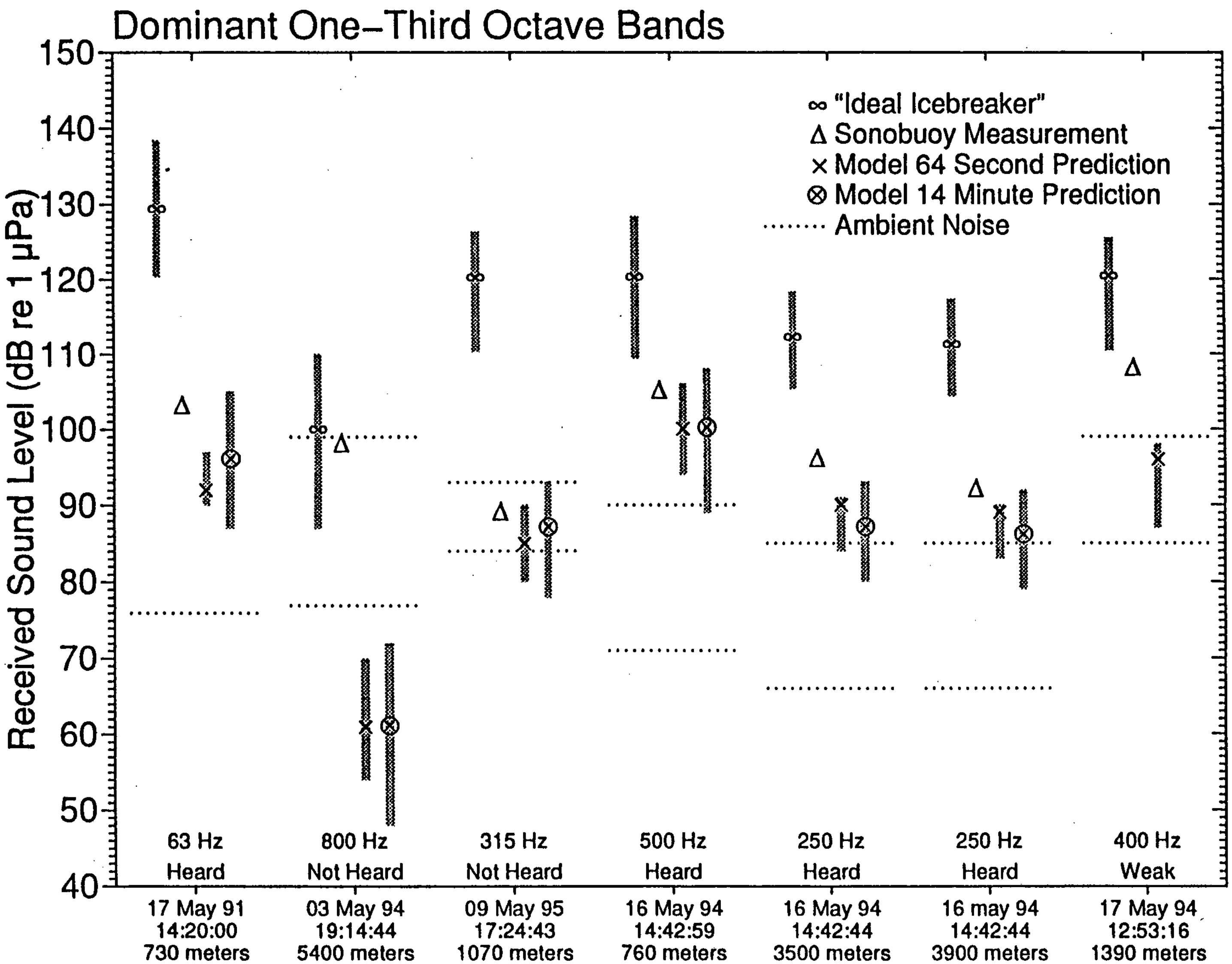


FIGURE 4.22. Measured 1/3-octave band levels at sonobuoys (triangles) vs. model predictions of received levels from actual icebreaker and playback source. The 1/3-octave band considered here was the one containing the strongest icebreaker sound. Otherwise plotted as in Figure 4.21.

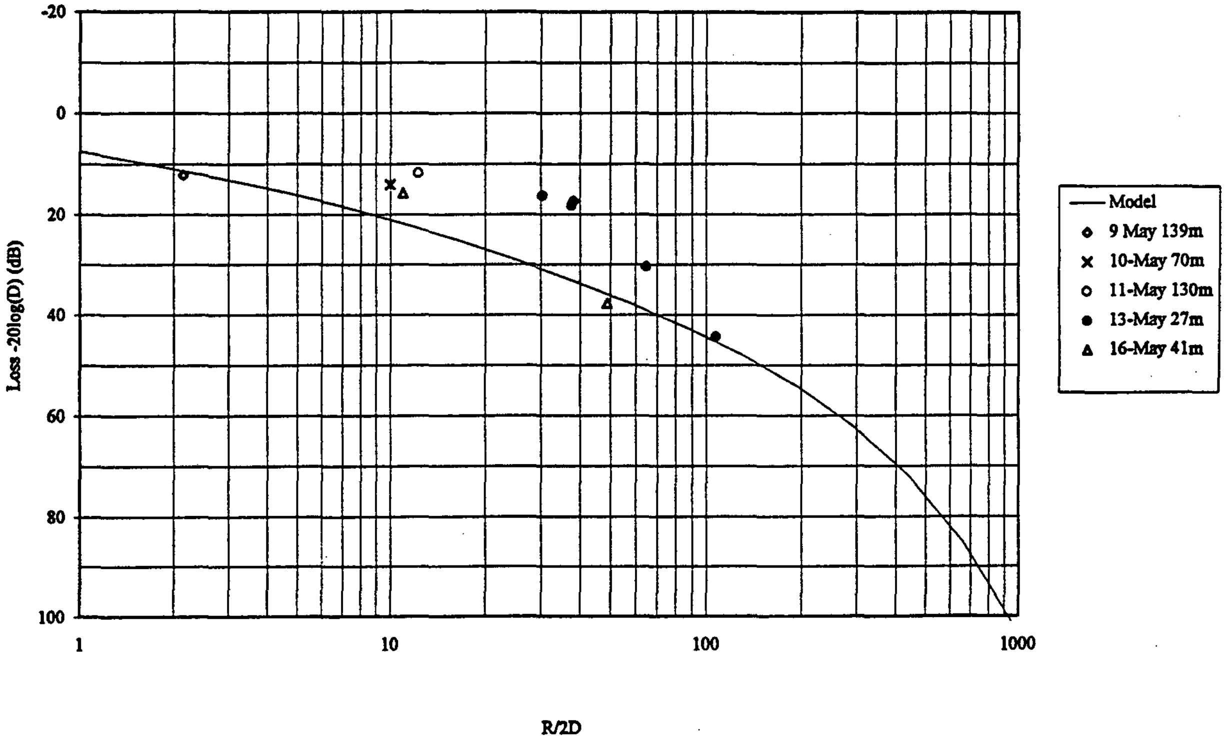


FIGURE 4.23. TL-20log(D) vs. scaled distance for 200 Hz transmission loss data, comparing sonobuoy measurements during *Karluk* playbacks in May 1990 with the TL model.

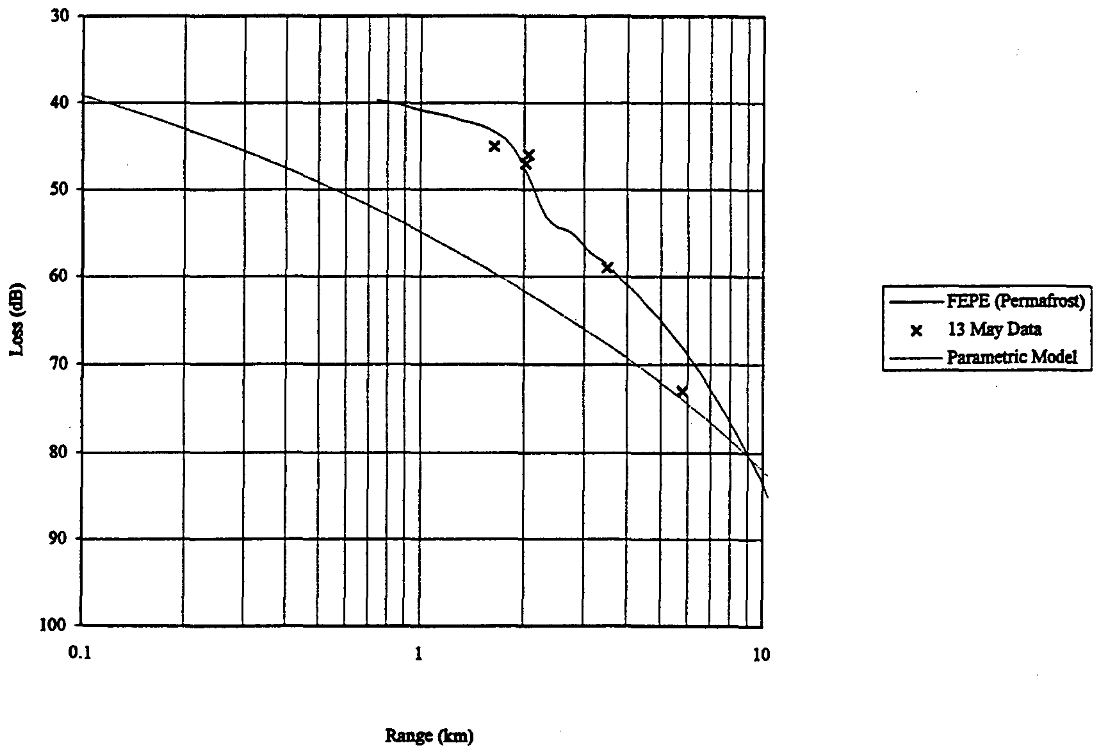


FIGURE 4.24. Transmission loss vs. distance for the 13 May 1990 playback experiment comparing the TL model developed in this study with a finite element parabolic equation (FEPE) model assuming "relic permafrost" (*per* Miles et al. 1986, 1987) to distance 2 km.

test data in the preceding section. The possibility of such low boundary losses is discussed in Miles et al. (1986, 1987). In these reports, the occurrence of relic permafrost and overconsolidated sediments is reviewed and some nominal sound speeds are given for those materials. In particular, sound speeds of 2000 to 4000 m/s are suggested for the permafrost. To examine the acoustic consequences of such material, a speed of 3000 m/s for the bottom was used in a Finite Element Parabolic Equation (FEPE) model that is capable of treating such large sound speed contrasts. Although such a bottom is indeed capable of producing the low propagation losses observed in the shortest range 13 May 1990 data, it will not predict the observed rapid increase of loss beyond a range of about 2 km. To account for this latter behavior, it was necessary to assume that the bottom changed from high to low speeds at about the range of the lowest propagation losses.

The results of such a model calculation are shown in Figure 4.24. This figure compares the 13 May 1990 data to an FEPE calculation that assumes a permafrost bottom at distances to 2 km, with a transition back to a low-speed representative of shallow water unconsolidated sediments. Also shown is the prediction by the model developed here. The FEPE calculation for the combination high- and low-speed bottoms suggests that the occurrence of a permafrost patch surrounded by normal sediments might account for the 13 May 1990 data. This project did not collect any data that could confirm the presence of permafrost at the 13 May 1990 site. However, the Miles et al. reports summarize observations of such material near the water-sediment interface in similar shallow coastal shelf regions of the North Slope.

Based on the sonobuoy measurement data actually collected at the playback experiment site on 13 May 1990, a separate, simple empirical model for transmission loss on that date was developed. The spreading loss slope for distances from closer than 100 m to greater than 1000 m was cylindrical, or expressible as $10\log(R)$. Extrapolating the measured loss curve backward in range, the loss at 100 m was 32 dB re 1 m. Fitting the longer range sonobuoy data to an equation *not based on theory*, the following equations were found to fit the data:

$$\mathrm{TL} = 42 + 10*\log(R), \qquad 0.1 < R < 1.23 \text{ km}$$

$$\mathrm{TL} = 38.7 + 46*\log(R), \qquad 1.23 < R \text{ km}$$

The standard error of the fit is 3.5 dB, which compares with the nominal 4 dB of the model developed for most of the study area.

Summary Discussion of Transmission Loss

Propagation data from all four years (1989, 1990, 1991, 1994) of measurements near Barrow, Alaska, have been examined for consistency. The one environmental variable that changed significantly among measurements was the water depth; it ranged from 40 to 180 m and was sometimes not constant along a single measurement track. In examining the data for consistency, a simple model for propagation in an isovelocity channel was used to suggest the dependence of the propagation on this parameter. This model was used to scale the data from all four years at each frequency; this was found to reduce the residual variation among the measurements. The propagation loss predicted by this model was then used to fit the scaled data. The associated model coefficients provide the basis for predicting received levels at whale locations during the behavioral observations.

A significant result of comparing the scaled data is their consistency, both across years of the test and across source types. This suggests, primarily, that the acoustic bottom conditions are relatively homogeneous over the test area. Data collected with single-frequency tones were reasonably consistent with those from broadband sources, including frequency sweeps and recorded broadband noise from a drilling platform, especially when allowance was made for frequency averaging of data from the latter sources. The standard deviation of the differences between the model and the propagation measurements is estimated to be ~4 dB over the band from 50 to 1000 Hz for the broadband sources. For reasons to be expected, the corresponding value for the tone data is higher, varying from ±6 to ±8 dB over the same band. The behavioral experiments used broadband signals for playbacks so the smaller value (±4 dB) is most relevant in their interpretation.

In comparing the predicted levels during the disturbance tests with the levels measured by sonobuoys, it was learned that measured levels on 13 May 1990 were considerably higher at a range of 2 km than the propagation model predicts. The discrepancy is of order 15 dB, well outside the range of uncertainty found during propagation tests. The location of the 13 May 1990 data is also well outside the region sampled by the propagation tests and is in shallower water (Fig. 3.4; *cf* Fig. 2.1). The implication is that the bottom in the vicinity of these anomalous data is much more reflective than is the bottom over the area of the propagation tests. Drawing on work summarized by Miles et al. (1986, 1987), discussing evidence for relic permafrost and overconsolidated sediments, computations of propagation loss with the Finite Element Parabolic Equation model helped make plausible the possibility that such material is responsible for the observed behavior. The composition of the sea floor in this region has probably been documented by seismic exploration activities on behalf of the oil and gas industry, but much of this information is privately owned and not available. U.S. Geological Survey personnel (P. Barnes, pers. comm.) indicated that they have no specific data for the 13 May 1990 site but agreed that the occurrence of relic permafrost in the general area would not be surprising.

In view of the likely existence of relic permafrost in shallower regions than those in which the transmission loss tests were conducted, the transmission loss model in Equation (1), with the parameters in Table 4.5, may overestimate transmission loss, and hence underestimate received levels, in regions with relic permafrost.

There are three general influences in the frequency-related behavior of transmission loss. *(1)* As frequency increases, the volume absorption loss increases; transmission loss increases with increasing frequency. *(2)* At the lowest frequencies, for a given source depth, the Lloyd's Mirror effect leads to high transmission loss. As frequency increases, the transmission loss diminishes until a frequency is reached above which the Lloyd's mirror effect is no longer apparent. For the 18-m depths of sources and receivers used during this project, 50 Hz defines the breakpoint. *(3)* Bottom interaction effects are present at both low and high frequencies for the bottom conditions present in most of our operating areas of the Beaufort Sea northeast of Barrow. Transmission loss due to these effects diminishes with increasing frequency up to 100 Hz. Above 200 Hz the transmission loss increases with increasing frequency.

Until now, this project has attempted to average transmission loss over a broad band of frequencies, specifically, 20-1000 Hz. This has been useful for steady, low-frequency, broadband sources of drilling noise like *Karluk*. The model presented in this report differentiates transmission loss by 1/3-octave bands, providing a more realistic representation of actual physical sound transmission in the Beaufort Sea near Pt. Barrow without the complexities of full wave models.

Comparison of the transmission loss model developed in this project with the model developed by BBN Labs for other shallow regions of the Beaufort Sea indicates that the two models are comparable.

Transmission loss measurements in the Chukchi Sea during late winter conditions (heavy ice cover) were reported by Greene (1981). Those measurements were done in water generally 50 m deep. Figure 12 in that report presents curves for transmission loss vs. distance. A band of values is presented for frequencies from 75 to 500 Hz. At distance 10 km (5.4 n.mi. in Greene 1981:Fig. 12), the band extends from 81 to 84 dB. For frequency 200 Hz, depth 50 m, and distance 10 km, the model presented in this report predicts a loss of 88 dB, which is 4 dB higher than the higher value reported by Greene (1981). These results from the Chukchi Sea during March were similar to those from the western Beaufort Sea during late April and May.

4.4 Fidelity of Playbacks to Original Icebreaker Sound

How similar to the original icebreaker sound was the playback sound? To the human ear, sounds received with hydrophones anywhere from a few meters to 1 or 2 km from the projectors had the distinctive quality of the original icebreaker sounds. With increasing distance from the projectors, the icebreaker sound became less dominant, and natural sounds, e.g. bearded seal calls, became more evident. This would also occur with increasing distance from the actual icebreaker, but the actual icebreaker sound would dominate the ambient noise out to a considerably longer range because of its higher source level. The major differences between the playback sounds and the actual icebreaker were (1) the overall playback source levels were weaker than the actual icebreaker source levels (median difference 34 dB over the 40-6300 Hz frequency band), and (2) the playback sounds were comparatively weak at frequencies below 40 Hz (median difference of 63 dB in the source level at 20 Hz). However, as is explained in this section, the importance of the low frequencies diminishes with increasing distance because of high sound transmission loss at frequencies below 50 Hz.

It was important to obtain quantitative measures of the similarities and differences between the playback sounds and the actual icebreaker sounds. There are at least two levels of comparison: (1) how like the original taped sound (as received and recorded 460 m from the icebreaker) was the playback sound in the water (i.e., how like the lower distribution in Fig. 4.25); and (2) how like the "free-field" source level computed for the icebreaker was the playback sound in the water (i.e., how like the upper distribution in Figure 4.25). We have chosen to make the latter comparison, although we are at an immediate disadvantage in that the lowest frequencies, those below 50 Hz especially, were differentially attenuated by propagation effects at the recording site. Nevertheless, in an ideal experiment, the low frequency recorded sounds would have been differen-

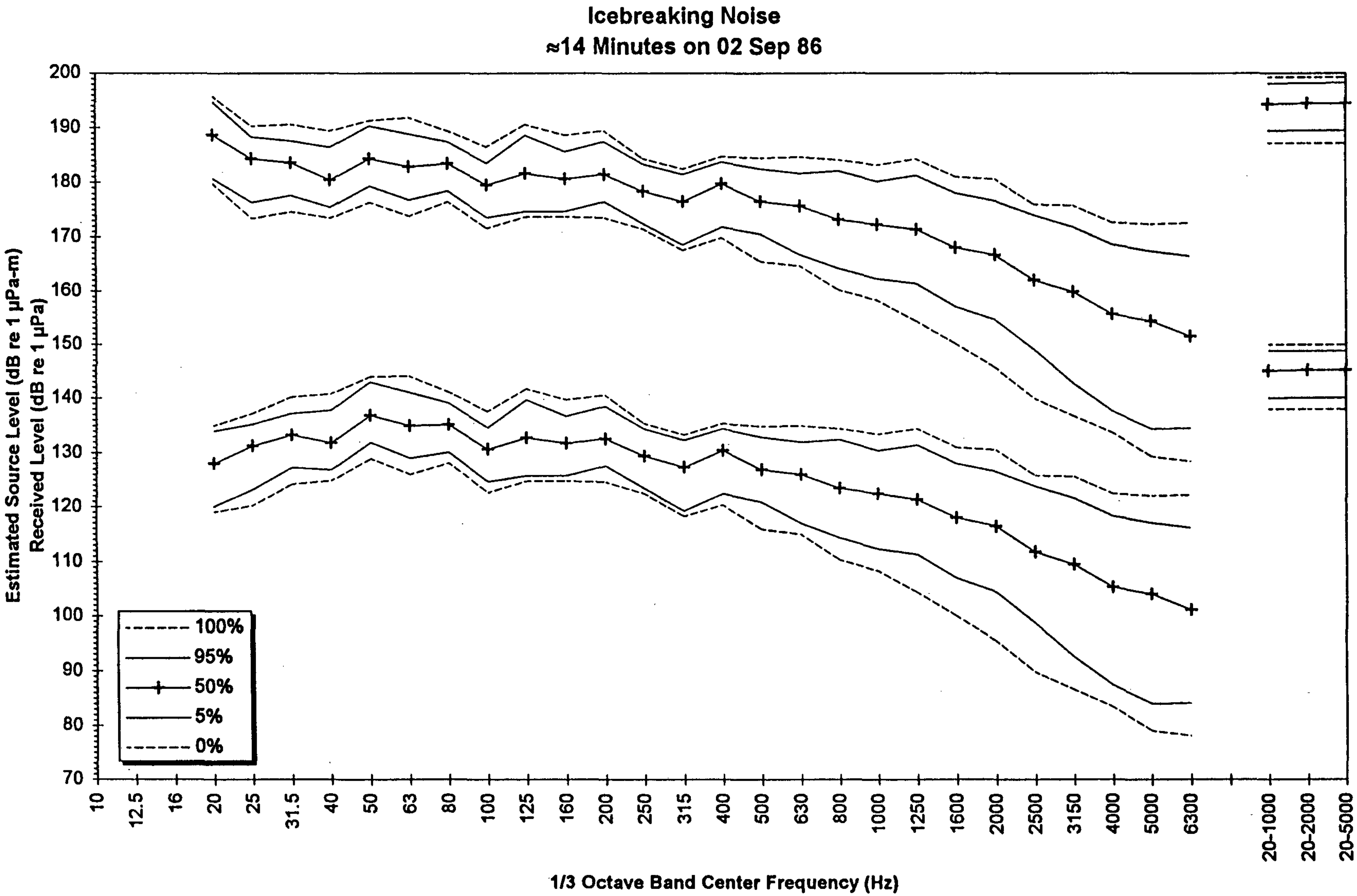


FIGURE 4.25. Distributions of received levels (460 m range, lower set of curves) and estimated source levels (upper curves) for the icebreaker *Robert Lemeur*, by 1/3-octave band center frequency; levels for three broad bands are also shown at right. The five curves show the minimum, 5th percentile, median, 95th percentile and maximum levels in each band over the 14-min period. These distributions were computed from the 14+ minute recording of Greene (1987a:48*ff*).

tially boosted to reproduce the hypothesized icebreaker source sounds. (This was not done because the playback transducers are inherently poor at reproducing those low frequencies.)

The monitor hydrophone sensed the sound field near the projector during all experiments and permitted computing the actual transmitted source levels for each 1/3-octave band. Knowing the actual source levels at an instant of time, and knowing where in the 14-min playback sequence that instant of time is (Fig. 4.26), it is possible to calculate the distribution of 1/3-octave band levels corresponding to the projector settings in use. Our playback fidelity test is to compare transmitted distributions with the source distribution in Figure 4.25.

For each day of playback experiments, a time or times were selected when whales were observed. For each such time, the corresponding playback source level distribution was calculated from the sound exposure level program. The median predicted source levels were subtracted from the median standard *Robert Lemeur* source level distribution shown in Figure 4.25 and the results were plotted (Fig. 4.27-4.34). As expected, the overall source levels are lower than the original and the low frequencies differ the most.

These figures are important. Note that the differences, although graphed for distance 1 m, apply at *all* ranges. At any range, the sound level difference between the actual icebreaker and the playback sound is the same as at 1 m. This occurs because the transmission loss would be the same for the actual icebreaker as for the playback, given that the acoustic propagation path and frequency are the same.

These differences in median levels varied by day, and sometimes by time of day, because of the different transducer/amplifier settings. Table 4.8 summarizes differences in level between the actual icebreaker and the playback, by 1/3-octave band, over the frequency range 40-6300 Hz.

TABLE 4.8. Comparison of playback vs. actual icebreaker sound levels for the 1/3-octave bands centered at 40-6300 Hz. The "Deviation from Flat" column applies across the 40-6300 Hz band of frequencies.

	Median Differences (dB)			
Date & Time	Minimum	Average	Maximum	Deviation from Flat
17 May 91 17:41	39	44	58	±9.5
7 May 94 18:04	43	47	54	±5.5
7 May 94 18:59	13	24	33	±10.0
9 May 94 16:40	24	37	51	±13.5
14 May 94 17:37	28	38	49	±10.5
16 May 94 14:25	20	25	31	±5.5
17 May 94[a] 14:49	15	32	60	±22.5
20 May 94 15:39	10	20	26	±8.0

[a] Low frequency components not projected on this date.

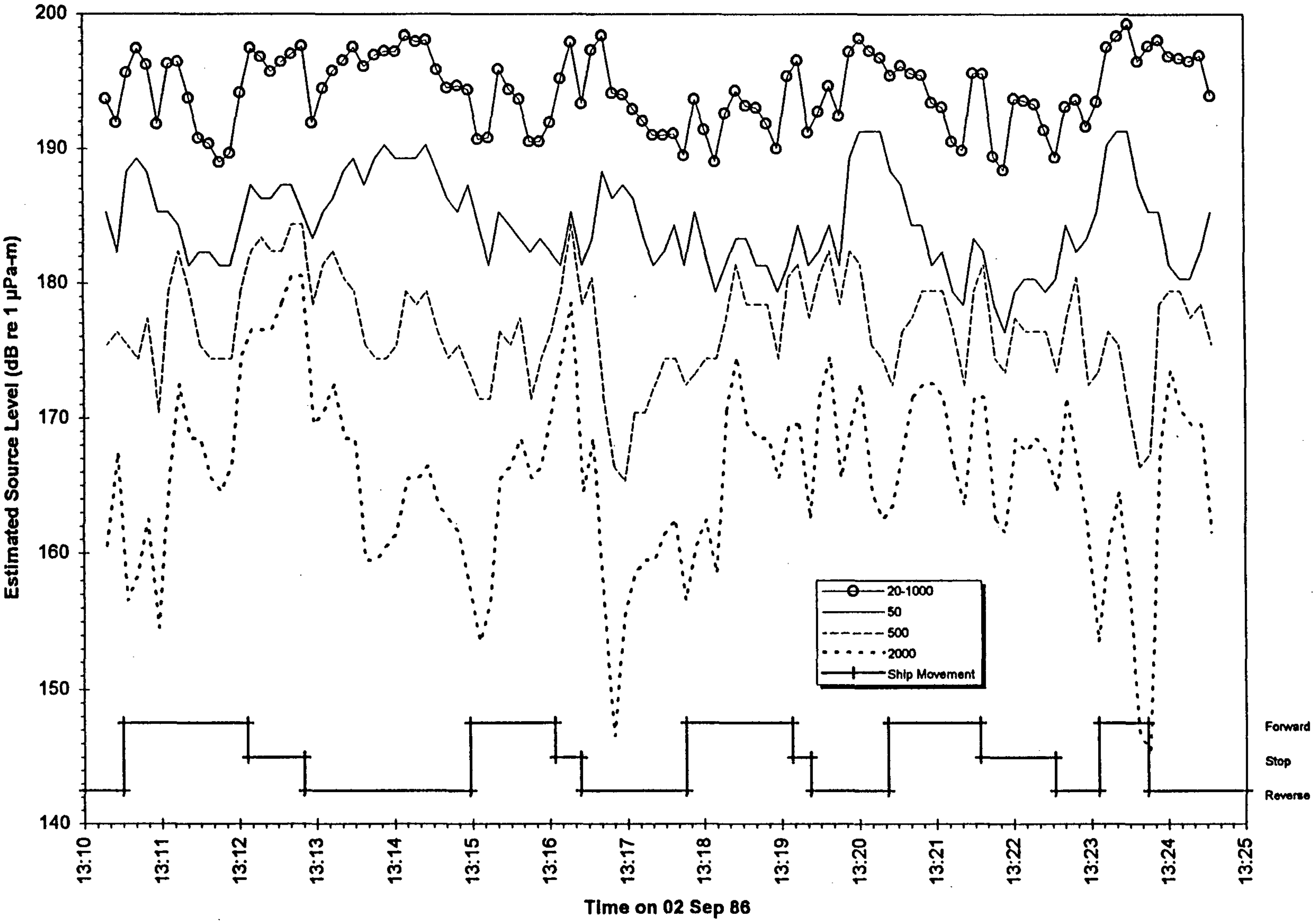


FIGURE 4.26. Variability of estimated source levels for the icebreaker *Robert Lemeur* over the 14+ min recording time at the Corona drillsite in 1986, considering the 20-1000 Hz band level and 1/3-octave band levels centered at 50, 500 and 2000 Hz. The original received level data at distance 460 m came from measurements described in Greene (1987a:44*ff*).

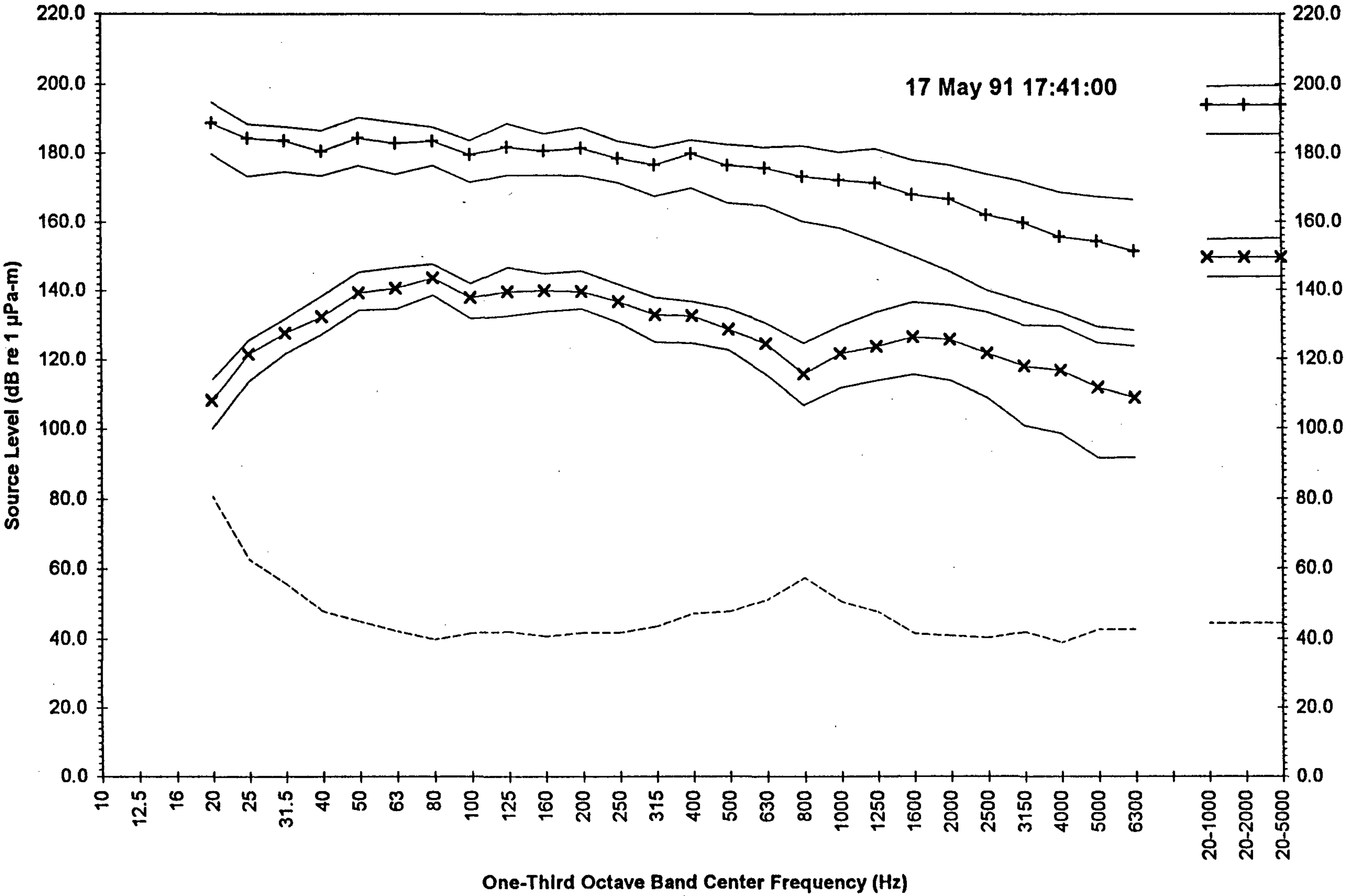


FIGURE 4.27. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (three curves at top) and the J-13/F-40 projector system used on 17 May 1991 (three curves at middle), by 1/3-octave band and for three broad bands. Curves show the 5th, 50th, and 95th percentiles for distance 1 m. The projector source level is based on measurements made at 17:41:00 but is applicable for the periods when whales were seen on that date. The bottom curve is the difference between the two medians, and is the same at all ranges because transmission loss would be the same for the icebreaker and the projector sounds.

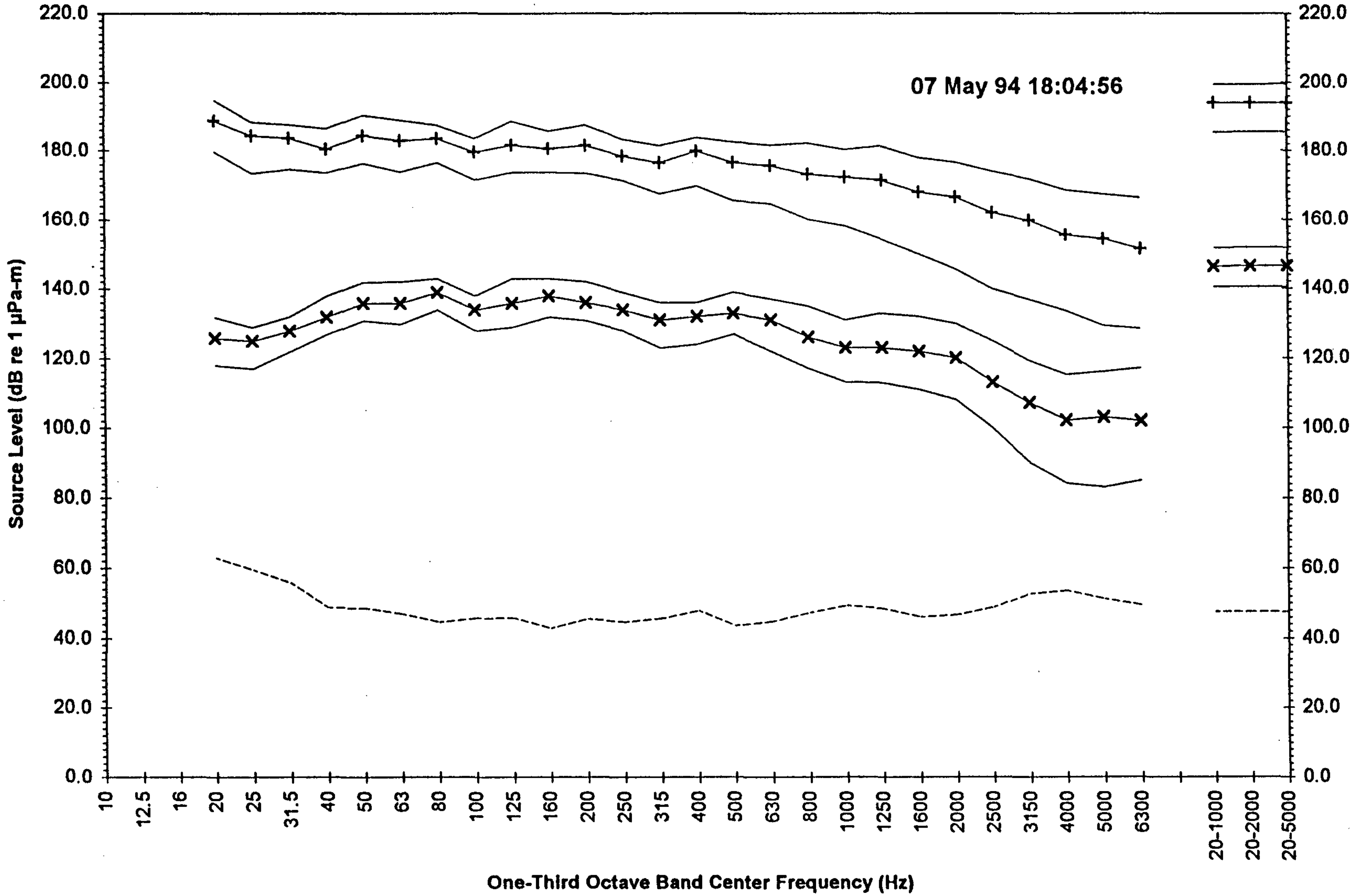


FIGURE 4.28. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the Argotec 220/J-11 projector system used on 7 May 1994 (middle). Levels increased shortly after 18:04:56. Otherwise as in Fig. 4.27.

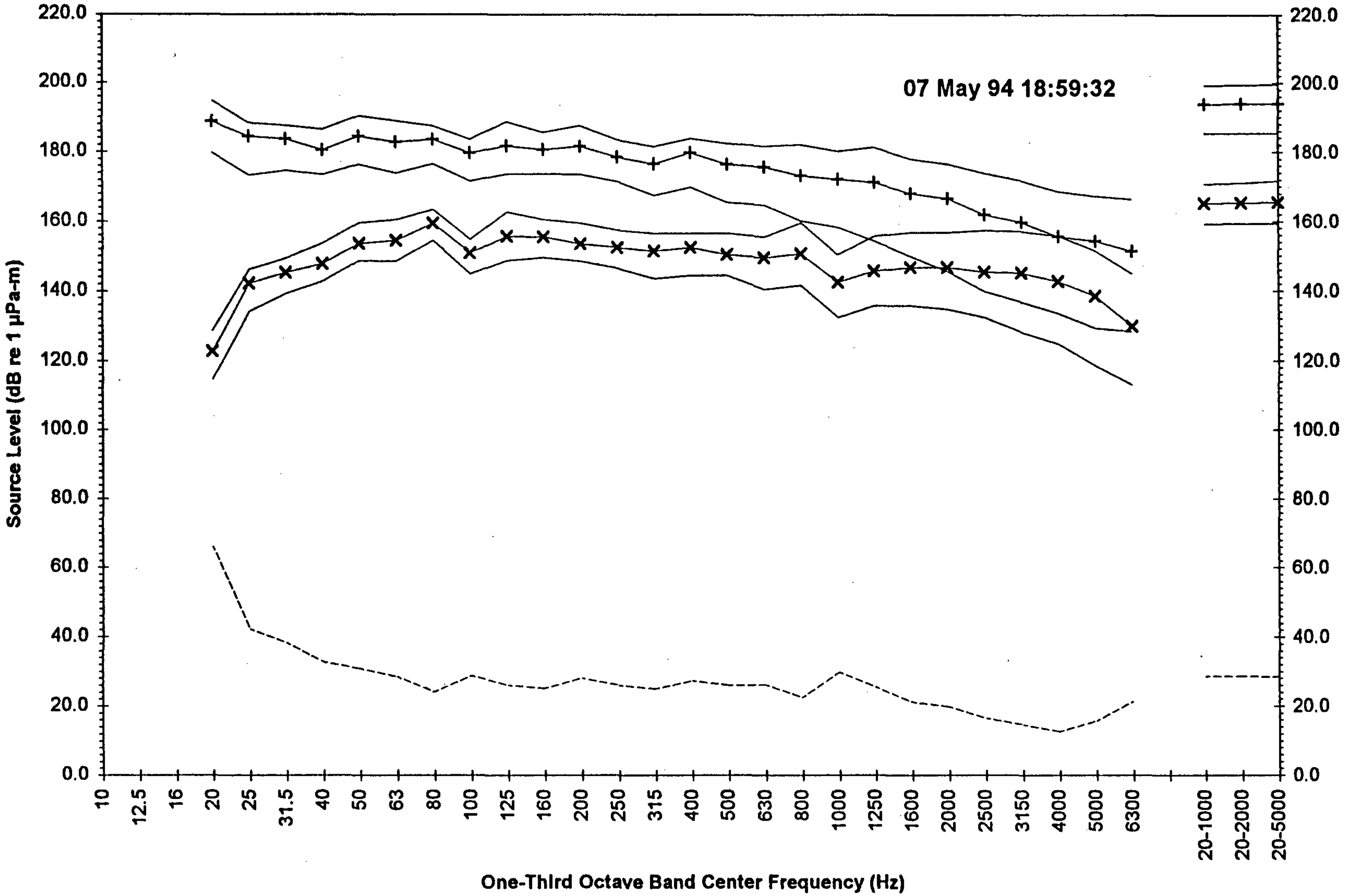


FIGURE 4.29. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the Argotec 220/J-11 projector system used on 7 May 1994 (middle). Projector source level is for 18:59:32, after the projector output was increased, and is applicable for later periods on that date. Otherwise as in Fig. 4.27.

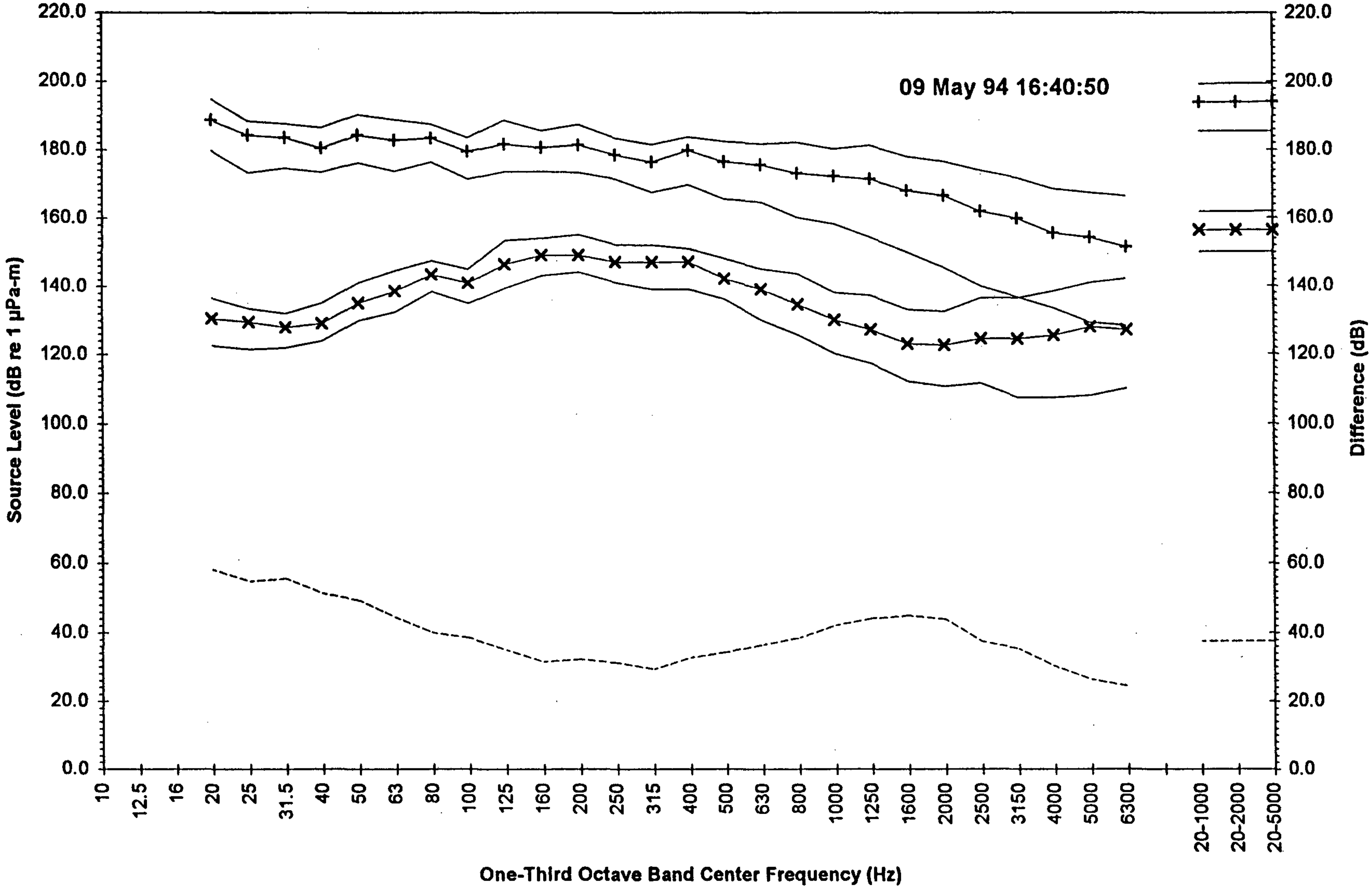


FIGURE 4.30. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the J-11 projector system used on 9 May 1994 (middle). Projector source level at 16:40:50 is applicable for periods when whales were seen on that date. Otherwise as in Fig. 4.27.

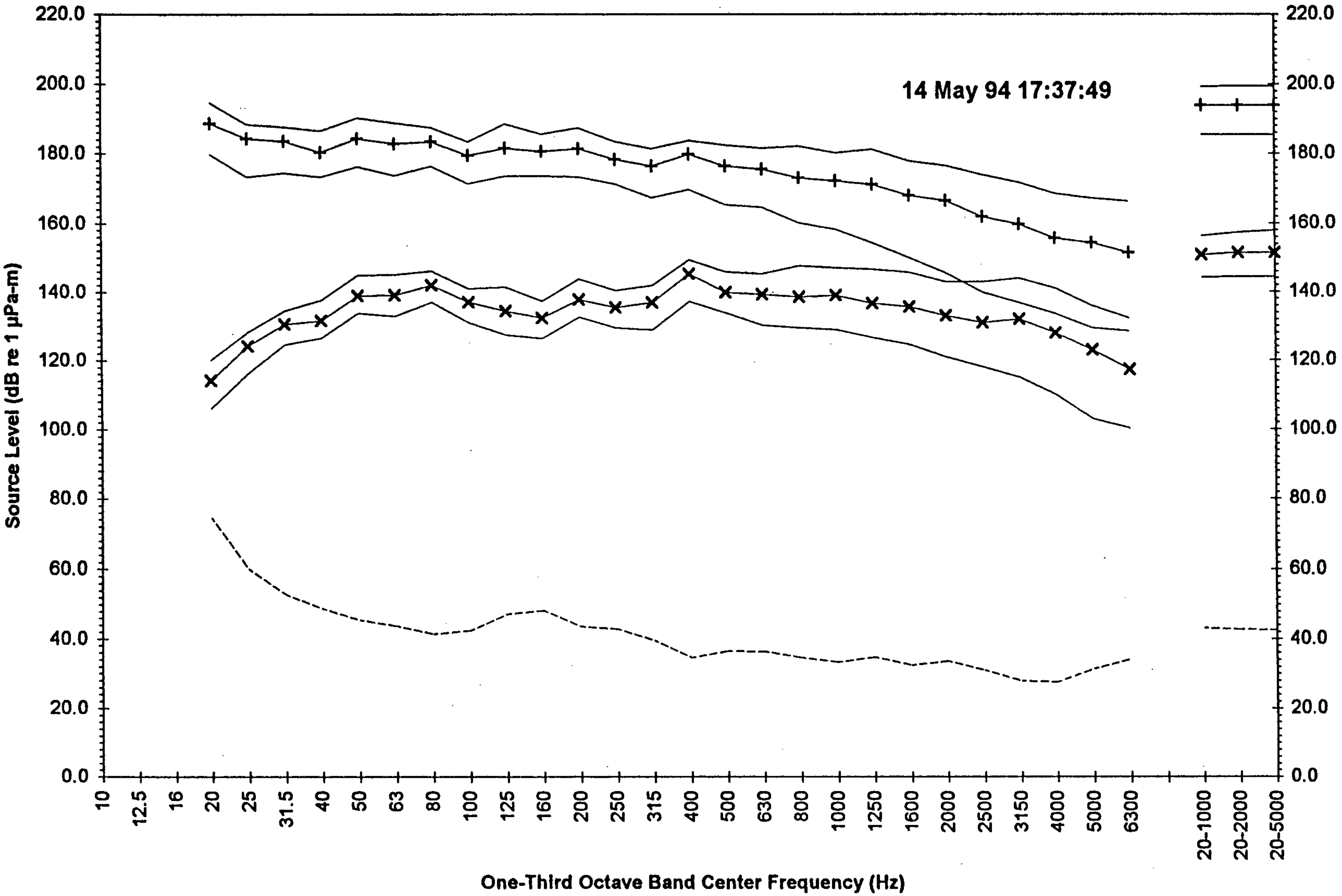


FIGURE 4.31. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the Argotec 220/J-11 projector system used on 14 May 1994 (middle). Projector source level at 17:37:49 is applicable for periods when whales were seen on that date. Otherwise as in Fig. 4.27.

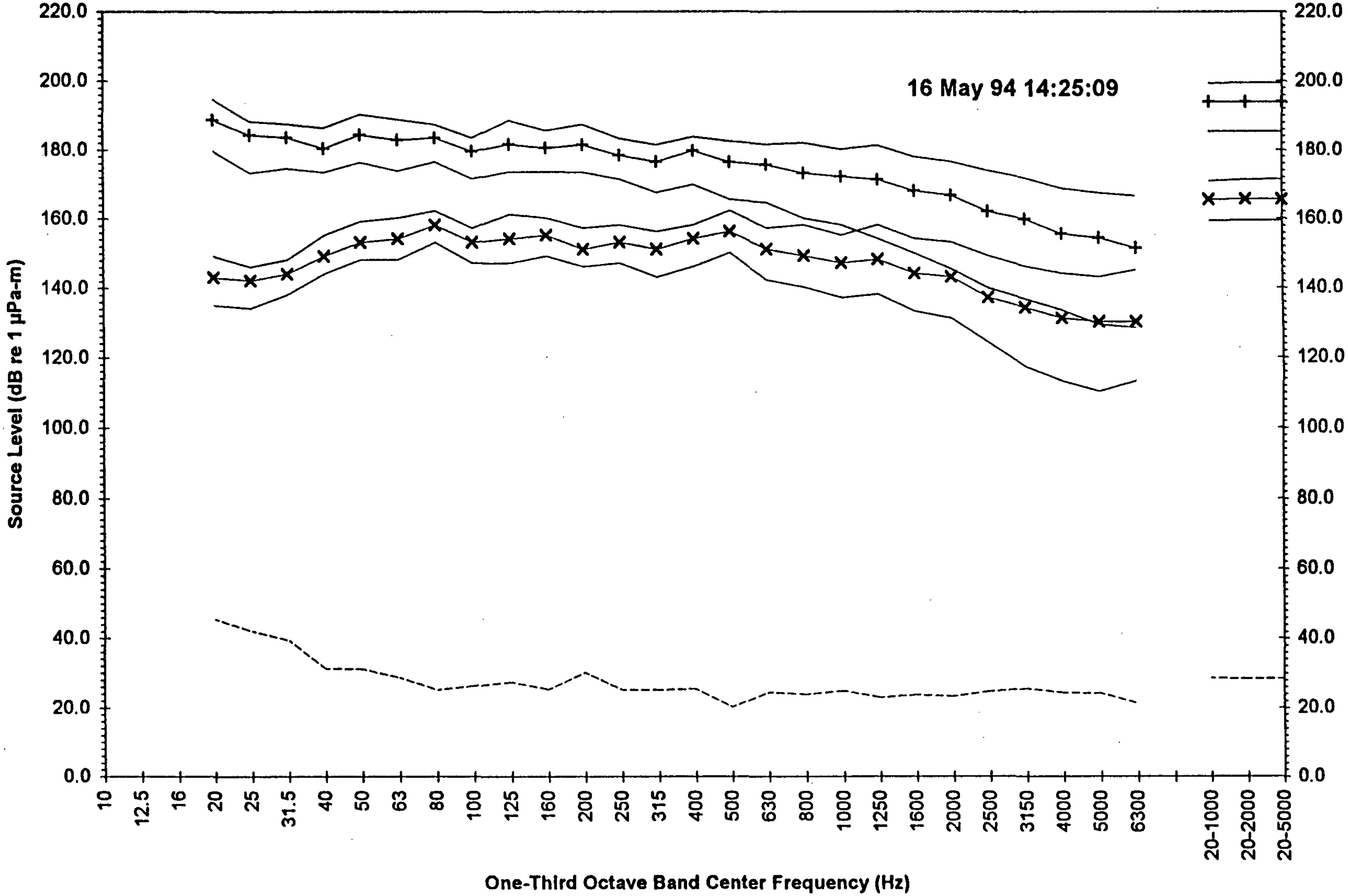


FIGURE 4.32. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the Argotec 220/J-11 projector system used on 16 May 1994 (middle), by 1/3-octave band and for three broad bands. Projector source level at 14:25:09 is applicable for periods when whales were seen on that date. Otherwise as in Fig. 4.27.

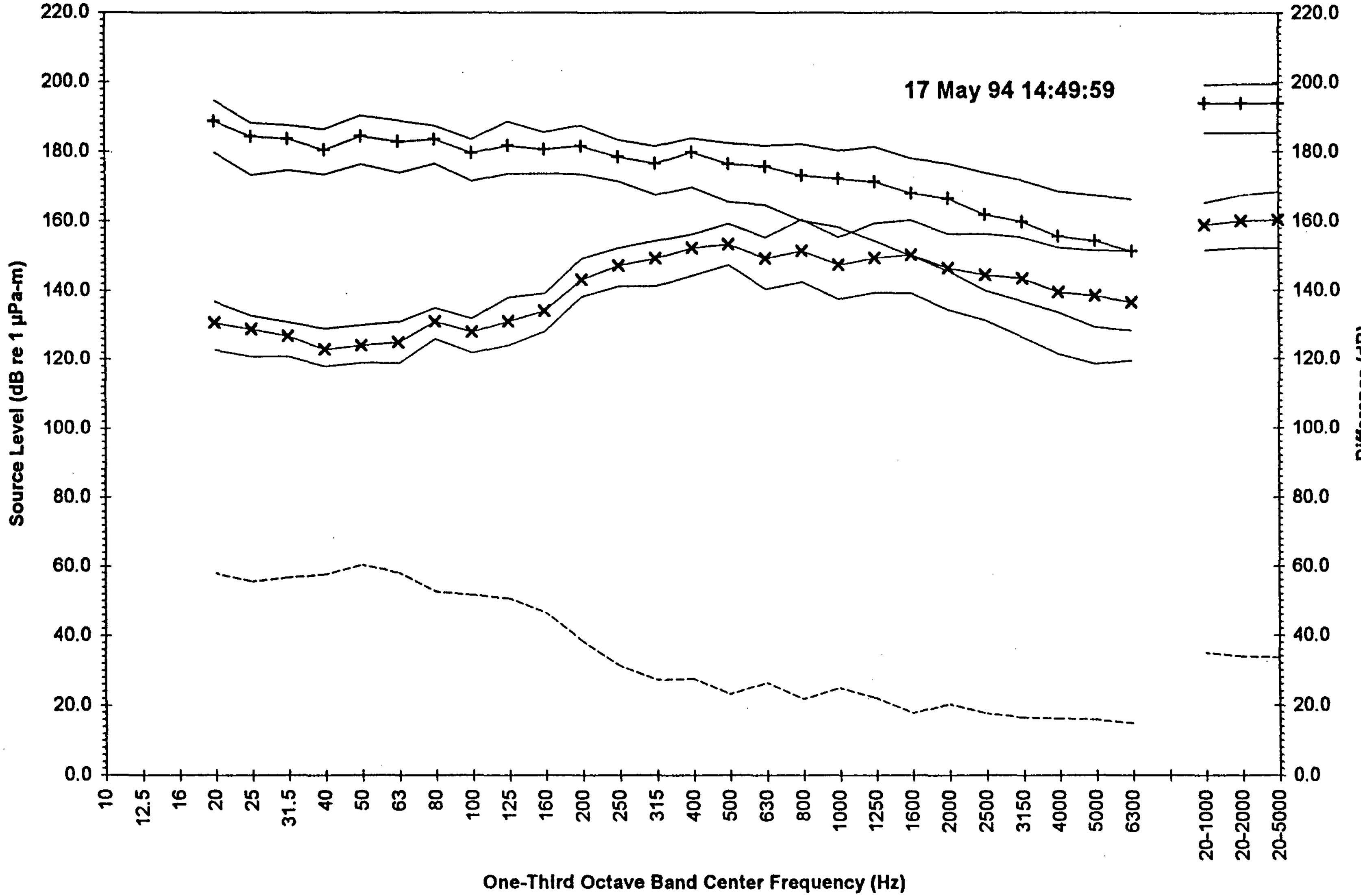


FIGURE 4.33. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the J-11 projector system used on 17 May 1994 (middle), by 1/3-octave band and for three broad bands. Projector source level at 14:49:59 is applicable for periods when whales were seen on that date. The model 220 low frequency projector was inadvertently disconnected, accounting for the low levels, especially below 500 Hz. Otherwise as in Fig. 4.27.

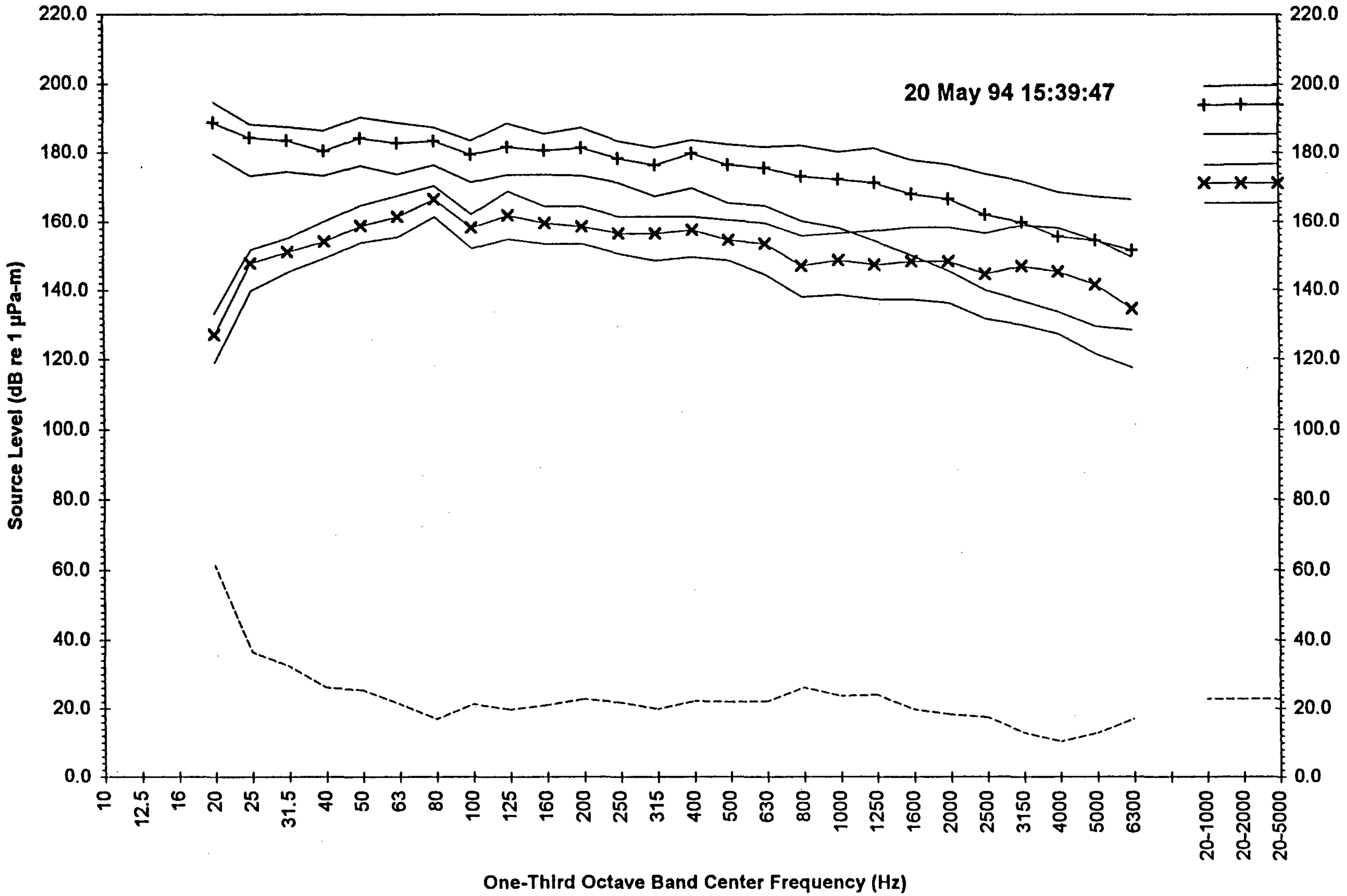


FIGURE 4.34. Radiated source levels of icebreaker sound from icebreaker *Robert Lemeur* (top) and the Argotec 220/J-11 projector system used on 20 May 1994 (middle), by 1/3-octave band and for three broad bands. Projector source level at 15:39:47 is applicable for periods when whales were seen on that date. Otherwise as in Fig. 4.27.

Over the 40-6300 Hz range of 1/3-octave band levels, the smallest average difference between the medians for the actual icebreaker and the simulated icebreaker was 20 dB on 20 May 1994. On this day, and several others as well, there were times when, at high frequencies, the maximum source level of the icebreaker sound playback slightly exceeded the median source levels emitted by the actual icebreaker. There also were times when the median source level of the ice-breaker playback exceeded the lowest source levels of the actual icebreaker sound. (Note the levels at 2000 Hz and higher in Fig. 4.34, 20 May 1994.) However, for most frequencies at most times, the source level of the playback sound was substantially weaker than that of the actual ice-breaker. The largest average median differences were 47 dB during a period of low-power trans-mission on 7 May 1994, and 44 dB during a transmission when the J-13/F40 projectors were operating on 17 May 1991.

The variability in the median difference with frequency is a measure of the departure from a desirable "flat" amplifier/projector response. This variability resulted from equipment limitations and non-optimum adjustments of the equalizers and amplifier gains for the various projectors. The least variability (flattest response) is seen in Figure 4.28 (low level on 7 May 1994 at 18:04) and Figure 4.32 (16 May 1994). On those occasions the range between the highest and lowest differ-ences was 11 dB. In reports on the fidelity of loudspeakers in air, this result would be described as "within ±5.5 dB of flat from 40 to 6300 Hz". Variability ranged between 16 and 27 dB (i.e. ±8 to ±13.5 dB) on the other days, as shown in the "Max-Min" column of Table 4.8, neglecting 17 May 1994 when the low frequency components were not projected.

Because the playback source level was, on average, some 20-47 dB less than the source level of the actual icebreaker over the 40-6300 Hz band, the received level at any given distance was correspondingly lower during playbacks than it would have been if the actual icebreaker were operating at those sites. Another way to describe this is that a given received level of icebreaker sound would be found much closer to the playback site than to the actual icebreaker. Some specif-ic examples of received level vs. range for playbacks vs. the actual icebreaker are given in §6.4 and §7.3 (Fig. 6.22, 6.23, 7.16, 7.17).

Summarizing, over the frequency range 40-6300 Hz, the median playback source level was 34 dB less than the actual icebreaker source level (0.04% of the acoustic power). The median deviation from a flat frequency response across the 40-6300 Hz range was ±10 dB. The differ-ences in source level at frequencies below 40 Hz increased with decreasing frequency to a median difference of 63 dB at 20 Hz.

What is the importance of the acoustic power at low frequencies relative to the power in the entire frequency band 20-6300 Hz? The answer depends on distance from the source, as the rate of attenuation of sound with distance is frequency-dependent. To calculate a quantitative answer, the 95th-percentile 1/3-octave band levels for the actual icebreaker at 20-6300 Hz were converted to "power" (μPa^2) and summed to compute the cumulative distribution of sound power with fre-quency (Table 4.9). For water depth 41 m and distance 1 m (the reference distance for the ice-breaker source levels), 45% of the power occurs in the 1/3-octave bands centered at 20-40 Hz, i.e. in the 18-45 Hz band. At increasing distances, the percentage decreases: 18% at 50 and 100 m, 17% at 1000 m, 14% at 3000 m, and 6.5% at 10,000 m. Thus, because sound propagation in shallow water is poor at frequencies below 50 Hz, the importance of the low frequencies diminishes with increasing distance. Given the distances from the projectors at which most bowhead whales were observed (§6), the 50 m to 3000 m values are the most relevant ones in judging the fidelity of the playbacks. At 50 to 3000 m range from the actual icebreaker, 18 to 14% (respectively) of the power would be in the 18-45 Hz band. In contrast, only a negligible proportion of the acoustic power in the playbacks (<<1%) was at 18-45 Hz.

TABLE 4.9. Cumulative distributions of the 95th-percentile sound power from the actual icebreaker by 1/3-octave band for six distances from the source. The transmission loss effects were computed by the model described in §4.3 (p. 96*ff*) for water depth 41 m, the median depth for the playback tests conducted in 1991/94.

1/3 OB Frequency (Hz)	Percentage of Energy At or Below Each Frequency at Six Distances					
	1 m	50 m	100 m	1000 m	3000 m	10,000 m
25	35.1	6.3	6.3	5.7	4.4	1.5
31.5	40.6	11.8	11.8	10.9	8.9	3.4
40	44.9	18.1	18.1	17.0	14.4	6.5
50	55.2	38.1	38.1	37.0	33.7	19.7
63	62.6	50.8	50.8	50.2	47.4	32.2
80	67.9	58.8	58.8	58.5	57.2	44.2
100	70.1	61.6	61.6	62.0	61.1	50.4
125	77.0	70.6	70.7	72.1	73.5	70.3
160	80.5	75.1	75.2	77.2	79.7	80.2
200	85.8	81.9	82.1	84.8	89.1	95.2
250	87.9	84.6	84.8	87.6	92.1	98.0
315	89.3	86.4	86.5	89.3	93.6	98.9
400	91.5	89.3	89.4	91.9	95.6	99.5
500	93.2	91.4	91.5	93.7	96.8	99.7
630	94.6	93.2	93.3	95.1	97.7	99.8
800	96.1	95.1	95.2	96.6	98.5	99.9
1000	97.1	96.4	96.5	97.6	99.0	100
1250	98.4	98.0	98.1	98.7	99.5	100
1600	99.0	98.8	98.8	99.2	99.7	100
2000	99.5	99.3	99.3	99.6	99.9	100
2500	99.7	99.6	99.6	99.8	99.9	100
3150	99.8	99.8	99.8	99.9	100	100
4000	99.9	99.9	99.9	99.9	100	100
5000	100	100	99.9	100	100	100
6300	100	100	100	100	100	100

4.5 Do Bowhead Calls Contain Infrasonic Components?

Data on the possibility that bowhead calls contain infrasonic components are relevant in evaluating the significance of industrial infrasounds to bowheads (see specific objective 5, p. 7). All bowhead calls recorded during ambient noise recordings in 1991 were analyzed for infrasonic energy content. Waterfall spectrograms were computed for 45 samples of recorded signals. These 45 spectrograms contained ~73 calls, of which 11 occurred coincidentally with infrasonic energy. Figure 4.35 shows two spectrograms and five calls without perceptible infrasonic components. Figure 4.36 shows two spectrograms and three (or possibly four) calls, of which at least one occurs with infrasonic energy. Figure 4.37 shows two more spectrograms with infrasonic energy associated with bowhead calls.

Of 45 calls recorded in the spring of 1990 and analyzed in a similar way, one call was associated with the occurrence of infrasonic energy (Richardson et al. 1991a:91-96).

Simultaneous arrival at the hydrophone of a bowhead call and an infrasonic signal does not prove that the infrasonic component came from the calling whale. However, it is possible that at least some of the cases listed above did represent bowhead calls with infrasonic components. This possibility could be tested more readily in a study employing widely-spaced hydrophones to localize calling whales (e.g., Cummings and Holliday 1985; Clark et al. 1986; Greene 1987a). If whale calls and infrasonic signals are received simultaneously from the same location, this would provide much stronger evidence that some bowhead calls include infrasonic components. Use of widely-spaced hydrophone arrays was not logistically feasible during this study.

4.6 Generator Noise

Underwater noise arising from use of a generator at the ice camp was a concern during every field season. The generator was necessary for prolonged operation of the power amplifiers that drove the projectors. The generator was also operated during most periods when the projectors were silent. This was done to ensure that the presence or absence of the projected sound was the only difference between playback and "control" periods.

Results

In 1989-90 the 2.2 kw generator operated on the snow-covered ice; it was supported by four rubber pads. When the projector was not operating, generator noise was detected underwater at distances as far as 400 m from camp, depending on ambient noise conditions. The noise was manifested by tones at a nominal fundamental frequency of 60 Hz and integer multiples thereof. (The actual fundamental frequency depended on the generator speed, but was usually within 3 Hz of 60 Hz.) The received levels were weak compared to the projected sound levels at those frequencies. However, in the absence of playbacks the generator tones were audible at range 100 m and sometimes at 400 m (Richardson et al. 1990a:97*ff*, 1991a:98*ff*).

In 1991, at the suggestion of A. Milne (then-Chairman of the project's Scientific Review Board), the generator was suspended by bungee cords from a PVC pipe frame whose four legs

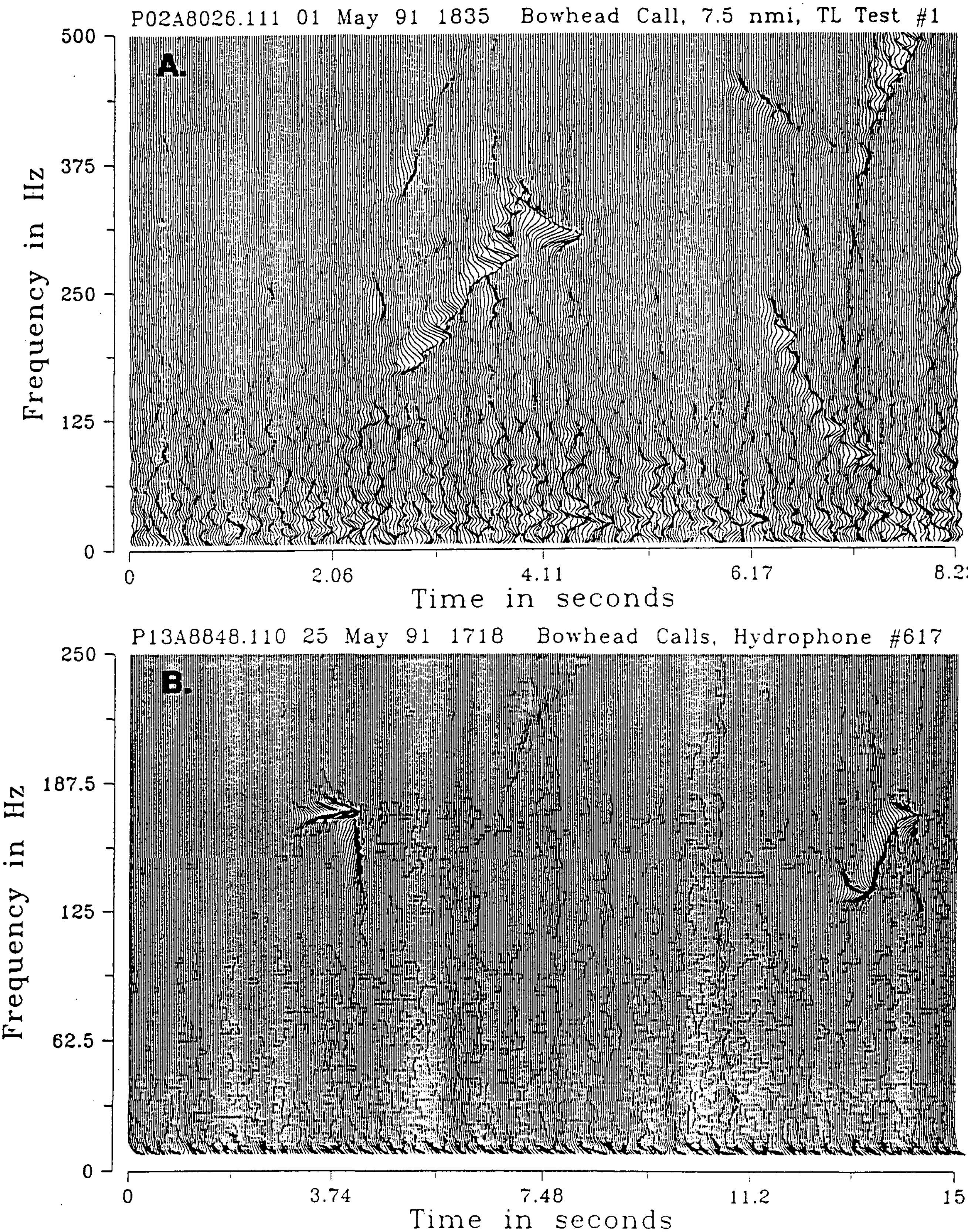


FIGURE 4.35. Waterfall spectrograms of bowhead calls without perceptible infrasonic components. *(A)* shows three calls; *(B)* shows two calls.

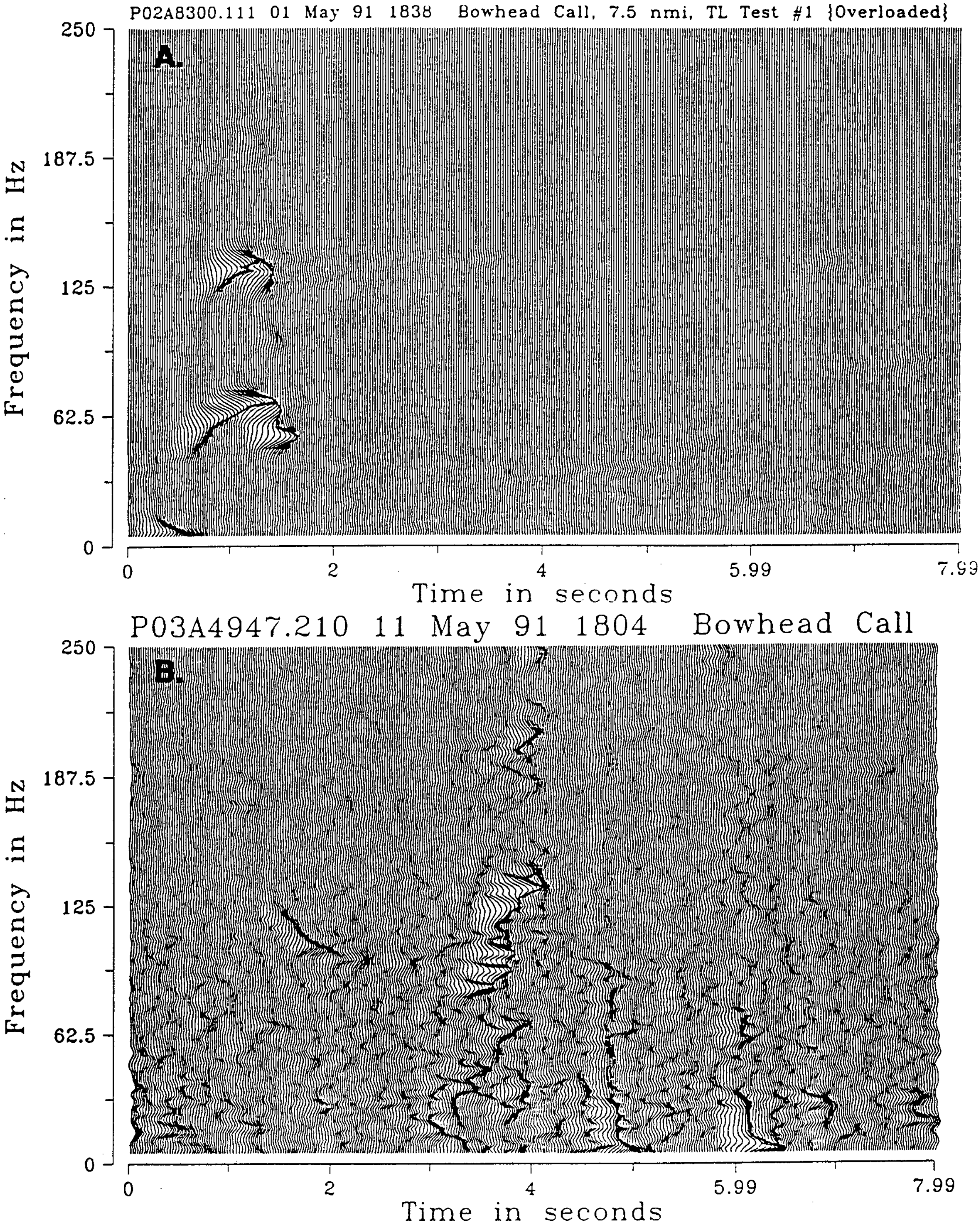


FIGURE 4.36. Waterfall spectrograms of bowhead calls with possible infrasonic components. *(A)* shows one call. *(B)* shows two calls, the second of which—at time 3-4 s—has associated infrasonic energy. A third possible call in (B) at time 6 s has energy only at frequencies below 30 Hz; it cannot be proven that this sound is from a bowhead.

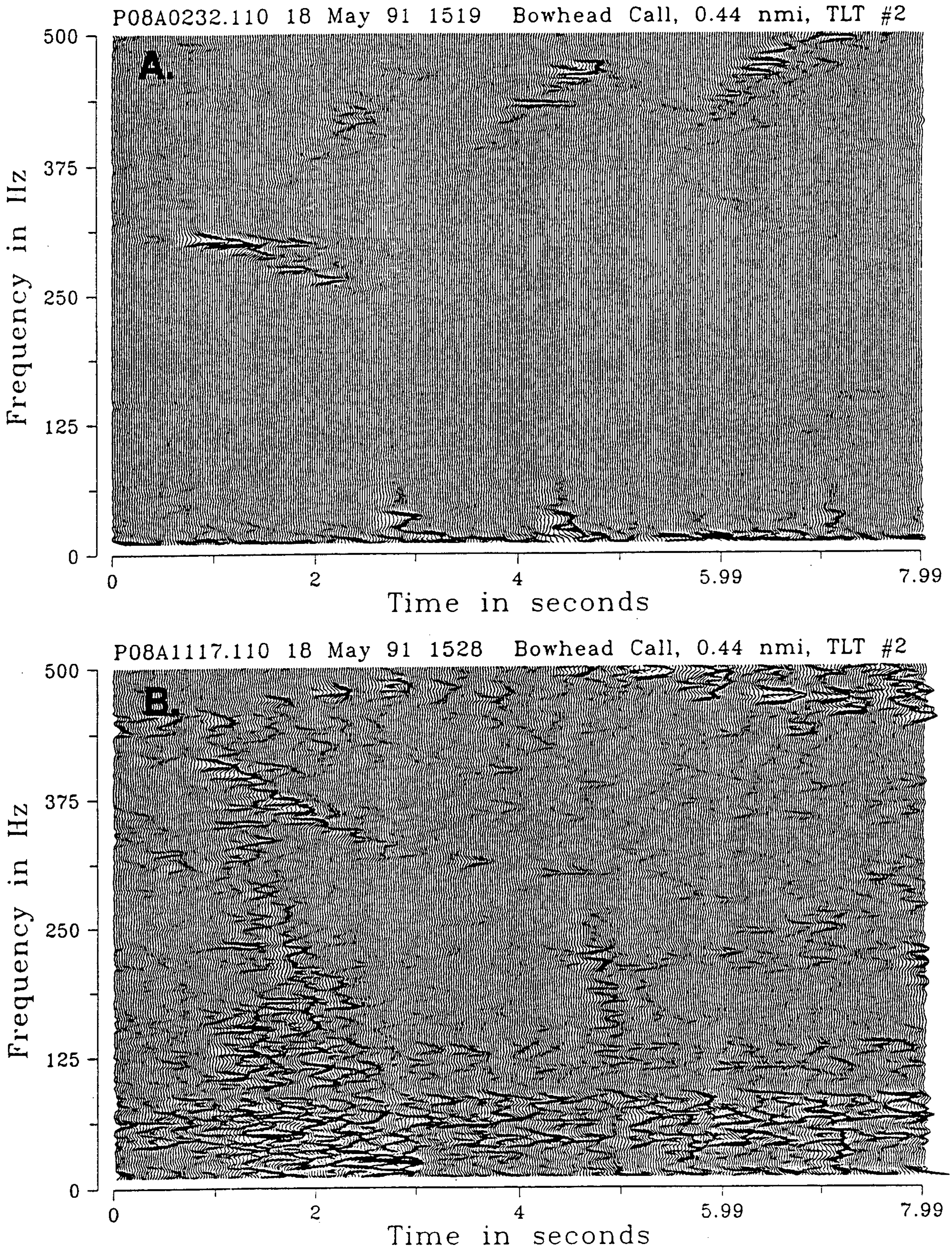


FIGURE 4.37. Waterfall spectrograms of bowhead calls with possible infrasonic components. *(A)* shows three calls, at 1, 4.5 and 7 s; infrasonic energy appears at 3 and 4.5 s. *(B)* shows two or three calls, at 1.5, 4.8 and possibly 8 s, with infrasonic components at 1.5-3 s.

stood on the ice. No part of the generator touched the ice. Background noise recordings with and without the generator running were made at ranges 0.1-1 km during each transmission loss experiment. The generator sounds were not audible, nor was any change in the background noise audible at any range, when the generator was started or stopped. Underwater sound spectra from depth 18 m were computed for the different ranges but no tones that could be associated with the generator were evident. For example, Figure 4.38 shows the spectra of the noise received at range 100 m, generator on and off, during each of the four transmission loss experiments in 1991. The peaks in the noise spectra do not occur at multiples of 60 Hz or show any other features that might be attributable to the generator. Thus, the suspension system adopted in 1991 successfully isolated the generator from the ice and avoided transmission of significant levels of generator sound into the water.

In 1994, it was essential to use a larger generator—5 kw—to power the four power amplifiers needed for the planned projector system. The 1991 PVC frame proved inadequate to support the heavier machine. A pipe tripod was assembled from which the generator was suspended by bungee cords. However, after the generator had run for an hour or so, the pipe legs melted down into the ice, necessitating repositioning. Sometimes, but not often and never for very long, the generator sagged onto the ice. Thus, there were times in 1994 when generator noise was present underwater near the ice camp. However, the generator noise, when present, was weak and undetectable in the presence of the playback sounds.

Figure 4.39 presents examples of background noise spectra with and without generator noise present in 1994. These examples are taken from recordings of the "ambient noise" hydrophone suspended below the ice camp, depth 18 m, generally within a horizontal distance of 30 m from the generator. The recordings were made while the camp was being disassembled for return to Barrow, just before and just after the generator was shut down. The higher levels at frequencies above 330 Hz at 19:29 on 3 May 1994 are from a bearded seal call, not the generator (Fig. 4.39A). In one case—at 16:03 on 7 May 1994, a prominent tone appears at 180+ Hz (Fig. 4.39B). Weaker peaks appear at frequencies slightly higher than 240 and 300 Hz. These are from the generator. In another case, at 19:47 on 9 May 1994, a 300 Hz tone appears in the noise spectrum, a clear manifestation of generator noise in the background sound (Fig. 4.39C). The peaks in the 18:27 spectrum on 16 May 1994 do not fall on power frequency harmonics and are thought to be normal variability in the ambient noise (Fig. 4.39D).

Discussion

Generator noise was not detectable during playback experiments in any of the four spring seasons. In ambient conditions (no playback) during 1991 the generator was not detectable at distances beyond about 100 m. In 1994, there were short periods during "control" (no playback) conditions when faint generator noise may have been detectable at distances up to 500 m (estimated).

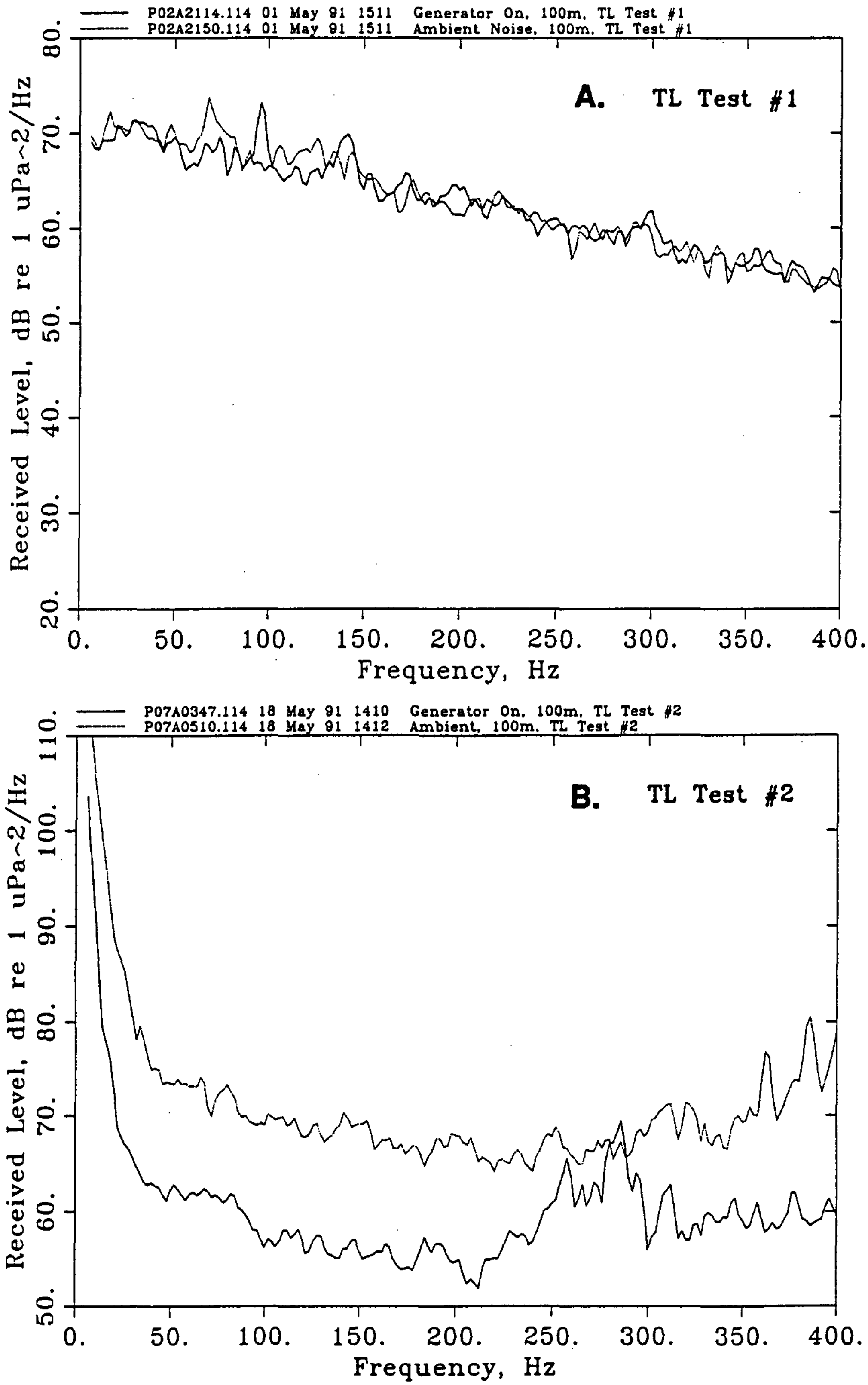
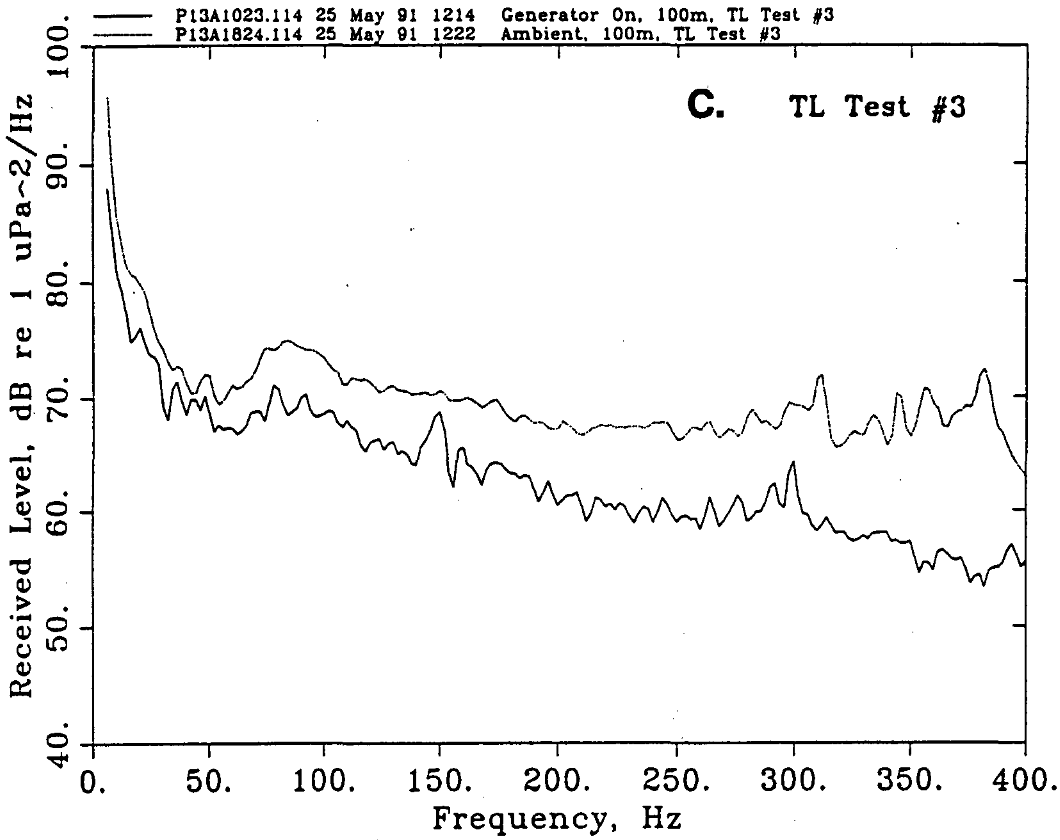


FIGURE 4.38. Paired noise spectra observed 100 m from the ice camp with generator on and off during the four transmission loss tests in 1991. The sound projectors were silent during these measurements.



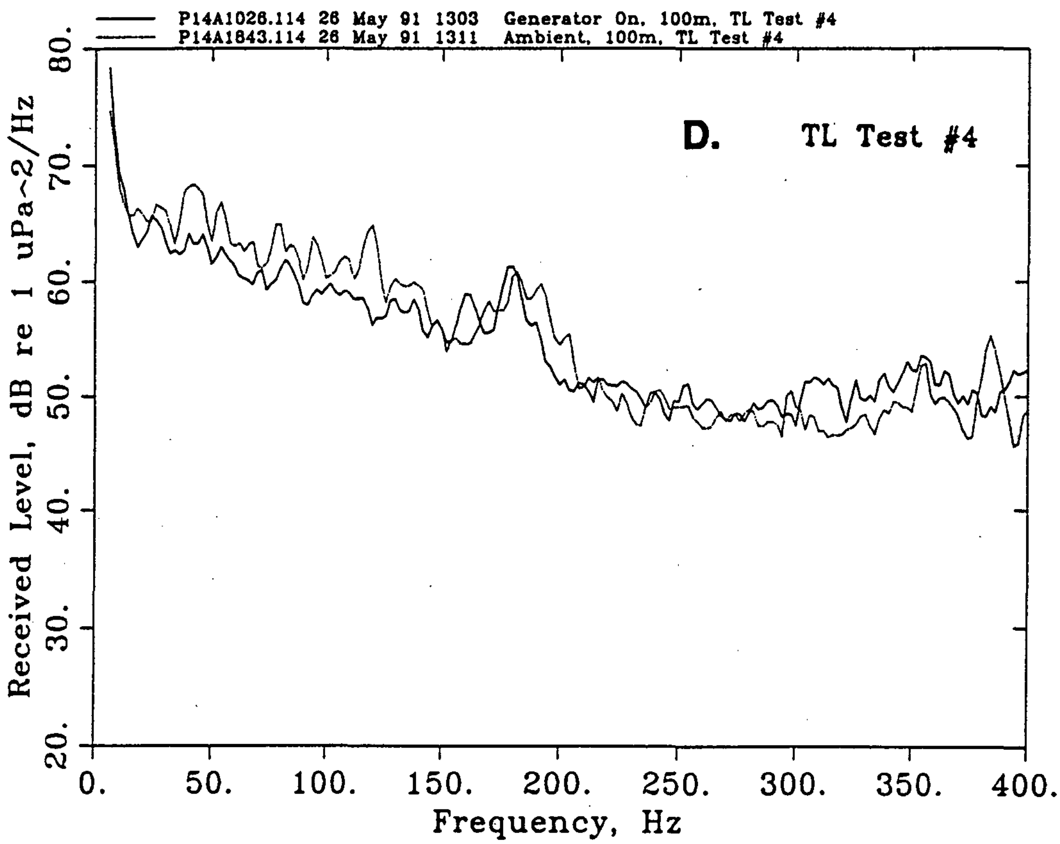


FIGURE 4.38 (continued).

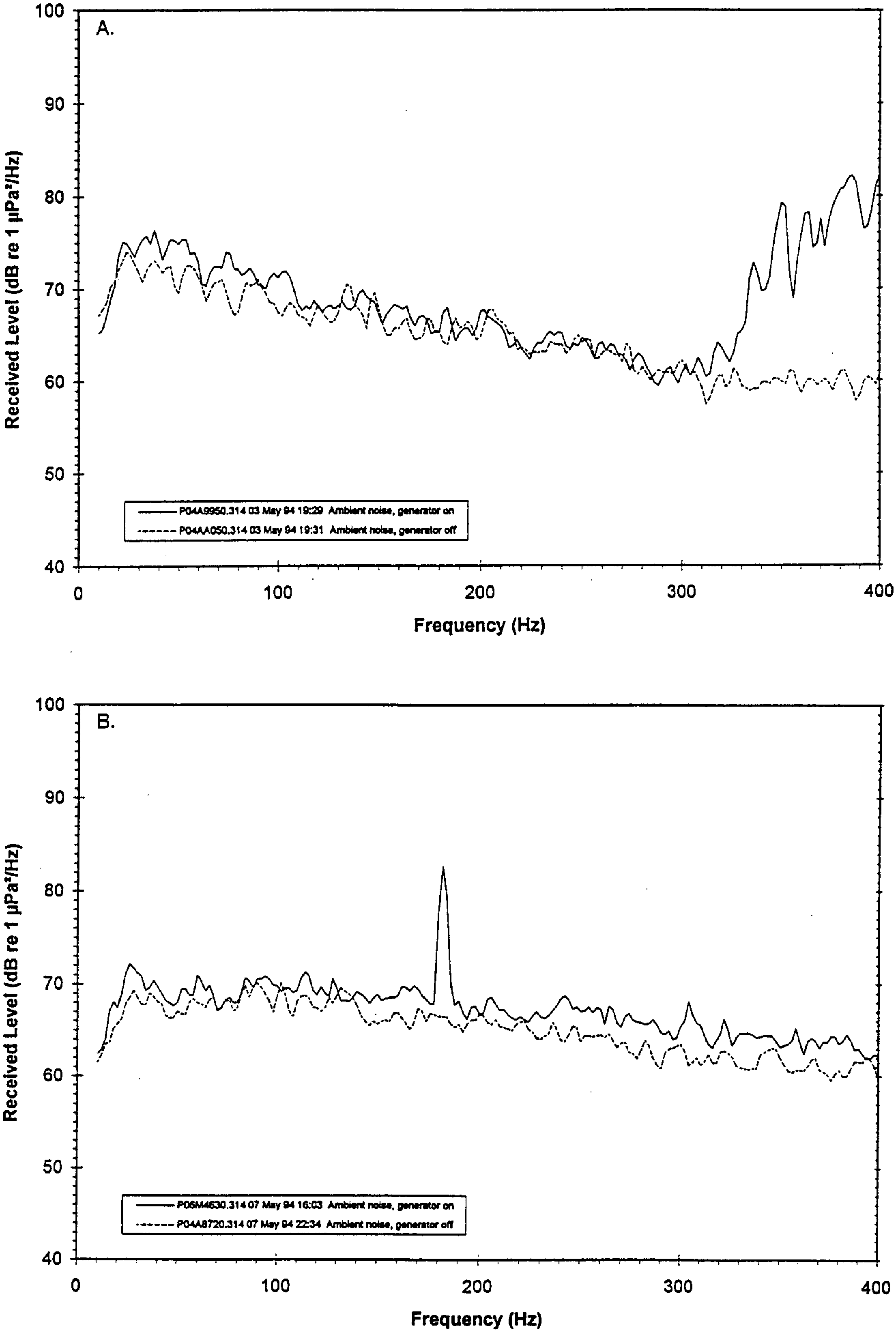


FIGURE 4.39. Paired noise spectra observed at "ambient noise" hydrophone 18 m below the ice camp with generator on and off on four dates in 1994. The sound projectors were silent during these measurements. *(A)* 3 May; *(B)* 7 May.

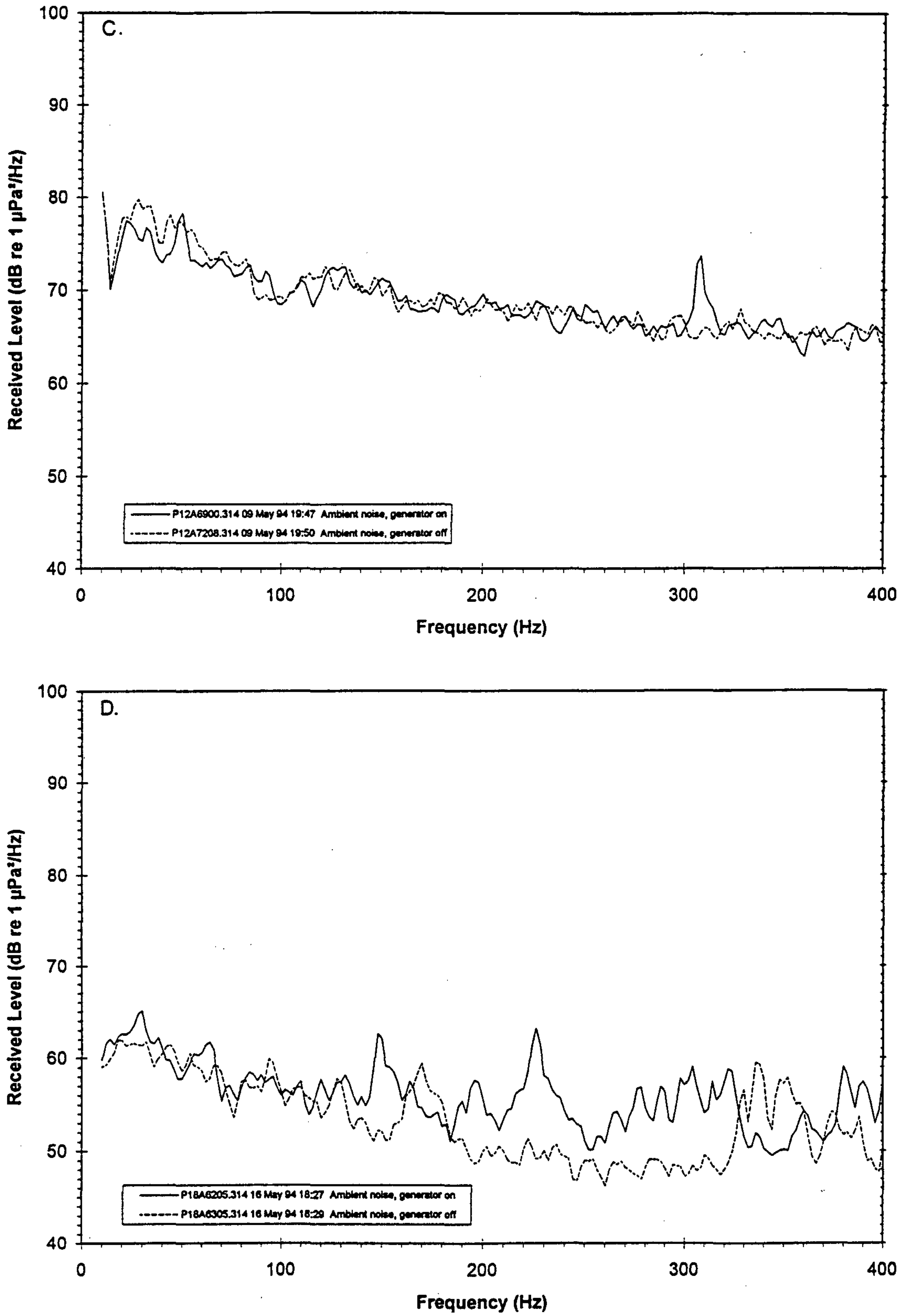


FIGURE 4.39 (continued). *(C)* 9 May 1994. *(D)* 16 May 1994.

5. BOWHEAD WHALE RESULTS: MOVEMENTS, BEHAVIOR AND BASIC BIOLOGY[9]

This section describes the distribution, general activities, and behavior of bowheads in the study area. Section 5.1 describes the spring bowhead migration east of Pt. Barrow as observed during the four years of this study. Section 5.2 describes the movements and sizes of bowheads observed in the study area as determined by photoidentification and photogrammetric methods. Section 5.3 describes bowhead behavior in the absence of human disturbance, excluding mothers and calves (which are covered in section 5.4). Together, these four subsections address specific objective 7, "To document ... the movements, behavior, basic biology ... of bowheads ..." (§1.1, p. 7). These data are needed as background information for the analysis of reactions to noise playbacks and aircraft overflights (specific objectives 4 and 6), covered in §6.

This report deals primarily with results from the 1991 and 1994 fieldwork. However, to maximize sample sizes and provide a more comprehensive account, §5.1-5.4 summarize data from 1989 and 1990 as well as the 1991 and 1994 data. More detailed information from 1989 and 1990 can be found in Richardson et al. (1990a, 1991a).

5.1 Bowhead Distribution & Movements

The bowhead sightings during reconnaissance flights, helicopter ferry flights, and ice-based work provided information about the timing and routes of spring bowhead migration through the study area during the years 1989-91 and 1994. Our primary objective when conducting reconnaissance flights was to locate the main bowhead migration corridor and, within that corridor, concentrations of bowheads. We did not conduct systematic surveys, and we devoted much less effort to areas where few or no bowheads were expected than to the more promising areas. Hence, the relative numbers of sightings in different parts of the study area in the following bowhead distribution maps should not be taken as a quantitative measure of densities of whales in those areas. The information on bowhead distribution and movements in 1989 and 1990, summarized below, is presented in more detail in Richardson et al. (1990a, 1991a).

Bowheads in General

Spring 1989.—In 1989, reconnaissance surveys were conducted from 29 April to 30 May. Ice cover was extensive and thick during this period. No well-defined leads occurred in our study area until 20 May, when an E-W lead started to form along the landfast ice edge within our study area. The heavy ice conditions in 1989 resulted in an unusually wide and northerly migration corridor (Fig. 5.1; see also Appendix D, Fig. D-1 to D-4, for distribution by 10-day periods). The absence of well-defined leads during much of the study may also have influenced the headings of whales. The vector mean heading of bowheads in 1989 was more northerly than in other years (71°True for 1989 vs. 79-93° for other years, Table 5.1). Also, the headings in 1989 were more

[9] By W.J. Richardson, W.R. Koski, G.W. Miller and B. Würsig, with R. Elliott and N. Patenaude

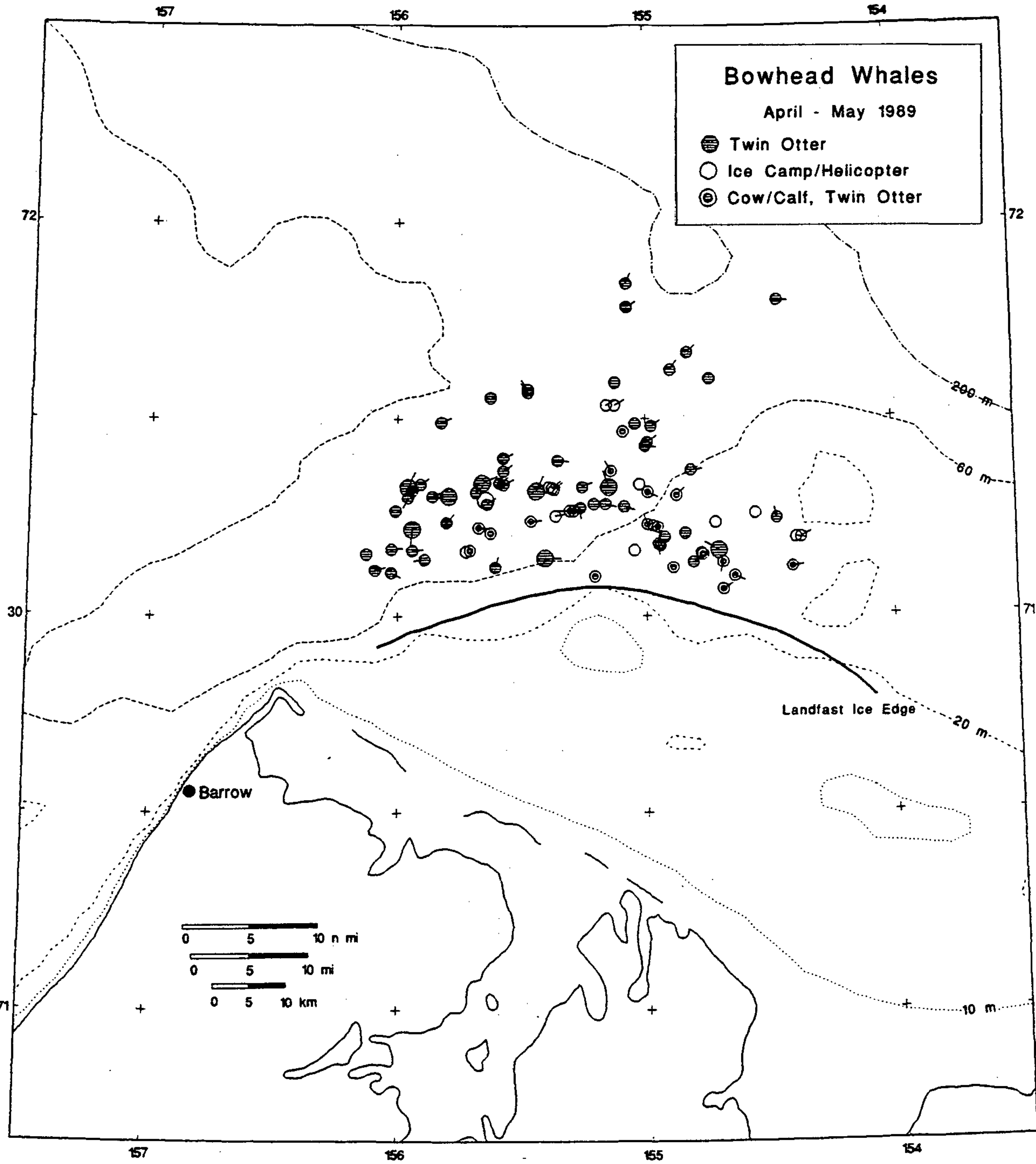


FIGURE 5.1. LGL sightings of bowhead whales, 29 April to 30 May 1989. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped.

TABLE 5.1. Headings (True) of bowhead groups by date, year and part of study area. Each group is counted only once.

True Heading	A. By 10-Day Period April	1-10 May	11-20 May	21-31 May	TOTAL	B. By Year 1989	1990	1991	1994	TOTAL	C. By Part of Study Area West	South Central	South East	North Central	North East	TOTAL	True Heading
0 N	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**N 0**
10	1	1	3	0	5	0	2	2	1	5	1	2	2	0	0	5	10
20	0	0	4	0	4	2	0	0	2	4	0	1	2	0	1	4	20
30	2	15	11	4	32	2	11	8	11	32	2	8	20	0	2	32	30
40	0	1	6	1	8	2	2	2	2	8	0	3	4	0	1	8	40
50	1	19	17	6	43	5	9	8	21	43	3	26	12	0	2	43	50
60	2	26	31	9	68	13	10	27	18	68	5	28	24	3	8	68	60
70	3	29	21	6	59	7	13	14	25	59	2	31	19	3	4	59	70
80	5	149	82	16	252	3	60	35	154	252	6	76	167	0	2	251	80
90 E	**6**	**31**	**42**	**7**	**86**	**8**	**14**	**21**	**43**	**86**	**4**	**31**	**45**	**1**	**5**	**86**	**E 90**
100	5	16	45	3	69	6	31	8	24	69	0	24	42	1	2	69	100
110	1	3	7	3	14	2	4	7	1	14	1	7	6	0	0	14	110
120	2	15	57	3	77	3	51	14	9	77	0	12	63	2	0	77	120
130	1	0	6	1	8	0	4	1	3	8	0	0	8	0	0	8	130
140	0	3	11	0	14	1	8	1	4	14	0	1	12	0	1	14	140
150	1	1	2	0	4	0	2	1	1	4	0	2	2	0	0	4	150
160	0	0	1	1	2	1	0	1	0	2	0	1	1	0	0	2	160
170	0	2	6	2	10	0	5	2	3	10	2	2	6	0	0	10	170
180 S	**1**	**0**	**3**	**6**	**10**	**2**	**4**	**4**	**0**	**10**	**0**	**3**	**4**	**1**	**2**	**10**	**S 180**
190	1	1	1	1	4	1	0	1	2	4	0	2	2	0	0	4	190
200	0	0	1	1	2	1	0	0	1	2	0	0	2	0	0	2	200
210	0	2	1	3	6	2	2	1	1	6	1	1	3	0	1	6	210
220	1	0	0	1	2	0	0	1	1	2	1	1	0	0	0	2	220
230	0	0	0	1	1	0	0	1	0	1	1	0	0	0	0	1	230
240	1	0	0	0	1	0	0	1	0	1	0	1	0	0	0	1	240
250	0	0	0	1	1	0	0	1	0	1	0	0	0	0	1	1	250
260	0	2	2	0	4	0	0	1	3	4	0	1	3	0	0	4	260
270 W	**0**	**1**	**5**	**1**	**7**	**3**	**0**	**4**	**0**	**7**	**0**	**3**	**1**	**2**	**1**	**7**	**W 270**
280	0	0	0	2	2	0	0	2	0	2	0	2	0	0	0	2	280
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	290
300	0	3	0	1	4	1	1	1	1	4	0	2	2	0	0	4	300
310	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	310
320	0	2	2	0	4	0	1	1	2	4	0	2	2	0	0	4	320
330	0	2	1	1	4	3	0	0	1	4	0	1	0	2	1	4	330
340	0	1	0	2	3	2	0	1	0	3	0	0	3	0	0	3	340
350	0	2	2	2	6	1	2	0	3	6	0	1	5	0	0	6	350
Total	34	327	371	85	817	71	236	172	338	817	29	275	463	15	34	816	Total
Vector																	
Mean	92	77	88	85	83	71	93	81	79	83	77	78	88	71	71	83	
Length	0.72	0.86	0.80	0.51	0.79	0.58	0.82	0.71	0.87	0.79	0.67	0.81	0.82	0.43	0.65	0.79	
Ang.Dev.	43	30	36	56	37	52	34	44	30	37	47	36	35	61	48	37	

TABLE 5.2. Headings (True) of bowhead mother-calf groups by date, year and part of study area. Each '+' symbol represents 1 group.

	A. By 10-Day Period					B. By Year					C. By Part of Study Area						
True Heading	April	1-10 May	11-20 May	21-31 May	TOTAL	1989	1990	1991	1994	TOTAL	West	South Central	South East	North Central	North East	TOTAL	True Heading
0 N	.	.	.	.	**0**	.	.	.	.	**0**	.	.	.	.	.	**0**	**N 0**
10	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	10
20	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	20
30	.	.	+	.	1	.	+	.	.	1	.	.	+	.	.	1	30
40	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	40
50	.	.	+	++	3	+	+	+	.	3	.	+	++	.	.	3	50
60	.	+	+	+	3	+	.	+	+	3	.	+	++	.	.	3	60
70	.	.	.	++	2	.	.	++	.	2	.	.	.	.	++	2	70
80	.	+	.	++	3	+	+	+	.	3	.	++	+	.	.	3	80
90 E	.	.	+	+++	**4**	++	.	++	.	**4**	+	++	+	.	.	**4**	**E 90**
100	.	.	.	+	1	+	.	.	.	1	.	+	.	.	.	1	100
110	.	.	.	+	1	.	.	+	.	1	+	.	.	.	.	1	110
120	.	.	+	++	3	++	+	.	.	3	.	.	+++	.	.	3	120
130	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	130
140	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	140
150	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	150
160	.	.	.	+	1	+	.	.	.	1	.	.	+	.	.	1	160
170	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	170
180 S	.	.	+	++	**3**	+	+	+	.	**3**	.	+	+	+	.	**3**	**S 180**
190	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	190
200	.	.	.	+	1	+	.	.	.	1	.	.	+	.	.	1	200
210	.	.	.	++	2	.	+	+	.	2	+	.	.	.	+	2	210
220	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	220
230	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	230
240	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	240
250	.	.	.	+	1	.	.	+	.	1	.	.	.	.	+	1	250
260	.	.	+	.	1	.	.	+	.	1	.	.	+	.	.	1	260
270 W	.	.	+	+	**2**	+	.	+	.	**2**	.	.	+	+	.	**2**	**W 270**
280	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	280
290	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	290
300	.	+	.	.	1	.	+	.	.	1	.	+	.	.	.	1	300
310	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	310
320	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	320
330	.	.	.	+	1	+	.	.	.	1	.	.	.	.	+	1	330
340	.	.	.	+	1	+	.	.	.	1	.	.	+	.	.	1	340
350	.	.	.	.	0	.	.	.	.	0	.	.	.	.	.	0	350
Total	0	3	8	24	35	14	7	13	1	35	3	9	16	2	5	35	Total
Vector																	
Mean		40	81	107	96	100	96	100	60	96	130	82	93	225	350	96	
Length		0.51	0.26	0.40	0.35	0.40	0.25	0.31	1.00	0.35	0.63	0.64	0.38	0.71	0.07	0.35	
Ang.Dev.		57	70	63	65	63	70	67	0	65	50	48	64	44	78	65	

variable than those in the subsequent three years of study. The angular deviation was 52° in 1989 vs. 30-44° in the other three years (Table 5.1).[10]

Late in the season, mothers and calves predominated among bowhead sightings. Mothers and calves tended to be found along or just north of the pack ice edge along the north side of the nearshore lead that separated the landfast and pack ice from 20 May onward. Their predominant heading was easterly (vector mean 100°T), but they were oriented in other directions somewhat more often than were other whales (angular deviation 63° vs. 52°; Table 5.2 vs. 5.1).

Spring 1990.—During 1990 there was a nearshore lead along the landfast ice edge ENE of Barrow during most of the study period. Bowheads were seen from the first day of aerial surveys in 1990 (29 April) until the last day (26 May). Bowheads were found on most days with surveys, except during the 30 April-6 May period. Numerous bowheads were present on 29 April and from ~8 May to 21 May. After 21 May, numbers declined and mother-calf pairs predominated.

The main migration corridor through our study area was narrower and tended to be farther south in 1990 than in 1989 (Fig. 5.2 vs. 5.1; see also Appendix D, Fig. D-5 to D-8). East of 156°W longitude, most of the 1990 sightings were concentrated in a west-to-east band near 71°30'N. West of 155°W many bowheads seen by us were moving east along the middle or north side of the lead along the landfast ice edge. However, farther east, where the lead veered to the SE, bowheads continued eastward through the pack ice, forsaking the lead. During 1990, the great majority of bowhead headings were in the sector from NE to ESE and the vector mean heading was almost due east (93° true, Table 5.1). In 1990 bowheads deviated from this heading considerably less than in 1989; the angular deviation was 34° in 1990 vs. 52° in 1989 (Table 5.1).

As during 1989, mothers and calves predominated among the whales seen at the end of the season. They were sighted either along or just north of the nearshore lead or about 50 km farther north among 80% pack ice. Although the vector mean heading was easterly (96°T), the easterly trend was weak, with an angular deviation of 70° (Table 5.2).

Spring 1991.—Ice conditions were loose enough to allow bowheads to travel northeast and east across the study area throughout the 1991 field season (28 April-26 May). There was a passable migration corridor close to the landfast ice edge throughout the spring. Early in the season, there was a wide nearshore lead extending northeast past Pt. Barrow far into the Beaufort Sea (Plate 3.1, p. 52). Later in the season, the broad continuous lead did not extend as far to the east, but there were—at the least—discontinuous openings near the landfast ice edge and elsewhere in the pack ice. Many bowheads traveled northeast and then east along that corridor (Fig. 5.3).

In 1989-90, almost all bowheads seen east of about 156°W had been either near the northern edge of the main nearshore lead or in the pack ice north of there. In contrast, in 1991 many

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[10] Because heading is distributed circularly rather than linearly, a simple arithmetic average often is not a meaningful measure of central tendency. The proper measure of central tendency is the vector mean, and the proper measures of variance are the mean vector length and the angular deviation (Batschelet 1981). The latter is analogous to the standard deviation of a linear variable (Batschelet 1981:276).

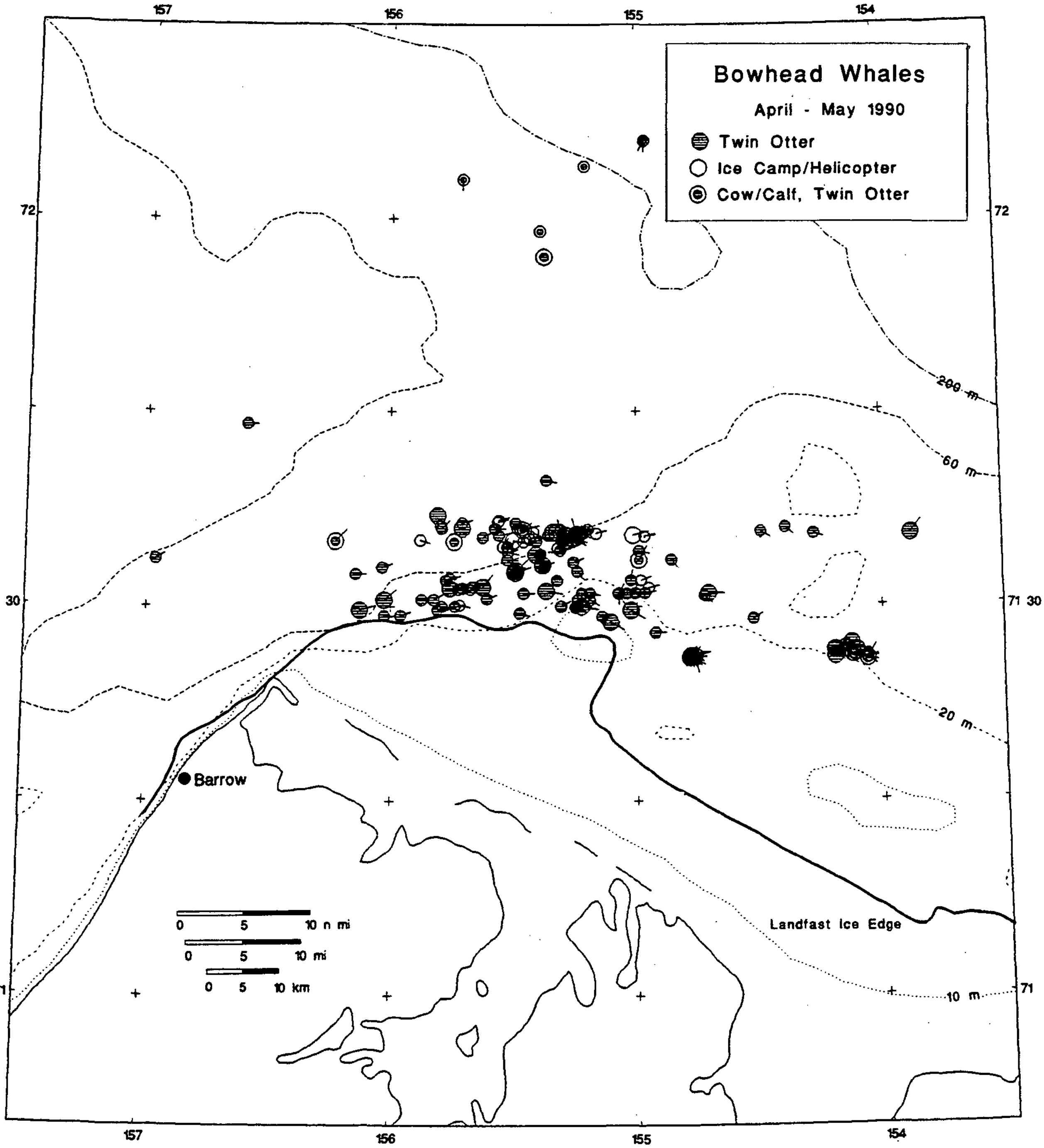

FIGURE 5.2. LGL sightings of bowhead whales, 27 April to 26 May 1990. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

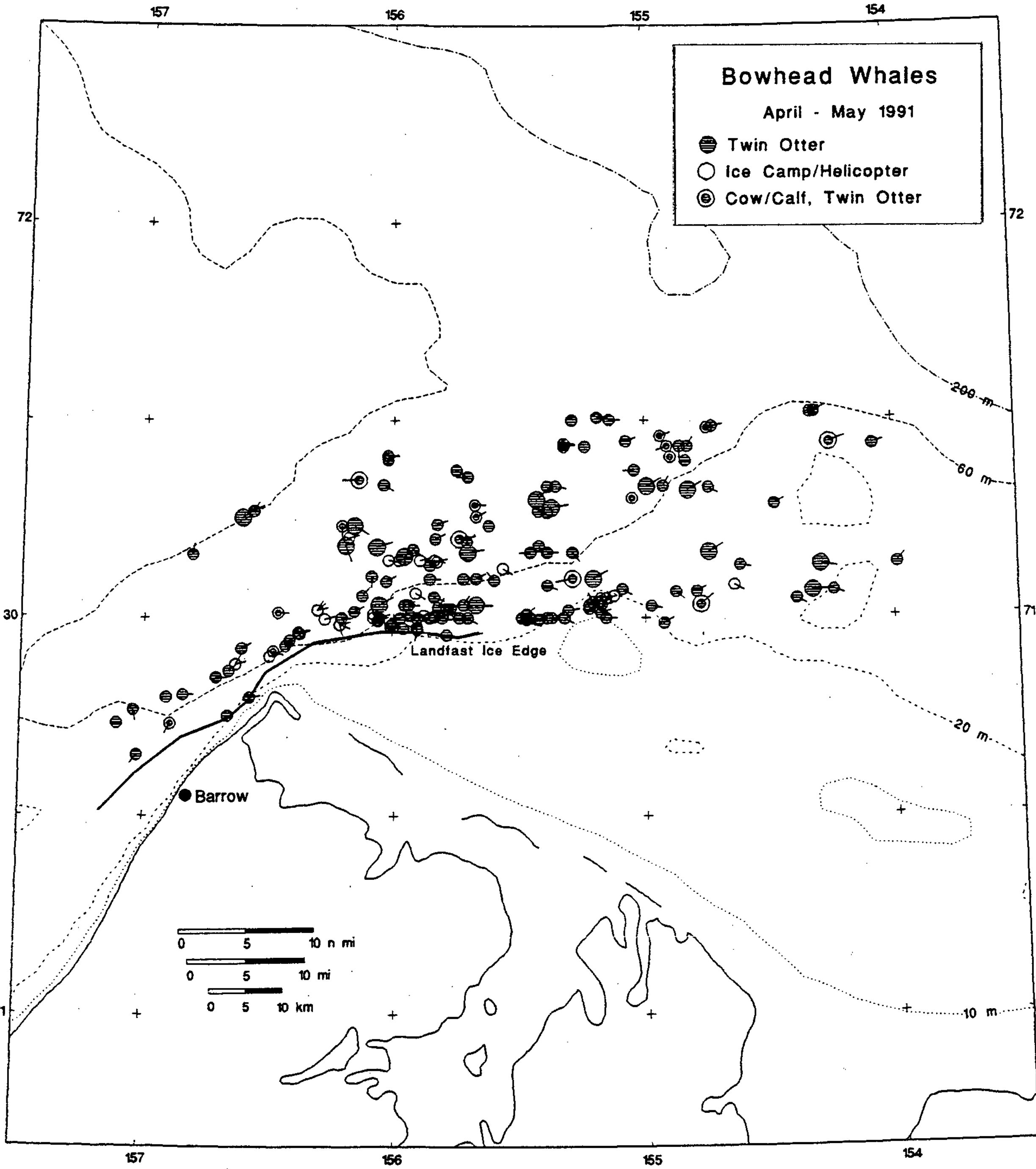

FIGURE 5.3. LGL sightings of bowhead whales, 28 April to 26 May 1991. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice. Surveys near Barrow in 1991 did not begin until 17 May, after whaling had ended.

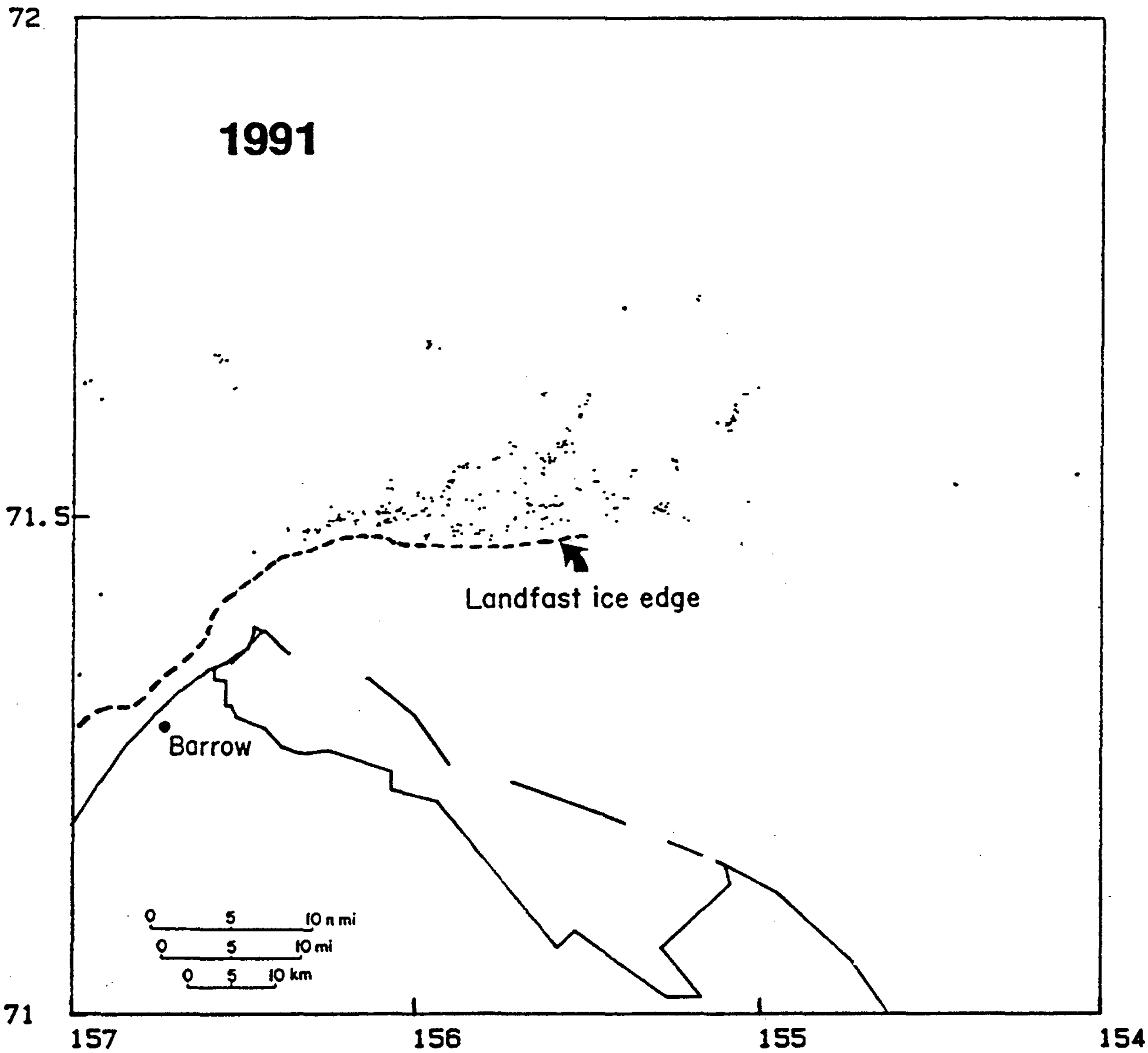

FIGURE 5.4. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Mammal Laboratory in 1991 (unpubl. data, courtesy D. Withrow and D. Rugh, NMML). Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

bowheads were seen along the south side of the nearshore lead and quite close to the landfast ice edge when they were well to the east of 156° (Fig. 5.3). Other bowheads continued to the NE or ENE after passing Pt. Barrow (similar to 1989-90), and moved well offshore into the pack ice as they traveled east (Fig. 5.3). This pattern was also evident in the distribution of sightings during the National Marine Mammal Lab's bowhead photography flights in 1991 (Fig. 5.4).

East of Pt. Barrow, both NMML and ourselves devoted much more effort to areas between 71°30'N and 71°40'N, the main bowhead migration corridor in 1991, than to areas farther north or south. However, occasional surveys north of 71°40'N showed that densities of bowheads were lower north of 71°40'N than in the main migration corridor.

We did some reconnaissance to the west and northwest of Pt. Barrow in 1991, but only after mid-May when spring whaling ended. During the latter half of May 1991, at least a few bowheads were present many kilometers to the northwest, far from the landfast ice edge (Fig. 5.3). The National Marine Mammal Lab's aerial photography crew also saw a few bowheads far to the northwest (Fig. 5.4).

Figures 5.5-5.8 show our 1991 bowhead sightings during late April and during 10-day periods in May. The area NE and east of Pt. Barrow was searched throughout the field season. The general distribution of sightings east of Pt. Barrow did not change substantially during most of this period. However, late in the season (21-26 May) there was a tendency for bowheads to continue to travel ENE rather than turning to the east after they passed Point Barrow. At that time, the nearshore lead provided an open corridor to the ENE as well as the east. This change in distribution may have been related to the more frequent sightings of mother-calf pairs during late May. As noted in 1989-90, mother-calf pairs tended to follow the offshore (pack ice) rather than the nearshore (landfast ice) side of the lead.

The vector mean heading of bowheads was 81°T in 1991, intermediate between the mean 71° and 93° mean headings in the two previous years (Table 5.1). Most bowheads or bowhead groups headed ENE to east. The among-group variability in headings (angular deviation 44°) was slightly greater than in 1990 but less than in 1989 when heavy ice cover influenced headings.

The numbers of bowheads seen each day are shown in Appendix A (Table A-2), along with a measure of reconnaissance survey effort—the number of hours of reconnaissance flying each day. Although the number of bowheads in the area varied from day to day, bowheads were detected quite consistently in 1991. We saw bowheads during 24 of the 25 effective offshore flights (those >1 h in duration). This is an unusually high proportion. In 1989, in contrast, bowheads were sighted during only 15 of the 24 days with flights (>1 h of flying on all 24 days). In 1991, the flight on 28 April was the only prolonged flight when no bowheads were seen. Indeed, bowheads were also seen during 2 of the 5 short flights that were terminated within 1 h because of bad weather.

As in 1989-90, mothers and calves were common toward the end of the study. Also as in previous years, mothers and calves tended to be sighted along or north of the northern side of the nearshore lead in areas north and NE of Pt Barrow. In contrast to previous years, in 1991 we

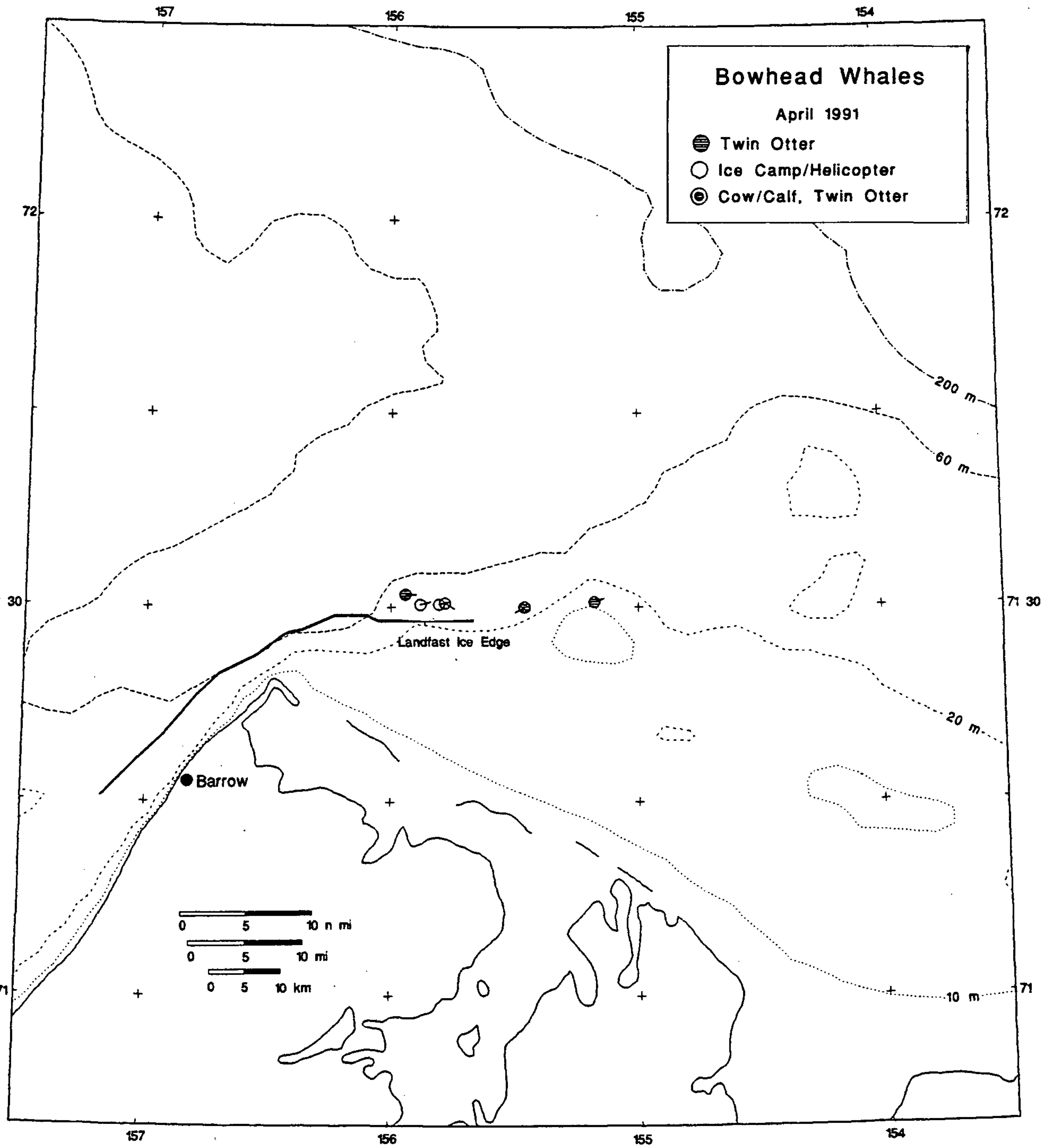

FIGURE 5.5. LGL sightings of bowhead whales, late April 1991. Format as in Fig. 5.3.

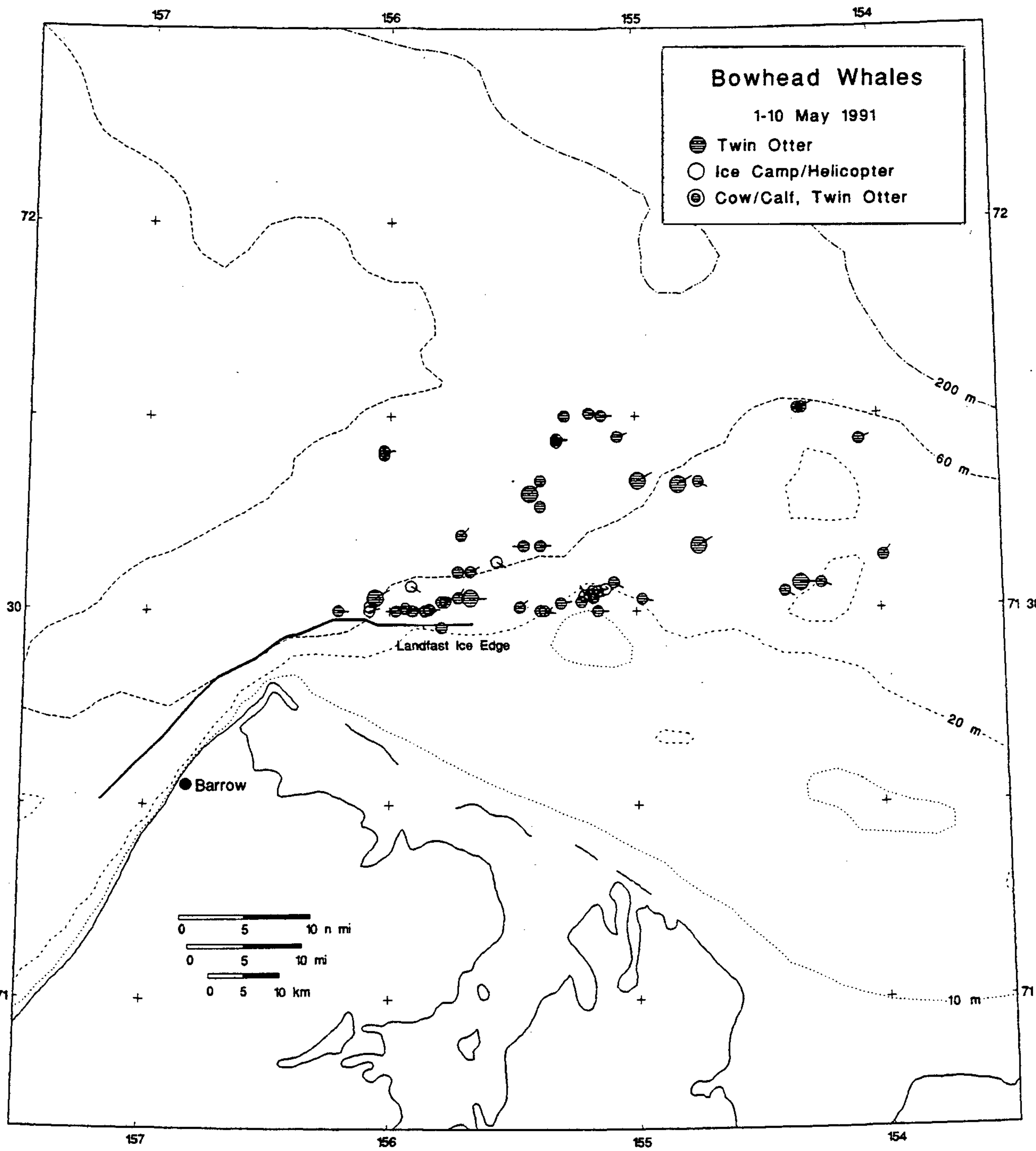

FIGURE 5.6. LGL sightings of bowhead whales, 1-10 May 1991. Format as in Fig. 5.3.

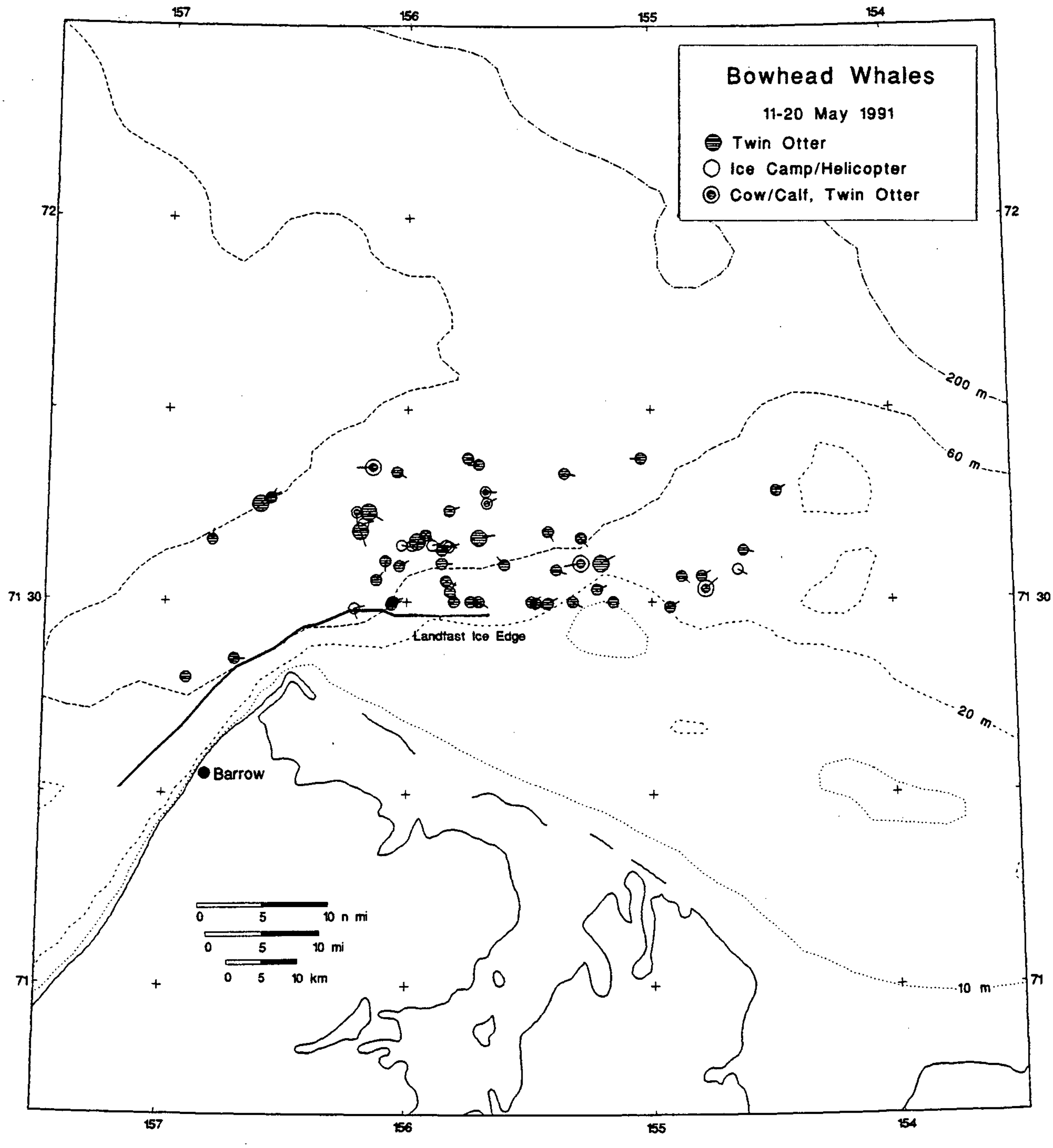

FIGURE 5.7. LGL sightings of bowhead whales, 11-20 May 1991. Format as in Fig. 5.3.

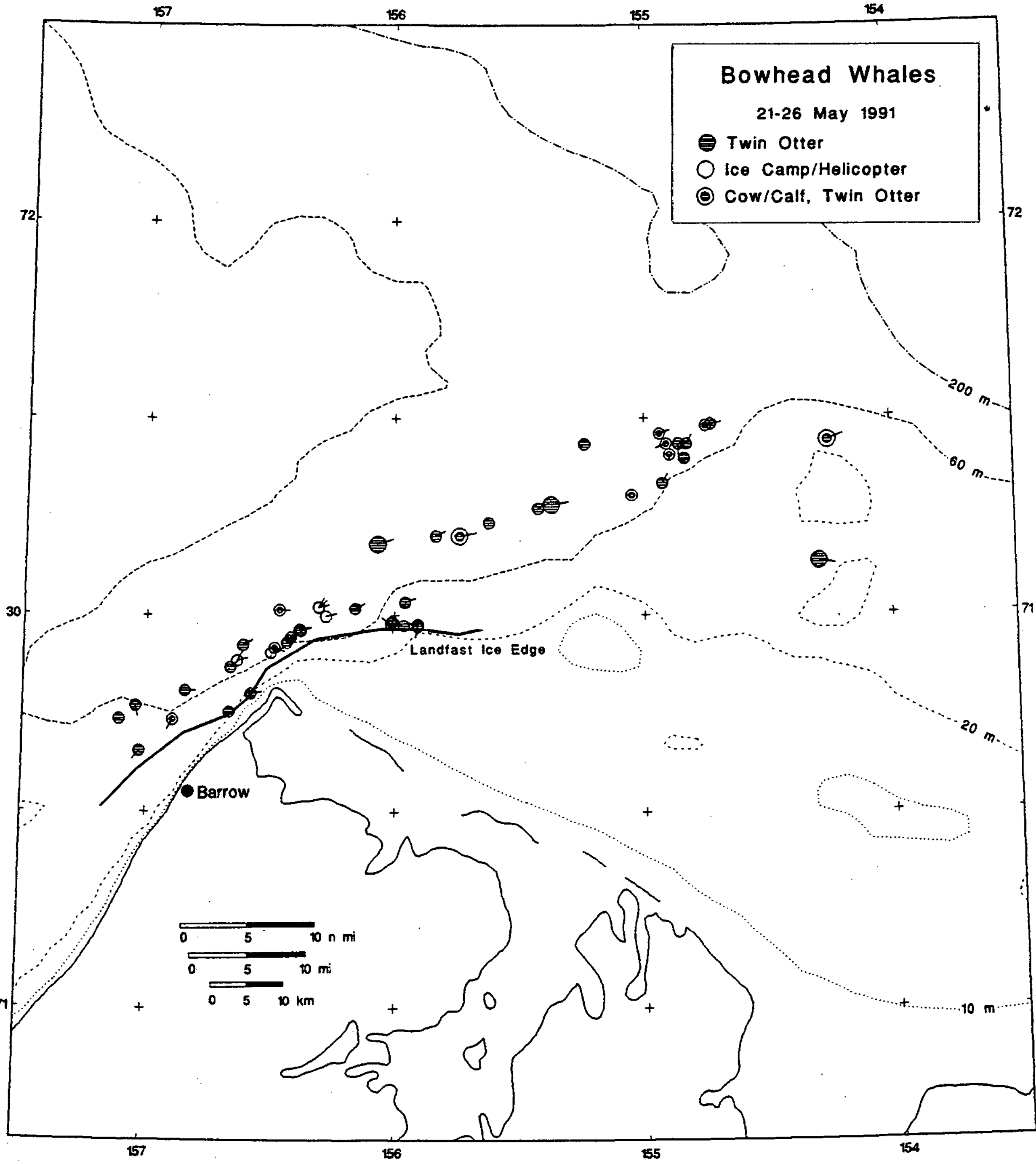

FIGURE 5.8. LGL sightings of bowhead whales, 21-26 May 1991. Format as in Fig. 5.3.

conducted some surveys near and SW of Point Barrow. Two of three mother-calf pairs sighted there were along the landfast ice edge. Headings of mother-calf pairs sighted in 1991 again tended to be easterly (vector mean 100°T), but with more scatter than for other whales (Table 5.2).

Spring 1994.—Ice conditions were heavy at the start (27 April) of the 1994 field season with little open water and no well-defined leads. However, by 3 May the pack ice began to loosen and on 4 May there was a major continuous lead along the landfast ice edge NE of Pt. Barrow. This extensive lead remained open and generally unbroken until 10 May. Although ice and lead conditions varied after 10 May, there usually was a large lead (although sometimes containing pack ice) near the landfast ice edge.

Throughout the 1994 field season, the landfast ice in areas east of longitude 156° W extended farther offshore than in 1990 and 1991. The landfast ice edge retained a WSW→ENE orientation across most of our study area until 15 May in 1994 (Fig. 3.8, p. 77). In contrast, during much of the spring migration season in 1989-91, the landfast ice edge as viewed by a migrating whale was W→E between 156 and 155°W, and then curved to the right, to an orientation of about WNW→ ESE, in areas east of about 155°.

During late April and early May 1994, few bowheads were sighted in our study area on some days. However, after the nearshore lead formed along the landfast ice edge on 3 May, moderate to large numbers of bowheads were consistently found in our study area through 17 May. During the two week period from 4 to 17 May, observers in the Twin Otter sighted 25-132 bowheads during each of the 8 days when reconnaissance surveys were conducted. Smaller numbers of bowheads were encountered during the 18-25 May period, but even then bowheads were sighted on 5 of 6 survey days. The numbers of bowheads seen each day during aerial surveys are given in Appendix A (Table A-3), along with the number of hours of reconnaissance flying each day as an indication of survey effort.

Bowhead sightings are mapped in Figures 5.9-5.12 for late April and for 10-day periods in May. The narrow corridor of bowhead sightings, especially evident for the early May period (Fig. 5.10), closely corresponds to the location of the lead along the landfast ice edge. From the longitude of Pt. Barrow, the landfast ice edge extended on an orientation of about 80°T. Thus, whales migrating along the ice edge lead gradually moved farther north as they proceeded east. The headings of bowheads sighted in our study area reflected their tendency to travel along the lead bordering the landfast ice edge. The great majority of the headings were in the range NE to ESE, with a vector mean of 79°T (Table 5.1). The angular deviation of headings in 1994 was only 30°, the smallest value of any of the four years.

In 1994 the main bowhead migration route followed the landfast ice edge to a greater degree than in the previous three years of the study. To some extent the concentration of sightings in this narrow corridor reflects the high proportion of the survey effort that was assigned to this area. The rather steady and concentrated stream of whales migrating along the ice edge provided a good opportunity for playback experiments, so most of our efforts were devoted to the nearshore lead. However, reconnaissance surveys farther north confirmed that few bowheads were traveling outside the narrow migration corridor depicted in Figure 5.13. The rather narrow and consistent migration

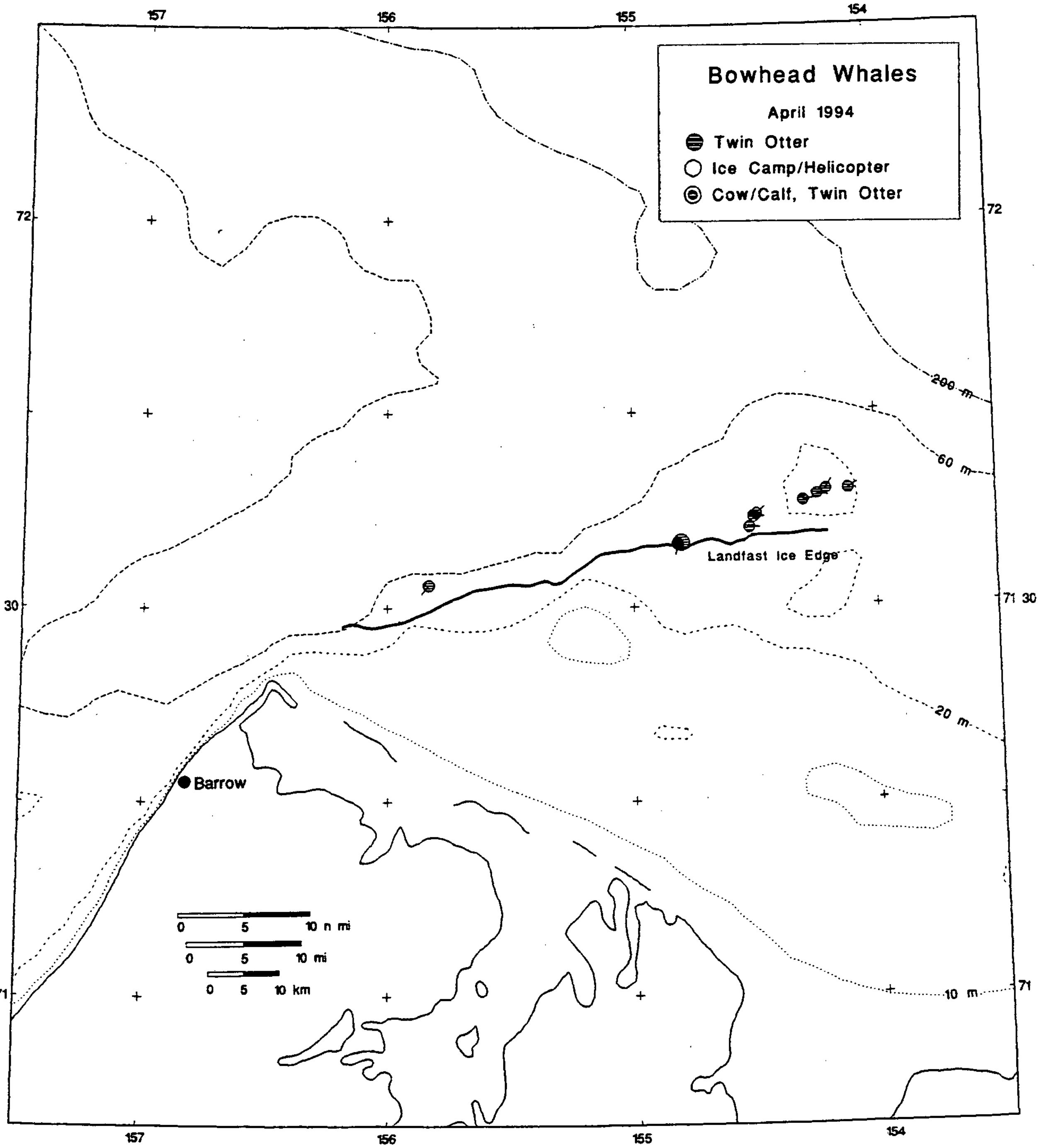

FIGURE 5.9. LGL sightings of bowhead whales, late April 1994. Format as in Fig. 5.3.

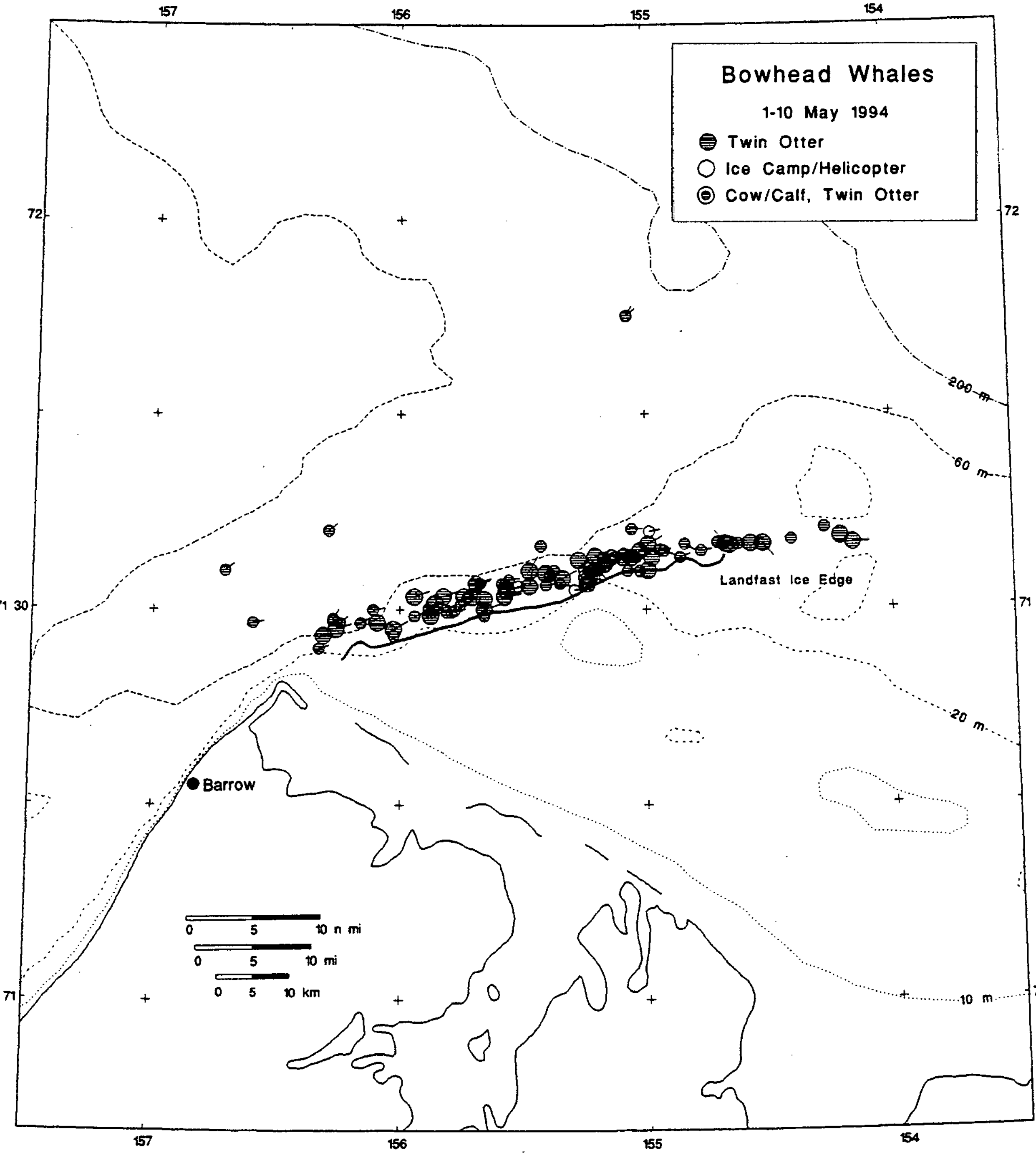

FIGURE 5.10. LGL sightings of bowhead whales, 1-10 May 1994. Format as in Fig. 5.3.

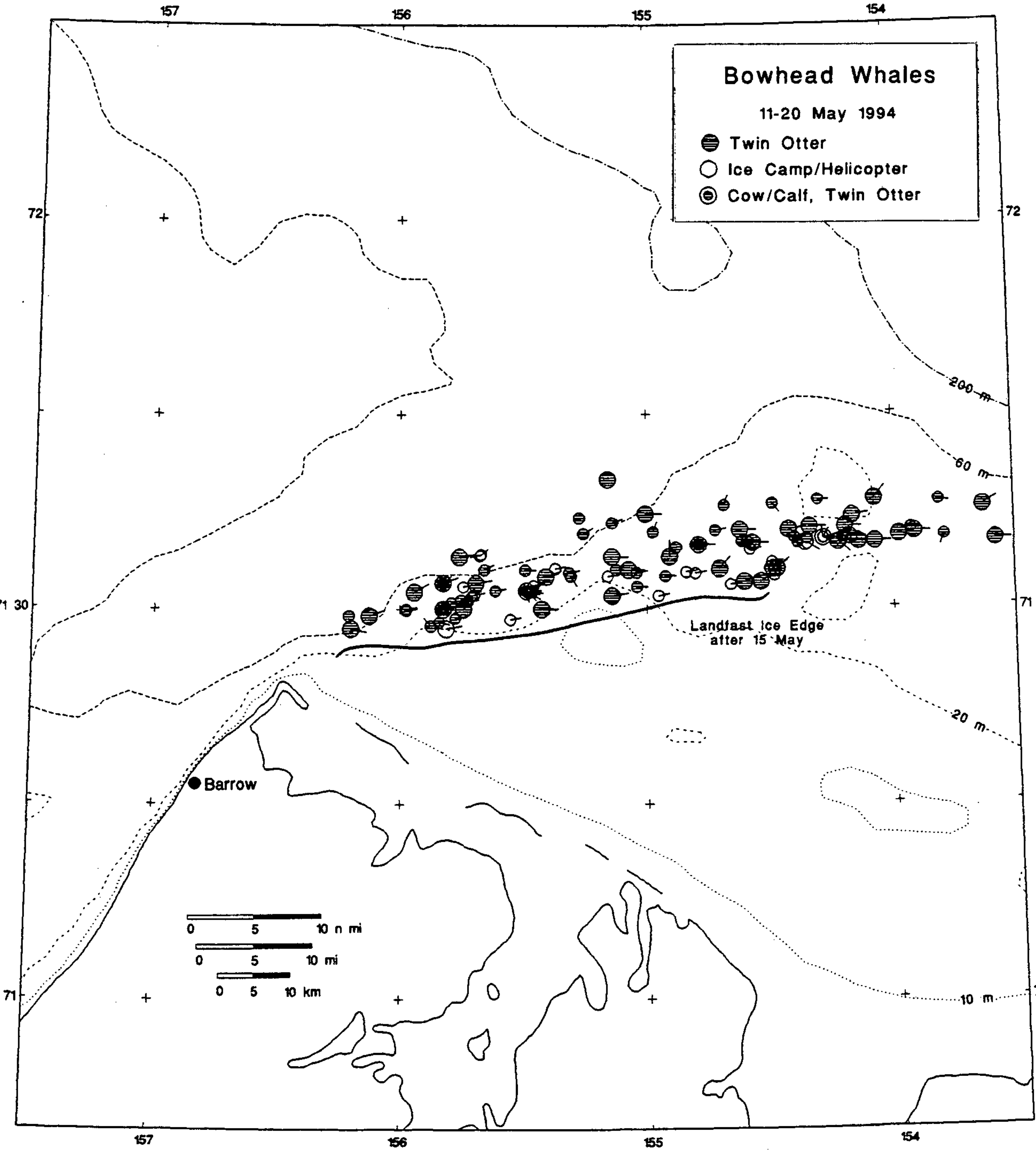

FIGURE 5.11. LGL sightings of bowhead whales, 11-20 May 1994. Location of ice edge changed on 15 May (*cf.* Fig. 5.10). Format as in Fig. 5.3.

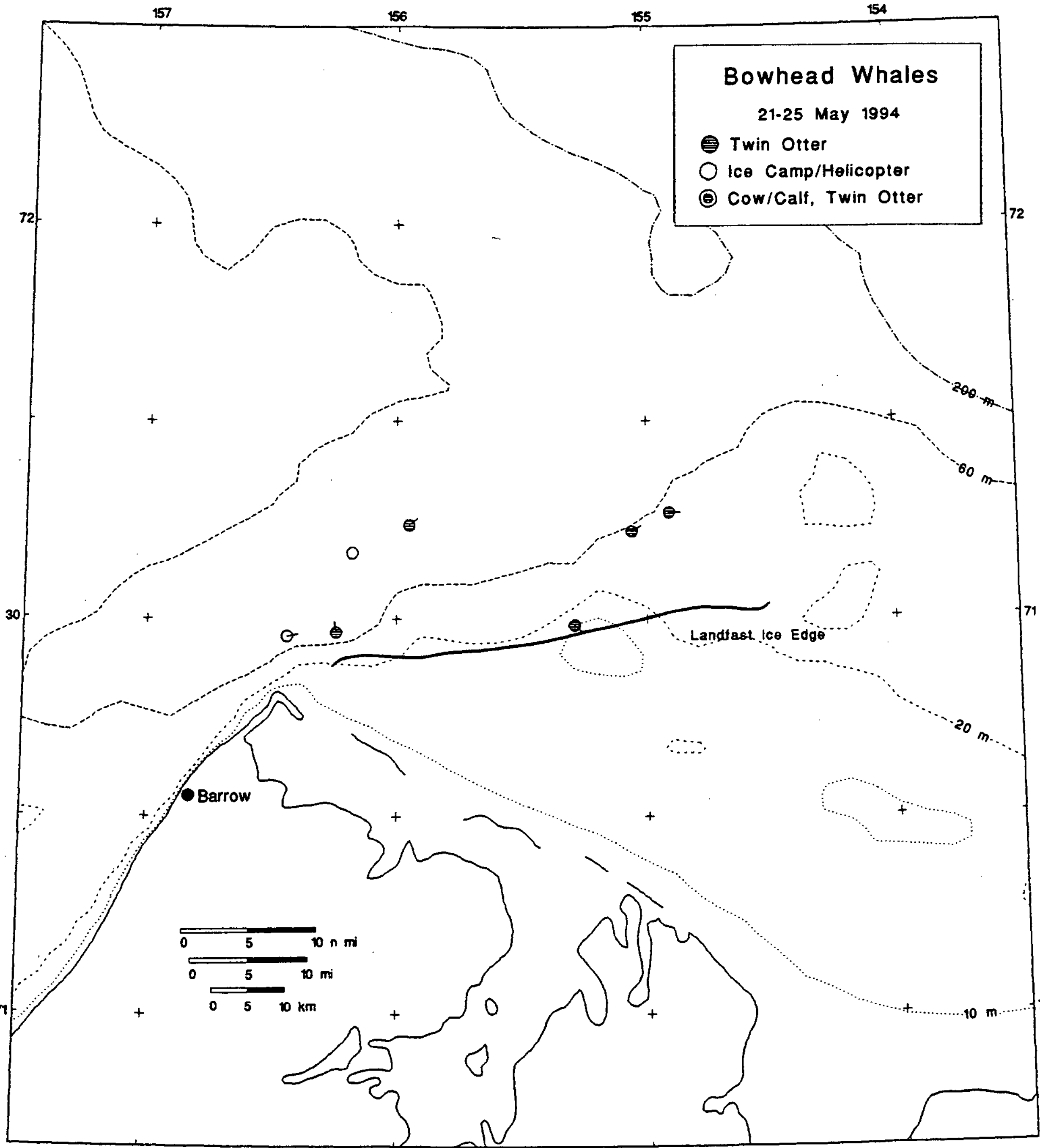

FIGURE 5.12. LGL sightings of bowhead whales, 21-25 May 1994. Format as in Fig. 5.3.

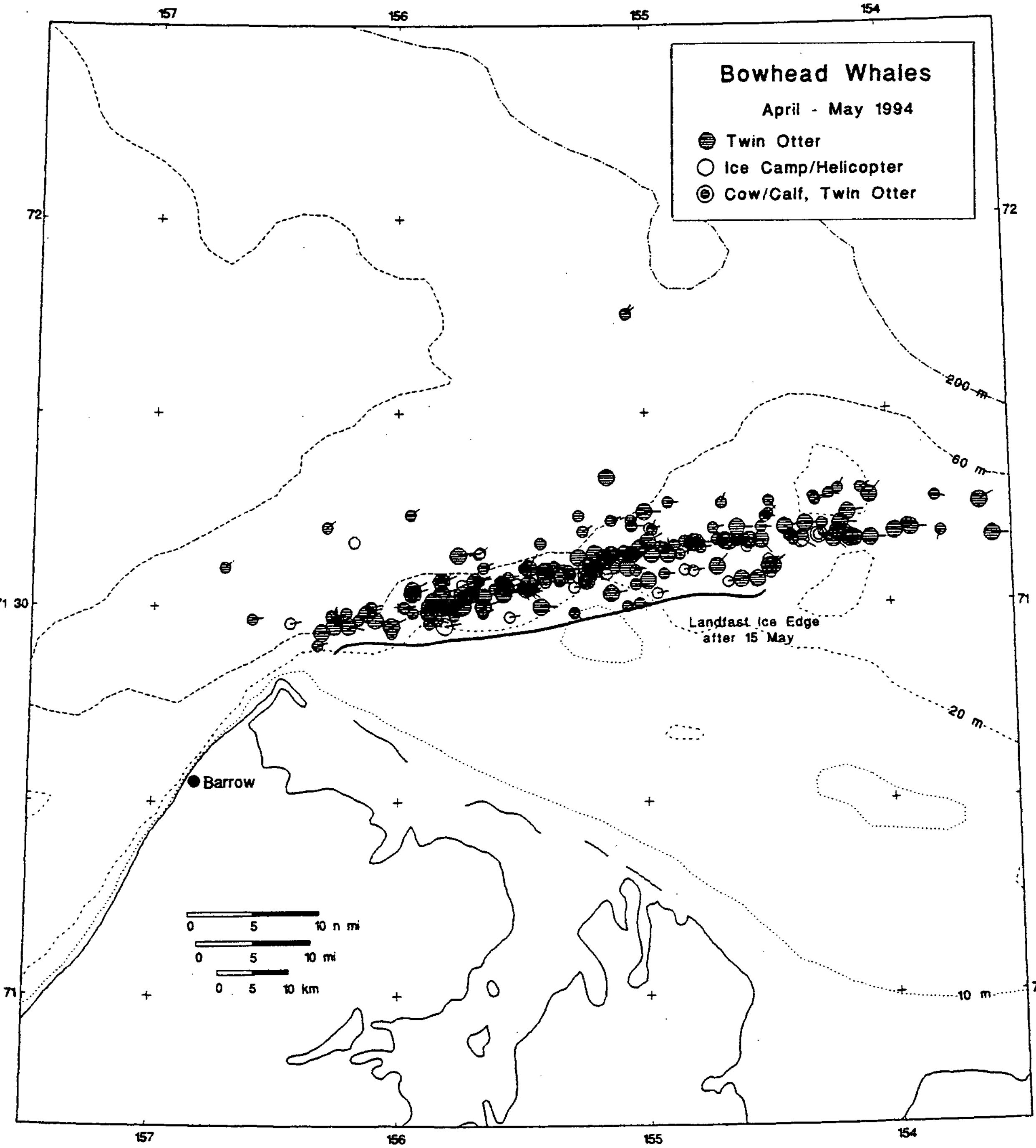

FIGURE 5.13. LGL sightings of bowhead whales, 27 April to 25 May 1994. Format as in Fig. 5.3.

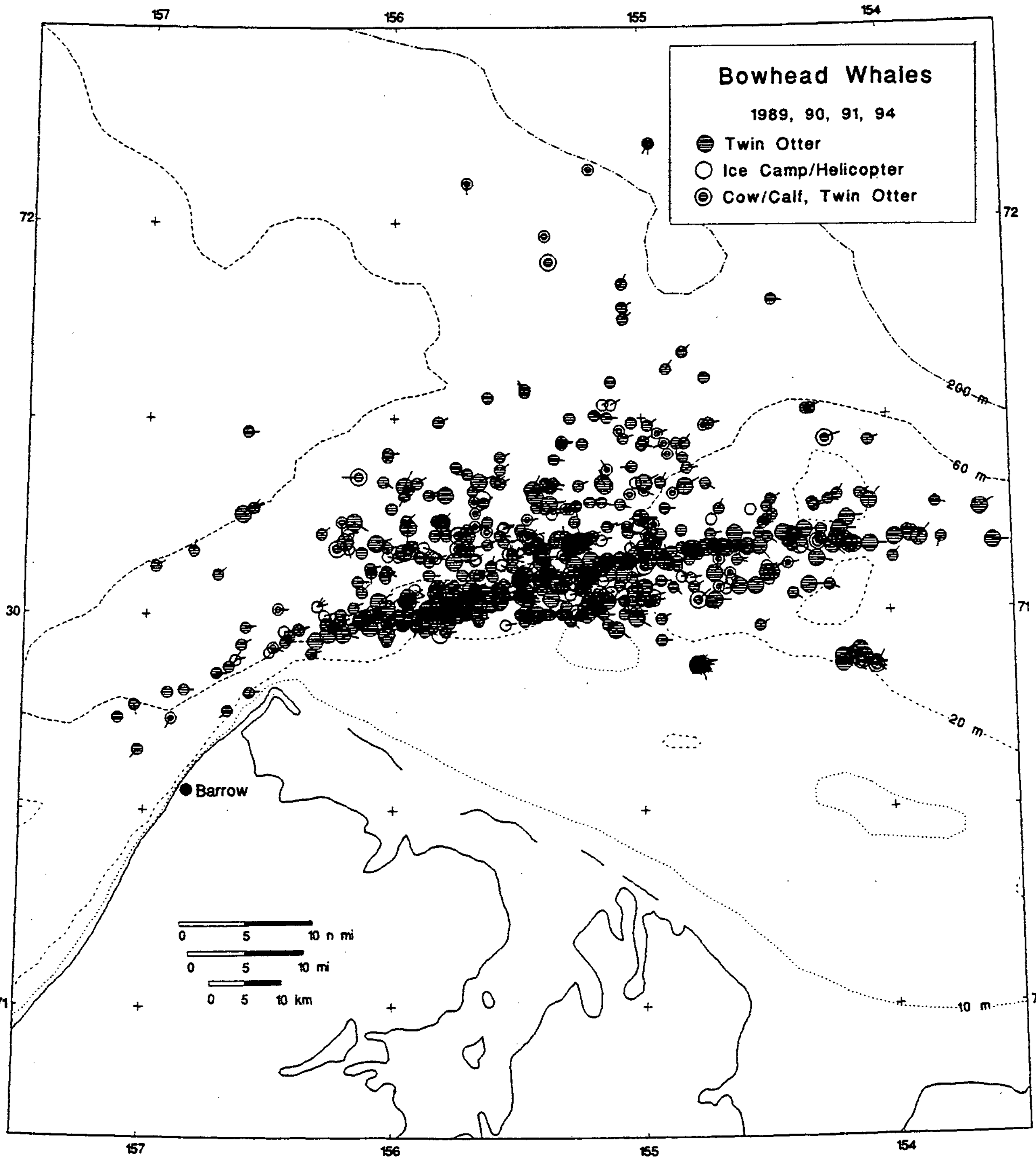

FIGURE 5.14. LGL sightings of bowhead whales during late April and May of 1989-91 and 1994. Format as in Fig. 5.3.

corridor in May 1994 was no doubt largely a function of the consistent "nearshore" lead, sometimes continuous and sometimes interrupted by incursions of pack ice, that was present along the landfast ice edge across the study area after 3 May. The consistent, narrow migration corridor was apparently also related to the fact that the landfast ice edge continued on an orientation of about 80°T across most of the study area for much of the 1994 field season, rather than curving to the ESE in the more easterly region as in previous years of the study.

Only one mother-calf pair was seen during our 1994 work. These two whales were traveling northeast along the nearshore lead on 9 May—an unusually early date for a calf to arrive in this study area.

All Years.—The distribution of all bowheads sighted during the four years of the study is plotted in Figure 5.14. This distribution is heavily influenced by the 1994 sighting data. More bowheads were sighted in 1994 than in the three previous years of the study combined.

Mothers and Calves

Spring 1989.—During 1989, mothers and calves moved through the study area later than most other bowheads. The first mother-calf pair sighted by us was seen from the ice camp on 16 May. However, mothers and calves were not common until 23 May. During the 23-29 May period, 67% (36 of 54) of the bowheads recorded were either mothers or calves (excluding a mother and yearling sighted on 24 May). In contrast, during the 29 April-19 May period only 3.5% (4 of 115) were mothers or calves.

Mothers and calves tended to be found along the north side of the lead that was present along the landfast ice edge during the last third of May 1989 (Fig. 5.15). Migrating mothers and calves tended to move along or just north of the pack ice edge. Mothers and calves engaged in other activities (resting or local travel) were found amidst the pack ice north of the lead and in the open water of the lead.

Spring 1990.—In 1990, mother-calf pairs again passed the Pt. Barrow area near the end of the spring migration period. A few migrating mother-calf pairs were present by mid-May of 1990, but their peak migration near Barrow was from 19 May onward. Nearly all bowheads seen during the last four days (23-26 May) of the field season were mother-calf pairs. During the 23-25 May period, 68% (21 of 31) of the bowheads recorded were either mothers or calves. In contrast, during the 29 April-22 May period only 2% (10 of 528) were mothers or calves. Similarly, the NMML aerial photography crew working in the same area saw their first mother-calf pair for 1990 on 12 May. They also saw numerous mother-calf pairs from 19 May onward, mostly far offshore (D. Withrow, pers. comm.).

The 11 mother-calf pairs observed from our aircraft in 1990 were seen in two parts of the study area (Fig. 5.16). *(1)* The four pairs seen on 19-23 May were near or just north of the north edge of the main nearshore lead crossing the study area. Most of these pairs were oriented on northeasterly headings. *(2)* The seven pairs seen on 24-26 May were about 50 km farther north

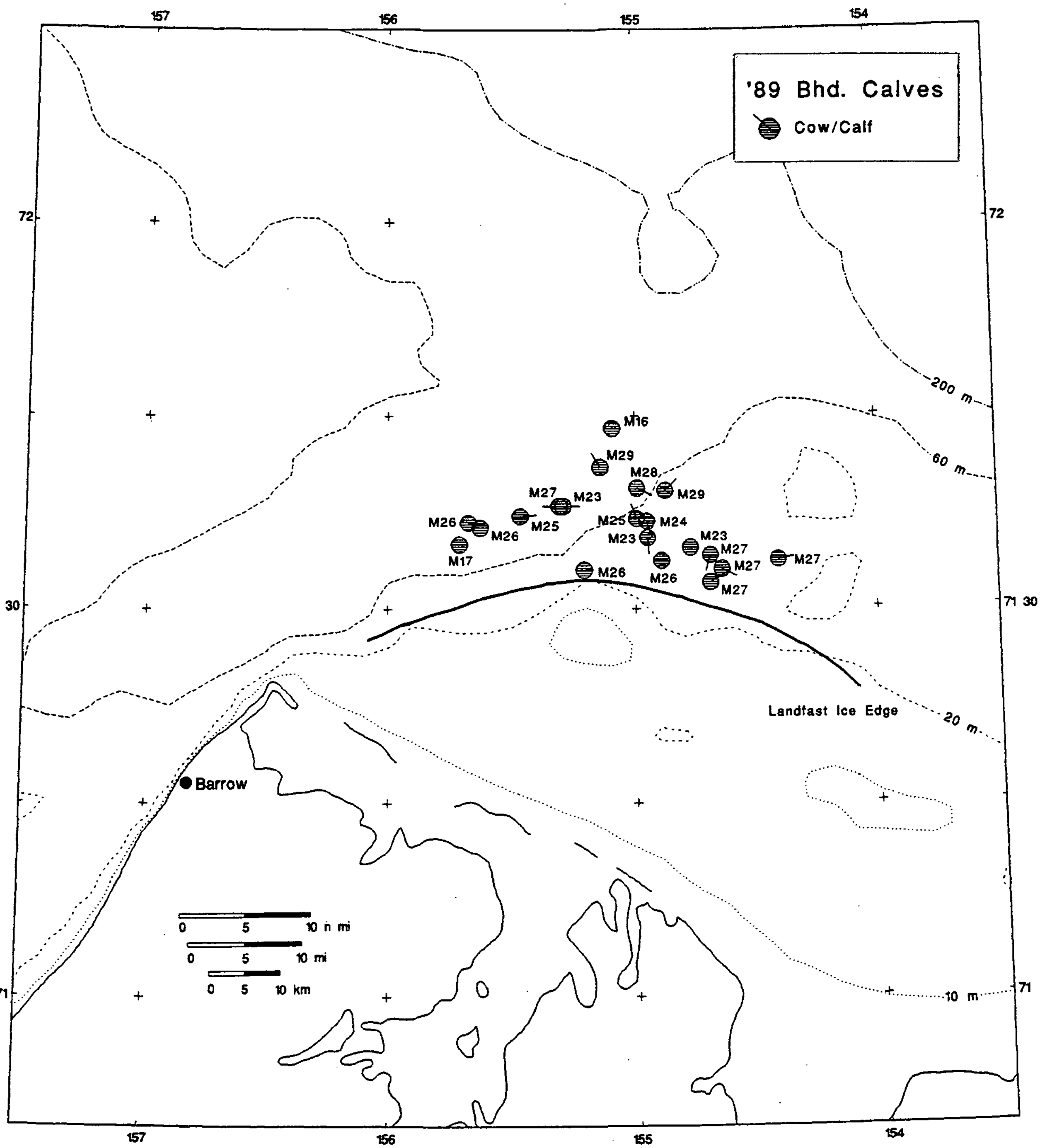

FIGURE 5.15. Locations where bowhead mothers and calves were seen by LGL, 1989. Numbers are dates in May 1989. Headings toward which the whales were oriented when first seen are also shown when available.

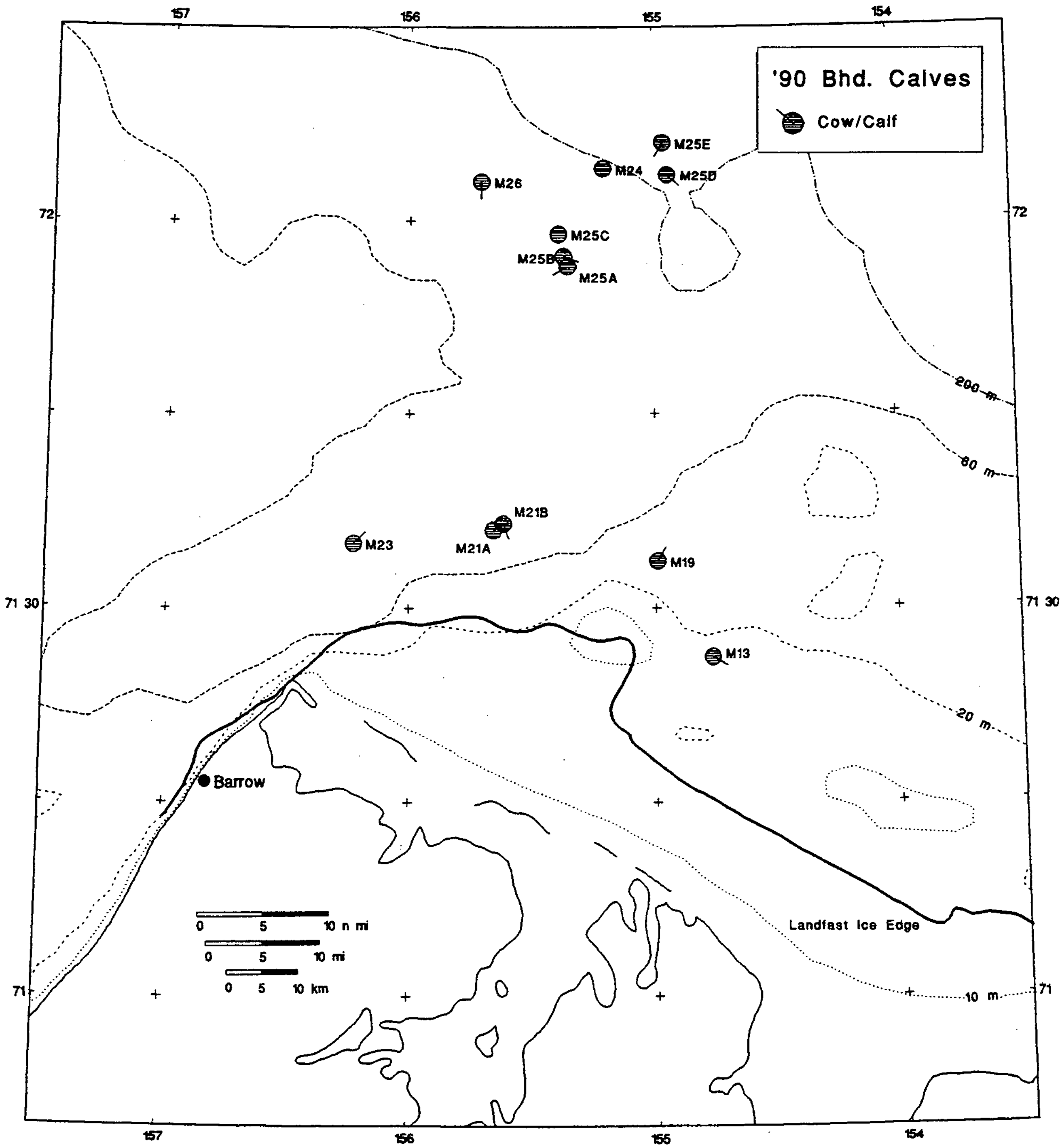

FIGURE 5.16. Locations where bowhead mother-calf pairs were seen by LGL, 1990. Numbers are dates in May. Headings toward which the whales were oriented when first seen are also shown when available.

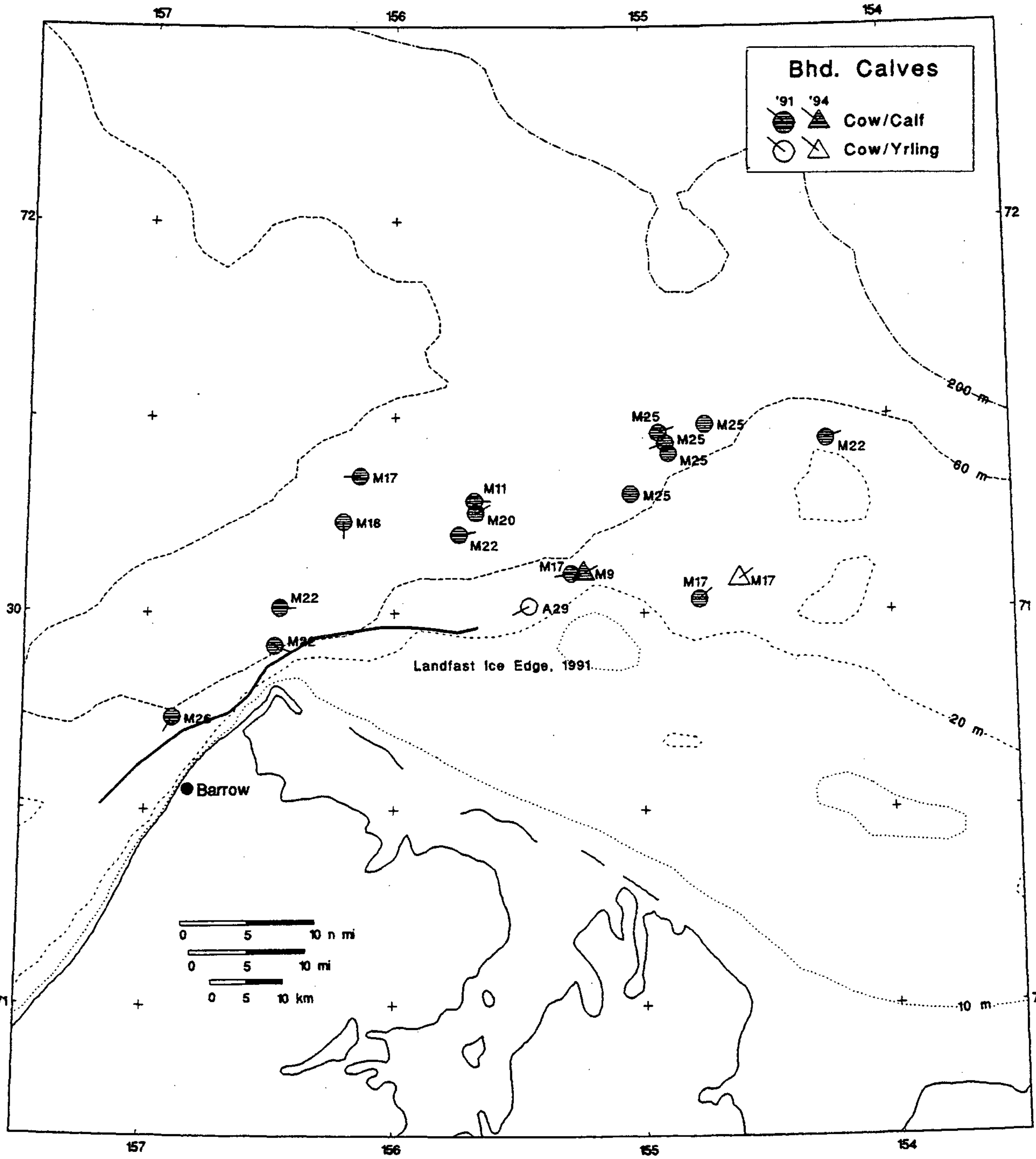

FIGURE 5.17. Locations where bowhead mother-calf and mother-yearling pairs were seen by LGL, 1991 and 1994. Numbers are dates in April (A) or May (M). Headings toward which the whales were oriented when first seen are also shown when available.

in areas that were 80% or more covered by pack ice. These pairs were traveling through the pack ice on a wide variety of headings, or not traveling.

Spring 1991.—Aside from a mother and yearling bowhead sighted on 29 April, our first mother-calf sighting in 1991 was on 11 May, and the next mother-calf sightings were not until 17 May. Mother-calf pairs were seen regularly from 17 May until the end of our field season on 26 May. They constituted a substantial proportion of all bowhead sightings during the last few days of the field season. Prior to 16 May in 1991, only 2 of 159 bowheads (1%) seen from the Twin Otter were mothers or calves (mother/yearling excluded). From 16 to 20 May, 12 of 82 bowheads (15%) seen from the Twin Otter were mothers or calves. From 21 to 26 May, 20 of 64 (31%) were mothers or calves.

Figure 5.17 shows all of our 1991 sightings of bowhead mothers accompanied by calves. Their distribution in 1991 was generally consistent with that of other whales seen during the latter part of the field season (Fig. 5.17 vs. 5.8). As in 1989-90, mothers and calves often headed in directions other than northeast or east (Fig. 5.15-5.17; Table 5.2).

Spring 1994.—Only one mother-calf pair was observed during our 1994 field season (Fig. 5.17). This pair was observed on 9 May in the nearshore lead, traveling northeast. Fieldwork continued until 25 May 1994, well within the usual migration period for mothers and calves.

There are at least two possible explanations for the very low number of mother-calf pairs seen in 1994. *(1)* Mothers with calves typically arrive during the latter part of the spring migration. In 1994, mothers with calves may have arrived in our study area after our field season ended on 25 May. However, a reconnaissance survey far to the southwest of Pt. Barrow (to within 25 miles of Cape Lisburne) on 25 May failed to find any mothers and calves approaching Pt. Barrow. Although the sea state was high along much of this route, 4 bowheads were seen, none accompanied by a calf. Thus, if the main migration of mother calf-pairs was late in reaching Pt. Barrow in 1994, it was very late: at least a week later than in 1990 and 1991, when the peak mother-calf migration through our study area began on 19 and 17 May, respectively; and at least a few days later than in 1989, when the peak mother-calf migration through the study area began on 23 May. *(2)* The annual production of bowhead calves appears to vary markedly from year to year (Koski et al. 1993). Perhaps 1994 was a year of very low calf production.

5.2 Bowhead Photogrammetry & Photoidentification

Data on bowhead sizes and on re-identifications of previously-photographed whales were relevant to specific objective 7, "to document ... other aspects of the movements, behavior, basic biology ... of bowheads" (§1.1, p. 7).

Bowhead Lengths and Timing of Migration

Bowhead Lengths, 1989.—-Vertical photographs of bowhead whales were obtained on eight days in 1989; however, photographs taken on 28 and 29 May were resightings of a mother-calf pair photographed on 27 May. Locations where photographs were taken are shown in Figure 5.19A,

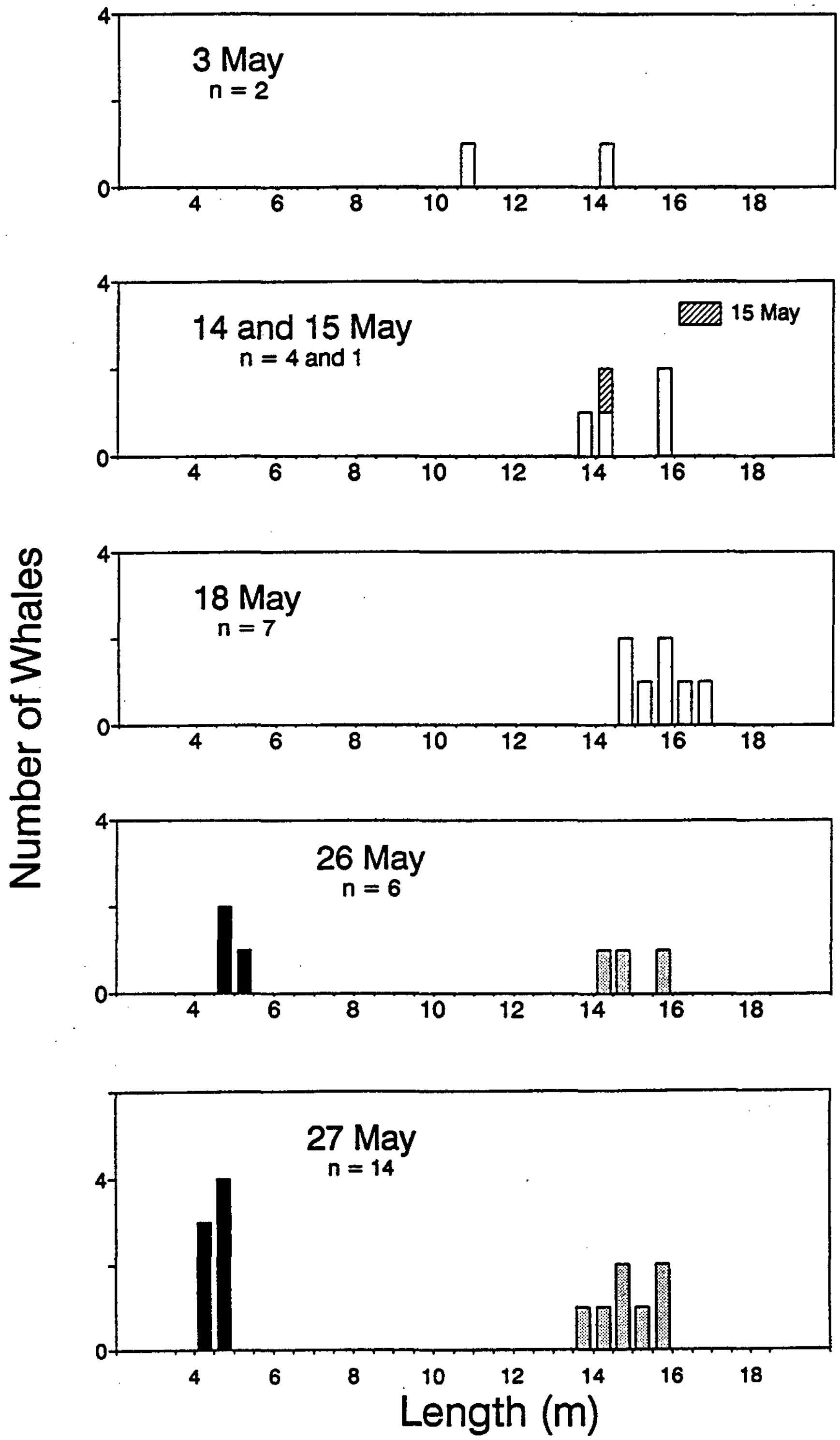

FIGURE 5.18. Length-frequency distributions for bowhead whales photographed during this study, 3-27 May 1989. Calves are represented by black bars and mothers by stippled bars. Repeat measurements are excluded within each day. A mother and calf photographed initially on 27 May and subsequently on 28 and 29 May are not shown for the latter two dates.

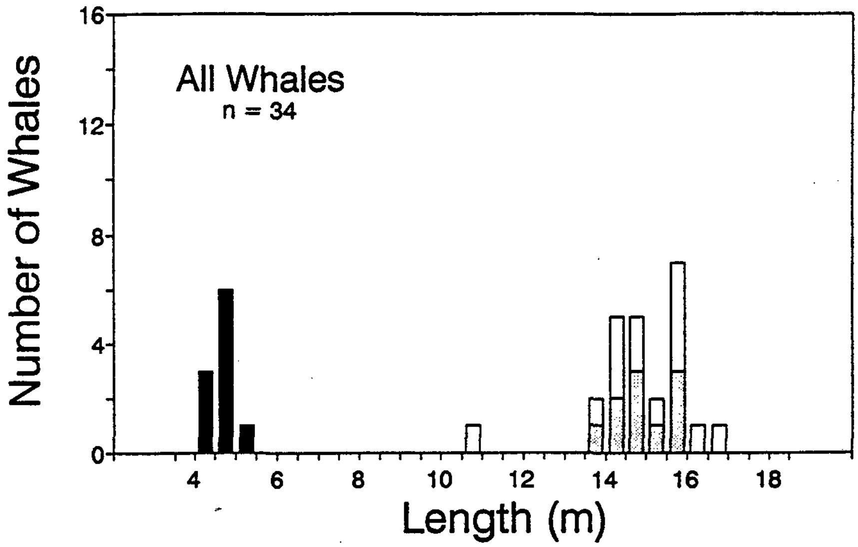

FIGURE 5.18. (continued).

later. Usable length measurements (grades 1-6 based on the scale described in Davis et al. 1986a,b) were obtained for 30 different bowheads. Approximate lengths were obtained for an additional four whales. The latter were whales that were deeply submerged or were photographed from uncertain altitudes (i.e. aircraft altitude <91 m or changing rapidly). We assume that bowheads <13 m long were subadults, and that those ≥13 m long were adults (Koski et al. 1993).

Few photographs were obtained during early May; thus the few length measurements obtained in 1989 represent the later stages of the bowhead migration (Fig. 5.18). In fact, over half of the measured whales were photographed after 25 May when mothers and calves were more abundant than other whales.

Bowhead Lengths, 1991.—Vertical photographs of bowhead whales were obtained on ten days in 1991; the locations where these photographs were taken are shown in Figure 5.19B. Most photographs were obtained on the many days when low overcast prevented us from conducting behavioral observations, for which a cloud ceiling above 460 m is necessary. Usable length measurements were obtained for 71 different bowheads. Approximate lengths were obtained for an additional 12 whales.

Following a brief behavior observation session on 29 April 1991, the mother of a mother-yearling pair was photographed; she was slightly shorter than 16.0 m (Fig. 5.20).

Length measurements were obtained for 20 different whales on 1 May. Most of these whales were small, which is typical of the early part of the migration (Nerini et al. 1987). Eighty percent of the whales measured on this day were subadults (<13 m; Fig. 5.20).

Two adult whales were photographed on 8 May and a large subadult and small adult were photographed on 10 May. Three subadult and three adult whales including the first mother of the season were photographed on 11 May. This was the earliest confirmed sighting of a mother-calf pair during the 1989-91 phase of this study. The mother was 14.8 m long; the calf was not measurable because it was below its mother.

Thirteen bowheads were measured on 17 May; they included 3 mother-calf pairs and 5 small subadult whales. The sighting of five small subadults 7.1-8.1 m in length this late in the season is interesting. The migration of adults, including mothers with calves, had already started. It is possible that these 7.1-8.1 m whales were yearlings that had recently separated from their mothers.

Bowheads photographed on 18 and 22 May were primarily adults (66% and 75%, respectively). On each of these days, we photographed one mother-calf pair and one small subadult—possibly yearlings (8.1 and 7.6 m long). The only other subadults photographed on these dates were 10.4, 11.2 and 12.9 m long (Fig. 5.20).

Seventy-three percent (11 of 15) of the whales photographed on 25 and 26 May were known mothers or calves. The remaining four whales were adults.

Bowhead Lengths, 1994.—Vertical photographs of bowhead whales for photogrammetry were obtained on 10 days in 1994, and video images for whale identification were obtained on one additional day (4 May). The locations where these photographs were taken are shown in Figure 5.21. Photogrammetry effort was concentrated during the 5-14 May period when generally low ceilings prevented us from conducting behavioral observations from 460 m ASL. Usable length measurements were obtained for 145 different bowheads in 1994. Approximate lengths were obtained for an additional 20 whales.

Only one bowhead was detected during surveys conducted previous to 30 April but 11 bowheads were seen during a survey on that date. Six of these whales were photographed and all were subadult bowheads (Fig. 5.22).

The size distributions of whales changed markedly from day to day during the next 10 days (Fig. 5.22). Fourteen bowheads were measured from photographs obtained on 5 May. Almost half (6) were adults. A 16.9 m whale photographed on this date was the largest bowhead measured by us during the three years of this spring study.

Length measurements were obtained for 46 different bowheads on 7 May. Most whales (80%) were subadults and 62% of the subadults were small subadults (<10 m).

The size distribution of whales photographed on 8 May was much different than that on the previous day. Seven of 15 whales that were measured were adults and six of the remaining eight were large subadults (10-13 m).

All but one of 15 bowheads photographed on 9 May was a subadult, and the presumed adult was a "borderline" animal 13.0 m long (Koski et al. 1993). Of the 14 subadults, nine were large subadults and five were small subadults.

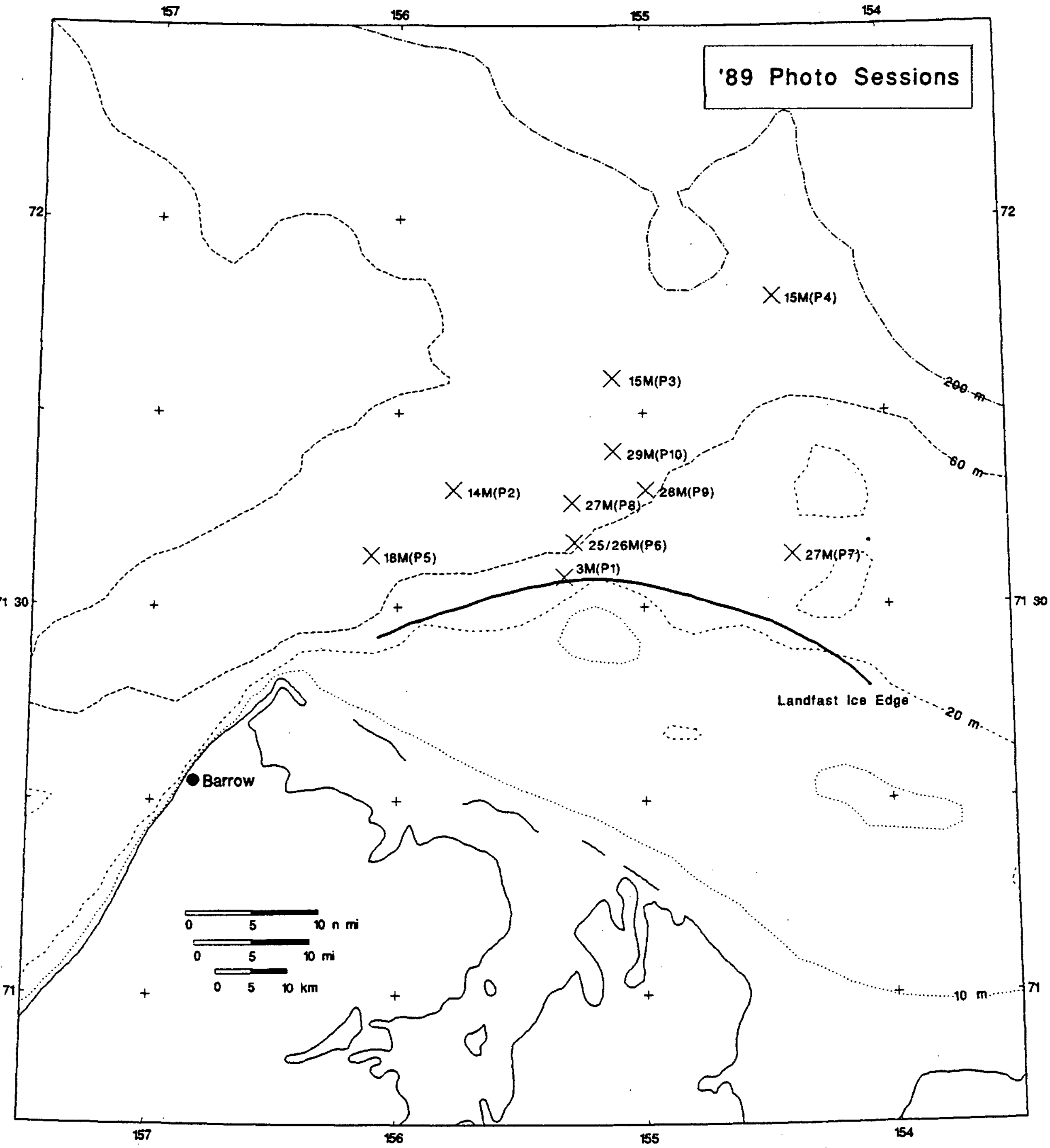

FIGURE 5.19A. Locations where vertical photographs of bowhead whales were obtained by the aerial crew, 3-29 May 1989. Annotations represent the date in May (M) and, in parentheses, the photo session number (P1-P10).

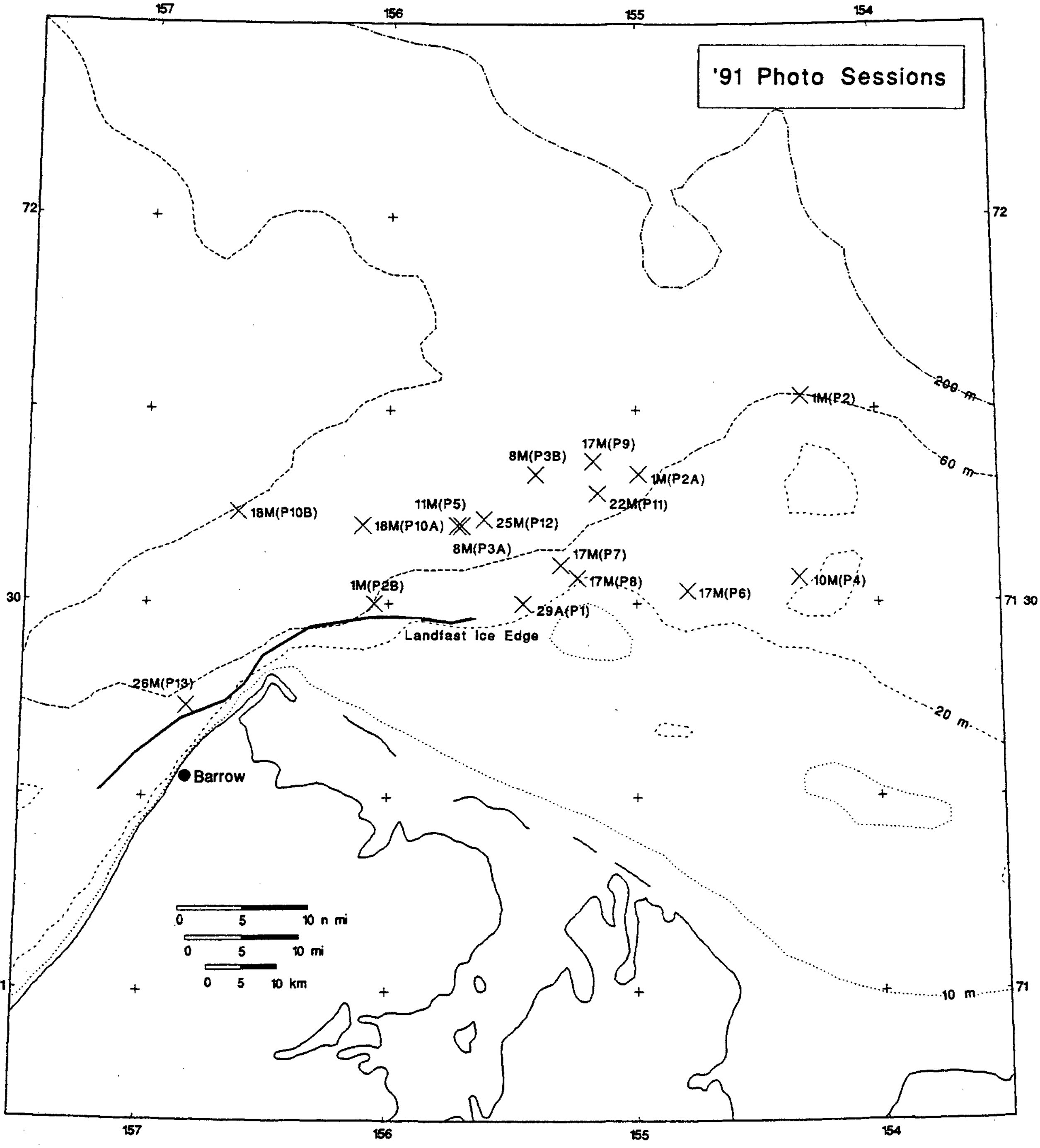

FIGURE 5.19B. Locations where vertical photographs of bowhead whales were obtained by the aerial crew, 29 April to 26 May 1991. Annotations represent the date in April (A) or May (M) and, in parentheses, the photo session number (P1-P13).

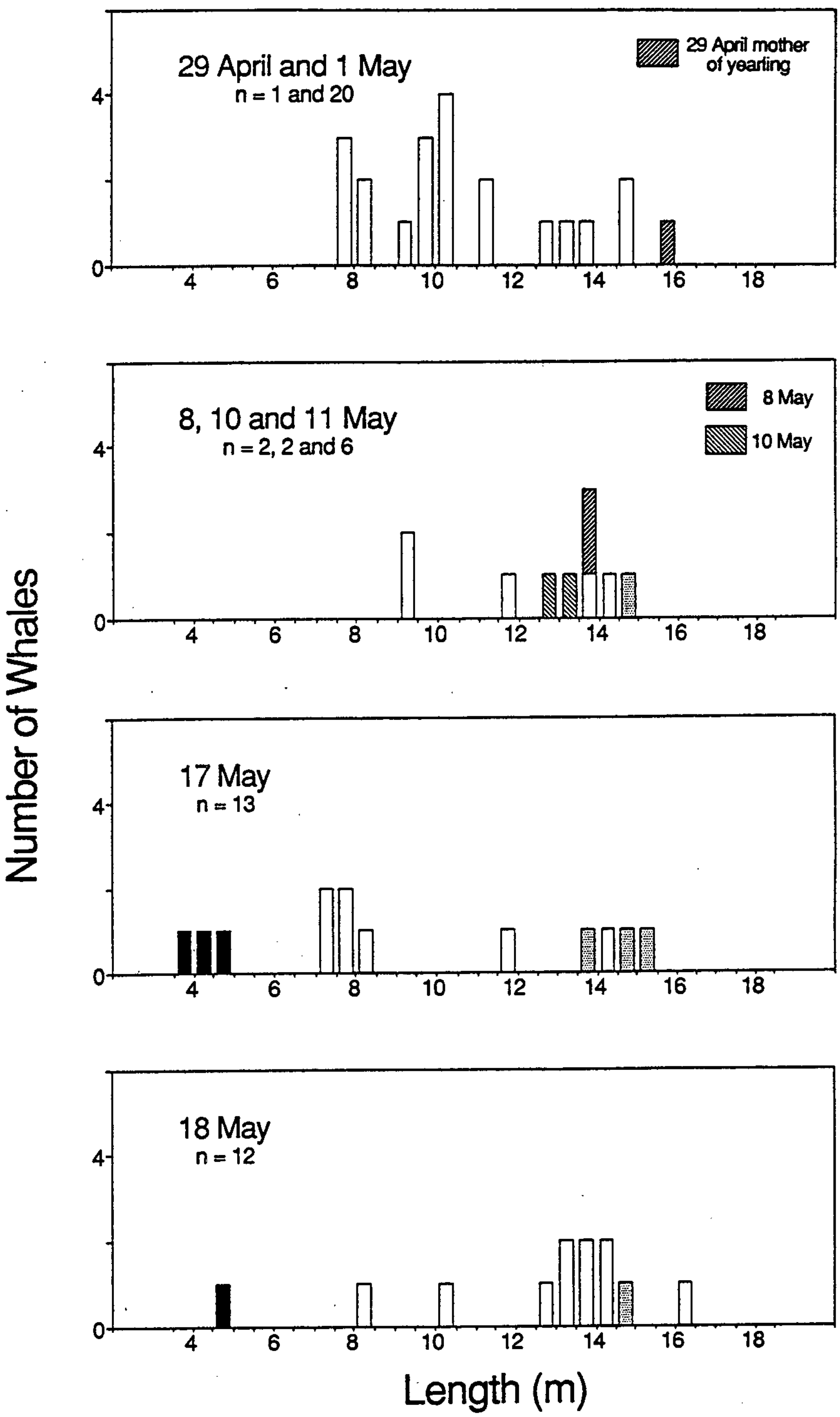

FIGURE 5.20. Length-frequency distributions for bowhead whales photographed during this study, 29 April-26 May 1991. Calves are represented by black bars and mothers by stippled bars. Repeat measurements are excluded.

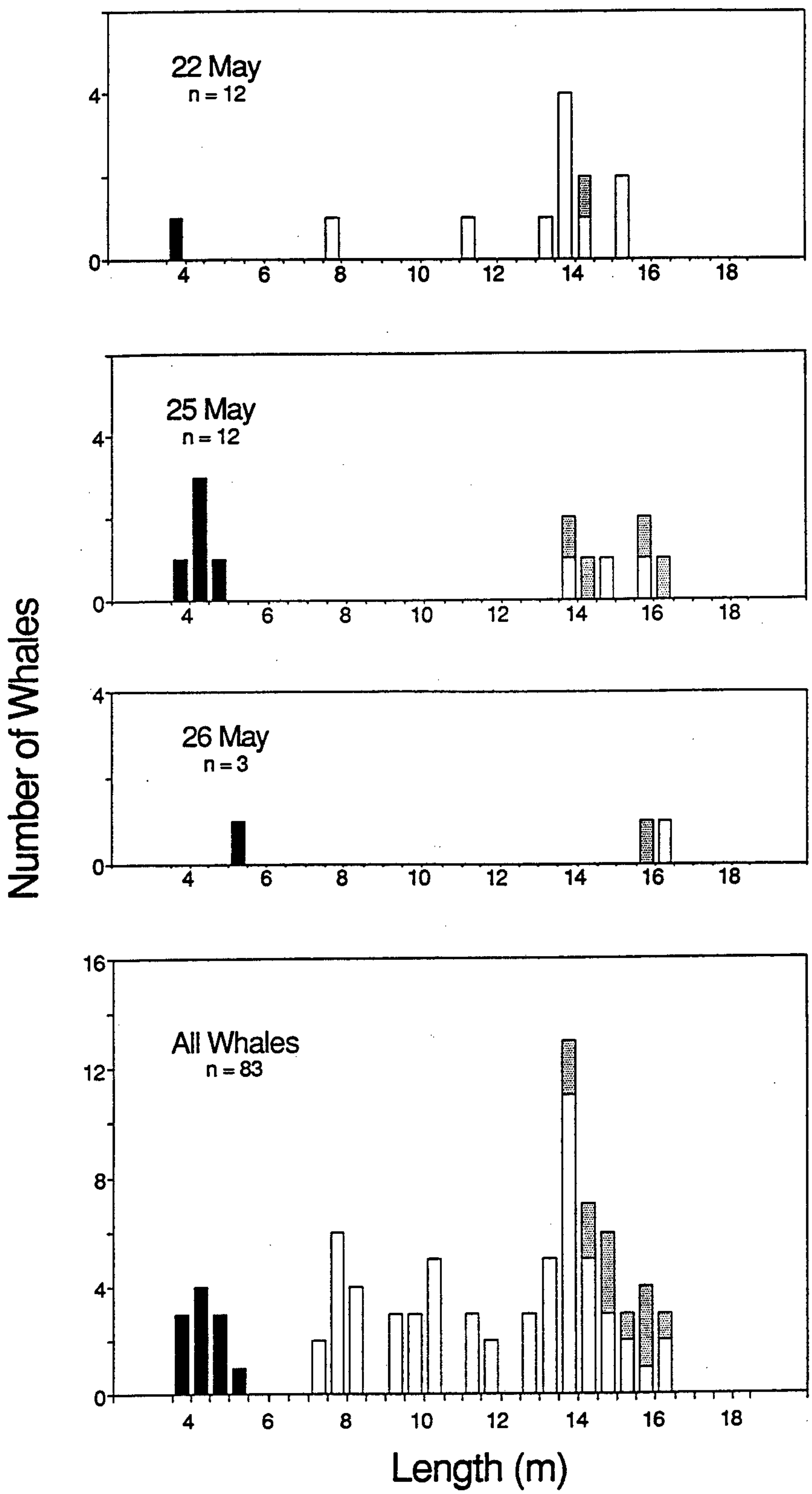

FIGURE 5.20 (continued).

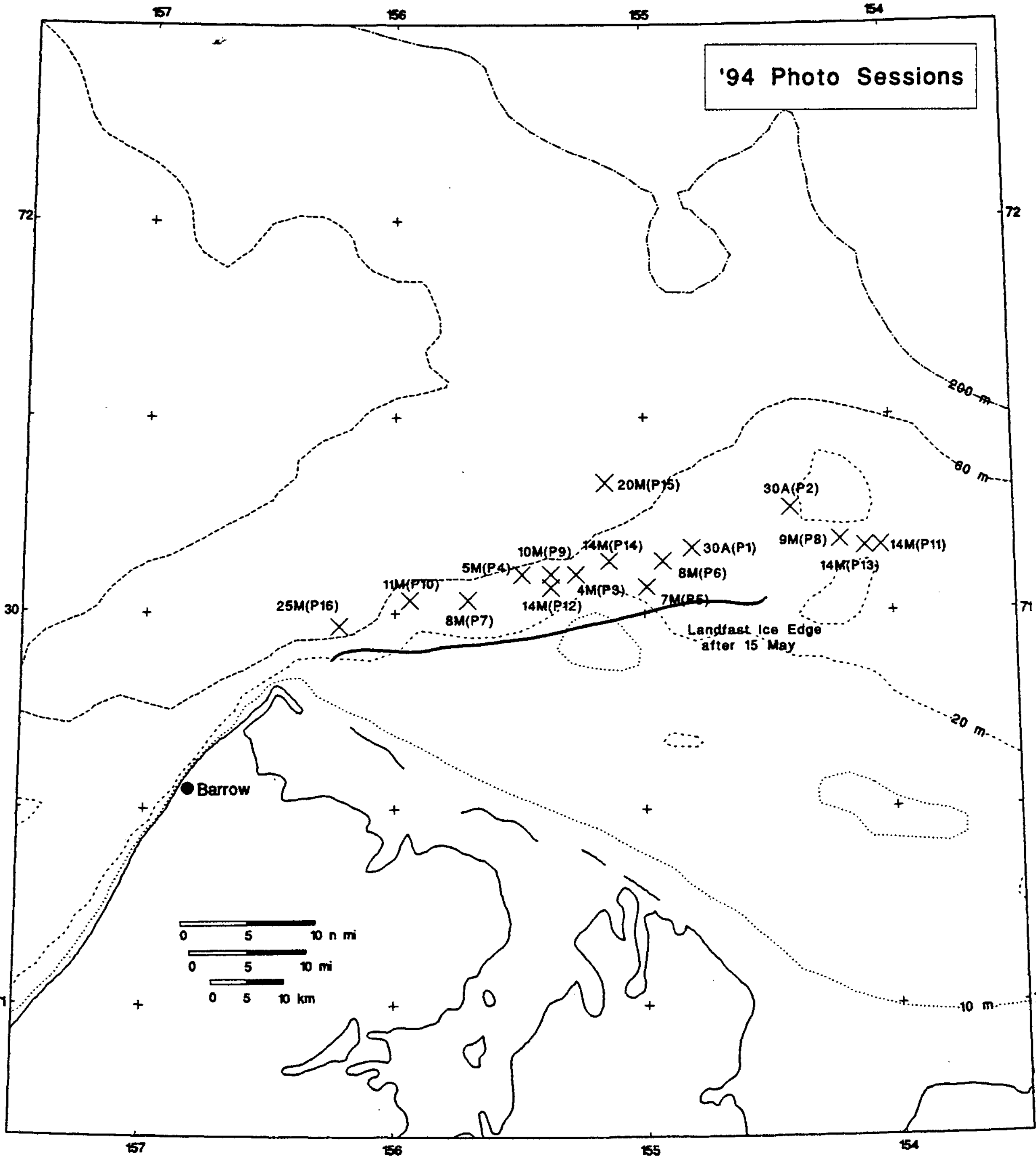

FIGURE 5.21. Locations where vertical photographs of bowhead whales were obtained by the aerial crew, 30 April to 25 May 1994. Annotations represent the date in April (A) or May (M) and, in parentheses, the photo session number (P1-P16).

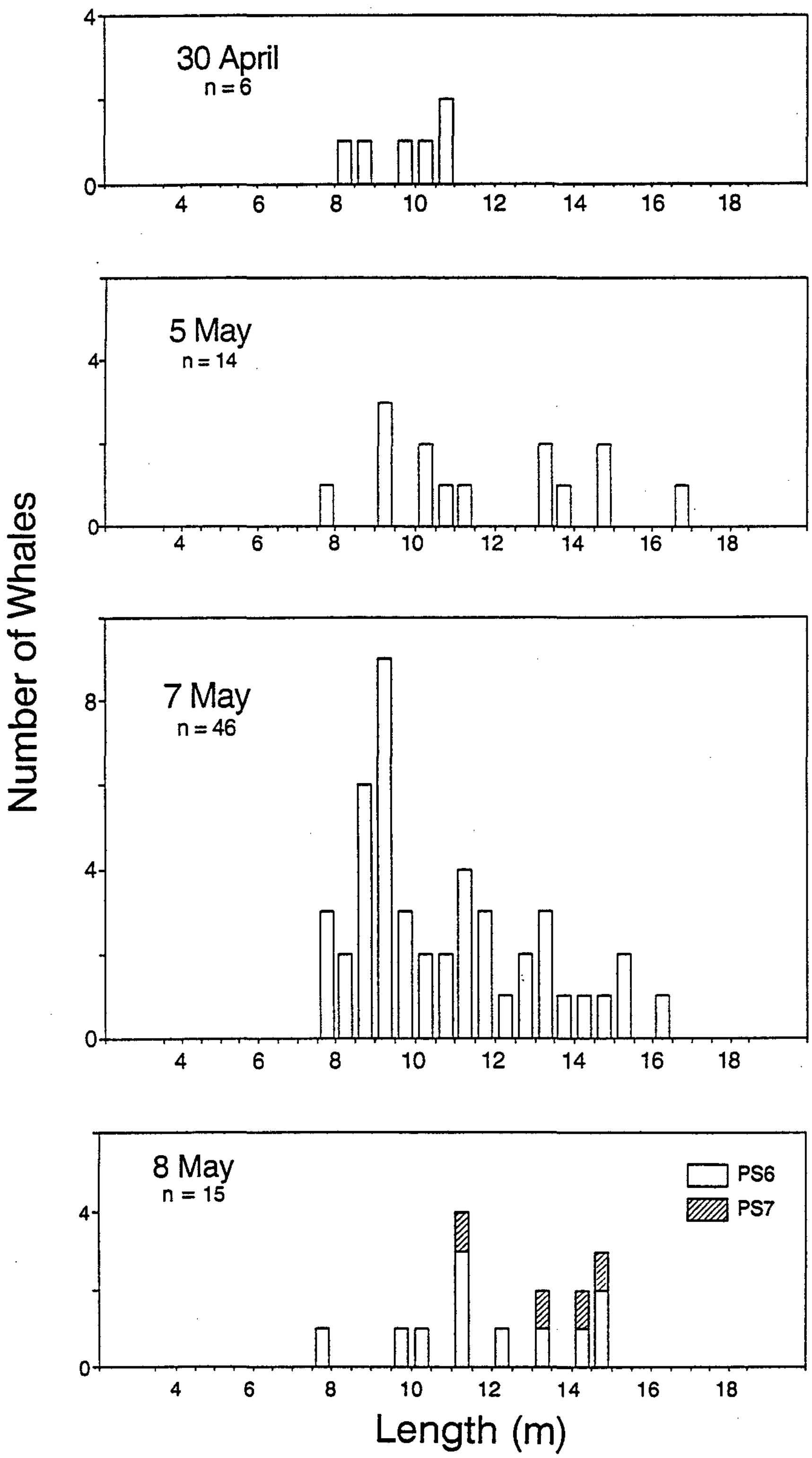

FIGURE 5.22. Length-frequency distributions for bowhead whales photographed during this study, 30 April-25 May 1994. Repeat measurements are excluded.

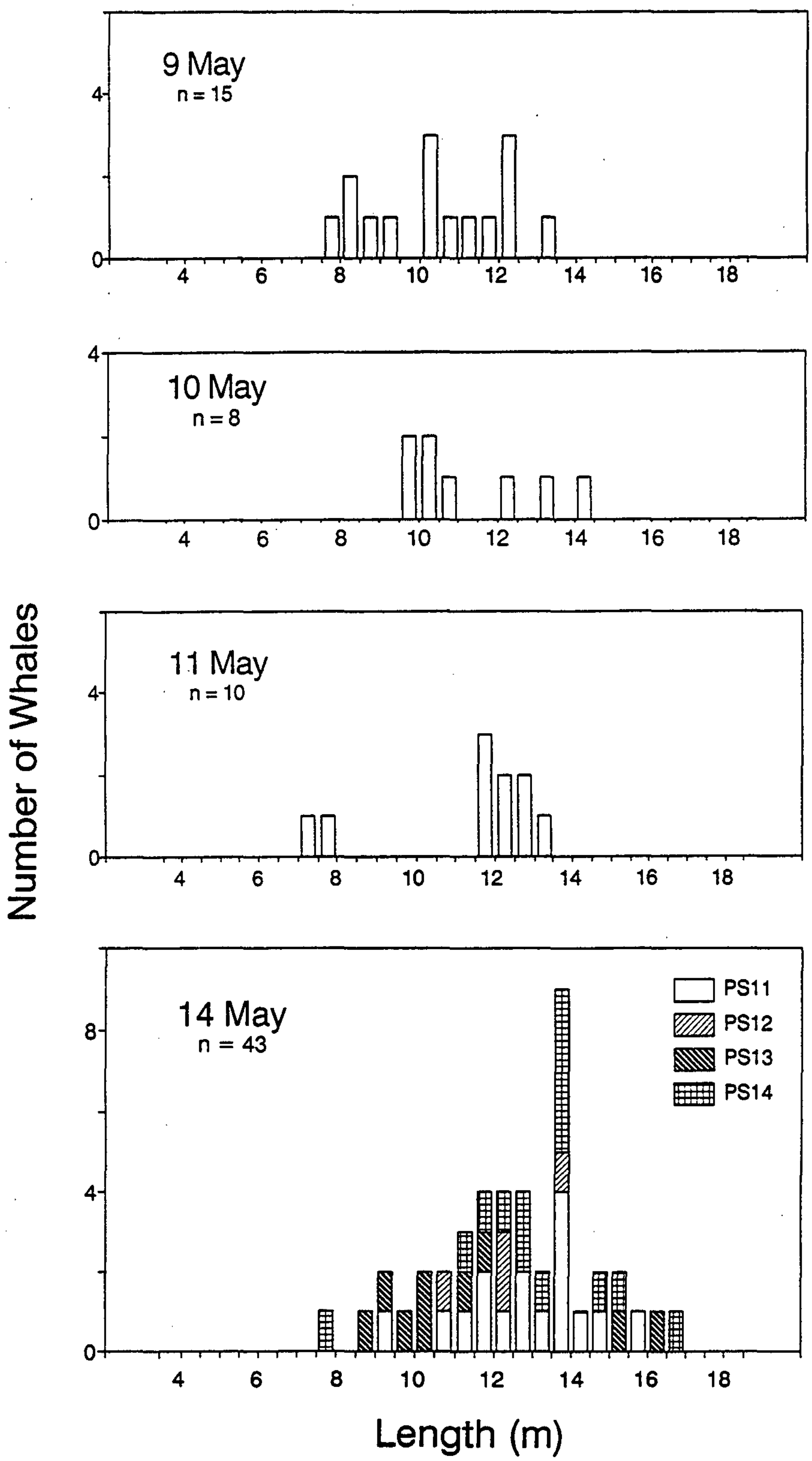

FIGURE 5.22 (continued).

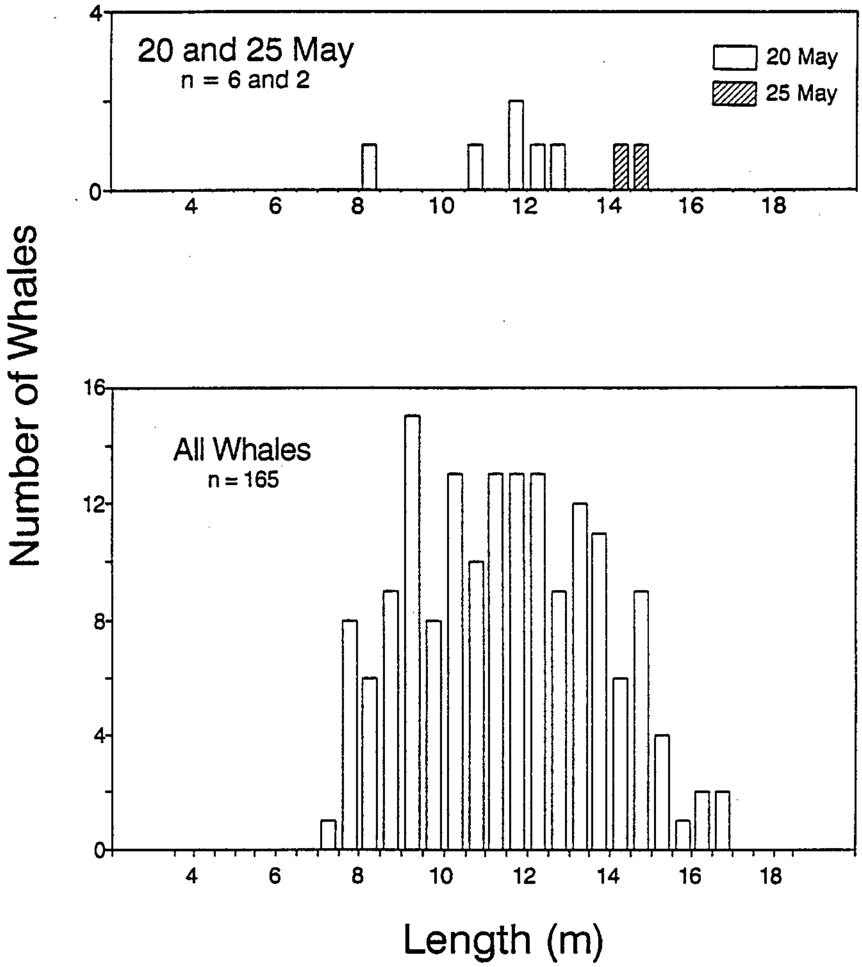

FIGURE 5.22 (continued).

Large subadults predominated (11 of 18) among whales measured from photographs obtained on 10 and 11 May. Furthermore, four of the other seven whales photographed on these dates bordered on the 10-13 m large subadult category; they were 9.5, <10.0, 13.1 and 13.2 m long. Two very small subadults were photographed on 11 May; they were 7.3 and 7.6 m long and may have been yearlings.

Forty-three different bowheads were measured from photographs taken on 14 May. The main migration of adult whales appears to have started about this time; 44% of the measured whales were adults. Most (44%) of the remaining whales were large subadults.

All of the few bowheads photographed on 20 May were subadults and all of those photographed on 25 May were adults (Fig. 5.22).

The combined length data from 1994 (Fig. 5.22) may not be representative of the overall length-frequency distribution of bowhead whales that migrated past Barrow in 1994 because of the limited effort to photograph whales after 14 May. Only 28% of all measured whales were adults.

This low proportion of adults would be expected given that few photographs were obtained during the last half of the migration when adult whales normally predominate near Barrow (Withrow and Angliss 1992, 1994). No mothers with calves were photographed in 1994; nor were any mothers from previous years photographed without a calf in 1994.

Bowhead Lengths, All Years.—Our data confirm observations by others that subadults predominate among the bowheads sighted before mid-May and that adults predominate among whales after mid-May (Fig. 5.23). Mothers and calves tend to occur during the latter stages of the migration. The earliest mother photographed (29 April) was accompanied by a yearling. The other early record was of a mother with a calf on 11 May 1991. Also, the latest adult photographed without a calf was an animal that was a mother in a previous year. The data from Figure 5.23 are summarized below by ten-day period according to whale status:

		Subadults		Adults[a]	
Period	Calves	Small[a]	Large[a]	Others	Mothers
Late April	0	3	3	0	1[b]
1-10 May	0	45	46	33	0
11-20 May	4	16	35	41	6
21-29 May	17	1	1	13	17

[a] Small: <10 m; Large: ≥10 and <13 m; Adult: ≥13 m. [b] This mother accompanied by yearling.

Figure 5.23 contains a small group of 11 whales ~7-8.1 m long that were photographed 11-22 May. By this time most small subadults have passed Barrow. Only one whale 8.1-9.3 m long was photographed by us later than 9 May during all years of this study. Based on the combination of size and temporal segregation, these small whales probably were yearlings that either had recently separated from their mothers or were migrating more slowly than other subadults.

The mean length of nine mothers measured in 1989 was 14.96 m ± s.d. 0.77 m, with range 13.9-15.9 (excluding one approximate length). The mean length of 10 mothers (excluding the mother of the yearling and one approximate length) measured during 1991 was 14.77 m ± s.d. 0.85 m, with range 13.3-15.8 m (no inter-day repeats). The mean length for mothers was not significantly different in 1991 than in 1989 ($t=0.51$, $P>0.50$) and was similar to the mean lengths of mothers reported in other studies (*cf.* Withrow and Angliss 1992; Koski et al. 1993). One of the mothers photographed in 1991 was the smallest mother photographed to date during the spring migration; it was 13.3 m long, slightly smaller than a 13.4 m mother photographed by NMML in 1989 (Koski et al. 1993).

The mean length of eight calves measured during 1989 was 4.62 m ± s.d. 0.32 m, with range 4.0-5.0 m (excludes two approximate lengths). The mean length of 10 calves measured during 1991 was 4.25 m ± s.d. 0.46 m, with range 3.7-5.1 m (excludes one approximate length; no inter-day repeats). This mean length for calves in 1991 is significantly smaller ($t=3.26$, $P<0.002$) than the value reported for the spring seasons of 1985-90: 4.74 m ± s.d. 0.45 m, $n = 88$ (Koski et al.

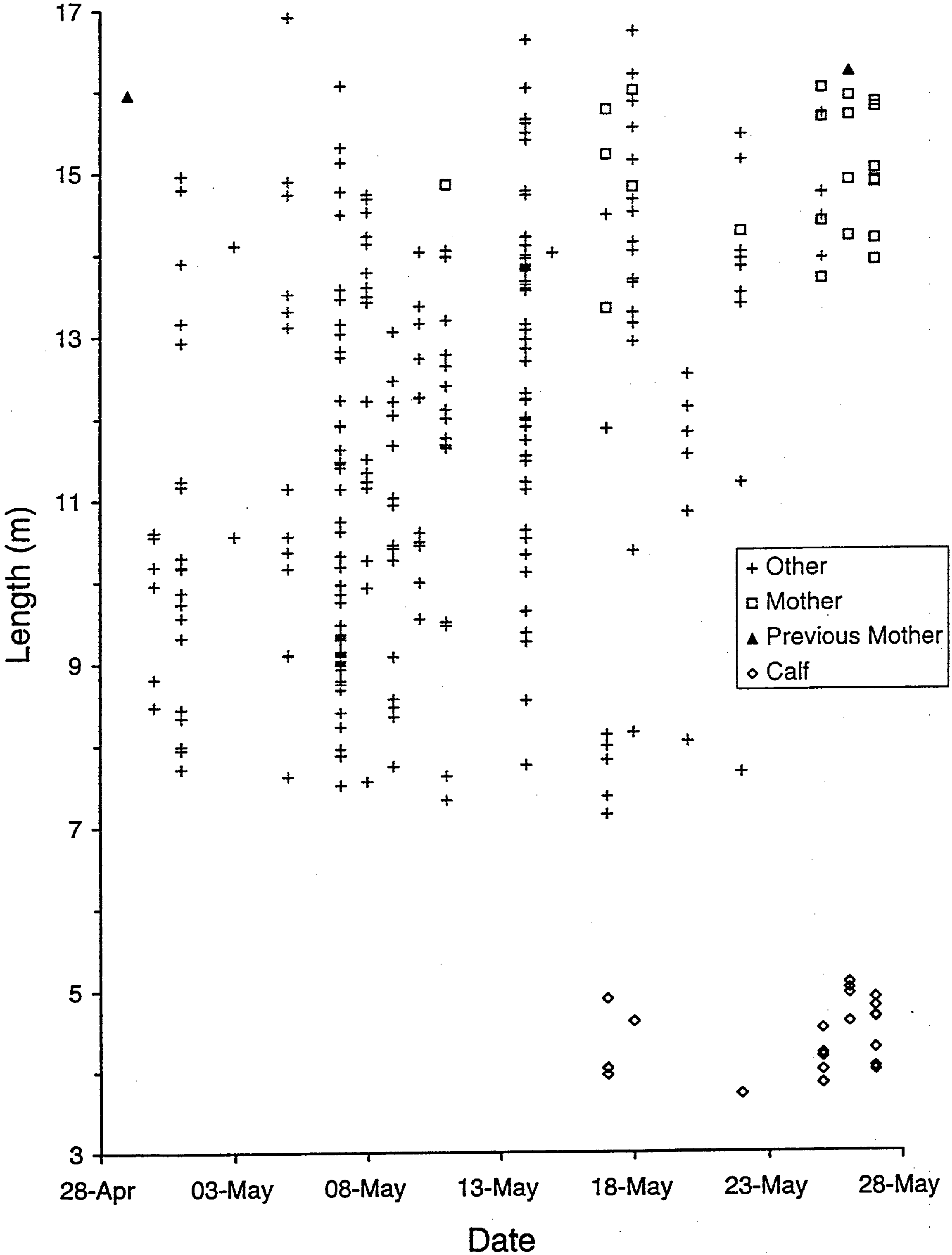

FIGURE 5.23. Lengths of bowheads vs. date photographed near Barrow, Alaska, during late April and May of 1989, 1991 and 1994. Different symbols are plotted for mothers with calves (open square), whales without calves that had been mothers with calves in previous years (closed triangle), calves (open diamond) and others (plus sign).

1993). The smallest calf that we measured during 1991 (3.7 m long) was, however, larger than the smallest calf (3.6 m) reported by Koski et al. (1993).

During this spring study we obtained 16 pairs of length measurements for both members of a mother-calf pair. There was a significant correlation between the length of a mother and the length of her calf ($r=0.70$, $df=14$, $P<0.01$; Fig. 5.24A). A similar correlation was found during summer studies (Davis et al. 1983), but has not been found previously for spring data (Nerini et al. 1987). This correlation suggests that larger whales either calve earlier, or have larger calves.

There was no strong correlation between the date a calf was photographed and its length ($r=0.23$, $df=16$, $P>0.05$; Fig. 5.24B). However, the brief period of spring migration past Barrow (mid-May to early June) in comparison to the prolonged calving period (March to July, Nerini et al. 1984; Koski et al. 1993) may obscure any possible correlation between length at birth and date. Fig. 5.24A shows that the minimum-sized calf was 3.8-4.2 m long regardless of the length of the mother. This suggests that, although minimum calf size may be slightly longer for larger mothers, the larger calves photographed with the longer mothers were probably born earlier in the season.

The length data collected during this study are consistent with previous studies in documenting temporal segregation of bowheads during the spring migration based on their length (Nerini et al. 1987; Withrow and Angliss 1991). Our data also hint that yearling bowheads may tend to migrate later than other small subadults. However, this needs confirmation from a larger data base (i.e. the NMML study) and from other years.

Photographic Resightings of Identifiable Bowheads

Many bowheads, especially the larger and older ones, have distinctive scars or other marks that make them individually identifiable in vertical photographs. Short-term resightings of the same known individuals during this study provided information on speed and direction of travel, including comparative data for mothers and calves vs. other bowheads. Resightings from one year to the next contributed to the gradually-accumulating datasets on growth rates of whales of varying sizes (Koski et al. 1992), calving intervals of adult females (Miller et al. 1992), and the timing of migration of the same whales in different years.

Sample Sizes.—In May ***1989*** LGL acquired a total of 45 potentially re-identifiable (Grade A and B, see §2.2, p. 34) photographic images of bowheads (Table 5.3A). These images were of 20 different bowheads photographed on 14-29 May at locations mapped in Figure 5.19A.

Nine re-identifiable bowheads were photographed once, seven were photographed twice, three were photographed three times, and one was photographed 13 times on three days (27-29 May). Seven of these re-identifiable bowheads were accompanied by calves, including the one photographed on 27-29 May. Images of 15 of the 20 different recognizable whales were Grade A.

We also obtained Grade A and B images of 47 bowheads photographed near Barrow by NMML on 12-31 May 1989. These NMML images were compared to each other and to all of the 1989 LGL images.

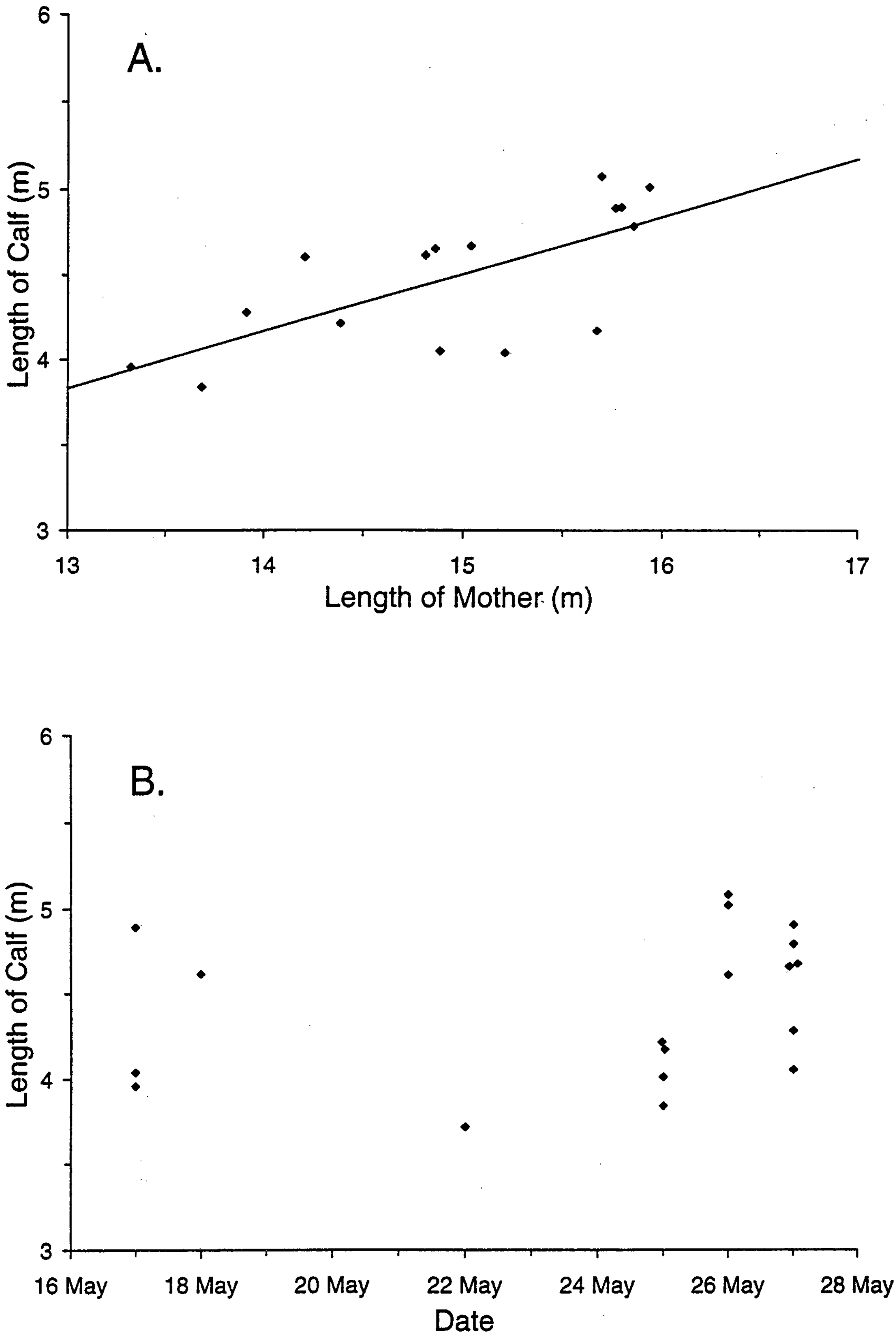

FIGURE 5.24. Lengths of bowhead whale calves vs. *(A)* the lengths of their mothers and *(B)* date.

TABLE 5.3A. Number of photographs of recognizable bowhead whales acquired during LGL's 1989 photo sessions.

Photo Session	Date	Number of Whale Images		Number of Whales Photographed 1, 2,....,5 Times[a]					Number of Whales Potentially Recognizable Between Days[b]	Number of Between-session Resightings
		Printed	Grades A and B[a]	1[b]	2	3	4	5		
P1	3 May	0	0						0	
P2	14 May	6	5	0	1	1			2	
P3	15 May	1	1	1					1	
P4	15 May	1	1	1					1	
P5	18 May	11	11	4	2	1			7	
P6	26 May	7	7	2	1	1			4	
P7	27 May	5	5	1	2				3	
P8	27 May	6	6	0	1	0	1		2	2 (P9, P10)
P9	28 May	5	5	0	0	0	0	1	1	2 (P8, P10)
P10	29 May	4	4	0	0	0	1		1	2 (P8, P9)
		—	—	—	—	—	—	—	—	
		46	45	9	7	3	2	1	20[c]	

[a] Excludes calves, which were individually recognizable primarily through their associations with their mothers.
[b] These figures are maxima because some repeat photographs may not have been recognized.
[c] This total was reduced by two to account for between-session resightings of the same whale.

TABLE 5.3B. Number of photographs of recognizable bowhead whales acquired during LGL's 1991 photo sessions.

Photo Session	Date	Number of Whale Images: Printed	Number of Whale Images: Grades A and B[a]	Number of Whales Photographed 1, 2,....,7 Times[a]: 1[b]	2	3	4	5	6	7	Number of Whales Potentially Recognizable Between Days[b]	Number of Between-session Resightings
P1	29 Apr	1	1	1							1	
P2	1 May	0	0								0	
P2A	1 May	20	20	9	2	1	1				13	
P2B	1 May	8	8	8							8	
P3A	8 May	1	1	1							1	
P3B	8 May	2	1	1							1	
P4	10 May	8	6	6							6	
P5	11 May	11	10	6	2						8	
P6	17 May	3	3	3							3	
P7	17 May	22	12		1	1				1	3	
P8	17 May	10	9	4	1	1					6	2 (P7)
P9	17 May	6	4		2						2	
P10A	18 May	5	5		1	1					2	
P10B	18 May	29	22	5	2	2				1	10	
P11	22 May	29	25	7	3	4					14	
P12	25 May	38	19	8	1	1			1		11	
P13	26 May	7	5		1	1					2	
		200	151	59	16	12	1		1	2	89[c]	

[a] Excludes calves, which were individually recognizable primarily through their associations with their mothers.
[b] These figures are maxima because some repeat photographs may not have been recognized.
[c] This total was reduced by two to account for between-session re-identifications.

In late April and May ***1991***, LGL acquired a total of 151 Grade A and B images of adult or sub-adult bowheads and 34 images of calves that were re-identifiable primarily only through their associations with their mothers. Locations of the 1991 photo sessions are shown in Figure 5.19B. Excluding the calves, 89 different bowheads were photographed from 29 April to 26 May (Table 5.3B). Images of 36 of these whales were considered likely to be recognizable if a photographic image of similar or better quality were acquired in another year.

We also obtained 285 images of 179 re-identifiable bowheads photographed near Barrow by NMML from 22 April to 3 June 1991. These images were compared to each other and to the 1991 LGL images. NMML images of 38 different bowheads were considered to be Grade A.

In late April and May ***1994***, LGL obtained 232 Grade A and B images of 204 different bowheads (Table 5.4). Locations of the 1994 photo sessions are shown in Figure 5.21. Grade A images of 41 bowheads were acquired. NMML did not conduct fieldwork near Barrow in the spring of 1994.

Within-Season Resightings

Aerial photography documented the within-season movements of recognizable bowheads that were photographed over intervals of minutes, hours or days. Three types of within-season resightings were considered. These included short-term within-session resightings of whales photographed by LGL, and longer-term between-session resightings of whales photographed by LGL and/or NMML during two sessions within one day or during two sessions on different days.[11,12]

Within-Session Resightings.—Of the short-term within-session resightings, only those obtained over intervals of ≥15 minutes are considered here. These intervals ranged from 15 to 68 minutes.[13]

In ***1989***, three adult whales were involved in four within-session resightings over intervals of ≥15 minutes (Table 5.5A). Two of these whales, including one photographed on two days, were accompanied by calves. The four resightings occurred over intervals of 18-43 min. These whales moved at apparent speeds of 2.4-5.2 km/h (mean 3.95 km/h) and on headings ranging from 90 to 276°T (vector mean heading 98°T, angular deviation (a.d.) 58°).

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[11] In 1989, five of our 20 different recognizable bowheads (25%) were also photographed by NMML, and a sixth bowhead, not photographed by us, was photographed by NMML on two different days.

[12] Among the 1991 photos, there were two bowheads that were each photographed during two different LGL photo sessions conducted 3.4 h apart on 17 May. One of these whales was also photographed by NMML 1 h after we first photographed it. There were an additional 8 between-session resightings of whales photographed by both LGL and NMML, and 6 between-session resightings of whales photographed by NMML only.

[13] Although bowheads were often re-photographed at intervals less than 15 min, their locations may not be known with sufficient accuracy for meaningful heading or speed estimates.

TABLE 5.4. Number of photographs of recognizable bowhead whales acquired during LGL's 1994 photo sessions.

Photo Session	Date	Number of Whale Images: Printed	Number of Whale Images: Grades A and B	Number of Whales Photographed 1, 2, 3 Times: 1[a]	Number of Whales Photographed 1, 2, 3 Times: 2	Number of Whales Photographed 1, 2, 3 Times: 3	Number of Whales Potentially Recognizable Between Days[a]	Number of Between-session Resightings
P1	30 Apr	4	4	4			4	
P2	30 Apr	3	3	1	1		2	
P3	4 May	5	5	5			5	
P4	5 May	30	16	14	1		15	
P5	7 May	76	63	54	3	1	58	
P6	8 May	21	19	10	3	1	14	
P7	8 May	8	4	4			4	
P8	9 May	23	22	18	2		20	
P9	10 May	12	7	7			7	
P10	11 May	17	15	11	2		13	
P11	14 May	26	20	18	1		19	
P12	14 May	9	8	8			8	
P13	14 May	15	14	11	0	1	12	
P14	14 May	18	17	14	0	1	15	
P15	20 May	12	12	2	2	2	6	
P16	25 May	3	3	1	1		2	
		282	232	182	16	6	204	0

[a] These figures are maxima because some repeat photographs may not have been recognized.

TABLE 5.5A. Within-session resightings (≥15 minutes) of bowheads photographed by LGL in 1989, 1991 and 1994.

Year	Whale Number	First Photographed Date	First Photographed Time	First Photographed Latitude	First Photographed Longitude	Resighting (s) Time	Resighting (s) Latitude	Resighting (s) Longitude	Minutes Between Sightings	Net Distance Between Sightings (km)	Apparent Speed (km/h)	Heading (°T)	Whale Length (m)	Accompanied by Calf?
1989	8610	18 May	11:31:20	71°35.9'N	156°01.1'W	12:14:00	71°35.4'N	155°57.4'W	43	2.4	3.3	113	15.5	no
	8641	27 May	11:50:30	71°33.2'N	154°24.9'W	12:17:30	71°33.2'N	154°20.9'W	27	2.3	5.2	90	15.9	yes
	8647	27 May	20:28:50	71°37.2'N	155°19.4'W	20:46:30	71°37.2'N	155°18.2'W	18	0.7	2.4	90	14.9	yes
	8647	28 May	12:41:10	71°39.1'N	155°03.3'W	13:04:45	71°39.2'N	155°06.6'W	24	1.9	4.9	276	14.9	yes
	Mean								**28.0**	**1.82**	**3.95**	**98**		
1991	9662	1 May	16:40:52	71°39.5'N	154°58.4'W	17:04:04	71°40.2'N	155°01.2'W	23	2.1	5.4	308	8.3	no
	9663	1 May	16:40:52	71°39.5'N	154°58.4'W	17:04:04	71°40.2'N	155°01.2'W	23	2.1	5.4	308	7.9	no
	9664	1 May	16:45:54	71°40.1'N	155°00.9'W	17:15:04	71°40.7'N	154°59.7'W	29	1.3	2.7	32	9.9	no
	9667	1 May	16:47:49	71°40.2'N	155°00.2'W	17:03:00	71°40.4'N	155°01.4'W	15	0.8	3.1	298	13.2	no
	9711	11 May	15:56:05	71°35.5'N	155°47.3'W	16:28:08	71°35.8'N	155°44.1'W	32	2.0	3.7	73	14.0	no
	9717	17 May	12:44:18	71°33.0'N	155°18.7'W	13:27:43	71°32.7'N	155°21.4'W	43	1.7	2.3	251	15.2	yes
	9719	17 May	12:52:13	71°33.4'N	155°17.6'W	13:21:30	71°32.5'N	155°19.4'W	29	2.0	4.0	212	13.3	yes
	4239	18 May	17:53:56	71°38.1'N	156°14.8'W	18:36:48	71°35.8'N	156°09.9'W	43	5.1	7.2	146	14.8	yes
	7781	18 May	18:28:58	71°35.6'N	156°06.2'W	19:02:20	71°35.4'N	156°02.4'W	33	2.3	4.1	99	14.0	no
	9763	18 May	18:00:26	71°37.6'N	156°13.9'W	18:17:45	71°37.6'N	156°14.0'W	17	0.1	0.2	270	8.1	no
	9767	18 May	18:09:49	71°36.7'N	156°14.3'W	18:54:10	71°35.9'N	156°08.0'W	44	4.0	5.4	112	12.9	no
	9779	18 May	18:32:08	71°35.6'N	156°06.5'W	18:58:43	71°35.2'N	156°04.1'W	27	1.6	3.6	118	13.6	no
	9800	22 May	20:49:14	71°36.0'N	155°50.7'W	21:17:54	71°36.6'N	155°46.3'W	29	2.8	5.9	67	11.2	no
	9823	25 May	16:23:13	71°42.2'N	154°50.3'W	17:31:29	71°44.4'N	154°52.8'W	68	4.3	3.8	340	13.7	yes
	9841	25 May	17:42:23	71°42.0'N	154°52.0'W	18:13:10	71°43.0'N	154°49.7'W	31	2.3	4.5	36	14.7	no
	Mean								**32.4**	**2.30**	**4.09**	**29**		
1994	10104	7 May	18:35:34	71°35.0'N	154°43.6'W	19:43:05	71°35.1'N	154°40.4'W	68	1.9	1.7	84	9.3	no
	10238	11 May	13:34:35	71°30.4'N	155°58.7'W	13:56:40	71°30.6'N	155°56.4'W	22	1.4	3.8	75	12.8	no
	10220	11 May	13:50:01	71°30.5'N	155°56.6'W	14:21:00	71°30.9'N	155°52.7'W	31	2.4	4.7	72	13.2	no
	1350	14 May	18:13:43	71°34.4'N	155°02.6'W	18:28:50	71°34.3'N	155°01.9'W	15	0.4	1.7	103	15.4	no
	10322	20 May	17:30:26	71°37.2'N	155°22.5'W	18:01:55	71°37.5'N	155°18.8'W	31	2.2	4.2	76	8.0	no
	10323	20 May	17:30:26	71°37.2'N	155°22.5'W	18:01:55	71°37.5'N	155°18.8'W	31	2.2	4.2	76	10.8	no
	Mean								**33.0**	**1.75**	**3.38**	**81**		

TABLE 5.5B. Between-session resightings of bowheads photographed by LGL and NMML, spring 1989 and 1991 (no such cases in 1994). * at right side denotes within-day between-session resightings.

Source of Photos	Year	Whale Number	First Photographed Date	First Photographed Time	First Photographed Latitude	First Photographed Longitude	Resighting (s) Date	Resighting (s) Time	Resighting (s) Latitude	Resighting (s) Longitude	Hours Between Sightings	Net Distance Between Sightings (km)	Apparent Speed (km/h)	Heading (°T)	Whale Length (m)	Accompanied by Calf?	
NMML-NMML	1989	1057	17 May	16:22:08	71°35.5'N	155°52.9'W	18 May	15:13:51	71°36.7'N	155°42.8'W	22.9	6.3	0.3	69	15.0	no	
NMML-LGL	"	1311	17 May	16:35:32	71°35.8'N	155°54.7'W	18 May	11:39:30	71°34.3'N	156°15.8'W	19.1	12.6	0.7	257	16.0	yes	
LGL-NMML	"	8617	18 May	12:00:30	71°34.6'N	156°07.7'W	18 May	15:09:08	71°36.3'N	155°46.6'W	3.1	12.7	4.1	76	14.5	no	*
LGL-NMML	"	8516	18 May	12:00:30	71°34.6'N	156°07.7'W	18 May	15:09:50	71°36.5'N	155°47.0'W	3.2	12.6	4.0	74	15.1	no	*
LGL-NMML	"	8622	26 May	00:04:15	71°37.7'N	155°30.1'W	27 May	11:23:10	71°39.9'N	155°20.6'W	35.3	6.9	0.2	54	14.2	yes	
LGL-NMML	"	8647	27 May	20:28:50	71°37.2'N	155°19.4'W	28 May	11:14:34	71°40.5'N	155°01.1'W	14.8	12.3	0.8	60	14.9	yes	
-LGL	"						28 May	12:50:30	71°38.9'N	155°04.7'W	1.6	3.6	2.3	215			*
-NMML	"						29 May	11:26:57	71°41.1'N	155°07.8'W	22.6	4.5	0.2	336			
-LGL	"						29 May	15:32:50	71°42.3'N	155°08.2'W	4.1	2.2	0.5	354			*
NMML-LGL	1991	9667	1 May	14:04:58	71°35.5'N	155°06.0'W	1 May	16:47:49	71°40.2'N	155°00.2'W	2.7	9.3	3.4	21	13.2	no	*
NMML-LGL	"	4220	1 May	14:54:20	71°35.9'N	155°04.5'W	1 May	16:55:15	71°40.3'N	154°55.9'W	2.0	9.6	4.7	32	12.9	no	*
NMML-LGL	"	9673	1 May	15:25:47	71°36.4'N	155°04.3'W	1 May	16:59:00	71°39.7'N	155°03.1'W	1.6	6.1	4.0	7	15.0	no	*
NMML-LGL	"	9304	10 May	12:33:33	71°37.4'N	155°37.6'W	11 May	16:38:01	71°38.6'N	155°41.3'W	28.1	3.1	0.1	316	14.8	yes	
NMML-LGL	"	9710	11 May	13:08:27	71°31.0'N	155°54.0'W	11 May	15:36:35	71°35.8'N	155°41.0'W	2.5	11.7	4.7	40	11.7	no	*
NMML-LGL	"	9708	11 May	13:20:00	71°32.0'N	155°53.4'W	11 May	15:26:50	71°35.4'N	155°44.5'W	2.1	8.2	3.9	40	11.7	no	*
NMML-LGL	"	9704	11 May	13:22:35	71°32.2'N	155°53.4'W	11 May	15:25:30	71°35.4'N	155°44.7'W	2.0	7.8	3.8	41	9.4	no	*
LGL-NMML	"	9719	17 May	13:21:30	71°32.5'N	155°19.4'W	17 May	14:21:55	71°32.4'N	155°22.3'W	1.0	1.7	1.7	264	13.3	yes	*
-LGL							17 May	17:06:05	71°33.4'N	155°17.5'W	2.7	3.4	1.2	57			*
LGL-LGL	"	9723	17 May	13:08:53	71°33.2'N	155°18.1'W	17 May	16:59:38	71°33.1'N	155°11.7'W	3.8	3.8	1.0	93	7.8	no	*
NMML-LGL	"	9813	20 May	14:36:35	71°40.6'N	155°57.2'W	22 May	22:09:46	71°43.2'N	154°15.5'W	55.6	59.3	1.1	85	13.6	yes	
NMML-NMML	"	10618	25 May	11:23:06	71°28.6'N	155°57.8'W	26 May	12:33:25	71°29.3'N	155°53.3'W	25.2	2.9	0.1	64	14.6	no	
NMML-NMML	"	10620	26 May	11:53:07	71°29.1'N	155°52.3'W	27 May	11:46:57	71°30.4'N	155°16.9'W	23.9	20.9	0.9	83	13.5	no	
NMML-NMML	"	10622	26 May	11:57:04	71°29.5'N	155°52.3'W	27 May	12:26:07	71°30.5'N	155°24.5'W	24.5	16.4	0.7	83	12.9	no	
NMML-NMML	"	10624	26 May	12:10:53	71°29.4'N	155°43.6'W	27 May	11:39:48	71°30.1'N	155°15.7'W	23.5	16.4	0.7	85	13.8	no	
NMML-NMML	"	10627	26 May	12:19:03	71°28.9'N	155°48.6'W	27 May	11:46:49	71°30.6'N	155°17.6'W	23.5	18.5	0.8	80	13.9	no	
NMML-NMML	"	10635	26 May	13:10:36	71°28.8'N	155°46.4'W	31 May	11:58:31	71°29.1'N	155°43.7'W	118.8	1.7	0.0	71	13.9	no	

In ***1991***, the 15 within-session resightings occurred over intervals of 15-68 min, and averaged 32.4 min (Table 5.5A). Net distances traveled were 0.1-5.1 km (mean 2.30 km) and apparent speeds averaged 4.09 km/h (range 0.2-7.2 km/h). Headings were extremely variable, ranging from 32 to 340°, with vector mean 29°T ± a.d. 75°.

In ***1994***, six within-session bowhead resightings were observed, consisting of four sub-adults and two adults. None of the adults were accompanied by calves (Table 5.5A). These resightings occurred over intervals averaging 33 min (range 15-68 min). The average net distance traveled was 1.75 km (range 0.4-2.4 km) and the average apparent speed was 3.38 km/h (range 1.7-4.7 km/h). Headings were easterly, ranging from 72 to 103°T (vector mean 81°T ± a.d. 10°).

In all years combined, excluding mother-calf pairs, ***other whales*** reidentified within sessions (n= 18) were resighted over intervals averaging 30.2 min (range 15-68 min). Their headings varied considerably, ranging from 32° to 308°T with a vector mean of 68° ± a.d. 55°. Net speeds averaged 3.74 ± s.d. 1.48 km/h (range 0.20-5.87).

There were no significant correlations between whale speed vs. resighting interval (r=0.011, df=16, P>0.50), whale speed vs. whale length (r= -0.002, df=16, P>0.50), or whale speed vs. date (r=0.063, df=16, P>0.50).

Mother-calf pairs reidentified within-sessions during the three years of study (n=7) were resighted over intervals averaging 36.0 min (range 18-68 min). Their headings varied markedly, ranging from 90° to 340°, with vector mean 195° ± a.d. 75°. Only 3 of 7 (43%) mother-calf headings had an easterly (1°-179°) component; four (57%) had a westerly (181°-359°) component. Among the resighted bowheads other than mothers and calves, 14 of 18 observed headings (78%) had easterly components and only four (22%) had westerly components. However, the observed mother-calf headings were not significantly different from those of other whales (Watson U^2=0.118, n_1=7, n_2=18, P>0.10)

Net speeds of mother-calf pairs averaged 4.26 ± s.d. 1.71 km/h (range 2.32-7.19). Net speed showed no obvious relationship to the interval between photos (r=0.066), whale length (r=0.106), or date (r= -0.059), but the sample size was very small (n=7). The net speeds of mother-calf pairs averaged slightly higher than those of "other" whales but the difference was not significant (t=0.76, df=23, P>0.2).

Considering ***all whales*** reidentified within sessions during the three years when we conducted photography (n=25), the mean speed over periods of 15-68 min was 3.89 ± s.d. 1.48 km/h and the vector mean heading was 73°T ± a.d. 64°). This is similar to the mean speed of 4.0 km/h and "normal headings" of 49-105° that were recorded by Rugh (1990).

<u>Between-Session Within-Day Resightings</u>.—A total of 13 same-day between-session resightings occurred over intervals of 1.0 to 4.1 h, considering the pooled LGL and NMML photographs from the three years (cases marked "*" in Table 5.5B).

In ***1989*** there were four between-session within-day resightings of three whales or mother-calf pairs (Table 5.5B, Figure 5.25). Two adult bowheads photographed together on 18 May were still near each other when resighted 3.1 h later. These bowheads had migrated about 13 km to the ENE at an apparent rate of 4.0 km/h. A mother-calf pair photographed on 27, 28 and 29 May was photographed during two different sessions on each of 28 and 29 May. (This pair was also among the whales resighted *within-sessions* in 1989, see above.) The between-session resighting intervals of this pair were 1.6 and 4.1 hours. This pair moved on headings of 215 (*southwest*) and 354°T (*north*), and traveled net distances between successive sightings of 3.6 and 2.2 km. Apparent speeds were 2.3 and 0.5 km/h. The calf in this pair was the smallest calf (4.0 m) photographed by us during 1989.

Overall in 1989, the four between-session within-day resightings occurred over resighting intervals averaging 3.0 h (range 1.6-4.1 h). Headings ranged from 74° to 354°T with vector mean 60° ± a.d. 65°. Net distances traveled were 2.2-12.7 km, and averaged 7.8 km. Apparent speeds were 0.5-4.1 km/h and averaged 2.72 km/h.

In ***1991*** there were nine between-session same-day resightings of bowheads.

- Three whales photographed in the same general area on 1 May were re-photographed 6.1-9.6 km to the NNE 1.6-2.7 h later. These whales (12.9-15.0 m in length) traveled at apparent speeds of 3.4-4.7 km/h (Fig. 5.26, Table 5.5B).
- Three subadult bowheads first photographed in the same general area on 11 May were resighted 2.0-2.5 h later 7.8-11.7 km to the NE. These whales traveled at apparent speeds of 3.8-4.7 km/h (Fig. 5.26, Table 5.5B).
- A 7.8 m bowhead resighted after 3.8 h on 17 May had traveled 3.8 km to the east, a rate of only about 1.0 km/h.
- A 13.3 m mother with a 4.0 m calf traveled 1.7 km to the *west* over a one hour period (1.7 km/h) on 17 May. This mother-calf pair was resighted again 2.7 h later about 3.4 km to the NE of its second location, having moved at an apparent rate of about 1.2 km/h. Considering only the first sighting and final resighting, this pair traveled 2 km to the NE over a 3.7 h period at an apparent rate of 0.53 km/h.

Overall in 1991, these 9 resightings occurred over intervals of 1.0-3.8 h, and averaging 2.27 h. Headings were 7°-264°T with vector mean 35°T ± a.d. 41°. Net distances traveled averaged 6.84 km (range 1.7-11.7 km), and apparent speeds averaged 3.16 km/h (range 1.0-4.7 km/h).

In ***1994***, no between-session resightings of bowheads were discovered. In part, this lack of inter-session resightings reflects the absence of 1994 NMML photographs. For example, in 1991 only 12% (2 of 16) of the between-session resightings were LGL-LGL resightings, and one of the whales involved in those resightings was also photographed by NMML. However, on some dates in 1994 (e.g., 14 May, Fig. 5.21, p. 170) we conducted several photo-sessions at different locations in our study area and over long time intervals (up to 8.7 h on 14 May)—a situation that offered the potential for resighting migrating bowheads.

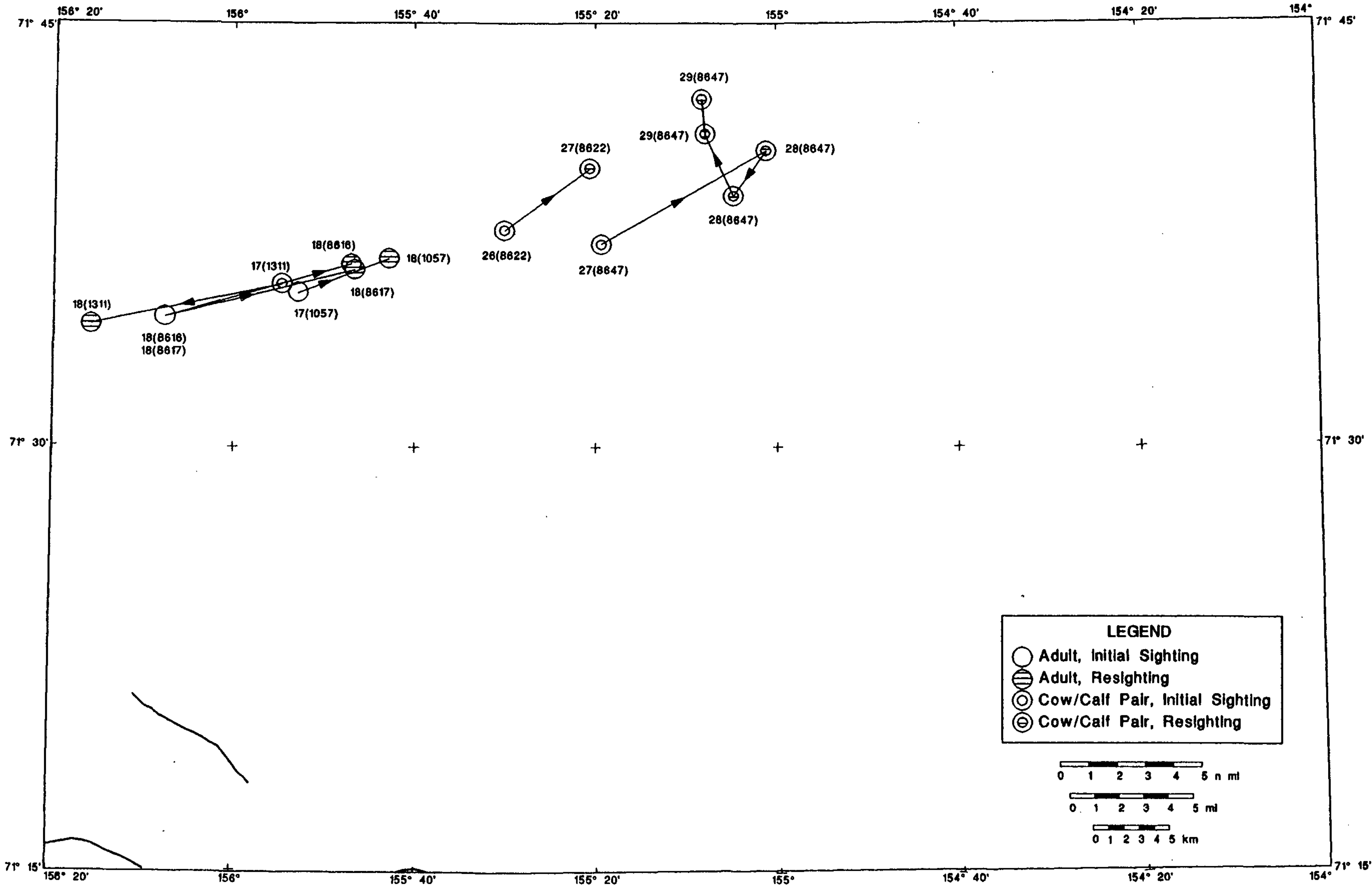

FIGURE 5.25. Between-session resightings of bowhead whales photographed northeast of Barrow during May 1989. Annotations show date in May and whale number in LGL's photo catalog. See Table 5.5B for details.

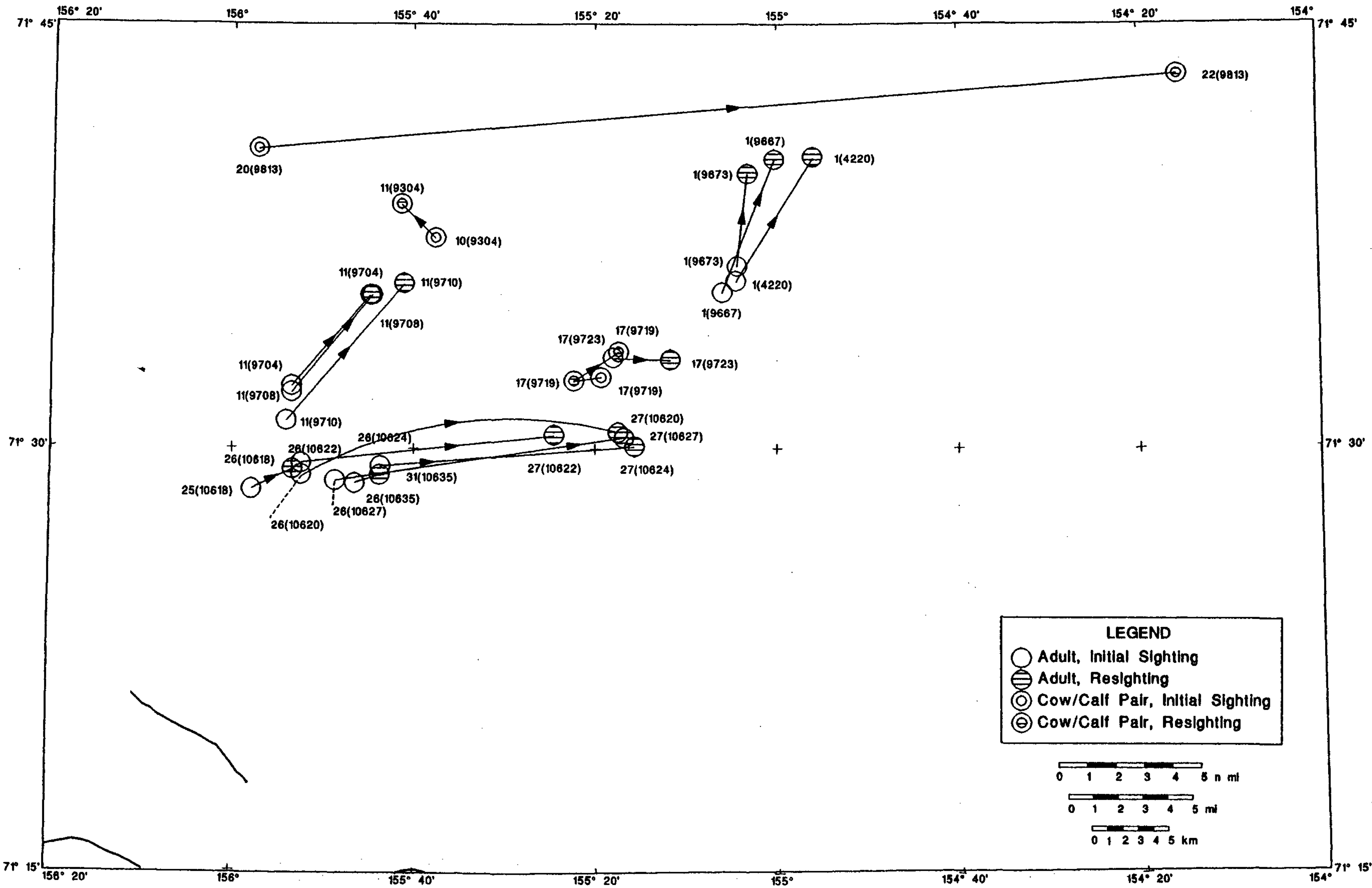

FIGURE 5.26. Between-session resightings of bowhead whales photographed northeast of Barrow during May 1991. Annotations show date in May and whale number in LGL's photo catalog. See Table 5.5B for details.

In 1989 and 1991 combined, excluding mother-calf pairs, ***other whales*** resighted on the same days during different sessions (n=9) were resighted at intervals of 1.6-3.8 h (mean=2.58 h). Net distances traveled were 3.8-12.7 km, averaging 9.09 km. Net headings were 7°-93°T with vector mean 85°T ± a.d. 48°, and the average net speed between resightings was 3.73 ± s.d. 1.12 km/h (Table 5.6). There were rather high correlation coefficients between whale speed and resighting interval (r= -0.656), whale speed and whale length (r=0.618) and, to a lesser degree, whale speed vs. date (r= -0.338). However, given the low sample size (n=7), none of these correlations was statistically significant (P>0.05 in each case).

Two ***mother-calf*** pairs were involved in four between-session within-day resightings during 1989 and 1991. These whales were resighted at intervals of 1.0-4.1 h, averaging 2.35 h. Headings ranged widely, from 57°-354°T, with vector mean 354°T and a large (74°) angular deviation (Table 5.6). Three of the four (75%) mother-calf resightings had headings with westerly components (215°, 264°, and 354°), as compared to zero of nine "other" whales (Fisher Exact P<0.05). Net distances traveled were 1.7-3.6 km, averaging 2.72 km. Net speeds were 0.5-2.3 km/h, averaging 1.44 ± s.d. 0.73 km/h. The speeds of mother-calf pairs were significantly slower than those of other whales resighted between sessions on the same day(t=3.71, df=11, P<0.01).

TABLE 5.6. Net speeds and headings of mother-calf pairs and other bowheads based on photographic resightings of three types (based on data in Table 5.5).

	Others			Mother-Calf			
	Mean	s.d.	n	Mean	s.d.	n	
A. Net Speeds							
Within-Session	3.74	1.48	(18)	4.26	1.71	(7)	ns[a]
Between-Session							
Within Day	3.73	1.12	(9)	1.44	0.73	(4)	**
Between Day	0.49	0.35	(7)	0.51	0.40	(6)	ns
Combined	2.31	1.86	(16)	0.88	0.70	(10)	*
	Vector Mean	Ang. Dev.	n	Vector Mean	Ang. Dev.	n	
B. Net Headings							
Within Session	68	55	(18)	195	75	(7)	ns
Between-Session							
Within Day	85	48	(9)	354	74	(4)	*
Between Day	77	8	(7)	13	60	(6)	*
Combined	60	25	(16)	356	67	(10)	**

[a] See text for statistical tests used; ns means not significant; * means P≤0.05, ** means P≤0.01.

Considering ***all whales*** involved in between-session within-day resightings during the study (n=13), the average resighting interval was 2.5 h (range 1.0-4.1 h). The vector mean heading was NE (39°T) ± a.d. 50°. The mean net distance traveled was 7.13 km (range 1.7-12.7) and apparent speeds ranged from 0.5 to 4.7 km/h, averaging 3.02 ± s.d. 1.48 km/h.

No significant correlations were found between whale speed vs. resighting interval (r= -0.347, df=11, P>0.20) or whale speed vs. whale length (r=0.069, df=11, P>0.50). However, a significant correlation was found between whale speed and date (r= -0.646, df=11, P<0.02). The correlation was negative with decreasing whale speeds as the season advanced. The correlation probably results from the slower speeds of the mother-calf pairs that were present and resighted only during the latter parts of the study period (17, 28, and 29 May; mean 1.44 km/h for mothers vs. 3.73 km/h for others).

Whale headings in 1991 were more northerly and less variable than in 1989 (vector mean heading 35° ± a.d. 41° in 1991 vs. 60° ± a.d. 65° in 1989). Apparent speeds were higher in 1991 than 1989 (3.16 vs. 2.72 km/h). However, sample sizes were small (n=4 in 1989 and n=9 in 1991).

<u>Between-Day Resightings.</u>—A total of 13 between-day within-year resightings occurred over intervals ranging from 1.6 hours to 5 days, considering the combined LGL and NMML photographs for the three years (cases with no "*" in Table 5.5B).

In ***1989*** there were five between-day resightings of four whales or mother-calf pairs. Two bowheads photographed in the same general location and at about the same time on 17 May had traveled in opposite directions when they were resighted on the following day (Table 5.5B, Figure 5.25). The resighting locations on 18 May were 19 km apart. One of these bowheads traveled 6.3 km ENE in 23 h (0.3 km/h, net). The other bowhead traveled 12.6 km WSW over 19 h (0.7 km/h). The latter bowhead was accompanied by a calf on 17 May, but the calf was neither observed nor photographed on 18 May.

Three other resightings involved mother-calf pairs. A mother-calf pair photographed early on 26 May had traveled 7 km to the NE when resighted 35 h later on 27 May. This pair had traveled at an apparent rate of only 0.2 km/h. Another mother-calf pair was photographed on 27, 28 and 29 May. This pair (also included among the 1989 *within-session*, and *between-session within-day resightings*, see above) traveled about 12.3 km to the ENE between 27 and 28 May, at an apparent rate of 0.8 km/h. Between 28 and 29 May this pair traveled about 4.5 km to the NNW, at a net speed of 0.2 km/h. The net distances traveled between successive sightings ranged from 2.2 to 12.3 km, and apparent speeds ranged from 0.2 to 2.3 km/h. The net distance and net rate of movement between the original (27 May) and final sighting locations (second sighting on 29 May, Table 5.5B) of this pair were 11.5 km (to the NE) and 0.27 km/h, respectively.

These 1989 resightings occurred over intervals averaging 22.9 h (range 14.8-35.3). The vector mean heading of these resighted whales was 30°T (range 54-336°, ± a.d. 58°). Net distances traveled averaged 8.5 km (range 4.5-12.6 km), and the mean net speed was 0.43 km/h (range 0.2-0.8 km/h).

In ***1991***, 8 bowheads or mother-calf pairs were photographed during more than one day. These 8 whales or pairs were resighted from 1 to 5 days after they were first photographed (Table 5.5B, Fig. 5.26):

- A 14.8 m mother and 4.2 m calf photographed on 10 and 11 May traveled a net distance of only 3.1 km, and this was to the *NW*, over a 28 h period; the apparent rate of movement was only 0.1 km/h.
- An unmeasured mother and calf photographed on 20 and 22 May traveled a net distance of 59 km to the E in 56 h—an apparent rate of movement of 1.1 km/h.
- A 14.6 m bowhead photographed on 25 and 26 May traveled a net distance of only 2.9 km over 25 h for an apparent speed of 0.1 km/h.
- Four bowheads photographed in the same general area on 26 May were re-photographed ~24 h later 16.4-20.9 km to the east. These whales traveled at apparent speeds of 0.7-0.9 km/h.
- Another adult (13.9 m long) traveled a net distance of only 1.7 km over a 5 d period (0.01 km/h, 26-31 May).

The last of these whales had a net speed lower than has been documented previously in the Barrow area during spring. Rugh (1990) resighted a bowhead over a 5-d period during spring migration, but that individual traveled at nearly 1 km/h. The lingering of an apparently healthy individual in our study area in the spring of 1991 was apparently unusual, especially for a bowhead not accompanied by a calf. This case cannot be accounted for by any hypothesized "migration blockage" as a result of the noise playback work. This whale was first photographed on the last day of our field season, when the projector site (for transmission loss test 91-4) was 15 km to the WNW of the whale. Thus, when first photographed this whale had already passed the last of the projector sites that we used.

The average interval at which these whales were resighted was 40.4 h (range 23.5-118.8). Headings were to the ENE (vector mean heading 71° ± a.d. 36°), and the average net distance traveled was 17.4 km (range 1.7-59.3 km). The mean apparent speed was 0.5 km/h (range 0.1-1.1 km/h).

No between-day resightings of bowheads were discovered in ***1994.***

In 1989 and 1991 combined, excluding mother-calf pairs, ***other whales*** resighted on different days (n=7) were resighted at an average interval of 37.5 h (range 22.9-118.8 h). Whale headings were consistently to the ENE and E, ranging from 64-85°T with vector mean 77°T and a.d. only ±8° (Table 5.6). Net distances traveled averaged 11.9 km (range 1.7-20.9 km). The average net speed between resightings was 0.49 ± s.d. 0.35 km/h (range 0.01-0.88 km/h).

There were rather large correlation coefficients between whale speed vs. resighting interval (r= -0.610), whale speed vs. whale length (r= -0.593) and, to a lesser degree, whale speed vs. date (r=0.331). However, given the low sample size (n=7), none of these correlations was statistically significant (P>0.1 in each case).

Between-day resightings of ***mothers and calves*** (n=6) occurred over intervals averaging 29.2 h (range 14.8-55.6 h). Headings varied widely (range 54°-336° with vector mean heading 13°T and a broad angular deviation of ±60°. Three of the six (50%) mother-calf headings had a westerly component (257°, 316°, 336°), whereas none of the seven "other" whales had westerly components. The headings of mother-calf pairs differed significantly from the headings of other whales (Rank Sum U=1, N_1=6, n_2=7, P=0.023). The average net distance traveled was 16.4 km (range 3.1-59.3 km) and the average net speed was 0.51 ± s.d. 0.40 km/h (range 0.1-1.1 km/h). Speeds of between-day mother-calf resightings did not differ significantly from those of other whales (t=0.1, df=11, P>0.8).

There were no significant correlations in this very small sample (n=6) between whale speed and resighting interval (r=0.311), whale length (r= -0.184) or date (r=0.100) (P>0.5 in each case).

Considering ***all whales*** photographed on different days in the same season (n=13), the average resighting interval was 33.7 h (range 14.8-118.8). The vector mean heading was 60°T (range 54-336°) ± a.d. 48°. The net distance traveled was 14.0 km (range 1.7-59.3 km), and the mean net speed was 0.50 ± s.d. 0.36 km/h (range 0.01-1.07).

Correlations between whale speed and resighting interval (r= -0.317), whale length (r= -0.313), and date (r=0.153) were not significantly different from zero (n=13, all P>0.1).

The whale headings based on between-day resightings in 1991 were slightly more southerly and less variable than in 1989 (vector mean heading 71°± a.d. 36° in 1991 vs. 30° ± 58° in 1989). As was the case among *between-session within-day resightings*, apparent speeds were slightly higher in 1991 than in 1989 (0.54 vs. 0.43 km/h), respectively. Sample sizes were low (n=5 in 1989 and n=8 in 1991).

All Between-Session Resightings.—As just described, between-session resightings included resightings over brief intervals within days, and over longer intervals between days. The data derived from the two types of between-session resightings can be summarized as follows:

	Same-Day	Between-Day
Resighting Interval (mean)	2.5 h	33.7 h
Vector Mean Heading	39°T	60°T
Angular Deviation	50°T	48°T
Net Distance (mean)	7.1 km	14.0 km
Net Speed (mean)	3.02 km/h	0.50 km/h

The major differences between the two sets of data concern resighting intervals, net distance, and net speed. Resighting intervals are by definition longer in the case of between-day resightings. The differences between the net distances and speeds in the two sets of data are related to the size of the study area. Considering the relatively small and almost totally overlapping areas within which the LGL and NMML photo sessions were confined (Fig. 5.19, 5.21, and 5.4), resightings over the longer (between-day) intervals inevitably involved whales that were traveling at low net speeds and moving relatively short distances between sightings. In the following section the pooled same-day and between-day between-session resightings are discussed.

In ***1989***, the 9 between-session resightings of bowheads were resighted at a mean interval of 14.1 ± s.d. 11.84 h (Table 5.5B). These whales traveled at a mean net speed of 1.45 ± s.d. 1.59 km/h and on a vector mean heading of 41°T ± a.d. 58°.

In ***1991***, the 17 between-session resightings occurred over an average interval of 20.21 ± s.d. 29.59 h (Table 5.5B). The average apparent speed was 1.93 km/h ± s.d. 1.72 km/h. The vector mean heading was 53°T ± a.d. 42°.

In all years combined, excluding mother-calf pairs, ***other whales*** reidentified between sessions (n=16) were resighted over intervals averaging 17.84 ± s.d. 28.89 h. Their vector mean heading was 60°T with a.d. only 25°, and net speeds averaged 2.31 ± s.d. 1.86 km/h (Table 5.6).

Net speeds were significantly correlated with resighting interval ($r = -0.614$, df=14, $p<0.02$) and date ($r = -0.784$, df=14, $P<0.001$). Thus, net speed decreased with increasingly long resighting intervals and increasingly later dates in May. The negative correlation of net speed with resighting interval is an inevitable result of the rather small sampling area, but it is interesting that net speed is lower late in the season even when mothers and calves are excluded. There was no significant correlation between whale speed and whale length ($r= -0.124$, df=14, $P>0.50$).

Mother-calf pairs reidentified between-sessions during the three years of study (n=10) were resighted over intervals averaging 18.50 ± s.d. 17.71 h. Their net headings were variable, with vector mean 356°T ± a.d. 67° (Table 5.6). Of the 10 resightings of mother-calf pairs, six had headings with westerly components, compared to zero of 16 resightings of other whales ($chi^2=9.33$, df=1, $P<0.01$).

Net speeds averaged 0.88 ± s.d. 0.70 km/h. Correlations between net speed and interval between photos ($r= -0.474$), whale length ($r= -0.327$) and date ($r=0.072$) were not significantly different from zero ($P>0.1$ in each case), but the sample size was small (n=10). The net speeds of mother-calf pairs averaged lower than those of "other" whales ($t'=2.78$, df=21.7, $P<0.02$).[14]

Considering ***all whales*** reidentified between sessions during the three years when we conducted photography (n=26), the average resighting interval was 18.09 ± s.d. 24.78 h. The vector mean heading was 50°T ± a.d. 59°. The mean speed was 1.76 ± s.d. 1.66 km/h.

The vector mean heading in 1991 was more northerly than in 1989 (53° in 1991 vs. 41° in 1989) and there was less variation in headings of whales resighted during 1991 photography (± a.d. 42°in 1991 vs. ±62° in 1989).

[14] The t' designation refers to the modified t-test not assuming equal population standard deviations.

Net whale speeds were negatively correlated with the interval between resightings ($r = -0.538$, df=24, $P<0.005$) and date ($r = -0.696$, df=24, $P<0.001$). There was no significant correlation between whale speed vs. whale length ($r= -0.248$, df=14, $P>0.20$).

Spring Migration of Mother-Calf Pairs vs. Other Bowheads.—Spring migration of mother-calf pairs through our study area differs in some respects from the spring migration of other bowheads. Mother-calf pairs tend to pass through the Barrow region late in the season, perhaps to avoid heavy pack ice conditions (§3.1, Ice and Weather Conditions). Differences in distribution between mother-calf pairs and other bowheads have been noted in some years (i.e., 1991).

The speeds of mother-calf pairs were slower than speeds of other whales when estimated from between-session within-day resightings or the combined between-session dataset (same-day and between-day; Table 5.6). Speeds of these two groups were similar when estimated from short-term within-session resightings or from between-day resightings. The between-day speeds are inevitably low and biased because only the slow-moving whales would be resighted.

The net headings of mother-calf pairs in all four categories appeared to differ from those of other whales. In each category, headings of mother-calf pairs were more variable, as indicated by a larger angular deviation (Table 5.6). A larger proportion of the mothers and calves were traveling toward the west.

Thus, over periods of hours, as represented by the within-day between-session resightings, mother-calf pairs traveled more slowly through our study area than did other bowheads, with more variable headings. Although net speeds of mother-calf pairs over brief intervals (15-68 min) did not differ significantly from those of other bowheads, they appeared to exhibit a weaker tendency to travel in an easterly direction even during those short intervals. Mother-calf pairs apparently traveled more circuitous routes through the study area, thereby passing more slowly through the area.

Between-Year Resightings

All Grade A (potentially recognizable between years) bowhead images obtained during this study have been compared to all Grade A photos obtained in previous summer and autumn photographic studies conducted in the Alaskan and Canadian Beaufort Sea by LGL, NMML and Cascadia Research Collective (CRC) (*cf.* Koski et al. 1988), and to each other. They were also compared to our collection of NMML's Grade A spring photos for 1984-1991.

In ***1989***, 4 of the 15 "Grade A" bowheads photographed by LGL had been photographed in earlier years by LGL or NMML (Table 5.7). All four of these resighted bowheads were adults, 14 to 16 m long:

- One bowhead (whale No. 1311) photographed near Barrow on 17 and 18 May 1989 was originally photographed on 18 August 1982 near Herschel Island, N.W.T. This whale was photographed with a calf in 1982. It was observed with a calf on 17 May 1989 but the calf was neither observed nor photographed on 18 May (Miller et al. 1992; Rugh et al.

Table 5.7. Between-year bowhead resightings, various origins and years, to MMS study area, May 1989, 1991, and 1994.

Source of Photos[a]	Whale Number	Year	First Photographed				Resighting at Barrow			Length in Year of Resighting (m)	Calf Present	
			Date	Loc'n[b]	Latitude	Longitude	Date	Latitude	Longitude		First Sighting	Resighting
LGL-(NMML-LGL)	1311	1982-89	18 Aug	HI	70°05.0'N	138°25.9'W	17,18 May	71°34.3'N	156°15.8'W	16.0	yes	yes
NMML-LGL	8609	1985-89	2 Jun	BR	71°24.1'N	156°36.8'W	15 May	71°54.0'N	154°28.0'W	14.0	no	no
NMML-LGL	2392	1985-89	2 Jun	BR	71°24.2'N	156°36.7'W	18 May	71°35.3'N	156°05.3'W	14.7	no	no
NMML-LGL	2392	1986-89	22 May	BR	71°28.9'N	156.06.1'W	"	"	"	"	"	no
NMML-(LGL-NMML)	8622	1986-89	19 May	BR	71°36.4'N	155°02.2'W	26,27 May	71°37.7'N	155°30.1'W	14.2	yes	yes
LGL-LGL	1552	1982-91	4 Sep	HI	70°02.3'N	138°50.9'W	26 May	71°22.6'N	156°40.5'W	16.2	yes	no
LGL-(NMML-LGL)	4220	1984-91	23 Aug	FB	70°21.7'N	127°03.0'W	1 May	71°40.3'N	154°55.9'W	12.9	no	no
NMML-LGL	1880	1984-91	8 May	BR	71°33.8'N	155°39.6'W	8 May	71°35.8'N	155°43.2'W	13.6[c]	no	no
LGL-LGL	4239	1984-91	23 Aug	OB	70°40.4'N	127°24.8'W	18 May	71°38.1'N	156°14.8'W	14.8	yes	yes
LGL-LGL	5679	1985-91	6 Sep	KP	69°13.7'N	137°19.5'W	1 May	71°40.3'N	154°55.9'W	10.3	no	no
NMML-NMML	2217	1985-91	23 May	BR	71°34.6'N	153°31.5'W	10 May	71°29.1'N	156°22.0'W	14.5	no	no

[a] LGL = Photographic studies by LGL during summer (Davis et al. 1983, 1986a,b), fall (Richardson et al. 1986, 1987) and spring (this study). NMML = Spring photographic studies by National Marine Mammal Laboratory. CRC = Summer photographic study by Cascadia Research Collective (Ford et al. 1987).

[b] HI = Herschel Island, Y.T., BR = Barrow Region, AK, FB = Franklin Bay, N.W.T., OB = Offshore Bathurst Peninsula, N.W.T., KP = King Point, Y.T., OK = Offshore Kaktovik, AK, TPS = Tuktoyaktuk Peninsula Shelf, N.W.T., DS = Mackenzie Delta Shelfbreak, N.W.T., EA = Eastern Alaska, CP = Cape Parry, N.W.T., K = Komakuk, Y.T.

[c] Approximate length.

Continued...

Table 5.7. Concluded.

Source of Photos[a]	Whale Number	Year	First Photographed				Resighting at Barrow			Length in Year of Resighting (m)	Calf Present	
			Date	Loc'n[b]	Latitude	Longitude	Date	Latitude	Longitude		First Sighting	Resighting
NMML-NMML	2200	1985-91	22 May	BR	71°30.3'N	155°26.1'W	26 May	71°29.1'N	155°47.7'W	16.2	no	no
LGL-NMML	6970	1985-91	26 Sep	OK	70°26.6'N	143°13.1'W	26 May	71°32.1'N	155°28.5'W	13.9	no	no
CRC-LGL	7781	1986-91	31 Aug	TPS	70°44.6'N	130°50.8'W	18 May	71°35.6'N	156°06.2'W	14.0	no	no
NMML-LGL	8288	1987-91	8 May	BR	71°27.9'N	156°10.7'W	25 May	71°39.1'N	155°03.5'W	16.0[c]	no	yes
NMML-(NMML-LGL)	9304	1989-91	31 May	BR	71°36.0'N	154°32.6'W	10 May	71°37.4'N	155°37.6'W	14.8	no	yes
NMML-(NMML-LGL)	9304	1990-91	29 May	BR	71°27.4'N	156°12.6'W	11 May	71°38.6'N	155°41.3'W	"	no	yes
LGL-LGL	1350	1982-94	23 Aug	DS	70°27.0'N	136°38.9'W	14 May	71°34.4'N	155°02.6'W	15.4	no	no
LGL-LGL	4230	1984-94	6 Sep	FB	70°34.0'N	127°24.6'W	8 May	71°35.2'N	154°30.4'W	14.5	no	no
LGL-LGL	4230	1985-94	22 Aug[c]	FB	69°54.8'N	126°23.8'W	"	"	"	"	"	no
LGL-LGL	6984	1985-94	29 Sep	EA	70°24.3'N	143°01.4'W	7 May	71°35.6'N	154°46.3'W	15.3	no	no
LGL-LGL	6962	1985-94	26 Sep	EA	70°28.3'N	143°16.1'W	14 May	71°30.8'N	155°42.5'W	13.1	no	no
LGL-LGL	5149	1985-94	21 Aug	CP	69°52.9'N	123°10.0'W	25 May	71°28.8'N	156°14.4'W	14.4	no	no
LGL-LGL	7346	1986-94	19 Sep	K	~69°37.0'N	~139°55.0'W	5 May	71°31.3'N	155°49.3'W	13.5	no	no

[a] LGL = Photographic studies by LGL during summer (Davis et al. 1983, 1986a,b), fall (Richardson et al. 1986, 1987) and spring (this study). NMML = Spring photographic studies by National Marine Mammal Laboratory. CRC = Summer photographic study by Cascadia Research Collective (Ford et al. 1987).

[b] HI = Herschel Island, Y.T., BR = Barrow Region, AK, FB = Franklin Bay, N.W.T., OB = Offshore Bathurst Peninsula, N.W.T., KP = King Point, Y.T., OK = Offshore Kaktovik, AK, TPS = Tuktoyaktuk Peninsula Shelf, N.W.T., DS = Mackenzie Delta Shelfbreak, N.W.T., EA = Eastern Alaska, CP = Cape Parry, N.W.T., K = Komakuk, Y.T.

[c] Approximate length.

1992b). This is the same bowhead that traveled 13 km to the W from 17 to 18 May in 1989 (Table 5.5B). Considering the presence of the calf on 17 May 1989, this whale calved at an apparent 7-year interval. It is not known whether this whale calved during an intervening year.

- The three other inter-year resightings involved whales that had been photographed during previous spring studies near Barrow in 1985-86 (Table 5.7). Two of these, photographed on 15 and 18 May 1989, had originally been photographed on 2 June 1985. One of these two (whale No. 2392) had also been photographed near Barrow on 22 May 1986. The final inter-year resighting (whale No. 8622) was of a bowhead photographed with a yearling (>7.0 m) in 1986 and a calf (<5 m) in 1989. This whale was photographed on 19 May in 1986 and on 26-27 May 1989. The yearling calf was presumably a newborn calf in the spring of 1985, indicating a 4-year calving interval.

In analyses conducted for other projects (Koski et al. 1992; Miller et al. 1992), 133 Grade A bowheads photographed by NMML near Barrow during the spring of 1989 were compared to all Grade A whale photos obtained in previous years. These comparisons resulted in an additional 22 between-year resightings of bowheads. These resightings are listed in Koski et al. (1992) and are shown in more detail in Appendix E, Table E-1.

Of these 22 resightings, 15 were of whales previously photographed on their summering grounds or during fall migration in the years 1981, 1982, 1984, 1985 or 1986. The remaining seven 1989 inter-year resightings were of whales photographed near Barrow during spring in 1985 or 1986 (Table E-1). One of these whales (whale No. 1483) was accompanied by a calf in 1982 and 1989—an apparent 7-year calving interval. Whether this whale calved during an intervening year is unknown. Another of these whales (No. 1617) had a calf in 1989 but not in 1982.

In ***1991***, eight of the 36 "Grade A" bowheads photographed by LGL had been photographed by LGL, NMML or CRC in one or more earlier years; #9304 was previously photographed in both 1989 and 1990. In addition, there were three between-year resightings of whales photographed only by NMML among the 38 "Grade A" whales they photographed in that year. The 12 resightings, including 2 resightings for #9304, spanned intervals of 1-9 yr (Table 5.7).

- Six of these resighted whales were originally photographed during summer or early autumn in the Canadian Beaufort Sea in 1982, 1984, 1985, or 1986. One of these whales (#4239) had a calf in both 1984 and 1991, a 7-year interval. Whether this whale calved in an intervening year is unknown. Another (#1552) had a calf in 1982 but not in 1991.
- The remaining six resightings involved whales first photographed during spring studies near Barrow during the years 1984, 1985, 1987, or 1989. One whale (#9304) was photographed in 1989, 1990 and 1991 in the Barrow region. This whale was photographed without a calf in 1989 and 1990, but was accompanied by a calf in 1991. Whale #8288 was photographed without a calf in 1987 but with a calf in 1991.

In ***1994***, six of 41 "Grade A" bowheads photographed by LGL had been photographed in earlier years on their summering grounds in the Canadian Beaufort Sea or during fall migration in the eastern Alaskan Beaufort Sea (Table 5.7). The intervals associated with these resightings were 8-12 years. The 12-year interval represents the longest inter-year resighting interval recognized to date. That whale was measured as 15.3 m long in 1982 and 15.4 m long in 1994, illustrating the very slow growth exhibited once bowheads reach adult size (Koski et al. 1992).

These between-year resightings, over the long term, provide some types of information about bowheads that are not available by other means. It is beyond the scope of this project to analyze these topics, as this requires consideration of the combined dataset from many projects. Recent papers by Koski et al. (1992) and Miller et al. (1992) have used between-year resighting data, including those from the 1989 and 1991 phases of this study, to analyze bowhead growth rates and calving intervals. We expect that these data will also be used in future studies to obtain an independent estimate of bowhead population size through "mark-recapture" methodology, and to estimate longevity through analysis of scar acquisition rates.

5.3 Behavior of Undisturbed Bowheads

Observation Effort and Circumstances

We observed the behavior of bowhead whales during a total of 112.7 hours of systematic aerial observations during the 29 April through 29 May periods. This effort was distributed over 76 behavioral observation sessions on 37 different days during the four years of spring work (Table 5.8).

Observation periods were counted as presumably undisturbed when the observation aircraft was at an altitude of at least 460 m (≥1500 ft), no other aircraft were nearby, the underwater sound projector was not operating, and there had been no known potential disturbance within the preceding 30 min period. Overall, there were 72.1 hours of observation of presumably undisturbed whales, which was 64% of the total 112.7 hours of observation time (Table 5.8). The percentage of the observations that were under presumably undisturbed conditions was lowest in 1989 (48%), intermediate in 1990 and 1994 (68 and 67%, respectively), and highest in 1991 (100% of 4.1 h).

The circumstances of observations varied widely within and among years. However, there were tendencies for low or high values of water depth, ice cover, and sea state in certain years. Table 5.8 summarizes, for each year, the circumstances of *(1)* all behavioral observation sessions and *(2)* sessions when "presumably undisturbed" whales were seen. The circumstances of individual observation sessions are summarized in Tables 3.6 (p. 74) and 3.8 (p. 80-1) for 1991 and 1994, and in Richardson et al. (1990a:75-6, 1991:38-40) for 1989 and 1990. The following two paragraphs concern the observation sessions when "presumably undisturbed" bowheads were observed.

In ***1989***, there was heavy ice cover (80-95%) at most observation sites and in the study area generally. Observations were largely in pack ice well north of the landfast ice edge. The median water depth at observation sites was 150 m. Sea states at observation sites were usually low in 1989 because of the dampening effect of ice on wave action. The number of bowheads within the area circled by the observation aircraft (typically a circle 2-3 km in diameter) was 1-5. However, on 3 May, ~15 whales were within 5 km of the center of the observation circle. In ***1990***, observations were more commonly in shallow water (median depth 40 m), ice cover was more

TABLE 5.8. Summary of behavioral observation sessions from aircraft, 1989-1994. For each year, first line includes all observations, and second (boldface) line includes only observations under "presumably undisturbed" conditions.

Year	Dates With Behavioral Observations	Number of Behavioral Observation			Water Depths (m)		Ice Cover in Obs. Circle (%)		Sea State		No. Bowheads in Obs. Circle	
		Hours	Sessions	Days	Range	Med.	Range	Med.	Range	Med.	Range	Med.
1989	3-29 May	25.6	17	10	40 - 280	140	0 - 99	85	0 - 2	1	1 - 5	2
	"	**12.3**	**12**	**8**	**40 - 260**	**150**	**0 - 99**	**85**	**0 - 2**	**1/2**	**1 - 5**	**3**
1990	29 Apr-25 May	46.8	29	12	18 - 475	40	0 - 90	60	0 - 3	1	1 - 10	3
	"	**31.6**	**25**	**12**	**18 - 475**	**40**	**0 - 90**	**60**	**0 - 3**	**1**	**1 - 8**	**3**
1991	29 Apr-25 May	4.1	7	5	19 - 210	130	1 - 90	50	1 - 5	1	1 - 4	2
	"	**4.1**	**7**	**5**	**19 - 210**	**130**	**1 - 90**	**50**	**1 - 5**	**1**	**1 - 4**	**2**
1994	3-22 May	36.2	23	10	20 - 300	37	2 - 80	45	1 - 6	3	0 - 9	3
	"	**24.1**	**20**	**10**	**20 - 300**	**37**	**2 - 80**	**30**	**1 - 6**	**3**	**0 - 9**	**3**
Total	29 Apr-29 May	112.7	76	37	18 - 475	42	0 - 99	60	0 - 6	1	1 - 10	3
	"	**72.1**	**64**	**35**	**18 - 475**	**40**	**0 - 99**	**60**	**0 - 6**	**1**	**1 - 10**	**3**

variable and generally lighter (median 60%), and sea state at observation sites tended to be slightly higher. Almost all 1990 data from waters ≥100 m deep were obtained late in the field season (21-25 May) and many of those data pertained to mother-calf pairs.

In ***1991***, low clouds prevailed and behavioral observations from 460 m altitude were possible on only five days. Only one observation session lasted >1 h (6 May), and only 4.1 hours of observations were obtained during the season. Ice cover at observation sites ranged from 1 to 90%, but most were in ≥35% ice cover. In ***1994***, weather was much clearer than in 1991, and we collected behavioral data for 36.2 h (24.1 h "presumably undisturbed). Depth of water at observation sites ranged from 20 to 300 m, but most observations were in 20-55 m (median 37 m). Ice cover varied from 2 to 80% (median 30%), with most observations being collected in or near the main "nearshore" lead between the landfast ice and the pack ice. Winds tended to be strong in 1994. This, combined with the often-extensive open water in the nearshore lead, resulted in notably higher sea states during the 1994 work (median 3 in 1994 vs. ½-1 in earlier years; Table 5.8).

General Activities

The predominant activity of most bowheads observed in spring was travel, with social interactions and presumed feeding being less common. Considering all 76 observation sessions, travel was noted during 64 sessions (84%), social activity during 22 (29%), and presumed feeding during eight (11%). During most of the observation sessions with social activity or presumed feeding, the bowheads were also traveling at least part of the time. Overt sexual activity was infrequent, being noted during only 4 of 76 sessions (5%). The activities of mothers and calves differed somewhat from those of other whales, so mothers and calves are treated separately in a later section (p. 228*ff*). The following material concerns only the "presumably undisturbed" whales, and excludes mothers and calves.

Traveling.—Traveling whales constituted the largest proportions of the bowheads observed during each of the four spring seasons with observations. The predominant activity was traveling for 624 of 954 observed surfacings (65%), and travel plus socializing for a further 205 surfacings (21%) (Table 5.9). Data on traveling whales seen during the undisturbed periods are important as control data for the playbacks.

Traveling was the predominant activity regardless of date, time of day, water depth, and ice cover (Table 5.9A-E). However, there was a tendency for the proportion of the whales that were traveling to be lower with high percentages of ice cover:

Ice cover	<30%	≥30%
% traveling	89%	50%
% traveling or traveling+socializing	97%	80%

(based on Table 5.9D).

Headings of all bowhead groups sighted during spring are summarized in Table 5.1. The overall vector mean was 83° True, with an angular deviation of 37°. Considering only the sightings when bowheads were classified as traveling, the vector mean was again 83°T with angular deviation reduced to 33° (n=638 groups). Most traveling groups were headed to the NE, E or ESE.

TABLE 5.9. Circumstances of observations of undisturbed bowhead whales engaged in various group activities. The table shows numbers (left) and percentages (right) of surfacings during spring migration near Barrow, AK, 1989-94, as observed from a Twin Otter aircraft. Mothers and calves are excluded. Because a given whale is counted more than once if more than one surfacing is observed, some data are not independent and statistical analysis is not justified. Also, we tended not to observe actively socializing groups for prolonged periods, and this affects the percentages of whales engaged in various activities. "Total n" varies because not all variables could be determined for each surfacing.

	Number of Surfacings					Percentage of Surfacings				
	Travel	Tr+Soc	Social	Other	All	Travel	Tr+Soc	Social	Other	All
A. Date										
21-30 Apr	9	0	6	1	16	1.4	0.0	12	1	1.7
1-10 May	198	120	44	49	411	31.7	58.5	88	65	43.1
11-20 May	394	82	0	17	493	63.1	40.0	0	23	51.7
21-31 May	23	3	0	8	34	3.7	1.5	0	11	3.6
Total n	624	205	50	75	954					
B. Hour (local)										
6-8	1	3	0	0	4	0.2	1.5	0	0	0.4
9-11	188	79	4	28	299	30.1	38.5	8	37	31.3
12-14	151	120	2	28	301	24.2	58.5	4	37	31.6
15-17	119	3	44	4	170	19.1	1.5	88	5	17.8
18-20	106	0	0	15	121	17.0	0.0	0	20	12.7
21-23	59	0	0	0	59	9.5	0.0	0	0	6.2
Total n	624	205	50	75	954					
C. Water Depth (m)										
10-19	23	0	6	9	38	3.7	0.0	12	12	4.0
20-49	527	197	32	15	771	84.5	96.1	64	20	80.8
50-99	37	0	0	5	42	5.9	0.0	0	7	4.4
100-250	28	8	12	42	90	4.5	3.9	24	56	9.4
> 250	9	0	0	4	13	1.4	0.0	0	5	1.4
Total n	624	205	50	75	954					
D. Ice Cover (%)										
None	43	0	0	2	45	6.9	0.0	0	3	4.7
1-9 %	226	29	0	0	255	36.2	14.1	0	0	26.7
10-29	67	0	0	10	77	10.7	0.0	0	13	8.1
30-59	89	86	0	6	181	14.3	42.0	0	8	19.0
60-79	125	87	0	25	237	20.0	42.4	0	33	24.8
80-90	64	3	38	21	126	10.3	1.5	76	28	13.2
>90	10	0	12	11	33	1.6	0.0	24	15	3.5
Total n	624	205	50	75	954					
E. Ice Ahead										
None	420	125	16	44	605	79.7	86.8	73	70	80.0
< 100 m	14	3	0	3	20	2.7	2.1	0	5	2.6
100-1000 m	59	10	6	9	84	11.2	6.9	27	14	11.1
> 1000 m	34	6	0	7	47	6.5	4.2	0	11	6.2
Total n	527	144	22	63	756					

Headings were also recorded at the start of each surfacing and dive during aerial observations of behavior. Table 5.10 summarizes those results, including data for whales engaged in traveling each year and overall (Table 5.10C). For traveling whales, the vector mean direction during behavioral observation sessions was 67°T with angular deviation 31°; vector means ranged from 59° in 1994 to 81° in 1991.

Most whales traveled along leads and cracks oriented SW→NE or W→E, with the result that there usually was not a large expanse of solid ice ahead of the whales as they dove. When the crack or lead in which a whale was swimming turned slightly left (north) or right (east or southeast), bowheads often adopted that course in order to remain within the crack or lead. However, when whales came to the eastern or northeastern end of a lead or crack, or when they surfaced in an isolated opening in the ice, they routinely headed under the ice to the NE, ENE, E or ESE. About 6% of the surfacings by traveling whales ended when the whale dove under ice that appeared to be solid (without potential breathing sites) for at least 1 km in the whale's direction of travel. An additional 10% of the surfacings ended when the whale dove beneath ice that appeared solid for 0.1 to 1 km ahead of the whale. (These percentages, based on Table 5.9E, consider both traveling and "traveling+socializing" whales, and exclude situations where the ice was obviously recently refrozen and thin.)

Bowheads usually traveled singly or in small groups, but group size depends on one's definition for a group. It was rare for there to be more than 4 bowheads within 5 body-lengths of one another, and by this definition the most common group sizes were one (48%) and two (32%; Table 5.11A). However, there usually were additional bowheads within about 1 km. Only about 5% of the traveling bowheads, and 3.5% of those traveling or "traveling+socializing", seemed to be unaccompanied by other bowheads within 1 km (Table 5.11B). Thus, most if not all bowheads were close enough to other bowheads to be in acoustic communication.

Bowheads whose general activity was classified as traveling were, in fact, traveling during the great majority of their individual surfacings (Table 5.11). However, during small proportions of the surfacings they socialized while traveling (6.6%), socialized without traveling (1%), rested nearly motionless (1%), or engaged in other activities such as aerial behaviors (breaches, flipper slaps, tail slaps). On rare occasions, traveling whales were suspected to be feeding as they traveled (Table 5.11E and later).

Socializing.—Social activity by bowhead whales consists of a considerable variety of behaviors, including

- two or more whales swimming parallel and close to one another but not otherwise interacting in any obvious way (categorized here as "passive socializing" if the whale was within ½ body length of another bowhead);
- two or more whales whose actions are clearly influenced by the presence of one another, generally involving turns toward or away from one another; often including touching with the rostrum, flippers, or other body parts; and sometimes involving rolling around the long axis (categorized here as "active socializing");

TABLE 5.10. Headings (True) of bowheads observed during behavioral observation sessions.
Excludes mothers, calves, and potentially disturbed whales. Each surfacing and dive with a known heading is counted separately.

True Heading	A. By Year (All Activities) 1989	1990	1991	1994	TOTAL	B. By Group Activity (All Years) Rest	Travel	Social-ize	Trav.+ Soc.	Trav.+ Feed	Tr.+So +Feed	Other & Unk	TOTAL	C. By Year, Traveling Bowheads 1989	1990	1991	1994	TOTAL	True Heading
0 N	**2**	**2**	**1**	**20**	**25**	**0**	**6**	**2**	**13**	**0**	**1**	**3**	**25**	**0**	**2**	**0**	**4**	**6**	**N 0**
10	0	3	0	8	11	0	6	0	3	0	1	1	11	0	3	0	3	6	10
20	3	0	0	22	25	0	20	3	2	0	0	0	25	0	0	0	20	20	20
30	7	28	2	81	118	1	83	2	24	0	1	7	118	4	23	2	54	83	30
40	0	19	0	46	65	0	53	0	11	0	1	0	65	0	19	0	34	53	40
50	2	31	1	113	147	0	98	1	42	0	5	1	147	0	31	0	67	98	50
60	5	93	0	192	290	0	221	3	55	3	5	3	290	3	86	0	132	221	60
70	1	92	4	77	174	0	140	0	32	0	2	0	174	1	84	2	53	140	70
80	1	43	0	45	89	0	70	0	16	0	0	3	89	0	42	0	28	70	80
90 E	**11**	**83**	**4**	**48**	**146**	**0**	**120**	**1**	**16**	**1**	**0**	**8**	**146**	**10**	**73**	**4**	**33**	**120**	**E 90**
100	3	46	2	16	67	1	39	2	24	0	0	1	67	0	27	2	10	39	100
110	2	21	0	7	30	0	18	1	7	2	1	1	30	1	14	0	3	18	110
120	10	18	4	16	48	3	25	6	7	2	0	5	48	1	14	1	9	25	120
130	0	19	0	0	19	0	16	0	3	0	0	0	19	0	16	0	0	16	130
140	1	2	0	5	8	0	4	0	3	0	0	1	8	1	1	0	2	4	140
150	3	4	0	7	14	0	6	2	2	0	1	3	14	0	2	0	4	6	150
160	2	1	0	7	10	2	6	0	1	1	0	0	10	0	0	0	6	6	160
170	0	0	0	4	4	0	4	0	0	0	0	0	4	0	0	0	4	4	170
180 S	**1**	**5**	**0**	**6**	**12**	**0**	**6**	**0**	**1**	**0**	**0**	**5**	**12**	**0**	**2**	**0**	**4**	**6**	**S 180**
190	2	0	1	1	4	1	1	0	1	0	0	1	4	1	0	0	0	1	190
200	0	0	1	1	2	0	0	0	1	0	0	1	2	0	0	0	0	0	200
210	2	0	0	6	8	0	2	2	0	0	0	4	8	0	0	0	2	2	210
220	1	0	0	1	2	0	0	1	0	0	1	0	2	0	0	0	0	0	220
230	0	0	0	2	2	0	1	0	1	0	0	0	2	0	0	0	1	1	230
240	4	0	3	6	13	2	1	0	4	0	0	6	13	0	0	0	1	1	240
250	1	0	4	5	10	0	0	0	0	0	0	10	10	0	0	0	0	0	250
260	0	0	2	1	3	0	0	0	0	0	1	2	3	0	0	0	0	0	260
270 W	**1**	**2**	**0**	**9**	**12**	**0**	**0**	**1**	**3**	**0**	**1**	**7**	**12**	**0**	**0**	**0**	**0**	**0**	**W 270**
280	2	0	0	0	2	0	0	2	0	0	0	0	2	0	0	0	0	0	280
290	0	0	0	1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	290
300	0	0	1	1	2	0	0	0	1	0	0	1	2	0	0	0	0	0	300
310	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	310
320	0	0	0	5	5	0	4	0	1	0	0	0	5	0	0	0	4	4	320
330	12	0	0	9	21	8	5	1	7	0	0	0	21	2	0	0	3	5	330
340	1	2	0	4	7	0	5	0	1	0	0	1	7	0	1	0	4	5	340
350	0	3	0	2	5	0	4	0	0	0	0	1	5	0	2	0	2	4	350
Total	80	517	30	775	1402	18	964	30	282	9	22	77	1402	24	442	11	487	964	Total
Vector																			
Mean	72	76	113	57	66	333	67	79	62	98	48	193	66	75	74	81	59	67	
Length	0.31	0.87	0.19	0.77	0.76	0.14	0.86	0.35	0.77	0.85	0.56	0.10	0.76	0.72	0.90	0.89	0.84	0.86	
Ang. Dev.	67	29	73	39	40	75	31	65	39	32	54	77	40	43	26	26	32	31	

TABLE 5.11. Frequencies of various group sizes and activities of undisturbed bowhead whales engaged in various group activities. Mothers and calves excluded. Presentation as in Table 5.9.

	Number of Surfacings					Percentage of Surfacings				
	Travel	Tr+Soc	Social	Other	All	Travel	Tr+Soc	Social	Other	All
A. Group Size (within 5 body lengths)										
1	290	37	3	60	390	47.9	18.5	6	81	42.0
2	195	52	24	7	278	32.2	26.0	48	9	29.9
3	74	20	10	7	111	12.2	10.0	20	9	11.9
4	31	68	8	0	107	5.1	34.0	16	0	11.5
5	7	22	5	0	34	1.2	11.0	10	0	3.7
>5	8	1	0	0	9	1.3	0.5	0	0	1.0
Total n	605	200	50	74	929					
B. # Bowheads Within 1 km										
1	29	0	0	32	61	4.6	0.0	0	43	6.4
2	81	5	0	2	88	13.0	2.4	0	3	9.2
3	197	3	12	39	251	31.6	1.5	24	52	26.3
4	120	29	6	0	155	19.2	14.1	12	0	16.2
5	47	0	32	2	81	7.5	0.0	64	3	8.5
6	52	82	0	0	134	8.3	40.0	0	0	14.0
7	74	0	0	0	74	11.9	0.0	0	0	7.8
8	24	0	0	0	24	3.8	0.0	0	0	2.5
>8	0	86	0	0	86	0.0	42.0	0	0	9.0
Total n	624	205	50	75	954					
C. Whale Activity This Sfc/Dive Sequence										
Rest	8	0	0	8	16	1.3	0.0	0	11	1.7
Travel	520	100	0	13	633	83.3	48.8	0	17	66.4
Socialize	9	48	48	0	105	1.4	23.4	96	0	11.0
Feed	2	0	0	7	9	0.3	0.0	0	9	0.9
Travel+Social	41	44	0	0	85	6.6	21.5	0	0	8.9
Travel+Feed	0	0	0	7	7	0.0	0.0	0	9	0.7
Social+Feed	0	0	0	1	1	0.0	0.0	0	1	0.1
Unknown/Other	44	13	2	39	98	7.1	6.3	4	52	10.3
Total n	624	205	50	75	954					
D. Group's Predominant Feeding Mode										
None	624	205	50	42	921	100.0	100.0	100	61	97.2
Water-column	0	0	0	19	19	0.0	0.0	0	28	2.0
Bottom	0	0	0	8	8	0.0	0.0	0	12	0.8
Near-surface	0	0	0	0	0	0.0	0.0	0	0	0.0
Total n	624	205	50	69	948					
E. Whale's Feeding Mode During This Sfc/Dive Sequence										
None	573	198	43	49	863	99.3	100.0	100	77	97.8
Water-column	4	0	0	8	12	0.7	0.0	0	13	1.4
Bottom	0	0	0	7	7	0.0	0.0	0	11	0.8
Near-surface	0	0	0	0	0	0.0	0.0	0	0	0.0
Total n	577	198	43	64	882					

- two or more whales engaged in sexual activities, as described by Everitt and Krogman (1979) and Würsig et al. (1985, 1993) (also included here as "active socializing").

For certain bowheads, it was somewhat arbitrary whether they should be classified as traveling or "traveling+socializing". Traveling bowheads were classified as "traveling+socializing" when social activity was evident during at least 1/3 of the surfacings. The circumstances in which "traveling+socializing" was seen were generally similar to those in which simple traveling was seen (Table 5.9). However, group sizes tended to be larger than for traveling (Table 5.11A,B). Socializing, with or without simultaneous travel, was evident during 45% of the surfacings by whales classified as "traveling+socializing" (Table 5.11C).

Bowheads were classified as "socializing" when a group of whales engaged in active socializing at one location without evidence of travel during the duration of observations. Observations of this type were less common than those of "traveling+socializing" (Table 5.9). Although socializing was certainly less common than active traveling, its relative frequency is probably understated in Table 5.9. We often chose not to observe groups of whales that were engaged in active socializing, or to curtail observations of these groups after only a brief period. (This was done because it is difficult to quantify their behavior and, in particular, difficult to compare that behavior during undisturbed and potentially disturbed conditions.) Because of this, it would not be meaningful to undertake a detailed examination of the circumstances when socializing was observed. Some socializing groups that were not observed systematically (excluded from our Tables) were in areas with little or no ice. However, all systematically observed cases of active socializing were in areas with extensive ice (Table 5.9D), suggesting a possible association between socializing and extensive ice. Group sizes for socializing whales were not especially large (Table 5.11A,B) but it was—of course—rare for there to be no other whale within 5 body lengths.

Headings of socializing whales and "travel+socializing" whales observed during behavioral observation sessions averaged 79° and 62° True, respectively. These average headings were similar to the 67° average for traveling whales (Table 5.10B). However, the variability in headings was much greater during socializing (angular deviation 65°) and slightly greater during "travel+socializing" (39°) than during travel without socializing (31°).

Sexual activity was noted during only 4 of 76 observation sessions within the four spring seasons: on 3 May and 6 May 1989; 10 May 1990; and 7 May 1994. This suggests that there may be more sexual activity earlier than later in the season, but the sample size is too low to be conclusive. These sexual interactions are described later (p. 227).

Feeding and Surfacing with Mud.—Feeding apparently was not common during spring migration through our study area. On rare occasions bowheads dove repeatedly at one location, suggesting but not proving that water-column feeding was occurring. On 9 May 1994, several bowheads, generally small individuals, lingered near the ice camp and repeatedly dove under the edge of the landfast ice, possibly feeding (§6.1-6.2 and Appendix F). Their behavior resembled that observed near Barrow in late May 1985 (Carroll et al. 1987), when lingering whales dove repeatedly under the landfast ice, and when feeding was confirmed by presence of copepods and euphausiids in the stomachs of harvested whales. Defecation, which often accompanies feeding in summer, was observed only once during this study, and that was during a bout of sexual activity on 3 May 1989. We saw no evidence of surface feeding.

Traveling whales sometimes seemed to have mud on their bodies when they surfaced. It is not known why or how often they contacted the bottom. On one day (16 May 1990), much mud was seen streaming out through the baleen of a small whale during one surfacing. It and three other whales near it had mud streaming from their bodies during one or more surfacings in water ~40 m deep.[15] On another day (12 May 1990), there was evidence of brief bottom or near-bottom feeding by three whales that had been observed for 2.7 h as they traveled east along the middle of the main nearshore lead. Mud was observed coming from the mouths of whales during four surfacings on this date; water depth was ~14 m. Another research team working in the same area also saw some bowheads surfacing with mud on their bodies in 1989 and 1990 (Angliss et al. 1993).

Resting.—It was quite rare for the general activity of bowheads observed during spring (aside from mothers and calves) to be classified as resting. Only 12 of 954 surfacings were in this category; in Table 5.9 these are combined with other rare group activities in the "Other" column. The 12 cases were on 3 and 7 May 1989, when two small groups of resting bowheads were found in small cracks within heavy ice. In addition, a few bowheads classed as traveling rested nearly motionless during one or more surfacings; however, these few surfacings comprised only about 1% of all surfacings by traveling bowheads (8 of 624; Table 5.11C).

Surfacing, Respiration and Dive Cycles

We determined the durations of surfacings and dives, the number of blows per surfacing, and the intervals between successive visible blows within a surfacing. Most definitions and criteria were the same as in our previous related studies (e.g. Dorsey et al. 1989; Richardson et al. 1995). In particular, a surfacing is again defined as the interval from the first arrival of a whale at the surface after a long ("sounding") dive to the time when the whale descends below the surface for the next long dive. A surfacing usually includes several blows, and is equivalent to a "surfacing sequence" as defined by some other authors.

Figure 5.27 summarizes the surfacing, respiration and dive characteristics of all presumably undisturbed whales, excluding calves and their mothers.[16] During surfacings, we observed an average of 5.2 blows at average intervals of 18.2 s (Fig. 5.27A,B). An average surfacing-dive cycle consisted of a 1.34 min surfacing and a 5.95 min dive (Fig. 5.27C,D). Short dives (<2 min) were common, with the majority of these being 1-2 min in duration (Fig. 5.27D). The longest documented dive, involving a traveling whale seen in 1994, was 39.0 min in duration. This is the

[15] These observations of mud on 16 May 1990 were 0.45-0.9 km from the ice camp during or within 20 min after the end of a drilling noise playback.

[16] The surfacing, respiration and dive cycles of calves and mothers differ from those of "other bowheads", and are summarized later (§5.4). Our data on the reactions of bowheads to playbacks of drilling and icebreaker noise rarely involved mothers or calves, so the appropriate control data are those for "other bowheads".

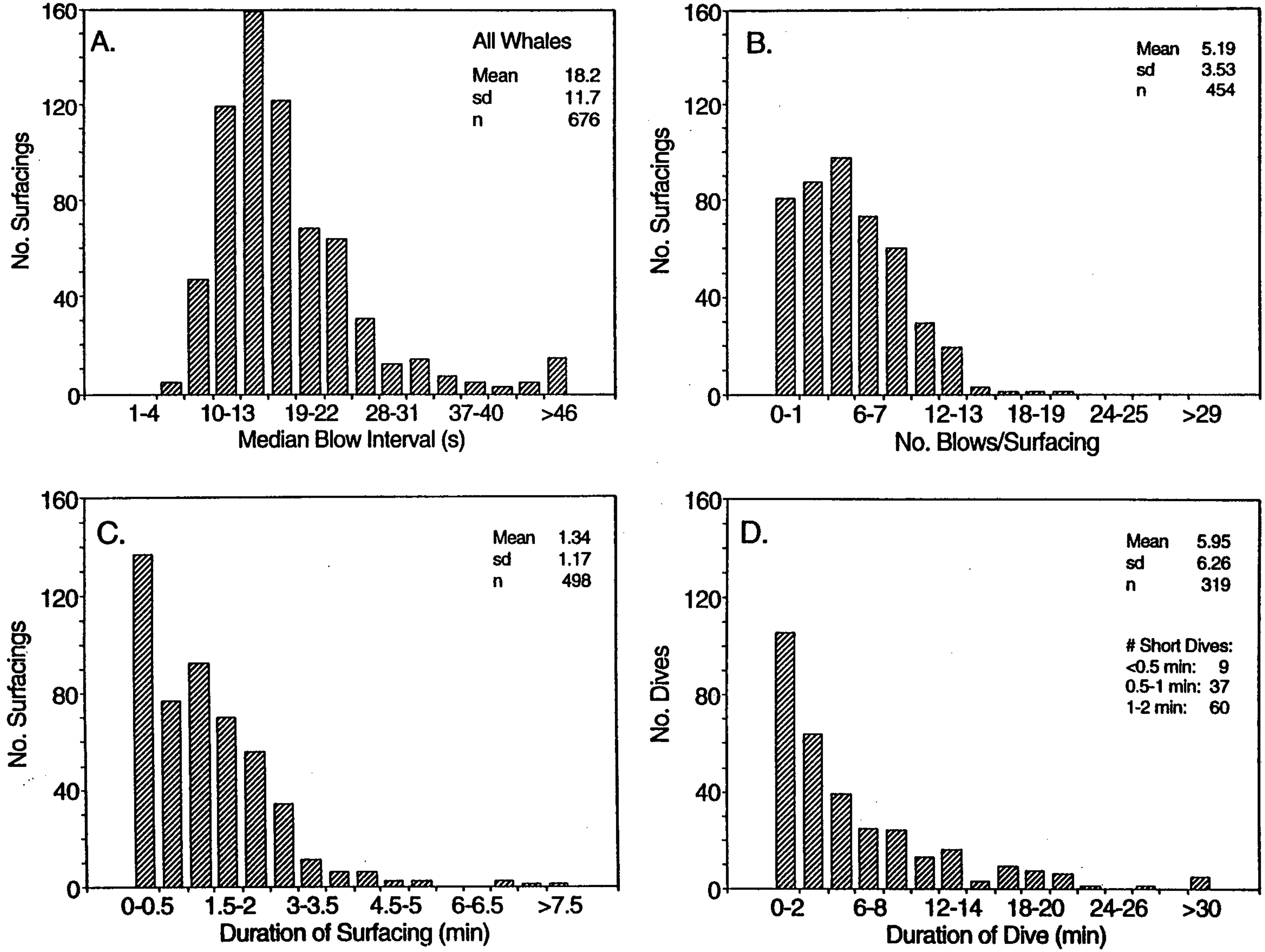

FIGURE 5.27. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowheads during the spring migration period near Barrow, Alaska. Other criteria: calves, yearlings, and accompanying mothers are excluded; based on aerial observations from a Twin Otter aircraft circling at altitude ≥460 m, 1989-94.

longest dive that we have documented during any of our studies of bowheads. Four additional dive durations (of 319 timed dives by presumably undisturbed bowheads) exceeded 30 min. In total, three of the five dives >30 min in duration involved traveling whales and two involved resting whales. The longest confirmed dives during our previous studies have been just over 30 min in duration: 31.0 min in the summer of 1980-84 in the Canadian Beaufort Sea (Dorsey et al. 1989), 31.6 min in the late summer/early autumn of 1985-86 near the Alaska/Yukon border (Richardson et al. 1987b:343), and 31.6 min in late summer in Baffin Bay (Richardson and Finley 1989:63).

Table 5.12 provides a more detailed breakdown of data on surfacing, respiration and dive cycles for bowheads engaged in various activities, including traveling, socializing, and various combinations of activities. Blow interval data in Table 5.12 are presented in two ways: ***(1)*** considering each individual blow interval as a unit, and ***(2)*** considering the median of all blow intervals within a single surfacing as a unit. In method (1), the sample size is the total number of blow intervals recorded, whereas in method (2) it is the number of surfacings during which one or more blow intervals were recorded. The sample sizes are smaller for median blow intervals (method 2) than for individual blow intervals (method 1). Also, standard deviations are smaller for method 2 than for method 1. Durations of successive individual blow intervals within a surfacing are presumably not independent. Hence, statistical comparisons of blow intervals are based on the median blow intervals.

Even when each surfacing or dive contributes only one observation to the analysis, there is still concern about possible lack of independence between successive surfacings or dives of a single whale (e.g. Machlis et al. 1985; Hoekstra and Jansen 1986). Because it is frequently impossible to determine whether a given whale has been observed previously, there is no way to obtain a single average value of each variable for each individual animal. Hence, in analyses in which each surfacing or dive contributes one observation, we place little emphasis on differences that, by standard statistical methods, are only marginally significant (e.g. $0.1 > P > 0.01$). Also, we refer to these P values as "nominal P" values (P_n).

Traveling Whales.—An average surfacing-dive cycle by an undisturbed traveling bowhead (mothers and calves excluded) consisted of a 1.35 min surfacing and a 6.63 min dive (Fig. 5.28; Table 5.12). There was an average of 5.0 blows per surfacing. Intervals between successive blows within a surfacing averaged 18.1 s.

The average dive duration reported here (6.63 min) may be realistic for bowheads traveling along open leads or through loose pack ice. However, it probably underestimates the overall average dive duration for traveling bowheads during spring migration. We were often unable to resight identifiable bowheads when they resurfaced after long dives under areas of extensive ice, so these long dives are underrepresented in our sample. As noted above, the longest documented dive by an undisturbed whale during this study was a 39.0 min dive by a whale traveling under ice on 7 May 1994. Two additional dives by traveling bowheads were slightly longer than 30 min.

Traveling+Socializing.—Bowheads that intermixed social interactions with travel had significantly ($P_n<0.001$) shorter surfacings and dives than did the bowheads that were simply traveling (Fig. 5.28C,D). The mean number of blows per surfacing was similar to that for

TABLE 5.12. Surfacing, respiration and dive behavior of undisturbed bowhead whales engaged in various activities during the spring migration period near Barrow, Alaska. Mothers and calves are excluded. Based on observations from a Twin Otter aircraft at altitude 460 m, 1989-1994.

	Group	Individual Blow Intervals (s)			Median Blow Intervals (s)			Number of Blows per Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
Year	Activity	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
89+90	Travel	19.39	8.90	963	19.78	7.28	225	4.76	3.14	200	1.37	1.07	208	7.11	5.63	163
	Travel+social	17.16	8.85	135	16.95	8.31	39	3.68	3.11	19	0.85	0.90	20	3.92	2.24	17
	Social	21.26	15.13	133	21.15	13.42	40	2.33	1.53	3	0.53	0.41	4	1.02	0.00	1
	Other/Unknown	48.64	96.79	214	30.10	39.78	29	8.82	4.69	17	3.13	2.07	19	11.58	10.20	11
	Travel+feed	17.20	7.20	30	17.31	6.35	8	6.50	2.38	4	1.43	0.64	5	1.43	0.00	1
	Tr+soc+feed			0			0			0			0			0
	Rest	95.64	141.34	85	53.45	62.70	10	7.60	3.65	5	4.64	2.79	5	13.70	13.19	6
	Other/unkn.	17.82	6.57	99	18.18	5.64	11	10.75	5.65	8	3.23	1.53	9	10.93	3.57	4
	All	23.68	39.65	1445	20.52	14.43	333	4.93	3.43	239	1.45	1.26	251	7.05	5.91	192
91+94	Travel	15.81	8.16	965	16.39	7.62	226	5.36	3.48	155	1.32	0.98	159	5.67	7.33	81
	Travel+social	14.79	8.24	413	15.37	7.74	95	5.16	3.68	51	1.06	0.97	60	2.60	4.44	21
	Social			0			0			0			0			0
	Other/Unknown	13.79	11.97	161	13.00	5.03	22	9.00	4.47	9	1.03	1.49	28	1.20	1.59	25
	Travel+feed			0			0			0			0			0
	Tr+soc+feed	14.08	7.90	76	13.96	5.79	13	8.40	3.65	5	2.04	1.05	3			0
	Rest			0			0			0			0			0
	Other/unkn.	13.54	14.74	85	11.61	3.53	9	9.75	5.85	4	0.91	1.50	25	1.20	1.59	25
	All	15.32	8.68	1539	15.89	7.55	343	5.47	3.63	215	1.23	1.05	247	4.28	6.43	127
1989-94	Travel	17.60	8.72	1928	18.08	7.64	451	5.02	3.30	355	1.35	1.03	367	6.63	6.27	244
	Travel+social	15.38	8.45	548	15.83	7.91	134	4.76	3.58	70	1.00	0.95	80	3.19	3.64	38
	Social	21.26	15.13	133	21.15	13.42	40	2.33	1.53	3	0.53	0.41	4	1.02	0.00	1
	Other/unknown	33.68	75.46	375	22.73	31.14	51	8.89	4.53	26	1.88	2.02	47	4.37	7.41	36
	Travel+feed	17.20	7.20	30	17.31	6.35	8	6.50	2.38	4	1.43	0.64	5	1.43	0.00	1
	Tr+soc+feed	14.08	7.90	76	13.96	5.79	13	8.40	3.65	5	2.04	1.05	3			0
	Rest	95.64	141.34	85	53.45	62.70	10	7.60	3.65	5	4.64	2.79	5	13.70	13.19	6
	Other/unkn.	15.84	11.29	184	15.23	5.77	20	10.42	5.47	12	1.52	1.82	34	2.54	3.90	29
	All	19.37	28.59	2984	18.17	11.69	676	5.19	3.53	454	1.34	1.17	498	5.95	6.26	319

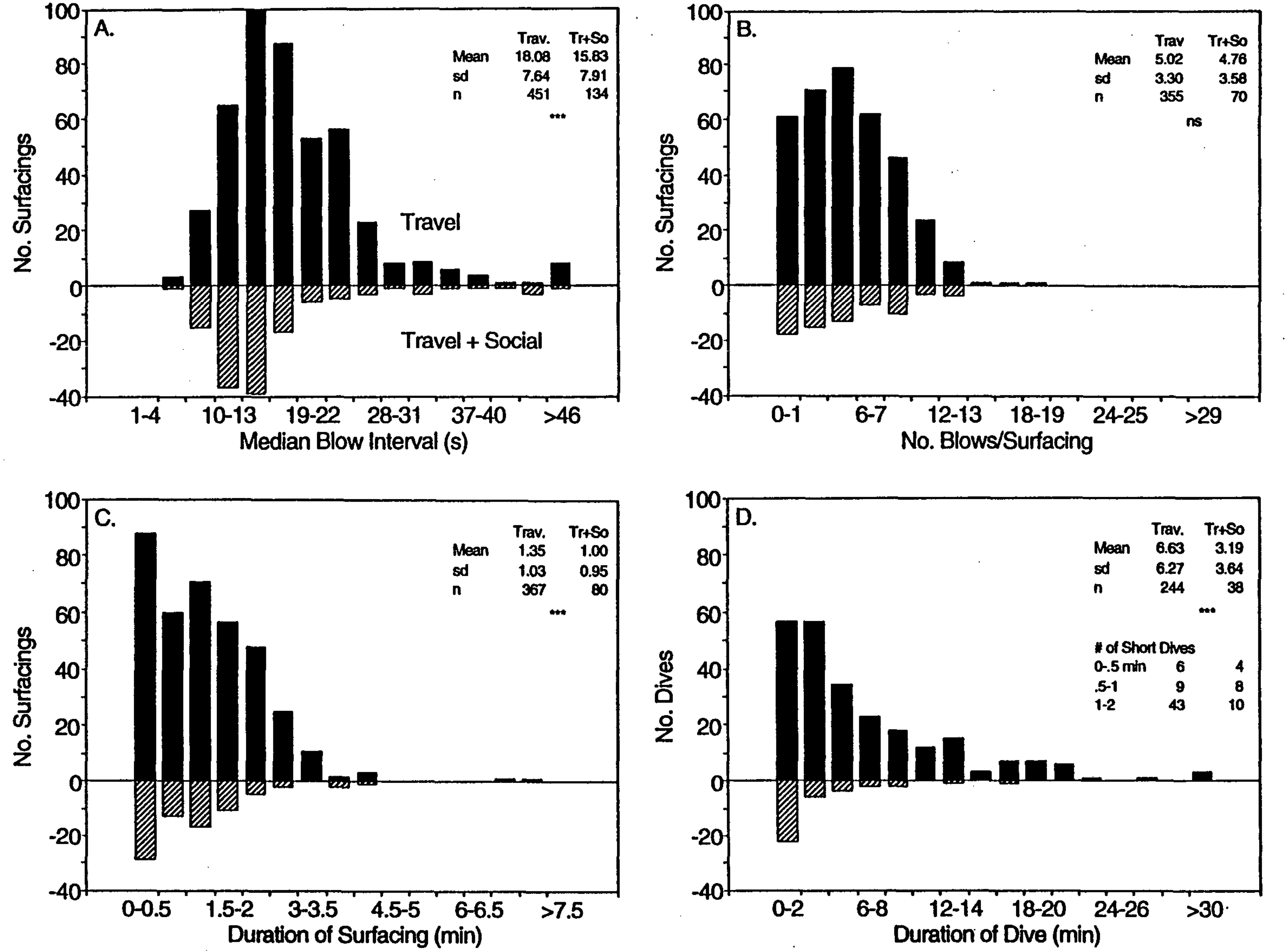

FIGURE 5.28. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowheads engaged in traveling (upward bars) or traveling+socializing (downward bars) during the spring migration period near Barrow, Alaska. Nominal significance levels come from t-tests on log-transformed data; ns means $P_n>0.01$ and *** means $P_n \leq 0.001$. Other criteria as in Fig. 5.27.

traveling whales (4.8 vs. 5.0, P_n>0.1). However, the median interval between successive blows within a surfacing was notably shorter for whales engaged in "travel+socializing" as compared with simple traveling, averaging 15.8 vs. 18.1 s (P_n<0.001). Note that the nominal significance levels quoted here are based on t-tests on log-transformed data; the log-transform eliminates or reduces the skewness evident in Figures 5.28A-D.

Socializing.—Bowheads whose general activity was socializing without travel were observed too infrequently to obtain meaningful sample sizes for most variables (Table 5.12). However, their median blow intervals (Fig. 5.29) tended to be long as compared with those for "traveling+socializing" whales, averaging 21.2 vs. 15.8 s (P_n<0.01).

Resting.—Resting whales were observed infrequently, and only in 1989. Although the sample size was very small, they tended to remain at the surface for unusually long periods (mean 4.64 min, n=5), and their blow intervals were usually very long. The median blow interval for the surfacing averaged 54 s in duration (n=10 surfacings), and the individual blow intervals averaged 96 s long (n=85) (Table 5.12). Although blow intervals by resting bowheads certainly tend to be longer than those by other bowheads, our blow-interval data for resting bowheads may be biased upward somewhat. Some blows by resting bowheads are invisible (Carroll and Smithhisler 1980; this study). We counted "no blow rises" as presumed blows in this study. However, resting bowheads do not exhibit the upward rolling motion characteristic of blowing by moving whales. Hence, invisible blows by resting whales would not always be recognizable as "presumed blows".

Other Behaviors

Many other behavioral variables, mostly of a categorical or ordinal nature, were recorded during the systematic behavioral observations from the circling aircraft. The most noteworthy of these are summarized in Tables 5.13 and 5.14 for the most commonly observed general activities: traveling, travel+socializing, and socializing.

Swimming Speed.—Speed during a particular surfacing cannot be determined quantitatively during aerial observations. However, we recorded relative speed during each surfacing on an ordinal "none, slow, medium, fast" scale (Table 5.13A). This scale is the same as the speed scale applied during our previous (1980-86) summer and autumn studies in the Beaufort Sea. Each of those studies involved 1 or 2 of the same aerial observers as in this study, so the categorization of speeds is consistent across studies.

Not surprisingly, traveling whales were usually moving at medium speed during surfacings, as were "traveling+socializing" whales (Table 5.13A). Whales engaged in socializing without travel had the most variable speeds during surfacings. The few resting whales were usually classified as having no forward speed (Richardson et al. 1991a:114).

Speeds of migrating whales were determined directly on a few occasions, mainly in 1990, when we followed recognizable individual bowheads for several kilometers. The majority of these

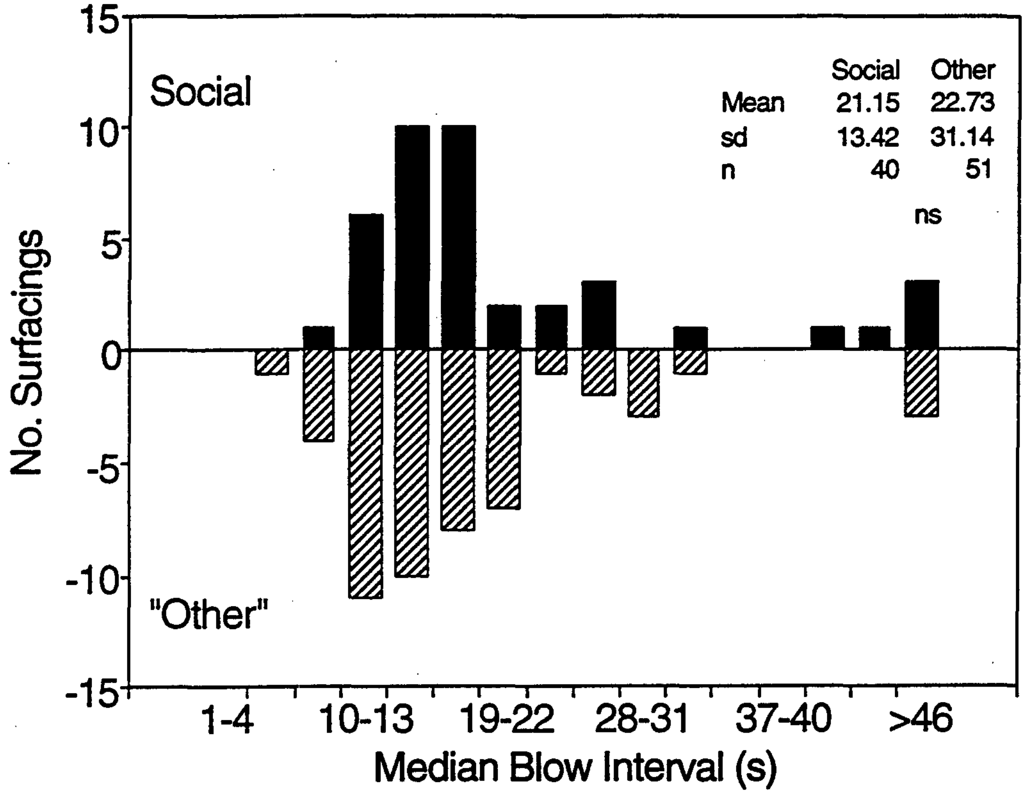

FIGURE 5.29. Frequency distributions of median blow intervals for undisturbed bowheads engaged in socializing (upward bars) or various other activities listed in Table 5.12 (downward bars) during the spring migration period near Barrow, Alaska. Nominal significance level comes from t-test on log-transformed data; ns means $P_n>0.1$. Other criteria as in Fig. 5.27.

data concerned mother-calf pairs or whales exposed to noise playbacks.[17] However, on 5 May 1990 we followed one undisturbed whale for about 1 h as it swam 4.3 km eastward along a narrow lead; the average "ground" speed (ignoring any current) was 4.4 km/h. The speed of this whale during each of its surfacings was recorded as medium. On 12 May 1990 we followed a group containing several recognizable whales for 2.1 h as they swam steadily eastward for 12.3 km along the main nearshore lead, i.e. average "ground" speed 5.9 km/h.[18] Speed during almost all surfacings within this 2.1-h period was recorded as medium. Additional data on speeds were obtained when the various recognizable whales were photographed twice at known locations (§5.2).

[17] Many whales were observed during two or more successive surfacings. Aircraft position during most surfacings was known reasonably accurately in 1989-90 (VLF navigation system) and very accurately in 1991/94 (GPS systems). However, we usually avoided flying directly over the whales in order to minimize the potential for aircraft disturbance. Therefore, exact whale positions during successive surfacings usually were not determined. The cases mentioned are ones where speed can be computed to within ±0.25 km/h based on good aircraft position data and long intervals between first and last observed surfacing.

[18] These whales were also followed for an additional 0.5 h, but during that time they began to bring mud to the surface and slowed down to about 2.6 km/h.

TABLE 5.13. Frequencies of various activities among undisturbed bowhead whales engaged in various group activities. Mothers and calves excluded. Presentation as in Table 5.9.

	Number of Surfacings					Percentage of Surfacings				
	Travel	Tr+Soc	Social	Other	All	Travel	Tr+Soc	Social	Other	All
A. Speed During This Surfacing										
Zero	10	0	6	17	33	1.7	0.0	23	30	4.0
Slow	131	32	7	14	184	22.5	19.3	27	25	22.1
Moderate	329	100	5	10	444	56.4	60.2	19	18	53.4
Fast	3	0	1	0	4	0.5	0.0	4	0	0.5
Unknown but >0	70	22	3	7	102	12.0	13.3	12	13	12.3
Milling	0	2	1	0	3	0.0	1.2	4	0	0.4
Change	40	10	3	8	61	6.9	6.0	11.5	14.3	7.3
Total n	583	166	26	56	831					
B. Flukes Out at End of Surfacing										
No	457	106	18	39	620	91.0	87.6	100	78	89.7
Yes	45	15	0	11	71	9.0	12.4	0	22	10.3
Total n	502	121	18	50	691					
C. Pre-Dive Flex Before End of Surfacing										
No	431	101	15	41	588	98.4	99.0	94	95	98.2
Yes	7	1	1	2	11	1.6	1.0	6	5	1.8
Total n	438	102	16	43	599					
D. Turns During Surfacing										
None	276	55	2	34	367	64.0	45.1	13	55	58.3
Right	56	28	4	11	99	13.0	23.0	27	18	15.7
Left	52	19	4	7	82	12.1	15.6	27	11	13.0
Multiple	47	20	5	10	82	10.9	16.4	33	16	13.0
Total n	431	122	15	62	630					
E. Degrees of Turn During Surfacing										
0	276	55	2	34	367	72.6	53.4	20	59	66.6
10	23	6	0	4	33	6.1	5.8	0	7	6.0
20	29	7	0	0	36	7.6	6.8	0	0	6.5
30	10	2	0	3	15	2.6	1.9	0	5	2.7
40	8	2	0	0	10	2.1	1.9	0	0	1.8
50-80	17	6	0	2	25	4.5	5.8	0.0	3.4	4.5
90+	17	25	8	15	65	4.5	24.3	80	26	11.8
Total n	380	103	10	58	551					
F. Social Activity During Surfacing										
None	449	84	0	67	600	80.8	44.4	0	93	69.8
Passive	52	17	0	4	73	9.4	9.0	0	6	8.5
Active	55	88	43	1	187	9.9	46.6	100	1	21.7
Total n	556	189	43	72	860					
G. Aerial Activity During Sfc/Dive Seq.										
None	440	93	31	43	607	93.6	81.6	74	61	87.2
Roll	5	9	11	0	25	1.1	7.9	26	0	3.6
Flip. slap (FS)	4	0	0	0	4	0.9	0.0	0	0	0.6
Tail slap (TS)	12	0	0	4	16	2.6	0.0	0	6	2.3
FS + TS	3	2	0	1	6	0.6	1.8	0	1	0.9
Breach	5	7	0	17	29	1.1	6.1	0	24	4.2
Breach + FS &/or TS	1	3	0	5	9	0.2	2.6	0	7	1.3
Total n	470	114	42	70	696					

TABLE 5.14. Number of surfacing/dive sequences with specific whale behaviors among undisturbed bowhead whales engaged in various group activities. Mothers and calves excluded. Totals exceed "Overall n" because >1 special behavior can occur at one time. Presentation as in Table 5.9.

	Number of Surfacings					Percentage of Surfacings				
	Travel	Tr+Soc	Social	Other	All	Travel	Tr+Soc	Social	Other	All
None	121	47	3	39	210	28.1	42.0	19	61	33.7
Defecation	0	0	1	0	1	0.0	0.0	6	0	0.2
Flukes raised during surfacing	6	5	0	0	11	1.4	4.5	0	0	1.8
Lunge or surge	5	6	0	1	12	1.2	5.4	0	2	1.9
Underwater blow	5	6	5	1	17	1.2	5.4	31	2	2.7
Arch during surfacing	30	4	0	4	38	7.0	3.6	0	6	6.1
Mouth open slightly/briefly	0	1	0	0	1	0.0	0.9	0	0	0.2
Mouth open	1	0	0	0	1	0.2	0.0	0	0	0.2
Echelon formation	0	0	0	0	0	0.0	0.0	0	0	0.0
Near-surface feeding	0	0	0	0	0	0.0	0.0	0	0	0.0
Mud from mouth	0	0	0	4	4	0.0	0.0	0	6	0.6
Mud behind whale	0	0	0	0	0	0.0	0.0	0	0	0.0
Streak in water	0	0	0	0	0	0.0	0.0	0	0	0.0
Penis visible	0	3	1	0	4	0.0	2.7	6	0	0.6
Presumed sexual activity	0	18	7	0	25	0.0	16.1	44	0	4.0
Nursing (mother or calf)	0	0	0	0	0	0.0	0.0	0	0	0.0
Play with log	0	0	0	0	0	0.0	0.0	0	0	0.0
Play with other large object	0	0	0	0	0	0.0	0.0	0	0	0.0
Play with particulates	0	0	0	0	0	0.0	0.0	0	0	0.0
Motionless at surface	12	0	1	12	25	2.8	0.0	6	19	4.0
Motionless just below surface	0	0	0	0	0	0.0	0.0	0	0	0.0
Motionless with head down	0	0	0	0	0	0.0	0.0	0	0	0.0
Spyhop	0	0	0	0	0	0.0	0.0	0	0	0.0
Travel along ice edge	87	14	0	4	105	20.2	12.5	0	6	16.9
Emerge from extens. ice (>1km)	21	2	0	0	23	4.9	1.8	0	0	3.7
Riding (mother or calf)	0	0	0	0	0	0.0	0.0	0	0	0.0
Accompanied by belugas	7	0	0	1	8	1.6	0.0	0	2	1.3
Visible below surface	174	19	0	0	193	40.4	17.0	0	0	31.0
Swims in tight circles	0	0	0	2	2	0.0	0.0	0	3	0.3
Overall n	431	112	16	64	623					

Fluke-out Dives.—Bowheads and other whales often raise their flukes out of the water at the end of a surfacing as they are diving. However, in the spring, only about 10% of the dives were fluke-out dives (Table 5.13B). Similarly low values were found in 1989/90 (8%) and 1991/94 (12%). For traveling whales, the overall 1989-94 figure was 9% (45 of 502). In contrast, during autumn migration, bowheads raised their flukes ~27% of the time in the Alaskan Beaufort Sea and ~58% of the time in Baffin Bay (Richardson et al. 1995).

Pre-dive Flex.—The pre-dive flex is a concave bending of the back that sometimes occurs 10-20 s before bowheads dive. Pre-dive flexes were rare during the spring; they were seen during only 11 of 599 surfacings when a flex, if present, would have been noted (2%, Table 5.13C). For traveling whales, there were pre-dive flexes during only 7 of 438 surfacings (2%). In some previous studies, pre-dive flexes have been much more common (Würsig et al. 1985).

Turns.—Frequency of turns during surfacings depended on whale activity (Table 5.13D): 36% for traveling whales (n=431), 55% for traveling+socializing whales (n=122), 87% for socializing whales (n=15). Surfacings with >1 turn were infrequent in traveling whales (11%) and traveling+socializing whales (16%), but more common in socializing whales (33%). Most turns by traveling or traveling+socializing whales were ≤30° (Table 5.13E). In contrast, socializing whales usually turned by ≥90° (although few of these cases were recorded systematically).

These results are consistent with previously-summarized data on variability in headings during behavioral observation sessions. Headings were least variable during travel, somewhat more so during travel+socializing, and most variable during socializing (Table 5.10, p. 202).

Social Behavior.—As previously discussed, bowheads whose general activity was classed as traveling were swimming parallel to and within ½ body length of one or more additional bowheads ("passive socializing") during about 9% of their surfacings. During an additional 10% of these surfacings, there was some form of more active social interaction (Table 5.13F). The frequency of active interactions was considerably higher for traveling+socializing" bowheads (47%). Whales classified as socializing without travel exhibited active social interactions during all surfacings.

Aerial Behavior.—Aerial activities are those in which a part of the body is raised above the surface: breaches, flipper and tail slaps, rolls, and various combinations, as described for bowheads by Würsig et al. (1985, 1989). Table 5.13G shows the frequencies of various aerial activities among presumably undisturbed bowheads during spring (mothers and calves excluded):

- ***Breaches*** were seen during 38 of 696 surfacings (5.5%), usually alone but sometimes combined with flipper or tail slaps during the same surfacing. A given whale was often seen to breach several times in succession, with breaches often spaced ~1 min apart.
- During a ***roll*** along the longitudinal axis of the body, at least one flipper is raised above the surface. Rolls were seen during about 4% of the surfacings (25 of 696). Rolls were most common when whales engaged in social interactions.
- ***Tail slaps*** or ***flipper slaps*** occurred during small percentages of the surfacings (2.3% and 0.6%, respectively). There were additional surfacings that included both flipper and tail slaps (0.9%), or a breach plus a flipper and/or tail slap (1.3%).

It is difficult to determine the frequency of occurrence of aerial behaviors during particular whale activities. When aerial activities occurred in extended bouts, the underlying whale activity, e.g. traveling or socializing, was sometimes impossible to determine. The general activity of these whales was classed as "Other". Thus, actual frequencies of various aerial activities during traveling, traveling+socializing, and socializing are probably somewhat higher than suggested by Table 5.13G, assuming that some whales in the "Other" column probably belong under traveling, etc.

Additional Behavioral Variables.—Table 5.14 summarizes the frequencies of numerous additional behavioral variables, almost all of which occurred quite infrequently during spring near Barrow. Table 5.14 lists all of the miscellaneous behaviors that we record whenever they are seen, including numerous behaviors that have been noted during previous summer/autumn studies but not (or rarely) during this spring study. The rarity or absence of certain behaviors is noteworthy, e.g. indications of feeding such as defecation, open mouth, or swimming in echelon formation; occurrence of play with objects in water; and occurrence of spyhopping.

In contrast, two of the behaviors listed in Table 5.14 occurred rather often:

- ***Travel along ice edge:*** Bowheads observed in this study were often swimming parallel to and within 100 m of the edge of a field of pack ice or brash ice, or (less often) along the edge of the landfast ice. This situation was noted during 105 of 623 surfacings (17%), and there were undoubtedly additional similar cases that were not recorded as such. The frequency of this behavior is related to the tendency for bowheads to adjust their headings to match the alignments of leads and cracks when these are oriented more or less toward the northeast or east.
- ***Visible below surface:*** This was noticed during dive(s) preceding and/or following 193 of 623 surfacings. These cases involved traveling bowheads (174 of 431 surfacings, 40%) and traveling+socializing bowheads (19 of 112, 17%). The rather high frequency of this type of observation indicates that spring-migrating bowhead whales often traveled within several meters of the surface. However, the frequency of this behavior cannot be compared across studies because of differences in observation conditions. Times when migrating bowheads were visible below the surface were times of good lighting and low sea state. The water northeast of Barrow during spring is clear, and sea state is often low because waves are dampened by nearby ice. In contrast, during our summer work in the eastern Beaufort Sea, sea states tended to be higher and the water was often very turbid.

Behavior of Subadults vs. Adults During Travel

It is sometimes possible to categorize whales observed during aerial observations as definitely subadult or definitely adult, based on size and markings. Many adults have prominent scars, whereas subadults tend to be more nondescript (Davis et al. 1986a). We categorized the bowheads as subadults or adults only in obvious cases. Only 36% of the records (mothers and calves excluded) were categorized in this manner. Thus, our subadult and adult categories no doubt include primarily the smaller subadults and the larger and/or older adults. We further restricted our analysis to whales whose general activity was classified as traveling.

Surfacing, respiration and dive cycles during travel differed significantly between adults and subadults (Fig. 5.30). A typical cycle by an adult consisted of a 6.81 min dive and a 1.46 min surfacing containing 4.9 blows spaced 20.6 s apart. A typical cycle by a subadult was a 5.26 min dive and a 1.35 min surfacing containing 6.2 blows spaced 14.1 s apart. Dive durations and median blow intervals were significantly shorter in subadults ($P_n<0.01$ and $P_n<0.001$, respectively). Durations of surfacing were similar for the two groups. This, combined with the notably shorter blow intervals in subadults, suggests that the number of blows per surfacing should be higher for subadults. There was only a weak indication of this (Fig. 5.30B).

Some other behavioral variables also differed between subadults and adults:

- Of the surfacings when swimming speed was estimated as zero, slow, moderate or fast, estimated speed was zero or slow during 62% of the surfacings by subadults but during only 25% of those by adults (Table 5.15A; $\chi^2=22.4$, df=1, $P_n<0.001$).

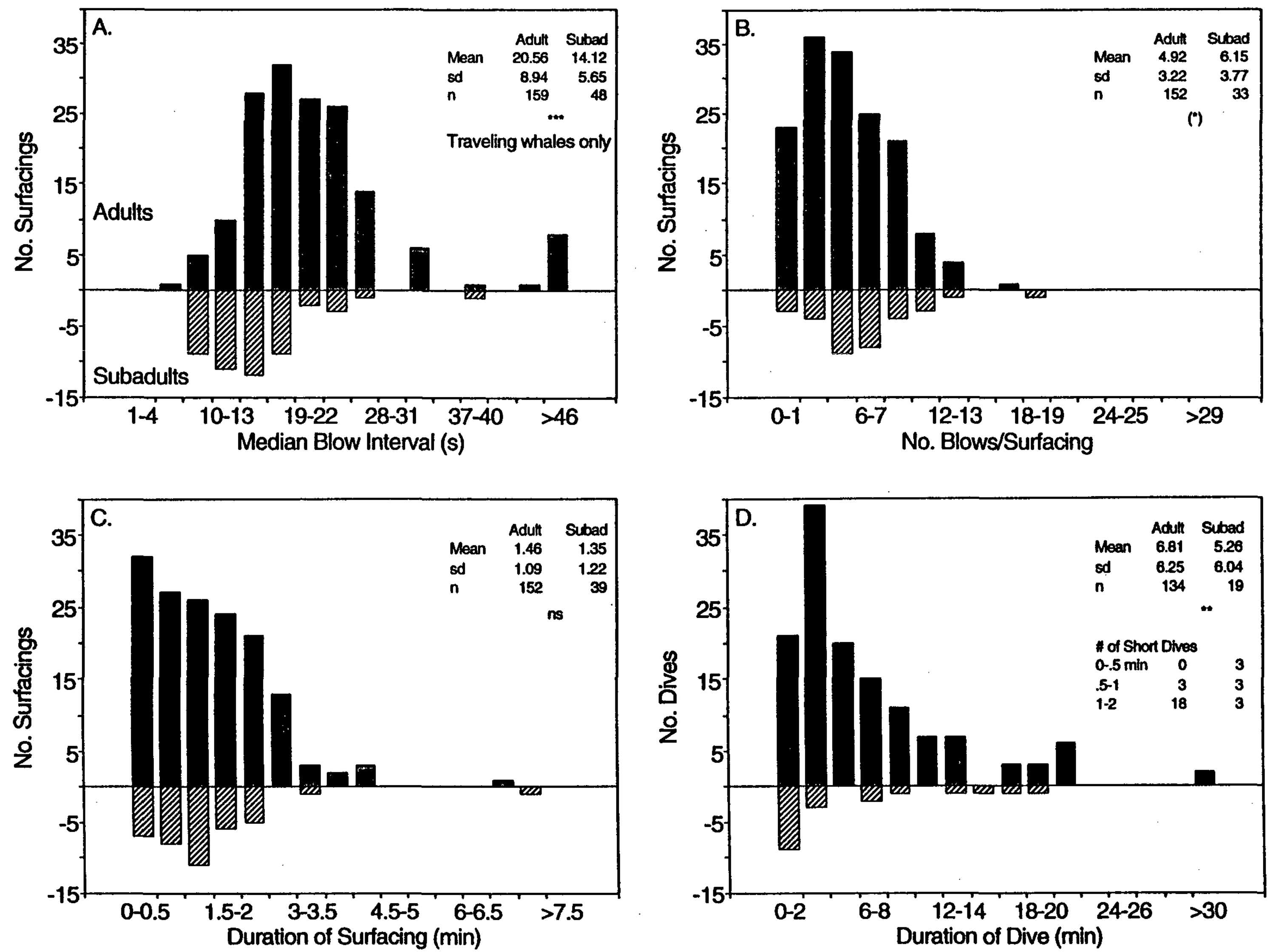

FIGURE 5.30. Frequency distributions of surfacing, respiration and dive variables for undisturbed adult bowheads (upward bars) and subadult bowheads (downward bars) engaged in traveling during the spring migration period near Barrow, Alaska. Nominal significance levels come from t-tests on log-transformed data; (*) means $0.1 \geq P_n > 0.05$ and ** means $0.01 \geq P_n > 0.001$. Other criteria as in Fig. 5.27.

TABLE 5.15. Frequencies of various activities among undisturbed bowhead subadults and adults engaged in traveling. Mothers and calves excluded. Presentation as in Table 5.9.

	Number of Surfacings			Percentage of Surfacings		
	Subadult	Adult	All	Subadult	Adult	All
A. Speed During This Surfacing						
Zero	3	1	4	4.9	0.5	1.6
Slow	28	40	68	45.9	21.7	27.8
Moderate	18	124	142	29.5	67.4	58.0
Fast	1	1	2	1.6	0.5	0.8
Unknown but >0	4	3	7	6.6	1.6	2.9
Milling	0	0	0	0.0	0.0	0.0
Change	7	15	22	10.3	7.5	8.2
Total n	61	184	245			
B. Flukes Out at End of Surfacing						
No	50	169	219	89.3	93.9	92.8
Yes	6	11	17	10.7	6.1	7.2
Total n	56	180	236			
C. Pre-Dive Flex Before End of Surfacing						
No	42	167	209	93.3	98.2	97.2
Yes	3	3	6	6.7	1.8	2.8
Total n	45	170	215			
D. Turns During Surfacing						
None	21	117	138	50.0	69.2	65.4
Right	8	20	28	19.0	11.8	13.3
Left	9	17	26	21.4	10.1	12.3
Multiple	4	15	19	9.5	8.9	9.0
Total n	42	169	211			
E. Degrees of Turn During Surfacing						
0	21	117	138	56.8	74.5	71.1
10	4	15	19	10.8	9.6	9.8
20	6	9	15	16.2	5.7	7.7
30	2	2	4	5.4	1.3	2.1
40	0	1	1	0.0	0.6	0.5
50-80	1	7	8	2.6	4.3	4.0
90+	3	6	9	8.1	3.8	4.6
Total n	37	157	194			
F. Social Activity During Surfacing						
None	50	144	194	82.0	77.8	78.9
Passive	6	20	26	9.8	10.8	10.6
Active	5	21	26	8.2	11.4	10.6
Total n	61	185	246			
G. Aerial Activity During Sfc/Dive Seq.						
None	42	166	208	85.7	97.6	95.0
Roll	0	1	1	0.0	0.6	0.5
Flip. slap (FS)	1	1	2	2.0	0.6	0.9
Tail slap (TS)	2	2	4	4.1	1.2	1.8
FS + TS	1	0	1	2.0	0.0	0.5
Breach	2	0	2	4.1	0.0	0.9
Breach + FS &/or TS	1	0	1	2.0	0.0	0.5
Total n	49	170	219			

- Simple left or right turns were more common in subadults than in adults (40% vs. 22% of surfacings; χ^2=6.46, df=2, P_n<0.05). Turns by ≥20° were more common in subadults than in adults (Table 5.15D,E; 32% vs. 16% of surfacings; χ^2=4.27, df=1, P_n<0.05)
- Aerial activities, although uncommon in both groups, were slightly more common in subadults (Table 5.15G; 14% vs. 2% of surfacings; χ^2=8.99, df=1, P_n<0.01).

Many other behaviors (listed in Table 5.14) were seen too infrequently for meaningful comparison of their frequencies in adults vs. subadults. However, a considerably higher percentage of the subadults were traveling parallel to and within 100 m of ice edges (36% of 44 surfacings by subadults vs. 13% of 171 surfacings by adults). Also, during dives, subadults were rarely visible below the surface (7%) whereas adults often were (63%). The latter result may be related to the larger size and more conspicuous markings of adults, which assist aerial observers in maintaining visual contact with whales migrating a few meters below the water's surface.

These results show that some aspects of surfacing, respiration and dive cycles, along with some other behavioral variables, differed significantly between subadult and adult bowheads even after mothers and calves were excluded from consideration. Thus, caution is necessary when comparing bowhead behavior in situations when the proportions of adults and subadults are unknown but potentially varying with location or time.

The situations in which these adults and subadults were observed overlapped strongly, but with some differences (Table 5.16). There was little difference in dates or times of observation. For both subadults and adults, most observations were in water 20-49 m deep, but the proportion of cases in deeper water was slightly higher for subadults (Table 5.16C). There tended to be slightly more ice near the subadults (Table 5.16D), and more of the subadults had extensive (>1 km) solid ice ahead of them as they dove (Table 5.16E). Subadults tended to be in smaller groups than did the adults, and were more often by themselves based on a 5 whale-length criterion (Table 5.17A,B). The only whales considered here were those classified as traveling, so other activities were infrequent or absent (Table 5.17C-E).

Some differences in behavior may have been related to the weak tendencies for subadults to occur in deeper water with more ice. The trends for slower speeds and greater frequencies of turning by subadults are consistent with heavier ice conditions. However, the tendencies for shorter dives and markedly shorter blow intervals by subadults are not obviously related to ice. Mean dive duration and blow interval are both even shorter for calves than for subadults (§5.4), suggesting that these variables are related to age or size. In general, however, multivariate analysis is needed to help understand the interrelationships of the many intercorrelated variables.

<u>Variables Correlated with Surfacing, Respiration and Dive Cycles of Migrating Bowheads</u>

<u>Multiple Regression Methodology</u>.—We used stepwise multiple regression analysis (SMRA) to identify factors correlated with

- duration of surfacing,
- number of blows per surfacing,

TABLE 5.16. Circumstances of observations of undisturbed bowhead subadults and adults engaged in traveling. Mothers and calves are excluded. Presentation as in Table 5.9.

	Number of Surfacings			Percentage of Surfacings		
	Subadult	Adult	All	Subadult	Adult	All
A. Date						
21-30 Apr	0	1	1	0.0	0.5	0.4
1-10 May	20	35	55	30.8	18.5	21.7
11-20 May	44	151	195	67.7	79.9	76.8
21-31 May	1	2	3	1.5	1.1	1.2
Total n	65	189	254			
B. Hour (local)						
6-8	33	64	97	50.8	33.9	38.2
9-11	8	48	56	12.3	25.4	22.0
12-14	3	42	45	4.6	22.2	17.7
15-17	15	24	39	23.1	12.7	15.4
18-20	6	11	17	9.2	5.8	6.7
21-23	0	0	0	0.0	0.0	0.0
Total n	65	189	254			
C. Water Depth (m)						
10-19	0	1	1	0.0	0.5	0.4
20-49	54	186	240	83.1	98.4	94.5
50-99	1	0	1	1.5	0.0	0.4
100-250	4	2	6	6.2	1.1	2.4
> 250	6	0	6	9.2	0.0	2.4
Total n	65	189	254			
D. Ice Cover (%)						
None	3	9	12	4.6	4.8	4.7
1-9 %	18	107	125	27.7	56.6	49.2
10-29	1	2	3	1.5	1.1	1.2
30-59	8	23	31	12.3	12.2	12.2
60-79	22	38	60	33.8	20.1	23.6
80-90	13	10	23	20.0	5.3	9.1
>90	0	0	0	0.0	0.0	0.0
Total n	65	189	254			
E. Ice Ahead						
None	31	158	189	54.4	87.3	79.4
< 100 m	4	4	8	7.0	2.2	3.4
100-1000 m	11	14	25	19.3	7.7	10.5
> 1000 m	11	5	16	19.3	2.8	6.7
Total n	57	181	238			

TABLE 5.17. Frequencies of various group sizes and activities of undisturbed bowhead subadults and adults engaged in traveling. Mothers and calves excluded. Presentation as in Table 5.9.

	Number of Surfacings			Percentage of Surfacings		
	Subadult	Adult	All	Subadult	Adult	All
A. Group Size (within 5 body lengths)						
1	42	60	102	65.6	32.3	40.8
2	13	84	97	20.3	45.2	38.8
3	9	28	37	14.1	15.1	14.8
4	0	7	7	0.0	3.8	2.8
5	0	5	5	0.0	2.7	2.0
>5	0	2	2	0.0	1.1	0.8
Total n	64	186	250			
B. # Bowheads Within 1 km						
1	3	0	3	4.6	0.0	1.2
2	16	5	21	24.6	2.6	8.3
3	20	67	87	30.8	35.4	34.3
4	21	47	68	32.3	24.9	26.8
5	2	11	13	3.1	5.8	5.1
6	0	31	31	0.0	16.4	12.2
7	3	15	18	4.6	7.9	7.1
8	0	13	13	0.0	6.9	5.1
>8	0	0	0	0.0	0.0	0.0
Total n	65	189	254			
C. Whale Activity This Sfc/Dive Sequence						
Rest	2	1	3	3.1	0.5	1.2
Travel	50	163	213	76.9	86.2	83.9
Socialize	0	0	0	0.0	0.0	0.0
Feed	2	0	2	3.1	0.0	0.8
Travel+Social	4	20	24	6.2	10.6	9.4
Travel+Feed	0	0	0	0.0	0.0	0.0
Social+Feed	0	0	0	0.0	0.0	0.0
Unknown/Other	7	5	12	10.8	2.6	4.7
Total n	65	189	254			
D. Group's Predominant Feeding Mode						
None	65	189	254	100.0	100.0	100.0
Water-column	0	0	0	0.0	0.0	0.0
Bottom	0	0	0	0.0	0.0	0.0
Near-surface	0	0	0	0.0	0.0	0.0
Total n	65	189	254			
E. Whale's Feeding Mode During This Sfc/Dive Sequence						
None	58	184	242	96.7	98.9	98.4
Water-column	2	2	4	3.3	1.1	1.6
Bottom	0	0	0	0.0	0.0	0.0
Near-surface	0	0	0	0.0	0.0	0.0
Total n	60	186	246			

- average interval between successive blows, and
- duration of dive

in migrating bowhead whales. These four dependent variables were each log-transformed to reduce skewing of residuals.

The SMRA methods used in this analysis were generally consistent with those used in previous studies of bowhead behavior (Dorsey et al. 1989; Richardson et al. 1995). However, some predictor variables were new or defined differently. Also, criteria for deciding which cases to include in the analysis were defined differently, in order to restrict the analysis to a relatively homogeneous dataset concerning actively-migrating bowheads.

A total of 25 variables, some of which were closely interrelated, were considered as potential predictors of surfacing, respiration and dive behavior:

- year = 1990? = 1991? = 1994? (3 measures, each 0 for no or 1 for yes),
- date in May (1-31) and date-squared
- decimal hour (0-23.99, local daylight time) and hour-squared,
- ice cover (5 measures),
    - percent ice cover within observation circle (0-100%),
    - >5% cover (1) or not (0),
    - moderate extent (0.1-1 km) of solid ice ahead as whale dives (1) or not (0),
    - large extent (>1 km) of solid ice ahead as whale dives (1) or not (0),
    - whale emerges from under ice at start of surfacing or end of dive,
- sea state (0-6),
- distance from shore (in kilometers, log transformed),
- water depth (in meters, log transformed),
- general activity travel+socializing (1) or travel (0),
- current activity travel+socializing (1) or not (0),
- current activity resting (1) or not (0),
- group size (1-6),
- number of bowheads within circle of ~1 km radius (1-9),
- number of bowheads within ~5 km (1-30),
- passive socializing during this surfacing (1) or not (0),
- flukes out as whale dove (1) or not (0),
- known to be adult (1) or not (0),
- known to be subadult (1) or not (0)

Years and many of the other variables were represented by dummy 0/1 variables (Draper and Smith 1981:241). By not including a dummy variable for 1989, that year was established as the standard year against which others were compared. Date (in days after 30 April), date^2, hour and hour^2 were included to allow for possible non-linear temporal effects.

In these analyses, each surfacing or dive for which all requisite variables were known constituted a case. Case selection criteria were established to include observations typical of traveling (i.e. actively migrating) bowhead whales, the predominant category of bowheads observed near Barrow in spring. These criteria excluded cases when the whale was actively socializing or engaged in aerial activity. Calves, their mothers, and potentially disturbed whales were also excluded. More specifically, cases included in the analysis met the following criteria:

- whale group classified as traveling or traveling+socializing,
- individual whale's present activity classed as traveling, traveling+socializing, or resting,
- no active socializing or aerial activity during the present surfacing or dive,
- whale was not a calf, yearling, or accompanying adult (presumed mother),
- presumably undisturbed; no known potential disturbance in previous 30 min.

Predictor variables were entered into the SMRA model one at a time in descending order of partial correlation until no remaining variable, if included, would improve the predictability of the dependent variable by an amount significant at the nominal $P<0.05$ level. After running the analyses with BMDP2R (Release 7.0 Dynamic, Dixon 1992), we examined scatter plots of residuals vs. all predictors to check for violations of assumptions (Draper and Smith 1981). For each case, the residual is the difference between the actual value of the dependent variable and the value predicted by the SMRA model. Analysis of residuals allows one to check for previously unrecognized non-linear effects and certain violations of the equality of variance assumption.

We also analyzed the residuals to evaluate whether there was any indication of partial correlation between the dependent variable and swimming speed or occurrence of turns, after allowance for all the variables mentioned above. Swimming speed and occurrence of turns were not included in the main SMRA because they were sometimes unknown, and their inclusion in the main analysis would have reduced the sample size to an undesirable degree. (All variables considered as potential predictors must be known for each case included in the main SMRA.)

Results of the SMRAs on the four dependent variables are summarized in Table 5.19, later. This table summarizes both simple and partial correlations of all predictor variables with each of the four dependent variables. Nominal significance levels are coded as

***, +++ or - - - if $P\leq0.001$,	**, ++ or - - if $0.001<P\leq0.01$,
*, + or - if $0.01<P\leq0.05$,	ns if $P>0.05$.

Plus or minus signs are used to indicate direction as well as significance of relationship, e.g. --- means a negative trend with nominal $P\leq0.001$. Simple and partial correlation coefficients are indicated, respectively, by "r" and "r_p". The quoted "percent of variance explained" is the adjusted percent, allowing for sample size (Dixon 1992). Trends stated to be "strong" are those with nominal $P\leq0.01$.

Little emphasis is given to correlations with nominal $P>0.01$, given *(1)* the large number of tests done, *(2)* the tendency, in SMRAs, for nominal P-values to overestimate the value of individual variables as predictors (Draper and Smith 1981:310), and *(3)* the frequent inclusion of data from more than one surfacing or dive of a given whale. The number of repeated observations of specific whales is unknown, as it was often impossible to re-identify whales from one surfacing to another. In addition, any multivariate analysis has important limitations when applied to uncontrolled field data with many intercorrelated predictor variables (e.g., James and McCulloch 1990). In the absence of experimental control over the environmental variables, it is usually impossible to identify with certainty which correlations represent direct causative links and which ones are incidental side-effects of intercorrelations among predictor variables.

TABLE 5.18. Simple correlations among various measures of surfacing, respiration, and dive cycles. Correlations are shown based on both *(A)* original variables and *(B)* logarithmically-transformed variables. We consider the durations of both the dive preceding and the dive following the surfacing in question. Sample size ranges from 158 to 345; values of $|r|>0.17$ are significant at the $\alpha=0.05$ level or better.

	Duration of Surfacing	Number of Blows per Surfacing	Median Blow Interval	Duration of Preceding Dive	Duration of Following Dive
A. ORIGINAL VALUES					
Duration of Surfacing (min)	—	0.867	0.079	0.286	0.284
No. Blows per Surfacing	0.867	—	-0.387	0.456	0.318
Median Blow Interval (s)	0.079	-0.387	—	-0.351	-0.135
Duration of Preceding Dive (min)	0.286	0.456	-0.351	—	0.329
Duration of Following Dive (min)	0.284	0.318	-0.135	0.329	-
B. LOG-TRANSFORMED VALUES					
Duration of Surfacing	—	0.868	0.158	0.297	0.242
No. Blows per Surfacing	0.868	—	-0.392	0.450	0.279
Median Blow Interval	0.158	-0.392	—	-0.244	-0.026
Duration of Preceding Dive	0.297	0.450	-0.244	—	0.257
Duration of Following Dive	0.242	0.279	-0.026	0.257	—

In reviewing the following interpretations of SMRA results, one should recall that there are intercorrelations among the various measures of surfacing, respiration, and diving cycles (Table 5.18). For example, long surfacings show a strong tendency to have many blows (r=0.867), and weak tendencies to be preceded and followed by long dives (r=0.286, and r=0.284). Surfacings with many blows tend to have short blow intervals (r=-0.387).

Factors Related to Durations of Surfacings.—Durations of surfacings by traveling bowheads were not strongly correlated with any one of the predictor variables (Table 5.19A, simple correlation column). However, after allowance for other variables, there were a few significant ($P_n<0.01$) trends. Surfacings tended to be short in *1991* and when there was some *socializing* intermixed with traveling (see also Fig. 5.28C). Surfacings tended to be long in the presence of much *ice*, and when the surfacing terminated with *raised flukes*. After allowance for other variables, there were also weak tendencies for longer surfacings with high *sea states* and for *adults*. Overall, however, only a small percentage (8%) of the variance in surface times could be explained by this combination of predictor variables.

Interestingly, the variables with the strongest partial correlations to duration of surfacing ($P_n<0.001$) were the occurrence of a *change in swimming speed* and the occurrence and magnitude of *turns* during the surfacing. These correlations are perhaps to be expected, as the longer the surfacing, the more the opportunity for a change in speed or a turn during the surfacing.

Factors Related to Number of Blows per Surfacing.—There were strong positive correlations between number of blows per surfacing and *ice cover*. There were strong ($P_n<0.01$) simple

TABLE 5.19. Correlations between (a) four surfacing, respiration, and dive variables in traveling [a] bowhead whales, and (b) various environmental and whale activity variables. Each pair of columns shows the direction and nominal significance of simple (r) and partial (r_p) correlations between a dependent variable (top) and various environmental and whale activity variables (predictors, left).[b] Bottom section of table shows "partial correlations" with variables that could not be included in the overall multiple regression analyses.[g]

Predictor Variable	A. Duration of surfacing (min) [b]		B. No. Blows/ surfacing (+1) [b]		C. Median blow interval (s) [b]		Duration of dive (min): D. Preceding [b,c]		Duration of dive (min): E. Following [b,c]	
	r	r_p [d]	r	r_p [d]	r	r_p [d]	r	r_p [d]	r	r_p [d]
Year = 1990 [e]	ns		ns		+++		++		+++	+++
Year = 1991 [e]	-	--	ns		ns		-	-	-	-
Year = 1994 [e]	+		ns		---		-		--	
Date (1=1 May)	ns		ns		+		ns		ns	
Date squared	ns		ns		+	+	ns		ns	
Hour (0-24)	ns		ns		ns		ns		ns	
Hour squared	ns		ns		ns		ns		ns	
Ice cover (%)	ns	++	+++	++	---		ns		ns	
>5% ice cover? [e]	ns		++		---	---	ns		ns	
Moderate ice ahead [e]	+		+++	++	-		ns		ns	
Extensive ice ahead [e]	ns		ns		---		ns		ns	
Emerge from under ice [e]	ns		++		-		++	+++	ns	
Sea state (SS 0-6)	ns	+	+	++	---		--	---	-	
Dist. offshore (log km)	ns		ns		---	---	ns		ns	
Water depth (log m)	ns		ns		---		ns		ns	
Gen. activ. trav.+social [e]	-	--	ns	--	--		-		ns	
Cur. activ. trav.+social [e]	-	-	ns		ns		ns		ns	
Cur. activ. rest [e]	ns		+	+	--	--	ns		ns	-
Group size (1-6)	ns		-		+++	++	ns		ns	
No. bhd within 1 km (1-9)	ns		ns		ns		ns		ns	
No. bhd within 5 km (1-30)	ns		ns		ns		ns		ns	
Passive socializing? [e]	ns		ns		ns		ns		ns	
Flukes out as diving? [e]	+	++	ns	+	ns		ns		-	-
Adult? [e]	ns	+	ns		+++	++	+	+	ns	
Subadult? [e]	ns		+		---	--	ns		ns	
Sample size [f]	367	367	356	356	418	418	213	213	227	227
Multiple correlation		0.312		0.353		0.489		0.378		0.330
Adjusted % variance explained		8.0		11.0		22.6		12.7		9.3
Overall significance (nominal)		***		***		***		***		***
Residuals vs. Other Variables [g]										
Speed slow(0) vs. moder.(1)	n=319	ns	n=310	ns	n=369	ns	n=195	ns	n=205	ns
Speed change [e]	n=344	+++'	n=335	+++'	n=405	ns	n=209	ns	n=218	ns
Turn: 0, 1 or >1	n=360	+++'	n=355	+++'	n=351	ns	n=213	ns	n=215	*'
Degrees of turn (log)	n=352	+++	n=353	+++	n=311	ns	n=210	ns	n=211	ns

[a] Whales included were those whose general activity was traveling or "traveling+socializing", and whose activity during the current surfacing or dive was resting, traveling or "traveling+socializing", excluding mothers, calves, and all surfacings with active socializing or aerial activity.

[b] The four dependent variables were all log transformed to avoid skewness. Pluses indicate positive correlations; minuses indicate significant negative relationships. Number of +, - or * symbols indicates nominal significance level: +++, --- or *** means P_a<=0.001; ++, -- or ** means P_a<=0.01; and +, - or * means P_a<=0.05.

[c] Separate analyses were done for durations of dives preceding and following the surfacing under consideration.

[d] Partial correlations are shown only for variables recognized as significant (nominal P <= 0.05) by stepwise multiple regression.

[e] 0 = false; 1 = true.

[f] Number of surfacings or dives for which all of the listed predictor variables were known.

[g] Potential predictor variable excluded from multiple regression because often unknown. t-test or ANOVA results summarized here indicate whether this predictor, if it could be in the multiple regression model, would be of significant value in accounting for otherwise-unexplained residual variance.

correlations with 4 of 5 measures of ice cover. Two of these remained evident as partial correlations after allowance for other variables (Table 5.19B).

Another noteworthy partial correlation (P_n<0.01) was for fewer blows per surfacing when some *socializing* was occurring. This effect was not evident until effects of other variables were taken into account (Fig. 5.28; Table 5.19B). There were also weak tendencies for more blows during surfacings when the whales *rested* or when they raised their *flukes* as they dove.

Despite these several seemingly-significant relationships, the multiple regression model accounted for only 11% of the variance in the number of blows per surfacing.

Number of blows per surfacing, like duration of surfacing, showed strong partial correlations with some of the variables not included in the SMRA model: the occurrence of a *change in speed* and with the occurrence and magnitude of *turn(s)* during the surfacing.

Factors Related to Median Blow Intervals.—Several potential predictor variables had strong simple correlations with the median blow interval, and a smaller number had strong partial correlations (Table 5.19C). As a result, the SMRA model accounted for more of the variance in median blow interval (22.6%) than in durations of surfacings or number of blows per surfacing.

Median blow interval tended to diminish with increasing *ice cover, sea state, distance from shore*, and *water depth*. There were also tendencies for long blow intervals in *1990* and short blow intervals in *1994*. Many of these potential predictor variables were also intercorrelated with one another. It is uncertain which of these interrelated predictor variable(s) were most directly related to median blow interval. However, the most parsimonious SMRA model included terms representing strong (P_n<0.001) tendencies for short blow intervals with >5% ice cover and with increasing distance offshore.

Median blow interval tended to be short when *socializing* was intermixed with travel (see also Fig. 5.28A) but long with larger *group size*. Interestingly, blow intervals tended to be short when the current whale activity was *resting*. This trend was still significant (P_n<0.01) after allowance for other predictors, indicating that bowheads resting briefly during travel tended to have shorter blow intervals than did actively traveling bowheads. In contrast, bowheads whose general activity was resting (not travel) tended to have very long blow intervals (Table 5.12).

The previously-recognized tendency for known *adults* to have longer blow intervals than known *subadults* (Fig. 5.30A) was still significant after allowing for other variables (Table 5.19C).

Factors Related to Durations of Dives.—Table 5.19D,E shows relationships of potential predictor variables recorded during a surfacing with the durations of the dives preceding and following that surfacing. The percentages of the variation in dive duration explained by these models was low, 12.7% and 9.3% respectively.

Dive durations documented in this study tended to be long in *1990* and short in *1991* and *1994* relative to those in 1989. This probably was at least partly an artifact of year-to-year differences in our ability to relocate and reidentify whales after long dives; there may or may not have been real differences in average dive duration among years. Observation conditions tended to be good in 1990, with most whales in well defined but narrow leads amidst the ice and with low sea states; and poor in 1994, with high sea states. Recorded dive durations tended to be shorter with high *sea state.*

When the whale *emerged from under ice* at the start of the surfacing, the duration of the dive preceding the surfacing tended to be long (P_n<0.001). Not surprisingly, duration of the dive subsequent to the surfacing was not related to the "emerge from under ice" variable. However, duration of subsequent dive was weakly and negatively related to occurrence of raised *flukes* as the whale dove. The tendency for longer dives by adults than subadults (Fig. 5.30D) was only weakly evident in this analysis, and was not evident after allowing for other variables (Table 5.19D,E).

Relationship Patterns.—The cases considered in deriving the SMRA models represent actively migrating bowheads that were not actively socializing, feeding, or exhibiting aerial behavior. Calves and their mothers were also excluded. The low percentages of the variance "explainable" by the SMRA models are doubtless partly attributable to the homogeneous dataset.

Temporal Variables: The first seven lines of Table 5.19 show correlations of surfacing, respiration and dive variables with year, date, and time of day. Some year-to-year differences were evident, especially for blow intervals and dive durations. As noted above, at least some of these trends probably represented observation artifacts. Correlations of surfacing, respiration and dive variables with date and time of day were lacking or, at most, weak.

Ice: The five lines in Table 5.19 dealing with various measures of ice cover show strong tendencies for more blows per surfacing and short blow intervals in areas with much ice. Ice effects on duration of surfacing and dives were less evident but there was some indication of longer surfacings and dives with much ice. The greater number of blows per surfacing when there is much ice may represent a tendency for bowheads to prepare for long dives when there is much ice. The shorter blow intervals with much ice are probably related to our subjective impression that traveling bowheads often respire at briefer-than-average intervals when they surface in a small opening in the ice. This increases the number of breaths that can be taken before the traveling whale reaches the ice at the other side of the open water area and is forced to dive under the ice or to interrupt its travel.

Whale Activity and Group Size: When socializing was intermixed with travel, surfacings and to a lesser degree dives tended to be shorter, with shorter intervals between blows (Fig. 5.28; Table 5.19). After allowance for the effects of other variables, the number of blows per surfacing also tended to be lower when there was some socializing. However, there was little evidence that surfacing—respiration—dive cycles were affected by the occurrence of "passive socializing" (whales swimming in parallel and within ½ body length). Traveling bowheads that were (briefly) resting during the surfacing in question tended to have short blow intervals relative to those of actively traveling whales although bowheads resting for more prolonged periods had long blow intervals. Median blow interval was the only variable related to group size.

Fluke-out Dives: Raised flukes at the end of a surfacing are sometimes taken as an indication of probable deep diving, and deep dives tend to be long. However, in spring raised flukes were not very common (Table 5.13B), and among actively migrating bowheads there was a weak tendency for shorter, not longer, dives with raised flukes. There were, nonetheless, tendencies for surfacings terminated with raised flukes to be longer and perhaps to have more blows.

Subadults and Adults: Traveling adults had longer blow intervals and longer dives than did subadults, according to univariate analysis (Fig. 5.30). After allowance for other variables, adults again had longer blow intervals (P_n<0.001), along with slightly longer surfacings and dives (P_n<0.05), than did subadults. A weak univariate tendency for fewer blows per surfacing in adults than in subadults was not evident after allowance for other variables.

These results suggest that a typical surfacing-dive cycle by a migrating adult is longer than that for a migrating subadult. Adults presumably would tend to travel farther per surfacing-dive sequence, especially if adults tend to travel faster (Table 5.15A).

Sexual Activity

Distinct bouts of definite or presumed sexual activity were seen in the study area four times during the four spring seasons: twice in 1989, once in 1990, and once in 1994. All occurred before or on 10 May.

In 1989, on 3 May, a group of at least 4 whales socialized by rolling together, creating whitewater, in a manner similar to that described by Everitt and Krogman (1979). This activity, which lasted for at least 4.2 min, was the most active socializing we saw in May 1989. We surmise that mating was occurring based on the similarity of the behavior to mating seen in bowheads (Everitt and Krogman 1979), right whales (Payne and Dorsey 1983), and gray whales (Norris et al. 1983). However, it was not possible to determine the sex of any individual during this brief observation. Several other bouts of probable sexual activity were seen on 3 May. At four times, we saw pairs of whales with ventrums touching for 5 to 67 s. In three cases, the whales appeared to be "stuck together" with no forward motion. One whale was dorsum up near the surface and the other ventrum up below it. In the fourth case, the two whales traveled forward slowly while ventrum to ventrum.

On 6 May 1989, we watched for 6 min as a pair of bowheads socialized, generally at low intensity and positioned side by side. At one point, the lower whale turned ventrum up, half-way underneath the dorsum-up whale. We clearly saw a penis snaking toward the belly of the dorsum-up animal. The two stayed in this position, with no forward motion, for ~14 s, but we do not know if copulation took place. A third whale was ~120 m from the sexually-active pair, and was not seen to interact with the pair.

On 10 May 1990, five bowheads engaged in active sexual activity and other social interactions as they traveled gradually northeast near the north (pack ice) side of the main nearshore lead. At one time the extended penises of two males were seen at the same time as the two whales oriented toward a third whale. That third whale was often belly-up, seemingly attempting to avoid the two males. At other times, whales were visible belly-up below the third whale. This active sexual activity was evident for at least 40 min, and other social interactions continued thereafter.

In 1991, sexual activity was not noticed during our few brief behavioral observation sessions.

In 1994, we saw apparent sexual activity once, on 7 May. An adult female rolled belly up (allowing sex to be ascertained), with one animal touching her side briefly and a third individual rolling, belly up briefly, underneath the female. The apparent sexual activity lasted for only 4 min, but other social activity continued for another 1.5 hours (when we left the area), and this may have included sexual activity as well.

Our brief views of sexual activity in early May reinforce the general impression that mating occurs in spring, and wanes in frequency thereafter (Nerini et al. 1984; Koski et al. 1993). Since we witnessed apparent mating during only 4 of 76 observation sessions, it is likely that most mating was over by the time we began our spring work in late April or early May. Although the main mating season is believed to be in spring, much mating by bowhead whales of this population was seen in September-October 1988 in the eastern Beaufort Sea (Würsig et al. 1993).

5.4 Mother and Calf Behavior

Bowhead mothers and calves were seen in the study area primarily during the latter half of May (§5.1). Systematic behavioral observations were obtained on "presumably undisturbed" mothers and calves during several dates in mid- and late May of 1989, 1990 and 1991. Circumstances in which we obtained systematic behavioral observations of calves, mothers and other whales are summarized in Tables 5.20 and 5.21.

Bowheads probably calve from about March to July (Nerini et al. 1984; Koski et al. 1993). Thus, calves encountered during May vary in age from newborn to about three months. These calves are smaller and younger than those whose behavior has been documented during previous late summer and early autumn studies. Thus, calf behavior in spring is expected to differ from that documented previously. There is the additional possibility that behavior in spring may vary among mother-calf pairs depending on the size (=age) of the calf.

Migration and Lingering by Mothers and Calves

Movements of mother-calf pairs were less consistently northeastward or eastward than were those of other bowheads. Traveling whales followed lead systems when leads were available, and deviations in their generally NE or E courses were related to changes in orientations of leads or cracks. Mother-calf pairs often behaved in a similar manner. However, sometimes they lingered in one area for a prolonged period, or even moved west. We obtained three types of evidence on this point: observations of whale headings, observations of behavior during extended behavioral observation sessions, and re-identifications from day to day based on photoidentification.

Headings.—The headings of bowhead groups when they were first encountered are summarized in Table 5.2 for groups containing one or more mother-calf pairs and in Table 5.1 for all groups

TABLE 5.20. Circumstances of observations of undisturbed bowhead calves, mothers and others. Calves and mothers that are and are not nursing are shown separately. Table shows numbers of surfacings during spring migration near Barrow, AK, 1989-94, as observed from a Twin Otter aircraft. Because a given whale is counted more than once if more than one surfacing is observed, some data are not independent and statistical analysis is not justified. "Total n" varies because not all variables could be determined for each surfacing.

	Calves					Mothers					Other Whales		
	Traveling		Other Activ.			Traveling		Other Activ.			Trav-	Other	
	Not	Nurse	Not	Nurse	All	Not	Nurse	Not	Nurse	All	eling	Activ.	All
A. Date													
21-30 Apr	0	0	0	0	**0**	0	0	0	0	**0**	9	7	**16**
1-10 May	0	0	0	0	**0**	0	0	0	0	**0**	193	213	**406**
11-20 May	26	0	0	0	**26**	8	0	0	0	**8**	394	99	**493**
21-31 May	147	25	81	16	**269**	55	16	20	7	**98**	23	10	**33**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
B. Hour (local)													
6-8	0	0	0	0	**0**	0	0	0	0	**0**	1	3	**4**
9-11	35	8	27	4	**74**	24	5	8	2	**39**	184	110	**294**
12-14	3	0	46	10	**59**	3	0	10	4	**17**	151	150	**301**
15-17	53	12	8	2	**75**	11	7	2	1	**21**	119	51	**170**
18-20	71	4	0	0	**75**	21	3	0	0	**24**	105	15	**120**
21-23	11	1	0	0	**12**	4	1	0	0	**5**	59	0	**59**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
C. Water Depth (m)													
10-19	0	0	0	0	**0**	0	0	0	0	**0**	23	15	**38**
20-49	31	8	0	0	**39**	20	5	0	0	**25**	523	244	**767**
50-99	0	0	20	1	**21**	0	0	5	1	**6**	37	5	**42**
100-250	82	0	31	1	**114**	25	0	10	1	**36**	28	61	**89**
> 250	60	17	30	14	**121**	18	11	5	5	**39**	8	4	**12**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
D. Ice Cover (%)													
0	22	0	0	0	**22**	7	0	0	0	**7**	43	1	**44**
1-9 %	30	0	0	0	**30**	6	0	0	0	**6**	226	29	**255**
10-29	26	0	0	0	**26**	8	0	0	0	**8**	67	10	**77**
30-59	31	8	0	0	**39**	20	5	0	0	**25**	85	92	**177**
60-79	4	0	0	0	**4**	4	0	0	0	**4**	125	112	**237**
80-90	60	17	81	16	**174**	18	11	20	7	**56**	63	62	**125**
>90	0	0	0	0	**0**	0	0	0	0	**0**	10	23	**33**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
E. Ice Ahead													
None	121	25	61	16	**223**	44	6	17	2	**69**	420	185	**605**
<100 m	21	0	1	0	**22**	7	4	0	0	**11**	14	6	**20**
100-1000 m	14	0	6	0	**20**	4	3	1	0	**8**	59	25	**84**
>1000 m	0	0	0	0	**0**	0	0	0	0	**0**	34	13	**47**
Total n	156	25	68	16	**265**	55	13	18	2	**88**	527	229	**756**

TABLE 5.21. Frequencies of various group sizes and activities of undisturbed bowhead calves, mothers and others. Presentation as in Table 5.20.

	Calves					Mothers					Other Whales		
	Traveling		Other Activ.			Traveling		Other Activ.			Trav-	Other	
	Not	Nurse	Not	Nurse	All	Not	Nurse	Not	Nurse	All	eling	Activ.	All
A. Group Size (within 5 adult lengths)													
1	13	0	12	0	**25**	0	0	0	0	**0**	288	100	**388**
2	160	25	69	16	**270**	63	16	20	7	**106**	195	82	**277**
3	0	0	0	0	**0**	0	0	0	0	**0**	74	37	**111**
4	0	0	0	0	**0**	0	0	0	0	**0**	31	76	**107**
5	0	0	0	0	**0**	0	0	0	0	**0**	6	27	**33**
>5	0	0	0	0	**0**	0	0	0	0	**0**	8	1	**9**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	602	323	**925**
B. # Bowheads Within 1 km													
1	0	0	0	0	**0**	0	0	0	0	**0**	29	32	**61**
2	142	17	81	16	**256**	43	11	20	7	**81**	77	6	**83**
3	0	0	0	0	**0**	0	0	0	0	**0**	197	54	**251**
4	31	8	0	0	**39**	20	5	0	0	**25**	120	35	**155**
5	0	0	0	0	**0**	0	0	0	0	**0**	47	34	**81**
6	0	0	0	0	**0**	0	0	0	0	**0**	52	82	**134**
7	0	0	0	0	**0**	0	0	0	0	**0**	73	0	**73**
8	0	0	0	0	**0**	0	0	0	0	**0**	24	0	**24**
>8	0	0	0	0	**0**	0	0	0	0	**0**	0	86	**86**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
C. Whale Activity This Sfc/Dive Sequence													
Rest	0	0	20	0	**20**	0	0	2	1	**3**	8	8	**16**
Travel	166	4	27	1	**198**	61	12	6	0	**79**	517	113	**630**
Socialize	0	0	0	0	**0**	0	0	0	0	**0**	9	96	**105**
Feed	0	0	0	14	**14**	0	0	1	4	**5**	2	7	**9**
Travel+Social	0	0	0	0	**0**	0	0	0	0	**0**	41	44	**85**
Travel+Feed	0	17	0	0	**17**	0	0	0	0	**0**	0	7	**7**
Social+Feed	0	0	0	0	**0**	0	0	0	0	**0**	0	1	**1**
Unknown/Other	7	4	34	1	**46**	2	4	11	2	**19**	42	53	**95**
Total n	173	25	81	16	**295**	63	16	20	7	**106**	619	329	**948**
D. Group's Predominant Feeding Mode													
None	173	25	60	5	**263**	63	16	17	3	**99**	619	296	**915**
Water-column	0	0	0	0	**0**	0	0	0	0	**0**	0	19	**19**
Bottom	0	0	14	10	**24**	0	0	1	4	**5**	0	8	**8**
Near-surface	0	0	0	0	**0**	0	0	0	0	**0**	0	0	**0**
Total n	173	25	74	15	**287**	63	16	18	7	**104**	619	323	**942**
E. Whale's Feeding Mode During This Sfc/Dive Sequence													
None	169	4	80	1	**254**	63	16	17	3	**99**	573	289	**862**
Water-column	0	0	0	0	**0**	0	0	0	0	**0**	4	8	**12**
Bottom	0	0	0	0	**0**	0	0	1	4	**5**	0	7	**7**
Near-surface	0	0	0	0	**0**	0	0	0	0	**0**	0	0	**0**
Total n	169	4	80	1	**254**	63	16	18	7	**104**	577	304	**881**

(§5.1, p. 140-1). The vector mean heading for both categories of bowhead groups was eastward. However, the proportion of the groups headed in directions other than 50-120°T was higher for mother-calf groups (15 of 35 or 43%) than for other groups (134 of 782 groups or 17%). This difference is further shown by the fact that the angular deviation of the headings (method of Batschelet 1981:276) was 65° for mother-calf groups vs. 37° for all groups. The angular deviation of headings was larger for mother-calf groups than for all groups during each year, 10-day period, and part of the study area with a meaningful sample size[19] (Table 5.2 vs. 5.1).

Headings were also recorded during systematic behavioral observation sessions, with heading being noted at the start of each surfacing and dive. Tables 5.22 and 5.10 (p. 202) show these heading data for mothers and for bowheads other than mother-calf pairs during "presumably undisturbed" conditions. The vector mean heading was to the NE, E or ESE for both mother-calf pairs and other bowheads during all years. However, the angular deviation was 59° for mothers but only 40° for bowheads exclusive of mothers and calves. Considering only traveling bowheads, the headings were more consistently eastward, but the angular deviation remained somewhat higher for traveling mothers (44°) than for traveling bowheads exclusive of mothers and calves (31°). Mothers engaged in "other/unknown" activities (including nursing) had highly variable headings (angular deviation 72°). Bowheads other than mothers and calves, when classed as resting or "other/unknown", also tended to have unusual or variable headings. However, these activities with unusual or variable headings accounted for a higher proportion of the surfacings and dives by mothers (26%) than of those by other bowheads (7%).

Behavioral Observations in 1989.—In 1989, we observed the behavior of three mother-calf pairs during periods when no known source of potential disturbance was present.

1,2. The first two pairs were observed from 9:36 to 11:45 on 27 May as they moved generally east along the north edge of the lead through open water or, at most, light pack ice. Lengths of whales (1)-(4) were, respectively, 4.8, 15.9, 4.9 and 15.7 m. Calves are 4.0-4.5 m long when born, so these calves were among the older calves seen in spring (§5.2). Both pairs moved steadily at moderate to slow speed and followed along or just inside the southern edge of the pack ice. Average rates of movement of whales 1 & 2 and 3 & 4 were 5.1 and 4.8 km/h, respectively—similar to mean short-term rates of movement recorded during previous studies of all bowheads (5.0 km/h—Koski and Davis 1980; 5.1 km/h—Rugh 1987) and mother-calf pairs near Barrow (4.8 km/h "best duplicate" speeds without current compensation—George and Carroll 1987).

3. The third mother-calf pair was observed on 27, 28 and 29 May 1989. Their identity was confirmed by vertical photographs taken after each day's behavioral observations were completed. The lengths of this mother and calf were 14.9 and 4.0 m. This calf, one of the smallest calves that has been measured photogrammetrically, was probably recently-born. From their initial position at 19:30 h on 27 May, this mother-calf pair moved 11.5 km NE over a 44.2 h period (Fig. 5.25, p. 186). Their net rate of movement was 0.27 km/h.[20] During the observations on 28 May this

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[19] Excluding two situations with extremely small sample sizes (<3).

[20] Rugh (1987) noted that whales that travel slowly or deviate from their migration route are more likely to be re-photographed on a later date than are whales that migrate steadily. Steadily migrating whales would pass through our study area in ~½ day, and thereafter would not be present to be rephotographed.

TABLE 5.22. Headings (True) of bowhead mothers observed during behavioral observation sessions. Excludes potentially disturbed mothers. Each surfacing and dive with a known heading is counted separately.

	A. By Year, All Bowhead Mothers					B. By Group Activ., All Mothers				C. By Year, Traveling Bowhead Mothers					
True Heading	1989	1990	1991	1994	TOTAL	Rest	Travel	Other & Unk	TOTAL	1989	1990	1991	1994	TOTAL	True Heading
0 N	**6**	**3**	**0**	**0**	**9**	**1**	**6**	**2**	**9**	**4**	**2**	**0**	**0**	**6**	**N 0**
10	1	2	0	0	3	0	1	2	3	0	1	0	0	1	10
20	2	0	0	0	2	0	2	0	2	2	0	0	0	2	20
30	8	3	0	0	11	0	10	1	11	8	2	0	0	10	30
40	4	9	0	0	13	0	8	5	13	2	6	0	0	8	40
50	0	6	0	0	6	0	6	0	6	0	6	0	0	6	50
60	0	8	3	0	11	0	11	0	11	0	8	3	0	11	60
70	4	6	8	0	18	0	18	0	18	4	6	8	0	18	70
80	2	2	0	0	4	0	4	0	4	2	2	0	0	4	80
90 E	**3**	**6**	**4**	**0**	**13**	**0**	**13**	**0**	**13**	**3**	**6**	**4**	**0**	**13**	**E 90**
100	2	1	0	0	3	0	3	0	3	2	1	0	0	3	100
110	5	13	0	0	18	0	17	1	18	4	13	0	0	17	110
120	6	1	0	0	7	0	5	2	7	4	1	0	0	5	120
130	7	7	0	0	14	0	11	3	14	7	4	0	0	11	130
140	8	1	0	0	9	0	9	0	9	8	1	0	0	9	140
150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150
160	1	2	0	0	3	0	2	1	3	0	2	0	0	2	160
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	170
180 S	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**S 180**
190	0	1	0	0	1	0	0	1	1	0	0	0	0	0	190
200	2	1	0	0	3	0	3	0	3	2	1	0	0	3	200
210	1	0	0	0	1	0	0	1	1	0	0	0	0	0	210
220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	220
230	0	0	0	0	0	0	0	0	0	0	0	0	0	0	230
240	6	0	0	0	6	0	0	6	6	0	0	0	0	0	240
250	2	0	0	0	2	0	0	2	2	0	0	0	0	0	250
260	2	2	0	0	4	2	0	2	4	0	0	0	0	0	260
270 W	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**W 270**
280	2	0	0	0	2	0	0	2	2	0	0	0	0	0	280
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	290
300	4	2	0	0	6	2	2	2	6	2	0	0	0	2	300
310	1	0	0	0	1	0	0	1	1	0	0	0	0	0	310
320	1	0	0	0	1	0	0	1	1	0	0	0	0	0	320
330	0	4	0	0	4	0	2	2	4	0	2	0	0	2	330
340	0	0	0	0	0	0	0	0	0	0	0	0	0	0	340
350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	350
Total	84	80	15	0	179	5	133	41	179	54	64	15	0	133	Total
Vector															
Mean	93	73	73		78	294	81	277	78	89	78	73		81	
Length	0.24	0.62	0.98		0.46	0.81	0.71	0.21	0.46	0.59	0.76	0.98		0.71	
Ang. Dev.	71	50	11		59	35	44	72	59	52	40	11		44	

pair meandered generally southwestward. On 29 May they were several kilometers NNW of the location where they last seen on 28 May (Fig. 5.25).

In only one other case did we obtain direct behavioral observations of bowheads moving generally west in 1989, also involving a mother-calf pair. That observation was during a drilling noise playback, and the westward movement may have been attributable to disturbance.

The back and forth movements of the mother and calf on 28 and 29 May 1989 (Fig. 5.25) may have been related to the overall heavy ice cover east of their locations. We presume that a small calf cannot travel as far under ice as can a larger whale, and that a small calf may be unable to surface through some new ice or brash ice that poses no obstacle to a larger whale. On both 28 and 29 May, the mother-calf pair was in an open water area among large ice pans and brash ice. Similar open water areas were absent east and northeast of their locations.

<u>Behavioral Observations in 1990</u>.—In 1990, the behavior of five presumably undisturbed mother-calf pairs was observed systematically for a total of 9.3 h during five different aerial observation sessions on 23-25 May. (Several other pairs were seen briefly.) Of the five pairs studied, two were actively migrating throughout the observations, one pair changed behavior from milling in one area to active migration, and the other two pairs were not actively migrating:

1. An actively migrating mother and calf were observed under undisturbed conditions for 0.9 h on 23 May ("23" *in* Fig. 5.16). They traveled steadily ENE at medium speed in the largely open water of the main nearshore lead, but within a few hundred meters of the pack ice edge forming its north side. During most dives, the mother remained faintly visible below the surface, and the calf "rode" on her back (see below for discussion of riding).

2. An actively migrating mother and calf were observed for 3.5 h on 24 May. They traveled east through moderately heavy pack ice, averaging 80% cover, far offshore NNE of Pt. Barrow ("24" *in* Fig. 5.16, p. 160). Their observed speeds were slow to medium, with a net speed of 1.5 km/h based on the initial and final positions. The actual average speed was somewhat greater because the route through the ice was circuitous. Speeds and headings were more variable than those of the mother-calf pair seen in open water. The headings varied in such a way that the whales did not have to travel more than a few hundred meters under continuous ice. The mother and calf sometimes surfaced synchronously, but the calf often surfaced by itself at intermediate times. The calf swam actively; it was not seen to "ride" the mother.

3. On 25 May a mother and calf were found milling in small openings amidst heavy pack ice (90% cover) far offshore NE of Pt. Barrow. The mother may have been feeding during her dives. She may also have been searching, in some unknown manner, for a route through the pack ice. The calf spent more time at the surface. It breached several times, and sometimes nursed when the mother was at the surface. About 1 h after we found the whales in that area, they began traveling. They initially moved NNE and NE, skirting through cracks and other openings along the west side of a very large ice pan (several kilometers in diameter) that obstructed the direct eastward route. Upon reaching the north end of the large pan, the whales turned north along a major lead through the pack ice. They passed only about 100 m to the side of another mother-calf pair migrating in the opposite direction. Neither pair changed course or hesitated when passing the other pair. Only one brief episode of riding was visible. The overall average speed after active migration

began was 4.7 km/h (6.8 km in 1.44 h). The average speed while moving through heavy pack ice was slightly less than that in the open lead (4.2 vs. 5.4 km/h).

4. Another mother and calf seen on 25 May were not actively migrating during 1.9 h of observation in an open area within heavy pack ice well offshore. The calf spent more time at the surface than did the mother, which was suspected to be feeding below the surface. Activities at the surface included rest, slow travel, nursing, and tailslaps by the calf.

5. Another mother-calf pair seen in the same area on 25 May were resting almost totally motionless during 0.5 h of observation.

Behavioral Observations in 1991 and 1994.—In 1991, the first mother-calf sighting was on 11 May, and the next mother-calf sightings were not until 17 May. Mother-calf pairs were seen regularly from 17 May until the end of our field season on 26 May. They constituted a substantial proportion of all bowhead sightings during the last few days of the field season. Prior to 16 May in 1991, only 2 of 159 bowheads seen from the Twin Otter were mothers or calves (mother/yearling excluded). From 16 to 20 May, 12 of 82 bowheads seen from the Twin Otter were mothers or calves. From 21 to 26 May, 20 of 64 were mothers or calves. The concentration of mother-calf sightings late in the spring was also evident in 1989 and 1990.

In 1991, there was only one >0.1 h behavior observation session of a mother-calf pair. During that session, for 0.7 h on 20 May, mother and calf moved at medium speed toward the NE.

In 1994, there was only one sighting of a mother-calf group from the air, on 9 May. The pair was observed only briefly, traveling at medium speed to the northeast. These whales were observed within ½ h after an icebreaker noise playback, about 1.3-1.5 km WNW of the ice camp.

Photoidentification Data on Mother-Calf Movements.—Additional information about movements of mothers and calves obtained through repeated photography of recognizable individual mothers appears in §5.2. In summary, the speeds of mother-calf pairs were slower than speeds of other whales when estimated from between-session within-day resightings or the all between-session data (Table 5.6, p. 188). Speeds of these two groups were similar when estimated from short-term within-session resightings or from between-day resightings. The between-day speeds are biased because only the slow-moving whales would be resighted.

The net headings of mother-calf pairs in all four categories appeared to differ from those of other whales. In each category, headings of mother-calf pairs were more variable, as indicated by a larger angular deviation (Table 5.6). A larger proportion of the mothers and calves were traveling west.

Migration and Lingering—Summary.—During spring migration east of Barrow, bowhead mothers with newly-born calves travel on the same generally eastward migration route as other bowheads. They travel past Barrow late in the spring migration period, starting in mid-May. Their headings are more variable than are those of other bowheads, and their routes are more circuitous. Mothers and calves-of-the-year seem less inclined to travel through heavy ice conditions than are other whales. They follow routes that provide frequent openings in which the calves can surfacing to breathe. Where the route is obstructed by ice, the calf occasionally surfaces and dives repeatedly in one place while the mother undertakes a long dive, possibly searching for a suitable route through the ice. When ice conditions to the NE and E are severe, these pairs often linger in areas of open water, as evident from our observations in 1989 and 1990. In one 1989 case, a pair lingered in one general area for at least three days.

"Riding" Behavior

During travel, calves alternated among *(1)* swimming beside the mother, usually just behind the broadest portion of the back and in front of the tail; *(2)* angling toward the teat area of the mother in apparent short nursing bouts, with each bout lasting less than 10 s; and *(3)* "riding" on the back of the mother while both mother and calf were submerged. Prior to this study, this last form of locomotion had not been described in detail for bowhead whales, but was mentioned by Carroll and Smithhisler (1980). The calf appears to be dragged along by the hydrodynamic forces created by the motion of the larger animal.

During riding, the calf appears to lie on the back of the mother, pointed in the same direction as mother, with rostrum slightly behind the midback of mother and in an area where the mother's back curves down toward the tail. From the air, we could not determine the exact spacing of mother and calf. The calf may not actually be touching the mother's back at all times, but may be sucked along by a Bernoulli effect of reduced (therefore attractive) pressure between two bodies that are almost but not quite touching (Kelly 1959). Carroll and Smithhisler (1980) suggested that a very small calf may grasp the mother with its flippers. We have no evidence of this. Dolphin young ride beside the backs of adults in what has been termed echelon-swimming (Kelly 1959; Norris and Prescott 1961). At times, dolphin calves are pulled along by the motions of the adults, without any fluke beats of their own (Norris and Dohl 1980; Irvine et al. 1981). However, it is more common for this behavior to supplement rather than totally replace swimming motions by the calf.

Bowhead calves beat their tails very little (and perhaps at times not at all) while in riding position. Riding by bowhead calves appears to function at least as efficiently as echelon swimming by dolphins.

Bowhead calves probably also receive some hydrodynamic advantage when not in "riding" position but very close to the side of or underneath the adult whale, behind the mid-back and just in front of the adult's tail. This advantage may continue when the calf is nursing underneath the mother during travel, although mothers and calves usually travel at slow speed when nursing. We here define riding to include only cases when the calf is on the adult's back. These cases are unequivocal and are observable from the air when the animals swim within several meters of the surface. Other positions, most likely the echelon position described by Kelly (1959) and by Norris and Prescott (1961) for dolphins, may provide at least a partial "ride" for the bowhead calf as well.

Because the calf is on top of the mother while riding, the mother has to be submerged well below the surface. Hence, riding can only be seen in clear water. Several times we observed lone calves apparently moving along effortlessly on their own. After several seconds or even minutes of observation from the aircraft, we saw the partially-obscured outline of the adult farther below the surface. The presence of the mother below the calf would not have been evident from the low vantage points available to ice-based observers. Riding may also occur with both animals well below the surface; we would not be able to detect these cases even from an observation aircraft.

Riding is disrupted when the calf sinks below the mother to nurse, and when either calf or mother surfaces to breathe. When the adult surfaces, the calf moves to either left or right of the adult's midback (and usually blows at about that time). When the calf surfaces to breathe, it may stay just above the adult's midback, in near-riding position, or it may briefly move to the side of the adult. In either case, calves that ride during travel consistently move back into riding position after breathing, indicating that riding is of importance for young calves during migration.

We saw most incidents of riding in 1989; riding was observed from 24 to 29 May, when mothers and their calves were migrating through the area. The first calf we saw, on 23 May, was not riding (Table 5.23). Riding observed on 27-29 May was mainly by a single mother-calf pair seen on three consecutive days. In 1990, we saw approximately as many calves (from 21-25 May) as in 1989, but witnessed riding for only one mother-calf pair, on 23 May. In 1991, we observed only one mother-calf pair in our focal animal circle (20 May), and briefly observed two other pairs outside of our circle (25 May). We witnessed no riding. In 1994, we saw only one mother-calf pair during the season (9 May), and the calf was riding.

In summary, we observed riding behavior involving five mother-calf pairs, out of ~17 mother-calf pairs whose behavior was observed during focal observations (29%). Because of the variable but often short (<1 h) durations of focal observations, some pairs not observed to ride may have engaged in this behavior at other times.

We compared calculated calf-to-adult size ratios for mother-calf pairs that were and were not observed in riding formation. The data came either from calibrated vertical photos obtained directly after the behavioral observations or, for pairs not photographed vertically, from videotape obtained from a side window during behavioral observation sessions (see §2.2, Methods). The length ratio was 0.283 ± s.d. 0.0131 ($n = 3$) for pairs seen riding (Table 5.23), and 0.312 ± s.d. 0.0072 ($n = 5$) for pairs not seen riding. All three "riders" had calves <0.3 the length of the mother whereas all five apparent "non-riders" had calves >0.3 the length of the mother. Given the absence of any overlap between the two groups, this difference is statistically significant despite the small sample size (Mann-Whitney $U=0$, $P=0.04$).

Riding is probably important to the calf only during the first few months of life. We have not observed riding in the Canadian Beaufort Sea in late summer or the Alaskan Beaufort in autumn. During late summer, the combination of the calf's increased size, its muscular development, and the absence of active migration make riding unnecessary.

Although calves may make direct contact with the mother during riding, it appears that they are at times merely close, likely being pulled along by the larger animal's slipstream as are dolphins and some fishes in interspecies associations. In bowheads, riding probably gives pronounced hydrodynamic and energetic advantages to migrating newborn. It probably is especially

TABLE 5.23. Occurrence of "riding" in relation to calf length, from observations during systematic behavioral observations of mother-calf pairs.

Year	Date in May	BOS No.	Duration of Observ. (h)	Potential Disturbance	Proportion of Time Riding	Length (m) [a] Calf, Mother	Length Ratio [b] Calf/Mother
1989	23	10	0.6	playback	0	-	-
	24	11	1.2	aircraft	50	-	0.287
	27	12	2.1	-	0	4.8, 15.9	0.302
	27	12	2.0	-	0	4.9, 15.8	0.310
	27	14	0.9 [c]	-	10-20	4.0, 14.9 [c]	0.268 [c]
	27	13	2.0	playback & sonobuoy	30	-	-
	28	15	0.7 [c]	-	40	4.0, 14.9 [c]	0.268 [c]
	29	16-17	2.0 [c]	-	40	4.0, 14.9 [c]	0.268 [c]
1990	21	21	0.05	-	0	-	
	21	21	0.05	-	0	-	
	23	25	1.0	-	60	-	0.293
	24	26	3.4	-	0	-	0.322
	25	27	1.9	-	0	-	0.315
	25	27	0.4	-	0	-	
	25	29	2.4	-	0	-	0.312
1991	20	6	0.7	-	0	-	-
	25	7	0.1	-	0	-	-
	25	7	0.1	-	0	-	-
1994	9	7	0.2	post-plbk	50	-	-

[a] Measured photogrammetrically.
[b] From photogrammetric data when available; otherwise from measurements from video screen.
[c] Same mother-calf pair.

important during spring migration when the calves are young and when mother-calf pairs sometimes need to travel under dense ice. As noted below, the maximum observed durations of dives by migrating calves (<14 min in this study) are much briefer than maxima for older whales. Thus, open water areas suitable for breathing may often be spaced too far apart to allow passage by small calves swimming unassisted, but close enough to allow passage by older whales, and possibly by a mother-calf pair in riding formation. Riding may be more important to bowheads than to other baleen whales, as other species rarely inhabit areas with near-100% ice cover.

Surfacing, Respiration and Diving Behavior

Table 5.24A summarizes the surfacing, respiration and diving (SRD) cycles of all mothers and calves that were observed under "presumably undisturbed" conditions. Durations of surfacings tended to be shorter for calves than for mothers. However, blow intervals were also markedly shorter for calves than for mothers. As a result, the total number of blows per surfacing was similar for the two categories of whales despite the shorter surfacings by calves. Dives tended to be much shorter for calves than for their mothers (Table 5.24A).

TABLE 5.24. Surfacing, respiration and dive behavior of undisturbed mothers and calves as compared with other bowhead whales during spring migration near Barrow, Alaska. Based on observations from a Twin Otter aircraft at altitude 460 m, 1989-1994.

Category of Undisturbed Bowhead Whales		Individual Blow Intervals (s)			Median Blow Intervals (s)			Number of Blows per Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
		mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
A. All Group Activities																
Calves	Not nursing	13.27	9.22	843	12.65	5.50	201	4.41	3.71	204	0.84	0.99	220	2.29	2.04	215
	Nursing	12.96	6.69	108	12.84	5.79	29	3.67	2.41	36	0.79	1.08	38	0.77	0.88	40
	All	13.23	8.97	951	12.67	5.52	230	4.30	3.55	240	0.83	1.00	258	2.05	1.99	255
Mothers	Not nursing	19.43	7.77	234	20.82	7.74	62	4.31	2.82	61	1.23	0.89	65	7.53	5.83	63
	Nursing	26.01	20.46	91	28.79	17.58	21	5.00	2.21	19	2.20	1.15	20	13.70	6.15	13
	All	21.27	12.98	325	22.84	11.49	83	4.47	2.69	80	1.46	1.04	85	8.58	6.30	76
All Other Bowheads		19.37	28.59	2984	18.17	11.69	676	5.19	3.53	454	1.34	1.17	498	5.95	6.26	319
B. Traveling Only																
Calves	Not nursing	12.64	7.18	493	12.34	5.45	143	4.50	3.36	138	0.82	0.78	148	2.50	2.26	143
	Nursing	13.88	6.61	54	14.59	6.78	16	3.57	2.41	23	0.63	0.57	23	0.91	1.08	25
	All	12.76	7.13	547	12.57	5.61	159	4.37	3.25	161	0.79	0.76	171	2.26	2.20	168
Mothers	Not nursing	18.47	6.46	142	20.20	8.09	48	4.93	2.82	42	1.33	0.84	46	8.15	6.22	46
	Nursing	24.23	20.28	58	26.17	16.38	15	4.92	2.47	13	2.13	1.34	14	11.27	5.78	9
	All	20.14	12.42	200	21.62	10.81	63	4.93	2.72	55	1.52	1.02	60	8.66	6.21	55
Others	All	17.60	8.72	1928	18.08	7.64	451	5.02	3.30	355	1.35	1.03	367	6.63	6.27	244
	Subadults	14.41	9.38	237	14.12	5.65	48	6.15	3.77	33	1.35	1.22	39	5.26	6.04	19
	Adults	19.41	8.48	738	20.56	8.94	159	4.92	3.22	152	1.46	1.09	152	6.81	6.25	134
C. Riding vs. Not Riding Mothers and Calves (Traveling and Not Nursing)																
Calves	Not riding	12.86	7.48	481	12.72	5.73	115	4.59	3.46	108	0.87	0.79	118	2.84	2.44	112
	Riding	11.51	5.32	95	10.77	3.77	28	4.17	2.98	30	0.65	0.72	30	1.28	0.44	31
Mothers	Not Riding	18.26	6.50	171	20.02	8.52	41	5.03	3.00	35	1.36	0.89	39	8.60	6.95	35
	Riding	20.00	6.04	24	21.21	5.20	7	4.43	1.72	7	1.19	0.46	7	6.72	2.59	11

Traveling Mothers and Calves.—Mother-calf pairs were traveling during the majority of the observation time, and traveling was the one whale activity that was common enough to warrant detailed analysis (Fig. 5.31). Most traveling whales were actively migrating, but some may have been traveling for some other reason.

The SRD cycles of traveling mothers (Fig. 5.31) were similar to those of other traveling "non-calves" (*cf.* Fig. 5.28) and especially other traveling adults (Fig. 5.30). Data for these groups are all summarized in Table 5.24B. In contrast, the traveling calves had significantly shorter blow intervals, surface durations, and dive durations than did their mothers (Fig. 5.31). Numbers of blows per surfacing were similar for traveling calves and mothers (4.37 vs. 4.93, Fig. 5.31B). Again, this reflected the fact that calves had shorter surfacings than did mothers, but also had shorter intervals between successive blows. Calves and mothers respired about the same number of times per surfacing even though surfacing-dive cycles were much shorter for calves. The sum of the average surface and the average dive duration was 3.05 min for calves but 10.18 min for mothers. Thus, the blow rate—average number of blows per minute, including dive as well as surface time—was much higher for calves (1.43) than for their mothers (0.48).

Nursing vs. Not Nursing.—Mother-calf pairs often engage in nursing, and nursing affects surfacing-dive cycles of both calf and mother. Table 5.24A shows data for nursing vs. non-nursing calves and mothers when all activities are considered. For traveling calves, all dives tend to be short, but nursing dives were shorter than other dives, averaging 0.91 vs. 2.50 min in duration (Fig. 5.32D). Other SRD variables were similar for traveling calves that were and were not nursing (Fig. 5.32). Presence or absence of nursing also affected the SRD cycles of traveling mothers (Fig. 5.33). When nursing, traveling mothers tended to have long surfacings with long blow intervals. Dive durations by traveling mothers also tended to average slightly longer when nursing.

Riding vs. Not Riding.—We compiled all surfacing, respiration and dive values for traveling mothers and calves classified as riding vs. not riding (Fig. 5.34; Table 5.24C). There were no pronounced differences in surfacing or respiration data for calves that were and were not riding (Fig. 5.34A-C). Durations of dives tended to be shorter for calves that were riding (Fig. 5.34D).

Other Behaviors

The same categorical variables that were recorded for whales other than mothers and calves were also recorded for mothers and calves. Tables 5.25 and 5.26 show many of the data, categorized according to whether the whales were traveling or not, and whether the mother and calf were nursing or not. For comparison, data for all whales other than mothers and calves are also shown.

Swimming Speeds.—Speeds of traveling mothers and calves were most commonly categorized as medium, but a substantial minority of the mothers and calves were categorized as moving slowly, especially when their general activity was not traveling (Table 5.25A). These estimates of swimming speeds were based on partly-subjective judgments by the aerial observers.

More specific data on speeds of several presumably undisturbed mother/calf pairs were determined in 1989-90 based on successive readouts from the aircraft's VLF navigation system.

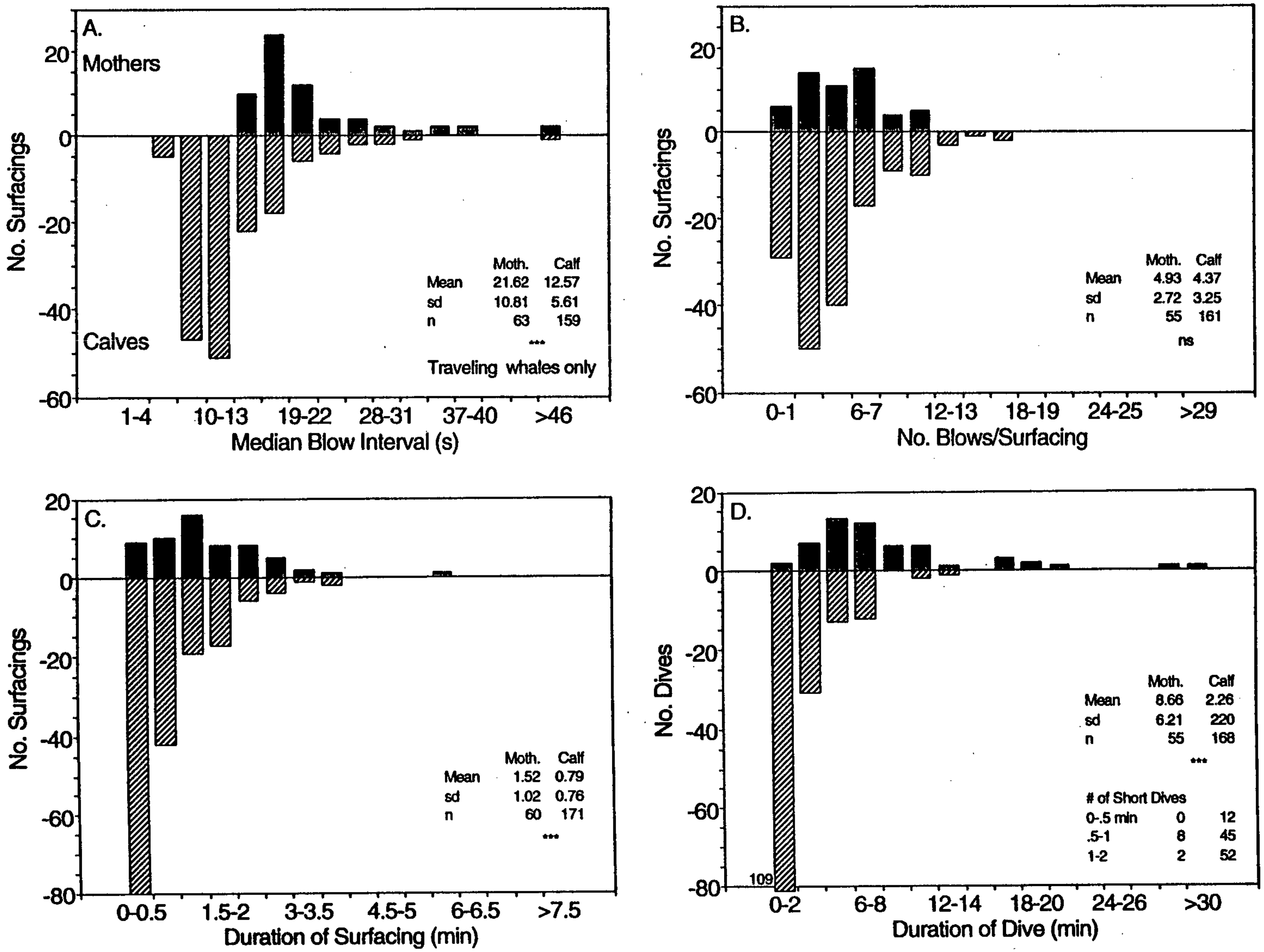

FIGURE 5.31. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowhead mothers (upward bars) and calves (downward bars) engaged in traveling during the spring migration period near Barrow, Alaska. Nominal significance levels come from t-tests on log-transformed data. Based on aerial observations from a Twin Otter aircraft circling at altitude ≥460 m, 1989-94.

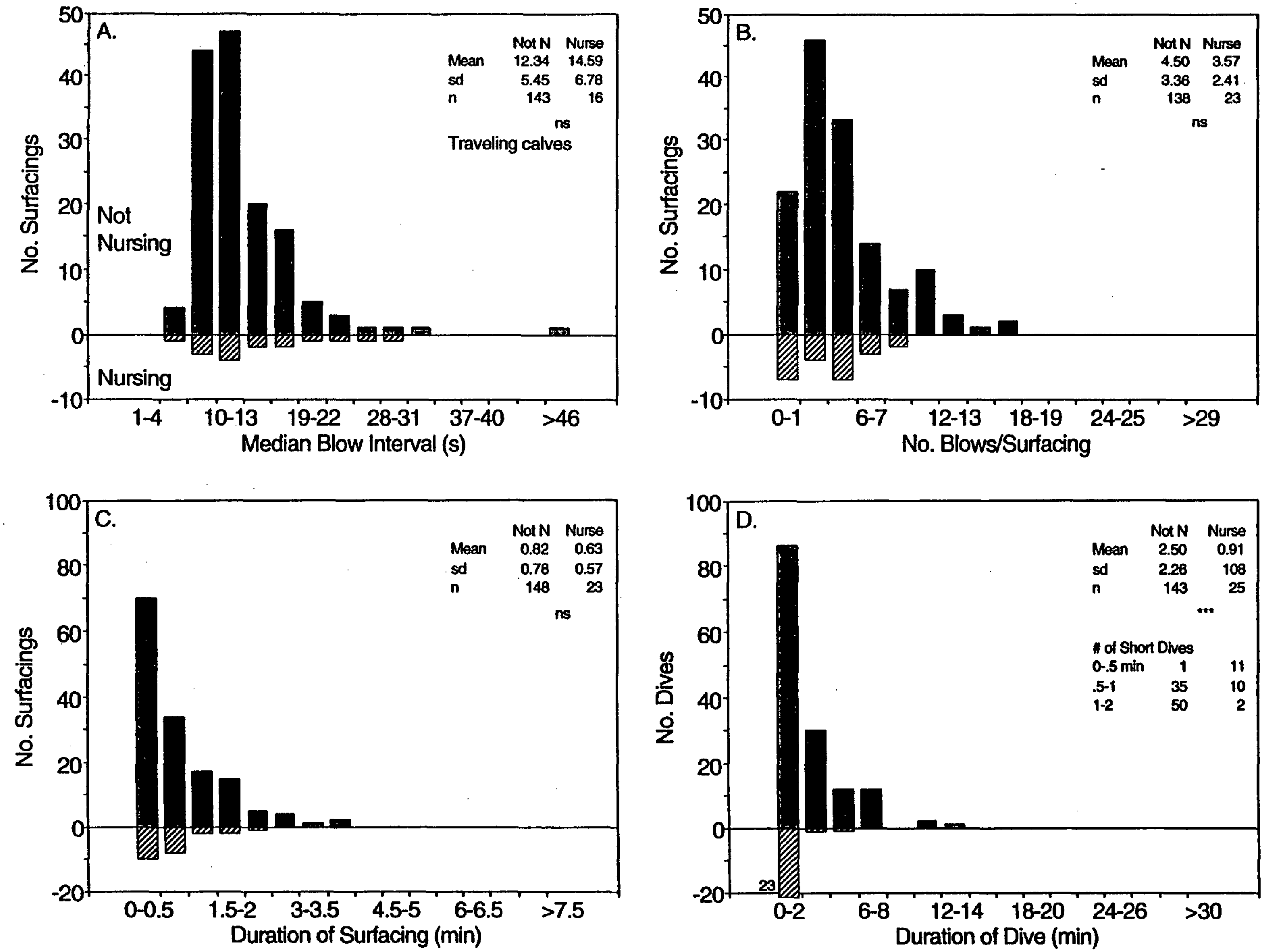

FIGURE 5.32. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowhead calves that were not nursing (upward bars) vs. nursing (downward bars) while traveling during the spring migration period near Barrow, Alaska. Otherwise as in Fig. 5.31.

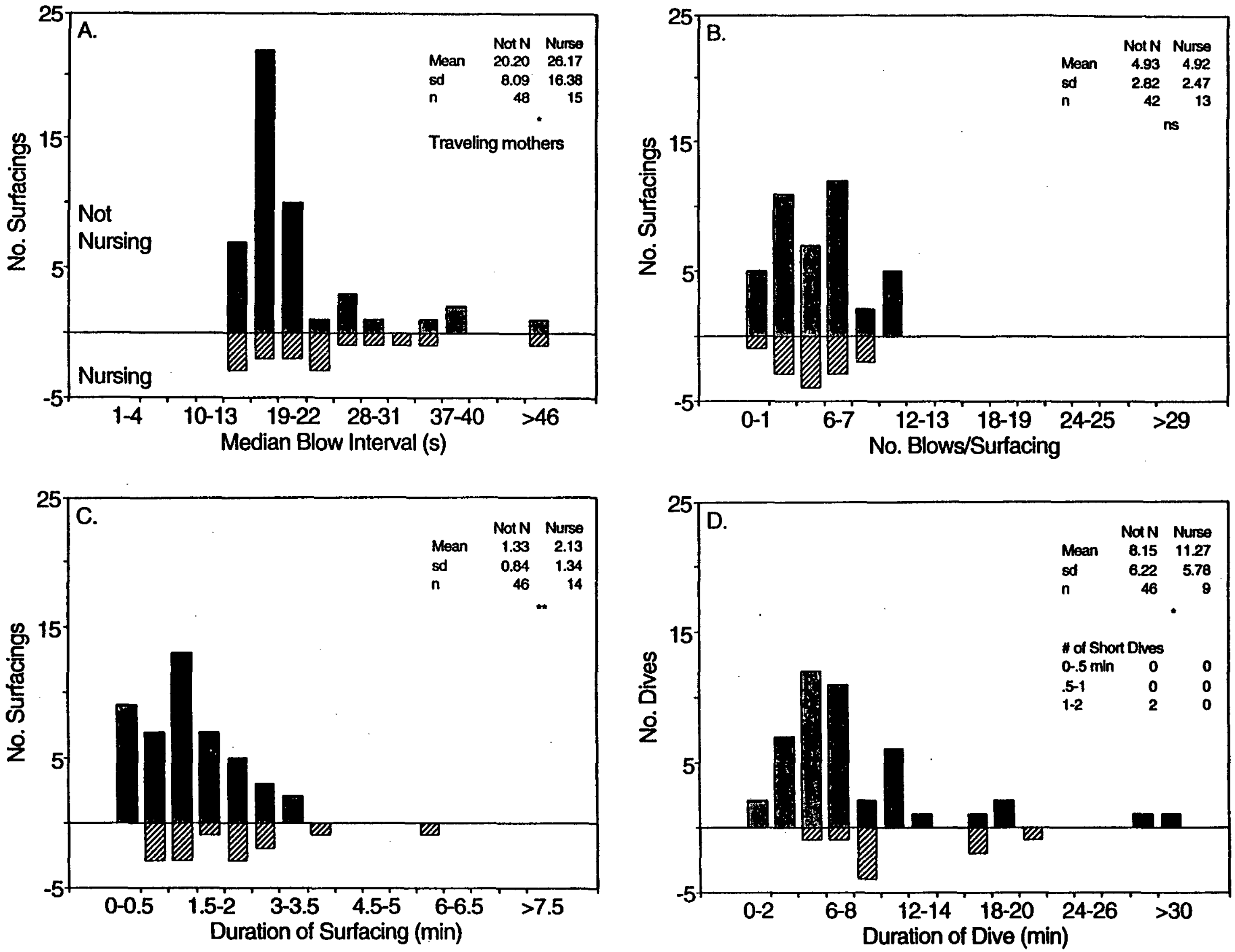

FIGURE 5.33. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowhead mothers that were not nursing (upward bars) vs. nursing (downward bars) while traveling during the spring migration period near Barrow, Alaska. Otherwise as in Fig. 5.31.

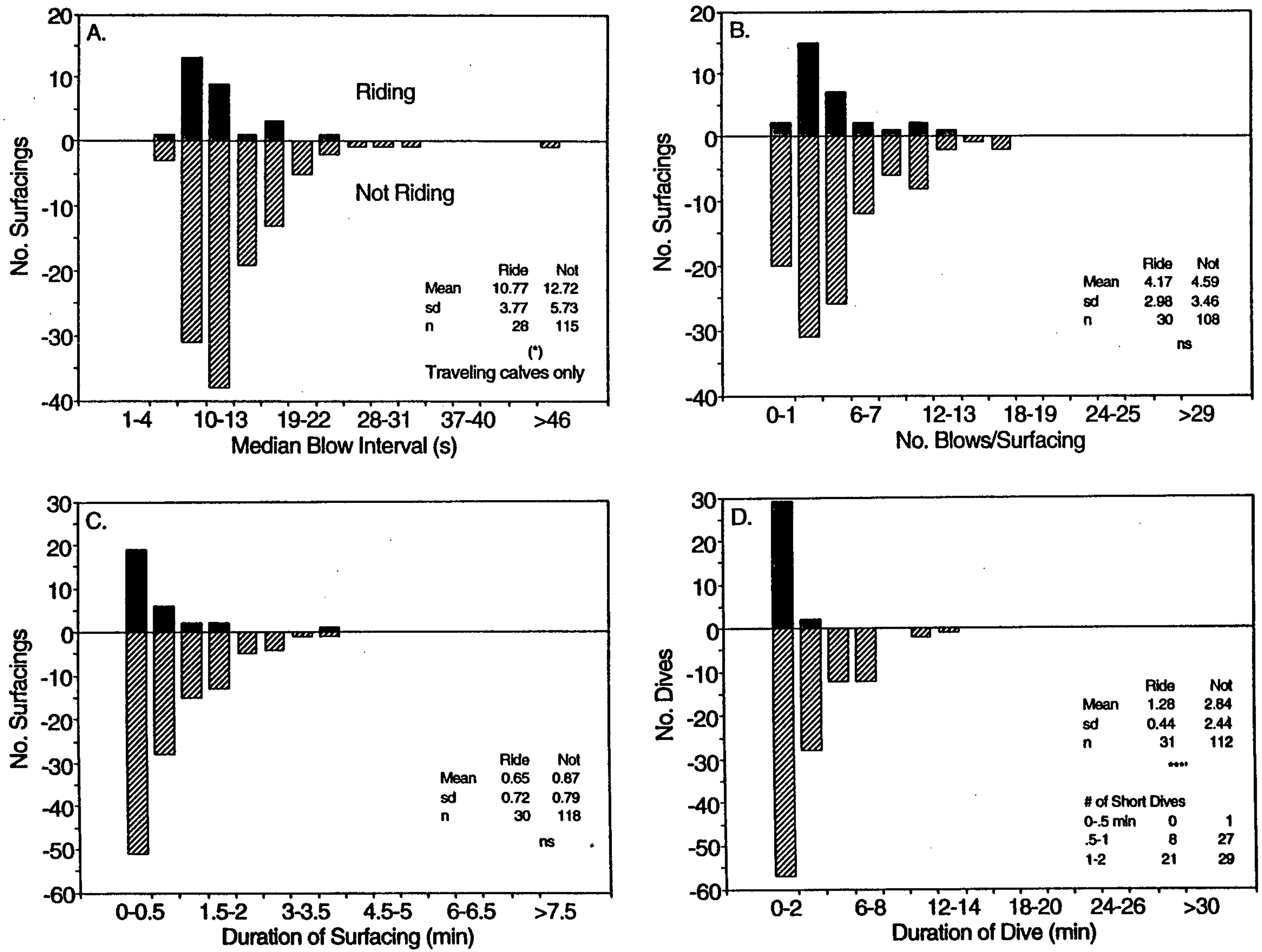

FIGURE 5.34. Frequency distributions of surfacing, respiration and dive variables for undisturbed bowhead calves that were riding (upward bars) vs. not riding (downward bars) while traveling during the spring migration period near Barrow, Alaska. Nursing calves excluded. Otherwise as in Fig. 5.31.

TABLE 5.25. Frequencies of various activities among undisturbed bowhead calves, mothers and others. Presentation as in Table 5.20.

	Calves					Mothers					Other Whales		
	Traveling		Other Activ.			Traveling		Other Activ.			Trav-	Other	
	Not	Nurse	Not	Nurse	All	Not	Nurse	Not	Nurse	All	eling	Activ.	All
A. Speed During This Surfacing													
Zero	1	1	3	2	**7**	0	2	1	1	**4**	10	22	**32**
Slow	26	7	33	4	**70**	15	0	7	4	**26**	129	53	**182**
Moderate	99	5	4	0	**108**	34	2	0	0	**36**	329	115	**444**
Fast	0	0	0	0	**0**	0	0	0	0	**0**	3	1	**4**
Unknown but >0	24	6	14	8	**52**	4	1	2	0	**7**	69	32	**101**
Milling	0	0	0	0	**0**	0	0	0	0	**0**	0	3	**3**
Change	16	3	4	1	**24**	5	9	3	2	**19**	40	21	**61**
Total n	166	22	58	15	**261**	58	14	13	7	**92**	580	247	**827**
B. Flukes Out at End of Surfacing													
No	158	25	71	16	**270**	53	16	20	6	**95**	457	163	**620**
Yes	5	0	9	0	**14**	1	0	0	0	**1**	45	26	**71**
Total n	163	25	80	16	**284**	54	16	20	6	**96**	502	189	**691**
C. Pre-Dive Flex Before End of Surfacing													
No	152	23	75	16	**266**	51	13	20	6	**90**	431	157	**588**
Yes	0	0	0	0	**0**	0	2	0	0	**2**	7	4	**11**
Total n	152	23	75	16	**266**	51	15	20	6	**92**	438	161	**599**
D. Turns During Surfacing													
None	122	20	55	12	**209**	39	13	12	4	**68**	276	90	**366**
Right	14	1	4	1	**20**	4	1	2	1	**8**	56	43	**99**
Left	12	0	5	1	**18**	6	1	5	1	**13**	52	30	**82**
Multiple	4	2	9	1	**16**	0	0	1	1	**2**	47	35	**82**
Total n	152	23	73	15	**263**	49	15	20	7	**91**	431	198	**629**
E. Degrees of Turn During Surfacing													
0	122	20	55	12	**209**	39	13	12	4	**68**	276	90	**366**
10	4	1	1	1	**7**	1	1	1	1	**4**	23	10	**33**
20	7	0	2	0	**9**	4	0	0	0	**4**	29	7	**36**
30	4	0	0	0	**4**	3	0	1	0	**4**	10	5	**15**
40	1	0	1	0	**2**	0	1	0	0	**1**	8	2	**10**
50-80	3	0	4	0	**7**	0	0	2	1	**3**	17	8	**25**
90+	3	0	9	2	**14**	0	0	2	1	**3**	17	48	**65**
Total n	144	21	72	15	**252**	47	15	18	7	**87**	380	170	**550**
F. Social Activity During Surfacing													
None	172	25	80	16	**293**	63	16	20	7	**106**	447	150	**597**
Passive	0	0	0	0	**0**	0	0	0	0	**0**	52	21	**73**
Active	0	0	0	0	**0**	0	0	0	0	**0**	54	132	**186**
Total n	172	25	80	16	**293**	63	16	20	7	**106**	553	303	**856**
G. Aerial Activity During Sfc/Dive Seq.													
None	161	24	68	15	**268**	56	16	20	6	**98**	440	166	**606**
Roll	0	0	0	0	**0**	0	0	0	0	**0**	5	20	**25**
Flip. slap (FS)	0	0	0	0	**0**	0	0	0	0	**0**	4	0	**4**
Tail slap (TS)	3	0	4	0	**7**	0	0	0	0	**0**	12	4	**16**
FS + TS	0	0	2	0	**2**	0	0	0	0	**0**	3	3	**6**
Breach	0	0	3	1	**4**	0	0	0	0	**0**	5	24	**29**
Breach + FS &/or TS	0	0	1	0	**1**	0	0	0	0	**0**	1	8	**9**
Total n	164	24	78	16	**282**	56	16	20	6	**98**	470	225	**695**

TABLE 5.26. Number of surfacing/dive sequences with specific whale behaviors among undisturbed bowhead calves, mothers and others. Totals exceed "Overall n" because >1 special behavior can occur at one time. Presentation as in Table 5.20.

	Calves					Mothers					Other Whales		
	Traveling		Other Activ.			Traveling		Other Activ.			Trav-	Other	
	Not	Nurse	Not	Nurse	All	Not	Nurse	Not	Nurse	All	eling	Activ.	All
None	60	0	39	0	99	19	0	9	0	28	121	89	210
Defecation	0	0	0	0	0	0	0	0	0	0	0	1	1
Flukes raised during surfacing	0	0	0	1	1	0	0	0	0	0	6	5	11
Lunge or surge	0	0	0	0	0	0	0	0	0	0	5	7	12
Underwater blow	0	0	1	0	1	0	0	0	0	0	5	12	17
Arch during surfacing	1	0	0	0	1	2	1	1	1	5	30	8	38
Mouth open slightly/briefly	0	0	0	0	0	0	0	0	0	0	0	1	1
Mouth open	0	0	0	0	0	0	0	0	0	0	1	0	1
Echelon formation	0	0	0	0	0	0	0	0	0	0	0	0	0
Near-surface feeding	0	0	0	0	0	0	0	0	0	0	0	0	0
Mud from mouth	0	0	0	0	0	0	0	0	0	0	0	4	4
Mud behind whale	0	0	0	0	0	0	0	0	0	0	0	0	0
Streak in water	0	0	0	0	0	0	0	0	0	0	0	0	0
Penis visible	0	0	0	0	0	0	0	0	0	0	0	4	4
Presumed sexual activity	0	0	0	0	0	0	0	0	0	0	0	25	25
Nursing (mother or calf)	0	25	0	16	41	0	16	0	7	23	0	0	0
Play with log	0	0	0	0	0	0	0	0	0	0	0	0	0
Play with other large object	0	0	0	0	0	0	0	0	0	0	0	0	0
Play with particulates	0	0	0	0	0	0	0	0	0	0	0	0	0
Motionless at surface	0	1	2	3	6	0	2	1	2	5	12	13	25
Motionless just below surface	0	0	0	0	0	0	0	0	0	0	0	0	0
Motionless with head down	0	0	0	0	0	0	0	0	0	0	0	0	0
Spyhop	0	0	0	0	0	0	0	0	0	0	0	0	0
Travel along ice edge	23	7	4	4	38	7	0	0	1	8	87	18	105
Emerge from extens. ice (>1km)	0	0	0	0	0	0	0	0	0	0	21	2	23
Riding (mother or calf)	30	0	10	0	40	7	0	0	1	8	0	0	0
Accompanied by belugas	0	0	0	0	0	0	0	0	0	0	7	1	8
Visible below surface	71	8	30	1	110	25	5	11	0	41	174	19	193
Swims in tight circles	0	0	0	0	0	0	0	0	0	0	0	2	2
Overall n	150	25	75	16	266	49	16	20	7	92	431	192	623

We considered only those pairs whose positions were determined over a period of at least 1 h. We excluded cases when the navigation data were suspect.

The two mother/calf pairs observed in 1989 during steady eastward migration in largely open water were traveling at speeds of 5.1 and 4.8 km/h, averaged over about 2 h. These whales were judged to be traveling at medium speed during most surfacings. The net motion of the third pair seen in 1989—the pair that lingered in the area for at least 2 days—was only 12 km NE over a 44.2 h period. The fourth pair moved 12.6 km WSW in 19.1 h.

In 1990, one mother/calf pair migrating steadily through heavy pack ice had a net speed of only 1.5 km/h, partly but not entirely due to its circuitous route through the ice. Another pair averaged 4.7 km/h, part of the time in moderately heavy pack ice. More details about the movements of these pairs are given in the descriptions of cases 2 and 3 on p. 233.

Fluke-out Dives.—Fluke-out dives were rarer for mothers (1 of 96 dives, 1%) than for other non-calves (71 of 691 dives, 10%, Table 5.25B). This difference is significant ($chi^2=7.57$, df=1, $P<0.05$). Calves raised their flukes above the water during 14 of 284 dives (5%; Table 5.25B).

Pre-dive Flexes.—Flexes were rarely exhibited by mothers or other non-calf bowheads observed during the springs of 1989-90. Flexes were noted during only 2 of 92 surfacings (2%) by mothers and during 6 of 599 surfacings (1%) by other non-calves (Table 5.25C). No calf was ever seen to exhibit a pre-dive flex in spring (0 of 266 surfacings).

Turns.—Among traveling whales, turns were less frequent in the cases of mothers and calves (19% of surfacings) than for other non-calves that were traveling (36%). Among whales engaged in other activities, sample sizes were small for mothers and calves, but again turns were less common than for other whales (Table 5.25D).

Social Activity.—Mothers and calves were not observed to socialize with whales other than the other member of the mother or calf pair. In contrast, other whales often interacted with other whales (Table 5.25F).

Aerial Behaviors.—Aerial behaviors, including breaches, tail slaps, and flipper slaps or rolls, were not seen in the case of mothers observed in spring. Other non-calves occasionally exhibited these behaviors, and a few breaches, tail slaps and flipper slaps were seen in the case of calves (Table 5.25G).

Additional Behavioral Variables.—Of the many other behaviors that are noted when seen, only a few were seen commonly in calves or their mothers (Table 5.26). These included nursing, riding, traveling parallel to and within 100 m of an ice edge, and visible below surface during dives. Nursing and riding were, more-or-less inevitably, seen only in mothers and calves. Traveling along ice edges and traveling close enough to the surface during dives to be visible from above were also common in other whales.

6. BOWHEAD DISTURBANCE[21]

The highest priority objective during the 1991 and 1994 phases of this project was to test the reactions of bowhead whales to underwater playbacks of recorded icebreaker sound. The aim was to determine whether, and in what circumstances, these variable sounds would affect the distribution, movements, and behavior of spring-migrating bowheads and, as possible, white whales. This top-priority task was identified as specific objective 4 in §1.1 (p. 7):

> "To measure the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of variable icebreaker sounds. Infrasonic components cannot be projected."

This work was a follow-on to earlier playback tests of bowhead and white whale reactions to the steadier, continuous sounds from drilling on a grounded ice pad (Richardson et al. 1990a, 1991a). Sections 6.1-6.6 of this report present and discuss the results of the 1991/94 tests of bowhead reactions to playbacks of variable icebreaker sounds. However, the discussion in §6.5 (Icebreaker vs. Drilling Noise Results) and §6.6 (Evaluation of Playback Hypotheses) mentions the results of the earlier drilling noise playbacks as well.

A lower-priority objective in all four years of this project was to measure, on an opportunistic basis, the short-term behavioral responses of bowheads and (as possible) white whales to actual helicopter overflights (specific objective 6 from §1.1). A Bell 212 helicopter was used for logistic support of the ice-based work during all four years of the project, and this afforded opportunities to observe reactions of whales to this type of helicopter. When possible, we also attempted to determine the reactions of the two whale species to the Twin Otter fixed-wing observation aircraft that was used during all four years of this project. Section 6.7 describes the results concerning reactions of bowheads to the two types of aircraft, based on the data from all four years of this project.

6.1 Summary of Icebreaker Playbacks

Number of Observations During Playbacks

In ***1991***, there were only a few observations of bowhead whales near the operating sound projectors, all on 17 May (Table 3.5 on p. 70; Table 6.1A; see also Table A-1 in Appendix A). Icebreaker sounds were projected into the lead for prolonged periods on a total of 6 days in 1991:

- During three playback days, no bowheads were seen near the projectors.
- Of the three playback days when bowheads were seen,
    - Two were days when bowheads were seen by the ice-based crew only during "control" periods, while the projectors were not operating (11 and 18 May 1991).

[21] By W.J. Richardson, W.R. Koski and N.J. Patenaude, with C.R. Greene Jr., G.W. Miller, M.A. Smultea, and B. Würsig.

TABLE 6.1. Observation effort and numbers of bowhead and white whales seen near ice camps during control periods and playback periods, 1991 and 1994. Only dates when icebreaker noise was projected are included. Whales seen during more than one period are counted once in each period. Numbers presented are the numbers of different whales estimated to have been present and are often less than the number of sightings in maps and tables in this report.

	Aerial Observations						Ice-based Observations						Combined Observations					
	Control			Playback			Control			Playback			Control			Playback		
Date	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs
A: Days with Whales during Playback																		
11 May 1991	0.0 [a]	0	0	0.0 [a]	0	0	3.6	6	23	1.0 [b]	0	6	3.6	6	23	1.0	0	6
17 May 1991	0.0 [a]	0	0	0.0 [a]	0	0	4.1	2	96	5.3	9	8	4.1	2	96	5.3	9	8
3 May 1994	0.0 [c]	0	0	0.0 [c]	0	0	5.6	1	0	4.1	0	32	5.6	1	0	4.1	0	32
7 May 1994	2.1	15	0	1.5 [a]	15	0	7.0	36	0	3.9	8	0	7.0	47	0	3.9	18	0
9 May 1994	1.9	24	0	2.2	27	0	6.4	22	0	3.0	25	0	6.4	42	0	3.0	32	0
14 May 1994	0.0 [a]	0	0	0.0 [a]	0	0	6.4	17	0	3.2	3	0	6.4	17	0	3.2	3	0
16 May 1994	0.5	7	0	3.2	9	0	4.2	0	0	4.2	4	0	4.2	7	0	4.2	13	0
17 May 1994	4.3	27	0	1.9	6	0	1.5	0	0	4.2	1	0	4.4	27	0	4.2	7	0
20 May 1994	2.6	9	0	0.0 [a]	0	0	5.2	6	0	4.6	11	0	5.5	9	0	4.6	11	0
Total	**11.4**	**82**	**0**	**8.8**	**57**	**0**	**44.0**	**90**	**119**	**33.5**	**61**	**46**	**47.2**	**158**	**119**	**33.5**	**93**	**46**
B: Other days with whales																		
Total	**0**	**0**	**0**	**0**	**0**	**0**	**4.0**	**0**	**46**	**2.4**	**0**	**0**	**4.0**	**0**	**46**	**2.4**	**0**	**0**
C: Days without Whales																		
Total	**0**	**0**	**0**	**0**	**0**	**0**	**5.0**	**0**	**0**	**4.0**	**0**	**0**	**5.0**	**0**	**0**	**4.0**	**0**	**0**

[a] Low cloud prevented or curtailed aerial observations.

[b] Deteriorating ice conditions curtailed ice-based work.

[c] No bowheads were seen approaching the ice camp during surveys west and SW of it, so observations were conducted away from the camp.

- Bowheads were seen during the playback itself on one day, 17 May 1991. On that date, the ice-based crew observed 9 bowheads (or possibly 10) that migrated within 1.3 km of the projectors while they were broadcasting icebreaker sounds.

In ***1994***, there were considerably more observations of bowhead whales near the operating sound projectors than in 1991 (Table 3.7 on p. 76; Table 6.1A). Icebreaker sounds were projected into the lead for prolonged periods on a total of 7 days in 1994:

- During one playback day (3 May), no bowheads were seen near the projectors during the playback period; however, white whales were seen (Table 3.7).
- Of the six playback days in 1994 when bowheads were seen during the playback period,
  - Two were days when the bowheads were seen by the ice-based crew only during playback periods, while the projectors were operating (16 and 17 May 1994). On 17 May high winds resulted in observers missing many whales that were passing and resulted in incomplete data for many whales that were seen. On both of these days the aerial crew was able to follow bowheads during both control and playback periods, but substantial changes in ice conditions throughout the day make comparisons between control and playback periods problematic.
  - 14 May was a day when the ice-based crew observed bowheads during both playback and control periods, but the aerial crew was not able to circle near the ice camp at any time during the day because ceilings were <460 m.
  - 20 May was a day when the ice-based crew saw bowheads during both playback and control periods; the aerial crew was able to circle near the ice camp during the control but not the playback period; ceilings were <460 m during the latter period.
  - 7 May was a day when the ice-based crew observed bowheads during both playback and control periods; the aerial crew was also able to circle near the ice camp during both periods, but scattered or broken clouds below the aircraft during the playback, along with high winds, resulted in incomplete data for most sightings.
  - 9 May was a day when both the aerial and ice-based crews were able to observe whales during the control and playback periods. On this day, poor observing conditions (primarily due to high sea states) reduced the quality and quantity of data that were collected.

Over the two-season period when icebreaker playbacks were attempted, an estimated 93 bowheads (80 groups) were seen near the ice camp when the projectors were transmitting icebreaker sounds into the water, and ~158 bowheads (116 groups) were seen near there during quiet periods (Table 6.1A). During 1989-90 playbacks of *Karluk* drilling noise, ~221 bowheads were observed near the ice camp during playbacks, and ~187 there during quiet control periods (Table 6.2A).

Although substantial numbers of bowheads were seen near the ice camp during control and playback periods in 1994, environmental conditions were unfavorable during most experiments. Low cloud and high winds often interfered, as just summarized. As a result, the quality and quantity of behavioral and movement data were often poor. On these days, we often were able to obtain only partial data on whale behavior during surfacings, and we usually could not see the markings that make many bowheads individually recognizable. Thus, we rarely could follow

TABLE 6.2. Observation effort and numbers of bowhead and white whales seen near ice camps during control periods and playback periods, 1989 and 1990. Only dates when *Karluk* noise was projected are included. Whales seen during more than one period are counted once in each period. Numbers presented are the numbers of different whales estimated to have been present and are often less than the number of sightings in maps and tables in this report.

	Aerial Observations						Ice-based Observations						Combined Observations					
	Control			Playback			Control			Playback			Control			Playback		
Date	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs
A: Days with Whales during Playback																		
14 May 1989	0.5	1	100	2.8	6	100	2.7	0	7	8.6	5	19	2.7	1	100	8.6	10	100
19 May 1989	0.0 [a]	0	0	0.0 [a]	0	0	4.3	0	0	4.3	4	2	4.3	0	0	4.3	4	2
23 May 1989	0.8 [a]	1	1	0.7 [a]	5	50	3.9	2	3	5.1	2	4	3.9	3	4	5.1	5	54
27 May 1989	3.1	10	0	1.8	2	0	8.7	0	0	2.7	0	14	9.2	10	0	2.7	2	14
9 May 1990	0.0 [a]	0	0	0.0 [a]	0	0	2.2	2	0	5.0	22	0	2.2	2	0	5.0	22	0
10 May 1990	1.7	21	35	3.6	25	30	2.0	4	7	5.3	22	0	2.3	23	35	5.3	40	30
11 May 1990	3.5	15	0	1.0	3	0	6.0	13	6	1.6	1	0	6.0	28	6	1.6	4	0
13 May 1990	0.7	6	0	4.1	26	0	3.4	37	0	4.7	93	0	3.4	40	0	4.7	105	0
16 May 1990	2.2	27	0	1.4	12	0	1.3	36	0	3.7	21	0	2.7	63	0	3.7	25	0
21 May 1990	2.3	17	200	2.7	4	3	3.0	1	49	4.1	1	16	3.9	17	220	4.1	4	19
Total	**14.8**	**98**	**336**	**18.1**	**83**	**183**	**37.5**	**95**	**72**	**45.1**	**171**	**55**	**40.6**	**187**	**365**	**45.1**	**221**	**219**
B: Other Days with Whales																		
Total	**1.7**	**1**	**0**	**0.0**	**0**	**0**	**17.0**	**2**	**22**	**14.2**	**0**	**0**	**18.1**	**3**	**22**	**14.2**	**0**	**0**
C: Days without Whales																		
Total	**0.0**	**0**	**0**	**0.0**	**0**	**0**	**18.5**	**0**	**0**	**14.7**	**0**	**0**	**18.5**	**0**	**0**	**14.7**	**0**	**0**

[a] Low Cloud prevented or curtailed aerial observations.

known individuals from one surfacing to the next, which meant that we obtained few data on the dive durations of bowheads, or on their "tracks" as they passed the ice camp. (A "track" is the route followed by an animal, as shown by the sequence of animal positions during two or more surfacings.) For these reasons, the number of whales seen during an experiment was not always a good measure of the success of that experiment; few useful data were obtained from some whales that were observed only briefly.

The following subsections give brief summaries of the observations on the seven days (17 May 1991 and 7, 9, 14, 16, 17 and 20 May 1994) when bowheads were observed near the operating projectors during icebreaker playbacks, and therefore were exposed to simulated icebreaker sounds. The observation effort from the aircraft and ice camp, and the numbers of bowheads seen during control and playback periods on each of the seven days, are summarized in Table 6.1. Table 6.3 shows the projector systems used, the median source levels of projected sounds, and the average ambient noise levels for each of these seven days. Finally, the estimated maximum received levels near whales on each date are summarized in Table 6.4. The levels in Table 6.4 do not always refer to the closest observed whales, as whales passing when the source level was near its peak sometimes received stronger icebreaker noise than did other whales passing closer to the projector at times when the source level was lower.

More detailed descriptions of observations, environmental conditions, and sound levels received by whales on each of the days described in the following daily summaries are given in Appendix F. Figures 6.1-6.3 are included here as examples of bowhead "track maps" and sound exposure summaries for specific playback days. Appendix F includes more diagrams of these types, dealing with all days when bowheads were exposed to playbacks. Results from all days are summarized in §6.2 concerning playback effects on distribution and movements, and in §6.3 concerning playback effects on behavior.

Levels of icebreaker sound received by every observed bowhead at its Closest Estimated Point of Approach (CEPA) were estimated via the sound exposure model described in §2.3 (p. 46*ff*). This model produces many different measures of sound exposure. Those quoted in this section are the estimated received levels in the 20-5000 Hz band ("broadband") or in the 1/3-octave band with highest received level ("dominant 1/3-octave band). We considered 1/3-octave bands centered at 20 through 6300 Hz. For both the 20-5000 Hz band and the dominant 1/3-octave, we refer to both the median or the maximum level in the 64-s period preceding the observation in question. These four estimates of received level are often abbreviated as $RL_{BB,med}$, $RL_{BB,max}$, $RL_{1/3,med}$, and $RL_{1/3,max}$. When the average ambient noise level in the corresponding band, as measured before and/or after the playback, is subtracted from one of these received levels, the result is the estimated icebreaker-signal to ambient-noise ratio, $S{:}N_{BB,med}$, $S{:}N_{BB,max}$, $S{:}N_{1/3,med}$, and $S{:}N_{1/3,max}$.

17 May 1991

On 17 May 1991, the projectors were set up along the edge of the landfast ice several kilometers northeast of Point Barrow (Fig. 3.6 on p. 72; Fig. 6.1). Spring whaling at Barrow had ended by this date, allowing work closer to Barrow than at previous times in 1989-91. All

TABLE 6.3. Projector configuration, source levels of icebreaker sounds (dB re 1 μPa-m), and ambient noise levels (dB re 1 μPa) during projection experiments when bowheads were seen. Quoted source levels are medians over the 14-min cycle of icebreaker sound. On most days the median source level was adjusted one or more times during the playback; the values presented here are from the times when most whales were seen.

			Median Source			Ambient Noise Levels	
			20-5000 Hz	Dom. 1/3-Oct. Band		20-5000 Hz	In Dom.
Date	Time	Projector System	Band Level	Level	Freq. (Hz)	Band	1/3-Oct.
17 May 1991	12:42 - 16:49	J-13 + F-40	161	155	80	99	76
17 May 1991	16:50 - 18:01	J-13 + F-40	149	144	80	99	76
7 May 1994	16:07 - 18:08	J-11 + one side Argotec 220	146	139	80	95	82
7 May 1994	18:09 - 20:01	J-11 + one side Argotec 220	166	159	80	95	82
9 May 1994	14:22 - 15:02	J-11	162	157	500	100	86
9 May 1994	15:03 - 16:20	J-11	153	146	315&400	100	87&86
9 May 1994	16:26 - 17:30	J-11	156	149	200	100	85
14 May 1994	15:50 - 19:00	J-11 + one side Argotec 220	157	151	80	98	79
16 May 1994	13:03 - 17:13	J-11 + one side Argotec 220	166	158	80	89	75
17 May 1994	12:48 - 17:02	J-11	160	154	400	98-107 [a]	90-93 [a]
20 May 1994	12:38 - 17:16	J-11 + one side Argotec 220	170	163	80	86	68

[a] The ambient noise gradually increased throughout the day from the lower level before playback to the higher level after playback.

TABLE 6.4. Maximum estimated received levels (dB re 1 μPa) and maximum estimated icebreaker: ambient ratios (dB) of sounds near bowhead whales each day when the projector was broadcasting icebreaker sounds. Medians and maxima are based on estimated sound levels in 8 intervals of 8.5-s duration within the 64 s preceding the closest estimated point of approach. Only traveling whales are considered, except in the italicized 9 May 1994 line.

	Strongest Sound Levels near Whales					Ambient	Highest Icebreaker:Ambient			
	20-5000 Hz		Strongest 1/3-Oct.			Noise	20-5000 Hz		1/3-Oct.	
Date	Med.	Max.	Freq.	Med.	Max.	(20-5000 Hz)	Med.	Max.	Med.	Max.
17 May 1991	111	115	160	104	106	99	12	16	25	28
7 May 1994	116	119	80	110	113	95	21	24	29	32
9 May 1994	115[c]	118[c]	200	108[c]	111[c]	100	15[c]	18[c]	23[c]	26[c]
9 May 1994[b]	*132*	*135*	*160*	*126*	*129*	*100*	*32*	*35*	*41*	*44*
14 May 1994	107	109	80	101	103	98	9	11	22	24
16 May 1994	114	119	80	108	110	89	24	30	34	36
17 May 1994	119	123	500	112	117	99	20	24	22	26
20 May 1994	**132**[a,c]	**138**[c]	80	**125**[c]	**131**[c]	86	**46**[c]	**50**[c]	**57**[c]	**63**[c]

[a] Boldface type indicates that this whale modified its track in apparent response to the icebreaker noise.
[b] Data from feeding whales observed on 9 May 1994 are in italics. None of the feeding whales appeared to react to the icebreaker sounds.
[c] These levels may be slight underestimates of levels that would be received below the surface.

observations of whales near the projector site on 17 May 1991 were obtained by the ice-based crew because the cloud ceilings were too low for the aerial crew aboard the Twin Otter to observe bowhead behavior from an altitude of 460 m. The main nearshore lead adjacent to the landfast ice edge was several kilometers wide and largely ice-free (Fig. 6.1). The crew was on the landfast ice edge from 10:46 through 20:59. Icebreaker sounds were projected into the lead from 12:42 through 18:01. The median broadband (20-5000 Hz) source level, measured over the full 14-min duration of the icebreaker playback cycle, was 161 dB re 1 μPa-m from 12:42 to 16:49; after that time the source level was reduced by ~12 dB until the end of the session at 18:01. Because of variation in the source level associated with the icebreaking activities within the 14-min period of the tape, the source and received levels at certain times were as much as 4-15 dB higher or lower than the median levels in corresponding 1/3-octave bands (Fig. 6.2). Even with the reduced source level after 16:49, median levels of icebreaker sounds in the 1/3-octave band centered at 63 Hz were estimated to have exceeded ambient levels beyond 3 km from the projectors (Fig. 6.3), and therefore were presumably audible to bowheads 3 km or more away from the projectors.

No bowheads were sighted from the ice during the period of pre-playback control observations. Five or six single bowheads plus two pairs were seen traveling east past the ice camp during or immediately after the icebreaker playback, i.e. a total of 9 or 10 whales in 7 or 8 groups. There

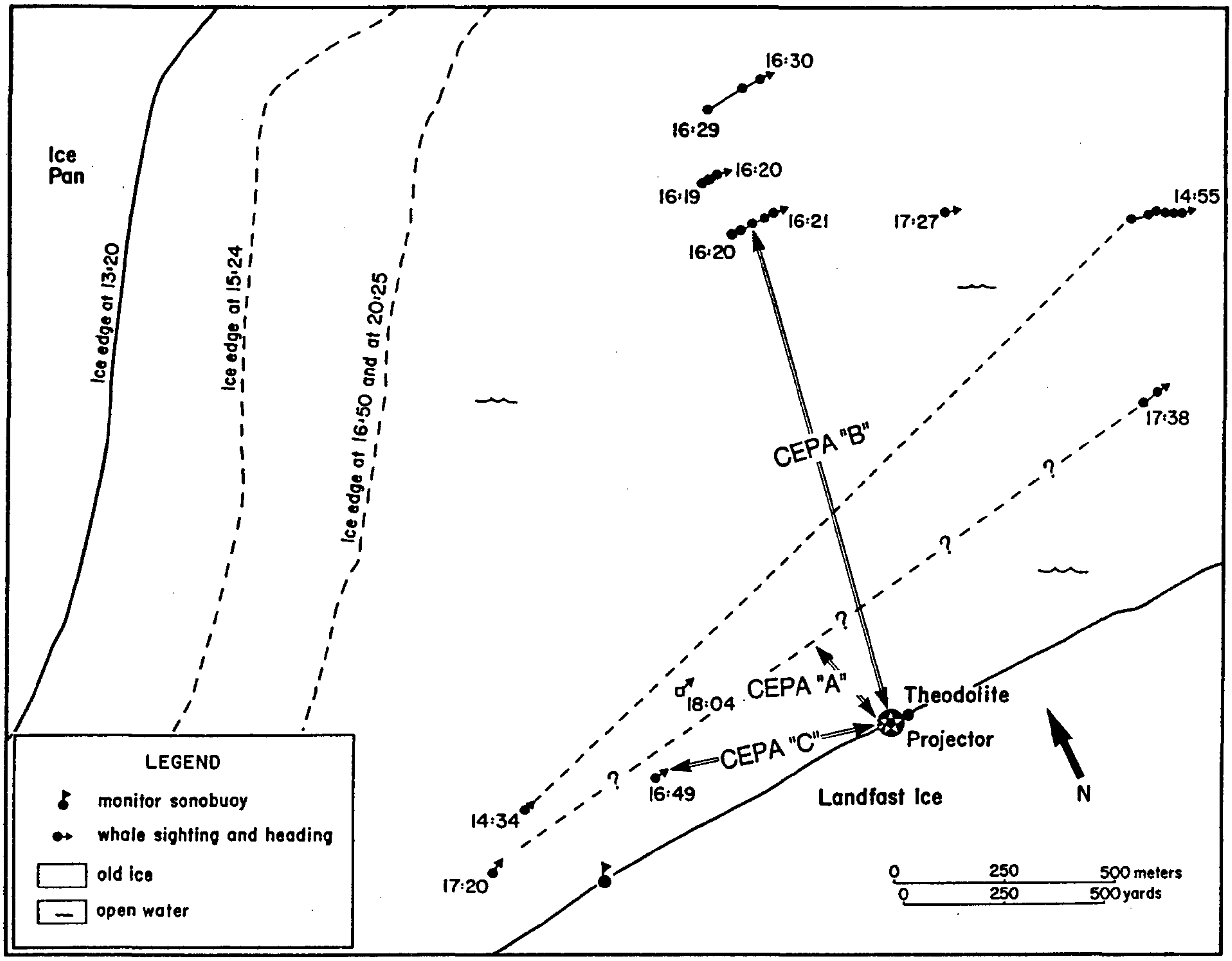

FIGURE 6.1. Ice-based theodolite observations of bowhead whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991, while the projectors were broadcasting icebreaker sounds from 12:42 to 18:01. The whale seen at 18:04, 3 min after the end of the playback, is shown because it was exposed to icebreaker noise as it approached. Dashed lines represent presumed paths of whales while they were below the surface. Double lines indicate the closest estimated point of approach (CEPA) for selected whales. CEPA "A" and CEPA "B" approximate actual closest points of approach (CPA), but CEPA "C" likely underestimates the actual CPA.

were two additional "control" sightings of single bowheads well after the playback had ended (see Appendix F for details).

The closest estimated points of approach (CEPA) by the whales for which we have reliable measurements or estimates were ~450 to 1300 m (n=4 sightings). Calculation of CEPA assumed that a whale sighted both as it approached and as it receded from the projector traveled in a straight line between consecutive sightings. The shortest distance between the assumed path and the projector was the CEPA (e.g., CEPA "A" in Fig. 6.1). For whales that were seen only as they

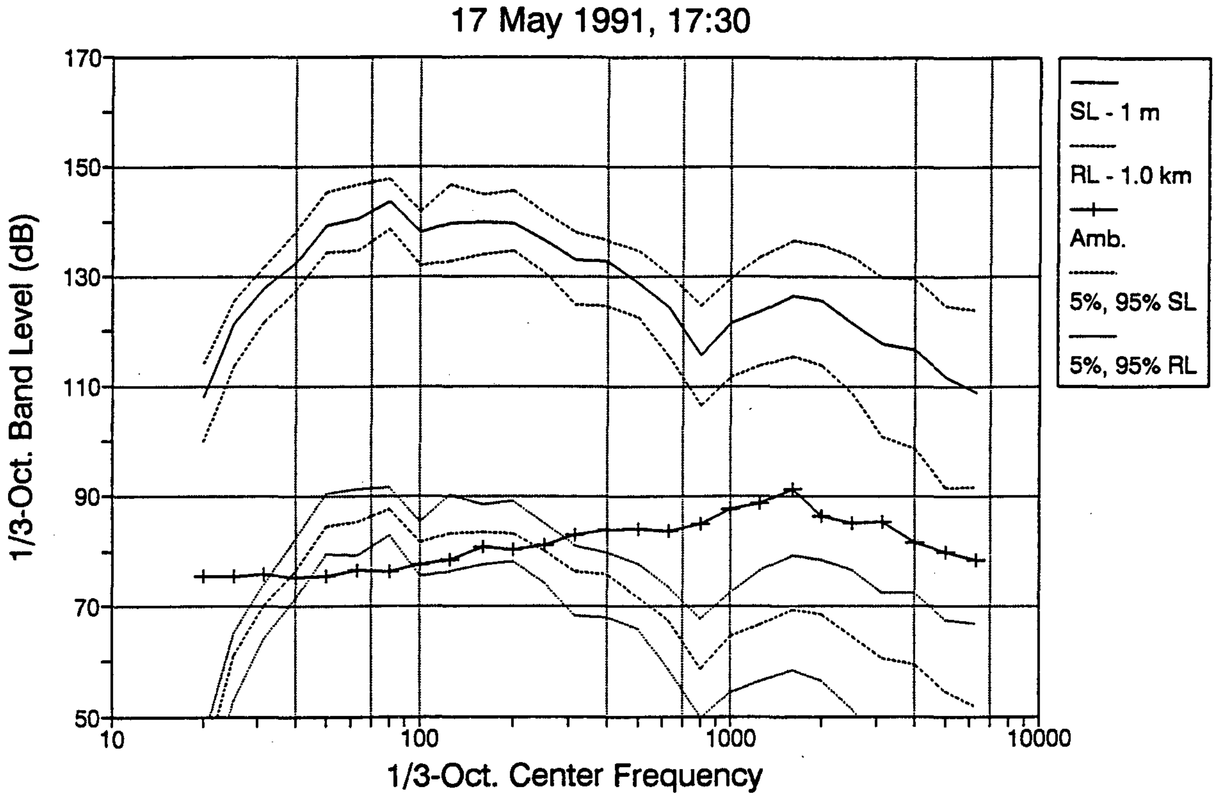

FIGURE 6.2. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 17:16-17:30: variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). Plus signs show average ambient noise level after playback.

Explanatory notes: *(1)* Source levels are in dB re 1 μPa-m, and ambient and received levels are in dB re 1 μPa. *(2)* Because of projector limitations, components of the icebreaker sounds at low frequencies are underrepresented in the projector output relative to components at higher frequencies. *(3)* The tape of icebreaker sounds is repeated every 14 min. As illustrated by the 5th and 95th percentiles, the actual source or received level at any particular time can be substantially different than the median level, depending on the precise location along the 14-min loop that is being projected or received. *(4)* Source and ambient levels were measured; received levels at 1.0 km were estimated via an empirically-validated propagation model, as described in section 2.3. *(5)* Received levels within a few meters of the surface will be lower than estimated here.

approached or only as they receded from the projector, the CEPA was the closest observed distance from the projector (CEPAs "B" and "C" in Fig. 6.1). We did not assume that the whales continued on a straight line from their last observed heading because some approaching whales may have diverted after they were sighted, and some receding whales may have diverted before they were sighted. Thus CEPA for a whale that was seen only as it approached or receded likely overestimates the actual closest point of approach, and therefore underestimates the maximum sound levels received by that whale. A fifth whale seen on 17 May 1991 appears to have passed ~300 from the operating projectors; it was linked after an 18-min dive, although distinctive

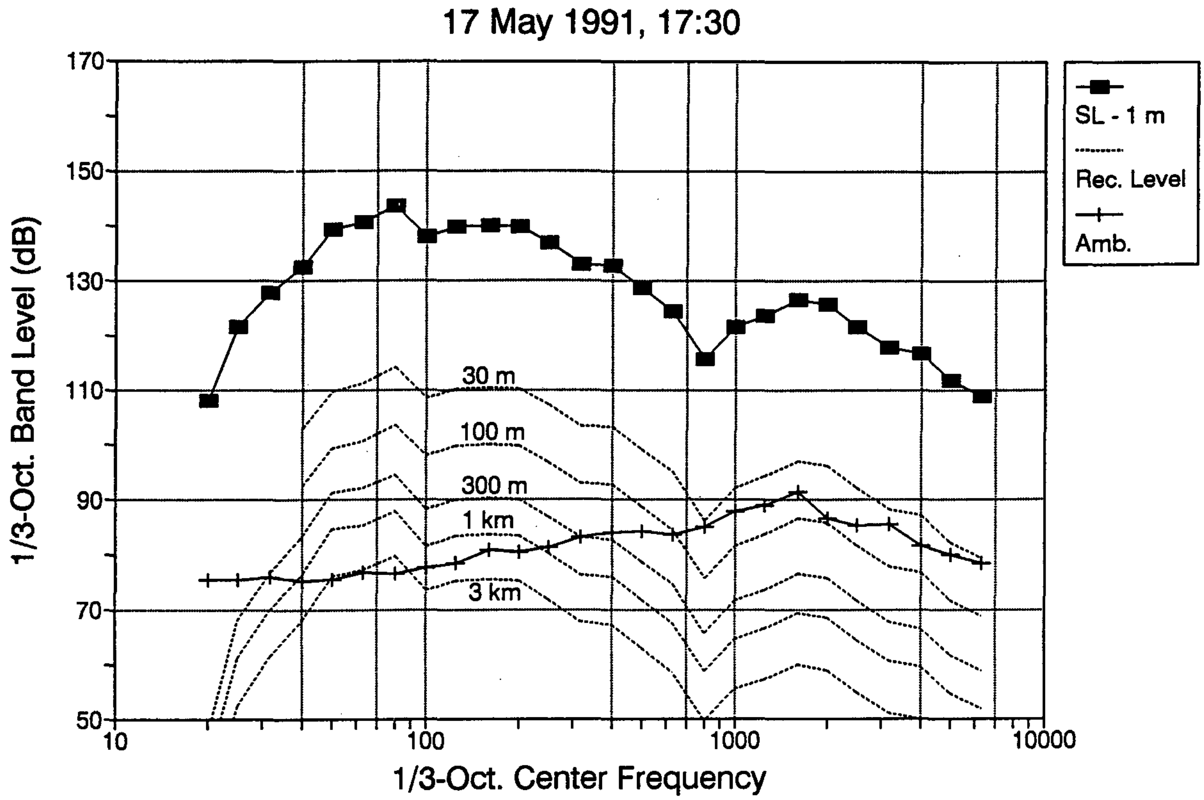

FIGURE 6.3. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 17:16-17:30: median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level after playback.

Explanatory notes: See notes to Fig. 6.2. Figure 6.3 shows median received levels at more ranges, but does not show 5th and 95th percentiles. Estimated received levels at 0.03 and 0.1 km assume spherical spreading; model of §2.3 was used to derive estimates for 0.3 to 3 km.

markings that would confirm the link were not seen (Fig. 6.1).

At their CEPAs, six of eight groups observed on 17 May 1991 were exposed to icebreaker sounds 22-28 dB above the ambient noise level ($S:N_{1/3,max}$). No overt reactions to the sounds were observed by the ice-based crew. Additional details are given in Appendix F.

7 May 1994

On 7 May 1994, the ice camp was set up along the landfast ice edge about 45 km ENE of Pt. Barrow (Fig 3.8, p. 77). Tones and later icebreaker sounds were projected into the nearshore lead adjacent to the landfast ice. Before the playback of tones and icebreaker sounds, large numbers of bowhead whales were sighted traveling NE at medium speed through the middle and southern third of the lead. Sighting rates were lower when tones were projected into the lead from 14:14 to 16:03, but the distribution and behavior of most whales seen then were similar to those during the preceding control period.

Bowheads continued to travel past the ice camp during the period of icebreaker playback from 16:07 to 20:01, but sighting rates were lower and some whales apparently diverted away from the landfast ice edge where the sound projectors were located. No bowheads were seen from the ice camp during the first 80 min of icebreaker projections and only a few whales were seen, all in the central and offshore sides of the lead, during the following 2½ hours of icebreaker playback. The broadband source levels were ~20 dB higher during the final 1.9 h of the playback than during the initial 2.0 h (Table 6.3). Aerial observations west of the projectors sighted large numbers of bowheads heading toward the projectors; few of them were later seen by ice-based observers. These whales apparently moved past the ice camp through the offshore side of the lead.

Some whales seemed to alter their paths at distances where icebreaker sounds in the strongest 1/3-octave bands were similar to the ambient noise levels in those bands and thus (presumably) barely detectable. The whale seen closest (362 m) to the operating projectors appeared to be detouring to the north to avoid a closer approach. It was seen during the first half of the projection experiment when source levels were low. This whale was exposed to an estimated $S{:}N_{1/3,max}$ of 18 dB when it started to detour (maximum estimated icebreaker:ambient ratio in the 1/3-octave band centered at 50 Hz). However, not all bowheads diverted. One bowhead was seen that had apparently passed well within 500 m of the projectors on a normal northeasterly heading, tolerating $S{:}N_{1/3,max}$ well over 20 dB. Thus it appears that, on 7 May 1994, some whales altered their tracks to avoid the projectors by >1 km, but a few approached within a few hundred meters where they were exposed to $RL_{BB,max}$ as high as 119 dB re 1 μPa and $S{:}N_{1/3,max}$ as high as 32 dB.

<u>9 May 1994</u>

On 9 May 1994, the ice camp was set up along the landfast ice edge about 2.5 km northeast of the 7 May location (Plate 6.1), and 3.9 h of pre-playback control observations were obtained from the ice. During this period 10 presumably undisturbed bowheads were sighted. Then icebreaker sounds were projected into the lead adjacent to the landfast ice for 3 h, during which 32 bowheads were observed from the ice and aircraft. There was a further 3-h period of observations after the playback ended, during which ~43 bowheads were seen from the ice and aircraft. Interpretation of the distribution and heading data was complicated by lingering whales that were probably feeding under the landfast ice near the ice camp.

During all periods, bowheads traveled predominantly NE or ENE along the lead. A few whales sighted from the ice camp and aircraft may have altered their headings to avoid closer approaches to the projector (see Table 6.5, p. 274), but other whales that appeared to be feeding headed generally south toward the landfast ice and projector. Two bowheads seen 940 m WSW of the operating projector at 17:26 appeared to temporarily modify their path at that time and distance in response to the icebreaker playback. They resumed traveling toward the ice camp a few minutes after the projector was turned off at 17:30. Another group reversed course WSW away from the projector; that group may have been feeding. Some of the whales sighted WSW to N of the ice camp during the playback had northerly rather than NEerly headings, suggesting that they may have been altering their tracks to avoid closer approach to the projector. However, during the post-playback period, bowheads did not resume traveling along the landfast ice near the ice camp; after the playback more bowheads traveled along the pack-ice edge forming the north

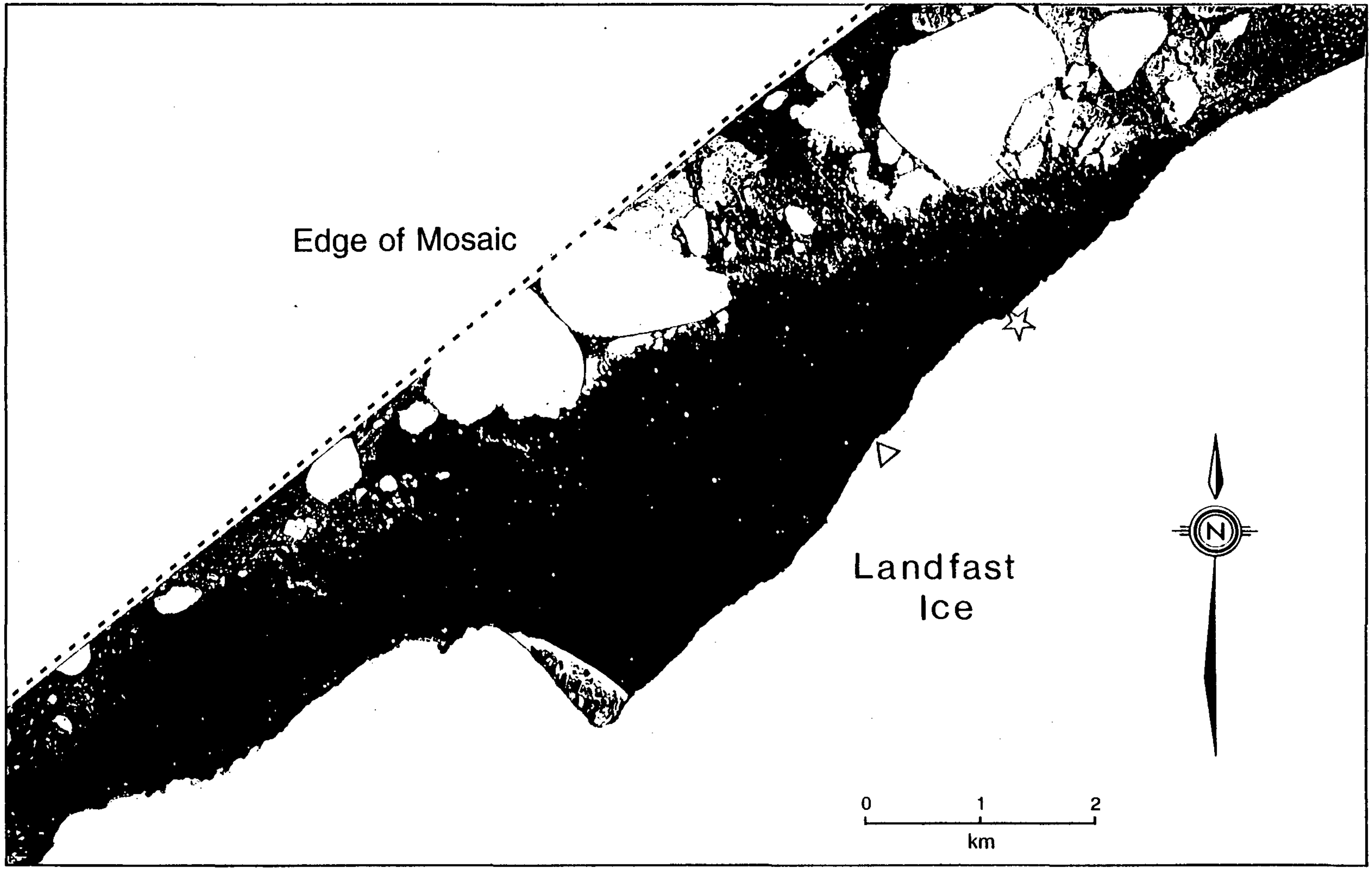

PLATE 6.1. Mosaic of the lead configuration along the landfast ice edge NE of Barrow, 9 May 1994, photographed from 2835 m ASL at 20:10. The star shows the location of the ice camp on 9 May. The triangle shows the location of the ice camp on 7 and 8 May. This series of photographs was taken shortly after completion of the aerial observation session shown in Figure F-23 (in Appendix F).

(far) side of the nearshore lead than along the landfast ice, in contrast to the situation before and during the playback.

On 9 May 1994, traveling whales at their CEPA were exposed to $RL_{BB,max}$ as high as 118 dB re 1 µPa, $RL_{1/3,max}$ as high as 111 dB re 1 µPa, $S:N_{BB,max}$ as high as 18 dB, and $S:N_{1/3,max}$ as high as 26 dB. The group sighted 940 m from the projector at 17:26 appears to have modified its path at $RL_{BB,max}$=107 dB re 1 µPa, $RL_{1/3,max}$=101 dB re 1 µPa, $S:N_{BB,max}$=7 dB, and $S:N_{1/3,max}$=16 dB.

There were no clear differences in the distribution or behavior of presumably-feeding bowheads during the control versus playback periods. Bowheads that were apparently feeding near the projector while it was silent continued to do so, sometimes within a few tens of meters of the projector, while icebreaker sounds were transmitted. The strongest levels received by feeding whales exceeded 130 dB re 1 µPa ($RL_{BB,max}$); the highest icebreaker:ambient ratio was >40 dB ($S:N_{1/3,max}$). These whales appear to have tolerated levels 15-20 dB higher than did the closest traveling whales on this date. For more information concerning these whales, see Appendix F.

<u>14 May 1994</u>

On 14 May 1994, the ice camp was set up on the landfast ice edge 70 km ENE of Pt. Barrow (Fig. 3.8, p. 77) along a 3-4 km wide nearshore lead. All observations were from the ice because low ceilings prevented behavioral observations from the aircraft. A total of 17 bowheads (13 groups) were observed during 4.3 h of pre-playback observation while the projectors were silent. Nine of these groups were seen relatively close (<500 m) to the silent projectors. The closest CEPA relative to the ice camp was ~50 m, during the pre-playback control period.

During playbacks of tones (for 1.6 h) and icebreaker sounds (for 3.2 h), five and three groups, respectively, were sighted. They were all >500 m from the projectors; the closest sighting was 509 m away during the icebreaker playback. Three other groups sighted <30 min after the playback ended were also >500 m from the projectors. Thus the distribution of whales relative to the ice edge appears to have changed during the day. The closest whale observed during the icebreaker playback was exposed to an estimated $S:N_{1/3,max}$ of 17 dB. One whale seen farther from the projectors at a time of higher source level was exposed to $S:N_{1/3,max}$=24 dB. During the pre-playback control period, many of the whales seen were socializing and perhaps feeding, but during and after playbacks only traveling whales were observed.

<u>16 May 1994</u>

The ice camp was set up about 35 km NE of Pt. Barrow (Fig. 3.8, p. 77) on the north side of a large elongated ice pan along a secondary (offshore) lead oriented ENE-WSW ~8 km north of the landfast ice edge. The ice camp was present from 09:56 to 19:00, and icebreaker sounds were projected from 13:03 to 17:13. On this date the median broadband (20-5000 Hz) source level of icebreaker sounds was ~166 dB re 1 µPa-m (relatively high) and the average broadband (20-5000 Hz) ambient noise level was 89 dB re 1 µPa (relatively low; Table 6.3).

Only ~4 bowheads (3 groups or singletons) moved by within view of the ice camp. All sightings there occurred while the projectors were broadcasting icebreaker sounds. The closest observed approach was to 570 m. The other two CEPAs were at 840 m and 775 m. These whales were exposed to strong icebreaker sounds (up to $S{:}N_{1/3,max}$=29-36 dB) but no obvious reaction was noted.

During one aerial observation session, bowheads were followed from 4.8 km SW of camp at 12:17 to 5.9 km SE of camp at 14:21. After the icebreaker playback started at 13:03, these whales diverted SE from the offshore lead through a narrow crack into the inner lead. They passed 2.0-2.3 km SSW of the operating projectors and continued east along the south side of the pan along whose north edge the ice camp was located. At CEPA, $RL_{BB,med}$ and $RL_{BB,max}$ were ~105 and 109 dB re 1 µPa, and $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were 22 and 27 dB. It is possible that the whales diverted SE to avoid closer approach to the projectors broadcasting tones and then icebreaker sounds. However, given the rapidly-changing ice configuration at the time (see Appendix F), this "diversion" may have been related to ice conditions instead of (or in combination with) the man-made noise.

A second aerial observation session was conducted 9 km SW of the operating projectors, at the SW extent of the outer lead, from 14:31 to 16:22. Five bowheads were observed socializing or traveling slowly eastward. During this session, one whale turned from a NE to a SE heading when 9.2 km from the projectors and traveled SE. At that time and distance, $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were at least 14 and 16 dB. The unusually high icebreaker:ambient ratio for a range of 9.2 km was related to the high source level and low ambient noise on this date (see Appendix F, Fig. F-34). Again, it is uncertain whether the SEward diversion was related to the icebreaker sounds, to changing ice conditions, or both (Appendix F).

17 May 1994

On 17 May 1994, 35+ bowheads were observed as they passed within 3 km of a projector set up in the pack ice at the east end of the main nearshore lead, some 70 km ENE of Pt. Barrow (Fig. 3.8, p. 77). High sea states hindered both ice-based and aerial observations, and caused high ambient noise levels. Also, the source level of the projected sounds was low, and the low-frequency components were largely missing, because only the J-11 projector was operating on this date. Throughout the day bowheads approached the projector from the WSW through a major lead. Most appeared to continue NE along a secondary lead extending NEward south of the projector. Only one bowhead was seen by the ice-based observers. It was seen 210 m north of the operating projector and would have been exposed to estimated $RL_{BB,med}$ and $RL_{BB,max}$ of 119 and 123 dB re 1 µPa before it surfaced. At this location and time, the icebreaker:ambient ratio in the strongest 1/3-octave band (near 400 Hz) was up to ~26 dB ($S{:}N_{1/3,max}$).

There were five aerial observation sessions. During the first two sessions (projector silent), whales traveled NE along a path that came as close as 600-800 m south of the projector, along the southern (distant) side of the secondary narrow lead. During the third session, when icebreaker sounds were being projected, some whales continued to follow that path. However, the secondary lead had by then widened to 1.8 km and icebreaker sounds were barely detectable, if detectable at all, at 1.8 km distance ($S:N_{1/3,max}$ ~4 dB). Two whales, a suspected mother/yearling pair, approached to 2400 m from the operating projector and then appeared to reverse course to the SW. However, it is doubtful that they could have detected icebreaker sounds at that distance, except for very briefly and weakly, because the estimated $S:N_{1/3,med}$ and $S:N_{1/3,max}$ were -4 and +2 dB.

20 May 1994

On 20 May 1994, the projectors were set up on the NW side of a large pan that blocked the nearshore lead 40 km ENE of Pt. Barrow (Fig. 3.8, p. 77). During control observations from both the circling aircraft and the ice camp, bowheads were observed as they approached the projectors from the west and WSW. They arrived at the large ice pan near and south of the projectors, turned northward, and followed the edge of the pan north and east. Six of eight groups of bowheads came within 400 m of the ice camp during the control period.

On this date the icebreaker sounds were projected at a high source level, and the ambient noise level was low. Only ice-based observations were obtained during the playback due to formation of low cloud. Bowheads continued to approach the projectors from the west and WSW. However, the patterns of movement of most of the whales when they came within several hundred meters of the ice camp were different during the playback than during the preceding control period. During the playback, they seemed to divert both to the north and south of the projectors. Only one whale approached the projectors closely during playback (1 of 11 groups were seen within 400 m); it turned sharply away from the projectors when 58 m from them. (A whale that surfaced at the same location during the control period dove toward the ice camp.) The whale that approached closely during the playback voluntarily approached even though $S:N_{1/3,max}$ was near 60 dB. At the observed CPAs of other whales that came within 500-1000 m, $S:N_{1/3,max}$ values were ~40-50 dB. The proportion of whales that diverted, and the actual distances when diversions began, are unknown because of the limited viewing area from the ice and because low cloud prevented aerial observations during this playback.

6.2 Distribution and Movements During Icebreaker Playbacks

The first of the main null hypotheses to be tested, as described in §1.2 (p. 7-9), is that

> Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

This section concerns reactions to icebreaker noise, based on the data given in Appendix F and summarized in §6.1. Distributional effects of the 1989-90 playbacks of noise from drilling on an ice pad (*Karluk*) are described in Richardson et al. (1990a:196*ff*, 1991a:148*ff* + 218*ff*).

Closest Estimated Points of Approach

The best method of determining whether whales were altering their paths to reduce their exposure to icebreaker sounds would have been to compare the tracks of individual whales moving

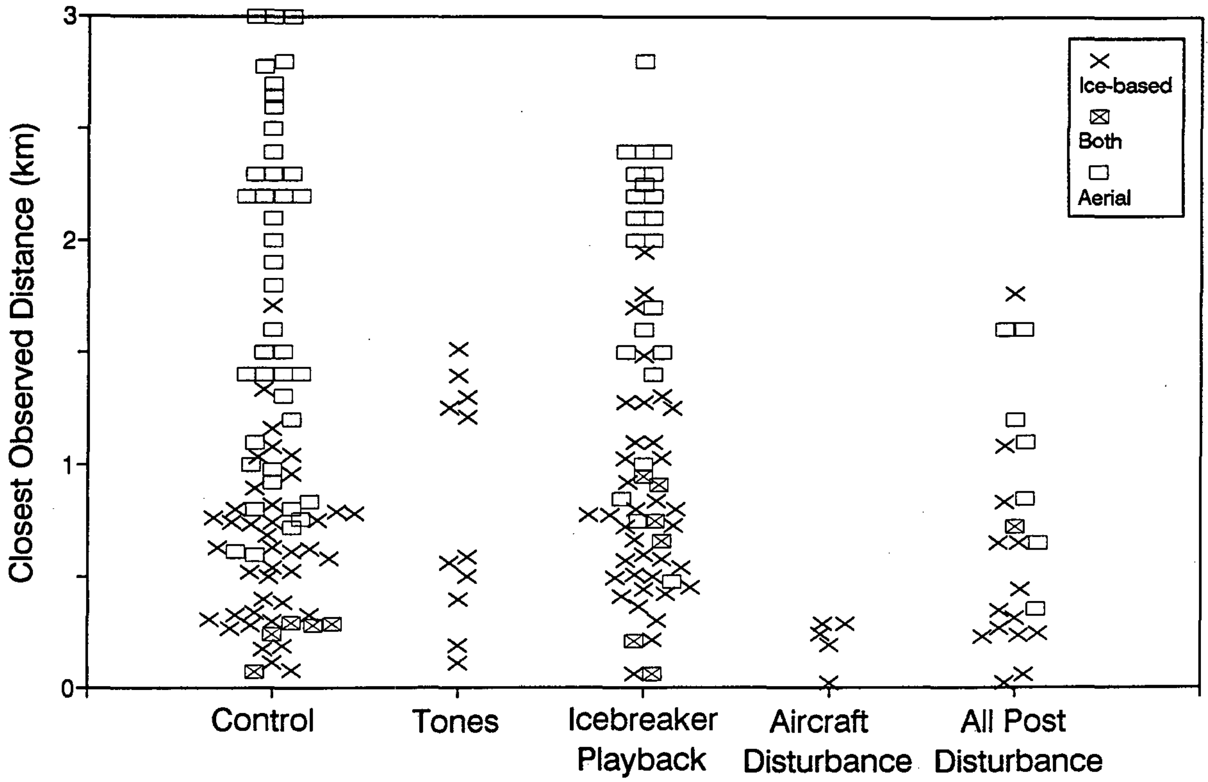

FIGURE 6.4. Closest estimated points of approach (CEPAs) of traveling bowheads sighted within 3 km of the ice camps during all days with playbacks of icebreaker sounds, 1991 and 1994. The different symbol types indicate whether the observation was made by ice-based observers, aerial observers, or both. Days included in the graphs are 17 May 1991 and 7, 9, 14, 16, 17, and 20 May 1994. CEPA is the closest observed point to the projector for a whale seen only approaching or receding from the projector; CEPA is the closest interpolated position to the projector for a whale followed as it approached, passed and receded from the projector. See Appendix F for maps of whale tracks and tables including corresponding estimates of CEPAs; this Figure summarizes the CEPAs given in those Appendix Tables.

past the ice camp during periods of silence ("control" periods) with the tracks of whales moving past the same location during periods with playbacks of icebreaker sounds at known source levels ("experimental" periods). Any consistent changes in distribution or in tracks (i.e., diversions) that were observed during experimental periods but not control periods could then have been attributed to avoidance of the sound source. Because of unfavorable environmental conditions, we were seldom able to follow whales as they approached and passed the projectors in 1991/94 as we had done in 1990 (*cf.* Richardson et al. 1991a). On most days in 1991 and 1994, weather conditions either prevented observations from the Twin Otter circling at 460 m ASL, or made resighting of whales difficult from both the Twin Otter and ice camp because of high sea states.

In the absence of many data on tracks of whales, we examined the distribution of sightings (i.e., closest estimated point of approach to the source, or CEPA) during control and experimental periods in order to assess changes in distribution (Fig. 6.4). However, comparisons based solely on sighting distribution, as opposed to tracks, require substantially larger numbers of sightings to on sighting distribution, as opposed to tracks, require substantially larger numbers of sightings to demonstrate a change. This is especially so in the present case, where many CEPA distances were overestimates, by unknown amounts, of actual CPA distances (see caption of Fig. 6.4 and examples on p. 254). Figure 6.4 shows the CEPAs of traveling whales sighted during 1991 and 1994 during periods of control observation and during different types of disturbance. Only days when icebreaker sounds were projected in the presence of bowheads are included in the control data, and only bowheads that approached within 3 km of the ice camp are plotted. As evident from this figure, ice-based observers saw few bowheads >1.4 km from the ice camp. Thus, sightings from the ice-based observers can only be used to monitor small-scale changes in distribution. Based on Figure 6.4, ***it appears that there was a reduction in sightings of traveling bowheads within 400 m of the projectors when they were transmitting icebreaker sounds as compared with control conditions***. It cannot be determined from these data if there was a reduction in sightings beyond this distance.

The effects of the playbacks of icebreaker noise on the distribution of traveling bowheads would be better analyzed by comparing the CEPA data from the control and playback periods of each individual experiment (day) than from the combined data in Figure 6.4. Some of the complications associated with differing ice conditions on different days might then be separated from distributional changes caused by icebreaker playbacks. In addition, because the source levels of icebreaker sounds varied among (and within) days, the effects may have been different on different days. However, sample sizes were not adequate for meaningful within-day comparisons on most days (Fig. 6.5). The two days with sufficient numbers of bowheads were 7 and 9 May 1994 (Fig. 6.5). On 7 May, there appears to have been a reduction in sightings within 400 m of the ice camp during the playback period in comparison to the control period. On 9 May, the difference in distribution between the control and playback periods is not as clear. However, sightings within 500 m of the ice camp were less frequent during the playback period. The 9 May experiment was complicated by the presence of feeding whales near the ice camp before and during the playback; this is discussed below (see "Effects on Feeding Whales", p. 277). Although feeding whales are excluded from Figures 6.4 through 6.11, the paths of the closest traveling whales seen on 9 May could have been influenced by feeding whales, and may include data from whales that were feeding earlier in the day.

Sound Exposure Levels

The variability of icebreaker sounds, and the problems associated with reproducing icebreaker sounds, complicated interpretation of the effects of this playback stimulus on bowhead distribution, movements, and behavior. The reactions by bowheads to icebreaker sounds are likely to be related, in part, to the sound levels that are received by the whales. There has been considerable discussion about the appropriate sound level measurements that best reflect the animals' ability to detect, and propensity to react to, acoustic disturbances (Richardson et al. 1990b, in press:336-8). Of the eight estimates of received level (RL) and icebreaker-to-ambient ratio (S:N) mentioned earlier (§6.1, p. 251), some of the most consistent relationships between bowhead behavior and estimated RL or S:N were found when we considered the maximum RL or S:N in the 1/3-octave band of strongest icebreaker sound during the 64-s period preceding the whale observation ($RL_{1/3,max}$ or $S{:}N_{1/3,max}$; §6.3).

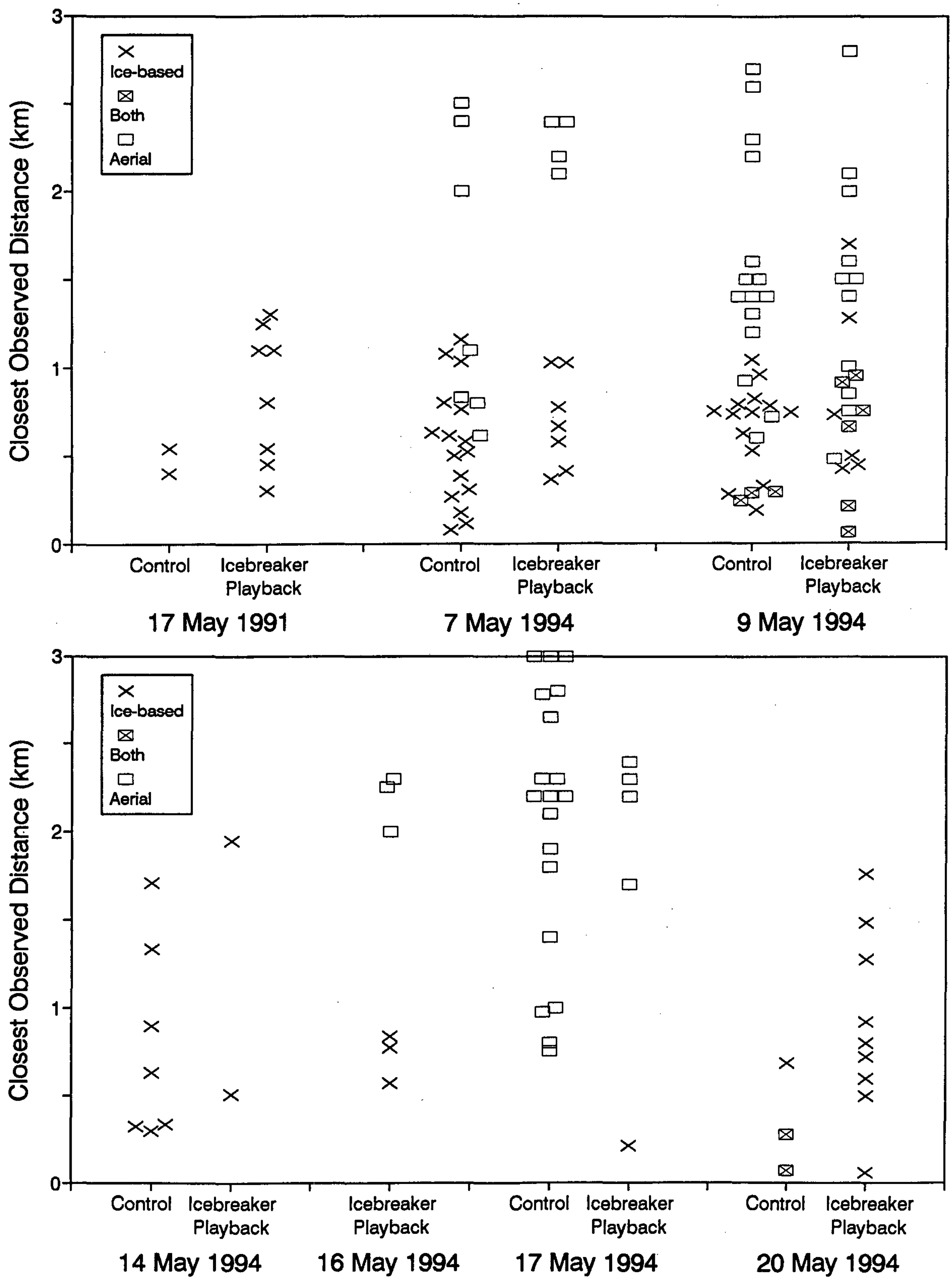

FIGURE 6.5. Closest estimated points of approach (CEPAs) of traveling bowheads sighted within 3 km of the ice camps during control and playback periods on each individual day with playbacks of icebreaker sounds, 1991 and 1994. See Figure 6.1 for explanatory notes.

Whatever acoustic measure is used, whale distribution and behavior need to be related to the sound exposure level, not distance. Icebreaker sounds, unlike many other sounds that have been projected to marine mammals, are highly variable in source level. Bowheads 500 m from the projectors at one time may be subjected to higher sound levels than the same (or different) whales would receive when 250 m from the projectors at another time. ***Distance is not a good criterion for assessing reaction thresholds when sounds are variable.***

The problem of assessing distribution relative to the levels of sounds received by the whales has been exacerbated by problems encountered while attempting to project icebreaker sounds into the lead. The average source level differed from day to day and at different times within some playback days (Table 6.3; see also Fig. 4.27-4.34 on p. 119*ff*). These variations in average source level added to the natural moment-to-moment variability of the recorded icebreaker sounds, and caused even greater variability in the received levels of sound at any given distance. Day-to-day variations in source level further confounded attempts to compare bowhead distribution during control and playback periods, and further emphasized the need to relate distribution (and behavior) during icebreaker playbacks to sound exposure level rather than distance.

Figure 6.6 shows the estimated median and maximum broadband levels of icebreaker sounds received near whales when they were at or near their CEPA to the projectors. This figure includes only whales seen within 3 km of the projectors. Figure 6.6 also shows the average ambient noise levels measured on each playback date. Ambient noise was usually measured just before and just after each playback.

- On a broadband basis, most whales observed within 3 km of the operating projectors were exposed to icebreaker sound at levels of 85 to 120 dB re 1 µPa ($RL_{BB,med}$ and $RL_{BB,max}$).
- For most whales, received levels at CEPA locations ranged from 10 dB below to 30 dB above the broadband ambient noise level. For several whales observed within 3 km of the operating projectors on 17 May 1991 and 7, 9 and 17 May 1994, the broadband icebreaker sounds ($RL_{BB,med}$ and $RL_{BB,max}$) were weaker than the average ambient levels. Even so, because of variation in ambient levels and in sound propagation, some of these whales probably were, at times, exposed to icebreaker sounds slightly exceeding broadband ambient levels.
- On 20 May 1994, all whales seen within 3 km of the projectors were estimated to have been exposed to high broadband levels of icebreaker sound, even in the cases of whales seen 1-2 km away (Fig. 6.5 vs. 6.6). The source level was high and the ambient noise level was low on 20 May 1994 (see Appendix F). For one whale observed approaching and passing 58 m from the projectors, $RL_{BB,med}$ and $RL_{BB,max}$ well below the surface were at least 132 and 138 db re 1 µPa. These were the highest estimated RL values for any traveling bowhead observed during icebreaker playbacks. (For this whale, and a traveling whale 60 m from the projector at 16:31 on 9 May, the sound exposure model may have underestimated RL and S:N at times when the whales were well below the surface.)

Levels of icebreaker sound in certain 1/3-octave bands may exceed the ambient noise level in those respective bands even when the overall broadband level of icebreaker sound is at or below the overall broadband level of ambient noise. This can be seen by comparing Figures 6.6 and 6.7.

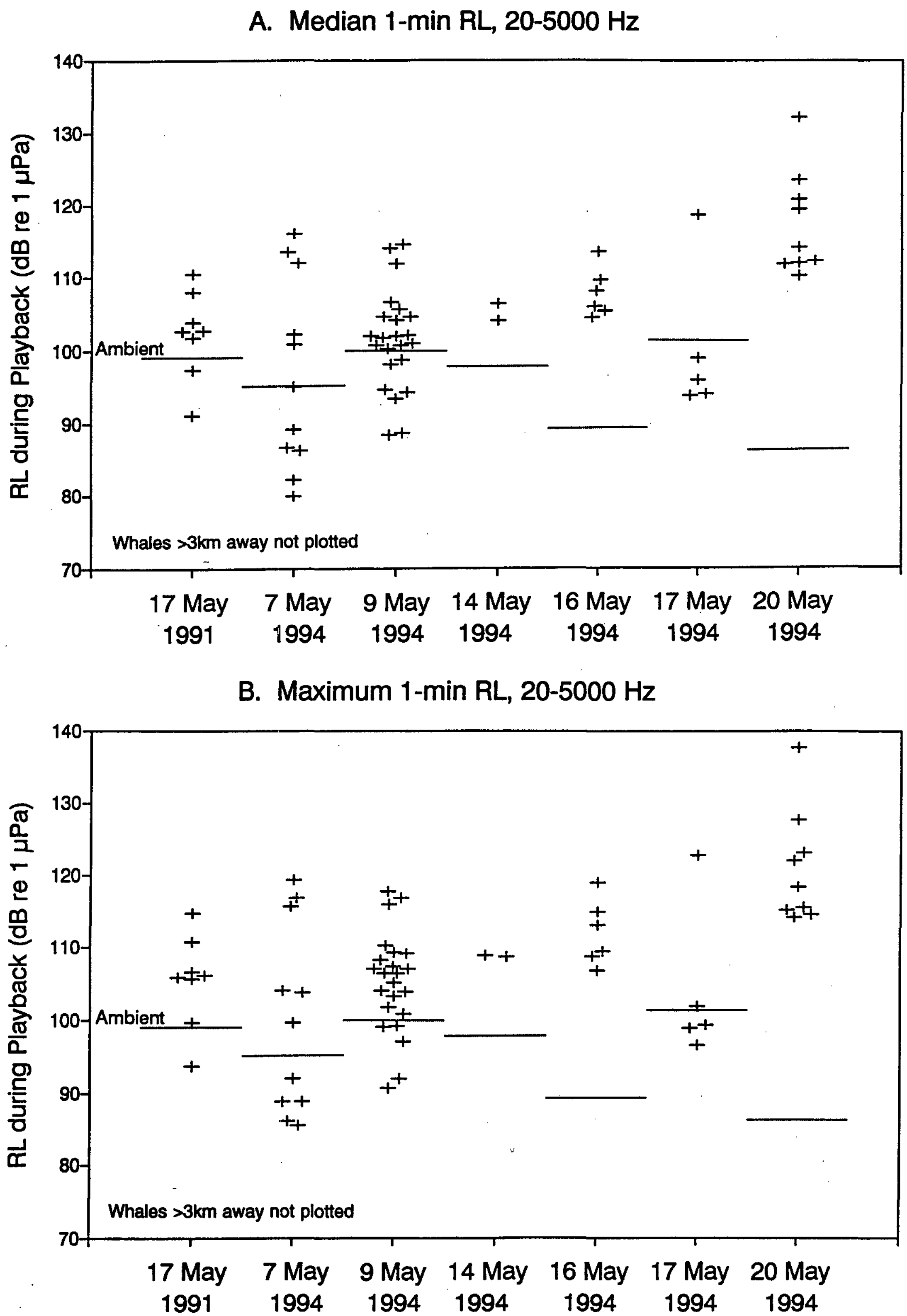

FIGURE 6.6. Estimated broadband received levels of icebreaker sounds near traveling bowheads at their CEPA distances during playback experiments, 1991 and 1994. $RL_{BB,med}$ and $RL_{BB,max}$ were estimated by the sound exposure model described in section 2.3. The distances used to estimate the RLs are shown in Figures 6.1 and 6.2. Because many CEPA distances are overestimated, many RL values are underestimated.

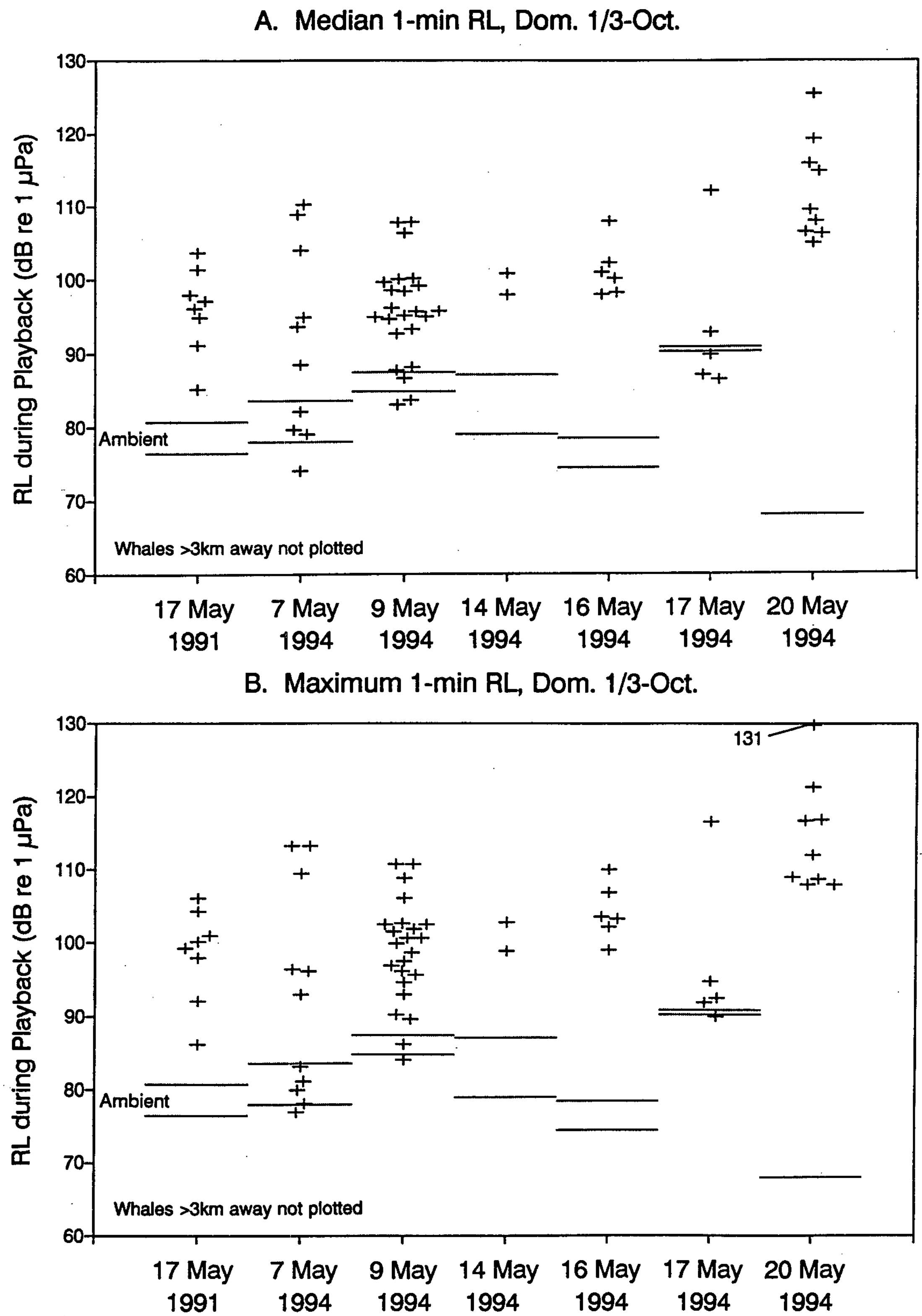

FIGURE 6.7. Estimated received levels of icebreaker sounds in the dominant 1/3 octave near traveling bowheads at their CEPA distances during playback experiments, 1991 and 1994. $RL_{1/3,med}$ and $RL_{1/3,max}$ were estimated by the sound exposure model described in section 2.3. The distances used to estimate the RLs are shown in Figures 6.1 and 6.2. Because many CEPA distances are overestimated, many RL values are underestimated.

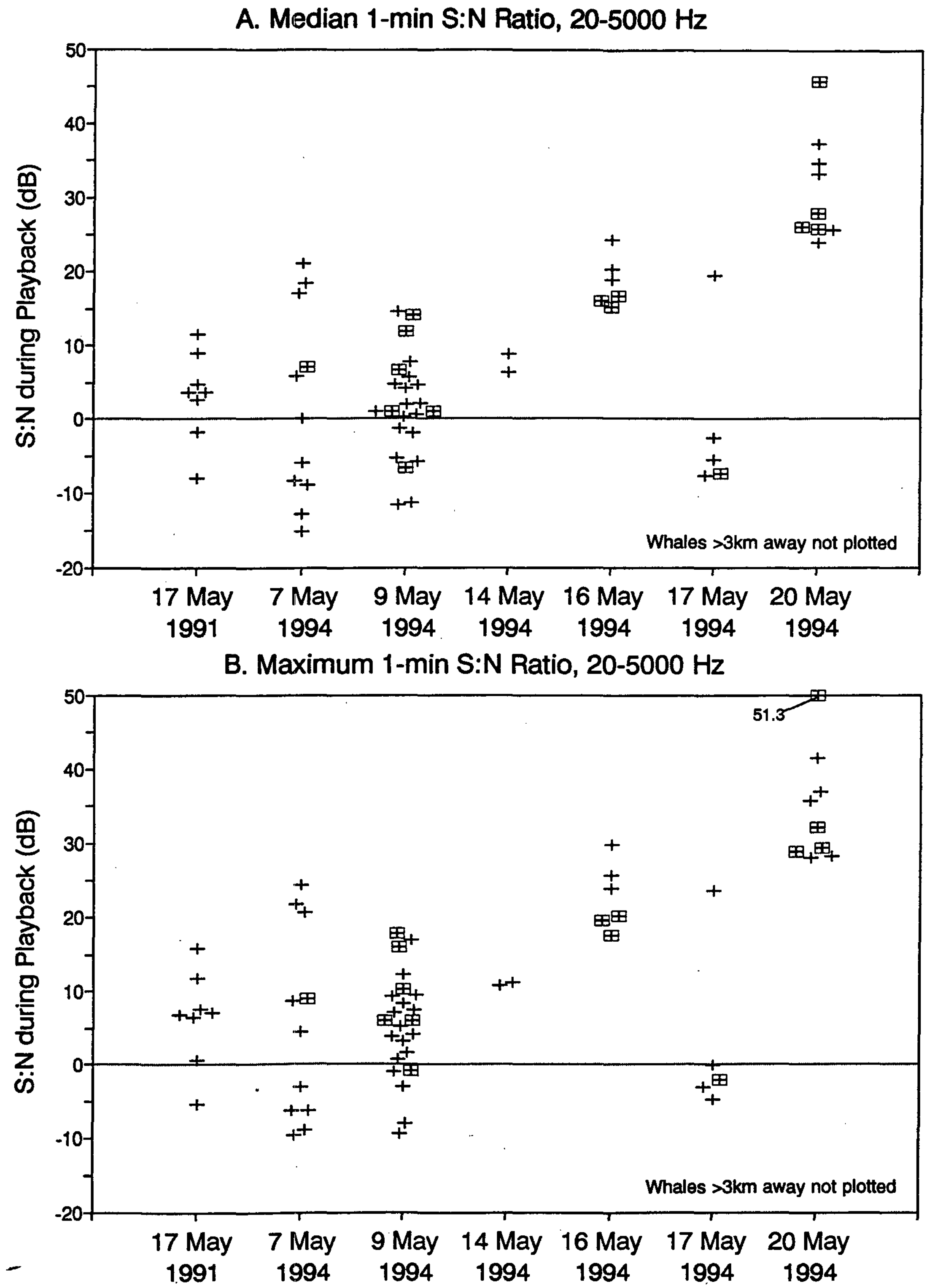

FIGURE 6.8. Estimated broadband icebreaker-to-ambient ratios ($S{:}N_{BB,med}$ and $S{:}N_{BB,max}$) near traveling bowheads at their CEPA distances during playbacks, 1991 and 1994. Ambient noise levels, measured for periods before and/or after icebreaker sounds were projected, were subtracted from estimated received levels shown in Figure 6.6 to get S:N. Squares show cases where tracks may have been diverted by icebreaker noise. Qualifications as in Fig. 6.6.

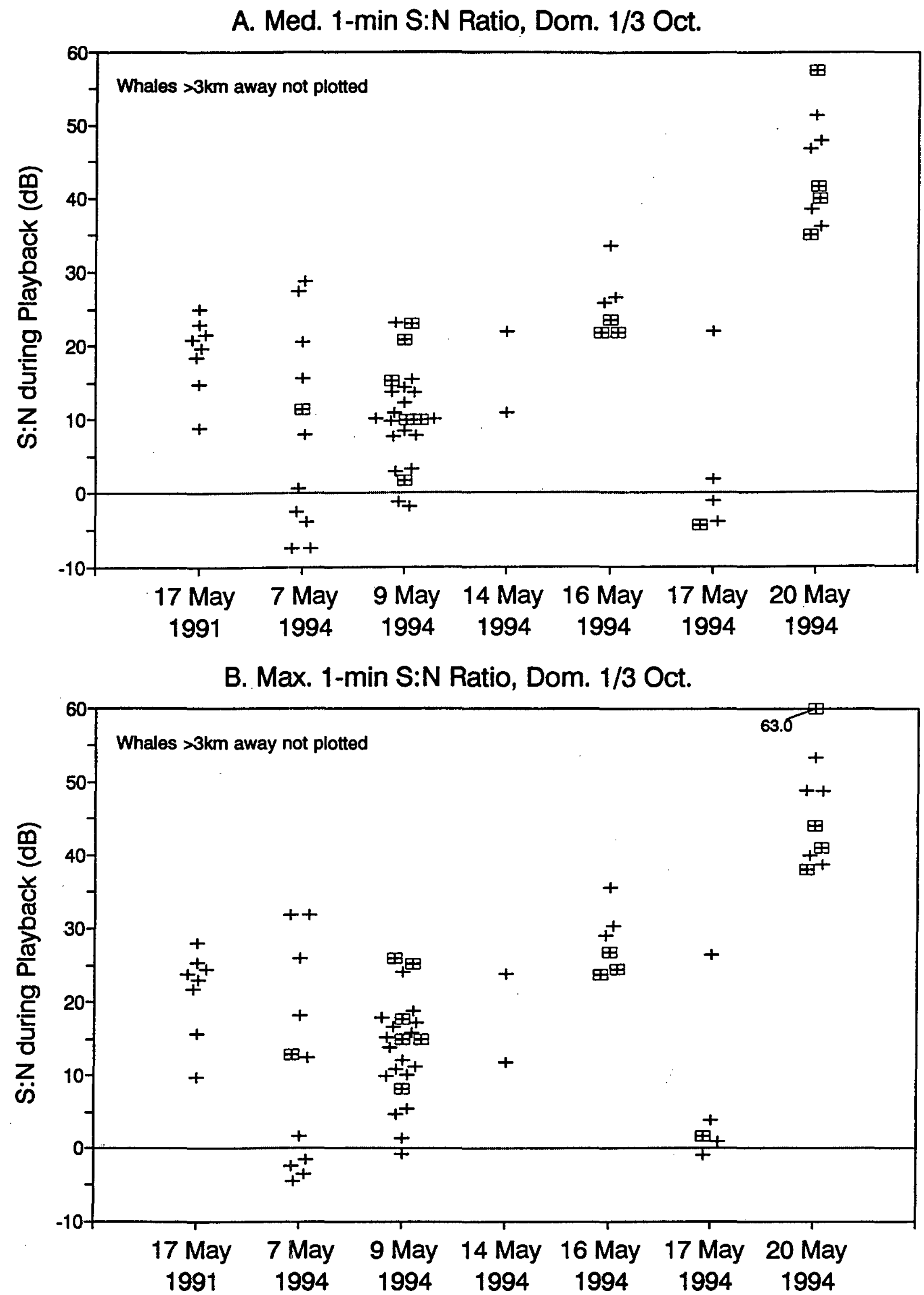

FIGURE 6.9. Estimated icebreaker-to-ambient ratios in the dominant 1/3 octave ($S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$) near traveling bowheads at their estimated CEPA distances during playbacks, 1991 and 1994. Ambient noise levels, measured for periods before and/or after icebreaker sounds were projected, were subtracted from estimated received levels shown in Figure 6.8 to get S:N. Squares show cases where tracks may have been diverted by icebreaker noise. Qualifications as in Fig. 6.8.

The icebreaker-to-ambient ratio in the 1/3-octave band of strongest icebreaker sound ("dominant 1/3-octave") is usually higher than the broadband icebreaker-to-ambient level (Fig. 6.8 vs. 6.9). Levels in 1/3-octave bands are relevant because the typical effective filter bandwidth of mammalian hearing systems is roughly 1/3-octave (Richardson et al. in press:226*ff*). This means that it is the background noise within a bandwidth of ~1/3-octave that determines the animal's ability to hear a sound, and determines its signal-to-ambient ratio.

Some bowheads were exposed to icebreaker sounds whose $RL_{1/3}$ in the "dominant" 1/3-octave band exceeded the ambient noise level in that band even though the RL_{BB} did not exceed broadband ambient levels (Fig. 6.7 vs. 6.6). If the natural variability in ambient noise is considered, almost all (if not all) bowheads that passed within 3 km of the operating projectors were exposed, at least intermittently, to icebreaker sounds exceeding the ambient noise level in one or more 1/3-octave bands. Also, many CEPAs are overestimated, so many RLs are underestimated. At least some whales whose estimated $RL_{1/3}$ values were below ambient may have approached closer to the projectors than CEPA and, therefore, may have been exposed to received levels that exceeded ambient levels.

Figure 6.10 shows that traveling bowheads were exposed to a wide range of received levels of icebreaker sounds at their CEPA distances from the operating projectors regardless of the type of sound measurement used. Figure 6.11 shows the frequency distribution of icebreaker-to-ambient ratios for the same whales at the same times and locations. Different measures of S:N lead to different conclusions about noise exposure. The $S{:}N_{BB,med}$ measure in Figure 6.11A suggests that over half of the bowheads were exposed to sounds that were either below ambient or exceeded ambient levels by <10 dB. In comparison, the $S{:}N_{1/3,max}$ measure shown in Figure 6.11D indicates that almost all whales observed within 3 km of the operating projectors were exposed to icebreaker sound whose level in the strongest 1/3-octave exceeded the ambient level in that band, at least briefly ($S{:}N_{1/3,max}$>0 dB). If allowance is made for the natural variability in ambient noise, probably all whales seen <3 km from the operating projectors were exposed to S:N>0 dB for at least brief periods. Almost half (29 of 63) of the whales observed within 3 km of the projectors were exposed to moderately strong ($S{:}N_{1/3,max}$>20 dB) icebreaker sounds, at least briefly, when they were near their CEPAs.

Most of these bowheads swam into the ensonified area around the projectors while the projectors were operating; bowheads were rarely under observation within 3 km of the ice camp when playbacks began. Therefore, it appears that many bowheads exhibited some tolerance of variable icebreaker sounds. Nonetheless, some diversion and avoidance were observed, so this tolerance of icebreaker sounds is limited.

It would be interesting to compare the RL and S:N data for various subsets of the bowheads observed during playbacks, including

- bowheads whose true CPA distances were determined, as opposed to those for which the closest observed distance was probably an overestimate of CPA;
- bowheads for which the received icebreaker sounds at the CEPA time were higher vs. lower than they had been in preceding minutes;

- bowheads observed by aerial vs. ice-based observers (or both); and
- bowheads that did vs. did not show evidence of diversion or avoidance.

Unfortunately, the sample sizes were too small to justify a multi-way subdivision of the data by all of these criteria, or to allow a meaningful multivariate analysis. However, the following subsections do discuss cases of apparent diversion and avoidance. Figures 6.8-6.11 distinguish the bowheads with possible diversion (⊞ symbols in Fig. 6.8-6.9; shaded bars in Fig. 6.10-6.11) vs. other bowheads (+ symbols or open bars).

Apparent Avoidance Reactions

Some bowheads were observed within a few hundred meters of the operating projectors, with no obvious diversion or avoidance. Other bowheads seemed to alter course at similar or greater distances in order to avoid close approach to the projectors. These observations provide some information about situations where reactions were and were not evident.

From the available data we cannot quantify the proportion of bowheads exhibiting overt diversion or avoidance when they approached within various distances, or within various RL or S:N contours. Unfavorable weather conditions during most playback days in 1991/94 prevented us from documenting tracks of most whales as they approached and passed the projectors. As a result, cases of diversion were difficult to identify, and the frequency of diversion was probably greater than recognized. Another limitation of not obtaining continuous tracks of whales is that CPA distances for many whales both during control and experimental periods were overestimated. Without knowing the track of a whale, we can only determine the closest observed point of approach, which will often exceed the actual CPA. Where complete tracks are obtained, CPA distances can be estimated by inferring paths taken by whales while they are below the surface.

Figures 6.4 and 6.5 suggest that some migrating whales changed their paths to remain more than ~400 m from the operating projectors. However, distance is not a very useful measure, given the variability in sounds received by whales at any given distance. In addition, the variability in received levels may obscure displacements at longer distances. There may have been changes in the paths of some whales passing at distances >400 m—changes that are not evident amongst the tracks of other whales seen at those distances during quieter periods.

Additional information on distances at which avoidance reactions occurred comes from the behavior of whales seen close to the operating projector. Table 6.5 summarizes observations of whales that appeared to have modified their behavior or tracks in the presence of icebreaker sounds. It is not certain that all of these modified behaviors or tracks resulted from exposure to icebreaker sounds; however, they represent behaviors and track characteristics that were not often exhibited by migrating whales in the absence of exposure to icebreaker noise playbacks.

Avoidance Within 400 m.—Not surprisingly, some of the whales seen within 400 m of the operating projectors showed apparent diversion (Table 6.5). At least one whale "voluntarily" approached the projectors when $S{:}N_{1/3,max}$ was near 60 dB before apparently reacting by turning sharply away (see 20 May 1994 section of Table 6.5 and Appendix F).

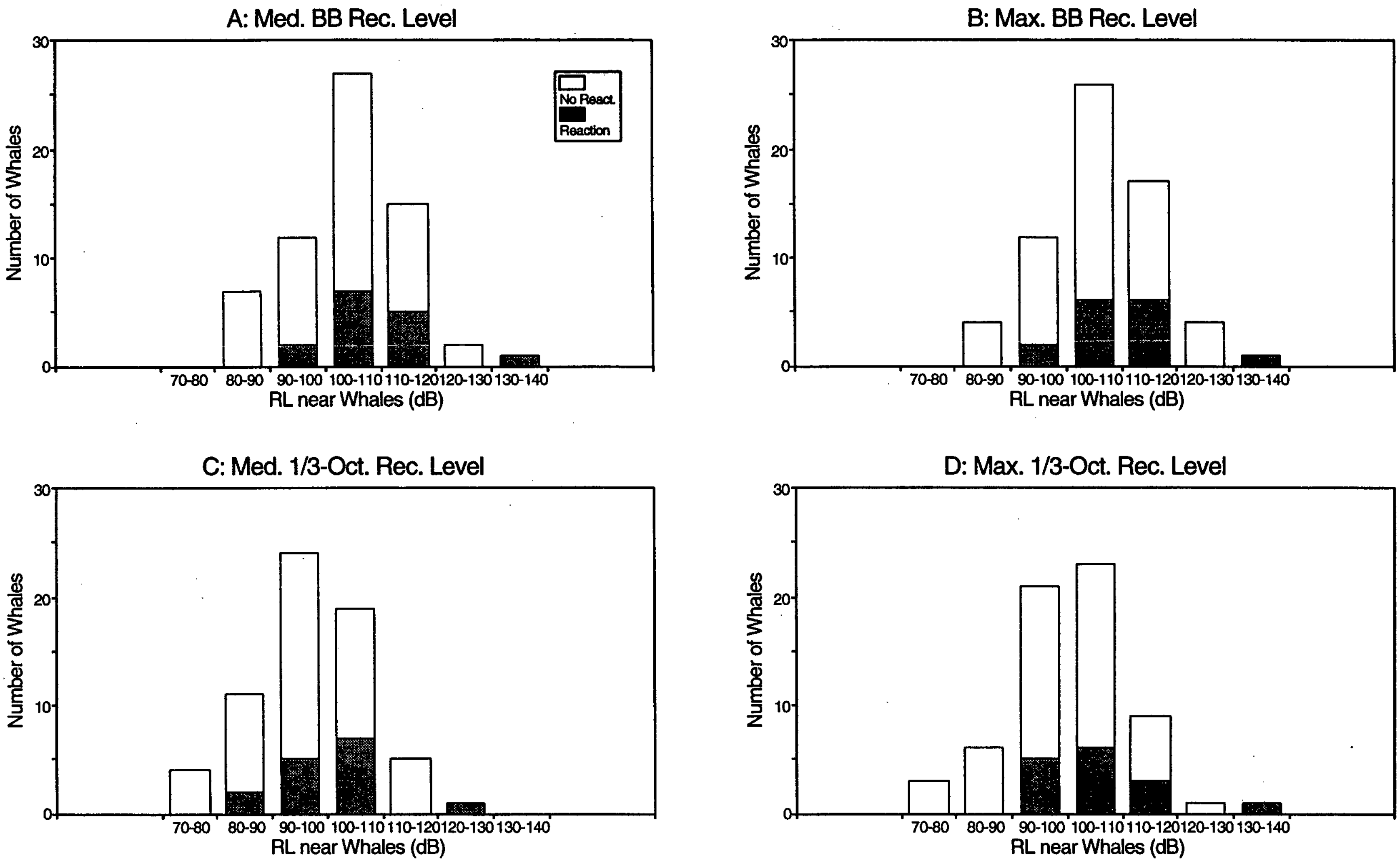

FIGURE 6.10. Frequency distributions of estimated received levels of icebreaker sounds near traveling bowhead whales at their CEPA distances from the operating projectors, 1991 and 1994. *(A)* $RL_{BB,med}$, *(B)* $RL_{BB,max}$, *(C)* $RL_{1/3,med}$, and *(D)* $RL_{1/3,max}$. Only whales sighted within 3 km of the ice camp are plotted. Many CEPA distances are overestimated; therefore, many received levels are underestimated. Bowheads that were and were not observed to modify their tracks near the ice camp are distinguished (shaded vs. open parts of bars); see text for cautionary notes.

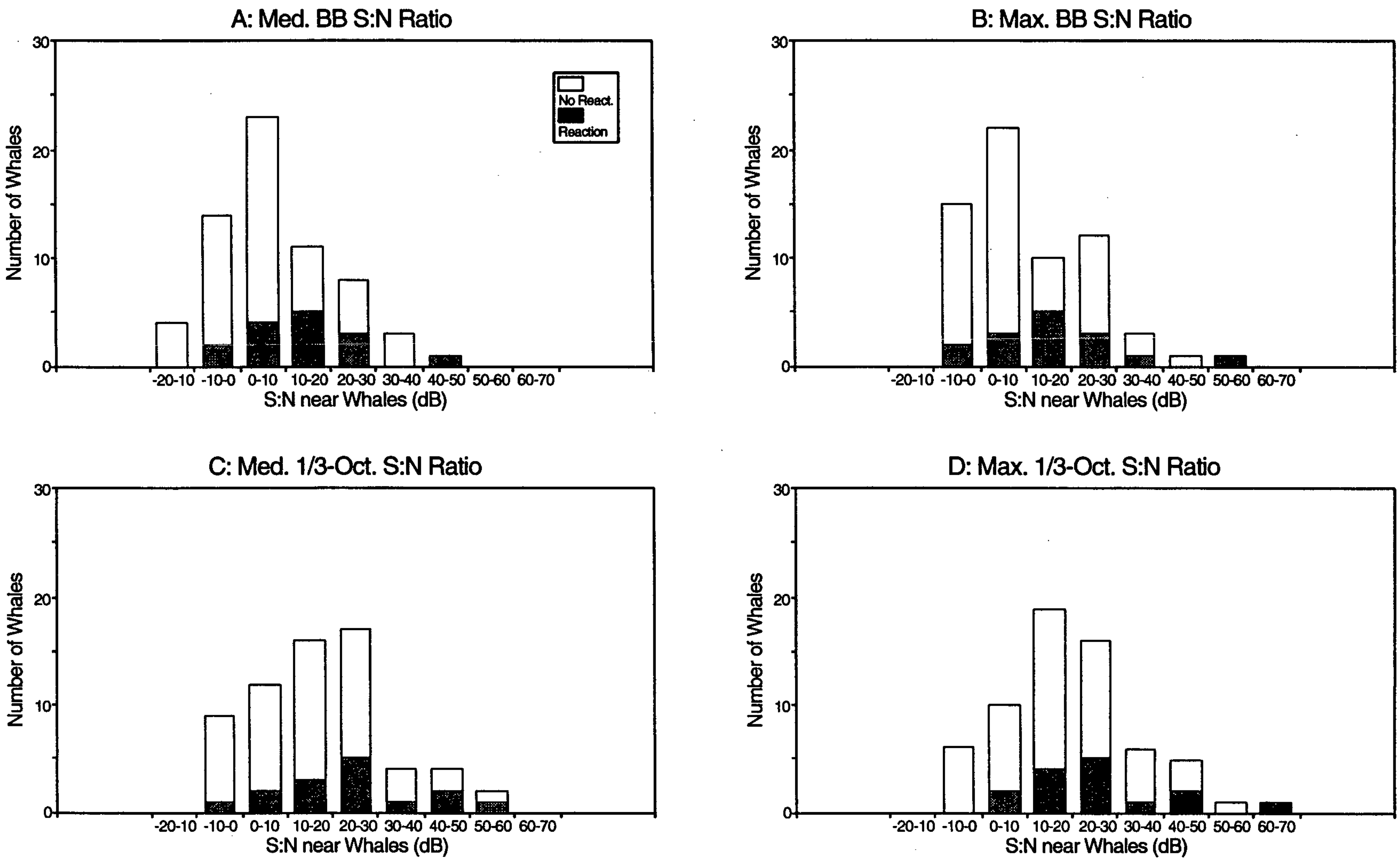

FIGURE 6.11. Frequency distributions of icebreaker-to-ambient ratios near traveling bowhead whales at their CEPA distances from the operating projectors, 1991 and 1994. *(A)* $S{:}N_{BB,med}$, *(B)* $S{:}N_{BB,max}$, *(C)* $S{:}N_{1/3,med}$, and *(D)* $S{:}N_{1/3,max}$. Otherwise as in Fig. 6.10.

TABLE 6.5. Summary of sightings of traveling bowhead whales that appeared to modify their tracks near the operating projectors during 1994.

	Distance (m)		Noise[a]		
Date	Reaction	Observed	RL	S:N	Nature of Track
7 May	362	362 to 706	96	13	W of projectors swimming N. Large wake and long blow intervals. Turned ENE when 700 m away.
7 May	3000?	3000 to 3300	78[b]	-4[b]	Several groups seen heading north along lead west of ice camp. Earlier whales were not seen traveling north.
9 May	206	206 to 260	111	26	NW of projector turned to N from NE and headed N
9 May	430	430 to 420	111	25	W of projector heading N, turned to NE.
9 May	940	940 to 500	101	16	W of projector heading N, turned E, turned S, then **projector turned off**; turned ENE and approached camp to 500 m, then dove.
9 May	<660	660 to 1400	>101	>16	NNE of projector heading NE toward N side of lead, turned to E when arrived at ice edge and dove under small pan.
9 May	500	1600 to 500	103	18	Dove NNE under brash ice when open water available to ENE.
9 May	<2000	2000	>93	>8	NW of and heading NW away from projector, turned N and dove toward brash and pans on N side of lead.
16 May	~2500	-3150 to +5900	102	27	3 groups heading ENE toward projectors turned SSE through narrow crack between 2 large pans and passed S of projectors 2 km.
16 May	9200	9900 to 9200 then turned SE to 9400 then E to 8200	91	16	Turned from NE heading to SE and resurfaced SE of that location, then traveled E.
17 May	~2200	5900 to 2400	93 (97)[b]	1 (6)[b]	Adult and yearling appear to have reversed course, but were not seen again. Last seen traveling south.
20 May	58	115 to 58	131[c]	63[c]	Turned sharply to NNW away from projectors.
20 May	>600	600 to 1225	<108	<38	NNW of projectors traveled NE; earlier whales traveled E.
20 May	>725	725	<112	<44	SW of projectors traveled SE; earlier whales traveled E.
20 May	<1275	1275	>109	>41	NNW of projectors traveled NE; earlier whales traveled E.
20 May	<3250	3250 to 3750	>100	>30	Same as above.

[a] Sound levels are maximum levels in the dominant 1/3-octave band during the previous 1-min period ($RL_{1/3,max}$ and $S{:}N_{1/3,max}$).

[b] These are the highest levels during the previous 14 minutes for the same distance.

[c] These levels may be slight underestimates of levels that would be received below the surface.

Avoidance at 400-1500 m.—There is evidence that several whales altered their tracks when 400-1500 m from the operating projectors.

- On 9 May 1994, a combination of observations by the aerial and ice-based observers documented a bowhead modifying its track when it was 940 m from the operating projector. The whale followed an irregular course while the projector was operating, but when icebreaker sounds stopped the whale turned and swam toward the silent projector (Table 6.5; Fig. F-18, F-19 in Appendix F). It then dove toward the projector, surfaced 500 m from it, and finally dove toward the silent projector. It was not resighted.
- On 20 May 1994, several whales apparently changed course when >600 m from the projector. Aerial observations could not be conducted at that time because of low cloud, so the diversions could not be confirmed nor could their initial distances be determined.

The following tabulation summarizes the eight sound measures in the seven cases when bowheads were observed to alter course 400-1500 m from the projectors:

		Sound Measure (dB)							
Date	Distance	$RL_{BB,med}$	$RL_{BB,max}$	$RL_{1/3,med}$	$RL_{1/3,max}$	$S:N_{BB,med}$	$S:N_{BB,max}$	$S:N_{1/3,med}$	$S:N_{1/3,max}$
9 May	430 m	112	116	106	111	12	16	21	25
9 May	940 m	105	107	99	101	5	7	14	16
9 May	<660 m	>102	>107	>96	>101	>2	>7	>11	>16
9 May	500 m	107	110	100	103	7	10	15	18
20 May	>600 m	<112	<116	<105	<108	<26	<29	<35	<38
20 May	>725 m	<114	<118	<110	<112	<28	<32	<42	<44
20 May	<1275 m	>112	>115	>108	>109	>26	>29	>40	>41

Avoidance at >1500 m.—Avoidance at distances more than ~1½ km from the operating projectors usually was evident only from aerial observations. The ice-based observers usually cannot see bowheads more than ~1½ km from the ice camp. When sea states are high, they cannot reliably detect whales beyond 1 km, or possibly closer on windy days such as 17 May 1994. Without aerial observations, it is impossible to determine whether some bowheads that are more than 1½ km away change course to divert around the projector site. Because low ceilings prevented the Twin Otter crew from watching whales near the ice camp on all or parts of several days in 1991 and 1994, and because we were rarely able to follow individual whales for prolonged periods, our ability to identify larger scale avoidance was limited in 1991/94.

On ***16 May 1994,*** we followed three small groups of whales that changed course as they approached within ~2.5 km of the projectors, appearing to divert around them. However, the local and rapidly changing pattern of ice pans could have accounted for the paths taken, as described in Appendix F. On the same date we observed a whale that was heading toward the projectors change its path from a NE heading to a SE heading when it was 9.2 km from the projectors. This whale then traveled E and passed 8.2 km south of the projectors. Again, the distribution of ice could have caused the change in path (Appendix F). Sound levels reaching these whales are summarized in the text table below. Because the source level was strong and ambient noise was weak on 16 May 1994, the RL and S:N values of icebreaker sounds at these distant locations were similar to those where small-scale avoidance reactions were seen on other days.

There was evidence of diversion at ranges >1½ km on other days as well. On ***20 May 1994,*** observers at the ice camp recorded a bowhead traveling NE when it was 3250 m NNE of the projectors. Based on its heading the whale may have diverted when >2 km from the projectors. On ***9 May 1994***, the aerial observers sighted a bowhead ~2 km NW of the projector heading NW, away from the projector. This whale turned and dove northward into the brash ice along the north side of the lead. This whale may have approached closer to the operating projector than 2 km, but it appears to have moved at least 2 km from the operating projector before returning to a normal NNE heading. On ***7 May 1994***, some whales may have diverted offshore into a narrow N↔S lead that was ~3 km west of the projector. If these whales did divert, we do not know how close they approached the projectors before they diverted. Estimated sound levels near these whales when they were sighted are presented in the table below, but the levels that were received near the whales when they diverted cannot be estimated because the distance where the diversion was initiated is unknown.

		Sound Measure (dB)							
Date	Distance	$RL_{BB,med}$	$RL_{BB,max}$	$RL_{1/3,med}$	$RL_{1/3,max}$	$S:N_{BB,med}$	$S:N_{BB,max}$	$S:N_{1/3,med}$	$S:N_{1/3,max}$
7 May	<3000 m	>81	>86	>74	>78	>-14	>-9	>-8	>-4
9 May	<2000 m	>93	>99	>86	>93	>-6	>-1	>2	>8
16 May	2500 m	105	108	100	102	16	19	25	27
16 May	9200 m	93	99	89	91	3	9	14	16
17 May	~2200 m	94	99	86	92	-7	-2	-5	1
20 May	<3250 m	>102	>107	>97	>100	>16	>21	>27	>30

In summary, there were two occasions, both on 16 May 1994, when we reliably determined the distances where bowheads showed apparent diversion >1½ km from the projectors. The values of $S:N_{1/3,max}$ for these cases were 16 and 27 dB. The occurrence of a course change under these conditions was confirmed, but whether these course changes were caused by icebreaker noise or changing ice configuration is uncertain. In another case, a whale that had probably passed its CPA was exposed to $S:N_{1/3,max}$=30 dB at the time it was seen.

These values of $S:N_{1/3,max}$ associated with possible avoidance >1½ km from the projectors are consistent with S:N values where some whales closer to the projectors at other times apparently showed avoidance reactions to icebreaker sounds. However, the proportion of whales >1½ km from the projectors that showed avoidance reactions when subjected to these levels of icebreaker noise is unknown, as few bowheads could be followed for long enough in 1991/94 to document such diversion. Many other whales did not appear to avoid the projectors when exposed to similar or higher levels of sound.

Avoidance During Playback and Control Conditions.—Table 6.5 summarizes $RL_{1/3,max}$ and $S:N_{1/3,max}$ for all diverting whales. Figures 6.8 and 6.9 show levels received by the "apparently diverting" whales listed in Table 6.5 (⊞ symbols) and by the whales showing no evidence of a change in course (+ symbols). Overall, Table 6.5 lists 18 cases in which bowhead whales (singles or groups) exhibited apparent avoidance reactions to the projectors during icebreaker playbacks. In contrast, during control conditions near the ice camp in 1991/94, a possible avoidance reaction was noticed on only one occasion: On 7 May 1994, three bowheads heading ENE directly toward the ice camp turned ESE and dove under the landfast ice when they were ~300 m WSW of the ice camp (see Fig. F-6 and Table F-2 in Appendix F, time 11:58). The higher number of bowhead groups showing apparent avoidance reactions during playback conditions (18 of 80) than during control conditions (1 of 116) was highly significant (chi^2=22.9, df=1, P<0.001).

Avoidance vs. Icebreaker:Ambient Ratio.—A substantial proportion (9 of 29 or 31%) of the traveling bowheads showed signs of avoidance upon (or before) exposure to $S:N_{1/3,max}$ levels above 20 dB (⊞ symbols in Fig. 6.9B; shaded bars in Fig. 6.11D). However, 14% (4 of 28) of the traveling bowheads exposed to $S:N_{1/3,max}$ levels of 0-20 dB also showed indications of avoidance. Two additional cases are not included on Figure 6.9 because they were at >3 km distance ($S:N_{1/3,max}$ -4 dB and 16 dB; Table 6.5). These observations suggest that a typical traveling bowhead might begin to divert when the icebreaker-to-ambient ratio ($S:N_{1/3,max}$) is somewhere around 20 dB, with some individuals diverting at considerably lower S:N, and some not diverting even at considerably higher S:N. However, this interpretation of the 1991/94 data must be treated very cautiously because of the small sample size (Table 6.5), high variability, and known observation biases:

1. CEPA distances were often overestimated, so S:N at CEPA was often underestimated.
2. Frequency of diversion was probably underestimated in 1991/94 because ice-based observers saw only the closer whales, and neither ice-based nor (in 1991/94) aerial observers could follow many whales for long enough to document their tracks past the ice camp.

The reaction threshold would tend to be underestimated as a result of difficulty (1) and overestimated as a result of difficulty (2).

Figures 6.10A-D and 6.11A-C show corresponding results for the other seven RL and S:N measures. Inspection of these diagrams shows that, for all sound measures, bowheads that diverted tended to be exposed to somewhat higher RL or S:N levels than were the bowheads not noticed to divert. However, this tendency was weak, with much overlap in sound levels at which bowheads did and did not react. The problems and cautionary notes mentioned in the preceding paragraph apply to all of these measures of RL and S:N.

Effects on Feeding Whales

The projection experiment on 9 May 1994 provided information on the reactions of lingering whales, possibly engaged in feeding, to playbacks of icebreaker sounds. On this date several whales appeared to be feeding beneath the landfast ice edge in the area <300 m from the ice camp before the playback experiment started. In previous analyses, we have considered only traveling whales because our sample size of traveling whales is substantially larger than for any other behavioral category during spring migration. However, the special case of the apparently-feeding bowheads observed on 9 May 1994 warrants individual presentation. There are difficulties in interpreting these data because it was often not possible to identify individual whales. To the degree possible, individual whales have been counted only once, but it is almost certain that several sightings were unrecognized repeat sightings. Thus the number of different feeding whales present was no doubt considerably less than implied by the raw counts.

On 9 May 1994, feeding whales were seen closer to the operating projector than were traveling whales, and they voluntarily subjected themselves to higher levels of icebreaker sounds than did traveling whales (Fig. 6.12). One or two small bowheads (the identity of the whale(s) could not be confirmed in most cases) dove ~8 times within 150 m of the operating J-11 projector, in one case diving below the surface only 17 m from the projector at a time when its source level

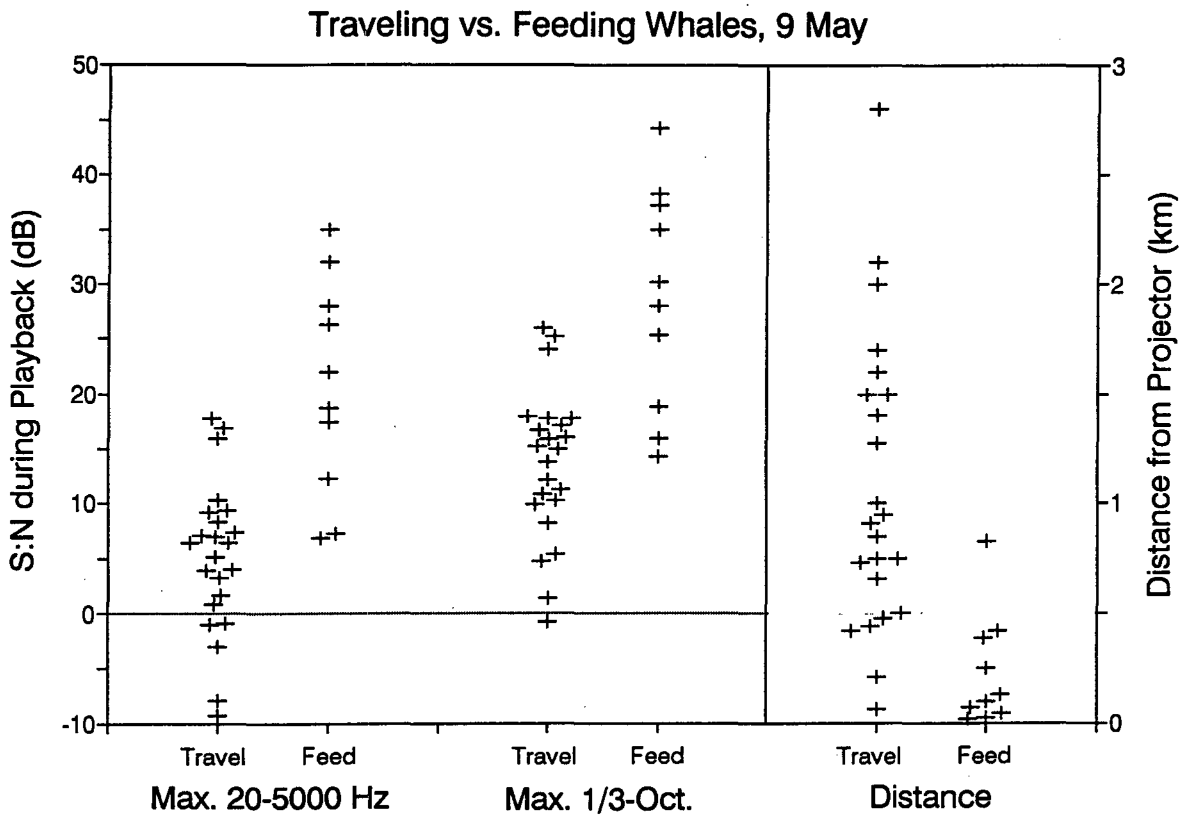

FIGURE 6.12. Estimated icebreaker-to-ambient ratios near traveling vs. feeding bowheads at their CEPA distances, 9 May 1994, considering bowheads seen within 3 km of the ice camp ($S{:}N_{BB,max}$ and $S{:}N_{1/3,max}$). Many CEPA distances are overestimated, so many S:N values are underestimated. Also shown on the right side are the CEPA distances for which the S:N ratios are computed.

was 153 dB re 1 µPa-m. The estimated $RL_{BB,max}$ at 17 m was 132 dB re 1 µPa, and $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were 36 and 38 dB. The whale dove partially toward the projector, so its actual CPA when below the surface may have been slightly less than 17 m. This same whale (identity confirmed from photographs) was seen <20 m from the projector 83 min later, 13 min after the projector was turned off. It was probably seen on several additional occasions between these times, but its identity was not always confirmed. Another bowhead sighting, at distances as close as 24 m from the operating projector, occurred at a time with higher source level than during the 17 m case. Hence, RL and S:N were higher than for the 17 m case despite the slightly greater distance: during the 24 m sighting, $RL_{BB,med}$ and $RL_{BB,max}$ at 24 m were 132 and 135 dB re 1 µPa, $RL_{1/3,med}$ and $RL_{1/3,max}$ were 126 and 129 dB, and $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were 41 and 44 dB. Appendix F provides additional details for all feeding whales seen on 9 May 1994.

In general, these lingering bowheads appeared to tolerate signal-to-noise ratios as much as 15-20 dB higher than did traveling whales observed migrating toward the northeast on this date. On this date there was no obvious avoidance of the projector by feeding whales, except possibly at extremely close ranges (<15 m).

6.3 Behavior During Icebreaker Playbacks

The second null hypothesis to be tested during this study, from §1.2 (p. 7-9), is that

> Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

The present section concerns the reactions to icebreaker noise. Reactions to the 1989-90 playbacks of noise from a drilling operation on an ice pad (*Karluk*) were described in Richardson et al. (1991a:163*ff* and 228*ff*).

Data Considered

Data considered here came from systematic aerial observations of bowhead behavior during the icebreaker playbacks in 1994. One icebreaker playback to bowheads was done in 1991, but aerial observations were not possible then because of low cloud. Overall, we obtained partial or "complete" behavioral data for 149 surfacings and 83 dives during icebreaker playbacks, and for an additional 26 surfacings and 20 dives during the period 0-30 min after the ends of icebreaker playbacks (Table 2.2, p. 37). These data were obtained on 7, 9, 16 and 17 May 1994 (Table 6.1, p. 248). Aerial observations of presumably undisturbed bowheads were obtained during pre- and/or post-playback control periods on these four dates, and also during the pre-playback period on 20 May 1994 (Table 6.1). These behavioral observations tended to be less complete than usual, largely because of the prevailing high winds and high sea states in 1994. Because of the high sea state, we often sighted whales some time after they surfaced rather than as they surfaced. In these cases, we could not characterize the variables that depend on observation of the full surfacing (e.g., duration of surfacing, number of blows per surfacing, degrees of turn during surfacing).

Analyses in this section consider only whales whose group activity was classified as "traveling" or "traveling plus socializing". Individual surfacings and dives were excluded if there was active socializing or aerial behavior (a breach, flipper or tail slap, or roll). Mothers and calves were also excluded. These criteria restricted the analysis to a relatively homogeneous category of whales, representing the migrating animals. These selection criteria retained most of the observations, but excluded special cases where behavior would be expected to be "unusual" even in the absence of any type of disturbance (*cf.* §5.3, 5.4). These restrictions were similar to those adopted in the corresponding analyses of *Karluk* data (Richardson et al. 1990a).

Surfacing, Respiration and Diving Behavior

Behavior vs. Distance from Projectors.—There was no strong correlation between any of the standard four measures of surfacing/respiration/dive cycles and distance from the operating sound projector during icebreaker playbacks (Table 6.6A; Fig. 6.13). There also was no strong correlation of any such variable with distance under control conditions, i.e. when the ice camp was present within 10 km but there was no known source of potential disturbance at the observation time or within the previous 30 min (Table 6.6A; Fig. 6.14). There was a weak negative correlation

Playback Data vs. Range

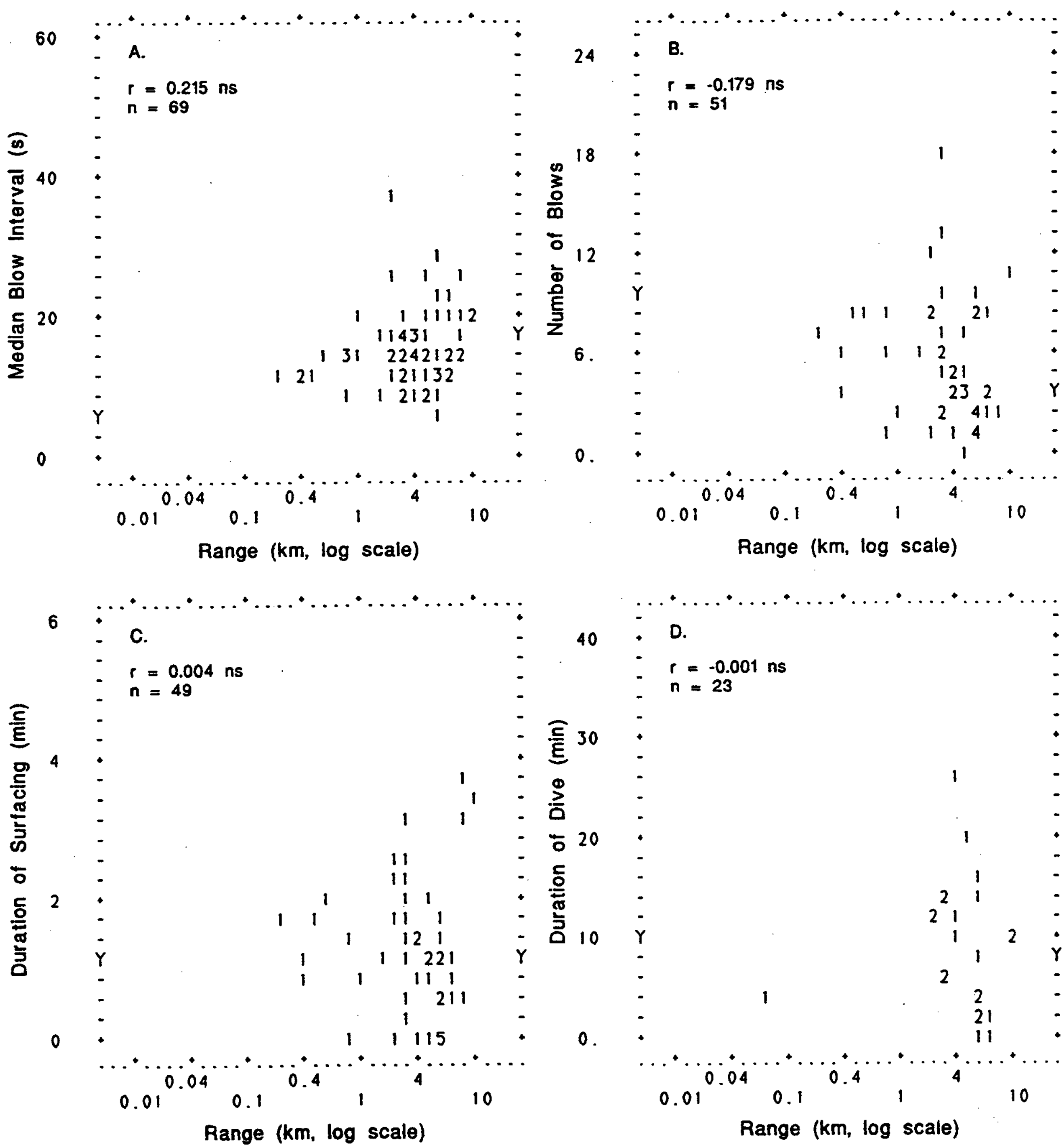

FIGURE 6.13. Surfacing, respiration and dive behavior in relation to distance from projectors during 1994 playbacks of icebreaker sounds. Aerial observations only; only traveling bowheads included; mothers, calves, and surfacings with active socializing or aerial behavior excluded. Numerals in graphs depict number of cases at each location.

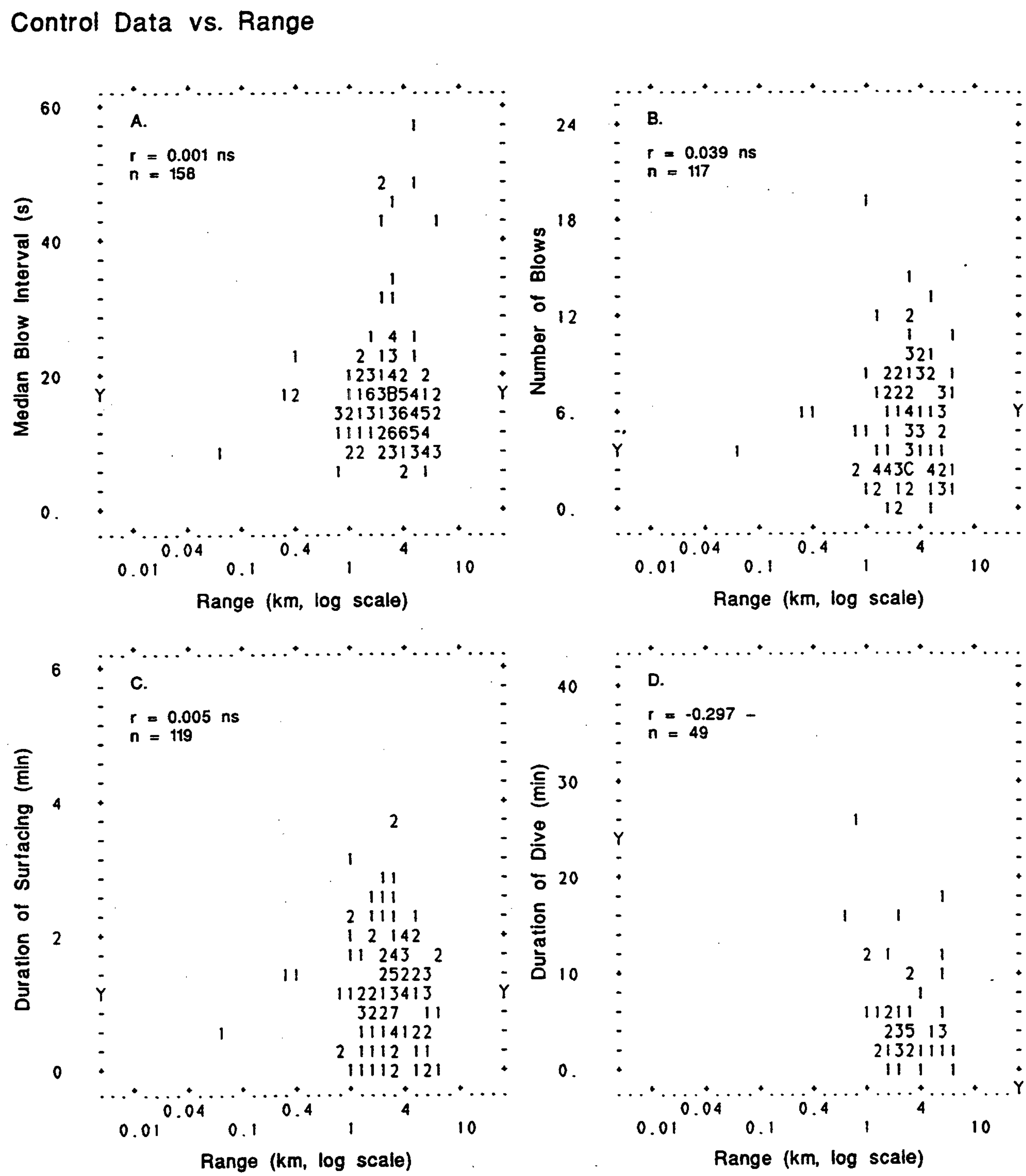

FIGURE 6.14. Surfacing, respiration and dive behavior in relation to distance from silent projectors during 1994 control periods (ice camp present within 10 km but projectors off). Case selection criteria as in Fig. 6.13. Numerals and letters (A,B,...) in graphs depict numbers of cases at each location (A=10, B=11, ...).

TABLE 6.6. Correlation of surfacing, respiration and dive behavior of traveling bowheads vs. *(A)* distance from projector, *(B)* estimated received sound level, and *(C)* estimated received signal to ambient-noise ratio during (A,B,C) icebreaker playbacks and (A only) associated control conditions, 1994. Acoustical variables (B) and (C) are measured during the 64 s preceding the behavioral observation. Mothers, calves, and surfacings with active socializing or aerial behavior are excluded. Aerial observations only. P_n is nominal 2-tailed significance level of the correlation coefficient. See associated scatter diagrams corresponding to boldface sections.

Behavioral	**A. vs. Distance (log km)**				Acoustical Variable		**B. vs. RL (dB re 1 μPa)**			**C. vs. S:N (dB)**		
Variable	*Condition*	r	n	P_n	(Measured Over 64 s)		r	n	P_n	r	n	P_n
Median	*Playback*	**0.215**	**69**	**(+)**	20-5000 Hz	median	0.008	68	ns	0.055	68	ns
Blow	*Control*	**0.001**	**158**	**ns**		maximum	-0.024	68	ns	0.029	68	ns
Interval					Dom. 1/3-Oct.	median	0.022	68	ns	0.061	68	ns
						maximum	**0.003**	**68**	**ns**	**0.046**	**68**	**ns**
# Blows	*Playback*	**-0.179**	**51**	**ns**	20-5000 Hz	median	0.278	50	(+)	0.268	50	(+)
per Sur-	*Control*	**0.039**	**117**	**ns**		maximum	0.279	50	+	0.271	50	(+)
facing					Dom. 1/3-Oct.	median	0.284	50	+	0.281	50	+
						maximum	**0.280**	**50**	**+**	**0.282**	**50**	**+**
Duration	*Playback*	**0.004**	**49**	**ns**	20-5000 Hz	median	0.265	48	(+)	0.318	48	+
of Sur-	*Control*	**0.005**	**119**	**ns**		maximum	0.280	48	(+)	0.332	48	+
facing					Dom. 1/3-Oct.	median	0.270	48	(+)	0.329	48	+
						maximum	**0.304**	**48**	**+**	**0.356**	**48**	**+**
Duration	*Playback*	**-0.001**	**23**	**ns**	20-5000 Hz	median	0.122	22	ns	0.100	22	ns
of Dive	*Control*	**-0.297**	**49**	**-**		maximum	0.124	22	ns	0.104	22	ns
					Dom. 1/3-Oct.	median	0.114	22	ns	0.060	22	ns
						maximum	**0.104**	**22**	**ns**	**0.057**	**22**	**ns**
Degrees	*Playback*	**-0.079**	**57**	**ns**	20-5000 Hz	median	0.374	56	++	0.423	56	+++
of Turn	*Control*	**0.150**	**128**	**(+)**		maximum	0.365	56	++	0.419	56	+++
(log)					Dom. 1/3-Oct.	median	0.387	56	++	0.443	56	+++
						maximum	**0.407**	**56**	**++**	**0.461**	**56**	**+++**

(P_n<0.05) between duration of dive and distance from camp under control conditions. There was no hint of any similar distance effect during playbacks. (The "P_n" designation, following the notation used in §5.3-5.4, refers to a nominal probability level, recognizing that some whales contributed more than one dive or surfacing to these analyses.)

The absence of obvious relationships between distance from projector and any of the four surfacing, respiration and dive cycles during playbacks is not necessarily surprising, given the highly variable sounds being emitted from the projectors, along with differences in propagation loss rates at sites with different water depths (§4.3). The received level of icebreaker sound at any given distance varied greatly depending on date (=location) and time. Some aerial observations of behavior during playbacks, although within 10 km of the ice camp, were at distances and times where the received sound level was below the ambient noise level, and probably undetectable to bowheads.

Behavior vs. Received Level (RL).—In contrast, two of the four measures of surfacing/respiration/dive cycles were significantly correlated with some estimates of the received level (RL) of icebreaker sound at the whales' locations (Table 6.6B). We used the model described in §2.3 and §4.3 to estimate RL at the locations and times of each whale observation. This model takes account of the water depth, distance of the whale from the projectors, and the source level and spectral properties of the projected icebreaker sound during the 64-s period immediately preceding the time of the observation. We use the same four RL estimates as described in §6.1 (p. 251): $RL_{BB,med}$, $RL_{BB,max}$, $RL_{1/3,med}$, and $RL_{1/3,max}$.

With increasing RL, duration of surfacing and number of blows per surfacing each showed a weak tendency to increase. Depending on the specific estimate of RL used, correlation coefficients ranged from 0.278 to 0.284 for number of blows and 0.265 to 0.304 for duration of surfacing (0.1>P_n>0.01 in each case). Figure 6.15 shows scatter diagrams corresponding to the boldfaced correlation coefficients in Table 6.6B, depicting relationships to $RL_{1/3,max}$. This estimate of RL tended to show some of the highest correlation coefficients with various measures of behavior (Table 6.6B,C). Even so, relationships of estimated RL to duration of surfacing and number of blows per surfacing were all weak, as evident from the extensive scatter of data points in Figure 6.15B,C, the rather low correlation coefficients, and the associated low levels of nominal statistical significance.

There was no evidence of any significant correlation between RL and either median blow interval or duration of dive (Table 6.6B, Fig. 6.15A,D).

Behavior vs. Icebreaker:Ambient Ratio (S:N).—The duration of surfacing and the number of blows per surfacing also showed weak but significant positive correlations with some measures of the icebreaker-signal to ambient-noise ratio (Table 6.6C, Fig. 6.16B,C). The stronger the RL of icebreaker sound relative to the prevailing natural background noise level, the longer the surfacings and the more blows per surfacing. Although the correlations were again weak, duration of surfacing showed slightly stronger correlations with all measures of S:N than with corresponding RLs (Table 6.6C vs. B).

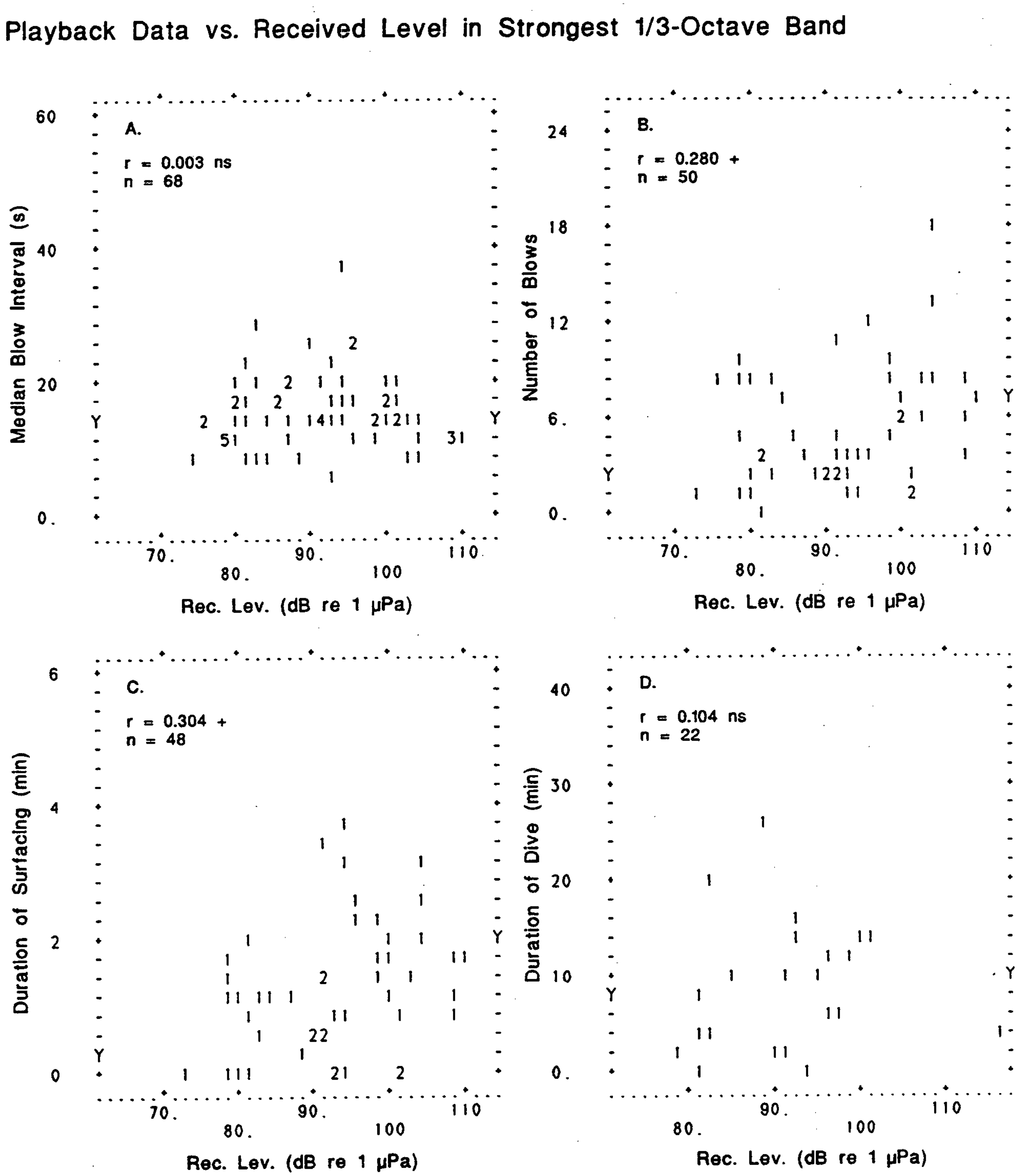

FIGURE 6.15. Surfacing, respiration and dive behavior in relation to estimated received level of icebreaker sound ($RL_{1/3,max}$) at bowhead locations during 1994 playbacks. Case selection criteria as in Fig. 6.13.

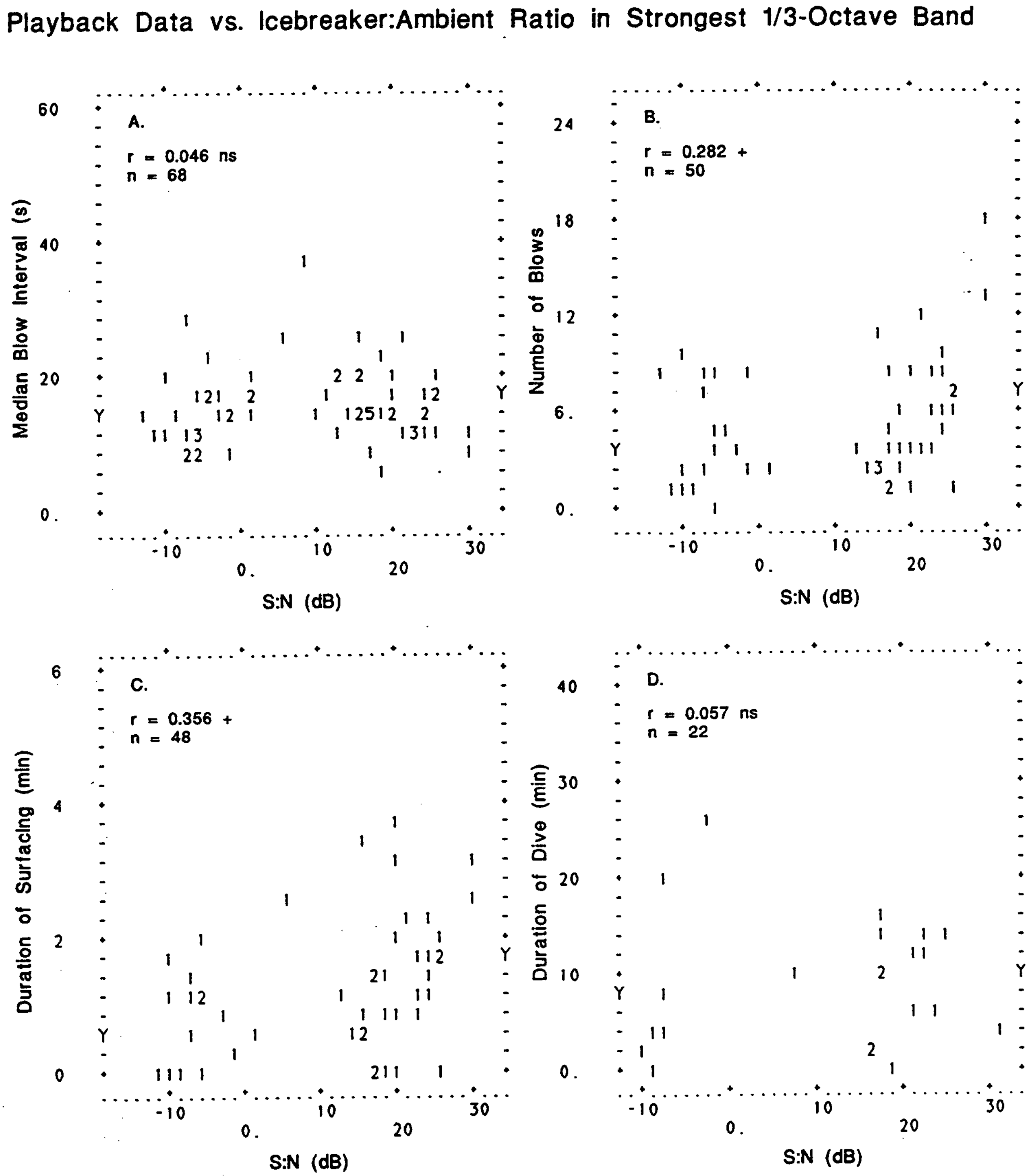

FIGURE 6.16. Surfacing, respiration and dive behavior in relation to estimated icebreaker-to-ambient noise ratio ($S{:}N_{1/3,max}$) at bowhead locations during 1994 playbacks. Case selection criteria as in Fig. 6.13.

In these analyses, the icebreaker-signal to ambient-noise "ratio" (S:N) was determined from the same four measures of RL mentioned above. From these RL estimates, we subtracted the average ambient noise level in the corresponding frequency band. Ambient levels for a given playback day were determined by averaging several measurements of ambient noise taken shortly before and after that playback[22]. The measured ambient noise in the 20-5000 Hz band was subtracted from the estimated RL in this band, and measured ambient noise in the 1/3-octave with the strongest icebreaker noise was subtracted from the RL of icebreaker noise in that band.

Apparent Response Thresholds.—The correlation analyses indicate that duration of surfacing and number of blows per surfacing tended to increase with increasing RL and icebreaker-signal to ambient-noise (S:N) ratio. It is important to determine the RL and S:N values that elicited behavioral effects. It is not possible to do this objectively from scatter diagrams like Figures 6.15B,C and 6.16B,C. Figure 6.17 shows the same data on durations of surfacings and number of blows per surfacing, summarized by 10-dB categories of $RL_{1/3,max}$ or $S{:}N_{1/3,max}$. Also included in Figure 6.17 are the data for "control" conditions: aerial observations of presumably-undisturbed bowheads within 10 km of the ice camp. Page 40 in §2.3 describes "Control" conditions, which included exposure to some noise and other stimuli associated with observational efforts.

For consistency with previous work on behavior relative to playbacks of *Karluk* drilling sounds, Figure 6.17 shows the data categorized by distance-from-projector as well as $RL_{1/3,max}$ and $S{:}N_{1/3,max}$. However, no obvious relationship to distance was expected, given the aforementioned lack of significant correlation between distance and either duration of surfacing or number of blows per surfacing.

Analysis Procedures: Analysis of variance and orthogonal contrasts were used to help identify RL and S:N categories in which behavioral effects were evident (Table 6.7A,B). This was done for the "$_{BB,med}$", "$_{BB,max}$" and "$_{1/3,med}$" measures of RL and S:N, as well as for the "$_{1/3,max}$" measure depicted in Figure 6.17. The ANOVAs and orthogonal contrasts were done in two ways: *(A)* including only the playback data, categorized by RL or S:N, and ***(B)*** including the control data as an additional "treatment".

In Table 6.7A, the orthogonal contrasts were set up first to compare behavior under the two lowest-level RL or S:N categories,

RL 90-100 dB vs. RL ≤ 90 dB, or alternatively S:N 0-10 dB vs. S:N ≤ 0 dB;

If behavior in these categories is not significantly different, then it is useful to compare behavior of whales exposed to that combined range of RL or S:N values with behavior of those in the next higher category,

- RL 100-110 dB vs. RL ≤ 100 dB, or S:N 10-20 dB vs. S:N ≤ 10 dB;

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[22] For 17 May 1994, when wind speed and ambient noise level increased notably during the experiment, ambient noise levels were estimated separately for each hour based on linear interpolation between the average values before the playback and the average values after the playback. This was done for the overall 20-5000 Hz band and for each 1/3-octave band from 20 Hz to 6300 kHz.

Similarly, if behavior in those RL or S:N categories does not differ significantly, then it is appropriate to continue to the next contrast,

- RL > 110 dB vs. RL ≤ 110 dB, or S:N > 20 dB vs. S:N ≤ 20 dB.

A parallel procedure was used to compare behavior in distance categories >4 km, 2-4 km, 1-2 km, and ≤1 km, for consistency with the previous *Karluk* analyses. Contrasts with higher categories of RL or S:N, or with closer distance categories, were not possible because of low (or nil) sample size. In some cases, one of the aforementioned RL, S:N or distance categories and the associated contrast had to be skipped because of low sample size.

Table 6.7B shows the results when control data were included as a treatment. In this case, the first contrast looked for a difference between control conditions and the lowest RL or S:N category (or the longest distance category), and then proceeded to compare behavior with successively higher RL or S:N categories vs. the combined control and lower-noise categories, e.g.

- RL ≤ 90 dB vs. Control, or S:N ≤ 0 dB vs. Control;
- RL 90-100 dB vs. RL ≤90 dB plus Control, or S:N 0-10 dB vs. S:N ≤ 0 dB plus Control;
- RL 100-110 dB vs. RL ≤100 dB + Control, or S:N 10-20 dB vs. S:N ≤ 10 dB + Control;
- RL >110 dB vs. RL ≤110 dB + Control, or S:N > 20 dB vs. S:N ≤ 20 dB + Control.

The significance levels shown in Figure 6.17 refer to these analyses, as applied using the $RL_{1/3,max}$ and $S{:}N_{1/3,max}$ acoustic measures.

The "control" data include observations near the ice camp during control periods on some days when no or few aerial observations were obtainable during icebreaker playbacks. Even when both playback and control data were obtained on a given day, relative numbers of playback and control observations varied from day to day. These departures from a strictly balanced design may account for some differences in behavior between whales observed in "control" periods and whales observed with the lowest categories of RL or S:N conditions (e.g. Table 6.7B,C, bottom half).

Distance: Consistent with the correlation results, ANOVA and orthogonal contrasts provided no indication that duration of surfacing or number of blows per surfacing were related to distance from the sound projectors during icebreaker playbacks (Fig. 6.17A,D; Table 6.7A).

Received Level (RL): The received level of icebreaker sound at which effects on surfacing and respiration cycles became evident depended on

- the behavioral measure being considered (duration of surfacing vs. number of blows per surfacing),
- the acoustical measure being used (broadband vs. 1/3-octave; median vs. maximum level).

Encouragingly, the results were similar for the two methods of analysis: comparing RL categories during playbacks and comparing RL categories during playbacks with control data (Table 6.7B, top vs. bottom).

There was some evidence (P_n<0.05) of an effect on duration of surfacing at $RL_{1/3,max}$ values as low as 90-100 dB re 1 µPa (Fig. 6.17E, Table 6.7B). There was evidence of an effect on

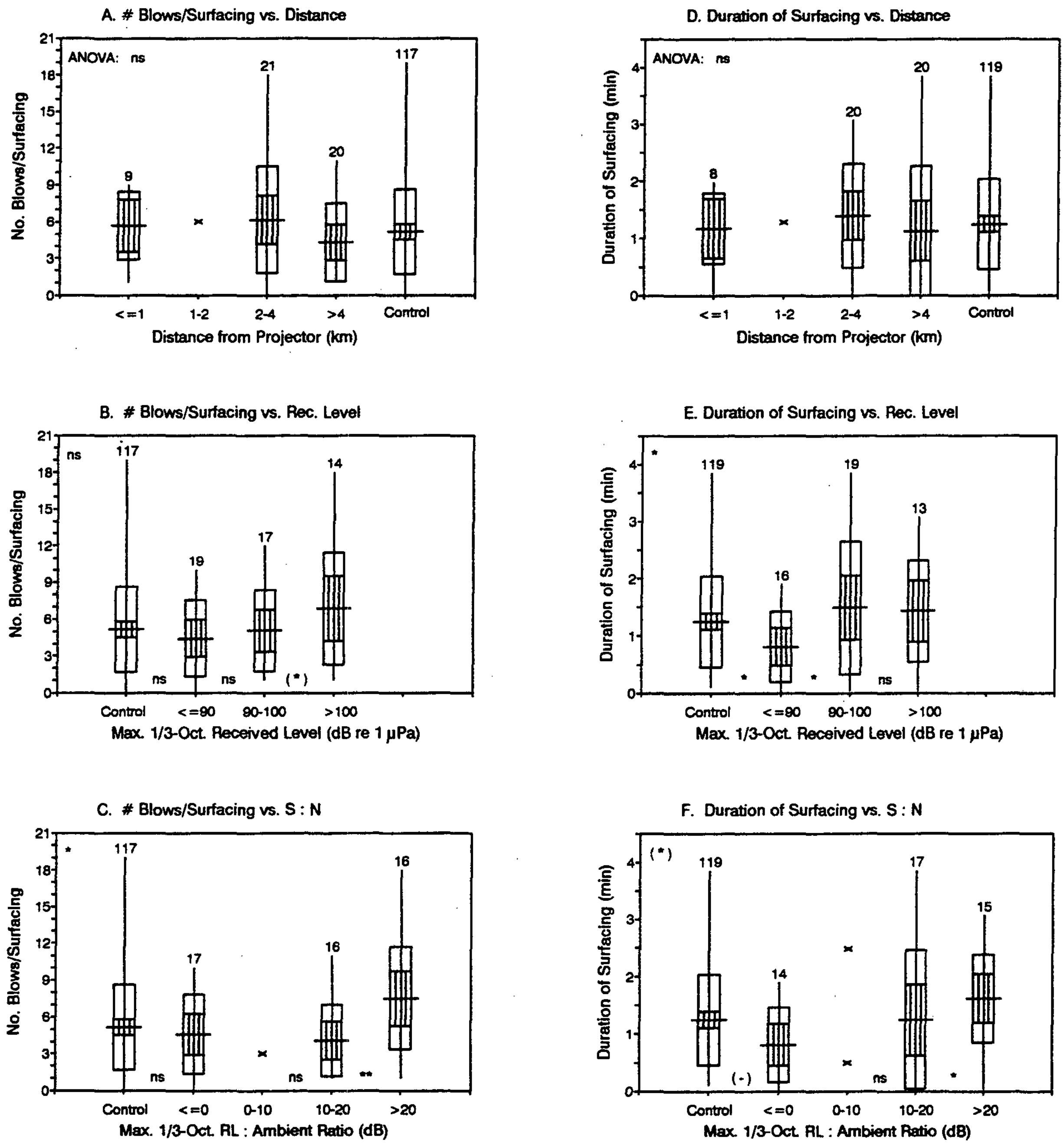

FIGURE 6.17. Surfacing and respiration behavior for various categories of distance from projectors, estimated received level, and estimated icebreaker-to-ambient ratio during 1994 playbacks of icebreaker sound. Also shown are control observations obtained within 10 km of the ice camp when the projectors were silent. The mean, range, ±1 s.d. (open rectangle) and ±95% confidence interval (hatched rectangle) are shown. Significance levels near bottoms of panels depict orthogonal contrasts for the category immediately right of each symbol vs. the combination of all categories to the left (see also boldface sections of Table 6.7, and associated text). Same data as in parts B,C of previous four graphs. Case selection criteria as in Fig. 6.13.

TABLE 6.7. ANOVA and related analyses of surfacing, respiration and dive behavior of traveling bowheads vs. *(A)* distance from projector, *(B)* estimated received sound level, and *(C)* estimated received signal to ambient-noise ratio during icebreaker playbacks. Lower half includes control data as an additional treatment level. ANOVAs test for differences among distance, received level, or S:N categories. See text for details concerning the orthogonal contrasts. Cases highlighted in boldface are shown in Figure 6.17.

Behavioral Variable	A. vs. Distance (log km)[a] Comparison	A. P_n	B. vs. RL (dB re 1 μPa) Comparison	B. Sound Measure 20-5000 Hz Med.	B. 20-5000 Hz Max.	B. Dom. 1/3 Med.	B. Dom. 1/3 Max.	C. vs. S:N (dB) Comparison	C. Sound Measure 20-5000 Hz Med.	C. 20-5000 Hz Max.	C. Dom. 1/3 Med.	C. Dom. 1/3 Max.
Excluding Control Data												
# Blows	Correl. n=51	ns	Correl. n=50	(+)	+	+	+	Correl. n=50	(+)	(+)	+	+
per Sur-	ANOVA df=2,47	ns	ANOVA	+	+	ns	ns	ANOVA	+	ns	(+)[b]	+
facing	2-4 vs. >4 km	ns	>90-100 vs. <=90 dB	ns	ns	ns	ns	>0-10 vs. <=0 dB	ns	ns		
	<=1 vs. >2	ns	>100[c] vs. <=100	++	ns	ns	(+)	>10 vs. <=10	++	ns		
			>110 vs. <=110		++			>10-20 vs. <=0 dB			ns	ns
								>20 vs. <=20[d]			+	++
Duration	Correl. n=49	ns	Correl. n=48	(+)	(+)	(+)	+	Correl. n=48	+	+	+	+
of Sur-	ANOVA df=2,45	ns	ANOVA	(+)	ns'	ns	(+)'	ANOVA	(+)	(*)'	(+)[b]	(+)
facing	2-4 vs. >4 km	ns	>90-100 vs. <=90 dB	ns	(+)	ns	+	>0-10 vs. <=0 dB	(+)	++		
	<=1 vs. >2	ns	>100[c] vs. <=100	+	ns	ns	ns	>10 vs. <=10	(+)	ns		
			>110 vs. <=110		(+)			>10-20 vs. <=0			(+)	ns
								>20 vs. <=20[d]			+	(+)
Including Control Data												
# Blows	ANOVA df=3,163	**ns**	ANOVA	+	+	ns	**ns**	ANOVA	(+)	ns	(+)	+
per Sur-	>4 km vs. Control	**ns**	<=90 dB vs Control	ns	ns	ns	**ns**	<=0 dB vs. Control	ns	ns	ns[b]	**ns**
facing	2-4 vs. >4 km+C	**ns**	>90-100 vs. <=90+C	ns	ns	ns	**ns**	>0-10 vs. <=0+C	ns	ns		
	<=1 vs. >2+C	**ns**	>100[c] vs. <=100+C	++	ns	ns	(+)	>10 vs. <=10+C	++	ns		
			>110 vs. <=110+C		++			>10-20 vs. <=0+C			ns	**ns**
								>20 vs. <=20+C[d]			++	++
Duration	ANOVA df=3,163	**ns**	ANOVA	ns	ns'	ns	*'	ANOVA	*	ns'	*	(*)
of Sur-	>4 km vs. Control	**ns**	<=90 dB vs Control	ns	ns	ns	-	<=0 dB vs. Control	-	-	-[b]	(-)
facing	2-4 vs. >4 km+C	**ns**	>90-100 vs. <=90+C	ns	ns	ns	+	>0-10 vs. <=0+C	ns	++		
	<=1 vs. >2+C	**ns**	>100[c] vs. <=100+C	+	ns	ns	**ns**	>10 vs. <=10+C	+	ns		
			>110 vs. <=110+C		+			>10-20 vs. <=0+C			ns	**ns**
								>20 vs. <=20+C[d]			+	+

[a] Too few cases at 1-2 km to consider.
[b] Too few cases at 0-10 dB S:N to consider.
' Variances unequal; ANOVA based on Brown-Forsythe test.
[c] For 20-5000 Hz/Maximum, includes >100 to 110 dB cases only.
[d] Excluding >0 to 10 dB category with few data.

duration of surfacing (P_n<0.05) and especially number of blows per surfacing (P_n<0.01) at $RL_{BB,med}$ values as low as 100-110 dB, and at $RL_{BB,max}$ values as low as 110-120 dB (Table 6.7B).

Icebreaker:Ambient Ratio (S:N): Results were again similar for the two methods of analysis. Both duration of surfacing and number of blows per surfacing became significantly higher at $S{:}N_{1/3,max}$ values above 20 dB, i.e. when the noise level in the 1/3-octave band of strongest icebreaker noise exceeded the ambient noise level in that band by at least 20 dB (Fig. 6.17C,F; Table 6.7C). The same 20 dB threshold seemed to apply for the $S{:}N_{1/3,med}$ acoustic measure. Thresholds based on broadband sound levels appeared to be lower: about 10 dB above ambient for $S{:}N_{BB,med}$, and possibly as low as 0 dB above ambient for $S{:}N_{BB,max}$ (Table 6.7C).

Statistical Power and Apparent Response Thresholds.—Statistical power is a measure of the ability of an analysis to reject the null hypothesis when it is false, i.e. to obtain a statistically significant effect when an effect does exist. Power increases with increasing sample size and with decreasing within-group variability. With low sample size or high variability, and especially when both occur together, the analysis will have little ability to reject the null hypothesis even if it is false. When an analysis provides no evidence of a statistically significant effect, it is important to evaluate its power. The objective is to determine whether, with the available sample size and the observed within-group variability, there was a reasonable chance of detecting, as statistically significant, a disturbance effect deemed to be biologically meaningful. If not, it is not justifiable to conclude that there is "no effect"; instead, one must conclude that the analysis is inconclusive.

Duration of surfacing and number of blows per surfacing were significantly related to the received level (RL) and S:N ratio of icebreaker sound (see above). Because the null hypothesis of no icebreaker noise effect on behavior must be rejected, the power of these analyses to reject the null hypothesis is not an issue. However, the orthogonal contrasts suggest that effects on these behavioral variables were detectable only above certain RL or S:N values. The power of these contrasts to detect effects at lower RL or S:N values, if such effects occurred, is an issue in determining reaction thresholds.

Number of Blows per Surfacing: The number of blows per surfacing was significantly (P<0.01) higher with $S{:}N_{1/3,max}$ >20 dB than with lower $S{:}N_{1/3,max}$ values (Fig. 6.17C; Table 6.7C). However, no such difference was found when results with $S{:}N_{1/3,max}$ 10-20 dB were compared with those at $S{:}N_{1/3,max}$ ≤0 dB (P>0.1). This was true whether or not the "control" data were included in the "≤0 db" category (Table 6.7C). Did this contrast have a reasonable prospect for detecting a difference if, in fact, there was such a difference? Power analysis indicated that a difference of the size observed (means of 4.06 vs. 5.10 blows/surfacing) was too small to be detected with reasonable power (actual power = 0.242). A difference of at least 2.3 blows/surfacing would be required in order to have a reasonable (80%) chance of demonstrating a significant (α=0.05) difference between the $S{:}N_{1/3,max}$ 10-20 dB vs. <0 dB (including control) situations.[23] A typical

[23] Power and minimum detectable difference were calculated by the "two means" procedure in BMDP SOLO Power Analysis (Hintze 1991:65*ff*). Variances were treated as unequal and estimated from the data. The test was two-sided. For $S{:}N_{1/3,max}$ 10-20 dB, mean 4.062 ± s.d. 2.909, n=16; for S:N < 0 dB (including control), mean 5.097 ± s.d. 3.447, n=134.

surfacing by a spring-migrating bowhead includes 5.0 blows (Fig. 5.28, p. 209), so a ±2.3 blows/surfacing change would represent a change of ~46%. Thus, in the $S{:}N_{1/3,max}$ 10-20 dB situation, a rather large change in "number of blows/surfacing" would have been necessary in order to detect a significant effect on this variable.[24]

The following percentage changes in "number of blows/surfacing" have been observed in cases of severe disturbance to bowheads:

- -23% with approaching boat within 4 km (Richardson et al. 1985b:117; Richardson and Malme 1993:669),
- -31% and -60% with operating seismic vessels within 5-10 and <5 km, respectively (Ljungblad et al. 1988:188, recalculated by Richardson and Malme 1993:672),
- -55% at ranges ≤1 km vs. >4 km during drilling noise playback on 13 May 1990 (Richardson et al. 1991a:171), and
- +47% with icebreaker noise playbacks at $S{:}N_{1/3,max}$>20 dB vs. "≤0 dB + Control" (this study, Fig. 6.17C).

Thus, in cases of severe disturbance to bowheads, "number of blows/surfacing" sometimes (but not always) changes by more than the 46% that we might reasonably have been able to detect in the $S{:}N_{1/3,max}$ 10-20 dB category. If severe disturbance had occurred with $S{:}N_{1/3,max}$ 10-20 dB, it might or might not have been evident through statistical analysis of this behavioral variable, given the available sample sizes and the observed variability in number of blows per surfacing.

Duration of Surfacing: This variable was significantly different with $S{:}N_{1/3,max}$ >20 dB than at ≤20 dB, but not with $S{:}N_{1/3,max}$ 10-20 dB vs. ≤0 dB. In the latter case, mean duration of surfacing was very similar in the 10-20 dB vs ≤0 dB (including control) situations: 1.244 vs. 1.200 min.[25] As one would expect, the power to detect a difference of only 0.044 min as significant was very low (power 0.052 with α=0.05). A 0.89 minute change in mean duration of surfacing would be required in order to have an 80% chance of demonstrating a significant effect. A typical surfacing by a spring-migrating bowhead is ~1.35 min in duration, so a ±0.89 min change would be a change of 66%. This is a large change—larger than the changes in duration of surfacing observed during cases of severe disturbance to bowheads:

- -29% with approaching boat within 4 km,
- -27% and -55% with operating seismic vessels within 5-10 and <5 km, respectively,
- -51% at range ≤1 km vs. >4 km during drilling noise playback on 13 May 1990, and
- +35% with icebreaker noise playbacks at $S{:}N_{1/3,max}$>20 dB vs. "≤0 dB + Control" (Fig. 5.17F).

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[24] A similar analysis based on the $RL_{1/3,max}$ measure of received level indicated that, with that acoustical measure, power was only 0.050 given the very similar mean numbers of blows/surfacing in the two conditions: for $RL_{1/3,max}$ 90-100, mean 5.059 blows/surfacing ± s.d. 3.325, n=17; for RL ≤ 90 dB (including control), mean 5.066 ± s.d. 3.433, n=136. A difference of at least 2.52 blows/surfacing would be required to achieve power 0.800 (α=0.05).

[25] For $S{:}N_{1/3,max}$ 10-20 dB, mean 1.244 min ± s.d. 1.210, n=17; for S:N ≤ 0 dB (including control), mean 1.200 ± s.d. 0.787, n=133.

If bowheads exposed to $S{:}N_{1/3,max}$ 10-20 dB had been strongly disturbed, this disturbance probably would not have been detected by analysis of "duration of surfacing". Therefore, the lack of an apparent effect at $S{:}N_{1/3,max}$ 10-20 dB is inconclusive as to the actual existence of effects on duration of surfacing at those S:N values.

Overall, duration of surfacing and number of blows per surfacing were different when levels of icebreaker sound were >20 dB above ambient ($S{:}N_{1/3,max}$ basis) than when they were ≤20 dB above ambient. Neither of these behavioral variables was significantly different at $S{:}N_{1/3,max}$ 10-20 dB than at lower S:N values. However, with available sample sizes and the observed variability in behavior, we might not have detected a significant effect (α=0.05) at S:N 10-20 dB even if the behavioral variables were affected to the same degree as in some previously-observed cases of strong disturbance to bowheads. Therefore, the response threshold for these two behavioral variables should be described as "≤20 dB", i.e. at or possibly below 20 dB, on an $S{:}N_{1/3,max}$ basis.

Turns

There were strong positive correlations between the number of degrees through which bowheads turned during a surfacing and all measures of received level ($P_n<0.01$ in each case) and all measures of icebreaker-to-ambient ratio ($P_n<0.001$ in each case). In contrast, there was no significant correlation between "degrees of turn" and distance from the ice camp during either icebreaker playbacks or control periods. Table 6.6A (p. 282, bottom part) shows all the correlation coefficients, which ranged from 0.365 to 0.407 for RL and 0.419 to 0.461 for S:N. Figure 6.18 shows the data for distance, $RL_{1/3,max}$ and $S{:}N_{1/3,max}$. These are the RL and S:N variables to which degrees of turn showed the highest correlation coefficients.

It is obvious from Figure 6.18C,D that degrees of turn tended to be higher than normal when $RL_{1/3,max}$ exceeded 100 dB re 1 µPa, and when $S{:}N_{1/3,max}$ exceeded 20 dB re 1 µPa. This Figure also suggests that degrees of turn may have been affected at lower RL and S:N values. However, an ANOVA/orthogonal contrast approach as applied above to surfacing and respiration variables is not applicable to "degrees of turn", which had a skewed and heteroscedastic distribution.

Figure 6.19A,B shows the same "degrees of turn" data grouped by 10 dB categories of $RL_{1/3,max}$ and $S{:}N_{1/3,max}$. Similarly, Figure 6.19C,D shows the occurrence of surfacings with no turns, one simple right or left turn, or multiple turns (including at least one left and one right turn during the same surfacing). These graphs show that the occurrence and extent of turning during surfacings was elevated at $RL_{1/3,max}$ values as low as 90-100 dB re 1 µPa, and at $S{:}N_{1/3,max}$ values as low as 10-20 dB. However, the lowest categories of RL and S:N for which the increased occurrence of turns was statistically significant were RL = 100-111 dB and S:N = 10-20 dB:

$RL_{1/3,max}$	Turn During		(1)	(2)	$S{:}N_{1/3,max}$	Turn During		(1)	(2)
Control	60 of 149 sfc	40%			Control	60 of 149 sfc	40%		
<80 dB	3 of 11	27%		ns	<0 dB	4 of 21	19%		ns
80-90	3 of 13	23	ns	ns	0-10	1 of 2	-		
90-100	10 of 22	45	ns[1]	ns[2]	10-20	13 of 24	54	*	ns[3]
100-111	13 of 18	72	*	*	20-31	11 of 17	65	ns	(*)

Degrees of Turn vs. Range and Sound Level Variables

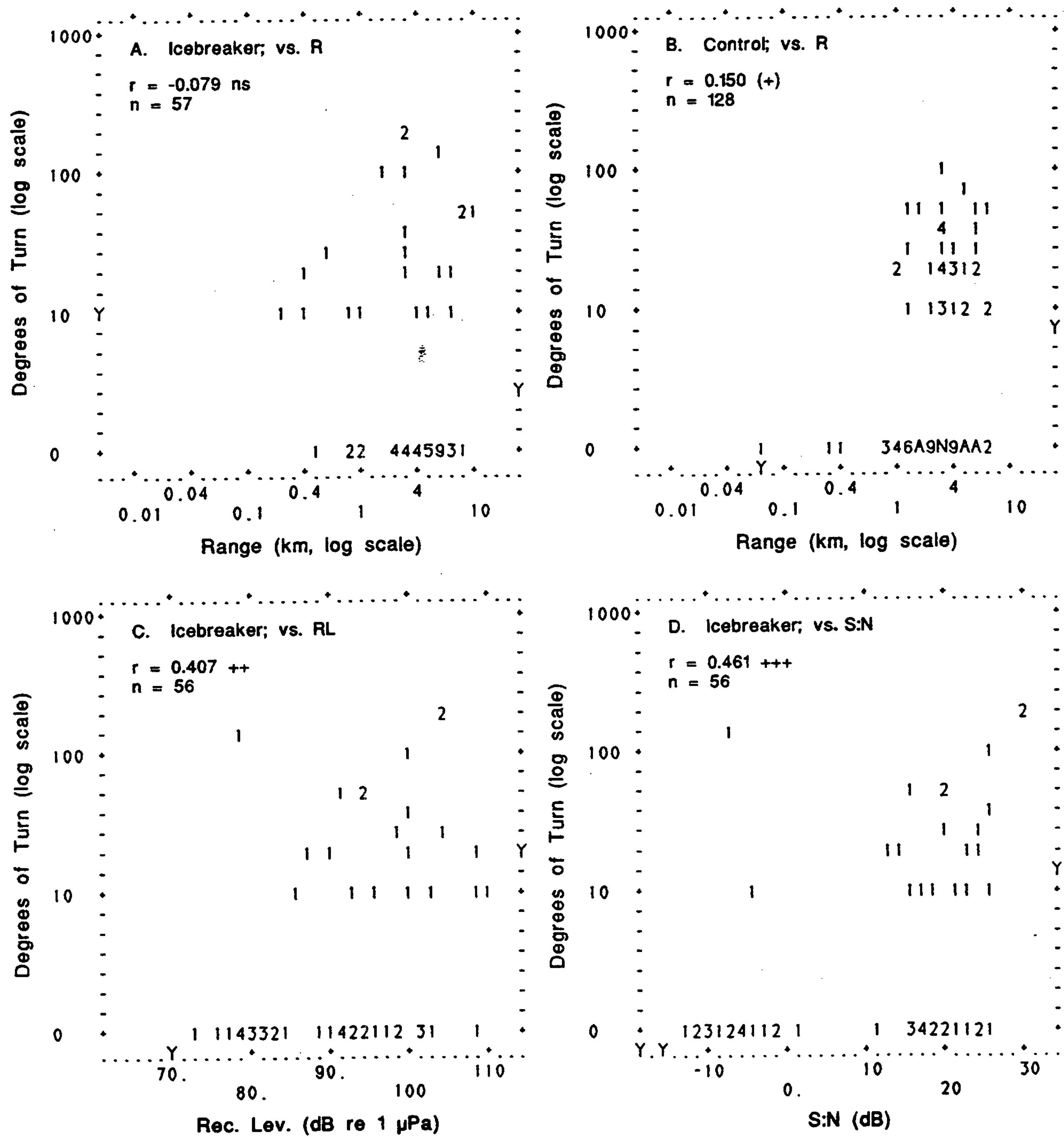


FIGURE 6.18. Degrees of turn during surfacings (log transformed) in relation to *(A)* distance from projectors during playbacks, *(B)* distance from ice camp during control (quiet) periods, *(C)* estimated received level during playbacks ($RL_{1/3,max}$), and *(D)* estimated icebreaker-to-ambient ratio during playbacks ($S:N_{1/3,max}$). Case selection criteria as in Fig. 6.13. Letters "A" and "N" in (B) depict, respectively, 10 and 23 cases at those locations.

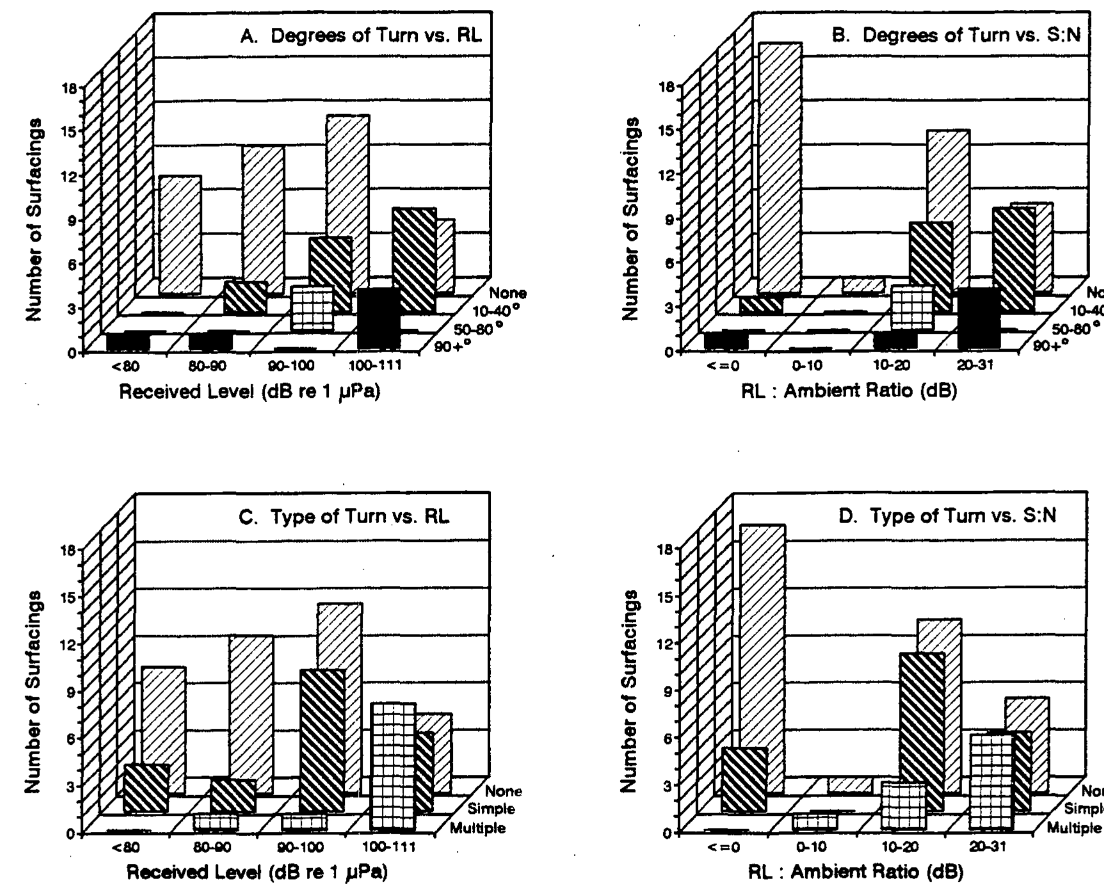


FIGURE 6.19. Degrees and types of turns during surfacings in relation to estimated received level ($RL_{1/3,max}$) and estimated icebreaker-to-ambient ratio ($S{:}N_{1/3,max}$) during 1994 playbacks of icebreaker sound. Data are given in Table 6.9D,E. Case selection criteria as in Fig. 6.13.

These significance levels are based on 2x2 chi^2 comparisons (with Yates correction) of the frequency of turns in that line vs. previous lines combined, either (1) excluding or (2) including data collected near the ice camp under "control" conditions. These comparisons are analogous to the orthogonal contrasts of surfacing/respiration data discussed earlier.

In evaluating the apparent reaction threshold for turns, it is important to consider the statistical power of the contrasts marked [1,2,3] in the above tabulation. In each case, power was low: 0.21, 0.07 and 0.26, respectively.[26] For $S{:}N_{1/3,max}$, there were only two observations in the 0-10 dB category, so it is impossible to assess whether turning frequency was elevated there relative

[26] Power calculations for these contrasts were done with the chi-square procedure in BMDP SOLO Power Analysis (Hintze 1991:159*ff*), in which effect size is defined as $w = \sqrt{(chi^2/N)}$. For contrasts [1,2,3], respectively, chi^2 values were 1.311, 0.185 and 1.723 (df=1 in each case). Effect sizes (w) were 0.169, 0.031 and 0.094, which are all low values. Respective ß values were all high, at 0.79, 0.93 and 0.74. Power was correspondingly low at 0.21, 0.07 and 0.26 (power = 1-ß).

to S:N $\leq$ 0 dB. Thus, we cannot reliably determine whether the turning threshold was lower than the lowest sound values at which statistically significant effects on turning were evident ($RL_{1/3,max}$ 100-111 dB re 1 µPa and $S{:}N_{1/3,max}$ 10-20 dB).

Other Behavioral Variables

The occurrence of various other categorical behaviors has been tabulated in relation to distance from the ice camp during playback and control periods (Table 6.8, 6.10), and in relation to $RL_{1/3,max}$ and $S{:}N_{1/3,max}$ (Table 6.9, 6.11).

Swimming speeds showed no obvious tendency to vary according to distance from the ice camp under playback or control conditions (Table 6.8A). Speeds also did not seem to be related to RL or S:N during playbacks (Table 6.9A). Bowhead surfacings with a change in speed tended to occur in the highest RL category and the highest two S:N categories, but the frequency of "change in speed during surfacing" was too low to rule out coincidence.

Fluke-out dives were scarce at all times in spring, and there was no obvious tendency for the proportional frequency of fluke-out dives to vary with distance, RL or S:N (Table 6.8B, 6.9B). ***Pre-dive flexes*** were even less common, being seen during 0 of 72 surfacings during playbacks and only 3 of 148 surfacings during corresponding control observations (Table 6.8C).

Active socializing was sometimes seen during playbacks as well as control observations. However, we rarely selected actively socializing groups for focal animal observations, especially during playbacks, given their complex and "atypical" behavior. The few surfacings when active socializing was observed during playbacks are excluded from all analyses in this section.

"Passive" socializing, which we define as two (or more) whales within ½-whale-length of one another and oriented parallel to one another, occurred during a minority of the surfacings during both playback and control periods. There was no obvious relationship between occurrence of passive socializing and distance from ice camp, RL, or S:N (Tables 6.8F, 6.9F).

Other behaviors that we routinely record whenever they are noticed are listed in Table 6.10 in relation to distance from ice camp, and in Table 6.11 in relation to $RL_{1/3,max}$ and $S{:}N_{1/3,max}$, if they were ever seen during the icebreaker playbacks or associated control periods in 1994. (Table 5.14 on p. 213 lists other such behaviors observed sometime during this 1989-94 study, but not during icebreaker playbacks or associated control periods in 1994.) Most of these behaviors were infrequent at any time. There was a weak tendency for bowheads to emerge from under areas of extensive (>1 km) ice unusually often when RL and S:N were high. There was also a weak tendency for bowheads to be visible during dives more often when RL and S:N were low than when they were high. These tendencies involved small sample sizes, and it is not known whether they represented real biological effects.

TABLE 6.8. Frequencies of various activities among traveling bowhead whales at various distances from ice camp (A) during icebreaker playbacks and (B) under control conditions. Mother, calves, and surfacings with active socializing or aerial behavior are excluded. Units of observation are surfacings by an individual whale, as observed from Twin Otter aircraft, spring 1994. Total n varies because not all variables could be determined for each surfacing.

	A. Distance (km) from Operating Projector						B. Distance (km) from Silent Projector					
	up to 0.5	>0.5 to 1	>1 to 2	>2 to 4	>4	All	up to 0.5	>0.5 to 1	>1 to 2	>2 to 4	>4	All
A. Speed During This Surfacing												
Zero	0	0	0	0	1	1	0	1	0	1	0	2
Slow	1	0	2	19	12	34	0	2	15	44	14	75
Moderate	2	5	2	17	21	47	4	7	17	39	28	95
Fast	0	0	0	0	0	0	0	0	0	0	0	0
Unknown but >0	0	1	0	1	3	5	1	2	4	9	3	19
Milling	0	0	0	0	0	0	0	0	0	0	0	0
Change	2	2	0	1	2	7	0	0	3	7	2	12
Total n	5	8	4	38	39	94	5	12	39	100	47	203
B. Flukes Out at End of Surfacing												
No	5	5	1	24	29	64	5	9	32	82	35	163
Yes	0	2	0	5	4	11	0	2	5	10	2	19
Total n	5	7	1	29	33	75	5	11	37	92	37	182
C. Pre-Dive Flex Before End of Surfacing												
No	5	8	1	28	30	72	5	8	29	73	30	145
Yes	0	0	0	0	0	0	0	0	0	3	0	3
Total n	5	8	1	28	30	72	5	8	29	76	30	148
D. Turns During Surfacing												
None	1	4	0	15	15	35	3	4	22	44	16	89
Right	1	1	1	2	9	14	0	1	2	19	5	27
Left	2	1	0	1	2	6	0	0	2	11	5	18
Multiple	1	2	0	6	1	10	0	2	3	7	3	15
Total n	5	8	1	24	27	65	3	7	29	81	29	149
E. Degrees of Turn During Surfacing												
0	1	4	0	15	15	35	3	4	22	44	16	89
10	2	2	0	1	2	7	0	0	2	6	2	10
20	1	0	0	1	2	4	0	2	0	9	2	13
30	1	0	0	1	0	2	0	0	1	2	1	4
40	0	0	0	1	0	1	0	0	0	4	1	5
50-80	0	0	0	0	3	3	0	0	2	2	2	6
90+	0	0	1	4	2	7	0	0	0	2	0	2
Total n	5	6	1	23	24	59	3	6	27	69	24	129
F. Social Activity During Surfacing												
None	5	5	2	23	23	58	2	9	34	86	41	172
Passive	0	3	0	10	11	24	3	3	2	8	5	21
Active (Excl.)*	0	0	0	0	0	0	0	0	0	0	0	0
Total n	5	8	2	33	34	82	5	12	36	94	46	193

* Surfacings with active socializing were excluded.

TABLE 6.9. Frequencies of various activities among traveling bowhead whales at various (A) received sound levels and (B) signal to ambient-noise ratios (S:N) during icebreaker playbacks. Sound levels and S:Ns are for the dominant 1/3 octave and for the 8.5 s of highest sound level during the 64 s preceding the start of the surfacing. Presentation as in Table 6.8.

	A. Received Level (dB re 1 µPa)					B. Received S:N (dB)				
	up to 80	>80 to 90	>90 to 100	>100 to 111	All	<=0	>0 to 10	>10 to 20	>20 to 31	All
A. Speed During This Surfacing										
Zero	1	0	0	0	1	1	0	0	0	1
Slow	9	8	11	5	33	12	4	8	9	33
Moderate	10	16	13	8	47	21	7	13	6	47
Fast	0	0	0	0	0	0	0	0	0	0
Unknown but >0	1	1	2	1	5	1	1	3	0	5
Milling	0	0	0	0	0	0	0	0	0	0
Change	1	1	1	4	7	1	0	4	2	7
Total n	22	26	27	18	93	36	12	28	17	93
B. Flukes Out at End of Surfacing										
No	11	17	21	14	63	21	5	23	14	63
Yes	3	3	2	3	11	6	0	2	3	11
Total n	14	20	23	17	74	27	5	25	17	74
C. Pre-Dive Flex Before End of Surfacing										
No	11	19	23	18	71	23	5	26	17	71
Yes	0	0	0	0	0	0	0	0	0	0
Total n	11	19	23	18	71	23	5	26	17	71
D. Turns During Surfacing										
None	8	10	12	5	35	17	1	11	6	35
Right	2	2	7	2	13	3	0	7	3	13
Left	1	0	2	3	6	1	0	3	2	6
Multiple	0	1	1	8	10	0	1	3	6	10
Total n	11	13	22	18	64	21	2	24	17	64
E. Degrees of Turn During Surfacing										
0	8	10	12	5	35	17	1	11	6	35
10	0	1	2	4	7	1	0	3	3	7
20	0	1	2	1	4	0	0	2	2	4
30	0	0	1	1	2	0	0	1	1	2
40	0	0	0	1	1	0	0	0	1	1
50-80	0	0	3	0	3	0	0	3	0	3
90+	1	1	0	4	6	1	0	1	4	6
Total n	9	13	20	16	58	19	1	21	17	58
F. Social Activity During Surfacing										
None	14	11	19	13	57	20	6	18	13	57
Passive	4	10	5	5	24	11	1	8	4	24
Active (Excl.)*	0	0	0	0	0	0	0	0	0	0
Total n	18	21	24	18	81	31	7	26	17	81

* Surfacings with active socializing were excluded.

TABLE 6.10. Number of surfacing/dive sequences with specific whale behaviors among traveling bowhead whales at various distances from ice camp (A) during icebreaker playbacks and (B) under control conditions. Specific behaviors shown in Table 5.14 but excluded here were not observed during icebreaker playback tests or associated control periods. Presentation as in Table 6.8.

	A. Distance (km) from Operating Projector						B. Distance (km) from Silent Projector					
	up to 0.5	>0.5 to 1	>1 to 2	>2 to 4	>4	All	up to 0.5	>0.5 to 1	>1 to 2	>2 to 4	>4	All
None	3	2	1	7	10	23	2	4	12	23	14	55
Flukes raised during surfacing	0	1	0	2	0	3	0	0	2	0	0	2
Lunge or surge	0	0	0	1	2	3	0	0	3	1	0	4
Underwater blow	0	1	0	0	0	1	0	0	1	0	1	2
Arch during surfacing	0	0	0	3	2	5	0	0	3	0	2	5
Mouth open	0	0	0	0	0	0	0	0	1	0	0	1
Motionless at surface	0	0	0	1	1	2	0	1	0	1	0	2
Travel along ice edge	1	0	0	1	0	2	0	0	1	1	1	3
Emerge from extens. ice (>1km)	1	0	0	13	6	20	2	3	5	32	9	51
Accompanied by belugas	0	0	0	0	0	0	0	0	0	1	0	1
Visible below surface	0	0	0	1	6	7	0	0	7	14	4	25
Overall n	5	4	1	25	26	61	4	8	31	71	29	143

TABLE 6.11. Number of surfacing/dive sequences with specific whale behaviors among traveling bowhead whales at various (A) received sound levels and (B) signal to ambient-noise ratios (S:N) during icebreaker playbacks. Sound levels and S:Ns are for the dominant 1/3 octave and for the 8.5 s of highest sound level during the 64 s preceding from the start of the surfacing. Specific behaviors shown in Table 5.14 but excluded here were not observed during icebreaker playback tests or associated control periods. Presentation as in Table 6.8.

	A. Received Level (dB re 1 µPa)					B. Received S:N (dB)				
	up to 80	>80 to 90	>90 to 100	>100 to 111	All	<=0	>0 to 10	>10 to 20	>20 to 31	All
None	4	3	9	6	22	7	1	9	5	22
Flukes raised during surfacing	0	0	2	1	3	0	0	3	0	3
Lunge or surge	2	0	1	0	3	2	1	0	0	3
Underwater blow	0	0	0	1	1	0	0	1	0	1
Arch during surfacing	0	3	2	0	5	1	1	2	1	5
Mouth open	0	0	0	0	0	0	0	0	0	0
Motionless at surface	1	0	1	0	2	1	0	0	1	2
Travel along ice edge	0	1	0	1	2	1	0	0	1	2
Emerge from extens. ice (>1km)	1	3	8	8	20	2	2	4	12	20
Accompanied by belugas	0	0	0	0	0	0	0	0	0	0
Visible below surface	2	5	0	0	7	6	0	1	0	7
Overall n	10	14	21	15	60	20	4	19	17	60

All Behavioral Variables Combined

It is often difficult to evaluate changes in behavior when, as in this study, many different intercorrelated measures of behavior are recorded. One useful approach in such situations is the following two-stage procedure: (1) Use factor analysis to reduce the behavioral variables to a smaller number of uncorrelated indices of behavior. (2) Evaluate the relationships between these few behavior indices and environmental circumstances—in this case playbacks of icebreaker noise. This approach was applied in analyzing behavioral results from the *Karluk* drilling noise playbacks (Richardson et al. 1991a:181*ff*, 240*ff*), and it is applied here to the 1994 icebreaker playback data.

We used factor analysis (BMDP4M, release 7.0, 1993) to reduce 15 intercorrelated measures of behavior (Table 6.12) into a smaller number of uncorrelated indices or factors. The list of 15 behavioral variables used here was very similar to the list used in the 1989-90 analysis (*cf.* Richardson et al. 1991a:182). Prior to factor analysis, four of the original measures of behavior were logarithmically transformed to reduce skewness. Several other measures were adjusted, relative to the original coding system, to ensure that their scales were at least ordinal. The observations included in the factor analysis are described in the caption to Table 6.12. Principal components were extracted from the correlation matrix, and the seven components whose eigenvalues exceeded 1.0 were subjected to Varimax rotation. These 7 components accounted for 73% of the variance represented by the 15 original variables.

Relationships between the original variables and the 7 derived behavior indices are shown in Table 6.12. Each index was strongly ($|r|>0.4$) related to two or three of the original variables. The underlying behavioral attribute indexed by each factor can be identified by reference to these heavily-weighted variables. For example, Factor 1 measures the occurrence of turns, which were also associated with whales emerging from under extensive ice. Factor 2 is a measure of the duration of dive and associated behavioral attributes, most notably number of blows per surfacing. The underlying behavioral attribute indexed by Factor 3 is less clear, but there was strong weighting on median blow interval and "visible below surface during dive". Similarly, factors 4-7 can be interpreted by reference to Table 6.12.

Table 6.13 shows the correlation coefficients between all seven behavioral indices (factors) and distance from ice camp, estimated received sound level at whale locations (RL), and estimated icebreaker-to-ambient ratio at whale locations (S:N). For distance (Table 6.13A), correlation coefficients with behavior indices were calculated for the playback periods and, separately, for the control periods. RL and S:N cannot be calculated meaningfully for control data, so only the playback periods are considered in Table 6.13B,C. Correlation coefficients were calculated based on all four of our usual methods for estimating RL and S:N: "BB,med", "BB,max", "1/3,med", and "1/3,max" (see p. 251).

Behavior Factors vs. Distance.—During icebreaker playbacks, none of the seven behavioral indices was significantly related to distance from the projectors ($P_n>0.05$ in each case; Table 6.13A). This is consistent with what was found based on individual behavioral variables. Curiously, one of the seven behavioral indices, Factor 1, was significantly ($P_n<0.01$) correlated with distance from ice camp under control (quiet) conditions (Fig. 6.20B). The reason for this is not

TABLE 6.12. Weighting placed on 15 behavioral variables by seven behavior factors; dominant variables are in boldface[a]. Based on aerial observations of 170 surfacings by traveling bowheads during undisturbed and playback conditions, 1994. Excludes whales engaged in active socializing or aerial behavior; also excludes mothers and calves.

Original Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
No. blows / surfacing (log)	**0.252**	**0.840**	**-0.343**	0.036	0.057	-0.068	0.111
Duration of surfacing (log)	0.249	**0.874**	0.121	-0.014	0.089	0.080	0.132
Median blow interval (log)	-0.019	-0.143	**0.812**	-0.040	0.029	0.195	0.020
Turn (1,2) or not (0)	**0.929**	0.154	-0.004	0.034	-0.056	0.023	0.030
Degrees of turn (log [deg.+1])	**0.939**	0.146	-0.019	0.014	-0.038	0.034	0.009
Change speed (1) or not (0)	0.178	0.220	-0.008	**-0.648**	-0.082	0.143	**-0.353**
Speed nil/slow (1) or not (0)	0.110	0.128	0.165	**0.810**	-0.161	-0.034	-0.158
Group size	0.069	-0.148	0.062	-0.085	**0.664**	**0.403**	-0.036
Passive socializing (1) or not (0)	-0.095	0.152	0.014	0.022	**0.846**	-0.138	-0.001
Flukes out (1) or not (0)	0.016	0.057	0.009	-0.011	0.052	**0.829**	-0.001
Paralleling ice edge (1) or not (0)	0.181	0.001	**-0.388**	**0.523**	0.158	**0.322**	-0.101
Emerge from under ice (1) or not (0)	**0.437**	0.086	-0.213	0.045	**0.278**	**-0.395**	-0.214
Visible below surface (1) or not (0)	-0.010	0.021	**0.863**	0.115	0.043	-0.113	-0.078
Arch in mid-surfacing (1) or not (0)	-0.034	0.193	-0.064	-0.039	-0.083	0.030	**0.813**
Motionless at surface (1) or not (0)	**-0.286**	**0.478**	-0.055	-0.083	-0.224	0.003	**-0.444**
% of variance 'explained' by factor							
Relative to all 15 original variables	19.2	11.5	9.9	9.6	8.4	7.7	7.1
Relative to all 7 factors	26.2	15.6	13.5	13.1	11.5	10.5	9.7

[a] The weighting placed on each variable by a factor is proportional to the absolute value of the correlation coefficient between the variable and factor. Correlation coefficients for variables heavily weighted (| r | > 0.4) are large boldface, and those for variables moderately weighted (0.4 > | r | >0.25) are in boldface.

TABLE 6.13. Correlation of behavior indices (factor scores) for traveling bowheads vs. ***(A)*** distance from projector, ***(B)*** estimated received sound level, and ***(C)*** estimated received signal to ambient-noise ratio during (A,B,C) icebreaker playbacks and (A only) associated control conditions, 1994. Acoustical variables (B) and (C) are measured during the 64 s preceding the behavioral observation. Mothers, calves, and surfacings with active socializing or aerial behavior are excluded. Aerial observations only. P_n is nominal 2-tailed significance level of the correlation coefficient. See Figures 6.20 and 6.21 for scatter diagrams corresponding to boldface correlations involving Factors 1 and 3. Sample size = 36 for every case in (B) and (C).

Behavioral Factor	A. vs. Distance (log km) Condition	r	n	P_n	Acoustical Variable (Measured Over 64 s)		B. vs. RL (dB re 1 µPa) r	P_n	C. vs. S:N (dB) r	P_n
1	*Playback*	**-0.160**	**37**	ns	20-5000 Hz	median	0.373	+	0.392	+
	Control	*0.286*	*90*	*++*		maximum	0.354	+	0.380	+
					Dom. 1/3-Oct.	median	0.395	+	0.420	+
						maximum	**0.404**	+	**0.435**	++
2	*Playback*	-0.116	37	ns	20-5000 Hz	median	0.144	ns	0.162	ns
	Control	*0.078*	*90*	*ns*		maximum	0.142	ns	0.162	ns
					Dom. 1/3-Oct.	median	0.133	ns	0.166	ns
						maximum	0.130	ns	0.167	ns
3	*Playback*	**0.303**	**37**	(+)	20-5000 Hz	median	-0.345	-	-0.271	ns
	Control	*0.114*	*90*	*ns*		maximum	-0.375	-	-0.296	(-)
					Dom. 1/3-Oct.	median	-0.350	-	-0.295	(-)
						maximum	**-0.365**	-	**-0.314**	(-)
4	*Playback*	0.137	37	ns	20-5000 Hz	median	0.116	ns	0.244	ns
	Control	*0.018*	*90*	*ns*		maximum	0.149	ns	0.273	ns
					Dom. 1/3-Oct.	median	0.115	ns	0.228	ns
						maximum	0.127	ns	0.238	ns
5	*Playback*	0.270	37	ns	20-5000 Hz	median	-0.246	ns	-0.152	ns
	Control	*-0.236*	*90*	-		maximum	-0.214	ns	-0.127	ns
					Dom. 1/3-Oct.	median	-0.267	ns	-0.198	ns
						maximum	-0.198	ns	-0.153	ns
6	*Playback*	0.035	37	ns	20-5000 Hz	median	-0.091	ns	-0.051	ns
	Control	*-0.064*	*90*	*ns*		maximum	-0.074	ns	-0.038	ns
					Dom. 1/3-Oct.	median	-0.095	ns	-0.021	ns
						maximum	-0.088	ns	-0.018	ns
7	*Playback*	0.078	37	ns	20-5000 Hz	median	-0.132	ns	-0.123	ns
	Control	*0.061*	*90*	*ns*		maximum	-0.086	ns	-0.087	ns
					Dom. 1/3-Oct.	median	-0.160	ns	-0.152	ns
						maximum	-0.148	ns	-0.146	ns

Factor 1 vs. Range and Sound Level Variables

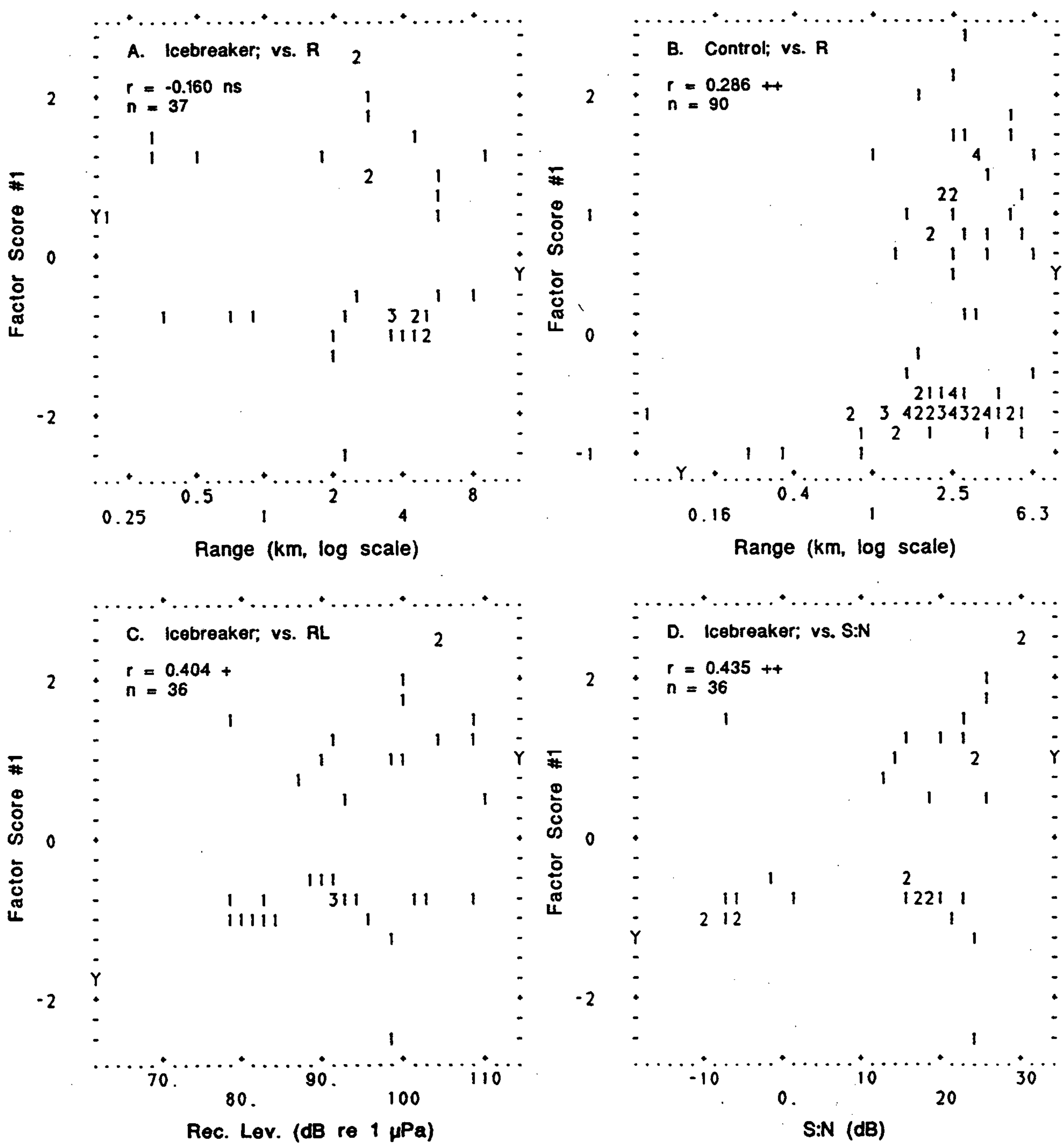


FIGURE 6.20. Factor scores for behavior index #1 in relation to *(A)* distance from projectors during playbacks, *(B)* distance from ice camp during control (quiet) periods, *(C)* estimated received level during playbacks ($RL_{1/3,max}$), and *(D)* estimated icebreaker-to-ambient ratio during playbacks ($S:N_{1/3,max}$). Factor 1 measures the occurrence of turns, which were also associated with whales emerging from under extensive ice. Case selection criteria as in Fig. 6.13.

Factor 3 vs. Range and Sound Level Variables

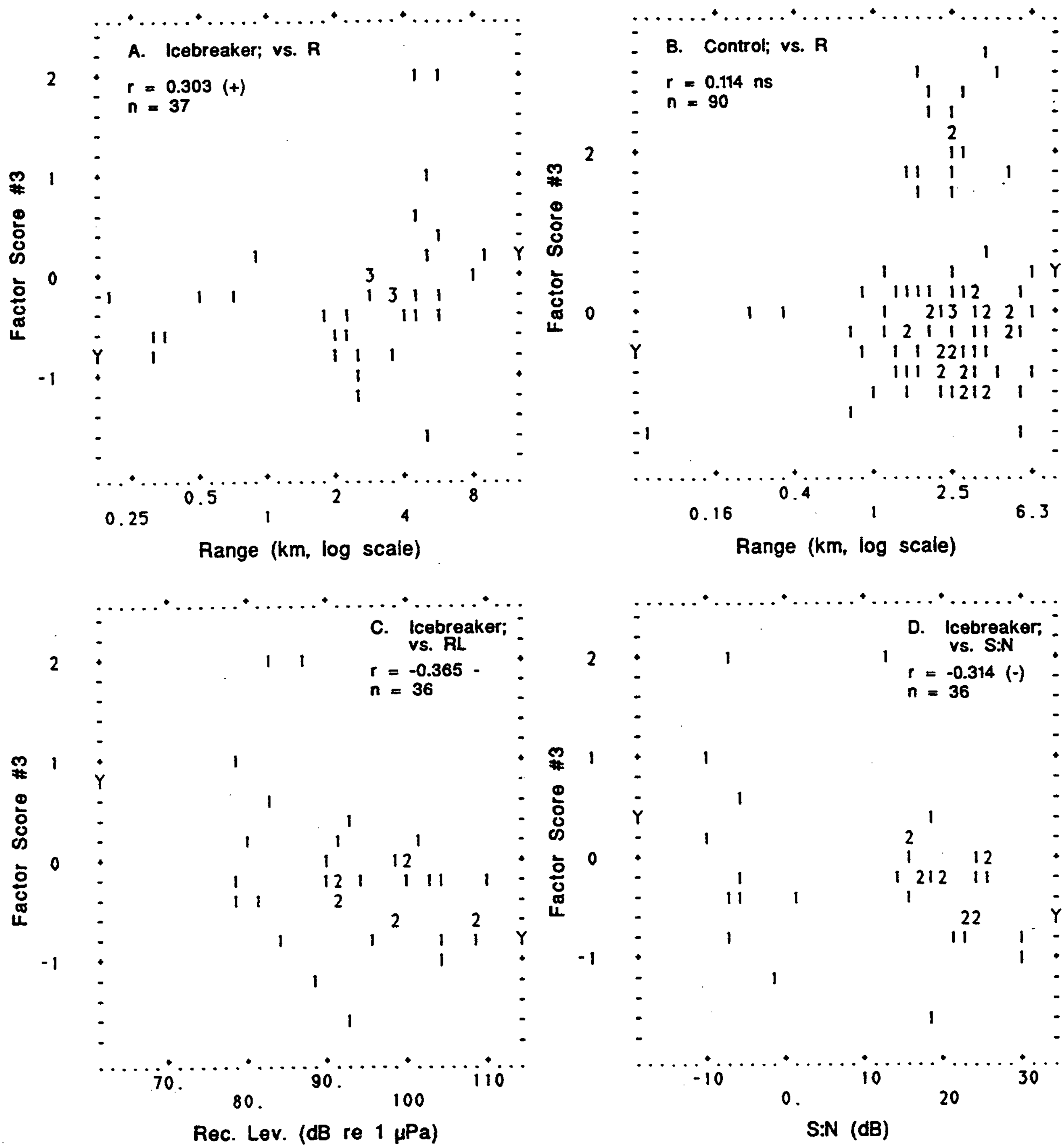


FIGURE 6.21. Factor scores for behavior index #3 in relation to *(A)* distance from projectors during playbacks, *(B)* distance from ice camp during control (quiet) periods, *(C)* estimated received level during playbacks ($RL_{1/3,max}$), and *(D)* estimated icebreaker-to-ambient ratio during playbacks ($S{:}N_{1/3,max}$). Factor 3 included strong weighting on median blow interval and "visible below surface during dive". Case selection criteria as in Fig. 6.13.

known, but the apparent effect was largely attributable to observations during three surfacings—the ones at the lower left corner of Figure 6.20B.

Behavior Factors vs. RL and S:N.—Behavioral index 1 was significantly and positively correlated with all eight measures of RL and S:N (Table 6.13B,C). As noted above, this index was primarily a measure of the occurrence of turns and emergence from under extensive ice (Table 6.12). Figure 6.20C,D shows the relationships between factor (behavioral index) #1 and $RL_{1/3,max}$ or $S{:}N_{1/3,max}$, which were the RL and S:N variables to which factor 1 was most strongly correlated (r=0.404 and 0.435, respectively). This positive relationship between the turning index and icebreaker sound is consistent with previously-described relationships of other simple measures of turning to RL or S:N.

Behavioral index 3 was weakly and negatively related to the RL and S:N variables, in most cases at the $P_n<0.05$ or $P_n<0.1$ levels (Table 6.13B,C). Figure 6.21C,D shows the relationships between factor #3 and $RL_{1/3,max}$ or $S{:}N_{1/3,max}$.

None of the other five behavioral indices identified by factor analysis was significantly correlated with any of the eight measures of RL or S:N ($P_n>0.1$ in all cases; Table 6.13).

Apparent Response Thresholds.—Factor scores could only be calculated for bowhead surfacings when *all* 15 of the variables listed in Table 6.12 were observed. The full duration of the surfacing had to be observed in order to document all 15 variables. Because of the often-windy conditions in 1994, we obtained complete data for an unusually low proportion of the surfacings. During icebreaker playbacks in 1994, there were only 36 usable surfacings when all 15 variables were documented. The 36 usable surfacings include the cases meeting our usual selection criteria: traveling animals, excluding mothers, calves, active socializers, and those exhibiting aerial activity.

This small multivariate dataset corroborates other evidence that certain aspects of behavior (e.g. occurrence of turning) were related to the RL and S:N of icebreaker sound. These relationships occurred within the ranges of RL and S:N values to which these particular bowheads were exposed: estimated $RL_{1/3,max}$ 78-110 dB re 1 μPa, and $S{:}N_{1/3,max}$ -10 to +30 dB (Fig. 6.20C,D, 6.21C,D). The threshold values must be at least a few decibels below the upper limits of these ranges (i.e. at least a few decibels below $RL_{1/3,max}$=110 dB and $S{:}N_{1/3,max}$=30 dB) to account for the existence of non-zero correlations. However, a sample size of 36 is too small to allow a meaningful quantitative determination of the threshold sound level or S:N within these observed ranges of RL or S:N. Full data were available for another 90 surfacings under control conditions near the ice camps in 1994 (Fig. 6.20B, 6.21B). However, those additional data are not directly usable in identifying threshold RL or S:N values.

6.4 Icebreaker Reaction Thresholds and Radius of Influence

Icebreaker Reaction Threshold Criteria

Several estimates of the RL and S:N values above which bowheads showed evidence of reactions have been given in the preceding two sections on distributional and behavioral effects of the icebreaker sound playbacks.

Icebreaker-to-Ambient Ratios.—The strongest relationships between bowhead activities and icebreaker sound levels were often found when we considered the maximum icebreaker-to-ambient ratio in the 1/3 octave of strongest icebreaker sound ($S{:}N_{1/3,max}$). Section 6.2, concerning distributional effects, concluded (with qualifications) that a typical traveling bowhead might begin to divert when the $S{:}N_{1/3,max}$ is **near 20 dB**, with some whales diverting at considerably lower S:N, and some not diverting even at considerably higher S:N (Fig. 6.9). In §6.3, concerning behavioral effects, we found statistically significant evidence that duration of surfacing and number of blows per surfacing both tended to be higher at $S{:}N_{1/3,max}$ values **>20 dB** (Table 6.7C, Fig. 6.17C,F). The frequency of turning during surfacings was significantly increased when $S{:}N_{1/3,max}$ was as low as **10-20 dB**. Attempts to estimate the overall threshold by using factor analysis to consider many behavioral variables simultaneously were hampered by the small sample size after we excluded records missing one or more variables. However, the threshold ($S{:}N_{1/3,max}$ basis) was **at least a few decibels below 30 dB** (Fig. 6.20D, 6.21D).

Overall, these analyses indicate that projected icebreaker sounds often caused alterations in the tracks or behavior of traveling bowheads when the received level of icebreaker sounds in the 1/3-octave band of strongest icebreaker sounds was >20 dB above the ambient level in that band during at least one 8.5-s period within the 64-s period preceding the observation time (i.e., **$S{:}N_{1/3,max}$>20 dB**). Some individual whales showed no obvious reaction even when exposed to higher S:N values, but others reacted at lower levels. Statistically-significant effects on the frequency of turning during surfacings were evident at $S{:}N_{1/3,max}$ as low as 10 dB. The statistical power analyses described on p. 290 and p. 294 show that we cannot exclude the possibility of effects at somewhat lower S:N values.

We have not attempted to identify the threshold based on all other measures of S:N for all other distributional and behavioral measures. However, duration of surfacing and number of blows per surfacing both showed statistically significant (P_n<0.05 or better) "alterations" when $S{:}N_{1/3,med}$ exceeded 20 dB, when $S{:}N_{BB,med}$ exceeded 10 dB, and when $S{:}N_{BB,max}$ exceeded 0-10 dB (Table 6.7C). A lower apparent threshold when playback noise is measured on a broadband than on a "dominant 1/3-octave" basis is consistent with results from the 1989-90 *Karluk* playbacks (Richardson et al. 1991a) and earlier summer playback work (Richardson et al. 1990b).

Received Levels of Icebreaker Sound.—Some measures of bowhead activities were also related to icebreaker sound levels when the acoustic measure was the maximum received level in the 1/3-octave band of strongest icebreaker sound ($RL_{1/3,max}$). Duration of surfacing (P_n<0.05) tended to be higher at $RL_{1/3,max}$ values **90-100 dB re 1 µPa** than at lower RLs (Table 6.7B, Fig.

6.17E). Other measures suggested that the threshold was somewhat higher. The number of blows per surfacing showed a marginally significant tendency to be higher with $RL_{1/3,max}$>**100 dB** than with lower RL values. Likewise, frequency of turning during surfacings was significantly increased (P_n<0.05) when $RL_{1/3,max}$ was **>100 dB**. Results of the factor analysis suggested that the threshold for behavioral reactions ($RL_{1/3,max}$ basis) was **at least a few decibels below 110 dB re 1 μPa** (Fig. 6.20C, 6.21C).

Overall, these analyses indicate that projected icebreaker sounds often altered behavior of traveling bowheads when the received level of icebreaker sounds in the strongest 1/3-octave band was >100 dB re 1 μPa during at least one 8.5-s period within the 64-s period preceding the observation time (i.e., **$RL_{1/3,max}$>100 dB re 1 μPa**). Some individual whales showed no obvious reaction even when exposed to higher RL values, but others reacted at lower levels. Effects on the duration of surfacing may have been evident at $RL_{1/3,max}$ as low as 90-100 dB. Again, power analyses showed that the possibility of behavioral effects at somewhat lower RL values cannot be excluded.

We did not attempt to identify the threshold based on all other measures of RL for all other distributional and behavioral measures. However, duration of surfacing and number of blows per surfacing both showed statistically significant (P_n<0.05 or better) "alterations" when $RL_{BB,med}$ exceeded 100 dB re 1 μPa, and when $RL_{BB,max}$ exceeded 110 dB re 1 μPa (Table 6.7B).

Tolerated Levels of Icebreaker Sound.—Bowheads are believed to be well adapted for hearing low-frequency sounds, probably including some infrasonic sounds below 20 Hz (Ketten 1994). Most acoustic energy emitted by an icebreaker, and essentially all of that emitted by a drilling operation like *Karluk*, is in the low frequency range where bowheads and other baleen whales apparently have good hearing abilities. At these frequencies, bowhead hearing is probably limited by the ambient noise level, not by absolute sensitivity (Richardson et al. in press:236*ff*).

If so, bowheads receiving low levels of icebreaker or *Karluk* sounds, e.g. levels 0-20 dB above the ambient level in the 1/3-octave band of strongest industrial sounds, probably can hear these sounds. However, the majority of bowheads did not exhibit strong, overt reactions unless the received level in the strongest 1/3-octave band was ≥20 dB above ambient. Thus, many spring-migrating bowheads seem to tolerate exposure to weak but presumably detectable icebreaker or drilling noise without exhibiting conspicuous behavioral reactions or avoidance. Tolerance of weak man-made noise has also been observed in some previous bowhead studies in late summer and autumn (Richardson and Malme 1993).

The upper limit of this tolerance varies widely, with some whales showing apparent reactions at received levels well below $S{:}N_{1/3}$=20 dB, and others tolerating considerably higher received levels. On 9 May 1994, bowheads that were apparently feeding near the ice camp lingered there, in two cases coming within 17-24 m of the operating projector where $RL_{BB,max}$ was as high as 135 dB re 1 μPa and $S{:}N_{1/3,max}$ was as high as 44 dB. On 20 May 1994, a traveling bowhead came within 58 m of the operating projectors and was exposed to $RL_{BB,max}$ ~138 dB re 1 μPa and $S{:}N_{1/3,max}$ near 60 dB. The latter whale apparently diverted after it had come close enough to be exposed to those sound levels.

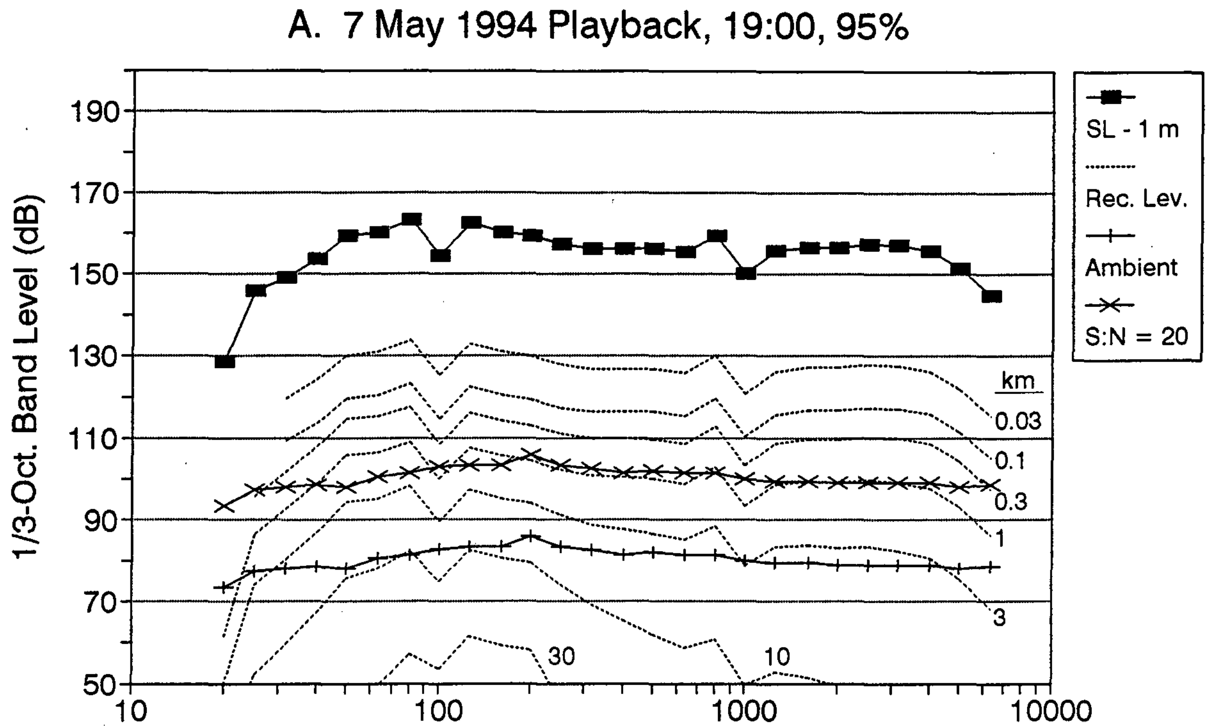
Potential Radius of Influence of Actual Icebreaker

The source level of an actual icebreaker is much higher than the maximum source level that could be emitted by our projectors (Fig. 4.27-4.34, p. 199*ff*). Therefore, bowheads would be expected to detect icebreaker sounds out to a considerably greater radius from the actual icebreaker than from the projectors. Likewise, avoidance or other behavioral reactions are expected to extend out to a greater radius around the actual icebreaker. The playback results can be used to predict potential reaction distances around an actual icebreaker, given a number of assumptions (§1.3).

Figure 6.22A shows, for one part of the playback on 7 May 1994, the estimated 95th percentile received levels in various 1/3-octave bands ($RL_{1/3,95\%}$, in dB re 1 μPa) at distances ranging from 0.03 to 30 km from the projectors. These are the levels exceeded 5% of the time during the 14-min cycle of icebreaker sounds. This "95th percentile" measure of icebreaker sound is an appropriate one to use in comparisons with observed reaction thresholds based on the $RL_{1/3,max}$ and $S{:}N_{1/3,max}$ measures (maximum 8.5-s segment in a 64-s period). The 0.03 and 0.1 km spectra assume spherical spreading; other spectra are based on the propagation model of §4.3. In the 1/3-octave bands centered at 40-200 Hz, $RL_{1/3,95\%}$ is at or above the ambient level on 7 May at distances out to 5-10 km, and thus presumably detectable to bowheads at those ranges. In the 1/3-octave bands centered at 50-80 Hz, $RL_{1/3,95\%}$ is ~20 dB above ambient at distances near 2 km. As $S{:}N_{1/3,max} \approx 20$ dB is one of the reaction thresholds mentioned above, reactions might be common out to ~2 km from the projectors.

Figure 6.22B shows estimated 95th percentile received levels at various distances if the actual icebreaker *Robert Lemeur*, rather than the projectors, were in operation at the 7 May 1994 playback site. Given the average ambient noise levels that prevailed on 7 May 1994, the actual icebreaker sounds ($RL_{1/3,95\%}$) are predicted to equal or exceed ambient levels in the 1/3-octave bands centered at 80-200 Hz, and thus be audible at those frequencies, at distances up to about 30 km. Likewise, the actual icebreaker sounds would be 20 dB above ambient out to about 10-15 km in certain 1/3-octave bands. Thus, given the propagation conditions and ambient noise level encountered on 7 May 1994, reactions might be expected to be common out to a radius of **~10-15 km** from the actual icebreaker, as opposed to ~2 km from the projectors.

Figure 6.23A,B, shows a similar analysis of the situation on 20 May 1994. Predicted received levels of sound from the actual icebreaker were very similar to those at corresponding ranges on 7 May (*cf.* Fig. 6.22B). Water depths at the two sites were similar (37 m on 7 May; 42 m on 20 May) and, as described in §4.3, water depth is the dominant variable in the acoustic propagation model used to derive the estimated received levels. Although RL estimates for these two sites were similar, the ambient noise level on 20 May 1994 was lower in many 1/3-octave bands. Hence, the estimated received level of icebreaker sound exceeded the ambient level in certain 1/3-octave bands at distances out to well beyond 30 km—farther than expected for the 7 May 1994 situation. At some frequencies, the predicted received level was ≥20 dB above ambient at distances out to ~30 km. Hence, reactions might have been common as much as **~30 km** from the icebreaker if it had been operating in the area on this quiet day.



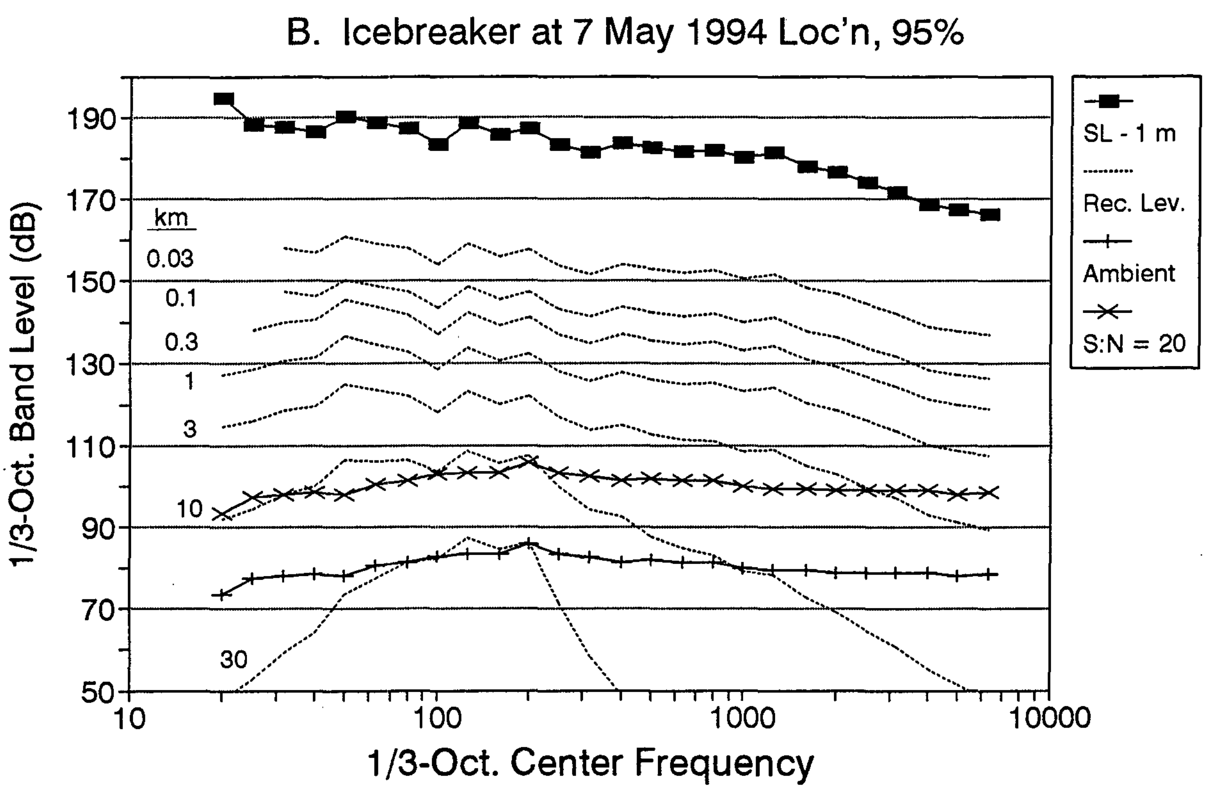


FIGURE 6.22. Estimated 95th percentile source and received levels of icebreaker noise, by 1/3 octave, *(A)* during playback on 7 May 1994, time 19:00, and *(B)* if actual icebreaker were operating at that site. Also shown is the average ambient noise level on 7 May 1994, and "20 dB above ambient", also on a 1/3-octave basis.

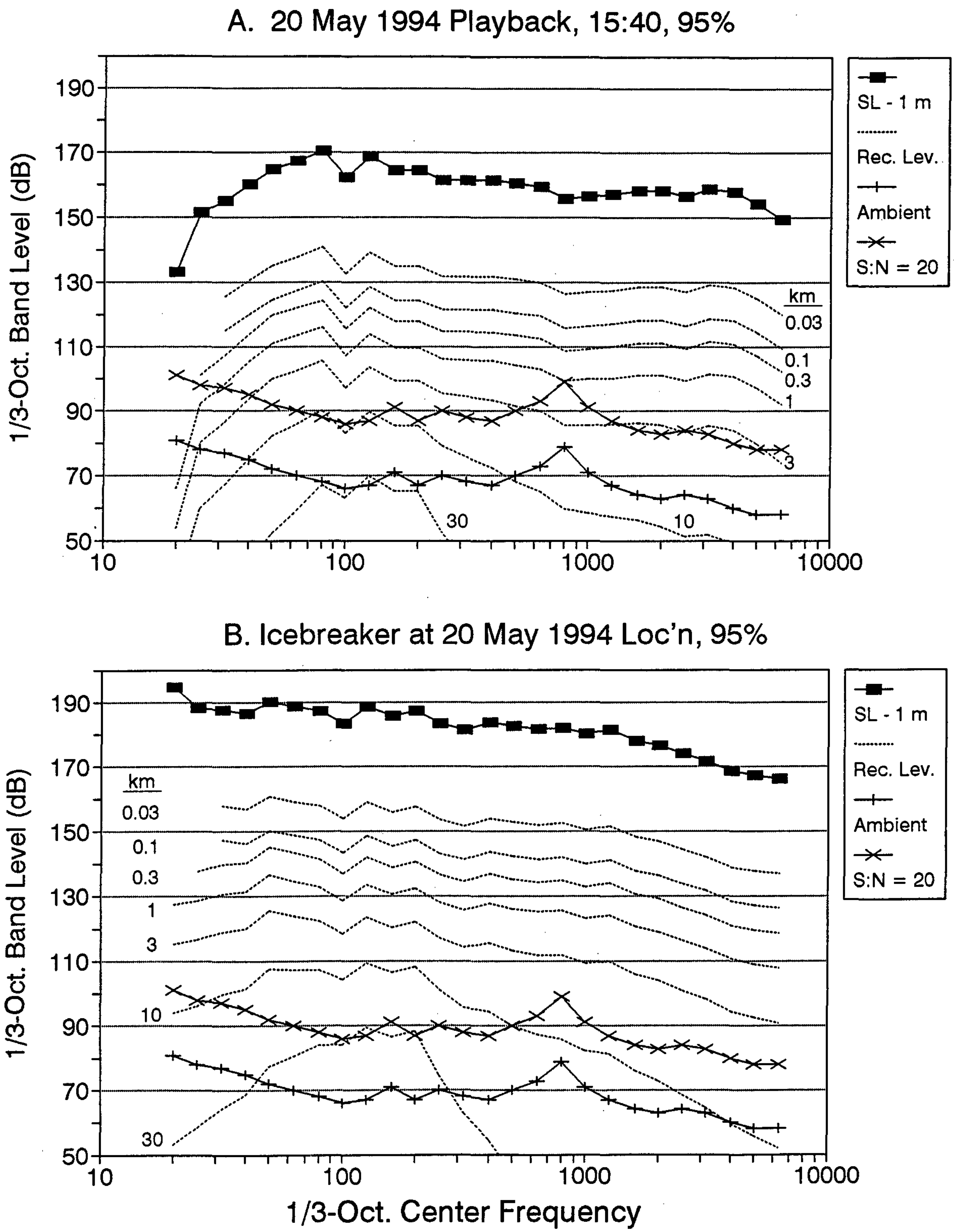


FIGURE 6.23. Estimated 95th percentile source and received levels of icebreaker noise, by 1/3 octave, *(A)* during playback on 20 May 1994, time 15:40, and *(B)* if actual icebreaker were operating at that site. Also shown is the average ambient noise level on 20 May 1994, and "20 dB above ambient", also on a 1/3-octave basis.

Figures 6.24A,B show predicted levels of icebreaker noise vs. range and frequency on the assumption that the icebreaker (rather than our projectors) was operating at two of the deeper playback sites—those where we worked on 17 May 1991 and 3 May 1994 (water depths 110 m and 105 m, respectively). Especially at the lower frequencies, predicted received levels at given distances were higher at the deeper sites (Fig. 6.24 vs. Fig. 6.22B and 6.23B). Predicted received levels in certain 1/3-octave bands were ≥20 dB above ambient at distances out to **20-30 km** in these situations. If the ambient noise level on these occasions had been as low as it was on 20 May 1994, the predicted reaction distance ($S{:}N_{1/3,max}$>20 dB criterion) would have been **~50 km**.

Variability and Uncertainty in Predicted Radius of Influence

The above estimates should be taken only as general indications of the likely radius of responsiveness for traveling bowheads exposed to noise from an icebreaker. The reaction criteria applied here are imprecise as a result of such factors as

- the limited sample sizes and weather problems during the playback tests;
- inevitable differences between playbacks and actual industrial operations, including the inability to project infrasonic noise components, the imperfect fidelity of projected sounds at sonic frequencies, the lower source level during playbacks, the steeper RL vs. range gradient during playbacks at the range where a given RL occurs,[27] and the exclusion during playbacks of non-acoustic cues associated with the actual industrial operation;
- the fact that received levels of icebreaker noise were estimates from the sound exposure model described in §2.3 (p. 46*ff*), not direct measurements; this model may tend to slightly underestimate received levels in the dominant 1/3-octave band (§4.3, p.107*ff*);
- the inherent variability in responsiveness of different bowheads, and probably of the same bowheads at different times or in different circumstances.

In addition to uncertainties in the reaction criteria, physical acoustic aspects vary widely from place to place and time to time. These variations are a result of

- variation in propagation conditions[28],
- among-icebreaker differences in emitted sounds,

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[27] Sound levels that elicit a response from whales might be influenced by the gradient of the sound level with distance. A given level may have more effect if the level increases rapidly with diminishing distance than if level increases more slowly as a migrating whale approaches [see p. 11, item (e)]. The rate of change with distance is generally greater near a source than far away. Whales receiving a given sound level far from a strong source like an icebreaker might show less response than if receiving the same sound level closer to a weaker source like a playback site. Nonetheless, the expected radius of responsiveness around an actual icebreaker would be far larger than that around a playback site. Furthermore, any tendency to overestimate the radius of responsiveness because of this consideration may be partly or entirely offset by the possibility that bowheads would react more strongly to actual icebreaker sound than to a playback of icebreaker sound lacking the infrasonic and other low-frequency components.

[28] Depending on water depth, vertical profiles of temperature and salinity, sea state, ice cover, composition of the sea bottom (including subsea permafrost and compacted sediments), and variations in these phenomena along the propagation path.

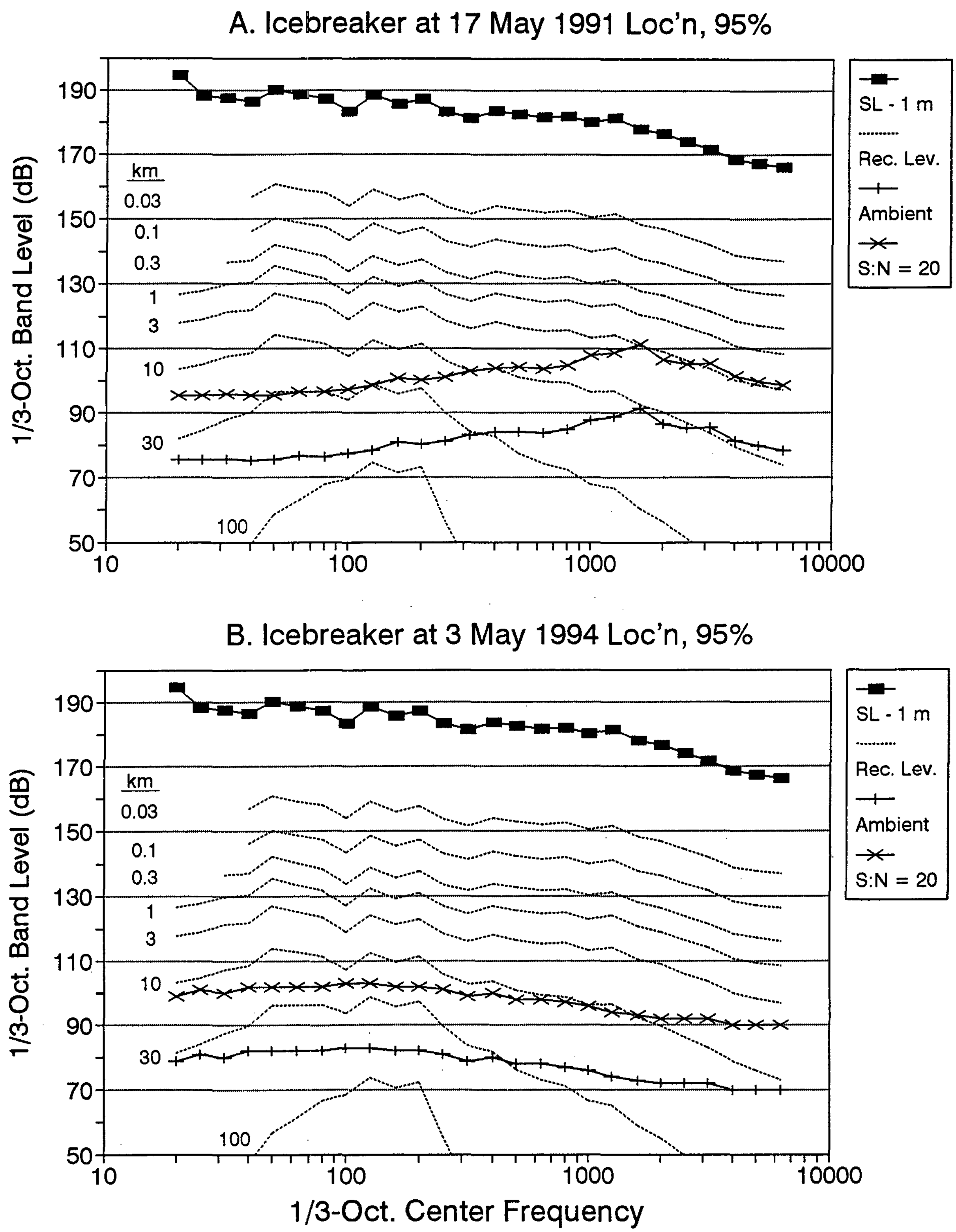


FIGURE 6.24. Estimated 95th percentile source and received levels of icebreaker noise, by 1/3 octave, if actual icebreaker were operating at the deeper sites where playbacks were done on *(A)* 17 May 1991, and *(B)* 3 May 1994. Also shown are average ambient noise levels on those dates, and "20 dB above ambient", by 1/3-octave.

- temporal variability in the source level of a given icebreaker, and
- variation in ambient noise levels.

Given these physical variations, wide variations in S:N ratio will occur at a given distance from the icebreaker. Likewise, there will be wide variations in the distance from the icebreaker at which a given S:N ratio (reaction criterion) will occur.

Playbacks.—Figure 6.25 gives an indication of the very strong influence that variability in physical acoustic phenomena can have on potential detection and reaction distances. The descending received level vs. range curves on these graphs show, for the icebreaker playback on 17 May 1991, the maximum and minimum levels of icebreaker sound expected at various distances during the icebreaker playback. These maximum and minimum levels show the range of values expected during a 14-min playback cycle. In deriving these curves, 4 dB were added to the maximum received level predicted by the sound exposure model, and 4 dB were subtracted from the predicted minimum received level, to account for the ±4 dB uncertainty and variability in the transmission loss estimates (§4.3). Measured ambient noise levels on 17 May 1991 are also graphed as horizontal lines, with one alteration: before plotting, 2 dB were subtracted from the minimum and maximum noise levels (8.5 s averaging time) to allow for short-term variability in the ambient noise (*cf.* Richardson et al. 1991a:55*ff*). Then, distances were noted for which the difference between the maximum icebreaker noise and the minimum ambient noise was S:N=15, 25 and 35 dB. Those distances are shown as vertical lines on the graph.

The distance from the playback source at which the received level falls below the ambient level, and presumably becomes inaudible to a bowhead, varies greatly depending on both the ambient noise level and the icebreaker noise level. In this example, the predicted minimum RL_{BB} falls below the high ambient level at a distance of only about 300 m, whereas the predicted maximum RL_{BB} remains above the low ambient level out to a distance of almost 20 km.

Actual Icebreaker.—As illustrated in Figures 6.22A vs. B and 6.23A vs. B, detection distances for sound from the actual icebreaker would be much greater than those from the playback. The effects of variability in propagation loss, ambient noise, and reaction thresholds evident in Figure 6.25 for playbacks would also apply, on a larger scale, to the actual icebreaker. However, if we assume that it is the peak or near-peak levels of icebreaker sound that are most relevant to bowheads (i.e. $RL_{1/3,\,max}$ or $RL_{1/3,95\%}$), the variability in received level at a given range is reduced from that shown in Fig. 6.25. Figure 6.26 shows zone of acoustic influence models for icebreaker *Robert Lemeur* operating in shallow and deep water, based on predicted 95th percentile levels of icebreaker sound in the 1/3-octave band centered at 200 Hz ($RL_{1/3,95\%}$). This frequency is one of those for which RL and S:N would be highest at long ranges. In Fig. 6.26, predicted received levels are shown ±4 dB, representing the uncertainty associated with variability in propagation loss at a given water depth (§4.3, p. 106*ff*). At close ranges, $R < 2*$(water depth), where the fitted propagation model of §4.3 overestimates propagation loss, spherical spreading is assumed. The received levels shown by the solid curves are the same as those shown, for 200 Hz and selected ranges, in Fig. 6.22B (shallow site) and 6.24A (deep site). The ambient noise levels shown in Fig. 6.26 are the 1991/94 median (and 5th and 95th percentiles) in the 1/3-octave band near 200 Hz

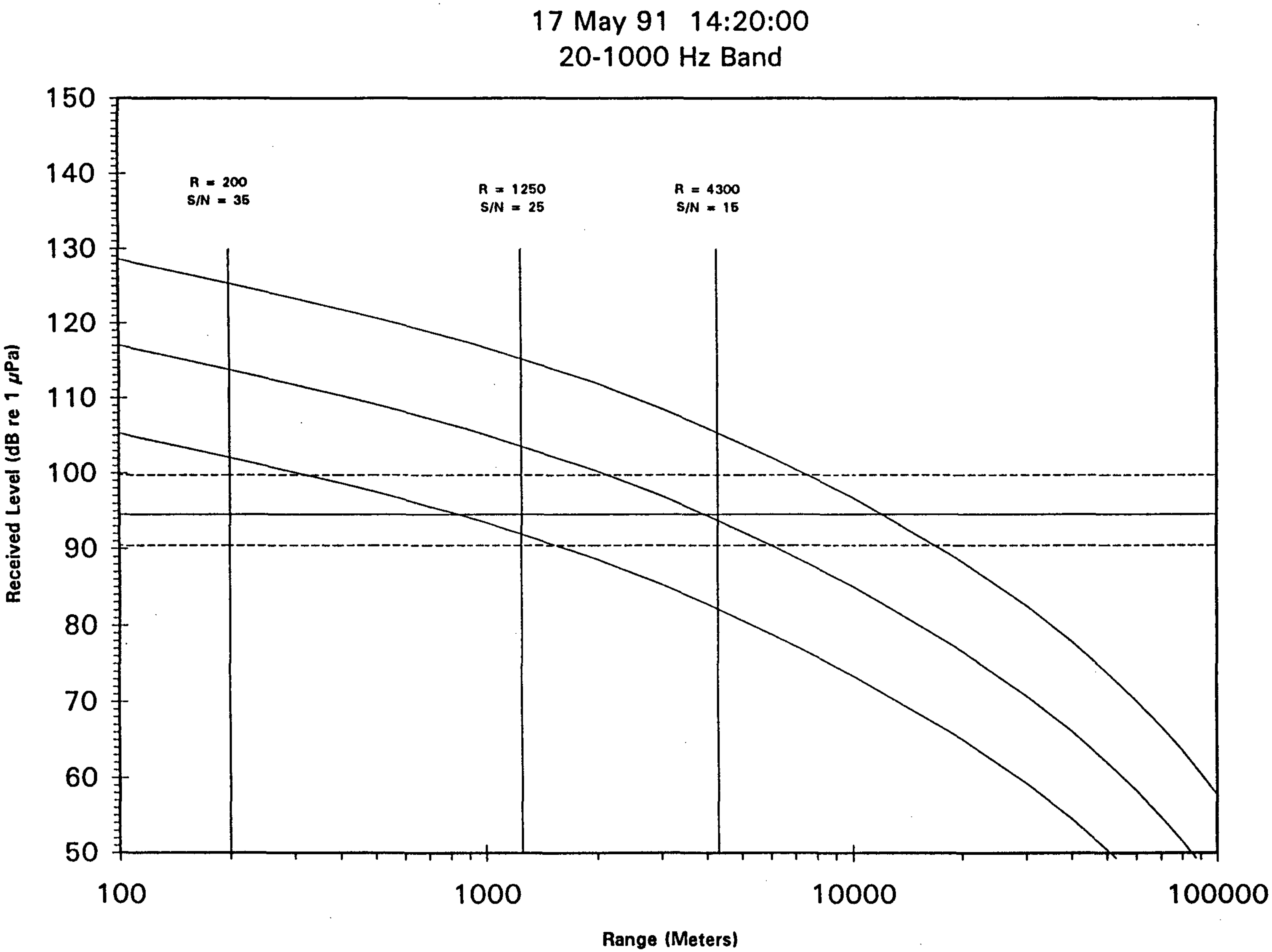


FIGURE 6.25. Example of the effects of variable source level, uncertainty in propagation loss, variable ambient noise, and variation in criterion of responsiveness (S:N 15-35 dB) on potential radius of noise influence. The source levels, propagation model, and ambient noise are appropriate to the icebreaker playback test on 17 May 1991, time 14:20, 20-1000 Hz band. See text for further explanation.

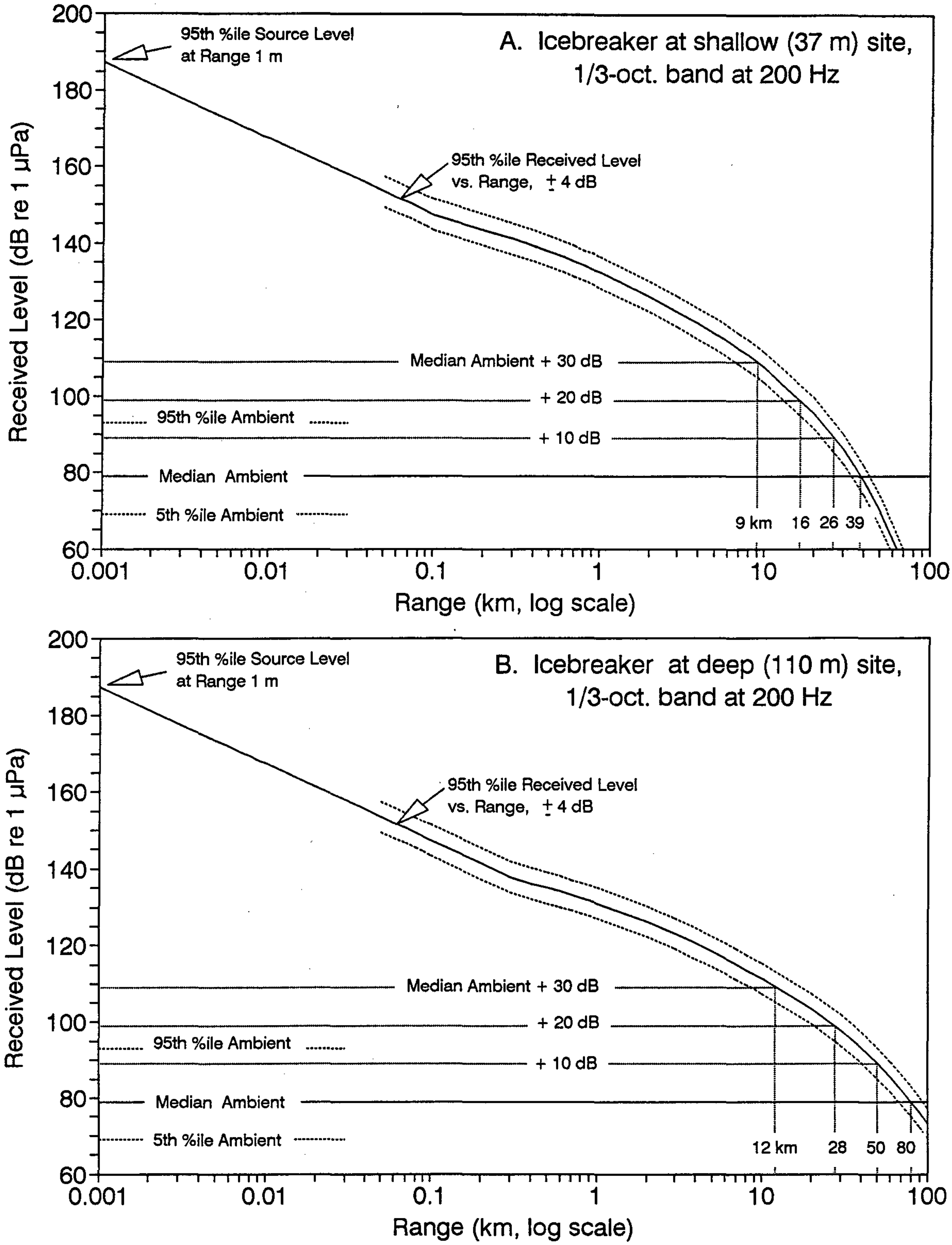


FIGURE 6.26. Zone of acoustic influence models for icebreaker *Robert Lemeur* operating in water *(A)* 37 m and *(B)* 110 m deep, based on predicted 95th percentile levels of icebreaker sound in 1/3-octave band at 200 Hz ($RL_{1/3,95\%}$), ±4 dB model uncertainty (§4.3). Ambient noise levels are 1991/94 median (and 5th and 95th percentiles) in the 1/3-octave band near 200 Hz (Table 4.3C, p. 88).

(from Table 4.3C, p. 88); these values differ from the ambient noise values shown in Fig. 6.22-6.24 for specific dates. Also shown in Fig. 6.26 are the ranges at which the nominal $RL_{1/3,95\%}$ curve diminishes below the ambient, and the ambient + 10 dB, + 20 dB and + 30 dB levels ($S{:}N_{1/3,95\%}$ = 0, 10, 20, 30 dB).

The nominal received level of icebreaker sound near 200 Hz ($RL_{1/3,95\%}$ basis) is predicted to fall below the median ambient noise level, and thus become inaudible, at a range of ~39 km at a shallow (37 m) site, and at a range of ~80 km at a deeper (110 m) site. These ranges would be reduced to ~21 km and ~35 km on a day, respectively, when the ambient noise was at the 95th percentile level. There would be a further reduction to ~18 km and ~30 km if the ambient noise were at the 95th percentile level and propagation loss were 1 standard error (4 dB) more than the average. Conversely, with ambient noise at the 5th percentile level, the maximum range of audibility would be near 50 km at a shallow site and >100 km at a deeper site. Thus, maximum detection distance for the near-peak (95th percentile) levels of *Robert Lemeur* icebreaking sound would be expected to range from a low of about 18-30 km to a maximum of 50 to >100 km, depending on water depth, ambient noise level, and propagation conditions.

The predicted distance out to which bowheads would commonly show avoidance or other behavioral reactions can be estimated from Fig. 6.26 in a similar way if we assume that reaction thresholds to the actual icebreaker sound would be similar to those during our playbacks. Reactions appear to be common among bowheads exposed to icebreaker:ambient ratios > 20 dB. The nominal received level of icebreaker sound near 200 Hz ($RL_{1/3,95\%}$) is predicted to fall below the "median ambient + 20 dB" level at a range of 16 km in shallow (37 m) water, and 28 km in deeper (110 m) water. The ±4 dB variability in propagation loss results in some variability in these estimates, i.e. 13-21 km in shallow water and 20-35 km in deep water. Also, day-to-day variability in ambient noise levels causes much variation in the predicted ranges at which $S{:}N_{1/3,95\%}$ = 20 dB: about 7-26 km in shallow water and 9-50 km in deep water (with 95th and 5th percentile ambient noise and nominal propagation loss). Allowance for simultaneous variation in both propagation loss and ambient noise would result in further expansion of the spans of predicted $S{:}N_{1/3,95\%}$ reaction distances.

The playbacks showed that some bowheads receiving icebreaker sound with $S{:}N_{1/3,max}$ 10 dB or even less react, whereas other bowheads receiving $S{:}N_{1/3,max}$ 30 dB or even more do not react. Figure 6.26 shows that, with nominal propagation loss and median ambient noise, $S{:}N_{1/3,95\%}$ = 10 dB and 30 dB are expected to occur at 26 vs. 9 km at a shallow site, and at 50 vs. 12 km at a deeper site. These spans of distance expand greatly if one allows, simultaneously, for variation in propagation loss and/or ambient noise level. For example, at the shallower site, a whale reacting at $S{:}N_{1/3,95\%}$ = 10 dB on a day with 5th percentile ambient noise and propagation loss 4 dB less than average would be expected to react at ranges out to ~45 km. In contrast, a whale reacting at $S{:}N_{1/3,95\%}$ = 30 dB on a day with 95th percentile ambient noise and propagation loss 4 dB more than average would not be expected to react at ranges more than ~1¾ km. Corresponding values for the deeper site would be ~95 and ~2 km. Even these extreme spans of predicted ranges may not cover every case, as reaction thresholds ($S{:}N_{1/3,max}$) for some bowheads appear to have been <10 dB, and thresholds for others appear to have been >30 dB (§6.2, 6.3).

In this study, we were not able to determine with certainty whether bowheads were more closely attuned to received levels (RL) of icebreaker sound or to icebreaker:ambient (S:N) ratios. The estimates in preceding paragraphs assume that S:N ratios are more relevant. Because the received level of icebreaker noise is not affected by ambient noise, predicted ranges for a specific $RL_{1/3,95\%}$ are much less variable than are those for a specific $S:N_{1/3,95\%}$. Reaction thresholds of bowheads to playbacks of icebreaker sounds were on the order of 90-100 dB re 1 μPa on an $RL_{1/3,max}$ basis. Predicted ranges for $RL_{1/3,max}$ 90 and 100 dB can be extracted from Figure 6.26. With average propagation loss, these are ~25 and 15 km at the shallower site, and ~48 and 26 km at the deeper site. Again, these spans of ranges widen if one allowed for uncertainty in propagation loss and for the fact that some bowheads may react at $RL_{1/3,max}$ <90 dB re 1 μPa whereas others may not react unless $RL_{1/3,max}$ >100 dB.

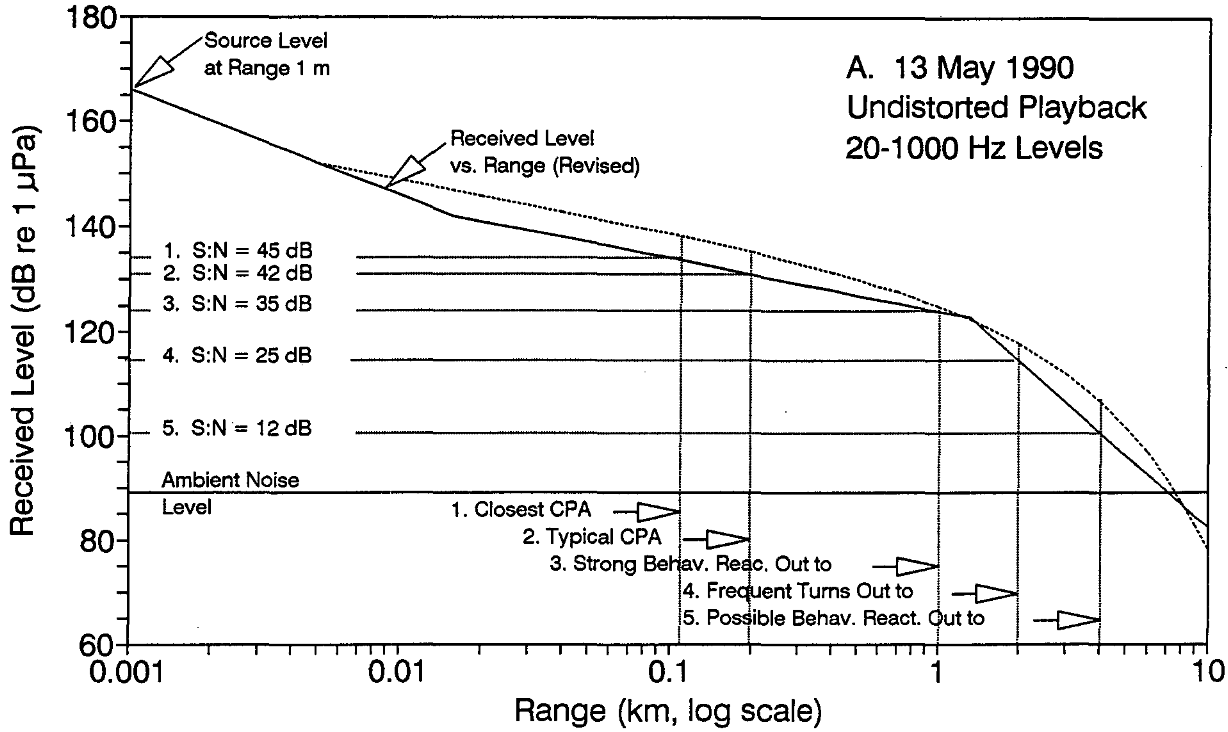
Overall, it is apparent that expected reaction distances are highly variable, depending on the responsiveness of a particular bowhead, water depth, propagation conditions, and probably ambient noise. However, under typical conditions along the spring migration route of bowhead whales off northern Alaska, reactions are expected to be common at distances up to 10-50 km from an icebreaker like *Robert Lemeur*, assuming that reaction thresholds derived from the playbacks can be applied. Occasionally, reactions might occur even farther away in cases involving some combination of unusually responsive whales, deep water, better-than-average propagation, low ambient noise, and/or a noisier icebreaker. In other cases, involving some combination of unresponsive whales, shallow water, poorer-than-average propagation, high ambient noise, and/or a less-noisy icebreaker, some of the bowheads within 10 km of the operating icebreaker may not react.

6.5 Icebreaker vs. Drilling Noise Results

Reaction thresholds for traveling bowheads exposed to playbacks of steady, low frequency sounds from the *Karluk* drilling operation on a grounded ice pad were described in Richardson et al. (1991a). In that report, we concluded that typical traveling bowheads showed avoidance reactions to *Karluk* sounds at RL_{BB} values near 120 dB re 1 μPa when not confined by ice, but tolerated levels up to ~135 dB when there was no alternative route through the ice ($S:N_{BB}$ 26-46 dB). On a "dominant 1/3-octave basis", corresponding figures were $RL_{1/3}$ about 115 or 131 dB re 1 μPa, and $S:N_{1/3}$ 32 or 50 dB. In each case, the higher figure refers to levels tolerated by bowheads with no alternative route through the ice, based on results of a playback experiment on 13 May 1990 (Richardson et al. 1991a:148*ff*).

Sound propagation at the 13 May 1990 playback site has been re-evaluated based on all propagation data collected during the four years of the study (§4.3). This re-evaluation suggests that received sound levels at most distances from the 13 May site were slightly lower than estimated in our earlier report. Figure 6.27 compares the revised (solid curve) and old (dashed curve) estimates of RL vs. range. Based on this reanalysis, the various threshold RL and S:N estimates for bowheads confined by ice should be reduced by ~1-7 dB.

Based on the revised propagation loss estimates, the avoidance threshold for bowheads exposed to *Karluk* sounds was about RL_{BB} 131 dB when confined by ice vs. 120 dB re 1 μPa in



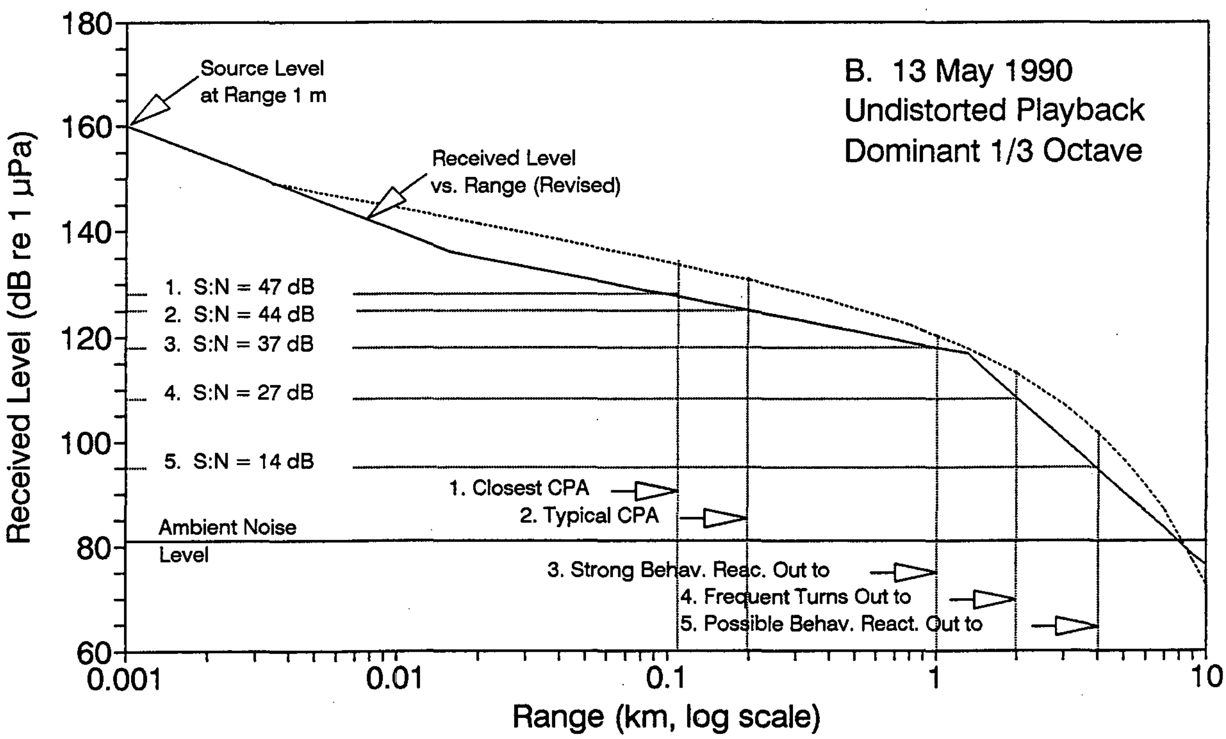


FIGURE 6.27. Zone of acoustic influence models for *Karluk* drilling noise playback, 13 May 1990, based on *(A)* broadband 20-1000 Hz sound levels, and *(B)* levels in dominant 1/3-octave band, centered near 200 Hz. Modified from Richardson et al. (1991a:Fig. 95), with revised propagation loss estimates from §4.3 (p. 109*ff*). Dashed curves are former estimates of RL vs. range.

open conditions. This corresponds to $RL_{1/3}$ 125 vs. 115 dB, $S{:}N_{BB}$ 42 vs. 26 dB, and $S{:}N_{1/3}$ 44 vs. 32 dB (for "confined by ice" vs. "open water" in each case). The "confined by ice" estimates are the RL and S:N values at range 200 m in Figure 6.27. The "open water" estimates are unchanged from those in Richardson et al. (1991a).

As discussed in our earlier report, reaction thresholds to *Karluk* sounds varied widely depending on the criterion considered. Subtle behavioral effects were evident at RL and S:N values lower than those quoted above for active avoidance. In the "confined by ice" conditions on 13 May 1990, subtle behavioral effects may have been evident at $S{:}N_{BB}$ values as low as 12 dB (RL_{BB} 101 dB re 1μPa), and $S{:}N_{1/3}$ values as low as 14 dB ($RL_{1/3}$ 95 dB), based on the updated sound exposure model for 13 May 1990 (Fig. 6.27). Nonetheless, traveling whales typically approached to much closer distances, where they were exposed to RL and S:N values as high as those mentioned in the preceding paragraph.

During the icebreaker playbacks in 1991/94, there were again some indications of different response thresholds depending on the behavioral measure under consideration. For example, the occurrence of turns during surfacings seemed to be increased at $S{:}N_{1/3,max}$>10 dB, whereas duration of surfacing and number of blows per surfacing were not significantly altered unless $S{:}N_{1/3,max}$ >20 dB (§6.3). However, such differences must be interpreted cautiously, given the low sample size and the consequent limitations on the power of the statistical comparisons of observations in different S:N or RL categories (see p. 290*ff*).

In general, the icebreaker playback tests showed that traveling bowheads often reacted behaviorally or by alteration of swimming tracks at icebreaker-to-ambient ratios ($S{:}N_{1/3,max}$ or $S{:}N_{1/3,med}$ basis) as low as 20-30 dB. Subtle behavioral reactions to *Karluk* drilling sounds were evident at similar or slightly lower S:N levels. However, obvious avoidance of *Karluk* sounds required higher $S{:}N_{1/3}$ values, on the order of 32+ dB.

Received levels of sounds from the actual *Robert Lemeur* icebreaker managing ice were much higher than those from the *Karluk* drilling operation at any given distance. Sonic components of *Karluk* sound (>20 Hz) had diminished to 124 dB re 1 μPa at range 0.13 km, and to ≤87 dB (near or below ambient) at 2 km (Richardson et al. 1990a:86). In contrast, broadband noise from the actual *Robert Lemeur* diminished to 124 dB only at range ~6 km (Greene 1987a), and would be >87 dB out to well over 30 km. Broadband (20-1000 Hz) levels of *Karluk* sound received by bowheads during our 1989-90 playbacks were at least as high as those that bowheads would have received at corresponding distances from the actual *Karluk* site. In contrast, icebreaker sounds received by bowheads during our playbacks were similar in broadband level to those that would be experienced by bowheads much farther away from an actual icebreaker. Thus, the radius of responsiveness around an actual icebreaker would be far larger than that around an actual drillsite like *Karluk*, assuming that bowheads react in a similar way to real industrial sites and playbacks.

6.6 Evaluation of Playback Hypotheses

As discussed in §1.2, Null and Alternate Hypotheses, the two null hypotheses applicable to playback effects on bowheads were as follows:

1. Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter *measures of migration routes and spatial distribution of whales* in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
2. Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter *subtle aspects of individual whale behavior* in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

During the 1989-90 work with *Karluk* drilling noise, we found it appropriate to narrow the wording of hypotheses (1) and (2) as follows:

> "Playbacks of recorded ***continuous*** noise from a bottom-founded platform ***like the Karluk drilling operation on a grounded ice pad*** will not (or alternatively will) significantly alter ... of bowhead whales ***visible*** in open water ***amidst the pack ice and in the seaward side of the nearshore lead system*** during spring migration ***east of*** Pt. Barrow, Alaska."

Here "..." refers to either *measures of migration routes and spatial distribution* (hypothesis 1) or *subtle aspects of individual behavior* (hypothesis 2).

Hypotheses 1 and 2 have already been addressed with respect to the effects on bowheads of playbacks of recorded continuous noise from a bottom-founded platform like *Karluk* (Richardson et al. 1991a:226*ff*, 246*ff*). In the circumstances studied,[29] *Karluk* playbacks resulted in statistically-significant small-scale changes in migration routes, spatial distribution, and individual behavior. However, there was no evidence of migration blockage, and we concluded that the observed effects were likely to be biologically non-significant. One purpose of the 1991/94 tests with a second and more variable type of industrial sound was to evaluate the generality of the 1989-90 results.

In 1991/94, as in 1989-90, observations during playbacks were restricted to bowheads visible in open water within areas east of Pt. Barrow. In 1991/94, the playback noise was variable icebreaker noise from *Robert Lemeur* rather than continuous drilling sound, and the observations were on both the landfast ice side and the seaward side of nearshore lead systems, but not in the offshore pack ice. Thus, for 1991/94, hypotheses (1) and (2) should be formulated as

> "Playbacks of recorded ***variable*** noise from an icebreaker **like *Robert Lemeur*** working on ice will not (or alternatively will) significantly alter ... of bowhead whales ***visible*** in the open water of nearshore lead systems during spring migration ***east of*** Pt. Barrow, Alaska."

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[29] For whales visible in open water amidst the pack ice and in the seaward side of the nearshore lead system during spring migration east of Pt. Barrow, Alaska.

The hypotheses, as stated above, concern reactions to *playbacks* of icebreaker noise rather than to noise from the icebreaker itself. Thus, questions about the fidelity of the playback noise to the noise from the original industrial activity are not directly involved. Also, the greater radius of anticipated effects around an actual icebreaker is not directly dealt with by the hypothesis (but see "Implications for Actual Icebreaking", later).

Distribution & Movement Hypothesis/Icebreaker Playbacks

The hypothesis uses the phrase, "*significantly* alter measures of...", but does not define whether "significantly" refers to statistical or biological significance.[30,31] No direct statistical test of the distribution and movement hypothesis was meaningful with the data available. However, many of the bowheads exposed to $S{:}N_{1/3,max}$ levels above about 20 dB, and a minority of those exposed to lower S:N levels, did show changes in their tracks indicative of diversion (see §6.2). Also, statistical tests confirmed that there was a positive relationship between sound exposure level and the frequency and magnitude of turns during surfacings. Therefore, on a "weight of evidence" basis[32], we conclude that there were significant localized diversions of the migration routes of many of the bowheads that came close enough to the noise source to receive maximum levels of icebreaker sound 20+ dB above the ambient noise level in the same 1/3-octave band ($S{:}N_{1/3,max}$ basis). However, there was no evidence of migration blockage during the 1991/94 playbacks.

The spatial scale of this localized diversion was more difficult to judge than had been the case during the *Karluk* playbacks. The highly variable nature of the icebreaker sounds meant that distance was not a good measure of response probability. Responsiveness had to be assessed in relation to sound exposure level, either on a received level or an icebreaker-to-ambient ratio basis. The area around a playback site within which some bowheads showed diversion of their migration tracks, although hard to define, was localized. The migration diversion caused by a single icebreaker playback site comparable to those in this study would not, in our view, be significant to the bowhead population.

Thus, available data allow a "weight of evidence" evaluation of a modified null hypothesis concerning effects of playbacks of icebreaker noise on distribution and movements during spring:

> "Playbacks of recorded ***variable*** noise from an icebreaker **like *Robert Lemeur*** working on ice will not (or alternatively will) significantly alter the migration routes or spatial distribution of bowhead whales ***visible*** in open water of nearshore lead systems during spring migration ***east of*** Pt. Barrow, Alaska."

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[30] By "**biologically significant**", we mean "likely to affect the long-term well-being or reproductive productivity of individuals or of the population".

[31] Another possibility, "**sociocultural significance**", is outside the scope of this study. If icebreaker disturbance caused a change in the migration corridor, the accessibility of bowheads to hunters might be reduced. This could have sociocultural significance.

[32] By "**weight of evidence**", we mean an evaluation considering all relevant datasets and variables, some or all of which are not amenable to specific statistical tests.

There were detectable but inconsistent alterations in migration routes and spatial distribution. There were also statistically significant alterations in measures of turning, which are related to distribution and movements. Thus, we conclude that the null hypothesis should be rejected: playbacks will cause statistically significant alterations in localized migration routes and spatial distribution in the circumstances described in the hypothesis. However, there was no evidence of biologically significant alterations in migration routes or spatial distribution, or of migration blockage. Note that this assessment applies to <u>***playbacks***</u> ***of icebreaker noise, not to noise from an actual icebreaker (see below).***

<u>Behavior Hypothesis/Icebreaker Playbacks</u>

The amended "behavior" hypothesis for 1991/94, consistent with the circumstances in which the 1991/94 data were acquired, is as follows:

> "Playbacks of recorded ***variable*** noise from an icebreaker **like** ***Robert Lemeur*** working on ice will not (or alternatively will) significantly alter subtle aspects of individual behavior of bowhead whales ***visible*** in the open water of nearshore lead systems during spring migration ***east of*** Pt. Barrow, Alaska."

The 1991/94 data show that—from a statistical viewpoint—this null hypothesis must be rejected. There were statistically significant changes in individual behavior among the bowhead whales exposed to the highest received levels and signal-to-noise ratios of icebreaker noise. The number of blows per surfacing, duration of surfacing, occurrence of turning, and two multivariate indices of behavior were significantly correlated with various measures of RL and S:N.

The biological significance of these changes in behavior is less obvious. The altered behavior was not statistically significant until the whales had approached within a few kilometers of the projectors, with the occurrence of effects being more closely related to received icebreaker sound levels than to distance from the projectors. Assuming that behavior was rarely affected at distances beyond 2 km from the projectors, and that bowheads migrate at 4 km/h or more, significantly altered behavior would usually not persist for more than 1 hour as bowheads passed a projector site.

The data provide no objective basis for determining the biological significance of the observed changes in behavior. Our subjective judgement, based on experience in conducting behavioral and other studies of undisturbed and disturbed bowheads, is that the observed behavioral reactions to a single playback site emitting icebreaker (or *Karluk*) sound are biologically insignificant. Again, this assessment applies to <u>playbacks</u> of icebreaker noise, not to noise from an actual icebreaker (see below).

<u>Implications for Actual Icebreaking</u>

The specific hypotheses discussed above concern playbacks of icebreaker sounds. Of much more importance is the likely effect of one or more actual icebreakers. If the two null hypotheses discussed above were reworded to apply to an actual icebreaker rather than playbacks, we would conclude that existing playback data are sufficient to justify rejection of both null hypotheses on statistical grounds, and probably also insofar as biological significance is concerned.

The radius of influence on distribution, movements and behavior around an actual icebreaker would be much greater than that around a playback site, given the much stronger source level of the noise from the icebreaker as compared with the projectors. Playbacks may also underestimate the radius of influence because of the poor reproduction of low-frequency components of icebreaker sound during playbacks (§4.4). ***Response distances around an actual icebreaker would be highly variable but, for typical traveling bowheads, detectable effects on movements and behavior are predicted to extend commonly out to radii of 10-30 km, and sometimes to 50+ km*** (§6.4). This assumes that response thresholds to an actual icebreaker like *Robert Lemeur*, on an S:N or RL basis, are comparable to those near the playback site. This assumption is discussed on p. 10-11 (§1.3) and on p. 115-128 (§4.4). Given that assumption, an actual icebreaker in or near the spring lead system in the NE Chukchi Sea or western Beaufort Sea might affect bowhead whale migration through a broad area of ice for the duration of icebreaker operations.

The predicted "typical" radius of responsiveness around an icebreaker like *Robert Lemeur* is quite variable because propagation conditions and ambient noise vary with time and with location. In addition, icebreakers vary widely in engine power and thus noise output, with *Robert Lemeur* being a relatively low-powered icebreaker. Furthermore, the reaction thresholds of individual whales vary by at least ±10 dB around the "typical" threshold, with commensurate variability in predicted reaction radius.

Notwithstanding these qualifications, there is strong evidence that distribution, movements, and behavior would be altered in a statistically significant manner within a substantial radius, at least on the order of 10-30 km. There is also substantial reason for concern about potential biologically significant effects, given the time that it would take whales to travel through an area 20-60 km in diameter, the potential difficulties in diverting around an area of this size under heavy ice conditions, and the unknown consequences if bowheads were unable or unwilling to pass through or around such an ensonified area.

Of greatest concern would be any diversion or interruption of migration during the late spring when mothers and calves are migrating. During spring, calves are very young and appear to have much less ability than older bowheads to travel through heavy ice conditions. Their swimming abilities seem limited. This is evident from their short dives, the frequent occurrence of "riding", and their frequent lingering in one area for prolonged periods, especially when there is much ice in the area (§5.2, 5.4). There would be fewer situations in which the spring migration corridor in our study area would be sufficiently confined to leave older bowheads with no alternative migration corridor around an area of icebreaking.

It is not known whether bowheads would continue to travel through a strongly-ensonified lead if there were no alternative migration corridor through the ice. Migration blockage probably would be confined to a smaller radius around the icebreaker than would subtler effects on movement and behavior patterns. As observed during the *Karluk* playback on 13 May 1990, when there is no alternative corridor through heavy ice, many spring-migrating bowheads will travel through a strongly-ensonified migration corridor, although their behavior is conspicuously altered while they do so (Richardson et al. 1991a:148). We would expect the same general phenomenon to apply to icebreaker noise. However, the maximum levels of variable icebreaker noise that bowheads would tolerate might differ from the maximum levels of steady drilling noise tolerated during the 13 May 1990 *Karluk* experiment.

In heavy ice conditions, two or more icebreakers often work in coordination with one another within a given area. This would cause a higher overall sound level in the area, and an increase in the size of the area ensonified to levels above various RL or S:N criteria. Also, icebreaker sound would reach some locations from two or more directions. The longest-distance apparent response of bowheads to vessels reported to date (at ≥15 km) involved a mother and calf located between two ships approaching from different directions (Koski and Johnson 1987:54*ff*). On a smaller scale, a common guideline for boat-handling during whalewatching operations is that whales should not be approached from different directions simultaneously, as this often causes more disturbance than does a single boat. Some extrapolation is required to apply these observations to the case of two or more icebreakers operating in one area. However, it would be prudent to assume, unless demonstrated otherwise, that two or more icebreakers operating in an area probably would result in a significantly greater disturbance effect than one icebreaker.

We speculate that any migration blockage of migration that did occur because of icebreaking would cease soon after the icebreaking stopped. This suggests the possibility of partially mitigating any icebreaker-induced blockage that might occur by ensuring that icebreaker operations do not occur continuously in one area for more than some specified duration. The upper limit on the allowable duration of continuous icebreaking would need to be evaluated, but might be chosen not to exceed the durations for which bowheads occasionally interrupt their spring migration for "natural" reasons. The necessary duration of "gaps" in icebreaking in order to allow passage of bowheads would also need to be evaluated.

6.7 Bowhead Reactions to Aircraft

Overflights of bowheads and other baleen whales by low-flying helicopters or fixed-wing aircraft sometimes elicit obvious disturbance reactions, generally involving abrupt dives or sharp turns. Also, bowheads and other baleen whales exposed to aircraft and other human activities sometimes exhibit breaches or tailslaps. Those behaviors often occur in the absence of disturbance, but at times are suspected to be stimulated by disturbance (Richardson et al. in press). Reactions of bowheads to aircraft have been described and reviewed by Richardson et al. (1985a) and Richardson and Malme (1993). Before this study, most of the data on reactions of bowheads to aircraft pertained to summer and autumn.

Bowhead Reactions to Bell 212 Helicopter

Specific objective 6 in 1991 and 1994 was

> To measure, on an opportunistic basis, the short-term behavioral responses of bowheads and (as possible) white whales visible in open water areas along their spring migration

TABLE 6.14. Incidental observations of bowhead whales near the operating helicopter northeast of Barrow during spring in 1989-1994.

Date	Time	Group Size	Altitude (m)	Lateral Distance (m)	Reaction?	Observ. Platform[a]	Comments
A. Observed During Overflight							
01/05/90	18:25	1	150	0	Yes	H	Dove immediately in short narrow crack
10/05/90	21:05	1	100	500	No	I	Continued travel then dove after 4-5 blows
10/05/90	21:14	1	25	0	No	I/H	Continued travel at surface as helicopter circled then flew over whale and landed
11/05/90	10:07	1	150	?	No	H	Continued travel
11/05/90	10:09	3	150	500	No	H	Continued at surface, including tail slaps
11/05/90	14:38	1	90	?	No	H	No observed reaction as whale traveled NE
11/05/90	18:56	2	150	0	No	T	Controlled overflight, whales began social interactions as helicopter approached and continued after it departed
16/05/90	13:48	2	150	800	No	H	Continued medium speed travel
16/05/90	19:07	1	150	?	No	H	Behavior unknown
24/05/90	13:41	4	100	200	No	H	Continued travel, surfacing twice
01/05/91	18:19	1	75	150	Yes	H	Whales traveling ENE dove immediately
01/05/91	18:20	2	60	1000	No	H	Continued travel ENE at surface
11/05/91	10:28	1	90	?	No	H	No observed reaction as whale traveled E
03/05/94	11:23	1	?	400	Yes?	A	Breached and tailslapped; continued aerial activity for 2.4 h after overflight. Potentially disturbed by sonobuoy launch
03/05/94	22:09	1	250	500	No	H	Continued travel
07/05/94	9:27	1	100	800	No	H	Continued travel
07/05/94	9:30	2	90	800	No	H	Continued travel
07/05/94	9:35	1	150	500	No	H	Continued travel
07/05/94	9:36	2	125	500	No	H	Continued travel
07/05/94	9:39	1	150	0	Yes	H	Dove sharply
07/05/94	9:40	1	150	50	No	H	Sighted below surface while diving at ice edge
08/05/94	15:53	1	75	800	No	H	Continued travel
08/05/94	15:54	2	75	800	No	H	Continued travel
09/05/94	10:14	1	100	300	No	H	Continued travel
09/05/94	10:15	2	100	200	No	H	Continued travel
09/05/94	20:39	1	150	1600	No	H	Continued travel
10/05/94	12:22	1	50	15	No	H	Continued travel
10/05/94	12:25	1	50	250	Yes	H	Dove immediately
10/05/94	12:26	1	50	800	No	H	Travel then dove at ice edge
10/05/94	13:53	1	150	500	No	H	Continued medium speed travel
10/05/94	18:19	1	150	500	No	H	Travel then dove at ice edge
11/05/94	9:03	1	?	1000	No	H	Continued travel
14/05/94	9:13	1	50	300	No	H	Behavior unknown
14/05/94	9:24	1	90	800	No	H	Behavior unknown
14/05/94	9:33	1	90	400	No	H	Behavior unknown
14/05/94	9:36	3	125	200	No	H	Continued rest at surface
14/05/94	9:37	2	0 - 15	100	No	H	Remained at surface while helicopter passed twice and landed within 100 m
14/05/94	9:51	3	0 - 15	500	Yes?	H	At least one whale breached but group remained at surface as helicopter passed, turned around, then landed within 500 m of whales. Whales continued approaching (CPA = 150 m) as helicopter stationary on ice with engines on. Dove at ice edge ~20 s after helicopter landed.
16/05/94	19:04	3	250	100	No	H	Helicopter passed then circled group once for ~1.5 min; whales continued medium speed travel at surface
17/05/94	9:39	1	275	700	No	H	Continued travel at surface
17/05/94	9:44	1	200	800	No	H	Remained at surface near ice edge
17/05/94	9:46	2	150	0	No	H	Continued travel at surface
17/05/94	18:31	2	300	200	No	H	Continued travel at surface
17/05/94	19:49	2	200	400	No	H	Continued travel

TABLE 6.14. Continued.

Date	Time	Group Size	Altitude (m)	Lateral Distance (m)	Reaction?	Observ. Platform[a]	Comments
20/05/94	9:16	1	180	1600	Yes?	H	Breached 3 times 30 s after helicopter passed
20/05/94	9:19	1	90	800	No	H	Behavior unknown
25/05/94	13:56	1	175	1200	No	H	Continued travel
B. Observed Within 2 min of Landing or During Take-off							
13/05/90	11:56	2	60	200	No	I	Continued travel ESE at surface as helicopter lifted off. Helicopter had been operating in area for 13 min while deploying sonobuoy
11/05/91	14:33	1	0	50-100	No	I	Continued travel E, respired at least 6 times as it traveled past helicopter that landed 2 min earlier, paralleling the ice edge
17/05/91	20:38	1	0	700	No	I	Whale surfaced and continued travel E while helicopter landed. Engines were turned off 1.2 min before it resurfaced and blew 8 times
25/05/91	9:53	1	0	125	Yes?	I	Whale surfaced ESE of helicopter 30 s after landing, traveled NE and blew 3 times. Engines were turned off at 09:58:30 and whale resurfaced 15 s later and tailslapped 4 times.
07/05/94	11:06	1	0	240	No	I	No apparent reaction as helicopter landed
07/05/94	11:43	1	0	350	Yes	I	Dove for 1.5 min as helicopter landed, then single blow surfacing 1.5 min later when helicopter stationary on ice with engines on
10/05/94	10:27	2	0	250	No	I	Continued medium speed travel as helicopter landed
20/05/94	10:02	1	0	500	No	I	Dove under ice after 5-6 blows while traveling at medium speed as heli. landed
20/05/94	12:11	1	0-15	190	No	I	Continued travel during helicopter lift off
C. Helicopter Stationary on Ice, Engines Operating, >2 min After Landing							
13/05/90	11:40	1	0	500	No	I	Continued travel ESE as helicopter stationary on ice with engines on
16/05/90	13:36	2	0	450	No	I	Continued travel at surface as helicopter stationary on ice with engines on
16/05/90	13:38	2	0	520	No	I	Continued social activity as helicopter on ice with engines on for 6 min
16/05/90	13:41	2	0	495	No	I	Continued social activity as helicopter on ice with engines on for 6 min
03/05/91	11:58	2	0	300	No	I	Surfaced >2 min after helicopter landed, continued travel ENE at surface while helicopter engines on
03/05/91	11:59	1	0	300	No	I	Surfaced NNW of helicopter 3 min after landing, continued travel ENE, blew 8 times. Helicopter engines were turned off during surfacing
03/05/91	13:35	1	0	600	No	I	Continued travel at surface, blew 4-5 times as helicopter stationary on ice with engines on 6 min after landing
09/05/94	12:30	1	0	230	Yes	I	Subadult surfaced and blew once; then slipped under water without an arch as helicopter stationary on ice with engines on
D. Repeated passes Over Mother & Calf							
16/05/89	11:51	2				I	Mother & calf remained in small, refrozen lead for 2.8 h as helicopter ferried between sonobuoy and camp for a total of 5 passes (see below)
			15-30	100	No	(I)	Calf remained stationary at surface; mother not at surface
			15-30	~150	No	(I)	Calf remained at surface; mother not at surface
			15-30	~125	No	(I)	Calf remained at surface
			15-30	~50	Yes?	(I)	Mother dove
			15-30	500	Yes?	(I)	Mother & calf dove, surfaced in same location <2 min later, then relocated a few minutes later farther to side of helicopter route

[a] I = Ice camp, H = helicopter, T = Twin Otter.

corridor in the western Beaufort Sea to actual helicopter overflights (supplementing limited data from 1989-90).

There were corresponding specific objectives during the 1989 and 1990 phases of the project. This work was assigned a lower priority than the playback work. However, some opportunistic observations concerning responses to the project's Bell 212 helicopter were obtained in all four years. In addition, during 1990 there was one planned overflight of bowheads by the Bell 212 (Richardson et al. 1991a:265). Helicopter sounds were measured in 1989 (Richardson et al. 1990a:81*ff*). The present analysis takes account of the results from all four years of the project.

Methods.—Whenever bowheads were accessible during the springs of 1989-91 and 1994, helicopter-supported work was devoted to noise playback experiments. Aside from the one planned helicopter overflight in 1990, we performed no specific tests of bowhead reactions to the helicopter. However, we kept notes on opportunistic observations of the behavior of bowheads seen near the Bell 212 helicopter including, in most cases, the helicopter altitude and lateral distance from the whales.

Most observations of bowhead whale reactions (or lack of reactions) to the operating helicopter consisted of brief (<3 min) opportunistic sightings made from the helicopter, the ice camp, or the Twin Otter. Probable disturbance reactions were defined as an immediate dive, sudden turn, aerial activity (breach, tail slap), unusually short surfacing, or unusual change in surface behavior during the surfacing. This classification is inevitably somewhat subjective, but is based on our experience in observing the behavior of undisturbed bowheads, and on the characteristics of the obvious reactions to aircraft that sometimes occurred during low altitude overflights. A digital theodolite was used to measure positions of whales in relation to the operating helicopter when observations were made by the ice-based crew. Other estimates of lateral distance were by visual estimate. Altitudes during overflights were in most cases obtained from the aircraft altimeter.

Chi-square tests were used to test for differences in frequency of response in relation to aircraft altitude and lateral distance. Cases when the helicopter took off or landed on the ice during the observation (or landed <2 min before the observation) were included with the overflights in most analyses. Cases in which the helicopter's engines were running but the helicopter had landed >2 min before the whale observation are treated separately.

Results.—During the four years of this study, there were 65 occasions when whale behavior was noted at known lateral and/or vertical distances from the operating helicopter (Table 6.14). Observations of bowheads were made

- during single overflights (n=47; Table 6.14A),
- within 2 min of landing or during takeoff (n=9; Table 6.14B),
- when the helicopter was stationary on the ice with its engines operating >2 min after landing (n=8; Table 6.14C), and
- during multiple overflights of a mother-calf pair (n=1; Table 6.14D),

The mother-calf pair exposed to five low-altitude passes was considered to be a special case, and was excluded from the general analysis, leaving 47 cases of single overflights (Table 6.14A), 56 cases including landing/takeoff cases (Table 6.14A+B), and 64 cases in total (Table 6.14A+B+C).

Frequency of Reactions: Apparent reactions to the helicopter were observed during 10 (15.6%) of these 64 occasions. Apparent reactions consisted of 5 immediate dives (including an abbreviated surfacing), 4 instances of breaching or tailslapping, and one single-blow surfacing. Reactions were noticed when the helicopter was stationary on the ice (1 of 8 cases), within 2 min of helicopter landing (2 of 9 cases), and during overflights (7 of 47 cases). The remaining 54 bowheads or bowhead groups (84.4%) exhibited no overt reaction to the helicopter, and generally maintained their course and continued respiring at the surface.

Although some bowheads appeared to react to the helicopter when it was operating at altitudes up to 180 m ASL and lateral distances as far as 1600 m, most reactions occurred when the helicopter was flying lower and closer to the whales (Fig. 6.28). Of the 8 reactions for which both altitude and lateral distance were known during the overflight, including cases observed within 2 min after the helicopter landed, most reactions (5 of 8 or 62.5%) occurred when the helicopter was operating at altitudes ≤150 m above sea level (ASL) and at lateral distances ≤250 m (Table 6.15, Fig. 6.28, 6.29).

Helicopter Altitude: Altitude ASL during 56 helicopter overflights ranged from 0 m (when bowhead groups were observed during helicopter takeoff or within 2 min of landing) to 300 m (Table 6.14A,B). Altitude was not recorded on two occasions. Thus, there were 54 observations with the helicopter at known altitudes. Immediate dives occurred during 5 of 46 overflights when the helicopter approached at altitudes ≤150 m. In a few additional cases at ≤150 m (2 of 46), other types of reactions, including breaching and tailslapping, were seen. More often, however, no

TABLE 6.15. Bowhead reactions to helicopter overflights in relation to helicopter altitude and lateral distance, 1989-1994. Each bowhead group is counted only once. Includes data from Table 6.14A,B, involving overflights (n=47) and cases when whales where observed within 2 min of landing or takeoff (n=9).

	Helicopter Altitude (m)							
Lateral	≤150		>150		Unknown		Total	
Distance (m)	Reaction	No Reaction	Reaction	No Reaction	Reaction	No Reaction	Reaction	No Reaction
≤250	5	14	0	2	0	0	5	16
>250	2	21	1	5	1	1	4	27
Unknown	0	4	0	0	0	0	0	4
Total	7	39	1	7	1	1	9	47

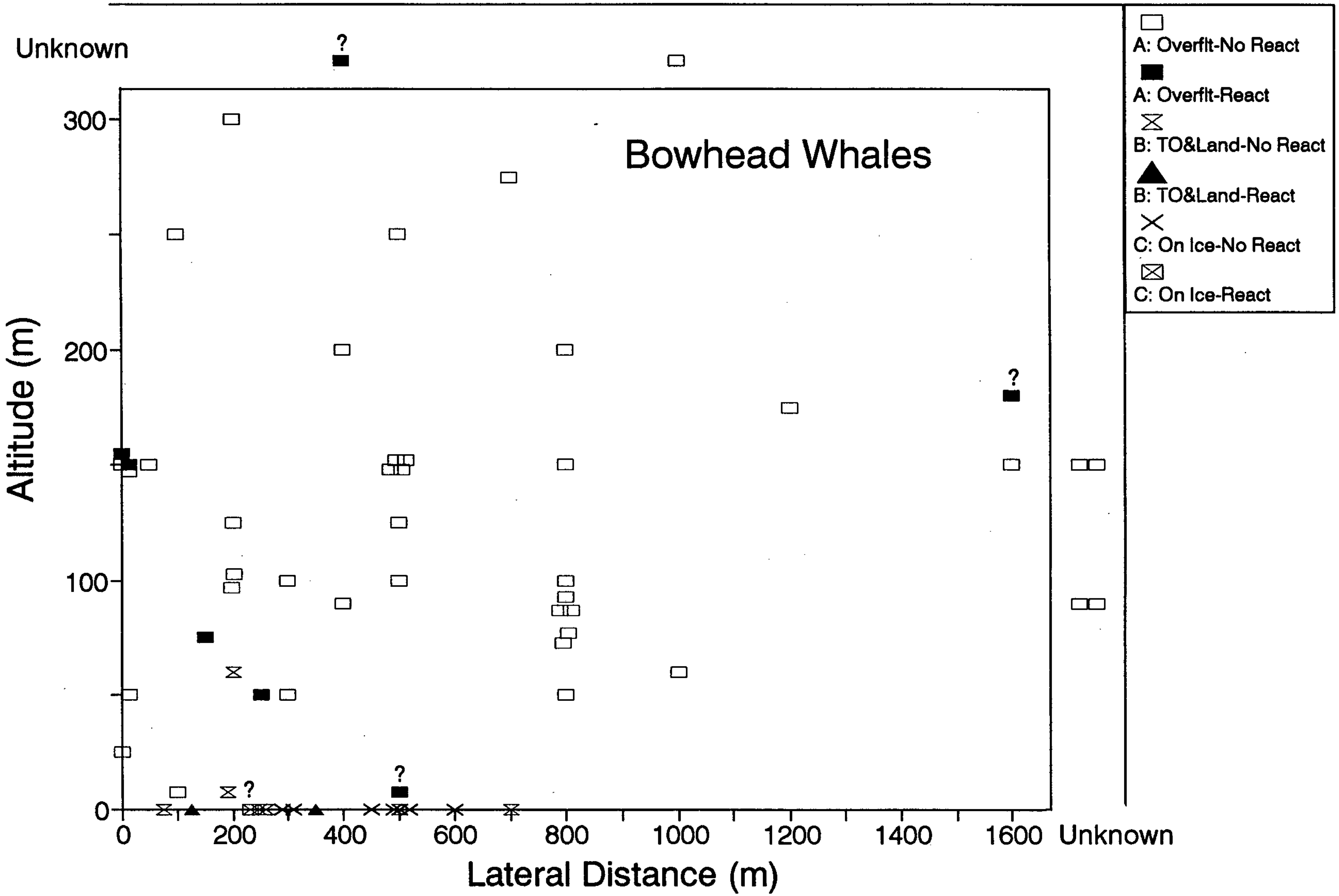

FIGURE 6.28. Reactions of bowhead whales to the operating Bell 212 helicopter in relation to helicopter altitude and lateral distance, 1989-94. Includes cases when helicopter was *(A)* flying, *(B)* taking off (TO) or had landed within preceding 2 min, and *(C)* was on ice with engines running (*cf.* Table 6.14A,B,C). "?" denotes cases where it is uncertain whether the whale was reacting to the helicopter.

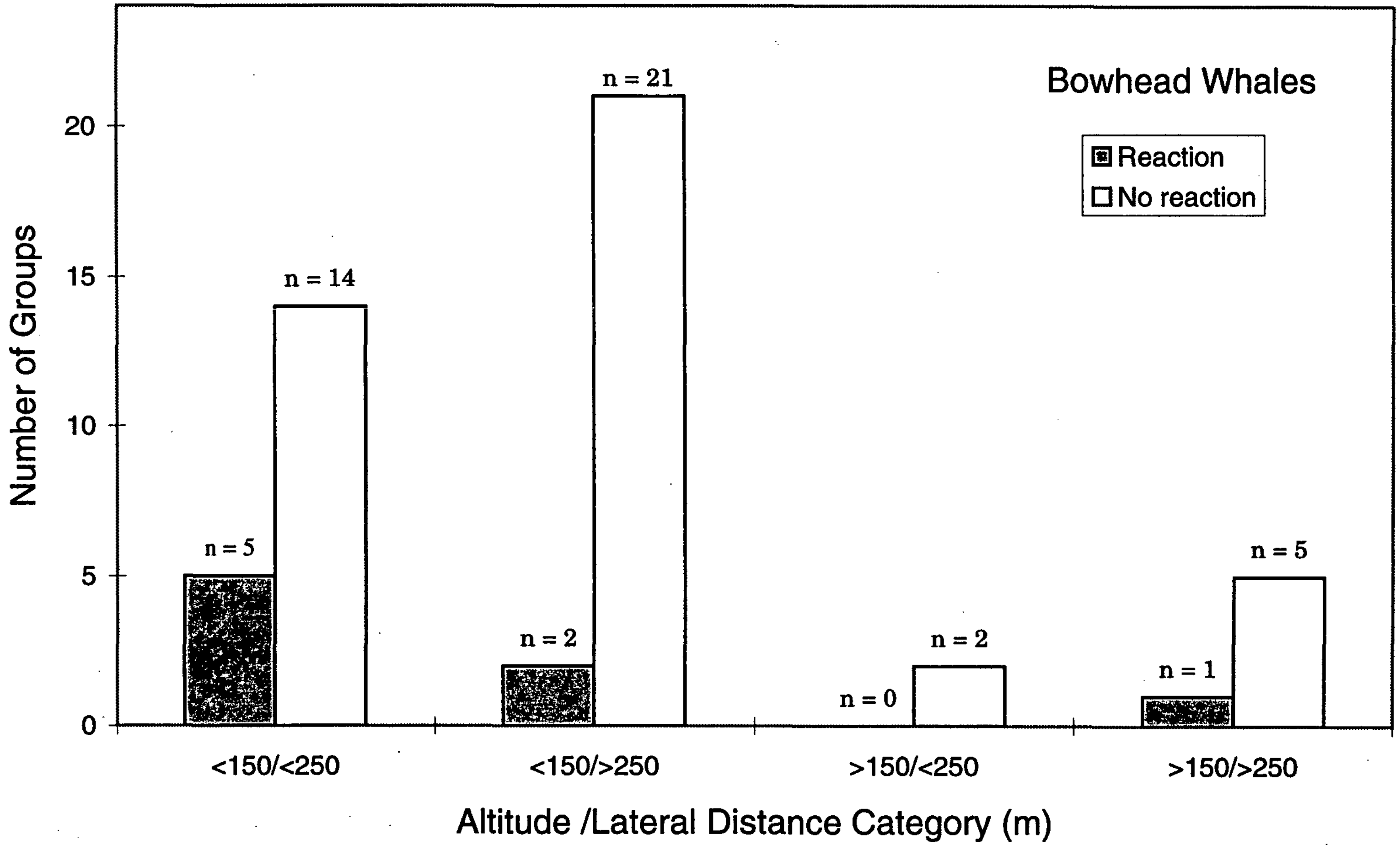

FIGURE 6.29. Reactions of bowhead whales to the operating Bell 212 helicopter vs. helicopter altitude (≤150 m vs. >150 m) and lateral distance (≤250 m vs. >250 m), 1989-94. Includes cases when helicopter was flying, taking off, or had landed within the preceding 2 min (Table 6.14A,B).

immediate reaction occurred when the helicopter approached at ≤150 m (39 of 46 cases). Bowheads often remained at the surface without apparent reaction. The sample size for altitudes >150 m was small. There was no indication that reactions occurred significantly more frequently during overflights at altitudes ≤150 m (7 of 46 groups, 15.2%) than at altitudes >150 m (1 of 8 groups, 12.5%). However, the latter sample size was too small for a meaningful comparison, and the one case of a reaction to the helicopter at a known altitude >150 m involved a pass at altitude 180 m.

This altitude analysis should be regarded with caution. Observers in the helicopter are more likely to notice apparent reactions when the helicopter is at >150 m ASL. Whales are in view for a longer period of time when the helicopter flies at >150 m than when it flies below 150 m, affording better opportunities to detect reactions during flights at >150 m. Thus, the proportion of groups reacting when overflown at altitudes ≤150 m is probably underestimated.

Helicopter Lateral Distance: Lateral distance from helicopter to whales during 56 overflights ranged from 0 m (during direct overflights) to 1600 m (Table 6.14A,B). Lateral distance is unknown for four observations. Based on the 52 observations at known lateral distances, reactions did not occur significantly more often when the helicopter was operating at ≤250 m lateral distance from bowheads (5 of 21 groups, 23.8%) than when >250 m away (4 of 31 groups, 12.9%; chi^2=1.07, df=1, P>0.05) (Table 6.15). However, only one case classified as a potential reaction was noticed at a lateral distance >500 m. A case at lateral distance 1600 m involved a whale that breached three times 30 s after the helicopter passed. Whether the breaches were actually caused by the helicopter is uncertain. In general, it appears that reactions were less frequent (if they occurred at all) at lateral distances beyond 400-500 m from the low-flying helicopter.

Helicopter Stationary on Ice: Few observations were made when the helicopter was stationary on the ice with engines operating (n=8; Table 6.14C). The one whale at distance ≤250 m apparently reacted: a subadult bowhead exhibited a brief surfacing while the helicopter was on the ice at a lateral distance of 230 m. Of the seven cases at distances >250 m (spanning 300-1000 m), no reactions were noticed.

Multiple Helicopter Passes: Most observations involved bowheads that were subject to a single helicopter overflight, or that swam past the ice camp while the stationary helicopter's engines were running. However, in 1989 we observed a mother/calf pair exposed to four close (≤150 m lateral distance) low-altitude (15-30 m ASL) passes by a Bell 212 helicopter plus a fifth pass at 500 m lateral distance (Table 6.14D; Richardson et al. 1990a:211). The mother was at the surface in a newly refrozen lead during two passes, and dove on each occasion. The calf was at the surface during all four close passes, and dove only once. In all four close cases, the low flying helicopter flew within 200 m of the whales and once was <50 m from the mother. These bowheads showed no obvious signs of disturbance other than the dives, which may or may not have been attributable to the overflights. The mother and calf remained near the path of the helicopter for about 25 min after the mother was overflown at close range.

Evaluation of Helicopter Overflight Hypotheses.—Overall, the limited 1989-94 observations show that a minority of spring-migrating bowheads dive or exhibit other short-term behavioral changes in response to a close approach by a turbine-powered helicopter. However, other bowheads show no obvious reaction to single passes—even at altitudes of ≤150 m and lateral distances ≤250 m.

Two of the hypotheses to be evaluated during this study concerned the effects of helicopter overflights on bowheads (§1.2). Those hypotheses were as follows:

- Helicopter overflights will not (or alternatively will) significantly alter measures of migration routes and spatial distribution of whales in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.
- Helicopter overflights will not (or alternatively will) significantly alter subtle aspects of individual whale behavior in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

The evidence available is mostly opportunistic, but is sufficient to indicate that the first null hypothesis—concerning lack of effect on migration routes and distribution—can be accepted, with some qualifications in wording. We conclude, on a weight of evidence basis, that ***single*** overflights by a ***Bell 212*** helicopter do not have ***biologically*** significant effects on the migration routes and spatial distribution of migrating bowheads ***visible*** in open water ***areas amidst pack ice or in*** nearshore lead systems during the spring migration near Pt. Barrow, Alaska. There have been no studies of the effects of other types of helicopters on the migration route and distribution in spring. However, it is worth noting that the Bell 212 used in this project is one of the noisier types of helicopters used by the offshore oil industry.

The second hypothesis concerns helicopter effects on subtle aspects of individual behavior. Most aspects of behavior are difficult or impossible to study during brief, opportunistic observations of the types that have contributed most available data concerning spring-migrating bowheads and helicopters. Therefore, the available data are largely opportunistic. They show that a minority of the bowheads overflown at low altitude exhibit short-term reactions such as abrupt dives and shortened surfacings. Thus, from one perspective, the second null hypothesis can be rejected. However, most if not all reactions seem brief, and obvious reactions occur during only a minority of the low-altitude straight-line overflights. Effects of single overflights, even at an altitude ≤150 m, on the behavior of spring-migrating bowheads may not be biologically significant.

This assessment concerns potential effects of single, straight-line overflights. We obtained very few data on reactions to repeated low-altitude passes (but see Table 6.14D), and no data on reactions to circling or prolonged hovering at low altitude. These types of helicopter flights would be more likely than single, straight-line overflights to cause significant disturbance effects.

Bowhead Reactions to Twin Otter

Tests of bowhead responsiveness to the Twin Otter observation aircraft were not identified as a priority during this study. However, data on reactions to the Twin Otter are of interest with respect to specific objective 7,

> "To document, as opportunities allow, other aspects of the...disturbance responses...of bowheads...",

and in relation to possible effects of the observation aircraft on the whales.

Methods.—During all four years of the project, observers in the Twin Otter noted all cases when bowheads showed behaviors that appeared likely to be in response to the aircraft. Aircraft operations during the project included ▸ extensive aerial reconnaissance, usually flown at altitudes between 150 and 460 m; ▸ systematic behavioral observations from the aircraft while it circled, almost always at 460 m ASL; and ▸ photographic passes directly over bowheads, generally at ~145 m ASL. Numbers of hours of flying of each of these types during each year of the study are shown in Table 3.2. The types of behaviors considered to be possible reactions to the aircraft were the same as during helicopter overflights (see above).

A G test was used to compare the number of apparent responses by altitude category with the number of bowheads seen from each altitude. Lateral distances of bowheads from the aircraft usually were noted only when a reaction was observed. Therefore, we cannot compare the lateral distances of whales that reacted with those of all whales seen.

To test for the possibility of an initial "startle" response when an aircraft begins to circle at altitude 460 m ASL over bowheads, we examined their surfacing, respiration and dive cycles as observed from the aircraft in relation to the number of minutes elapsed since the start of circling. The data used were the same as those used in the multiple regression analyses (SMRAs) of §5.3. We considered only the traveling whales, excluding mothers, calves, actively socializing whales, and surfacings with aerial activity. We also excluded all cases where there were playbacks or any other known source of potential disturbance aside from the observation aircraft. We re-ran the SMRAs of §5.3, adding the following additional variables as potential predictors:

1. minutes after start of circling,
2. minutes after start squared
3. log(minutes after start+1), and
4. whether (1) or not (0) >15 min after start.

Variables (2) and (3) were considered to identify any non-linear effects. Variable (4) was included to identify any effect evident only in the first 15 min of circling. We also examined the frequencies of various categorical measures of behavior during the periods 0-15 min, 15-30 min, 30-60 min, and >60 min after the start of circling.

Direct Observations of Reactions.—During the four spring seasons, only 11 bowhead whale groups were observed to react overtly to the Twin Otter. Eight of the 11 groups involved whales that reacted when overflown at low altitude (120-145 m ASL) during photo sessions, including five groups that reacted during a single photo session on 1 May 1991 (Table 6.16). The other three groups reacted when the aircraft was at 460 m ASL and within 300 m of directly overhead. Reactions consisted of 2 immediate dives, 1 unusual turn, and 8 brief surfacings. Two groups were mother-calf pairs.

The 11 bowhead groups that were seen to react to the aircraft in 1989-94 represent a very small percentage (~2.2%) of the total number of bowhead groups sighted from the Twin Otter in those four years (n=507; Table 6.17). The eight groups of bowheads seen to react to Twin Otter overflights at altitudes ≤182 m represent only 3.7% (8/218) of the total number of groups observed when the aircraft was at ≤182 m ASL. No groups were observed to react to the smaller number of Twin Otter overflights (n=66) at altitudes 183-427 m. The three groups reacting to the aircraft at altitudes >427 m represented 1.3% of the total number of groups observed from those altitudes (3/223). The "altitudinal distribution" of the groups that reacted was not significantly different from that of the groups overflown ($G=5.54$, $df=2$, $P>0.05$).

The number of groups noticed to react to the low-altitude Twin Otter overflights was undoubtedly an underestimate of the actual number of groups reacting. As described previously for helicopter overflights, the probability of detecting a response when it occurred was lower for the low-altitude than for the higher-altitude overflights. The probability of detecting a response during behavioral observations from 460 m ASL was high because, at those times, the observers were watching the behavior of a particular focal group of whales for a prolonged period. Therefore, the tendency for more frequent reactions during low-altitude overflights was probably, in actuality, more pronounced than demonstrated above. If so, the difference in the proportions of whales that did and did not react probably would, if determined more accurately, be statistically significant, as even the observed difference was almost significant at $\alpha=0.05$.

Nonetheless, even after a direct low-altitude overflight, bowheads often do not dive. For example, during one photo session when we specifically tried to maintain a watch on bowheads that had been overflown, we noted on three occasions groups of bowheads remaining at the surface between two overflights at ≤182 m ASL. Two groups, one of which displayed mild social activity, remained at the surface for at least 32 s after a second direct overflight. A traveling bowhead remained at the surface for at least 27 s after a second overflight.

Lateral distance from the Twin Otter to whales that were observed to react ranged from 0 m during direct photo overflights to 300 m during one of the 460 m ASL cases (Table 6.16). Most reactions occurred when the Twin Otter approached within a lateral distance of ≤250 m (10 of 11 groups, 91%; Table 6.16). Eight of 11 reactions occurred during vertical photography sessions when whales were directly overflown at altitudes ≤182 m. The other three reactions occurred when the aircraft was at 460 m altitude and lateral distance ≤300 m. There was no indication of reactions by the much larger number of whales that were circled by an aircraft at an altitude of 460 m and a radius of 1 km.

<u>Behavior vs. Time After Start of Circling</u>.—Comparisons of behavioral variables at various times after the start of systematic behavioral observations from the circling aircraft (altitude 460 m

TABLE 6.16. Cases in which bowhead whales appeared to react to Twin Otter observation aircraft, spring 1989-1994[a].

Date	Group Size	Altitude (m)	Lateral Distance (m)	Comments
14 May 89	1	460	0-50	Dove hastily as aircraft flew almost directly overhead during behavioral observation session
26 May 89	2	145	0	Mother & calf, unusually brief surfacings during photo session
1 May 91	5 groups of 1 to 3 whales	130	0	Several bowheads in at least 5 separate groups showed brief surfacings and rapidly swam away or partly away from aircraft during a vertical photo session
22 May 91	2	152	0	Mother & calf exhibited hasty dives during photo session
9 May 94	1	460	300	Whale abruptly turned, almost stopped, dove with high fluke out during behavioral observation session
14 May 94	4	120	0	Socializing whales exhibited brief surfacings after repeated overflights during a vertical photo session
16 May 94	1	460	200	Whale traveling along ice edge exhibited a single blow surfacing during reconnaissance survey

[a] No groups of bowheads were observed overtly reacting to overflights in 1990

TABLE 6.17. Approximate number of bowhead groups overflown by the Twin Otter aircraft in 1989-1994, and number observed to react to the aircraft.

Year	Altitude Category (m)			Total
	≤182[a]	183-427	>427[b]	
1989	12	21	36	69
1990	17	1	89	107
1991	100	26	25	151
1994	89	18	73	180
Total	218	66	223	507
Reacted	8	0	3	11

[a] 600 ft [b] 1400 ft

ASL) provided no clear evidence of an initial 'startle' response, or of any other relationship between behavior and time after the start of circling at 460 m ASL.

Stepwise multiple regression analyses (SMRAs) to identify variables significantly associated with duration of surfacing, number of blows per surfacing, median blow interval, and duration of dive (Table 5.19) were repeated including, as additional potential predictors, four measures of the "time after the start of circling" (see Methods, above). There was no significant ($P_n \leq 0.05$) simple or partial correlation between any of the four measures of "time after start of circling" and any of the four measures of surfacing, respiration and dive cycles.[33] Perhaps most notably, none of the four behavioral measures was significantly different in either a univariate or a multivariate sense during the first 15 min of the observation sessions than later in the sessions.

The only hint of an effect on any measure of surfacing-respiration-dive cycles was that median blow intervals tended to be shorter in the first 15 min of observation sessions than in the periods 15-30 min or 30-60 min after the start of observations. However, median blow intervals were even shorter 60+ min after the start of observations than they were in the first 15 min (Table 6.18), and the overall difference between the ≤15 min vs. >15 min periods was not significant.

We also tabulated the categorical measures of behavior for surfacings <15, 15-30, 30-60 and 60+ min after the start of aerial observations. There was nothing unusual about the swimming speeds or the frequencies of turns, fluke-out dives, or aerial behavior during the first 15 minutes vs. later in the observation sessions. There was, however, a tendency for more turns and larger turns during surfacings >30 min and especially >60 min after the start of observations than during the earlier parts of observation sessions. The increased turning later in observation sessions probably was not indicative of any aircraft effect, but rather was related to tendencies for increased socializing and increased ice cover later in observation sessions. Those tendencies were to be expected given the criteria that we applied when deciding which whales to observe[34], and also were not likely a result of any aircraft disturbance effect.

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[33] This conclusion, as applied to dive durations, is based on analysis of the durations of dives *following* the surfacing under consideration. When "duration of preceding dive" was analyzed, dives were found to be significantly shorter in the first 15 min of observation sessions than later in the observation sessions. This is an artifact of the fact that any dive whose duration was determined within the first 15 min of an observation session had to be relatively short. The existence of this correlation does not comprise evidence of aircraft disturbance.

[34] Social interactions tended to be more frequent >30 min after initiation of observation sessions, and ice cover tended to become higher late in observation sessions. We tended to select whales that were not actively socializing for observation. Hence, it is to be expected that the frequency of socializing would be low early in the observation sessions, and might increase later in the sessions as some whales transitioned from "travel" to "travel+socializing" or "socializing". Also, we tended to select whales in relatively open water for observation. Hence, it is to be expected that ice cover would tend to increase later in the observation sessions as the whales traveled away from the relatively open locations where observations were initiated. Turns by bowheads at the surface become more common, and larger in magnitude, with increased socializing and with increased ice cover. Therefore, the increased frequency and extent of turns late in observation sessions were to be expected on the basis of the increased socializing and ice cover late in observation sessions.

TABLE 6.18. Surfacing, respiration and dive cycles of presumably-undisturbed traveling bowheads observed from the Twin Otter aircraft in relation to minutes after start of aerial observations. Based on observations from altitudes >427 m ASL in spring 1989-1994; excludes mothers, calves, and surfacings with active socializing or aerial activity.

Minutes	Median blow interval (s)			# of Blows/ Surfacing			Duration of Surfacing (min)			Duration of Dive (min)		
After Start	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n	mean	s.d.	n
≤15	16.95	7.19	74	5.27	3.84	60	1.31	0.95	62	7.23	5.11	45
15-30	19.47	7.13	82	4.21	2.79	82	1.15	0.91	88	5.08	4.67	52
31-60	19.76	8.26	105	4.68	2.93	99	1.30	0.95	99	6.34	5.63	73
>60	16.70	6.86	127	5.42	3.41	111	1.34	0.99	112	8.13	7.04	49
	F = 4.83, df = 3,384 **			F' = 2.56, df = 3,266 (*)			F = 0.71, df = 3, 357 ns			F' = 2.65, df = 3,180 (*)		

Notes: F' = F-statistic not assuming equal population variances (Brown-Forsythe test); ns when P_n>0.1; (*) when 0.1≥P_n>0.05; ** when 0.01>P_n>0.001.

Evaluation of Bowhead Reactions to Twin Otter.—Observations during this project confirm that, during spring migration, bowheads occasionally show evidence of brief disturbance when a medium-sized turbine-powered fixed-wing aircraft flies overhead, or within a few hundred meters to the side, at low altitude. The probability of reaction apparently diminishes with both aircraft altitude and lateral distance. However, regardless of aircraft altitude (within the range ~120 m to 460 m), only a low proportion of the bowhead groups overflown in this study showed evidence of obvious disturbance. The proportion of those overflown at low altitude (e.g., ≤182 m) that reacted to the aircraft was undoubtedly underestimated by some unknown extent in this study.

The cases with overt reactions represent a very small fraction of the total number of bowheads exposed to Twin Otter overflights, regardless of altitude. However, most low-level overflights were made during photo sessions, and bowheads observed from these altitudes were in view for short intervals. Behavioral responses occurring a few seconds after the overflight during a photo session are likely to be missed, as efforts are then being directed at finding new whales.

The analysis of bowhead behavior observed from the Twin Otter circling at 460 m altitude vs. time since start of the observation session provides no evidence of startle effects or other aircraft-related effects on the behavior of the focal animals. This result corroborates our previous conclusion (from summer and autumn studies) that an observation aircraft circling at 460 m altitude, at a low power setting, and at a radius of ~1-1½ km around the bowheads normally does not have significant effects on their behavior.

During studies on the reactions of bowheads to various industrial activities, it has been difficult to obtain quantitative data on the effects of aircraft on bowhead behavior. This difficulty is, to a degree, a consequence of the difficulty in obtaining matched data in the presence and absence of the aircraft. Many of the available behavioral data on bowheads have necessarily been obtained by observations from aircraft, precluding the collection of "control" data in the absence of the aircraft. In addition, the limited data on aircraft disturbance are partly a result of the fact that, during this and previous disturbance studies, studies of bowhead reactions to other types of disturbance have been a higher priority study objective.

The data limitations prevent detailed quantitative comparisons of bowhead reactions to observation aircraft in spring vs. other seasons. However, our general impression is that reactions of spring-migrating bowheads to the Twin Otter aircraft used in this study were consistent in type, frequency and circumstances of occurrence with those seen in previous summer and autumn studies (*cf.* Richardson et al. 1985a,b; Richardson and Malme 1993).

7. WHITE WHALE RESULTS[36]

Although white whales were not the primary focus of this study, the objectives included collecting information, as opportunities allowed, (1) on their movements, behavior and basic biology; (2) on their reactions to playbacks of icebreaker sounds; and (3) on their reactions to helicopter overflights and other aircraft disturbances. Those topics are covered, respectively, in §7.1, 7.2-7.3, and 7.4.

7.1 Distribution & Movements

Specific objective 7 required us to document, as opportunities allowed, the movements, behavior and basic biology of white whales along their spring migration corridor in the western Beaufort Sea.

The sightings during Twin Otter flights, helicopter ferry flights, and ice-based work provided information about the timing and routes of the spring migration of white whales through the study area in 1989-1991 and 1994. Survey effort was not systematic or uniform in different parts of the study area. Hence, the relative numbers of sightings in different parts of the study area must be interpreted cautiously. The results for 1989 and 1990, summarized below, are presented in more detail in Richardson et al. (1990a, 1991a).

Spring 1989

In late April and May 1989, we saw more white whales than bowheads. White whale sightings for the entire study period in 1989 are shown in Figure 7.1; sightings during late April and during 10-day periods in May are shown in Appendix G, Figures G-1 to G-4. Although there was broad overlap in bowhead and white whale distributions, the main migration route of white whales extended farther offshore into the pack ice than did the main route of bowheads. During the latter part of May 1989, when a broad nearshore lead developed along the edge of the landfast ice, the two species migrated both along the lead and amidst the pack ice just north of the lead.

White whales seen in 1989 were most often traveling or resting; there was seldom any indication of feeding and never any active socializing. Migrating whales tended to follow leads or cracks generally ENE, but they changed headings as necessary to remain within open-water areas. The vector mean heading of white whale groups seen in 1989 was 77°True, but headings from 0° to 130° were common (angular deviation 55°, Table 7.1B). Several groups of white whales were seen resting quiescent beneath the thin ice covering recently-refrozen cracks amidst heavy pack ice. In one case, a group of ~25 white whales vigorously swam back and forth between two holes ~15 m apart, apparently trying to keep the holes from freezing over.

[36] By W.R. Koski, G.W. Miller, N.J. Patenaude, W.J. Richardson and M.A. Smultea

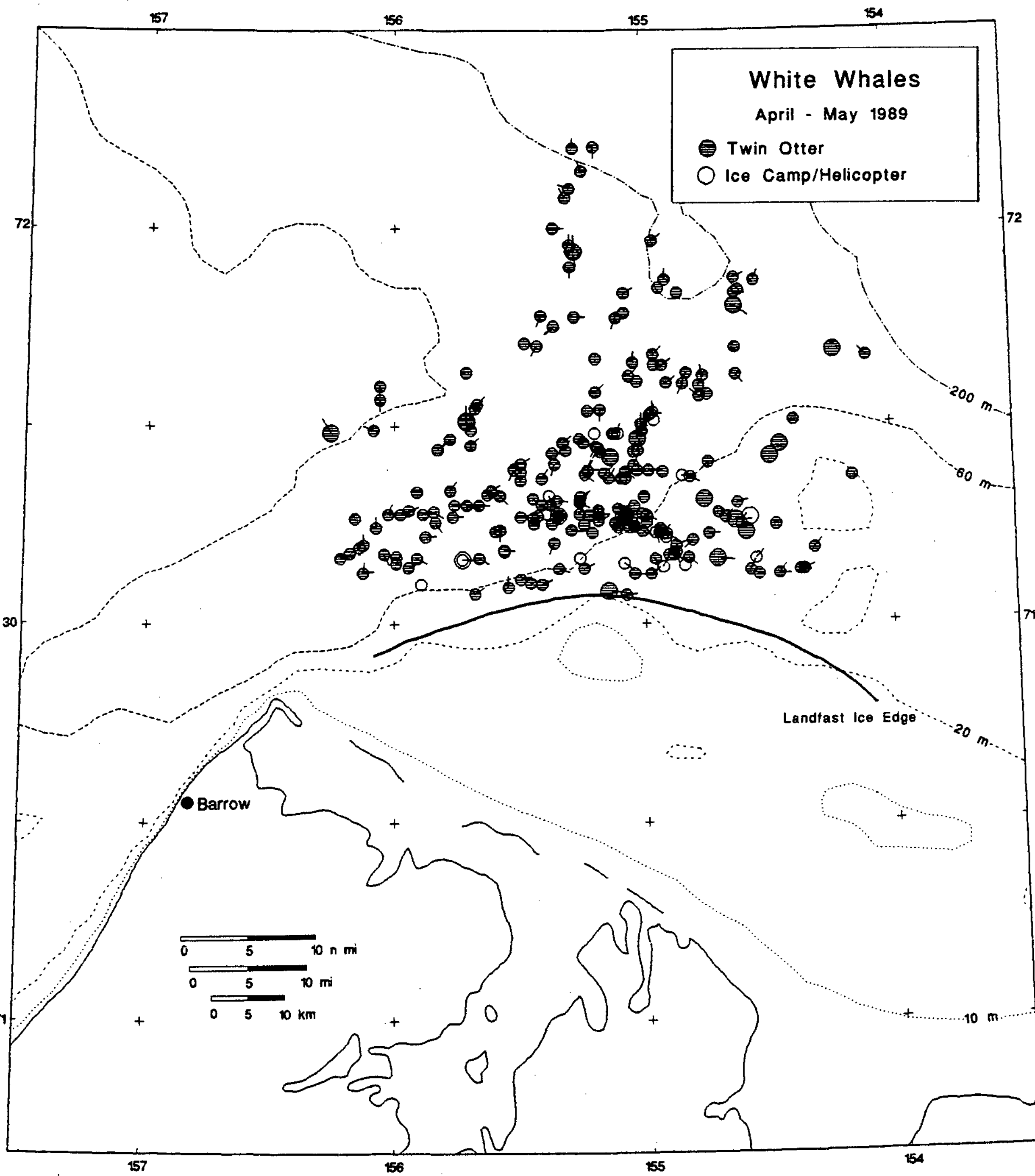

FIGURE 7.1. LGL sightings of white whales, 30 April to 29 May 1989. Symbol type distinguishes sightings by the two crews and sightings of 1-14 whales (small circles) vs. 15+ whales (large circles). Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped.

TABLE 7.1. Headings (True) of white whale groups by date, year and part of study area. Each group is counted only once.

True Heading	A. By 10-Day Period April	1-10 May	11-20 May	21-31 May	TOTAL	B. By Year 1989	1990	1991	1994	TOTAL	C. By Part of Study Area West	South Central	South East	North Central	North East	TOTAL	True Heading
0 N	**0**	**12**	**14**	**1**	**27**	**11**	**0**	**13**	**3**	**27**	**2**	**8**	**2**	**6**	**8**	**26**	**N 0**
10	0	7	9	0	16	4	0	8	4	16	0	7	1	6	3	17	10
20	0	5	5	2	12	5	0	4	3	12	0	7	1	1	3	12	20
30	0	16	20	13	49	17	4	20	8	49	3	13	10	4	19	49	30
40	0	4	6	4	14	5	1	6	2	14	2	3	6	2	1	14	40
50	1	15	10	34	60	16	8	18	18	60	4	13	27	6	10	60	50
60	0	10	21	17	48	12	0	28	8	48	7	19	8	3	10	47	60
70	3	9	18	24	54	14	1	31	8	54	13	25	11	0	5	54	70
80	2	18	41	20	81	12	22	34	13	81	6	46	24	3	2	81	80
90 E	**2**	**21**	**56**	**24**	**103**	**32**	**5**	**49**	**17**	**103**	**11**	**45**	**29**	**5**	**13**	**103**	**E 90**
100	0	9	24	15	48	7	8	26	7	48	2	27	11	3	4	47	100
110	0	3	9	7	19	3	2	14	0	19	2	11	6	0	0	19	110
120	0	13	20	30	63	16	12	31	4	63	3	34	15	7	4	63	120
130	0	3	10	12	25	9	7	8	1	25	1	10	7	0	7	25	130
140	0	7	5	1	13	3	1	8	1	13	1	10	1	0	1	13	140
150	0	5	11	3	19	4	0	13	2	19	0	10	6	0	3	19	150
160	0	6	3	1	10	3	0	5	2	10	0	6	1	0	2	9	160
170	0	6	0	10	16	3	5	8	0	16	0	4	5	3	4	16	170
180 S	**0**	**8**	**4**	**4**	**16**	**6**	**1**	**9**	**0**	**16**	**1**	**7**	**0**	**3**	**5**	**16**	**S 180**
190	0	3	2	1	6	0	0	4	2	6	0	4	1	0	1	6	190
200	0	0	7	1	8	3	0	4	1	8	0	2	0	2	2	6	200
210	1	6	8	5	20	8	2	9	1	20	0	9	0	3	8	20	210
220	0	1	1	2	4	0	0	4	0	4	0	0	2	1	1	4	220
230	0	3	5	1	9	5	0	3	1	9	0	3	2	3	1	9	230
240	0	2	5	0	7	0	0	6	1	7	0	3	3	1	0	7	240
250	0	1	1	0	2	0	0	1	1	2	0	0	0	1	1	2	250
260	1	2	1	2	6	0	2	3	1	6	0	4	2	0	0	6	260
270 W	**0**	**2**	**3**	**0**	**5**	**0**	**0**	**5**	**0**	**5**	**0**	**2**	**1**	**1**	**1**	**5**	**W 270**
280	1	0	1	0	2	0	0	2	0	2	0	2	0	0	0	2	280
290	0	1	2	1	4	1	2	1	0	4	0	2	0	1	1	4	290
300	0	3	1	2	6	2	1	3	0	6	0	2	2	2	0	6	300
310	0	3	2	0	5	1	0	4	0	5	0	3	1	0	1	5	310
320	1	4	1	1	7	5	0	2	0	7	0	3	2	0	2	7	320
330	0	7	3	0	10	3	0	7	0	10	0	3	0	3	4	10	330
340	0	3	2	1	6	1	0	4	1	6	0	2	1	2	1	6	340
350	0	4	2	0	6	1	0	3	2	6	0	2	0	3	1	6	350
Total	12	222	333	239	806	212	84	398	112	806	58	351	188	75	129	801	Total
Vector																	
Mean	67	72	83	87	82	77	97	86	69	82	75	90	82	48	69	82	
Length	0.40	0.42	0.59	0.70	0.57	0.54	0.69	0.53	0.70	0.57	0.87	0.60	0.68	0.29	0.42	0.57	
Ang.Dev.	63	62	52	44	53	55	45	55	44	53	29	51	46	68	62	53	

Spring 1990

White whales were seen much less regularly in 1990 than in 1989 (Fig. 7.2; see also Appendix G, Fig. G-5 to G-8). This was in part due to changes in survey effort within the study area. In 1990 we found many bowheads during surveys along, and just north of, the nearshore lead adjacent to the landfast ice. Therefore, we did not spend as much survey effort in areas farther offshore where white whales may have been more common. When seen, white whales were migrating steadily NE and E through the pack ice or along the north side of the main nearshore lead. The vector mean heading was almost due east (97°T). The white whales observed in 1990 deviated from their mean heading less than did those observed in 1989; the angular deviation was 45° in 1990 vs. 55° in 1989 (Table 7.1B). In 1990, unlike 1989, we did not see white whales whose migration was blocked by heavy ice.

Spring 1991

Although priority was given to finding bowheads, sightings of white whales were more numerous than those of bowheads (Fig. 7.3 vs. 5.3). We recorded ~1995 white whales in comparison to ~307 bowheads during Twin Otter flights in 1991 (Appendix A, Table A-2).

In 1991, there was much more survey effort between 71°30'N and 71°40'N than in areas farther north. Hence, the sighting maps undoubtedly underestimate the numbers of white whales in the northern parts of the study area relative to the numbers in the central portion. Also, as in other years, there was less survey effort near the eastern and western edges of the area mapped than in the middle of the study area.

Substantial numbers of white whales were seen throughout the 1991 field season (28 April to 26 May; Appendix G, Fig. G-9 to G-12). They were seen much more regularly in 1991 than in 1990. In 1991, as in past years, white whales were seen in the same areas where bowheads were seen (Fig. 7.3 vs. 5.3). However, at least during the first two weeks of our 1991 field season, there was a tendency for the main migration route of white whales to be somewhat farther offshore than that of bowheads (Appendix G, Fig. G-9, G-10 vs. Fig. 5.5, 5.6).

The vector mean heading of white whales observed in 1991 was almost due east (86°), but they frequently deviated from this heading (angular deviation=55°, Table 7.1B). They were seen heading in all possible directions, but most commonly NE, E and SE (30°-120°T).

Spring 1994

In 1994, as in 1989 and 1991, more white whales were sighted than bowheads. We recorded ~1282 white whales compared to ~790 bowheads during Twin Otter flights in 1994 (Appendix A, Table A-3). As in previous years the main migration corridor of white whales appeared to be farther offshore than that of bowheads (Fig. 7.4 vs. 5.14); however, white whales were sighted throughout the study area. The more northerly migration corridor was apparent throughout the study period (27 April-25 May, Appendix G, Fig. G-13 to G-16), but was most striking during the 1-10 May period (Fig. G-14 vs. 5.10).

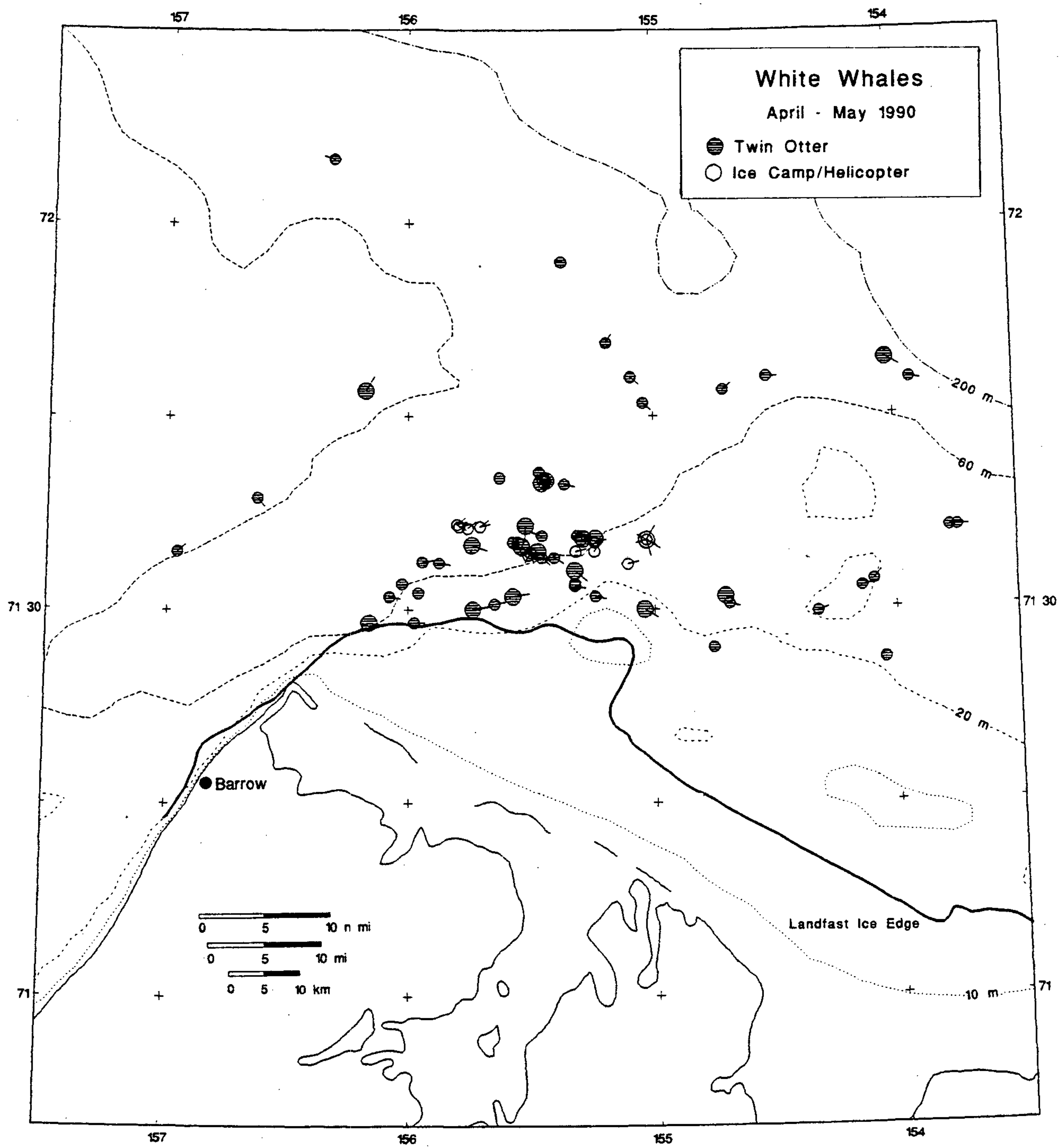

FIGURE 7.2. LGL sightings of white whales, 2-26 May 1990. Symbol type distinguishes sightings by the two crews and sightings of 1-14 whales (small circles) vs. 15+ whales (large circles). Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

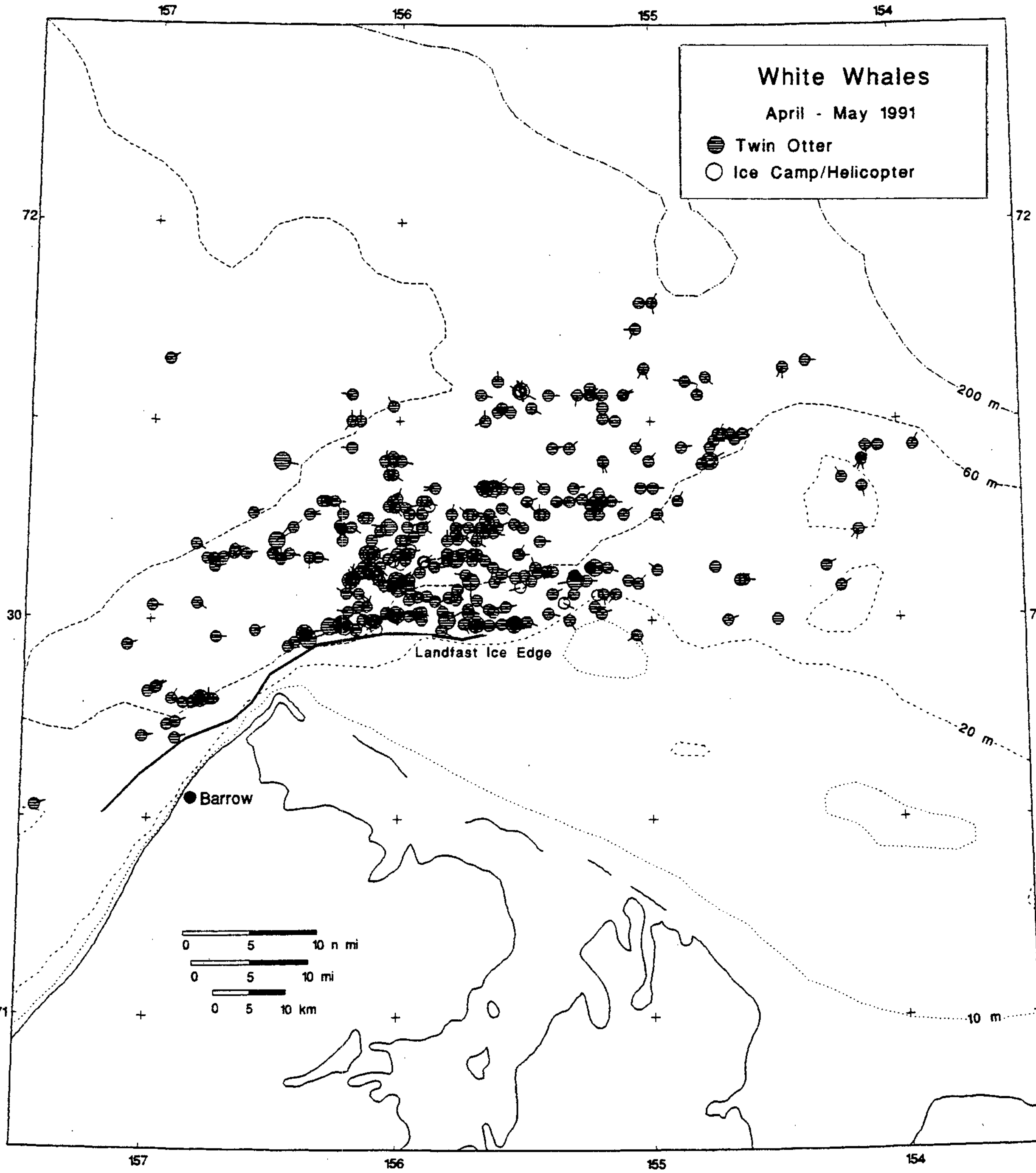

FIGURE 7.3. LGL sightings of white whales, 28 April to 26 May 1991. Symbol type distinguishes sightings by the two crews and sightings of 1-14 whales (small circles) vs. 15+ whales (large circles). Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

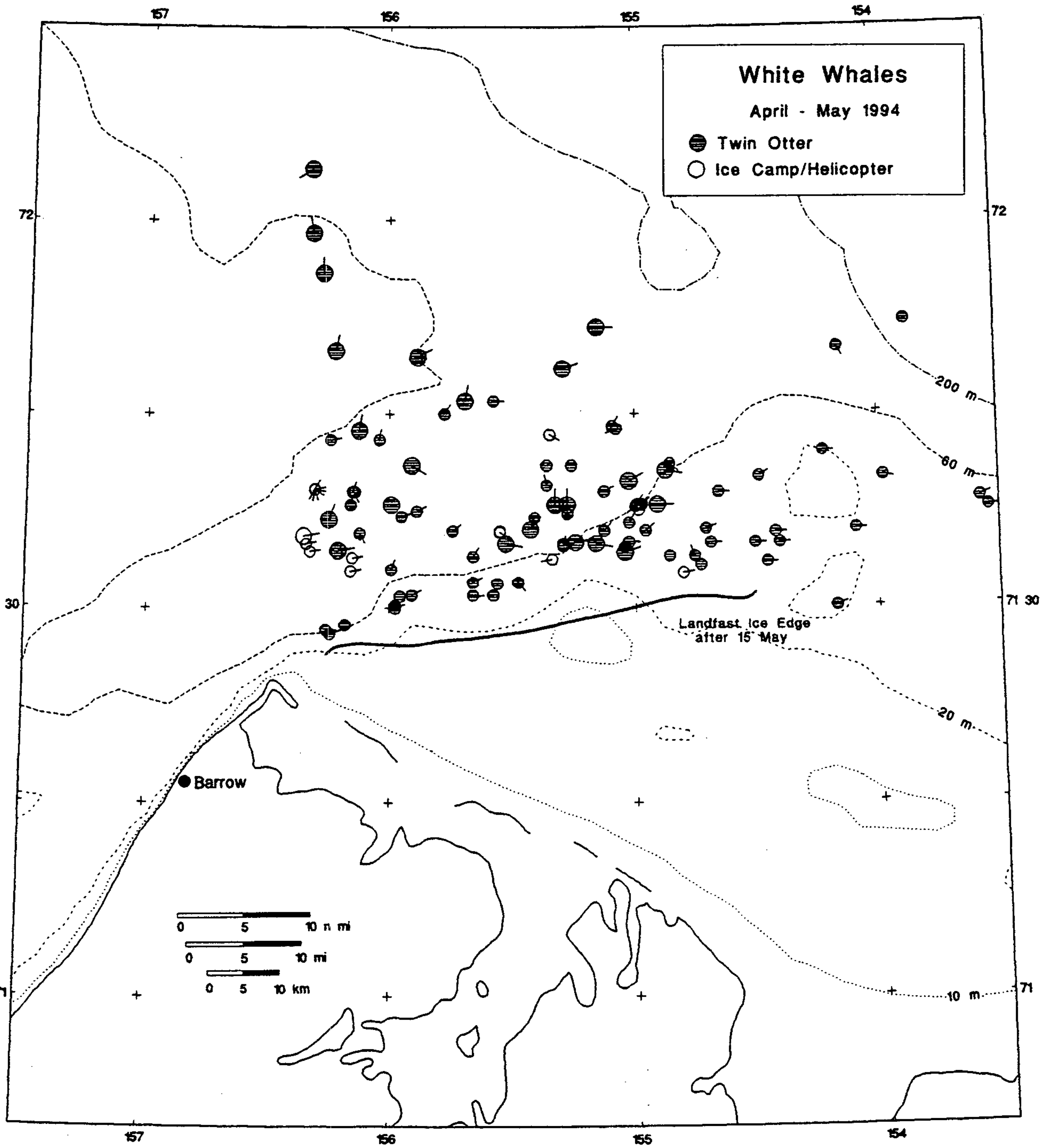

FIGURE 7.4. LGL sightings of white whales, 27 April to 25 May 1994. Symbol type distinguishes sightings by the two crews and sightings of 1-14 whales (small circles) vs. 15+ whales (large circles). Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

The more offshore corridor was apparent from the headings of white whales sighted during 1994. The vector mean heading (69°) was the most northerly recorded during the four years of this study, and the headings were more closely grouped around the mean direction than during other years (angular deviation 44° vs. 45°-55° in other years, Table 7.1B).

All Years

The distribution of all white whale sightings recorded during the four years of this study is shown in Figure 7.5. In comparison to the bowhead sightings (*cf.* Fig. 5.14), white whale sightings were more dispersed and had a more northerly distribution. This tendency for white whales to migrate north of the bowhead's typical migration corridor in the spring has also been noted during studies in previous years (Braham et al. 1984; Ljungblad et al. 1984).

The overall vector mean heading of white whales observed in the study area (82°, Table 7.1) was similar to that of bowheads (83°, Table 5.1). However, white whale headings were less consistently in the mean direction (angular deviation 53°, vs. 37° for bowheads). The headings of white whales seemed to vary depending on their geographic location within the study area. White whales in the southern part of the study area (southeast and south-central areas) tended to head eastward (vector mean headings 82°T and 90°T, Table 7.1C). On average, those in the western part of the study area headed ENE (75°), and those in the northern areas headed NE to ENE (48° and 69°). White whale headings tended to be toward the ENE early in the field season (67° and 72° during late April and early May) and toward the east in mid-to-late May (83° and 87°, Table 7.1). This may have been, at least in part, an artifact of our tendency to spend more time surveying along and near the nearshore lead, which was oriented more-or-less west→east, as it became more open in mid-to-late May. White whales traveling farther offshore may have continued to travel ENE, but we conducted fewer surveys there late in the season.

7.2 Icebreaker Playbacks

Specific objective 4 called for, as possible, measurements of the short-term behavioral responses of white whales visible in open water to underwater playbacks of variable icebreaker sounds. During 1991 and 1994, this was done opportunistically when white whales were present at sites where icebreaker playbacks to bowheads were being conducted. Reactions of white whales to playbacks of steady drilling sounds from the *Karluk* drillsite were tested in 1989-90, and described in Richardson et al. (1990a, 1991a).

In 1991, white whales were seen near the operating sound projectors on two dates: 11 and 17 May (Table 3.5). On both of these days, white whales were also seen near the projector site under quiet "control" conditions before and after the playback period. There were four additional dates in 1991 when icebreaker sounds were projected into the water for prolonged periods. On one of these days (5 May), white whales were seen during the pre-playback quiet period, but not during or after the playback. On the other three days, no white whales were seen during either the playback or the control periods. All systematic observations of white whales near the ice camp were obtained by the ice-based observers. The prevailing low cloud rarely allowed systematic aerial observations during 1991.

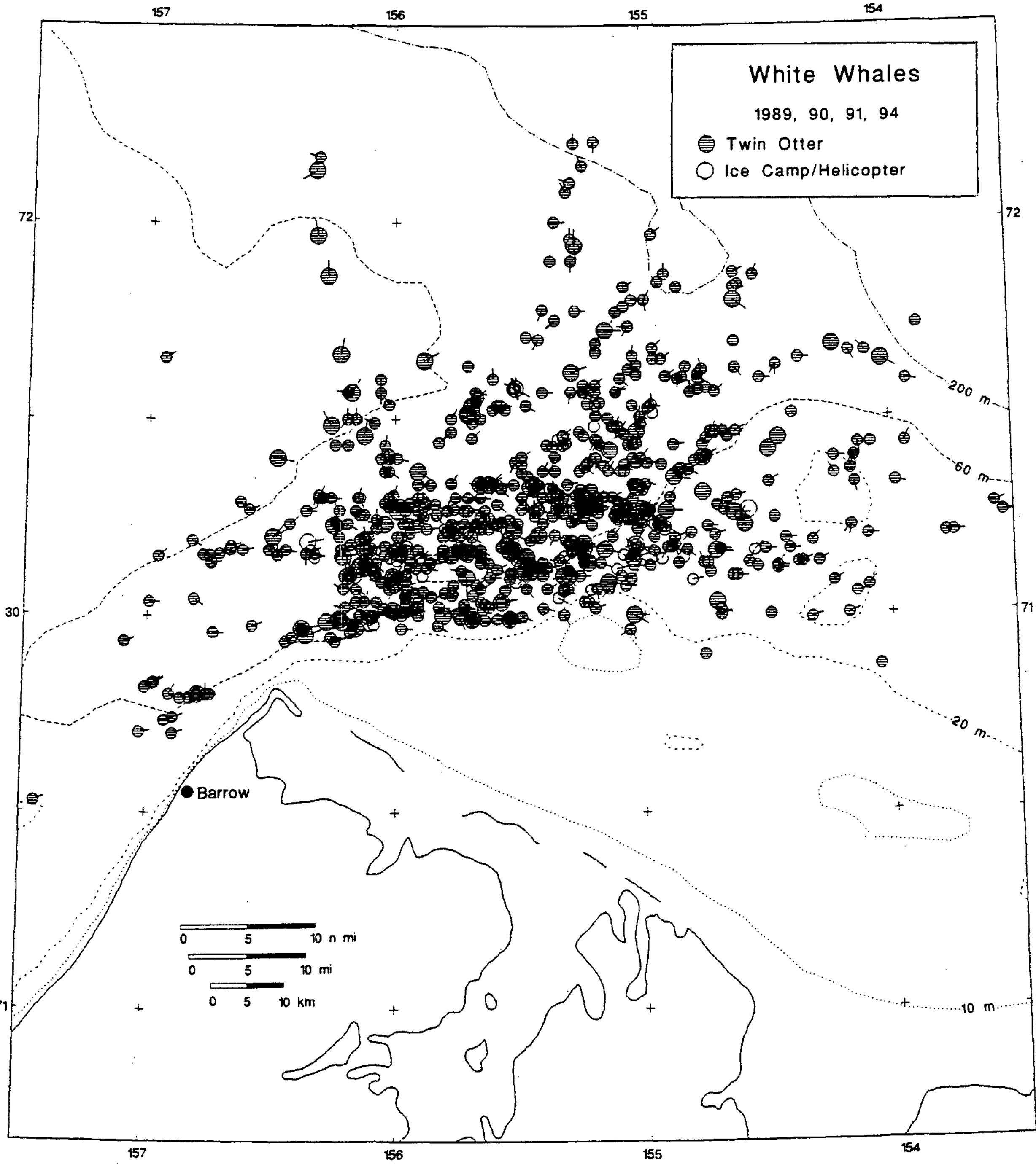

FIGURE 7.5. LGL sightings of white whales in all years, 1989-91 and 1994. Symbol type distinguishes sightings by the two crews and sightings of 1-14 whales (small circles) vs. 15+ whales (large circles). Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

In 1994, white whales were seen near the operating projector on one day: 3 May. They were seen near the projector while icebreaker sounds were being projected into the water but were not seen during control periods. White whales were also seen near the ice camp on two days without prolonged icebreaker sound playbacks: 22 and 25 May. On 22 May, white whales were seen both before and during the projection of tones during a transmission loss (TL) test. On 25 May, white whales were seen before tones were projected during a TL test.

17 May 1991

On 17 May 1991, the ice camp was situated NE of Pt. Barrow on the landfast ice edge, which formed the south side of the broad nearshore lead. The lead was oriented from west to east (True) at this location. The measured water depth was 110 m. The ice-based crew was at this site from 10:46 to 20:59, and icebreaker sounds were transmitted continuously from 12:42 to 18:01. Low cloud and fog patches prevented systematic aerial observations of whale behavior.

Ice-based Observations.—A total of about 165 white whales in 39 groups were observed by the ice-based crew on this day. Most groups (32) were seen prior to or >30 min after the playback period. Of these, 23 groups were seen under quiet pre- or post-playback control conditions; 9 groups were seen while the helicopter was operating close enough to be a potential source of disturbance. Five groups were tracked during the playback, and two more groups within 30 min after the playback ended; there was no helicopter activity at these times (Table 7.2).

Most groups of white whales were migrating eastward along the lead (Fig. 7.6). There were only three exceptions: two groups that oriented west, at least for brief periods, when the helicopter was operating nearby (Fig. 7.7), and one group traveling NNW 21 min after the playback ended (Fig. 7.8).

During the ***pre-playback control period***, 14 groups of white whales—a total of 52 individuals—were seen when there was no helicopter disturbance (Table 7.2A). All of these whales were traveling more or less eastward along the lead within 200 m of the landfast ice. Over half of the groups sighted (9 of 14) were within 50 m of the landfast ice. Twelve of the 14 groups were oriented to the east, one to the ENE, and one to the NE (Fig. 7.6A,B).

An additional 8 groups were seen during the pre-playback period while the Bell 212 helicopter was operating nearby (Table 7.2B; Fig. 7.7). These observations are taken into account in §7.4 on helicopter disturbance.

During the ***playback period***, 5 groups of white whales—a total of 8 individuals—were seen. An additional 2 single whales were seen within 30 min after the end of the playback (Table 7.2C,D; Fig. 7.8).

The first group was seen just before and during the start of the playback. Two white whales were first sighted at 12:38:30, 2 min before the start of the playback, traveling ENE well out in the lead (693 m NNW of the projectors). The playback began at low level while these whales were below the surface. The sound level increased gradually until 12:43:43. Two white whales,

TABLE 7.2. Summary of sightings of white whales seen passing the sound projector located on the landfast ice edge NE of Pt. Barrow on 17 May 1991. All observations were by the ice-based observers.

Time	No. of WW	Observed Distances (m)[a]	CEPA Distance (m)	CEPA Method[a]	CEPA Heading (True)	Notes
A. Pre-Playback Control (no helicopter)						
11:00	1	~130[b]	~130	2	E	
11:02	2	~50[b]	~50	2	E	
11:19/22	6	-200 to +130	90-175	1	E	Loose group
11:22	1	25-32	25	1	E	
11:23/26	8	-46 to +355	30	1	E	
11:26	2	+60 to +160	25	3	E	
11:30/33	2	-55 to +130	50	1	ENE	
11:31	2	22	<22	3	E	
11:34/35	5	+10 to +110	10	3	E	
11:44/46	2	+135 to +215	130	3	E	
11:48/53	8	-300 to +110	37	1	E	
11:57/59	6	-240 to -150	150	1	E	
12:07/08	2	-160 to -200	160	1	NE	
12:34/35	5	-315 to -235	235	4	E	
B. Pre-Playback, Helicopter Operating						
10:46	2	~100[b]	~100	2	E	Heli. landing ~150 m away
10:50	1	~30[b]	~15	2	E	Heli. on ice ~65 m away
11:09	18	~80[b]	~80	2	E	" " " ~130 m away
11:11	2	~50[b]	~50	2	E	" taking off ~100 m away
11:12	20	~50[b]	~50	2	E	<1 min after takeoff
12:08/13	5	-30 to +170	30	1	E→NE→E	Veered NE as heli. landed
12:08/18	10	-135 to +120	32	1	E→W→E	Temp. reversal as heli. landed
12:14/15	1	+70 to +32	30	3	W	<1 min after heli. landed
C. Icebreaker Playback						
12:38/44	2	-693 to +957	~750	3	E	Near CPA when plbk started
14:17/19	1	-205 to +100	95	1	E	Approached and passed; dove at CPA

Continued...

TABLE 7.2. Concluded.

Time	No. of WW	Observed Distances (m)[a]	CEPA Distance (m)	CEPA Method[a]	CEPA Heading (True)	Notes
14:17	1	210	<210	3	E	Seen briefly, approaching
14:18	3	185	<185	3	E	" " "
14:18/22	1	-225 to +195	80	1	E	Approached and passed at surface
D. <30 min After Playback						
18:11	1	340	<340	4	E	Seen briefly approaching
18:22/23	1	+720 to +750	<720	4	NNW	Far out in lead
E. Post-Playback Control						
18:48/50	8	+480 to +670	~375	3	ENE	Beyond CPA
18:58/00	7	-400 to -255	<255	4	E	Approaching
19:04/07	7	+540 to +600	540	1	E	Passing
19:07/09	5	+320 to 335	300	3	E	"
19:11	1	400	400	1	E	Seen briefly, passing
19:15	5	480	<480	4	E	Approaching
19:16/17	5	+560 to +630	~560	3	ENE	Beyond CPA
19:18/25	2	-600 to +745	~600	1	NE	Passing
19:25/26	?	+440 to +540	<440	4	E	Beyond CPA
19:58/13	3	-800 to +620	225	1	ENE	Passing; near heli. part of time

[a] **Observed Distances:** "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE, N or E.
CEPA Method (CEPA=Closest Estimated Point of Approach): 1 = measured by theodolite at CPA (Closest Point of Approach); 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacing(s); 4 = estimate based on whale position(s) and heading(s) during sighting(s) distant from CPA (possibly unreliable).

[b] Distance and position estimates before 11:15 are visual estimates made shortly after arrival on the ice, before the theodolite was set up.

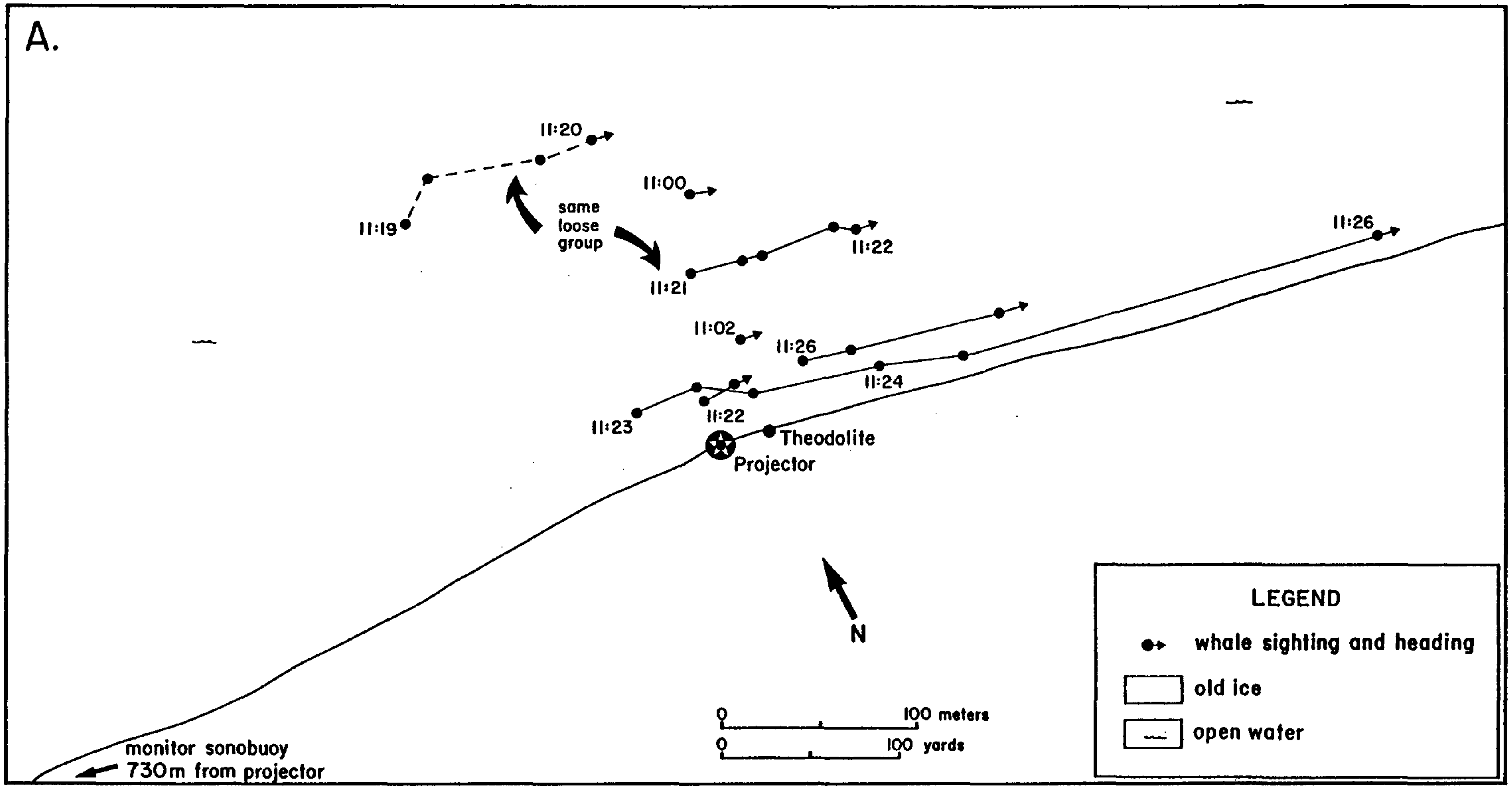

FIGURE 7.6. Ice-based observations of white whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991. *(A)* Initial pre-playback control observations, 10:46-11:28. *(B)* Continued pre-playback control observations, 11:28-12:42. Dashed lines represent presumed paths of whales while they were below the surface.

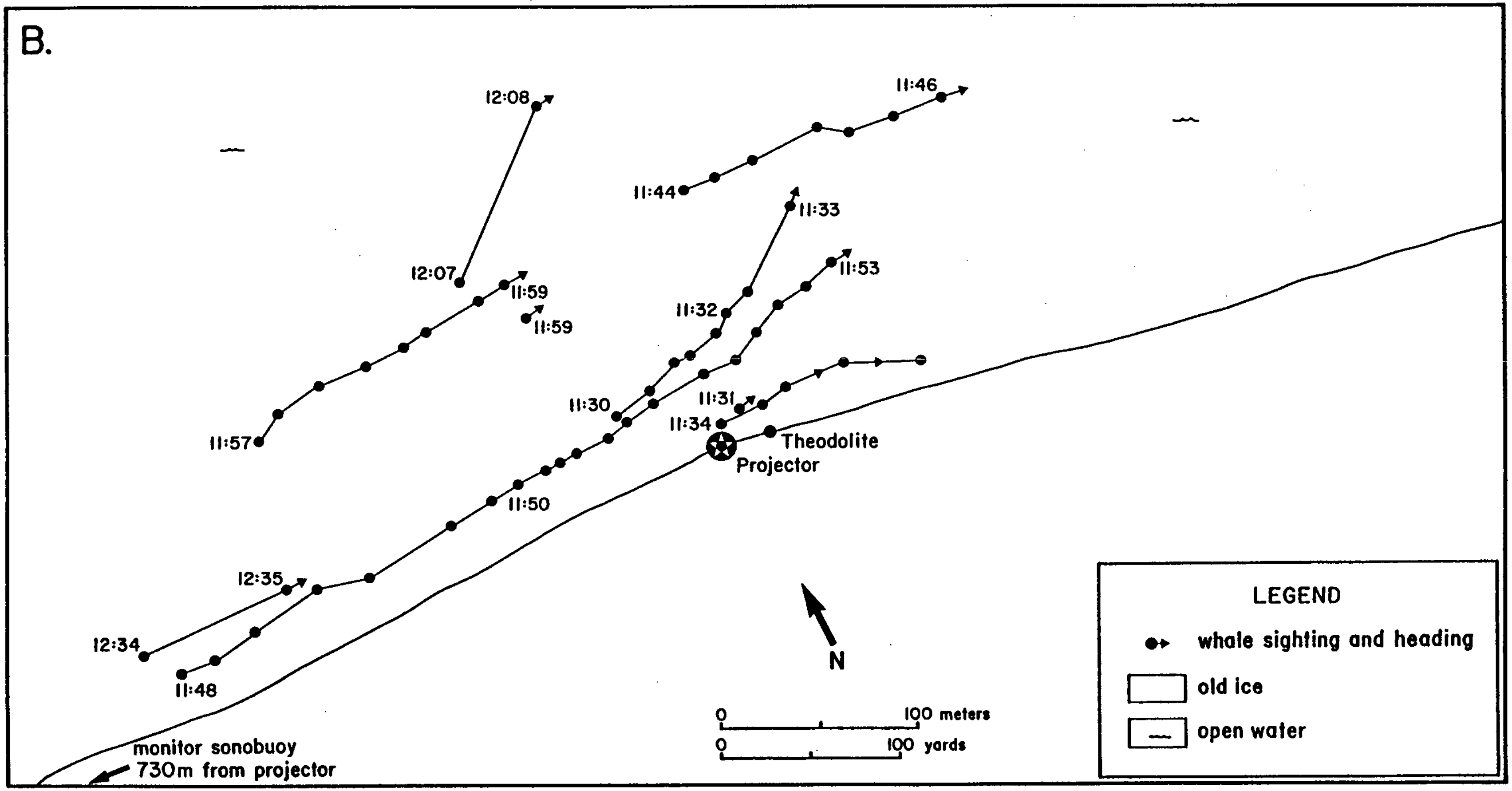

FIGURE 7.6 (continued).

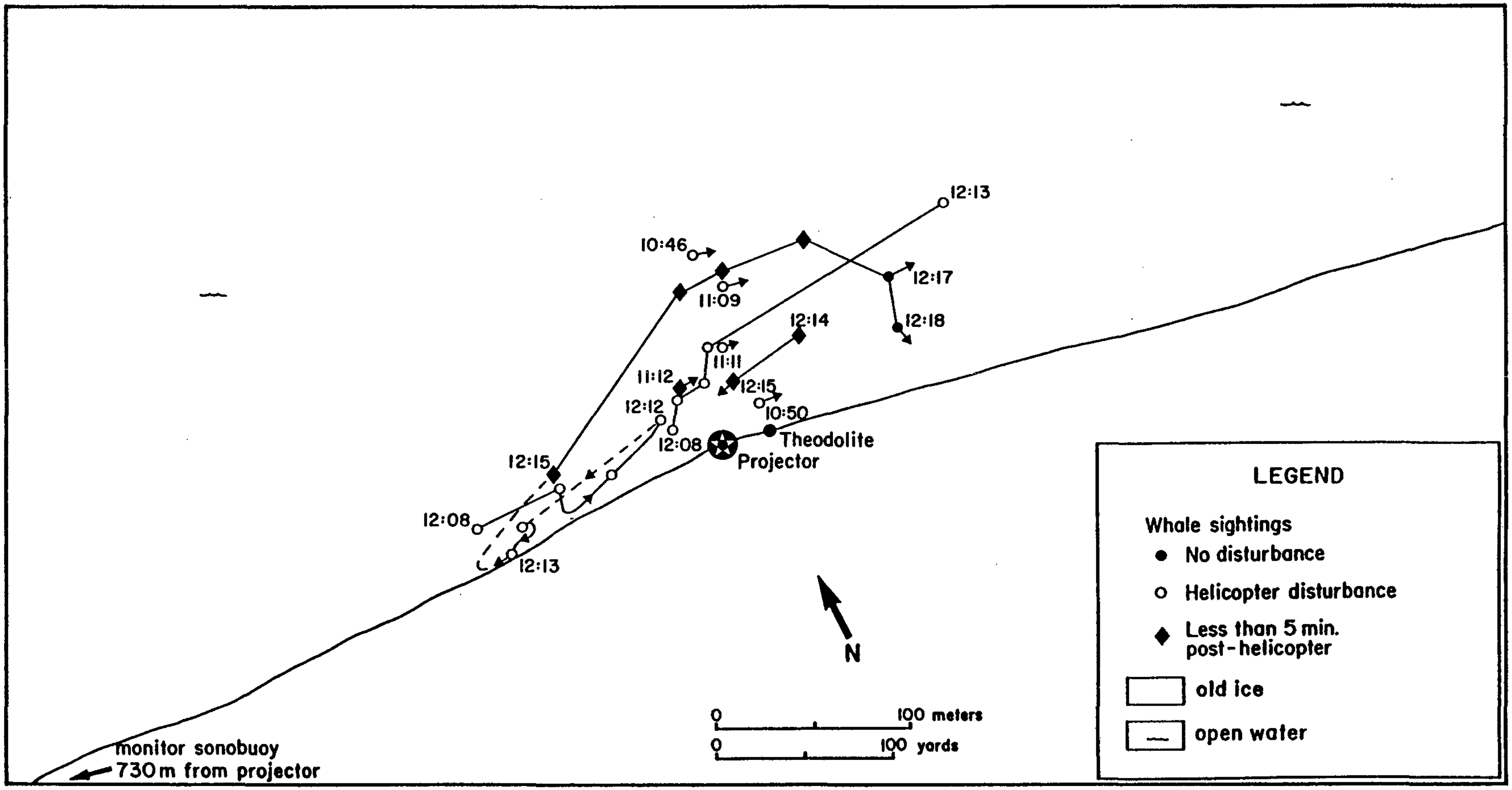

FIGURE 7.7. Ice-based observations of white whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991, during the pre-playback period while the helicopter was operating nearby. Dashed lines represent presumed paths of whales while they were below the surface.

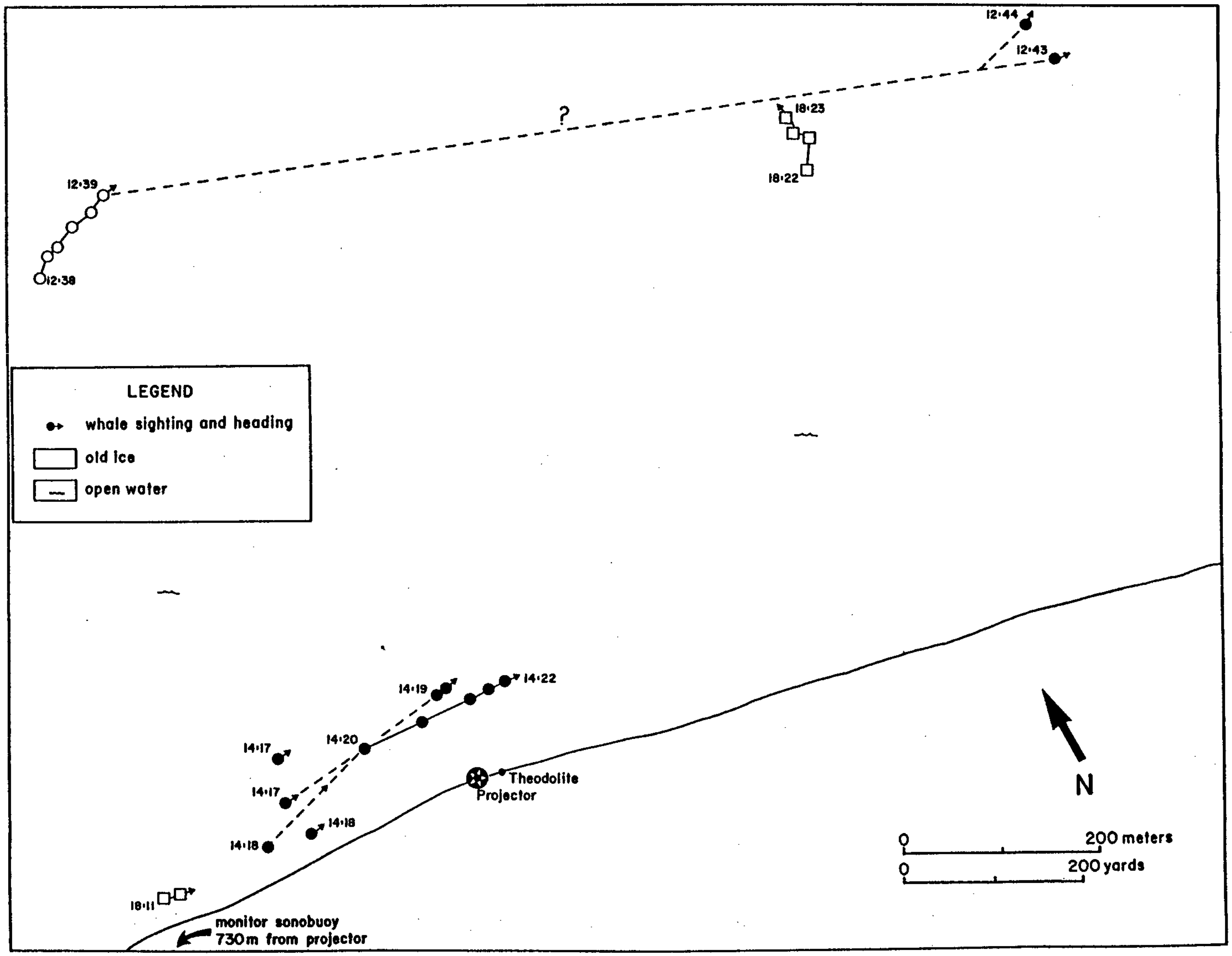

FIGURE 7.8. Ice-based observations of white whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991, during icebreaker playback from 12:42 to 18:01 and 30 min thereafter. Dashed lines represent presumed paths of whales while they were below the surface.

believed to be the same group, surfaced at 12:43:09 at a location 957 m to the NE of the operating projectors, with one whale apparently oriented N and the other ENE. These whales had apparently passed their CPA position before the playback began, and were last seen at about the time the projected sound reached its peak level.

At 14:17-14:22, four groups totaling seven white whales were observed while the projectors were operating at peak power. All groups were headed consistently eastward throughout these observations:

- The longest track involved a lone subadult for which six positions were determined between 14:18 and 14:22 (Fig. 7.8). When first seen, this approaching whale was about 35 m from the ice edge and 235 m west of the projectors. It moved slightly farther away from the ice edge as it approached, and was 80 m from the ice edge and at the surface as it passed the operating projectors and continued to the east.
- Another eastbound white whale was seen 95 m from the projectors at 14:19; it dove out of sight while at that CPA position.
- Two other groups (a singleton and a group of three) surfaced briefly 210 m and 185 m from the projectors as they approached. They were not seen again; if they did not change course subsequently, they would have come within ~120 m and ~30 m of the projectors.

The number of white whales seen from the projector site was considerably lower during the playback period than during the pre- and post-playback periods. This was true both on an absolute basis and (especially) on a "per hour" basis:

				Groups		Individuals	
	Start	End	Duration	No.	/Hr	No.	/Hr
Pre-playback	10:46	12:42	1.93 h	22	11	111	58
Playback	12:42	18:01	5.32	5	1	8	1½
Post-playback*	18:31	20:59	2.47	10	4	44+	18+

* 30-min post-playback period excluded (2 whales in 2 groups).

Furthermore, it should be noted that at least one of the two ice-based biologists was observing at all times during the playback period, with no other duties, whereas during parts of the pre- and post-playback periods one or both biologists were involved in equipment setup or breakdown. Thus, fewer white whales were seen during the playback even though there was less likelihood of missing passing whales then than during the control periods.

Two single white whales were seen 10 and 21 min after the icebreaker playback ended. One eastbound whale was approaching the ice camp, traveling within 30 m of the ice edge. The second was heading in an unusual NNW direction well offshore in the lead (Fig. 7.8).

During the ***post-playback control period*** (>30 min post playback), 10 groups of white whales totaling at least 44 individuals were observed. All groups were traveling east, ENE or NE along the lead (Table 7.2E, Fig. 7.9). Their estimated CPA distances (assuming travel on straight lines during dives) were ~100 to 600 m from the ice camp. One of these groups was exposed to helicopter operations for a small part of the period while it was under observation.

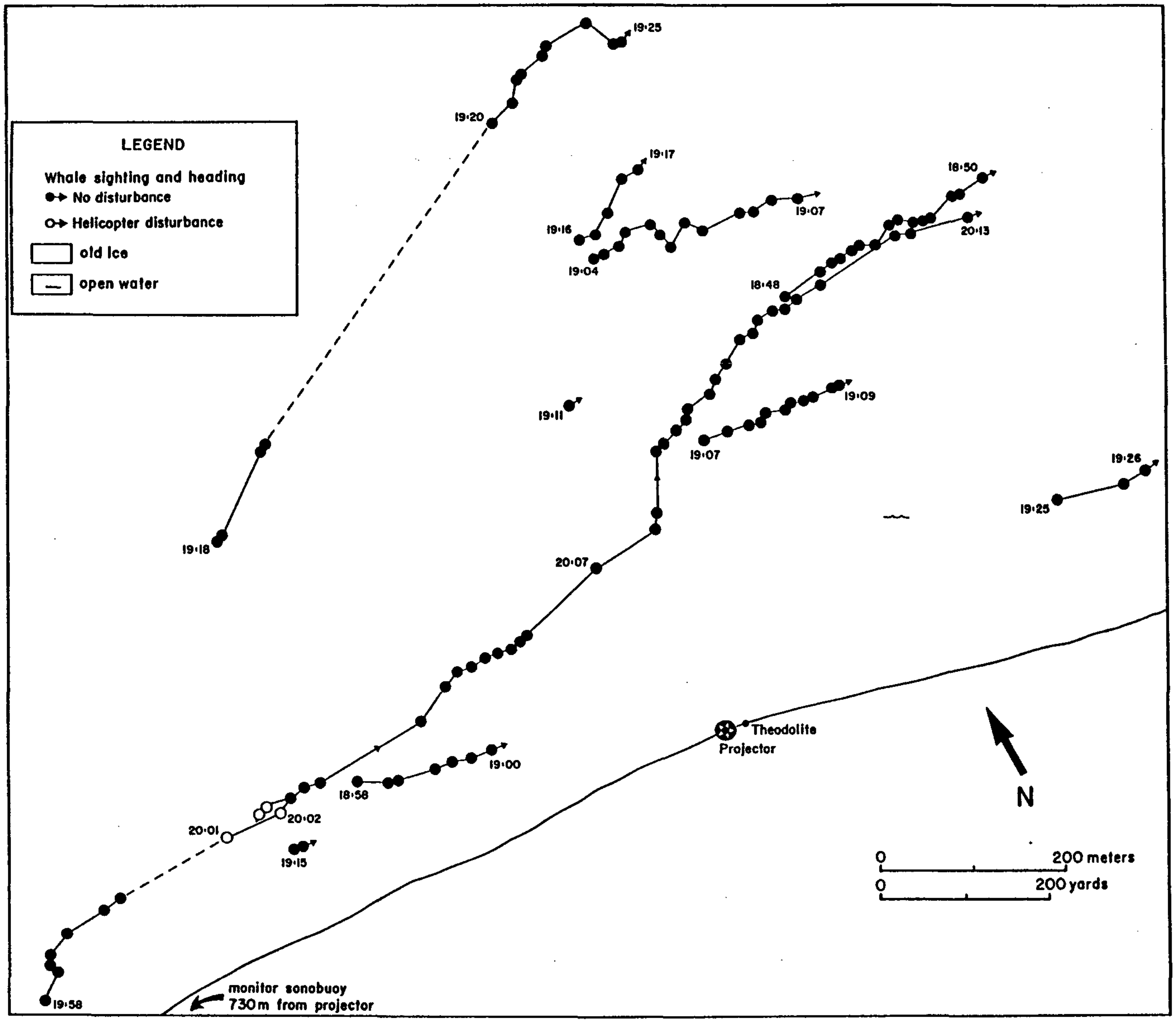

FIGURE 7.9. Ice-based observations of white whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991, more than 30 min after icebreaker playback ended. Dashed lines represent presumed paths of whales while they were below the surface.

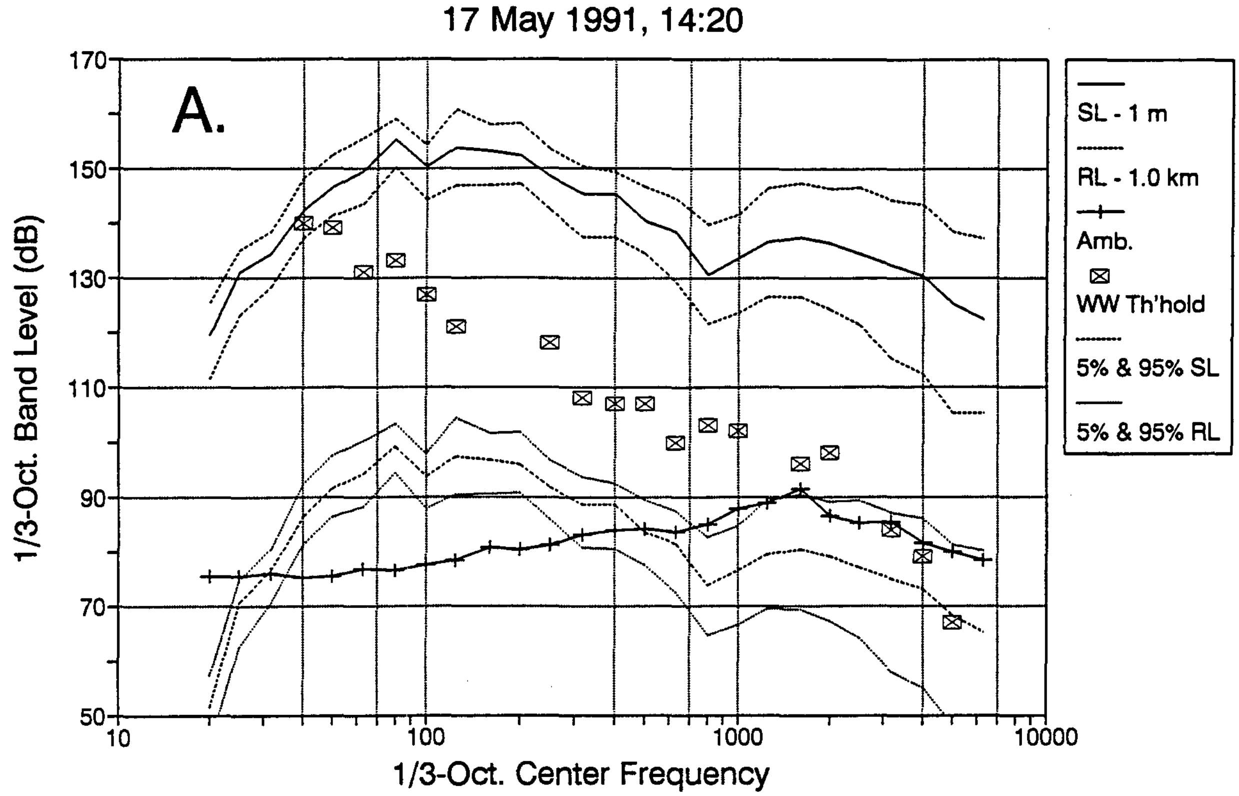

FIGURE 7.10A. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 14:06-14:20: variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). Plus signs show average ambient noise level after playback. ⊠ symbols are white whale hearing thresholds vs. frequency.

Explanatory notes: *(1)* Source levels are in dB re 1 μPa-m and ambient and received levels are in dB re 1 μPa. *(2)* Because of projector limitations, components of the icebreaker sounds at low frequencies are underrepresented in the projector output relative to components at higher frequencies. *(3)* The tape of icebreaker sounds is repeated every 14 min. As illustrated by the 5th and 95th percentiles, the actual source or received level at any particular time can be substantially different than the median level, depending on the precise location along the 14-min loop that is being projected or received. *(4)* Source and ambient levels were measured; received levels at 1.0 km were estimated via an empirically-validated propagation model, as described in section 2.3. *(5)* Received levels within a few meters of the surface will be lower than estimated here.

Noise Exposure.—Icebreaker sounds were projected into the lead by the J-13/F40 projector system from 12:42 to 18:01. The 5th, median, and 95th percentile broadband (20-5000 Hz) source levels over the full 14-min cycle of the icebreaker sounds were 156, 161, and 167 dB re 1μPa-m, respectively, from 12:42 to 16:49. After that time the source level was reduced by ~12 dB until the end of the session. Figure 7.10A indicates the variability in icebreaker sounds as projected (1-m source levels) and as received at 1 km range. Figure 7.10B shows the estimated median received levels at several standard distances at the same time. The received levels in this Figure, and the received levels in all similar figures, are estimated by the sound exposure model described

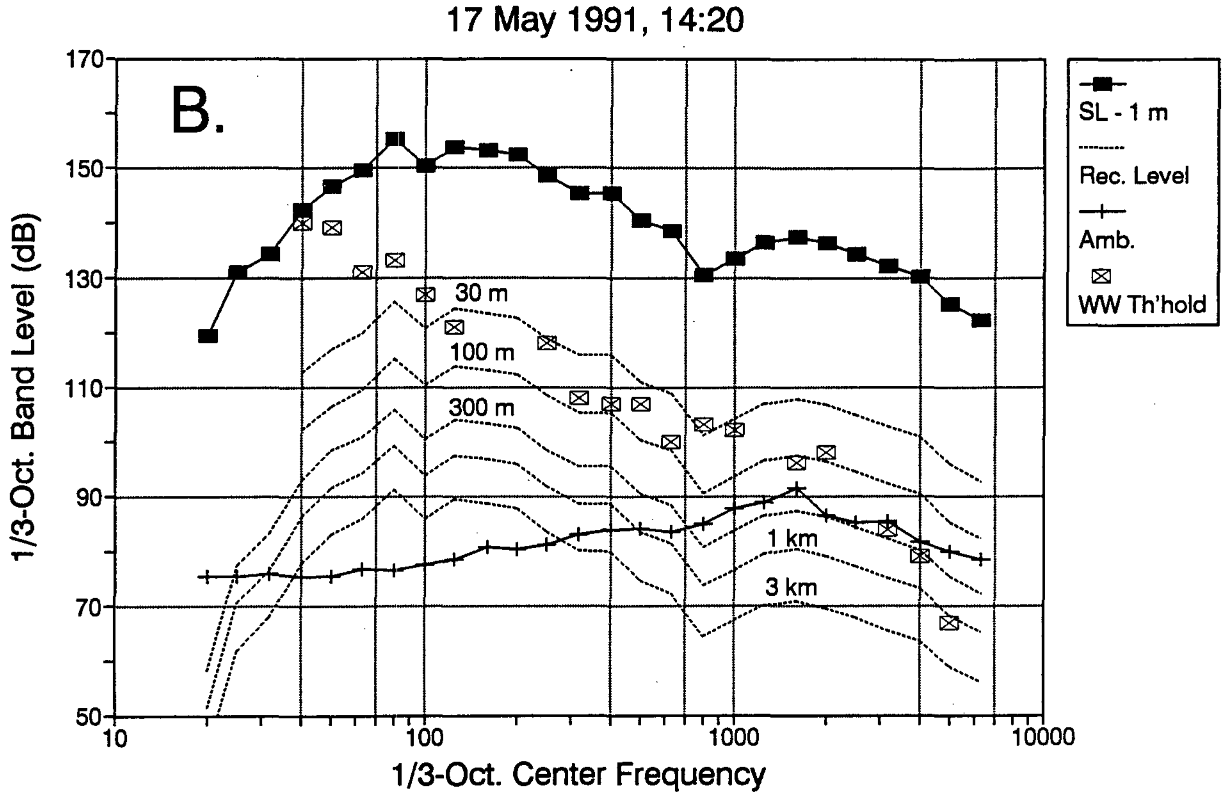

FIGURE 7.10B. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 14:06-14:20: median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level after playback. ⊠ symbols are white whale hearing thresholds vs. frequency.

Explanatory notes: See notes to Fig. 7.10A. Figure 7.10B shows median received levels at more ranges, but does not show 5th and 95th percentiles. Estimated received levels at 0.03 and 0.1 km assume spherical spreading; model of §2.3 was used to derive estimates for 0.3 to 3 km.

in §2.3. There will be small differences between the received levels estimated by the model and those actually received at the specific distance and time. Also, estimated received levels pertain to animals below the surface by at least several meters; while at the surface and under visual observation, whales are exposed to lower levels than predicted by the model, because of the pressure release (Lloyd's mirror) effect.

Ambient noise was measured near the projectors after icebreaker playbacks stopped. The broadband ambient noise level was 93 dB re 1 μPa. The level in the dominant 1/3-octave band, which was centered at 125 Hz, was 83 dB re 1 μPa.

During the period 14:17-14:22, 4 groups of white whales migrated eastward within 80-210 m of the operating projectors (Table 7.2). The maximum underwater sound levels during the 64-s period previous to each observation time were estimated for the CPA distances using the sound exposure model. The broadband (20-5000 Hz) source levels ($SL_{BB,max}$ dB re 1 μPa-m), and the

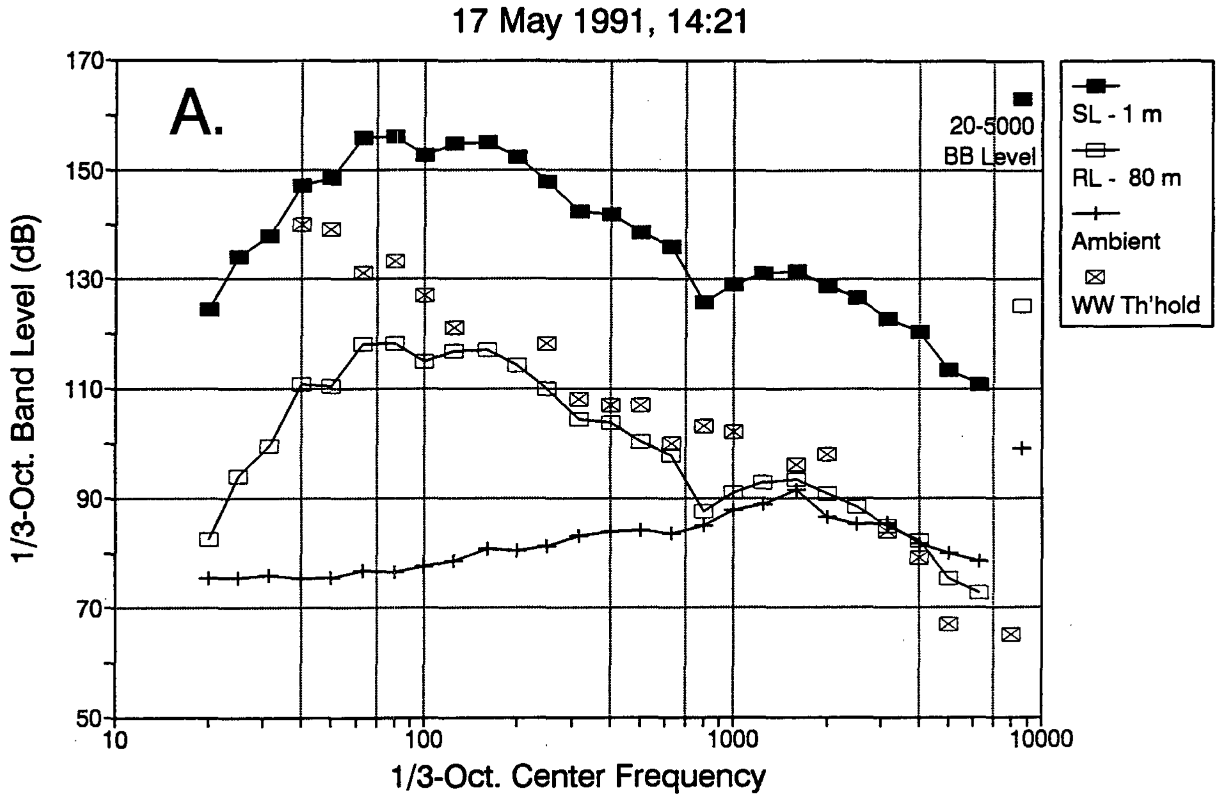

FIGURE 7.11. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near white whales *(A)* 80 m and *(B)* 95 m from the projector (median levels over 64 s), 17 May 1991, times 14:21 and 14:19. Plus signs show average ambient noise level after playback. ⊠ symbols are white whale hearing thresholds vs. frequency.

Explanatory notes: *(1)* Source levels are in dB re 1 μPa-m and ambient and received levels are in dB re 1 μPa. *(2)* Because of projector limitations, components of the icebreaker sounds at low frequencies are underrepresented in the projector output relative to components at higher frequencies. *(3)* The tape of icebreaker sounds is repeated every 14 min. The 64 s values are estimated by determining the location on the loop that was projected at the selected time and summarizing the data for the preceding 64 s. *(4)* Source and ambient levels were measured; received levels at 80 and 95 m were estimated via the empirically-validated propagation model of §4.3, incorporating spherical spreading (plus Lloyd's mirror factor) at close ranges. *(5)* Received levels within a few meters of the surface will be lower than estimated here.

broadband and 1/3-octave received levels ($RL_{BB,max}$ and $RL_{1/3,max}$, dB re 1 μPa) for the four whale groups were as follows:

```
     CPA @ 14:19:11,  SL = 164,  RL @   95 m =  124,  RL near 5 kHz =  96
Approach @ 14:17:00,  SL = 167,  RL @ <210 m = >120,  RL near 5 kHz = >90
Approach @ 14:18:17,  SL = 166,  RL @ <185 m = >119,  RL near 5 kHz = >88
     CPA @ 14:21:00,  SL = 167,  RL @   80 m = <129,  RL near 5 kHz = <93
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The above Table also shows the RL in the 1/3-octave band centered at 5000 Hz rather than in the 1/3-octave of strongest source level because white whale hearing is poor in the low frequencies

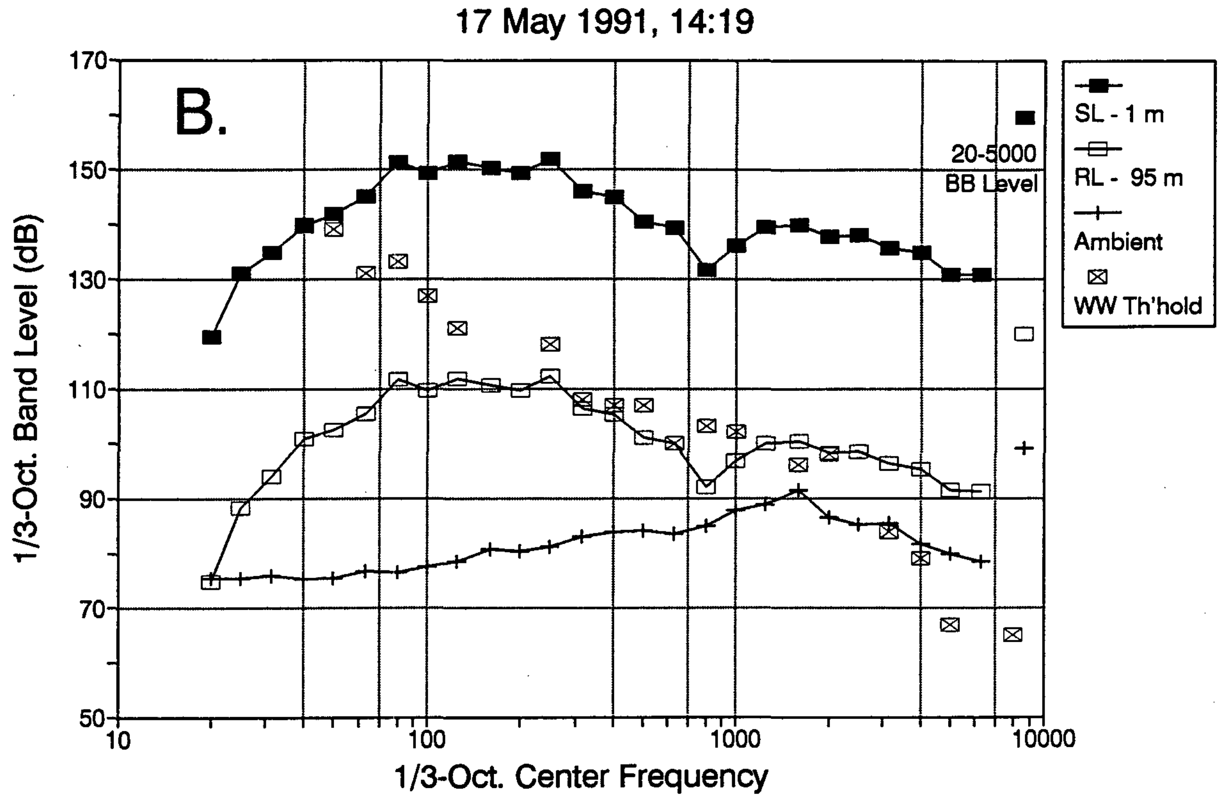


FIGURE 7.11 (continued).

where the dominant icebreaker sound was projected. Based on white whale hearing capabilities, background ambient noise, and the estimated received levels of icebreaker sounds at the distances where whales were likely to be seen by ice-based observer (Fig 7.10B), white whales were most likely to hear the higher components of the icebreaker sounds shown in Fig. 7.10, if they could detect them at all.

Ambient noise levels at the specific times when white whales were observed could not be determined because of masking by the projected icebreaker sounds. However, the broadband level (20-5000 Hz) after the playback was 93 dB re 1 μPa and the 1/3-octave level was 80 dB near 5000 Hz. If that level also occurred at the CPA times during the playback, $S{:}N_{BB,max}$ values were 26-36 dB, and $S{:}N_{1/3,max}$ values near 5000 Hz were 8-16 dB.

Figure 7.11A shows the median broadband source and received levels during the 64-s period previous to 14:21 when the white whale was 80 m from the operating projectors. The broadband received levels near this whale were stronger than those near the other whales, but above ~800 Hz the median received levels were near the ambient noise level. However, maximum levels near 5000 Hz probably did exceed the ambient level. This whale was at the surface, and because of pressure release effects near the surface, the actual received levels at the whale would—especially at low frequencies—have been a few decibels lower than those shown above. The other three groups listed here either dove or were below the surface as they passed the projectors (Fig. 7.8). Thus, those three groups of whales were exposed to the estimated noise levels. Figure 7.11B shows the estimated received levels near the whale estimated to be underwater 95 m from the projectors at 14:19. Although the estimated broadband levels were weaker than for the whale shown in Figure 7.11A, the levels near 5000 Hz were stronger—several dB above ambient levels.

The white whale hearing system has relatively low sensitivity at the low frequencies where the icebreaker sounds were concentrated. White whale hearing thresholds by 1/3-octave band are shown on Figure 7.10 and 7.11, based on White et al. (1978), Awbrey et al. (1988), and Johnson et al. (1989). It appears that, on 17 May 1991, white whales could only hear icebreaker sounds if they were within ~300 m during sections of the 14-min tape loop when source levels were near median levels in the 1/3-octave bands centered at 4000-5000 Hz. At greater distances, median received levels of icebreaker sounds were below the hearing threshold, below the ambient noise level, or both, in all 1/3-octave bands up to at least 6300 Hz (Fig. 7.10B). Maximum levels, being several decibels higher than medians (Fig. 7.10A), would have been detectable out to at least 1 km.

Despite the limited radius of audibility of these playbacks to white whales, fewer whales were observed to approach the projectors during the icebreaker playback than during adjacent control periods. Whether this was a meaningful or a coincidental relationship cannot be determined from a single day's observations.

11 May 1991

The ice camp was at the north end of a giant ice pan, adjacent to an irregularly-shaped lead amidst pack ice (Fig. 7.12). The measured water depth was 195 m. Icebreaker sounds were projected for 1 h, from 16:39 to 17:37. Unfortunately, the projector system then had to be removed from the water to protect it from drifting ice. Observers aboard the Twin Otter aircraft conducted an aerial reconnaissance in the area, but the cloud ceiling was too low (150-300 m) to allow systematic aerial observations of whale behavior.

Ice-based Observations.—A total of 11 groups of white whales consisting of 38 individuals were seen from the ice camp. Five groups were tracked during the 2.0-h pre-playback control period, one group during the playback, and five groups during the 2.9-h period of post-playback observations. The helicopter was at the ice camp with its engines running while four of the groups of white whales passed, including the one group seen during the playback period.

Figure 7.12A shows the paths of the five white whale groups observed during "control" conditions, i.e., while the projectors were silent and there was no helicopter disturbance. All five groups were seen before the playback, and all were traveling to the ENE in the southern part of the lead close to the ice camp:

- Two groups were seen at CPA distances 40 and 70 from the ice camp.
- Three groups surfaced after they had passed the ice camp and were 200-515 m away. If they were traveling on straight lines while underwater, they all passed the ice camp at CPA distances ≤200 m.

Figure 7.12B shows the paths of four groups of white whales seen during the playback and post-playback periods while the helicopter's engines were operating at the ice camp, plus two more groups that surfaced within 2 min after the engines stopped. (When the helicopter was standing by on the ice for prolonged periods, it was considered necessary to run the engines periodically to keep them warm.) Of the five groups seen during the post-playback period with possible helicopter disturbance, four showed no apparent reaction to the helicopter; one group that was heading NNE may have diverted in response to the helicopter.

The one group of white whales seen during the icebreaker noise playback was first sighted at 16:44. This was 5 min after the playback had begun and 3 min after the projected sounds had reached near-peak level. When first seen, the six white whales were 515 m NW of the projectors and were headed NE (Fig. 7.12B). As the whales surfaced for the second time <1 min later, the helicopter's engines were started. While the engines were operating, the position of the group was measured four more times. The group traveled NNE across the lead toward the opposite edge. They apparently turned about 30° to their left, away from the projectors and helicopter (Fig. 7.12B). The whales were last observed at 16:47, 900 m NNW of the projectors and helicopter.

Noise Exposure.—Icebreaker sounds were projected into the water using the J-13/F-40 system from 16:39 to 17:37 when encroaching ice forced the crew to retrieve the equipment from the water. The source level of the projected icebreaker sounds was gradually ramped up from 16:41 to 16:46, but was adjusted both upward and downward from 16:46 to 16:48. The estimated received levels at the whales' location—as they moved away from the camp—ranged from 100 to 111 dB re 1 μPa broadband and 46 to 94 dB re 1 μPa near 5000 Hz from 16:45 to 16:48. Before the helicopter disturbance, $RL_{BB,max}$ was 110 db re 1 μPa and the maximum 1/3-octave level near 5000 Hz was 73 dB re 1 μPa or 5 dB below the average ambient level. It appears that icebreaker sounds would not have been detectable by the white whales because of their poor hearing sensitivity at low frequencies and the negative S:N at high frequencies. However, given the uncertainties associated with the estimates of received levels and hearing thresholds, it is possible that the white whales were able to hear some components of the icebreaker sounds.

Therefore, the significance of the observations of the one group of white whales seen during the 11 May playback cannot be interpreted for certain. They may have been unable to hear icebreaker sounds. If so, the turn away from the camp was probably related to noise generated by the helicopter idling on the ice.

3 May 1994

The ice camp was set up amidst the pack ice on the eastern edge of a narrow lead oriented N-S. During the day, the width of the lead W of the camp narrowed from ~500 to 300 m. The lead was ~400 m wide when the white whales were sighted. The crew was at the site from 09:50 to 22:02. Tones were projected into the lead from 12:33 to 13:09 and icebreaker sounds were projected, using only the J-11 projector, from 15:12 to 19:20. The measured water depth was 105 m.

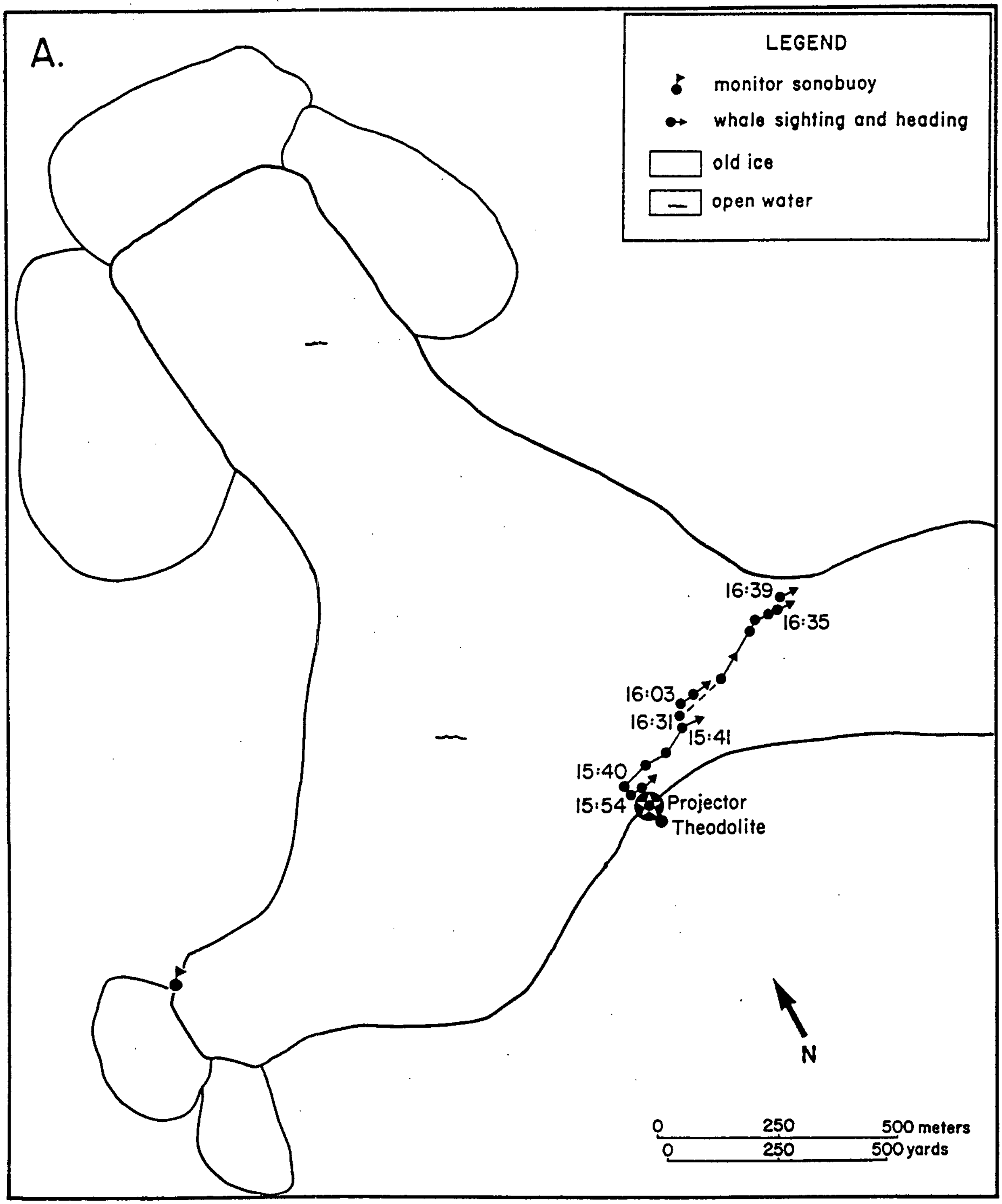


FIGURE 7.12. Ice-based observations of white whales that passed the ice camp amidst pack ice NE of Pt. Barrow, 11 May 1991. Icebreaker sounds were projected from 16:39 to 17:37. *(A)* Pre-playback control observations, no helicopter disturbance. *(B)* Observations during and after playback, with possible helicopter disturbance in each case.

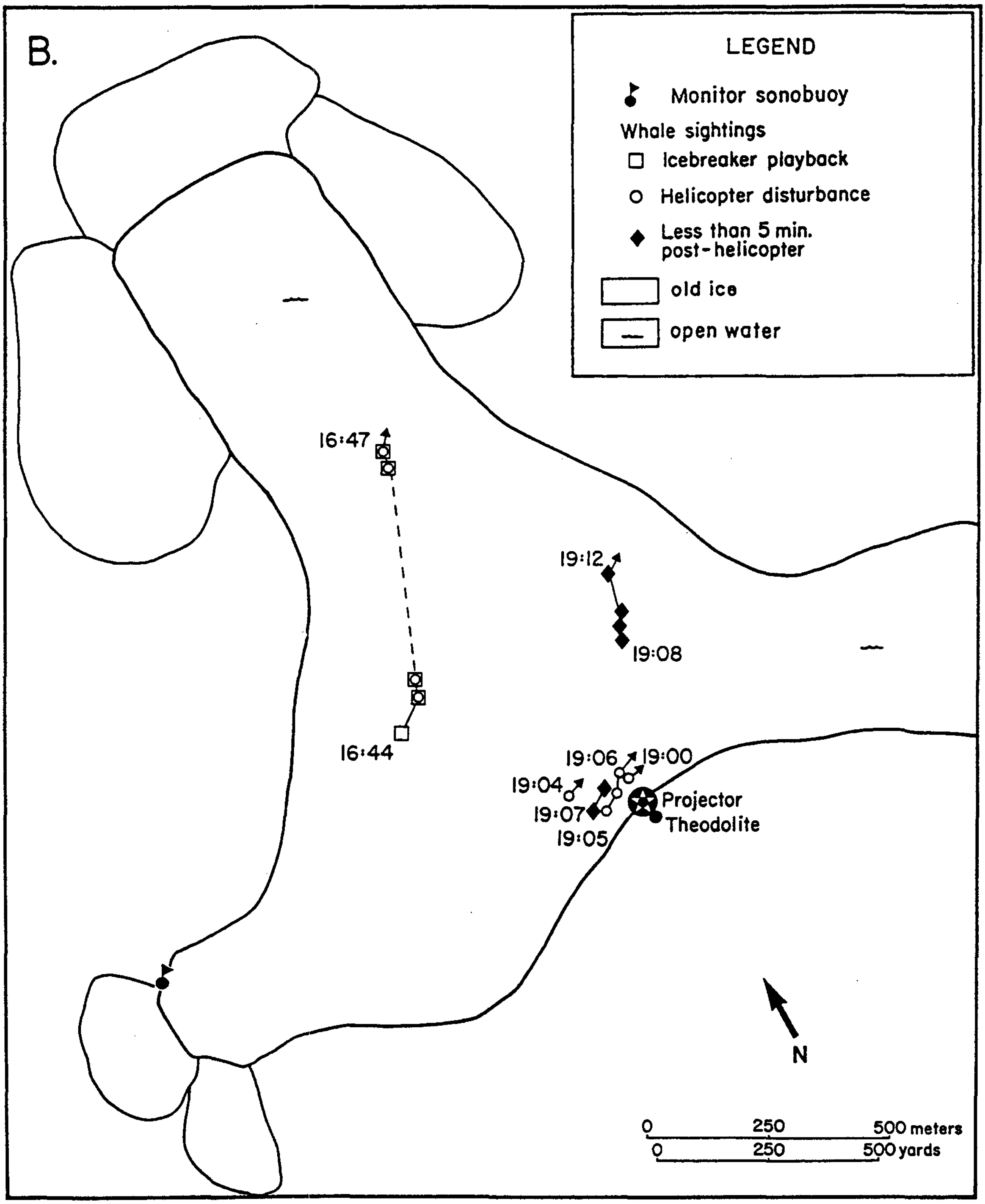


FIGURE 7.12 (continued). White whales, 11 May 1991, playback and post-playback, with possible helicopter disturbance.

Ice-based Observations.—About 32 white whales (~13 groups or singletons) were estimated to have moved by the ice camp during 12.1 h of observation; all white whale sightings were made from 15:40 to 16:31, during the icebreaker playback (Fig. 7.13). The 32 white whales included 25 adults and 7 subadults. The number of different whales that passed the projector is approximate because of uncertainties in discriminating "new" and "repeat" sightings, and because of the likelihood that some passing whales were missed.

All white whales observed passed while icebreaker sounds were being projected into the lead. Most groups were initially sighted generally NW or SW of the projector and headed either radially to or away from the projector.

Five of 7 groups sighted to the NW had orientations or headings that would be expected; that is, they generally followed the lead toward the NE (Fig. 7.13). Of the exceptional groups, one group of two whales surfaced 185 m north of the projector and swam directly toward it from 16:31 to 16:33; this group's CPA was 20 m. The whales were at the surface as they approached from 185 to 20 m; they dove as they passed the projector at their CPA. The other group was initially observed traveling to the NE some 345 m NW of the projector. It turned north until it reached the NW side of the lead, and then returned to a NE heading. The CEPA of this group was ~330 m from the projector. The turn to the north and crossing of the lead to the west side could have been in response to the icebreaker sounds, but did not represent much of a departure from the general N and NE travel of most other white whale groups. On balance, white whales sighted to the NW of the projector showed no obvious avoidance.

In contrast to the above, 5 of 6 groups sighted SW of the projector were headed generally south (135°-210°) and away from the projector. In particular, an adult/subadult pair seen 180 m SW of the projector was heading SW away from it. The sixth group was oriented ESE as it dove under the ice 390 m south of the projector. Based on the orientation of the lead and the headings and tracks of the whales seen NW of the projector, the whales south and SW of the projector would have been expected to travel north to NE past the projector. Thus there is circumstantial evidence to suggest that the whales seen S to SW of the projector altered their paths to avoid a closer approach to it. Their tracks indicate that they may have been closer to the projector before they were sighted. However, the lack of any white whale sightings near the ice camp during the pre- and post-playback control periods on 3 May 1994 makes it impossible to compare these observations with control data from the same site and date.

Aerial Observations.—About 40 white whales were seen 7 km south of the ice camp in heavy pack ice from 11:22 to 13:46. White whales were observed opportunistically as aerial observers in the Twin Otter crew circled a bowhead engaged in aerial activity. A steady stream of white whales traveled NNE past the bowhead in groups of one to 14 individuals. One white whale moved ~400 m NNW of the bowhead, hesitated, then turned toward the bowhead when it breached at 12:01. Another white whale traveling NNE approached within 100 m SSW of the bowhead at slow speed at 12:04.

Noise Exposure.—Icebreaker sounds were projected into the water using the J-11 projector from 15:12 to 19:20. The 5th, median and 95th percentile broadband source levels over the

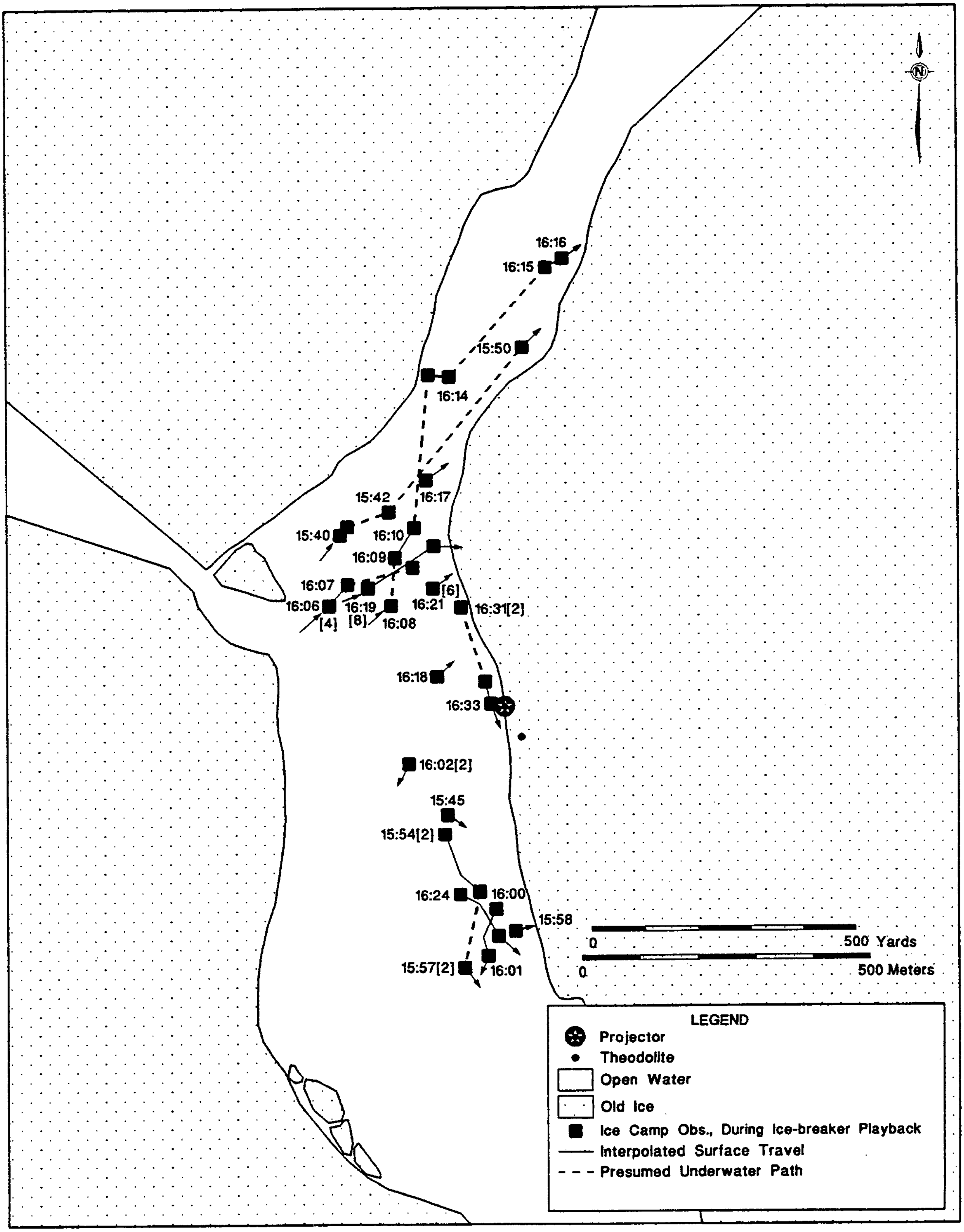


FIGURE 7.13. Ice-based observations of white whales that passed the ice camp amidst pack ice NE of Pt. Barrow while icebreaker sounds were being projected from 15:12 to 19:20, 3 May 1994.

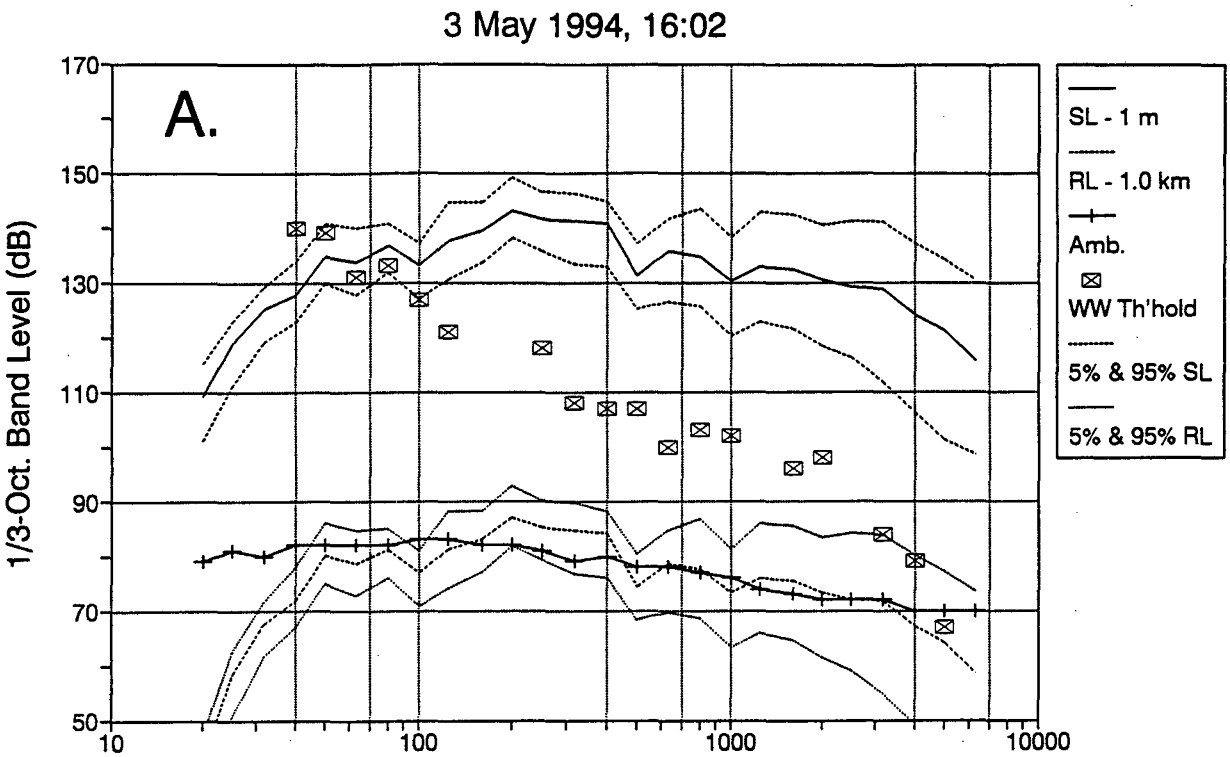
14-min cycle of the icebreaker sounds were 144, 150 and 156 dB re 1 μPa-m. The 1/3-octave band with the strongest source level was the one centered at 200 Hz, with a median source level of 143 dB re 1 μPa-m. Near 5000 Hz, where the white whale threshold is much lower ("better"), the 1/3-octave source levels were 121 Hz. Figure 7.14A shows the variability in the sounds as projected (1-m source levels) and as received at 1 km range at 16:02. Figure 7.14B shows the estimated median received levels at several standard distances at the same time. Given the prevailing ambient noise levels on 3 May 1994 plus the reported hearing thresholds of white whales, they would not be expected to have heard the median-level projected sounds at distances beyond about 300 m (Fig. 7.14B). It would be the sounds near 5000 Hz that would be detectable farthest away. Maximum levels of transmitted sound were several decibels higher than median levels (Fig. 7.14A), so maximum levels would be detectable somewhat farther away.

During the playback of icebreaker sounds, 13 groups of white whales were seen within 385 m of the operating projectors (Table 7.3). The maximum underwater sound levels during the 64-s periods previous to these times were estimated for the CEPA distances using the sound exposure model. The maximum broadband (20-5000 Hz) source levels (dB re 1 μPa-m) and the $RL_{BB,max}$ and $RL_{1/3,max}$ levels (dB re 1 μPa) for the 13 whale groups were as follows:

	CEPA @ 15:42:06,	SL = 153,	RL @ 385 m =	102,	RL near 5 kHz = 76
	CEPA @ 15:44:57,*	SL = 154,	RL @ 210 m =	108,	RL near 5 kHz = 78
past	CEPA @ 15:54:00,*	SL = 155,	RL @ <240 m >	108,	RL near 5 kHz > 80
	CEPA @ 15:58:25,	SL = 154,	RL @ 390 m =	103,	RL near 5 kHz = 74
past	CEPA @ 15:59:49,*	SL = 156,	RL @ <360 m >	105,	RL near 5 kHz > 83
past	CEPA @ 16:02:00,*	SL = 156,	RL @ <180 m >	111,	RL near 5 kHz > 79
	CEPA @ 16:08:00,*	SL = 156,	RL @ 260 m =	107,	RL near 5 kHz = 84
	CEPA @ 16:16:55,	SL = 156,	RL @ 410 m >	104,	RL near 5 kHz > 67
	CEPA @ 16:18:00,	SL = 152,	RL @ 125 m =	109,	RL near 5 kHz = 83
	CEPA @ 16:20:12,	SL = 150,	RL @ 295 m =	101,	RL near 5 kHz = 77
	CEPA @ 16:21:00,	SL = 154,	RL @ 230 m =	106,	RL near 5 kHz = 84
past	CEPA @ 16:24:20,*	SL = 154,	RL @ <330 m =	103,	RL near 5 kHz = 81
	CEPA @ 16:33:00,	SL = 156,	RL @ 20 m <	130,	RL near 5 kHz < 115

For comparison, the average ambient levels were 93 dB for the 20-5000 Hz band, and 70 dB for the 1/3-octave band centered at 5000 Hz. The latter value coincides with the hearing threshold of white whales at 5000 Hz. The asterisks indicate whales that may have altered their paths.

All but one of these whales probably heard weak icebreaker sounds at least briefly, given that, for all but one of these whales, $S:N_{1/3,max}$ at 5000 Hz >0 dB, and $RL_{1/3,max}$ at 5000 Hz exceeded the absolute hearing threshold. For example, Figure 7.15 shows the situation for a whale 180 m from the projector at 16:02. The median estimated received level in the 1/3-octave band around 5000 Hz was about equal to both the ambient noise and the white whale's auditory threshold, suggesting that this whale might, at times, have heard components of the projected sound near 5000 Hz. The whale seen closest to the projector was at the surface as it approached; therefore, it was subjected to lower sound levels than estimated in the above tabulation while it was being observed. However, it dove when at its CPA distance of 20 m, and would, at that time, have been exposed to the estimated levels shown in the above text table. There was no significant difference between the $S:N_{1/3,max}$ values at 5000 Hz near whales that appeared to modify their path (marked '*' in above tabulation) vs. those that did not (Mann-Whitney U=16, n=6,7, P=0.267). However, several



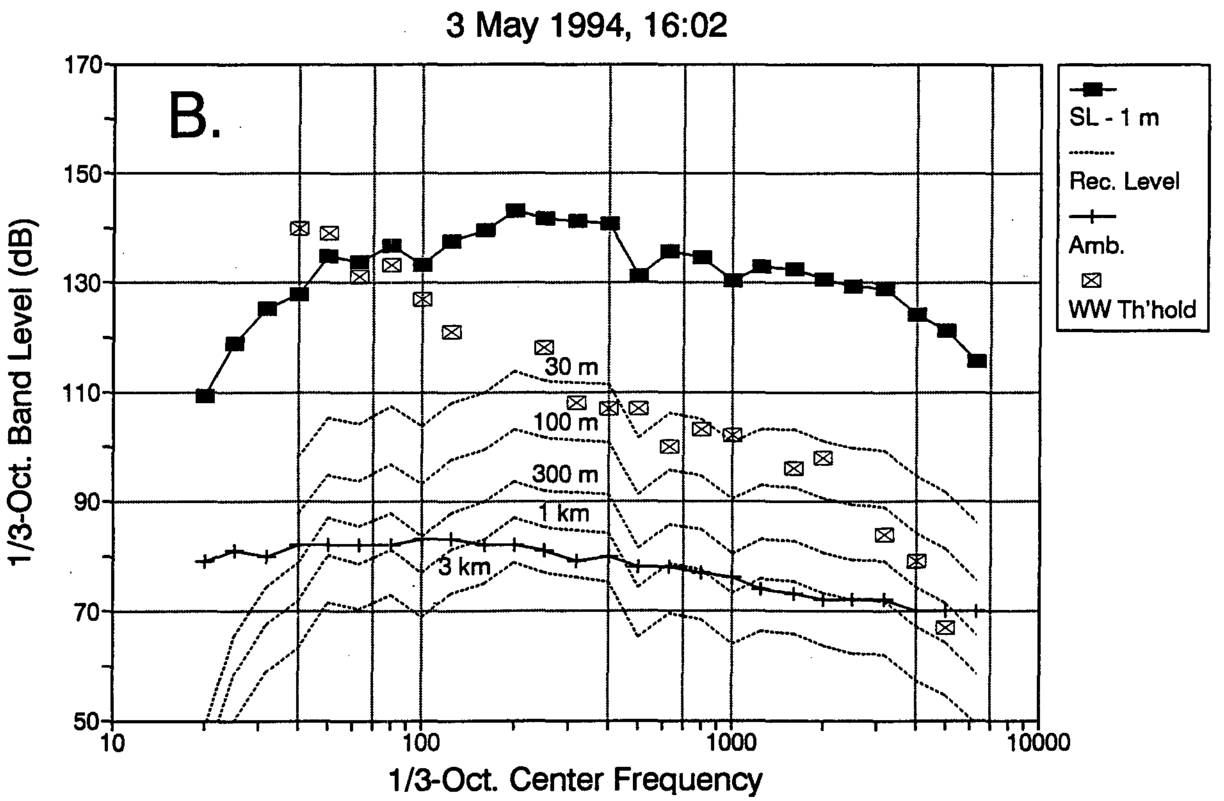


FIGURE 7.14. Third-octave levels of projected icebreaker noise vs. distance from projector and ambient noise, 3 May 1994, time 15:48-16:02. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level before and after playback. ⊠ symbols are white whale hearing thresholds vs. frequency. For additional explanation, see caption to Figure 7.10.

TABLE 7.3. Summary of sightings of white whales near the projector broadcasting icebreaker sounds on 3 May 1994. All observations were made from the ice camp located amidst the pack ice NE of Barrow. All CEPAs were determined from theodolite locations.

Time	Group size	Radial Distance Followed From Projector (m)	CEPA (m)	Nature of Track
15:40	1	+405 to +615	385	NW to N of projector heading fast NE across lead.
15:45	1	single sighting	210	SW of projector heading fast SE.
15:54	2	-240 to -450	<240	Adult & subadult SW of projector heading SSE at medium speed.
15:58	1	-360 to -425	360	Subadult S of projector heading SSW at medium speed.
16:00	1	single sighting	390	Subadult S of projector heading ENE under ice edge at medium speed.
16:02	2	-180 to -230	180	Adult & subadult SW of projector heading SSW at medium speed.
16:06	5	+345 to +770	330 & 260	4 Adults & 1 subadult NW then NNE of projector heading NE then NNE then NE at medium speed.
16:17	1	single sighting	<410	NNW of projector heading NE at unknown speed.
16:18	1	single sighting	125	Subadult NW of projector heading NE at medium speed.
16:19	8	+365 to +300	295	NW of projector heading E then ENE then dove E under ice edge at medium speed.
16:21	6	single sighting	230	NNW of projector heading NE under ice edge at medium speed.
16:24	1	-330 to -395	<330	Subadult SSW of projector heading SSE at medium speed.
16:31	2	+185 to +20	20	NNW then W of projector heading SSE along ice edge at medium speed.

of the whales that appeared to divert were probably exposed to higher sound levels before they were first sighted. Thus, the test underestimates any possible differences.

<u>Sighting Rates During Playback and Control Periods</u>

Meaningful results concerning reactions of white whales to playbacks of icebreaker sounds were obtained on 17 May 1991 and 3 May 1994. On 17 May 1991, white whales were migrating eastward close to the landfast ice edge prior to the playback. Eastward migration continued during the playback, including at least two whales whose closest points of approach were only 80 and

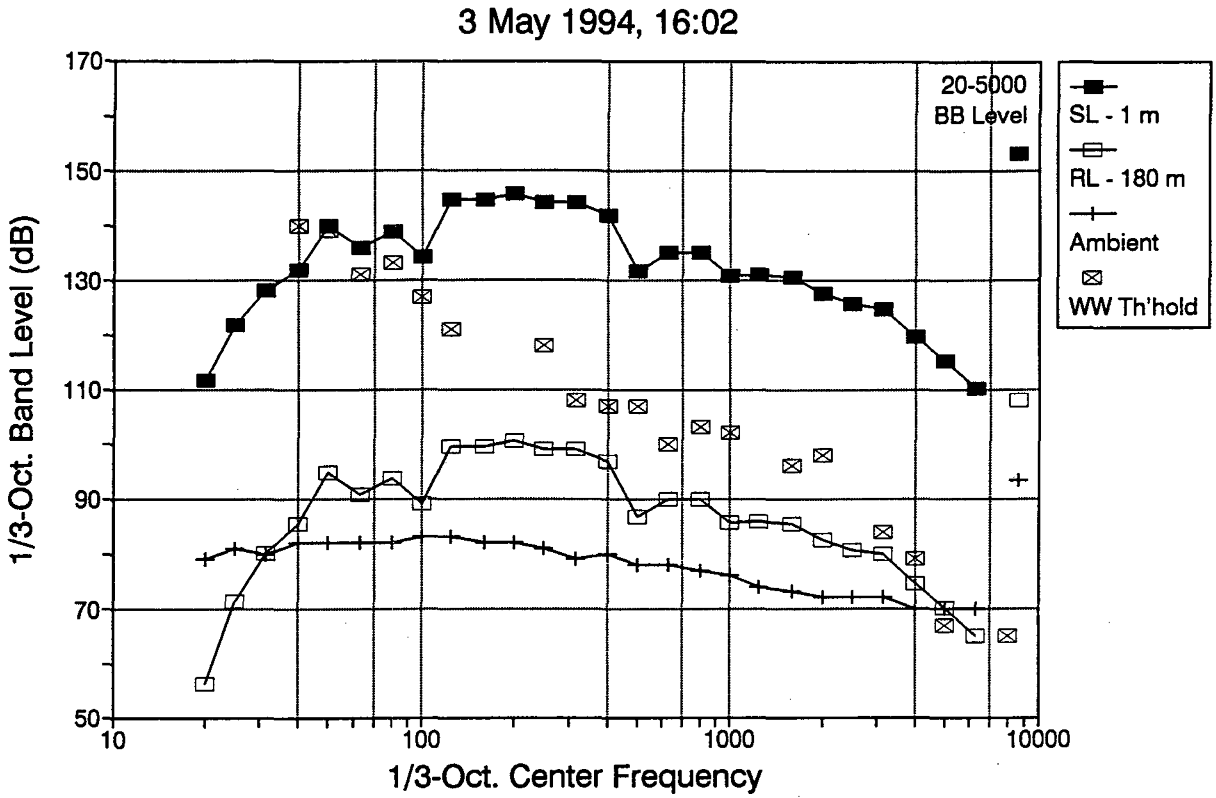


FIGURE 7.15. Third-octave levels of projected icebreaker noise 1 m from the projector (closed squares) and near a white whale 180 m from the projector (median level over 64 s), 3 May 1994, time 16:02. Plus signs show average ambient noise level before and after playback. ⊠ symbols are white whale hearing thresholds vs. frequency. For additional explanation, see caption to Figure 7.11. Propagation model includes spherical spreading (plus Lloyd's mirror factor) at close ranges.

95 m from the operating projectors. However, as described above, numbers of whales and of whale groups passing per hour were considerably lower during the 17 May 1991 playback than during the pre- and post-playback control periods on that date.

This difference in numbers is consistent with the possibility that some white whales avoided passing close to the ice camp as a result of the playback. However, observations from the ice-based platform on a single date cannot prove that the playback was the cause of the lower number seen during the playback. Pods of white whales often migrate in loose associations spread out over several kilometers. It is possible that the pre- and post-playback periods on 17 May 1991 happened to coincide with times when two such associations were passing the ice camp.

In contrast, on 3 May 1994, white whales passed the ice camp during but not before or after the playback. Thus, there was no consistent pattern for lower sighting rates during playbacks.

To determine whether the sighting rate at ice camps differs during playbacks vs. control periods, effective playback tests on more than two days would be necessary, preferably in conjunction with aerial observations to determine the distribution of whales over a larger area than can be seen from the ice camp.

Acoustic Response Thresholds

The maximum levels of icebreaker sound received by the whales seen passing on 17 May 1991 were well above ambient on a broadband basis (20-5000 Hz band). However, much of the energy in the projected icebreaker sounds was at relatively low frequencies and probably could not be heard by the white whales (Fig. 7.10, 7.11). Nonetheless, white whales probably could hear components of icebreaker sounds near 5000 Hz, where maximum received levels near whales were 88-96 dB ($RL_{1/3,max}$) and where maximum icebreaker-to-ambient ratios near whales were 8-16 dB ($S{:}N_{1/3,max}$). Sounds received at these low levels and S:N ratios would presumably be perceived as relatively weak sounds.

On 3 May 1994, 13 groups of white whales were seen while icebreaker sounds were being projected into the lead. Six of these groups appeared to alter their paths in response to the playback. Received levels of icebreaker sounds were weaker than on 17 May 1991 ($RL_{BB,max}$=102-111 vs. 119-129 dB re 1 μPa; $RL_{1/3,max}$ @ 5000 Hz=67-84 vs. 88-96 dB re 1 μPa). However, $S{:}N_{1/3,max}$ levels near 5000 Hz were generally similar near 11 of 13 groups sighted on 3 May 1994 (4-14 dB) as near the four groups sighted on 17 May 1991 (8-16 dB). The other two groups sighted on 3 May 1994 included one group that was not exposed to audible sounds ($SN_{1/3,max}$ = -3 dB) and another group (2 whales) exposed to $S{:}N_{1/3,max}$ near 5000 Hz of ~40+ dB when it approached the projector and 45 dB when it dove at its CPA.

Considering all 17 groups observed on the two dates, 6 groups apparently diverted. **Near 5000 Hz, diverting groups were receiving icebreaker sounds with estimated $RL_{1/3,max}$ levels of about 78-84 dB re 1 μPa, and $S{:}N_{1/3,max}$ values ~8-14 dB.** Corresponding estimated levels near the 11 groups for which no diversion was evident were $RL_{1/3,max}$ = 67-115 (96) dB re 1 μPa and $S{:}N_{1/3,max}$ = -3 to 45 (16) dB. The values in parentheses indicate the maximum levels near whales if the group that approached to 20 m from the projector is excluded.

The sample size is very small (17 groups), but the data suggest that some white whales responded to high-frequency components of icebreaker sounds at low received levels and low icebreaker-to-ambient ratios. White whales presumably were reacting to these rather weak high-frequency components (e.g., $S{:}N_{1/3,max}$ ~8-14 dB near 5000 Hz) of the icebreaker sound, which are believed to have been audible to them, rather than to stronger and higher S:N components at lower frequencies, which were probably not audible to these animals.

In summary, about one-third of the white whales sighted near the operating projectors appeared to show small scale avoidance reactions when exposed to icebreaker sound that was ~8-14 dB above the background noise in the 1/3-octave band centered at 5000 Hz ($RL_{1/3,max}$ = 78-84 dB re 1 μPa). Although icebreaker sounds were much stronger at lower frequencies, the white whale hearing threshold is such that they probably could not detect those sounds during the playback experiments.

Potential Radius of Influence of Actual Icebreaker

The median source levels of the projectors used during playbacks ($SL_{BB,med}$), typically 161 dB re 1 µPa-m on 17 May 1991 and 150 dB on 3 May 1994, were lower by ~36 and 47 dB than the corresponding median source level for the full-scale icebreaker (197 dB) whose recorded sounds were projected. Of more relevance to white whales is the difference between the source levels of the actual icebreaker and the projector(s) at high frequencies, e.g. near 5000 Hz. The top curves in Figure 7.16A vs. B and Figure 7.17A vs. B show this difference for times on 17 May 1991 and 3 May 1994 when white whales were observed.

If, during playbacks of *Robert Lemeur* icebreaker sound, some white whales begin to show diversion at a received level of ~80 dB re 1 µPa ($RL_{1/3,max}$ near 5000 Hz) or an icebreaker:ambient ratio of ~10 dB ($S{:}N_{1/3,max}$), at what distances from an actual icebreaker might diversion be evident?

Figure 7.16B shows estimated received levels of sounds from the icebreaker *Robert Lemeur* at various distances if the actual vessel had been operating at the 17 May 1991 projector site. The received level estimates are based on the 95th percentile source level estimates shown in Figure 4.25 (p. 116) and on the sound exposure model described in §2.3 (0.03 and 0.1 km spectra assume spherical spreading). The ambient noise levels actually measured on 17 May 1991 are also shown. If white whales often react to high frequency components of icebreaker sound at $S{:}N_{1/3,max}$ levels near 10 dB, they would be expected to react out to the approximate distance where the 95th percentile level of high-frequency icebreaker noise is 10 dB above the ambient noise level, provided that this level is above the absolute hearing threshold. Figure 7.16B shows that the 95th percentile received levels are expected to diminish to the "10 dB above ambient" or to the white whale hearing threshold, whichever is greater at a given frequency, at ranges of 5-10 km in all 1/3-octave bands from 315 to 6300 Hz. At lower frequencies, the received level diminishes below the auditory threshold at closer ranges (≤3 km). Thus, the expected maximum reaction distance would be expected to be **~5-10 km** if the actual icebreaker *Robert Lemeur* had been operating at the 17 May 1991 site under the ambient noise conditions prevailing on that date (Fig. 7.16B).

Figure 7.17B allows a similar evaluation of the situation if *Robert Lemeur* had been operating at the 3 May 1994 site under the ambient noise conditions prevailing there on that date. The 95th percentile received levels diminish below the hearing thresholds at 315-4000 Hz at ranges 5-10 km. Above 4000 Hz, received levels diminish below the "10 dB above ambient" curve before they diminish below the hearing threshold, at ranges 7-10 km. Thus, the expected maximum reaction distance would again be **~10 km** if the actual icebreaker *Robert Lemeur* had been operating at the 3 May 1994 site under ambient noise conditions prevailing on that date (Fig. 7.17B). At range 10 km, the predicted received level equals the "10 dB above ambient" curve and the hearing threshold in only one 1/3-octave band for the 17 May 1991 case, but in at least three bands in the 3 May 1994 case (Fig. 7.16B vs. 7.17B). This difference is attributable to the lower ambient noise

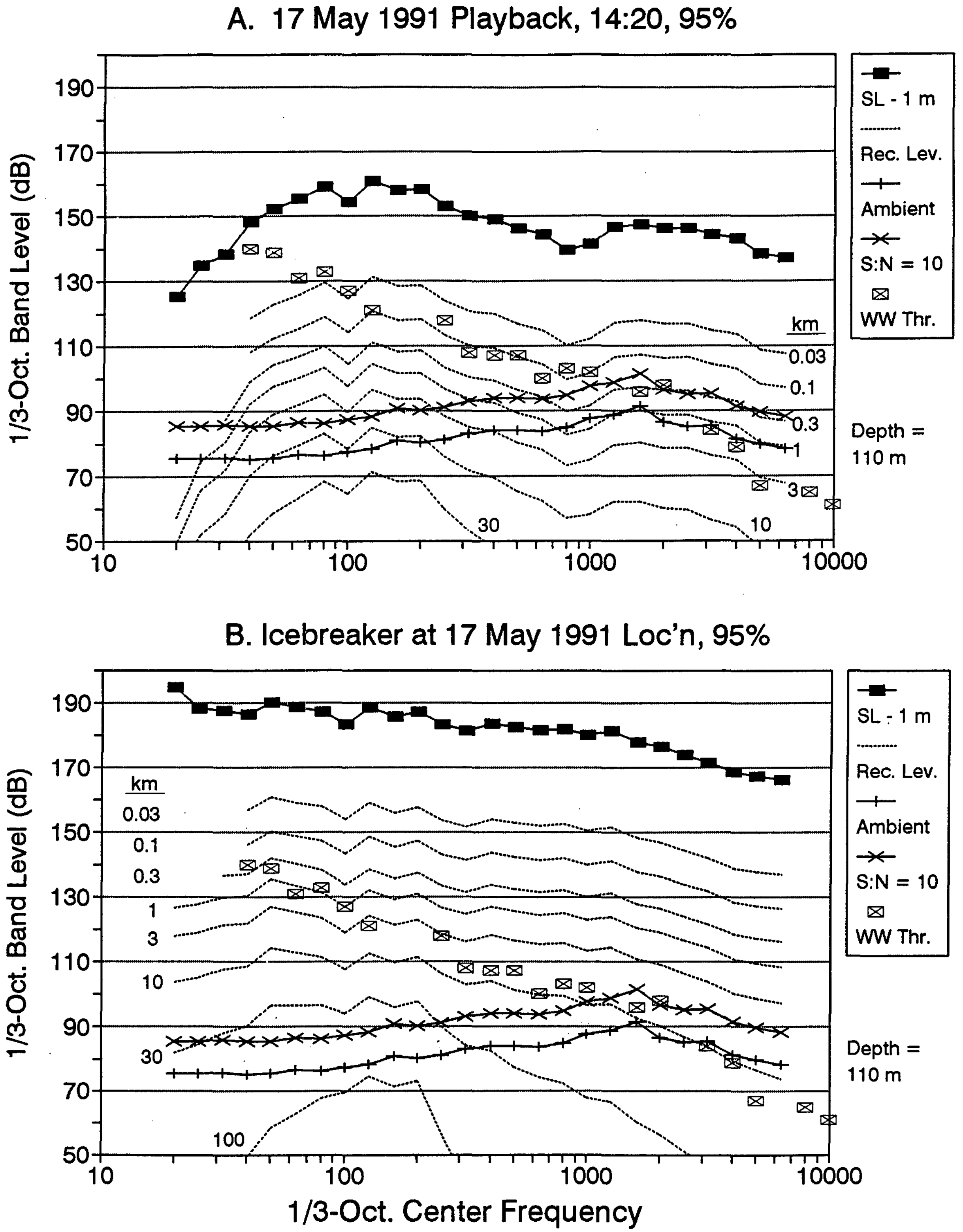


FIGURE 7.16. Estimated 95th percentile source and received levels of icebreaker noise, by 1/3 octave, *(A)* during playback on 17 May 1991, time 14:20, and *(B)* if actual icebreaker were operating at that site. Also shown is the average ambient noise level on 14 May 1991, and "10 dB above ambient", also on a 1/3-octave basis. ⊠-symbols are white whale hearing thresholds.

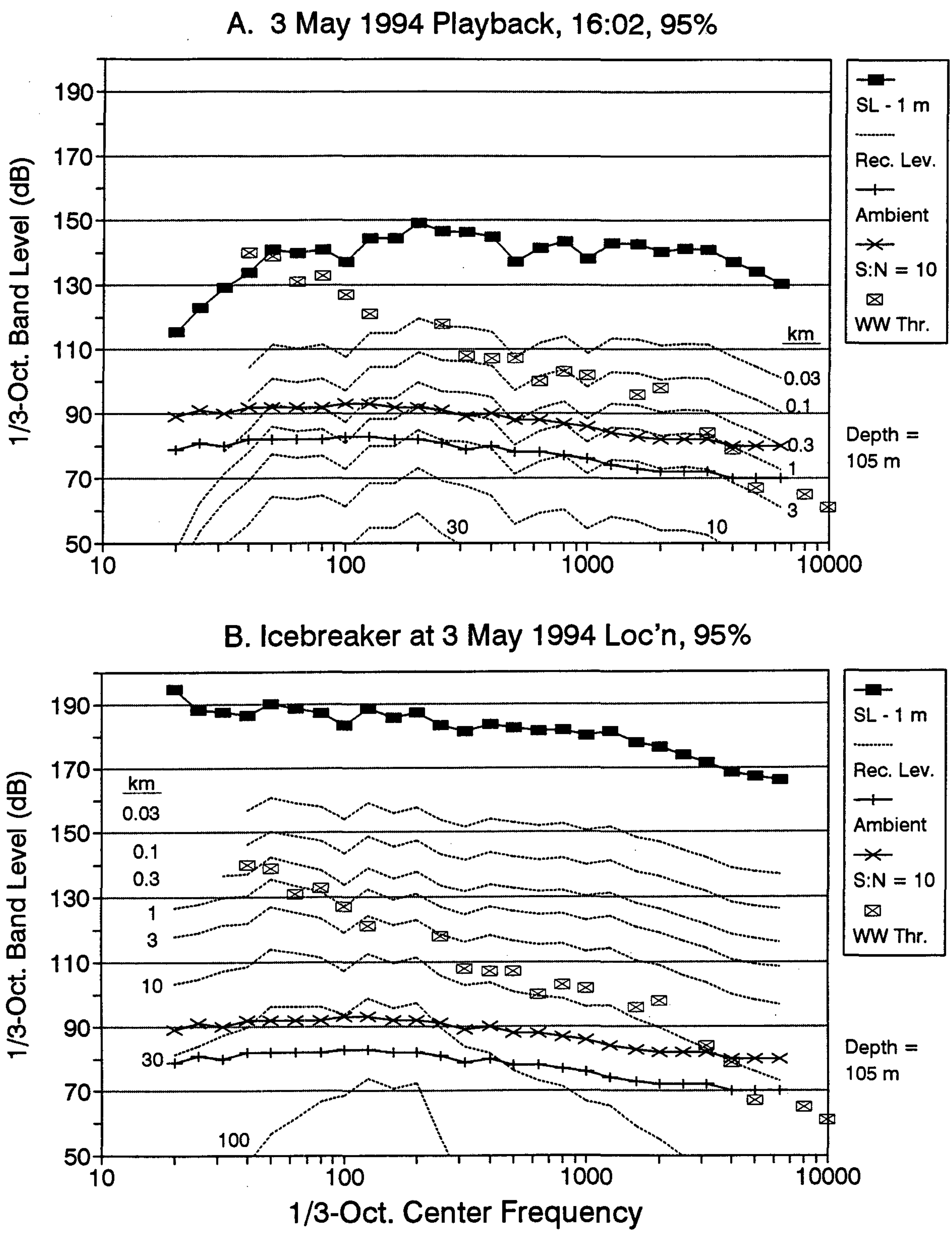


FIGURE 7.17. Estimated 95th percentile source and received levels of icebreaker noise, by 1/3 octave, *(A)* during playback on 3 May 1994, time 16:02, and *(B)* if actual icebreaker were operating at that site. Also shown is the average ambient noise level on 3 May 1994, and "10 dB above ambient", also on a 1/3-octave basis. ⊠-symbols are white whale hearing thresholds.

levels at high frequencies on 3 May 1994; predicted received levels vs. range are almost identical in the two cases.[37]

Numerous assumptions are involved in making these estimates. These assumptions are, for the most part, similar to those that apply in making corresponding "radius of responsiveness" estimates for bowheads (discussed in §6.4). Wide variations in maximum reaction distances are expected in different situations and when icebreakers with different high-frequency source levels are used. Sometimes white whales would be expected to tolerate an icebreaker managing ice closer than 5-10 km away, but at other times they are likely to avoid an area of radius substantially larger than 5-10 km. The limited available data from playbacks of icebreaker noise do not allow us to set meaningful upper and lower bounds on these predicted reaction distances.

Researchers in the Canadian High Arctic have documented reactions by white whales and narwhals to ships and icebreakers 40 km or more away (LGL and Greeneridge 1986; Cosens and Dueck 1988; Finley et al. 1990). In this situation, the whales appeared to be reacting to sounds that were barely detectable to them. High frequency components may have been the components most readily detected by white whales at the long ranges where reactions were first noted (Cosens and Dueck 1993). During the present study, we observed a few groups of white whales approaching and passing when projected icebreaker sounds were estimated to have been clearly audible in the 1/3-octave band near 5000 Hz. Some whales appeared to have diverted when $S{:}N_{1/3,max}$ was slightly higher than 8-14 dB (i.e. many whales were moving away when first seen).

The High Arctic observations involved actual icebreakers underway in open water or ice. There is considerable variation in the characteristics of sounds made by different vessels, and in the sounds made by an actual vessel vs. a projector broadcasting recorded vessel sound. Also, it has been suggested that the Canadian High Arctic whales are more "naive" and therefore more likely to react at greater distances. For these reasons, it is difficult to compare the results of the Canadian High Arctic studies with the present results. However, both studies provided evidence consistent with the idea that higher-frequency components of vessel sounds may be the components to which spring-migrating white whales are most likely to react.

7.3 Evaluation of Playback Hypotheses

As discussed in §1.2, Null and Alternate Hypotheses, the one null hypothesis applicable to playback effects on white whales was as follows:

> Playbacks of recorded noise from a bottom-founded platform (1989-90) or an icebreaker working on ice (1991/94) will not (or alternatively will) significantly alter *measures of migration routes and spatial distribution of whales* in the open water of nearshore lead systems during the spring migration near Pt. Barrow, Alaska.

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[37] Water depth, the dominant factor in determining predicted propagation loss at a given frequency in this study area and season (§4.3), was almost identical at the 17 May 1991 and the 3 May 1994 sites (110 m vs. 105 m, respectively).

The similar hypothesis concerning *subtle aspects of individual whale behavior* could not be addressed for white whales because it was not practical to obtain detailed observations of white whale behavior, aside from information about their swimming tracks.

Continuous *Karluk* Drilling Sound

During the 1989/90 playbacks with steady *Karluk* drilling sounds (Richardson et al. 1990a, 1991a), the wording of the above hypothesis was found to be somewhat broader than could be addressed with the available data. We could only draw conclusions about the effects of playbacks of ***continuous noise from drilling on a bottom-founded ice platform like Karluk***. Also, the 1989-90 data applied to white whales migrating through ***pack ice and along the seaward side of the nearshore lead east of Pt. Barrow***.

With these restrictions and amendments to the wording, the 1989-90 data showed that playbacks of sounds from drilling on a bottom-founded ice platform like *Karluk* have no ***biologically significant*** effects on migration routes and spatial distribution of white whales visible while migrating through pack ice and along the seaward side of the nearshore lead east of Point Barrow in spring. Furthermore, *Karluk* sounds attenuated rapidly with distance (§6.5; see also Richardson et al. 1990a:86). We concluded that maximum reaction distances of white whales to an actual drillsite like *Karluk* (a few hundred meters) would be similar to those observed during the playback experiments. In drawing these conclusions, we considered that the observed temporary hesitation and minor changes in migration paths exhibited by some white whales within 200-400 m of the projector emitting *Karluk* noise were not biologically significant. Our acceptance of the amended null hypothesis was based on a "weight of evidence" approach; the available data for *Karluk* were not suitable for a statistical test of the hypothesis.

Variable Icebreaker Sound

In 1991/94, as in 1989-90, observations during playbacks were restricted to white whales visible in open water within areas east of Pt. Barrow. In 1991/94, the playback noise was variable icebreaker noise rather than continuous drilling sound, and the observations were on both the landfast ice side of the nearshore lead (13 May 1991) and in a lead amidst pack ice (3 May 1994). Thus, for 1991/94, the hypothesis (1) should be formulated as

> "Playbacks of recorded ***variable*** noise from an icebreaker **like *Robert Lemeur*** working on ice will not (or alternatively will) significantly alter *measures of migration routes and spatial distribution of* white whales ***visible*** in the open water of lead systems during spring migration ***east of*** Pt. Barrow, Alaska."

The hypothesis concerns reactions to *playbacks* of icebreaker noise rather than to noise from the icebreaker itself. Thus, questions about the fidelity of the playback noise to the noise from the original industrial activity are not directly involved. Also, the greater radius of anticipated effects around an actual icebreaker is not directly dealt with by the hypothesis.

Because we saw few white whales near the projector(s) when icebreaker sounds were being projected, we would need to conduct additional field tests before this hypothesis could be evaluated with confidence. However, white whales must approach within a few hundred meters of the projectors in order to hear the playbacks of icebreaker sounds. Small-scale diversions sometimes occur at closer ranges. These are unlikely to be biologically significant.

As discussed for bowheads in §6.6, any conclusions regarding the effects of icebreaker playbacks whales cannot be applied directly to the question of actual icebreaker effects, given the much higher source level of the actual icebreaker than of the playback projectors. The radius of responsiveness around an actual icebreaker would be expected to be much larger than that around the playback site, probably on the order of several kilometers.

This conclusion assumes that response thresholds to an actual icebreaker like *Robert Lemeur*, on an S:N or RL basis, are comparable to those near the playback site. This assumption is discussed on p. 10-11 (§1.3) and on p. 115-128 (§4.4). For white whales, the poor reproduction of the low-frequency components of icebreaker sound during playbacks (§4.4) probably has little relevance. The hearing sensitivity of white whales is poor at those frequencies (Fig. 7.16, 7.17). White whales probably react primarily or exclusively to higher frequency components, which were reproduced with good fidelity during the playbacks.

The predicted radius of responsiveness around an icebreaker like *Robert Lemeur* would be quite variable because propagation conditions and ambient noise vary with time and location. Also, icebreakers vary widely in engine power and thus noise output, with *Robert Lemeur* being a rather low-powered icebreaker. Furthermore, reaction thresholds of individual white whales no doubt vary, with commensurate variability in predicted reaction radius.

7.4 White Whale Reactions to Aircraft

An assessment of the reactions of white whales to helicopter overflights was one of the secondary objectives of this project (see specific objective 6 in §1.1). Collection of data on their reactions to the project's Twin Otter fixed-wing aircraft was not an explicit objective, but this falls under the provisions of specific objective 7, "To document, as opportunities allow, other aspects of the...disturbance responses...white whales...".

Results from 1989-90 showed that reactions of white whales to turbine-powered aircraft during the spring migration near Pt. Barrow are variable (Richardson et al. 1990a:239, 1991a:282). Some individuals show no overt response to a Bell 212 helicopter or Twin Otter fixed-wing aircraft flying at low level, or to a Bell 212 standing on the ice edge with engines running within 100-200 m of the whales. Other white whales look upward or dive abruptly when an aircraft passes over at altitudes at least as high as 460 m (1500 ft). Some white whales whose paths come within 100 m of a helicopter on the ice with its engines running may divert as much as 100 m away from the helicopter. It is not known whether these small-scale and apparently brief reactions are to the noise from the aircraft, visual cues, or both.

In this section, we summarize the reactions of white whales to the project's Bell 212 helicopter and Twin Otter fixed-wing aircraft during all four years of the project.

Reactions to Bell 212 Helicopter

Results—During 1989-91 and 1994, there were 42 occasions when behavior of white whale groups was observed at known lateral and/or vertical distances (Table 7.4). Observations of white whale groups were made

- during overflights (n = 20; Table 7.4A),
- within 2 min of landing or during takeoff (n = 8; Table 7.4B), and
- when the helicopter was stationary on the ice with its engines operating >2 min after landing (n = 14; Table 7.4C).

Two cases are possible resightings and were excluded from the analysis, leaving 26 observations during overflights or within 2 min of landing or takeoff and 40 cases in total.

Frequency of Reactions: Apparent reactions to the helicopter were observed on 15 (37.5%) of these 40 occasions. Apparent reactions consisted of 7 immediate dives and 8 unusual headings or changes in heading. Reactions were noticed when the helicopter was stationary on the ice (7 cases), within 2 min of helicopter landing (2 cases), and during overflights (6 cases). The remaining 25 white whales or white whale groups exhibited no overt reaction to the helicopter and generally maintained their course and continued respiring at the surface.

Reactions were noticed when the helicopter was at altitudes 0-460 m, and at lateral distances 0-320 m (Fig. 7.18). Of the 7 reactions for which both altitude and lateral distance were known during overflight (including cases observed within 2 min of after the helicopter landed), most reactions (6 of 7 groups or 85.7%) occurred when the helicopter was operating at altitudes ≤150 m ASL and at lateral distances ≤250 m (Table 7.5, Fig. 7.19).

Helicopter Altitude: Altitude ASL during "overflights" ranged from 0 m (when white whale groups were observed within 2 min of helicopter takeoff or landing) to 460 m (n=25 cases at known altitudes; Table 7.4A,B). Immediate dives occurred during 4 overflights when the helicopter approached at altitudes ≤150 m. More often, however, no immediate dive occurred when the helicopter approached at ≤150 m (9 of 15 cases). In most of these cases, white whales remained at the surface without apparent reaction. In two cases at ≤150 m, other types of reactions, including change in heading and reduced speed, were seen. Reactions occurred more frequently during overflights at altitudes of ≤150 m (6 of 15 groups, 40%) than at altitudes >150 m (1 of 10 groups, 10%) (Table 7.5, Fig. 7.19). However, given the small sample size, the difference is not statistically significant (chi^2=1.397, df=1, P>0.05).

Helicopter Lateral Distance: Lateral distance from the helicopter to white whales during 26 "overflights" ranged from 0 m (during direct overflights) to 500 m. Significantly more reactions occurred when overflights were at ≤250 m lateral distance from white whales (8 of 15 groups, 53.3%) than when 250-500 m away (0 of 11 groups), ignoring helicopter altitude (chi^2= 6.155, df=1, P<0.05; Table 7.5). No white whales reacted during the 11 overflights at lateral

TABLE 7.4. Incidental observations of white whales near the operating helicopter northeast of Barrow during spring in 1989-1994.

Date	Time	Group Size	Altitude (m)	Lateral Distance (m)	Reaction?	Observ. Platform*	Comments
A. Observed During Overflight							
16/05/89	?	3	15-30	500	No	I	Continued travel at surface
17/05/89	?	1	150	0	Yes	I	Dove immediately before reaching end of lead whereas previously undisturbed groups did not dive until they were a few meters from the ice edge
17/05/89	?	4	460	0	Yes	I	Dove immediately before reaching end of lead whereas previously undisturbed groups did not dive until they were a few meters from the ice edge
26/05/89	14:00	1	120	50	Yes	H	Dove rapidly and steeply as helicopter passed at cruise speed
10/05/90	13:48	2	?	0	Yes	I	Dove during overflight
06/05/91	11:16	1	60	0	Yes	H	Made deep vertical dive
17/05/91	10:43	15-20	60	75	No	I	Continued traveling at surface as helicopter flew by
17/05/91	12:08	5	65-30	200-300	Yes	I	Social group changed heading away from ice edge as helicopter turned and landed, remained at surface and continued social activity
03/05/94	9:46	2	425	500	No	H	Continued travel SSE
03/05/94	22:04	16	250	400	No	H	Continued travel E
03/05/94	22:05	2	250	400	No	H	Continued travel E
03/05/94	22:06	3	250	400	No	H	Continued travel E
08/05/94	21:12	1	200	400	No	H	Continued travel W
17/05/94	19:48	5	200	200	No	H	Continued travel E
22/05/94	8:43	4	325	500	No	H	Continued travel ESE
22/05/94	8:44	8	325	500	No	H	Milling, asynchronous headings
22/05/94	8:51	5	375	500	No	H	Travel, generally SE with asynchronous headings
22/05/94	9:00	1	30	50	No	H	Remained at surface oriented NE
25/05/94	8:31	1	60	300	No	H	Remained at surface oriented E
25/05/94	8:32	10	60	300	No	H	Remained at surface oriented E
B. Observed Within 2 min of Landing or During Take-off							
10/05/90	14:04	2	0	200	Yes	I	Subadults continued travel at surface, after helicopter landed (14:04), dove as engine speed decreased
10/05/90	14:29	4	0	120	Yes	I	Approached quiet helicopter on ice, then milled (subadult spyhopped) as helicopter engines started; whales dove 20 s after helicopter lifted off ice (possible resighting)
10/05/90	14:33	4	0	45	No	I	Approached helicopter as it lifted off ice (possible resighting)
21/05/90	10:05	4	0	50-100	No	I	Travel at surface as helicopter lifted off ice
21/05/90	10:06	10	0	50-100	No	I	Travel at surface as helicopter lifted off ice
17/05/91	10:46	2	0	150	No	I	Continued travel as helicopter landed ~150 m away
17/05/91	11:11	2	0	100	No	I	Adult-yearling traveled past helicopter as it lifted off ice
17/05/91	12:08	10	30	100-250	Yes	I	Initially eastbound, milled in closely-spaced group as helicopter approached. Resumed E surface travel at reduced speed. Reversed course after helicopter landed. Whales resumed travel to NE after engines off.
C. Helicopter Stationary on Ice, Engines Operating, >2 min After Landing							
10/05/90	14:09	4	0	?	Yes	I	Swam past stationary helicopter operating on ice; then began milling and dove as helicopter taxied across ice (landed 6 min earlier)
21/05/90	9:19	3	0	95	Yes	I	Traveled past helicopter (landed 09:16) along far side of 100-m wide lead, farther than undisturbed whales
21/05/90	9:19	7	0	70	Yes	I	Traveled past stationary helicopter mid-way across 100-m wide lead, farther than undisturbed whales
21/05/90	9:20	2	0	95	Yes	I	Traveled past helicopter along far side of 100-m wide lead, farther than undisturbed whales
05/05/91	12:02	2	0	150	No	I	Milling before helicopter engines started; maintained heading tangential to helicopter after engines turned on
11/05/91	19:00	4	0	70	No	I	Continued travel as helicopter stationary on ice with engines on
11/05/91	19:00	3	0	70	No	I	Continued travel as helicopter stationary on ice with engines on
11/05/91	19:00	2	0	160	No	I	Continued travel as helicopter stationary on ice with engines on
11/05/91	19:07	2	0	90	No	I	Surfaced ~100 m away 30 s after helicopter engines turned off, then passed directly in front of ice camp/helicopter
11/05/91	19:08	4	0	320	Yes	I	Surfaced 2 min after engines off with NNE heading, contrasting with ENE headings of 9 other groups seen passing ice camp that day during engines off conditions.
17/05/91	10:50	1	0	65	No	I	Traveled ~15 m off ice edge past helicopter stationary (landed 10:46) with engines on
17/05/91	11:09	15-18	0	130	No	I	Traveled past helicopter stationary on ice with engines on (lift-off 11:11)
17/05/91	12:14	1	0	32	Yes	I	Unusual travel (sub-surface, slow, to W) past helicopter stationary (landed 12:11) 30 s after engines off.
17/05/91	19:58	3	0	250	Yes	I	Tracked for 15 min, headed ENE along nearshore lead, passing helicopter stationary on ice with engines on. The ENE heading, veering away from the E-W alignment of the ice edge, attributed to helicopter

* I = Ice camp, H = helicopter.

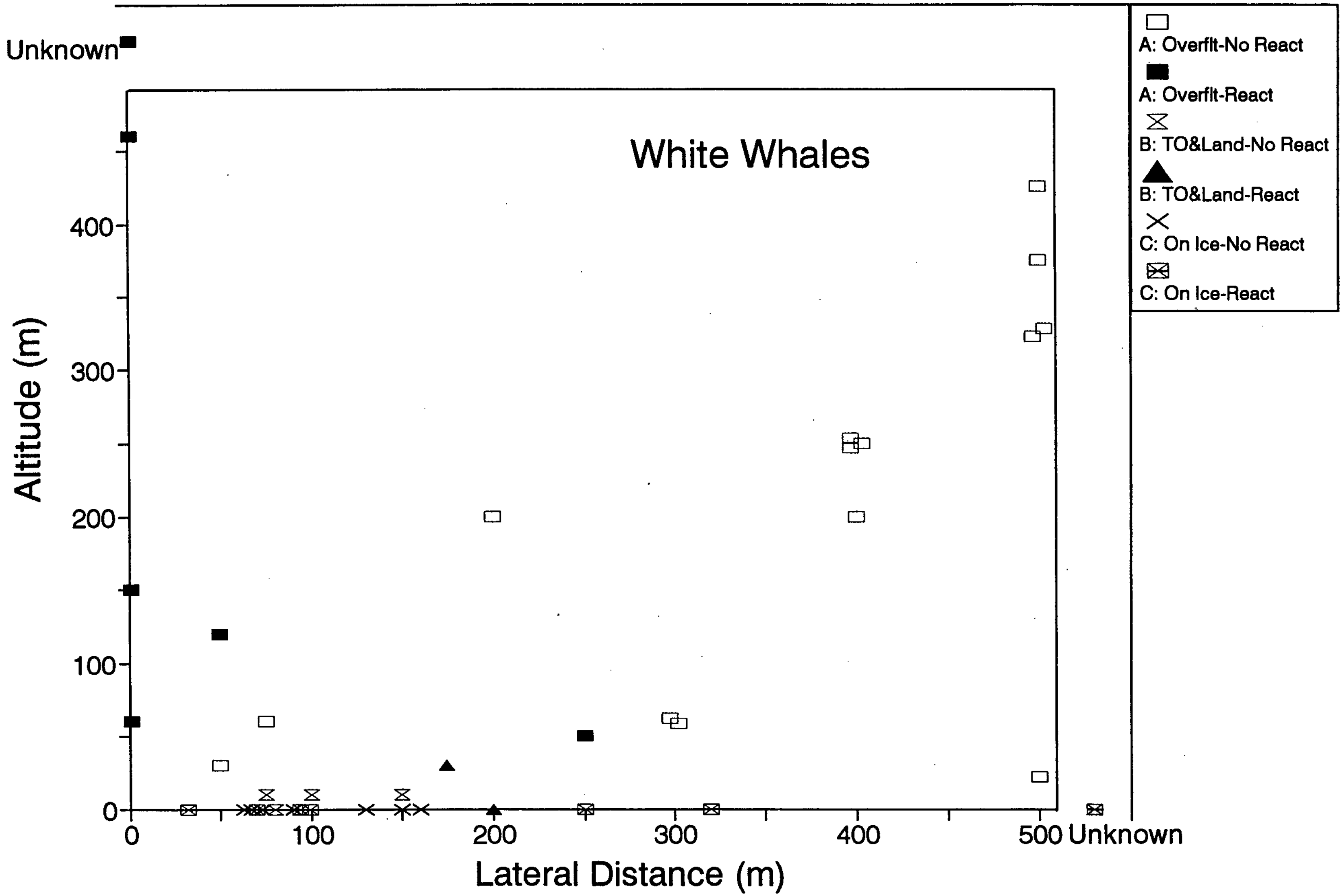

FIGURE 7.18. Reactions of white whales to the operating Bell 212 helicopter in relation to helicopter altitude and lateral distance, 1989-94. Includes cases when helicopter was *(A)* flying, *(B)* taking off (TO) or had landed within preceding 2 min, and *(C)* was on ice with engines running (*cf.* Table 7.4A,B,C).

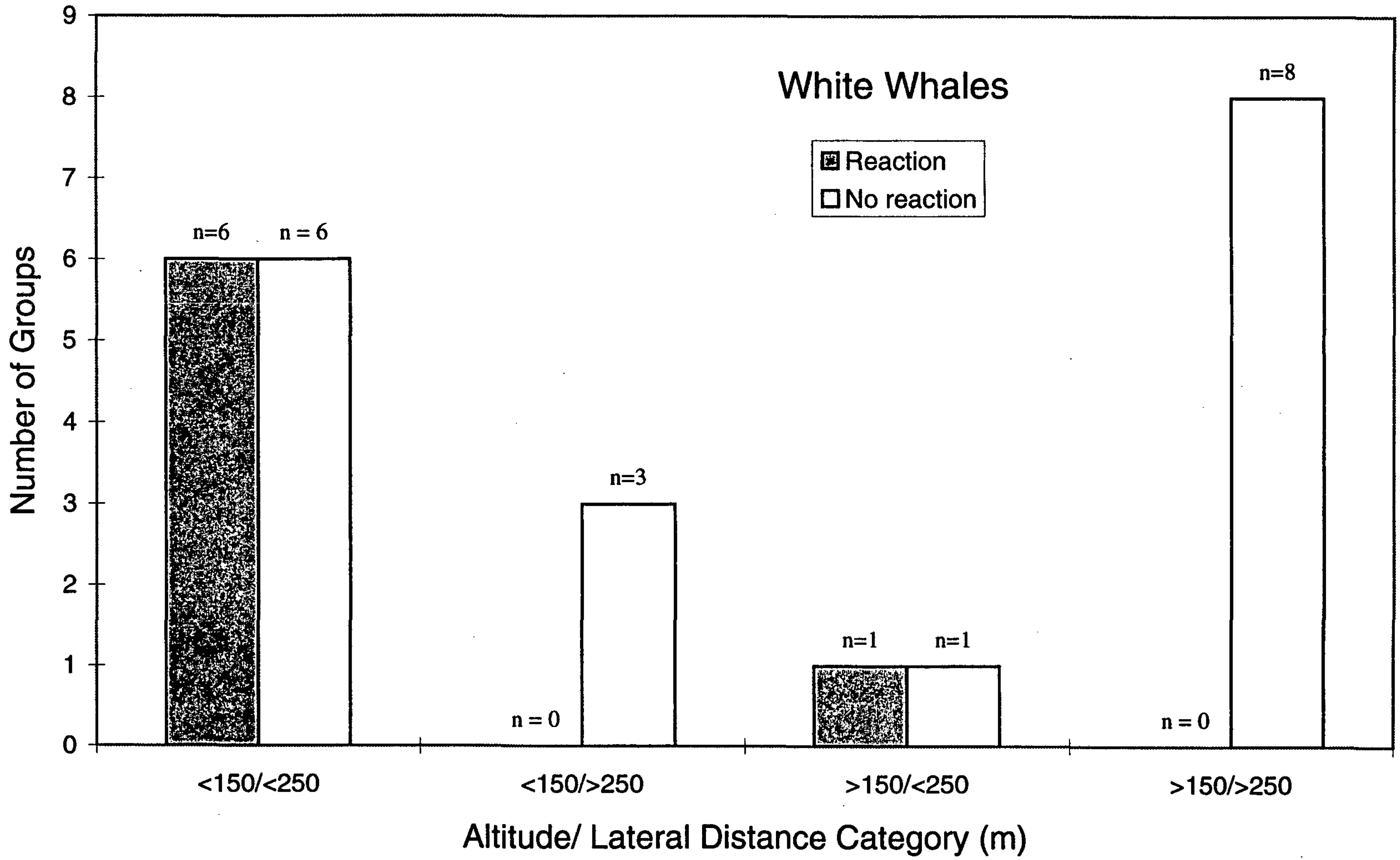

FIGURE 7.19. Reactions of white whales to the operating Bell 212 helicopter vs. helicopter altitude (≤150 m vs. >150 m) and lateral distance (≤250 m vs. >250 m), 1989-94. Includes cases when helicopter was flying, taking off, or had landed within the preceding 2 min (Table 7.4A,B).

TABLE 7.5. White whale reactions to helicopter overflights in relation to helicopter altitude and lateral distance, 1989-1994. Each white whale group is counted once. Includes data from Table 7.4A,B, involving overflights (n = 20) and cases when whales were observed within 2 min of landing or takeoff (n = 8).

Lateral Distance (m)	Helicopter Altitude (m) ≤150		>150		Unknown		Total	
	Reaction	No Reaction	Reaction	No Reaction	Reaction	No Reaction	Reaction	No Reaction
≤250	6	6	1	1	1	0	8	7
>250	0	3	0	8	0	0	0	11
Unknown	0	0	0	0	0	0	0	0
Total	6	9	1	9	1	0	8	18

distances >250 m (Table 7.5).

Helicopter Stationary on Ice: Apparent reactions were observed on 7 of 14 occasions (50%) when the helicopter was stationary on the ice with its engines operating. Reactions were noted for 5 of 12 groups seen at lateral distances ≤250 m. The only group observed at >250 m lateral distance reacted, as did another group at unknown lateral distance. Overall, the seven reactions consisted of 3 unusual headings or changes in heading, 3 apparent displacements, and 1 change in behavior state (from travel to mill). The remaining 7 white whale groups that did not react noticeably generally maintained their courses and continued respiring at the surface. Especially clear cases of displacement were observed on 21 May 1990, when white whales diverted to the far side or middle of a 100-m-wide lead while passing the helicopter (see Table 7.4C).

<u>Evaluation of Helicopter Overflight Hypotheses</u>.—Opportunistic observations in 1989-91 and 1994 showed that spring-migrating white whales often responded to a close approach by a turbine-powered helicopter. Apparent reactions were observed during 31% of overflights. Reactions were also noted during 50% of the occasions when the helicopter was stationary on the ice with its engines running. Whales reacted by diving, veering away, or showing other changes in behavior. During overflights, reactions occurred exclusively when the helicopter passed at ≤250 m lateral distance from the white whales, and at altitudes up to 460 m ASL. However, most white whales showed no obvious reaction to single passes at altitudes >150 m ASL. These white whales maintained their headings and continued respiring at the surface when the helicopter operated nearby.

It is unknown whether these small-scale and apparently brief reactions are to the noise from the aircraft, visual cues, or both. There have been no studies of the effects of other types of helicopters on migrating white whales in spring. However, the Bell 212 used in this project is one of the noisier types of helicopters used by the offshore oil industry.

We conclude that operations by a Bell 212 helicopter can locally alter the movements of white whales visible in the open water of nearshore lead systems and amidst the pack ice during spring migration near Pt. Barrow. However, these local effects do not cause migration blockage or biologically significant diversion from migration routes in the circumstances studied. Some white whales whose paths come within 100 m of a helicopter on the ice with its engines running may divert as much as 100 m away from the helicopter but continue their migration. We do not consider diversion of migration routes by 100 m to be biologically significant.

We also conclude that single overflights by a Bell 212 helicopter at lateral distances <250 m, especially at altitudes ≤150 m ASL, often affect the behavior of white whales visible in the open water of nearshore lead systems and amidst the pack ice during spring migration near Pt. Barrow. Also, white whales exposed to a stationary helicopter operating its engines within a lateral distance of 250 m often show overt behavioral reactions. Although there is no objective way to assess the biological significance of these behavioral reactions, the reactions appear to be brief and we suspect that they are not of lasting importance to the individual whales involved.

This assessment concerns potential effects of single, straight-line overflights. We did not obtain data on reactions to repeated passes, circling, or prolonged hovering at low altitude. These types of helicopter flights would be more likely than single, straight-line overflights to cause significant disturbance effects.

White Whale Reactions to Twin Otter

During the four spring seasons, 24 white whale groups were observed to react overtly to the Twin Otter fixed-wing aircraft at times when the lateral and/or vertical distances from the aircraft were noted (Table 7.6). Reactions were noticed when the Twin Otter was at altitudes ranging from 60 m (3 cases) to 460 m (4 cases), and at lateral distances of 0 m to 500 m. Reactions consisted of 10 immediate dives with tail thrash, 6 unusual turns or changes in heading (including a steep dive), 5 occurrences of twisting to look up at the aircraft, 2 changes in behavior state (travel to mill; increase swim speed), and 1 unrecorded. Strong reactions such as abrupt dives, vigorous swimming, or tail thrash occurred only during direct overflights, most frequently (10 of 12 groups, 83.3%) at altitudes ≤182 m ASL (Table 7.6).

The 24 white whale groups that were seen to react to the aircraft in 1989-94 represent a very small percentage (~3.1%) of the total number of white whale groups sighted from the Twin Otter in those four years (n=760; Table 7.7). The 18 groups seen to react to the Twin Otter at altitudes ≤182 m represent only 5.4% (18/336) of the total number of groups observed when the aircraft was at ≤182 m ASL. The two groups seen to react at aircraft altitudes 183-427 m represent only 1.4% (2/141) of the total number of groups observed from those altitudes. The four groups observed to react at aircraft altitudes >427 m also represent 1.4% (4/283) of observations from those altitudes.

The number of groups of white whales noticed to react to the Twin Otter was undoubtedly an underestimate of the actual number of groups reacting, as these reactions were only observed on an opportunistic basis. Because of the brevity of observations when the aircraft was low, the

TABLE 7.6. Cases in which white whales appeared to react to Twin Otter observation aircraft, spring 1989-1994.

Date		Group Size	Altitude (m)	Lateral Distance (m)	Comments
14/05/89	17:02	2	260	0	Adult and subadult rolled slightly and looked up at aircraft
24/05/89	20:13	7	200	0	Dove steeply and abruptly, while we were circling bowheads
29/05/89	?	13	460	0	One looked up at aircraft while we were circling bowheads
21/05/90	8:47	6	460	?	Reacted to aircraft, unknown behavior while we were circling bowheads
21/05/90	9:40	1	150	300	Whale heading SSE abruptly turned and headed ENE, opposite to aircraft heading as high power was applied to engines to begin a climb
21/05/90	11:08	7	460	0	Turned sharply away from aircraft, may have reacted to ice camp 200 m away
03/05/91	11:45	2	150	0	Whale heading W stopped and milled
17/05/91	11:18	30	80	0	One dove hastily
17/05/91	12:16	2	95	0	Violent reaction, unusually vigorous tail thrash
17/05/91	12:20	1	110	0	Dove
17/05/91	12:59	1	60	0	Tail thrash
17/05/91	13:00	1	60	0	Tail thrash
17/05/91	16:49	10	120	0	Sudden dive, tail thrash
18/05/91	10:30	1	60	0	Turned sharply away from aircraft
18/05/91	17:53	7	110	0	Dove hastily, some with unusually vigorous tail thrash
22/05/91	20:24	2	150	500	Whales traveling E, turned 90 degrees away from aircraft
03/05/94	9:12	52	460	?	One whale resting in pack ice turned slowly 180° towards aircraft
04/05/94	14:47	1	65	0	Twisted and turned
08/05/94	11:50	5	140	150	One whale resting turned and looked up
09/05/94	9:53	16	180	150	One dove hastily, surfaced, turned sharply to look up
14/05/94	9:48	8	75	1-100	Swam vigorously with fast fluke action during second pass. It did not react during the previous pass at 90 m ASL
19/05/94	17:22	3	150	0	One turned left, then right, another dove steeply
19/05/94	17:?	1	120	?	Looked up
25/05/94	10:52	4	150	?	Reacted, behavior unknown

TABLE 7.7. Number of white whale groups overflown by the Twin Otter aircraft in 1989-1994, and number observed to react.

	Altitude Category (m)			
Year	≤183[a]	184-427	>427[b]	Total
1989	44	82	102	228
1990	12	5	35	54
1991	246	52	99	397
1994	34	2	47	86
Total	336	141	283	760
Reacted	18	2	4	24

[a] 600 ft [b] 1400 ft

TABLE 7.8. Number of groups of white whales observed to react to Twin Otter overflights in relation to aircraft altitude and lateral distance, 1989-1994. Each group is counted only once.

Lateral	Altitude Category (m)				
Distance (m)	≤182	183-427	>427	Unknown	Total
≤250	14	2	2	0	18
>250	2	0	0	0	2
Unknown	2	0	2	0	4
Total	18	2	4	0	24

underestimation was probably more severe for whales overflown at low altitude. Nonetheless, the "altitudinal distribution" of the groups that reacted was significantly different from that of the groups overflown (Table 7.7; $G=9.39$, $df=2$, $P<0.01$). This confirms that there was a significantly higher likelihood of reactions by whales overflown at low altitude (≤182 m ASL) than by whales overflown at higher altitude.

Lateral distance from the Twin Otter to white whales that were observed to react ranged from 0 m during direct overflights to 500 m ($n=20$ observations at known lateral distances). Most of the observed reactions (18 of 20 groups, 90%) occurred when the Twin Otter was at lateral distances ≤250 m from white whales (Table 7.8).

Overall, 14 of 20 observed reactions (70%) occurred when the Twin Otter was at altitudes of ≤182 m and lateral distances of ≤250 m from the white whales (Table 7.8). On 6 of these occasions, reactions occurred when the Twin Otter flew directly over the groups of white whales.

In summary, white whale groups were sometimes observed reacting overtly to Twin Otter overflights. Most reactions occurred when the aircraft was at altitudes ≤182 m and lateral distances ≤250 m. Direct overflights generated the most pronounced reactions, such as vigorous swimming, abrupt dives, or tail thrashing. In a few cases, white whales responses involved turning directly away from the aircraft. In other cases, white whales responded to overflights by looking up at the aircraft, a behavior not necessarily indicative of a negative effect. Overall the number of white whales observed reacting overtly to Twin Otter overflights represented a very small fraction of the total number of white whales observed.

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APPENDICES A-H

APPENDIX A: Field Activities

Appendix A consists of three multi-page Tables:

TABLE A-1 shows the observation effort and the numbers of whales (bowheads and white whales) seen during each day when the ice-based crew was present on the ice watching for whales during the four years of the study. Observation time and number of whales seen are separated into "playback", "control", and "other" periods. Observation time and number of whales seen are presented for ▸ ice-based observations alone, ▸ systematic behavioral observations from the circling aircraft (when obtained near the ice camp), and ▸ the combination of aerial and ice-based observations. Whales observed during systematic aerial observations far from the ice camp (generally >10 km away) are not included in this Table.

TABLE A-2 summarizes the daily activities, weather, and ice conditions during the 1991 phase of the study, and TABLE A-3 provides corresponding information for the 1994 phase. Similar Tables giving this information for the 1989 and 1990 phases can be found in Richardson et al. (1990a:68*ff*, 1991a:35*ff*).

TABLE A-1. Observation effort and numbers of bowheads and white whales seen during control periods, playback periods and other periods, 1989-91 and 1994. Only dates when the ice-based crew were present on the ice and watched for whales are included. Whales seen during more than one period are included once in each period.[a]

		Aerial Observations									Ice-based Observations									Combined Observations								
		Control			Playback			Other			Control			Playback			Other			Control			Playback			Other		
Year	Date	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs
1989	29 April	0.0	0	0	0.0	0	0	0.0	0	0	3.3	0	0	0.0	0	0	0.0	0	0	3.3	0	0	0.0	0	0	0.0	0	0
	30 April	0.0	0	0	0.0	0	0	0.0	0	0	2.9	0	0	0.0	0	0	4.6	3	0	2.9	0	0	0.0	0	0	4.6	3	0
	2 May	0.0	0	0	0.0	0	0	0.0	0	0	2.8	0	0	0.0	0	0	0.0	0	0	2.8	0	0	0.0	0	0	0.0	0	0
	3 May	0.0	0	0	0.0	0	0	0.0	0	0	3.2	0	0	3.2	0	0	0.2	0	0	3.2	0	0	3.2	0	0	0.2	0	0
	6 May	0.0	0	0	0.0	0	0	0.0	0	0	3.3	0	0	4.8	0	0	1.2	0	0	3.3	0	0	4.8	0	0	1.2	0	0
	7 May	0.0	0	0	0.0	0	0	0.0	0	0	4.5	0	0	1.2	0	0	1.5	0	0	4.5	0	0	1.2	0	0	1.5	0	0
	9 May	0.0	0	0	0.0	0	0	0.0	0	0	1.8	0	0	0.0	0	0	0.0	0	0	1.8	0	0	0.0	0	0	0.0	0	0
	14 May	0.5	1	100	2.8	6	100	0.0	0	0	2.7	0	7	8.6	5	19	0.4	1	0	2.7	1	100	8.6	10	100	0.4	1	0
	16 May	0.0	0	0	0.0	0	0	0.0	0	0	8.3	2	13	2.0	0	0	0.5	0	0	8.3	2	13	2.0	0	0	0.5	0	0
	17 May	0.0	0	0	0.0	0	0	0.0	0	0	1.0	0	6	0.0	0	0	0.9	0	18	1.0	0	6	0.0	0	0	0.9	0	18
	19 May	0.0	0	0	0.0	0	0	0.0	0	0	4.3	0	0	4.3	4	2	0.7	0	0	4.3	0	0	4.3	4	2	0.7	0	0
	21 May	0.0	0	0	0.0	0	0	0.9	0	0	3.8	0	7	3.3	0	0	0.5	0	0	3.8	0	7	3.3	0	0	0.5	0	0
	23 May	0.8	1	1	0.7	5	50	0.1	2	1	3.9	2	3	5.1	2	4	0.7	0	0	3.9	3	4	5.1	5	54	1.5	2	1
	25 May	0.0	0	0	0.0	0	0	1.0	0	0	2.9	0	0	0.0	0	0	0.0	0	0	2.9	0	0	0.0	0	0	0.0	0	0
	27 May	3.1	10	0	1.8	2	0	0.0	10	0	8.7	0	0	2.7	0	14	1.0	0	0	9.2	10	0	2.7	2	14	2.0	10	0
	28 May	0.0	0	0	0.0	0	0	0.0	0	0	5.0	0	0	1.4	0	0	0.6	0	0	5.0	0	0	1.4	0	0	0.6	0	0
	29 May	0.0	0	0	0.0	0	0	0.0	0	0	2.5	0	2	6.7	0	0	0.4	0	0	2.5	0	2	6.7	0	0	0.4	0	0
	Total	**4.4**	**12**	**101**	**5.3**	**13**	**150**	**2.0**	**12**	**1**	**64.9**	**4**	**38**	**43.3**	**11**	**39**	**13.2**	**4**	**18**	**65.4**	**16**	**132**	**43.3**	**21**	**170**	**15.0**	**16**	**19**
1990	27 April	0.0	0	0	0.0	0	0	0.0	0	0	6.0	0	0	0.0	0	0	0.0	0	0	6.0	0	0	0.0	0	0	0.0	0	0
	29 April	3.8	11	0	0.0	0	0	0.0	0	0	4.5	3	0	0.0	0	0	0.0	0	0	8.3	13	0	0.0	0	0	0.0	0	0
	30 April	0.0	0	0	0.0	0	0	0.0	0	0	1.4	0	0	0.0	0	0	0.0	0	0	1.4	0	0	0.0	0	0	0.0	0	0
	1 May	0.0	0	0	0.0	0	0	0.0	0	0	1.7	0	0	0.0	0	0	0.0	0	0	1.7	0	0	0.0	0	0	0.0	0	0
	2 May	0.0	0	0	0.0	0	0	0.0	0	0	3.1	0	0	0.0	0	0	0.0	0	0	3.1	0	0	0.0	0	0	0.0	0	0
	4 May	0.0	0	0	0.0	0	0	0.0	0	0	2.5	0	0	4.1	0	0	0.5	0	0	2.5	0	0	4.1	0	0	0.5	0	0
	5 May	1.7	1	0	0.0	0	0	0.0	0	0	2.4	0	0	2.2	0	0	0.5	0	0	3.5	1	0	2.2	0	0	0.5	0	0
	9 May	0.0	0	0	0.0	0	0	0.0	0	0	2.2	2	0	5.0	22	0	0.6	3	0	2.2	2	0	5.0	22	0	0.6	3	0
	10 May	1.7	21	35	3.6	25	30	0.2	5	0	2.0	4	7	5.3	22	0	0.5	5	16	2.3	23	35	5.3	40	30	0.5	10	16
	11 May	3.5	15	0	1.0	3	0	0.7	8	0	6.0	13	6	1.6	1	0	1.0	0	0	6.0	28	6	1.6	4	0	1.0	8	0
	13 May	0.7	6	0	4.1	26	0	0.8	4	0	3.4	37	0	4.7	93	0	1.0	12	0	3.4	40	0	4.7	105	0	1.0	12	0
	16 May	2.2	27	0	1.4	12	0	0.2	1	0	1.3	36	0	3.7	21	0	0.2	6	0	2.7	63	0	3.7	25	0	0.2	6	0
	19 May	0.0	0	0	0.0	0	0	0.0	0	0	4.2	1	16	0.0	0	0	0.0	0	0	4.2	1	16	0.0	0	0	0.0	0	0
	21 May	2.3	17	200	2.7	4	3	0.5	4	3	3.0	1	49	4.1	1	16	0.5	0	23	3.9	17	220	4.1	4	19	0.5	4	26
	24 May	0.0	0	0	0.0	0	0	0.0	0	0	1.4	0	0	0.0	0	0	0.0	0	0	1.4	0	0	0.0	0	0	0.0	0	0
	25 May	0.0	0	0	0.0	0	0	0.0	0	0	0.7	0	0	0.0	0	0	0.0	0	0	0.7	0	0	0.0	0	0	0.0	0	0
	Total	**15.9**	**98**	**235**	**12.8**	**70**	**33**	**2.4**	**22**	**3**	**45.8**	**97**	**78**	**30.7**	**160**	**16**	**4.8**	**26**	**39**	**53.3**	**188**	**277**	**30.7**	**200**	**49**	**4.8**	**43**	**42**

		Aerial Observations									Ice-based Observations									Combined Observations								
		Control			Playback			Other			Control			Playback			Other			Control			Playback			Other		
Year	Date	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs	Effort (h)	No. Bhds	No. WWs
1991	28 April	0.0	0	0	0.0	0	0	0.0	0	0	3.4	2	0	0.0	0	0	0.0	0	0	3.4	2	0	0.0	0	0	0.0	0	0
	1 May	0.0	0	0	0.0	0	0	0.0	0	0	2.5	0	0	0.0	0	0	2.0	0	0	2.5	0	0	0.0	0	0	2.0	0	0
	3 May	0.0	0	0	0.0	0	0	0.0	0	0	1.9	5	0	0.0	0	0	0.0	4	0	1.9	5	0	0.0	0	0	0.0	4	0
	5 May	0.0	0	0	0.0	0	0	0.0	0	0	4.0	0	46	2.4	0	0	1.7	0	0	4.0	0	46	2.4	0	0	1.7	0	0
	6 May	0.0	0	0	0.0	0	0	0.0	0	0	2.3	0	0	0.0	0	0	0.0	0	0	2.3	0	0	0.0	0	0	0.0	0	0
	11 May	0.0	0	0	0.0	0	0	0.0	0	0	3.6	6	23	1.0	0	6	0.5	0	9	3.6	6	23	1.0	0	6	0.5	0	9
	17 May	0.0	0	0	0.0	0	0	0.0	0	0	4.1	2	96	5.3	9	8	0.5	1	61	4.1	2	96	5.3	9	8	0.5	1	61
	18 May	0.0	0	0	0.0	0	0	0.0	0	0	3.5	2	0	0.0	0	0	6.6	0	0	3.5	2	0	0.0	0	0	6.6	0	0
	20 May	0.0	0	0	0.0	0	0	0.0	0	0	1.5	0	0	0.0	0	0	0.0	0	0	1.5	0	0	0.0	0	0	0.0	0	0
	22 May	0.0	0	0	0.0	0	0	0.0	0	0	2.4	0	0	1.3	0	0	0.9	1	0	2.4	0	0	1.3	0	0	0.9	1	0
	23 May	0.0	0	0	0.0	0	0	0.0	0	0	2.6	0	0	2.7	0	0	0.7	0	0	2.6	0	0	2.7	0	0	0.7	0	0
	25 May	0.0	0	0	0.0	0	0	0.0	0	0	1.9	0	0	0.0	0	0	0.4	1	0	1.9	0	0	0.0	0	0	0.4	1	0
	26 May	0.0	0	0	0.0	0	0	0.0	0	0	1.7	1	0	0.0	0	0	0.1	0	0	1.7	1	0	0.0	0	0	0.1	0	0
	Total	**0.0**	**0**	**0**	**0.0**	**0**	**0**	**0.0**	**0**	**0**	**35.4**	**18**	**165**	**12.7**	**9**	**14**	**13.4**	**7**	**70**	**35.4**	**18**	**165**	**12.7**	**9**	**14**	**13.4**	**7**	**70**
1994	28 April	0.0	0	0	0.0	0	0	0.0	0	0	5.6	0	0	0.0	0	0	1.4	0	0	5.6	0	0	0.0	0	0	1.4	0	0
	2 May	0.0	0	0	0.0	0	0	0.0	0	0	5.8	0	0	0.0	0	0	2.3	0	0	5.8	0	0	0.0	0	0	2.3	0	0
	3 May	0.0	0	0	0.0	0	0	0.0	0	0	5.6	1	0	4.1	0	32	2.4	1	0	5.6	1	0	4.1	0	32	2.4	1	0
	7 May	2.1	15	0	1.5	15	0	0.0	0	0	7.0	36	0	3.9	8	0	2.4	19	0	7.0	47	0	3.9	18	0	2.4	19	0
	8 May	0.0	0	0	0.0	0	0	0.0	0	0	5.2	24	0	0.0	0	0	0.0	0	0	5.2	24	0	0.0	0	0	0.0	0	0
	9 May	1.9	24	0	2.2	27	0	0.5	15	0	6.4	22	0	3.0	25	0	0.5	11	0	6.4	42	0	3.0	32	0	0.5	21	0
	11 May	3.9	31	0	0.0	0	0	0.0	0	0	1.6	2	0	0.0	0	0	0.0	0	0	4.3	31	0	0.0	0	0	0.0	0	0
	14 May	0.0	0	0	0.0	0	0	0.0	0	0	6.4	17	0	3.2	3	0	2.2	11	0	6.4	17	0	3.2	3	0	2.2	11	0
	16 May	0.5	7	0	3.2	9	0	0.2	0	0	4.2	0	0	4.2	4	0	0.7	0	0	4.2	7	0	4.2	13	0	0.7	0	0
	17 May	4.3	27	0	1.9	6	0	0.4	1	0	1.5	0	0	4.2	1	0	0.2	0	0	4.4	27	0	4.2	7	0	0.4	1	0
	20 May	2.6	9	0	0.0	0	0	0.0	0	0	5.2	6	0	4.6	11	0	0.5	4.0	0	5.5	9	0	4.6	11	0	0.5	4	0
	22 May	1.7	6	17	0.0	0	0	0.0	0	0	2.9	0	15	0.0	0	0	1.0	0	6	2.9	6	22	0.0	0	0	1.0	0	6
	25 May	0.0	0	0	0.0	0	0	0.0	0	0	1.9	0	4	0.0	0	0	0.5	0	0	1.9	0	4	0.0	0	0	0.5	0	0
	Total	**17.0**	**119**	**17**	**8.8**	**57**	**0**	**1.1**	**16**	**0**	**59.3**	**108**	**19**	**27.2**	**52**	**32**	**14.1**	**46**	**6**	**65.2**	**211**	**26**	**27.2**	**84**	**32**	**14.3**	**57**	**6**

[a] Some whales may be included more than once in each period, particularly during 1994, because they may not have been identified as being seen previously during that period. However, the numbers presented here are the numbers of different whales estimated to have been present and are often less than the number of sightings in maps and tables in this and previous reports.

TABLE A-2. Summary of daily activities and weather and ice conditions, 28 April-26 May 1991.

Date	Ice-based Crew: No. Ferry Flights	Trans. Loss Test	Icebr. Plbk.	Number of: Bhd.	Number of: White Whales	Ice Camp Location	Other	Overall Ice Conditions
28 Apr	1	-	-	2 (2)*	0	71°30′ 155°51′	Control obs.; equip. checkout.	85%. Lead wide on Chukchi side; discontinuous to E. Much new ice.
29 Apr	0	-	-	-	-	-	Equip. checkout at Barrow.	85%
30 Apr	0	-	-	-	-	-	-	85%
1 May	2	#1	-	0 (3)	0 (5)	71°36′ 155°47′	TL test #1. 3 bhd. seen near 5 nmi TL station.	85%
2 May	0	-	-	-	-	-	-	85%
3 May	1	-	-	9 (4)	0	71°31′ 155°13′	Control obs. Plbk cancelled - weather & ice deteriorating.	85%
4 May	0	-	-	-	-	-	-	85%. Strong winds move pack ice close to fast ice. Many isolated openings but no leads.
5 May	2	-	P1	0	46 (39)	71°47′ 155°34′	Icebreaker plbk. No whales during plbk.	85%. Strong winds move pack ice close to fast ice.
6 May	1	-	-	0 (3)	0 (3)	71°32′ 155°25′	Brief control obs. Work aborted due to extreme winds & unstable ice.	93%
7 May	0	-	-	-	-	-	-	93%. Wide lead W of Barrow, intermittent to E. Elsewhere 90% pack ice.
8 May	0	-	-	-	-	-	-	93%
9 May	0	-	-	-	-	-	-	93%
10 May	0	-	-	-	-	-	-	93%. Nearshore lead closed to E, but corridor of 97% brash ice remains. Many N-S tracks in pack ice.
11 May	2	-	P2	7 (2)	38	71°34′ 155°58′	Icebreaker plbk.	93%
12 May	0	-	-	-	-	-	-	93%

* Numbers in parentheses indicate additional whales observed during ferry flights or at TL receiver stations.

Continued...

TABLE A-2. Continued.

		Aerial Crew					
					Number of		
Date	Weather	Survey (h)	Behavior Obser. Sess. (h)	Photogr. (h)	Bowheads	White Whales	Other
28 Apr	Low overcast, occ. light snow.	2.2	-	-	0	115	-
29 Apr	Scat. low cloud and fog.	1.2	0.9	0.7	5	0	Obs. of presum. undist. behav.
30 Apr	Fog.	-	-	-	-	-	Fog, no flying.
1 May	Low overcast, good vis.	2.5	-	1.8	49	17	
2 May	Fog.	0.5	-	-	0	0	Fog; aborted flight.
3 May	Low overcast, some fog.	1.7	-	-	6	57	-
4 May	Thin fog except in evening.	1.6	0.6	-	7	30	Obs. of presum. undist. behav.
5 May	Mostly clear.	5.2	-	-	2	128	No whales present during plbk.
6 May	Clear with strong ENE winds.	3.9	1.6	-	11	105	Obs. of presum. undist. behav.; abort. due to strong wind.
7 May	Low overcast after 10 AM. High winds.	1.0	-	-	10	0	Too windy; abort flight.
8 May	Low overcast, high winds, and poor vis.	0.8	-	0.8	7	0	-
9 May	Low overcast, high winds.	-	-	-	-	-	Poor weather, no flying.
10 May	Low overcast, high winds.	3.1	-	0.7	32	126	-
11 May	Low overcast, windy.	3.5	-	1.8	28	135	Cloud too low for aerial obs. during ice-breaker plbk.
12 May	Fog.	0.8	-	-	4	56	Fog; aborted flight.

Continued...

TABLE A-2. Continued.

	Ice-based Crew							
				Number of				
Date	No. Ferry Flights	Trans. Loss Test	Icebr. Plbk.	Bhd.	White Whales	Ice Camp Location	Other	Overall Ice Conditions
13 May	0	-	-	-	-	-	-	93%
14 May	0	-	-	-	-	-	-	93%
15 May	0	-	-	-	-	-	-	93%
16 May	0	-	-	-	-	-	-	90%
17 May	4	-	P3	11	165 (15)	71°30′ 156°13′	Icebr. plbk. from fast ice edge.	90%
18 May	4	#2	P4	2	0	71°30′ 156°13′	Brief icebr. plbk. from fast ice edge. No whales seen, so switched to TL test #2.	90%
19 May	0	-	-	-	-	-	-	90%
20 May	2	-	-	0 (1)	0	71°40′ 156°02′	Control obs.; plbk cancelled - weather & ice deteriorating.	90%
21 May	0	-	-	-	-	-	-	90%
22 May	1	-	P5	1 (2)	0	71°29′ 156°13′	Icebreaker plbk.	90%. Nearshore lead opens to 154°15′.
23 May	2	-	P6	0	0	71°26′ 156°35′	Icebreaker plbk. Camp on fast ice edge.	90%
24 May	0	-	-	-	-	-	-	90%
25 May	2	#3	-	2 (3)	0	71°31′ 156°19′	TL test #3. Camp on fast ice edge.	90%
26 May	1	#4	-	1	0	71°31′ 156°11′	TL test #4. Camp on pack ice.	90%

Continued...

TABLE A-2. Concluded.

		Aerial Crew					
					Number of		
Date	Weather	Survey (h)	Behavior Obser. Sess. (h)	Photogr. (h)	Bowheads	White Whales	Other
13 May	Fog.	0.4	-	-	0	0	Fog; aborted flight.
14 May	Fog.	-	-	-	-	-	Fog, no flying.
15 May	Fog.	-	-	-	-	-	Fog, no flying.
16 May	Patchy fog.	1.7	-	-	7	66	Flying hampered by fog.
17 May	Low overcast, fog patches, snow showers.	3.0	-	2.8	27	486	Cloud too low for aerial obs. during icebreaker plbk.
18 May	Low overcast, fog patches.	3.9	-	1.6	37	319	Icebreaker plbk; then TL test. Cloud too low for aerial obs.
19 May	Fog.	-	-	-	-	-	Fog, no flying.
20 May	Fog patches.	4.3	0.9	-	11	31	Obs. of presum. undist. behav.; curtailed by fog.
21 May	Low cloud, fog and snow.	0.7	-	-	0	6	Poor weather; aborted flight.
22 May	Low cloud, fog til late after-noon.	2.3	-	2.0	34	156	Cloud too low for aerial obs. during icebreaker plbk.
23 May	Low overcast.	2.5	-	-	4	82	Cloud too low for aerial obs. during icebreaker plbk.
24 May	Fog and snow.	-	-	-	-	-	Poor weather, no flying.
25 May	Mostly low overcast; briefly clear far to east.	5.4	0.1	2.4	20	79	Cloud near ice camp too low for aerial obs. during plbk. Brief obs. of behav. farther east until curtailed by low cloud.
26 May	Low overcast.	3.6	-	0.9	6	1	-

TABLE A-3. Summary of daily activities and weather and ice conditions, 25 April-25 May 1994.

	Ice-based Crew							
				Number[a] of				
Date	No. Ferry Flights	Trans. Loss Test	Icebr. Plbk.	Bhd.	White Whales	Ice Camp Location	Other	Overall Ice Conditions
25 April	0	-	-	-	-		Equipment testing at Barrow.	
26 April	0	-	-	-	-		Logistics preparation.	
27 April	0	-	-	-	-			97%. Discontinuous lead.
28 April	4	Test tones	-	0	0	71°42' 155°35'	Initial on-ice set up and test of projection system, test tones broadcast, no whales seen.	98%. Thin refrozen cracks, small openings SW-NE.
29 April	0	-	-	-	-			98%.
30 April	0	-	-	-	-			98%. Discontinuous lead, ENE.
1 May	1	-	-	-	-		Aborted flight due to poor visibility.	98%.
2 May	5	Test tones	-	0	0 (30)[b]	71°50' 155°48'	TL test cancelled due to concerns about deteriorating weather	99%.
3 May	4	Tone tones	P1	1 (1)	32 (23)	71°39' 156°19'	Tones 12:33-13:09. Icebreaker playback, 15:12-19:20.	95%. Major N-S lead with with minor cracks running NE-SW.
4 May	1	-	-	-	-		Aborted flight due to poor visibility.	90%. Major continuous lead E of Pt. Barrow along fast ice edge, 2-3 km wide in places, narrowing farther E.
5 May	0	-	-	-	-	-		90%. Major (2 km wide) lead E of Pt. Barrow along fast ice edge.
6 May	0	-	-	-	-	-		90%.
7 May	5	Test tones	P2	63 (8)	0	71°32' 155°15'	Tones 14:14-16:03. Icebreaker playback 16:07-20:01 from fast ice edge.	90%. Major lead E of Pt. Barrow along fast ice edge.

Continued...

TABLE A-3. Continued.

		Aerial Crew					
					Number of		
Date	Weather	Survey (h)	Behavior Obser. Sess. (h)	Photogr. (h)	Bowheads	White Whales	Other
25 April	Low overcast	-	-	-	-	-	Aircraft arrives at Barrow.
26 April	Low overcast, light snow, fog	-	-	-	-	-	Poor visibility. No flying. Equipment set up.
27 April	Low ceiling, light snow, fog clearing in p.m.	3.7	-	-	1	2	Recon. flights.
28 April	Overcast	2.8	-	-	0	0	Non-systematic survey. Recon. flight.
29 April	Low, overcast, light snow, poor visibility	-	-	-	-	-	Poor weather, no flying.
30 April	Low ceiling, fog visibility gradually improving in p.m.	2.6	-	1.1	11	46	-
1 May	Snow, with poor visibility	-	-	-	-	-	Poor weather, no flying.
2 May	Clear in a.m., low cloud in p.m.	3.9	-	-	0	20	2nd flight aborted due to fog.
3 May	Clear with strong NE wind	4.6	4.4	-	13	662	Icebreaker projection experiment.
4 May	Low ceiling, fog, poor visibility	1.3	-	0.8	45	1	Large number of bowheads migrating E, deteriorating weather ends photo session.
5 May	Low cloud, fog, freezing drizzle by 12 p.m.	1.4	-	2.6	57	31	Photo session in nearshore lead.
6 May	Low cloud, intermittent freezing drizzle, snow showers and fog	-	-	-	-	-	Poor weather, no flying.
7 May	Clear offshore in a.m.,	2.9	4.9	2.4	132	7	Icebreaker projection exp.; aerial obs. curtailed by low cloud.

Continued...

TABLE A-3. Continued.

	Ice-based Crew							
				Number[a] of				
Date	No. Ferry Flights	Trans. Loss Test	Icebr. Plbk.	Bhd.	White Whales	Ice Camp Location	Other	Overall Ice Conditions
8 May	2	-	-	24 (3)	0 (1)	71°32' 155°15'	Control obs. from fast ice edge.	90%. Major lead E of Pt. Barrow.
9 May	4	-	P3	57 (4)	0	71°33' 155°12'	Icebreaker playback from fast ice edge, 14:22-17:30.	90%. Major lead E of Pt. Barrow.
10 May	3	-	-	3 (5)	0		Unable to find suitable ice conditions for camp due to moving pack ice, no experiment.	85%. Pack ice against land fast ice, ice conditions changing rapidly.
11 May	3	-	-	2 (1)	0	71°32' 155°45'	Operations aborted when a large ice pan collided with the camp floe at the projection site.	85%. Discontinuous lead along fast ice edge, pans in rapid motion.
12 May	0	-	-	-	-	-		85%.
13 May	0	-	-	-	-	-		85%.
14 May	4	Test tones	P4	30 (9)	0	71°35' 154°33'	Tones (13:24-15:45) and icebreaker playback (15:50-19:00) from fast ice edge.	80%. Major lead to E of Pt. Barrow along fast ice edge.
15 May	0	-	-	-	-	-		80%. Outer 2.5 km wide sheet of fast ice has broken free, drifting off new landfast edge, forming inner and outer leads.
16 May	4	Test tones	P5	4 (3)	0	71°34' 155°41'	Tones (12:50-12:59) and icebreaker playback (13:03-17:13) from "outer" lead.	80%.
17 May	4	-	P6	1 (8)	0 (5)	71°33' 154°32'	Icebreaker playback from pack ice along main lead, 12:48-17:02.	80%.
18 May	0	-	-	- -	- -			80%.
19 May	0	-	-	-	- -			75%. Wide lead along fast ice, numerous cracks farther E.

Continued...

TABLE A-3. Continued.

		Aerial Crew					
					Number of		
Date	Weather	Survey (h)	Behavior Obser. Sess. (h)	Photogr. (h)	Bowheads	White Whales	Other
8 May	Low cloud, moderate E winds	1.7	-	2.4	75	24	Photo session curtailed by high sea states and fuel staining of camera port.
9 May	Low cloud offshore in a.m. clearing by p.m., strong E winds	3.1	4.7	1.1	94[b]	37	Icebreaker projection exp. with post-plbk control; high sea state hampers obs.
10 May	Clear with strong NE winds	3.3	2.2	1.1	51	21	Obs. of presum. undist. behav.
11 May	Clear with moderate E winds	2.2	3.9	1.2	34	0	Obs. of presum. undist. behav.
12 May	Low cloud, poor visibility, intermittent snow and fog	-	-	-	-	-	Poor weather, no flying.
13 May	Low cloud, poor visibility in snow and fog	-	-	-	-	-	Poor weather, no flying.
14 May	Overcast, moderate E winds, low cloud	3.9	-	3.4	99	42	Clouds too low for aerial obs. during plbk.
15 May	Clear with strong E winds, reduced visibility in blowing snow	3.1	1.3	-	54	8	Obs. of presum. undist. behav.
16 May	Clear, with light winds	4.4	3.9	-	48	7	Icebreaker playback exp. with pre-plbk control.
17 May	Clear in a.m., NE winds increasing to strong, in late p.m.	3.7	6.6	-	44	7	Icebreaker playback exp. with pre- and post-plbk control. High sea state hampers obs.
18 May	Clear with strong E winds, 50 kts off shore at 1500'	0.6	-	-	4	0	Heavy winds, aborted flight.
19 May	Low cloud, poor visibility, freezing rain	1.3	-	-	5	134	-

Continued...

TABLE A-3. Continued.

	Ice-based Crew							
				Number[a] of				
Date	No. Ferry Flights	Trans. Loss Test	Icebr. Plbk.	Bhd.	White Whales	Ice Camp Location	Other	Overall Ice Conditions
20 May	4	-	P7	20 (3)	0	71°31' 155°28'	Icebreaker playback from giant ice pan on edge of large area of open water, 12:38-17:17.	80%.
21 May	1	-	-	-	-	-		80%.
22 May	3	T.L. #1	-	0	21 (18)	71°38' 155°01'	Transmission loss test completed, 11:59-16:05	75%.
23 May	0	-	-	-	-	-	-	80%.
24 May	1	-	-	0	0	-	Pack ice drifting rapidly, no suitable projector site found.	80%.
25 May	4	T.L. #2	-	0 (2)	4 (11)	71°34' 156°15'	T.L. test (10:32-11:49) ended early due to encroaching ice.	80%.

[a] Numbers in parentheses indicate additional whales observed during ferry flights or at TL receiver stations.
[b] Includes one dead bowhead floating amidst pack ice.

Continued...

TABLE A-3. Concluded.

		Aerial Crew					
					Number of		
Date	Weather	Survey (h)	Behavior Obser. Sess. (h)	Photogr. (h)	Bowheads	White Whales	Other
20 May	Clear in a.m., low cloud in p.m.	3.2	2.6	1.5	22	62	Icebreaker playback exp. with pre-plbk control. Ceiling too low for aerial obs. during plbk.
21 May	Fog	-	-	-	-	-	Fog, no flying.
22 May	Clear in a.m., with increasing low cloud in p.m.	2.3	1.7	-	6	132	Low cloud prevented aerial obs. so ice crew did TL test.
23 May	Low cloud, fog, snow, freezing rain and sleet	-	-	-	-	-	Poor weather, no flying.
24 May	Low cloud, NE winds at 20-25 kts	1.8	-	-	0	18	-
25 May	Low cloud, moderate	7.2	-	0.2	7	21	Aerial photogrammetry calibration, recon. survey to NE and SW.

APPENDIX B: Transmission Loss Experiment Data, 1991/94

Tables B-1 through B-4 below give the measured losses by frequency, range and source type for the 1991 phase. Tables B-5 and B-6 give the corresponding information for the 1994 phase. Ranges from the base camp to the hydrophone locations are given in kilometers and the depths, where available, are given in meters. Corresponding results from four transmission loss tests in 1989 and four more tests in 1990 are given in Richardson et al. (1990a, 1991a).

Figures B-1 to B-14 summarize the transmission loss data from all four years of the project by frequency and type of test sound, scaling the data as described in §4.3.

Figures B-15 to B-18 show the source and receive stations during all transmission loss tests, superimposed on newly-refined bathymetric contours.

Figure B-19 presents four samples of sound velocity profiles computed from salinity-temperature-depth casts at 1994 ice camps. The apparent trend from two-layered on 28 April to near-isovelocity on 22 May is coincidental. Profiles from other days and locations differed from these profiles.

TABLE B-1. Transmission loss measurements by frequency and range for the tones during test #1 on 1 May 1991.

	Range (km) →	0.0	0.1	0.2	2.0	2.8	4.2	9.6	13.9
	Depth (m) →	56							
	Frequency (Hz)								
Tones	20		45	54	60	68			
	40		45	57	74	58	59		81
	50		47	56	57	59	61		80
	100		42	53	59	63	64	72	85
	200		54	48	59	75	66	74	80
	500		x2	57	60	67	67	80	85
	1000		38	43	55		62	83	87
	2000		49	37	63		66	83	87
	5000		49	57	58	66	70	92	105
	10000		37	48	54	65	71	91	

TABLE B-2. Transmission loss measurements by frequency and range for the tones and icebreaker sounds during test #2 on 18 May 1991.

	Range (km) →	0.0	0.1	0.2	0.8	2.1	4.1	10.0
	Depth (m) →	110.0			113.0	110.0	98.0	84.0
	Frequency (Hz)							
Tones	20		50	47	59			
	40		45	52	50	63	75	
	50		46	56	54	59	72	
	100		46	49	57	73	78	
	200		39	46	71	65	69	
	500		41	48	69	71	68	
	1000		52	55	75	71	78	
	2000		41	42	59	64	66	91
	5000		41	54	60	66	77	
	10000		44	51	60	71	84	
Icebreaking	10							
	13							
	16							
	20							
	25							
	32							
	40							
	50		45	52	53	60		
	63		47	56	55	63		
	80		46	50	55	60		
	100		45	48	56			
	125		42	45	54	58		
	160		44	46		63		
	200		43	46	64			
	250		42	47		57	59	
	315		45	47		59		
	400							
	500							
	630			36				
	800			41				
	1000			50				
	1250			55	56	45		
	1600		47			57		
	2000					59	49	
	2500		42				57	
	3150		48	55		57		
	4000							
	5000				56	54		
	6300			46	49			

TABLE B-3. Transmission loss measurements by frequency and range for the tones and icebreaker sounds during test #3 on 25 May 1991.

	Range (km) →	0.0	0.1	0.2	0.9	2.0	3.8	9.4	13.9
	Depth (m) →	146.0			136.0	128.0	117.0	73.0	90.0
	Frequency (Hz)								
Tones	20			47	51				
	40		41	51	54	60			
	50		42	54	49	64	69	75	
	100		40	49	48	57	66	79	104
	200		43	44	57	61	63	79	104
	500		57	53	51	64	68	82	103
	1000		42	51	56	71	75	84	
	2000		44	44	44	67	75	73	
	5000		45	51	51	71	80		
	10000		41	44	49	62	70		
Icebreaking	10								
	13					43			
	16						36		
	20						39		
	25			46	33				
	32		42	46	38		52		
	40		40	50	38	52			
	50		38	52	41	54			
	63		38	49	44	58			
	80		37	48	43	57	59		
	100		34	47	39	56	47		
	125		35	46	45	54	54		
	160		35	44	43	53	55		
	200		38	44	44	52	57		
	250		41	44	42	54			
	315		38	45	40	45			
	400		37	49	37				
	500		42	51					
	630			50	44				
	800		44	50	44				
	1000		42	50	36				
	1250		40	48	40				
	1600		39	46	43		60		
	2000		40	45	44		59		
	2500		41	44	44		62		
	3150		39	50	40		60		
	4000		45	49	42				
	5000		47	50	39				
	6300		49	46	33				

TABLE B-4. Transmission loss measurements by frequency and range for the tones and icebreaker sounds during test #4 on 26 May 1991.

	Range (km) →	0.0	0.1	0.2	1.0	1.6	3.4	9.2	13.7	18.9
	Depth (m) →	151.0			158.0	166.0	163.0	184.0	110.0	96.0
	Frequency (Hz)									
Tones	20									
	40		45							
	50		42	57	52	62	57		71	
	100		38	55	58	59	73		83	
	200		42	50	61	68	62	76	82	
	500		41	54	73	61	66	81		
	1000		40	42	66	72	92			
	2000		45	44	55	61	68	79	90	99
	5000		43	49	64	71	88	92		
	10000		38	38	51	54	76			
Icebreaking	10			44						
	13			48						
	16									
	20									
	25			43						
	32			42						
	40			39						
	50		44		52					
	63		41	48	55					
	80		39	48	55					
	100		38	48						
	125		37	47		54	61			
	160		36	46						
	200		42	44	58	61				
	250		48	45	58					
	315		39	49	55					
	400		39							
	500		34			53	59			
	630		36	47		53	59			
	800		40		52	63				
	1000		35	42	48		56			
	1250		46	41	60	57	58			
	1600		42	47	57	58	64			
	2000		44	46	57	58	64			
	2500		47	50	60	61				
	3150		45	51						
	4000		48	52						
	5000		47	50						
	6300		46	48						

TABLE B-5. Transmission loss measurements by frequency and range for the tones, Karluk and icebreaker sounds during test #1 on 22 May 1994.

	Range (km) →	0.0	0.1	0.2	1.0	2.0	4.5	9.9	14.7
	Depth (m) →	65.0			63.0	69.0	89.0	79.0	53.0
	Frequency (Hz)								
Tones	20.0		34.3	58.2	60.9				
	40.0		28.2	44.5		51.0	64.1		
	50.0		32.5	42.3	46.4	50.7	69.0	82.0	82.8
	100.0		30.6	49.2	50.1	54.6	68.0	78.9	85.6
	200.0		33.1	50.8	50.2	57.1	68.0	78.6	80.2
	500.0		26.8	41.0	48.0	61.6	67.6	95.5	85.6
	1000.0		29.0	35.9	43.7	52.0	63.8	82.6	
	2000.0		38.6	36.1	48.9	57.8	64.4	88.2	
	5000.0		36.2	43.3	53.9	58.5	70.0		
	10000.0		25.7	29.8	61.9	66.9			
Karluk	10.0		15.2	23.6	36.0				
	12.5		19.4	27.8	40.2				
	16.0		21.1	31.1					
	20.0		24.3	32.9					
	25.0		37.4	41.9		43.5			
	31.5		38.0	44.2	50.0	43.7			
	40.0		39.8	42.5	46.4	54.4			
	50.0		43.0	43.2	46.8	52.1			
	63.0		42.4	43.6	51.3	52.5	69.3		
	80.0		39.3	44.6	55.1	56.4	69.9		
	100.0		38.4	46.2	48.0	55.9	68.3	74.9	
	125.0		39.1	52.3	50.3	56.3	70.1		
	160.0		40.8	44.0	51.0	62.4	66.0		
	200.0		41.8	46.4	51.3	55.1	67.7		
	250.0		39.9	44.6	59.8	52.9	64.8	74.5	
	315.0		39.7	43.6	53.3	54.4			
Icebreaking	10.0		20.3	28.1	38.8			33.3	
	12.5		25.6	31.3		27.9		36.4	
	16.0		30.9	36.9		28.2			
	20.0		40.3	43.9		47.6		48.3	
	25.0		38.1	42.3	52.3	50.4		54.8	
	31.5		36.5	43.8	49.5	50.7		62.9	
	40.0		37.8	42.7	47.1	51.6			
	50.0		39.0	42.0	44.8	49.8			
	63.0		41.9	43.0	52.1	51.4	67.3		
	80.0		40.1	43.4	57.3	53.7	67.4		
	100.0		38.7	46.3	46.7	51.5		63.4	
	125.0		38.0	51.8	49.5	53.7	70.4		
	160.0		39.3	40.8	48.5	60.8		64.2	
	200.0		39.9	44.3	49.5	52.3			
	250.0		37.3	42.9	55.4	49.4		60.9	
	315.0		36.8	41.7	53.9	52.3			
	400.0		36.9	40.5	51.6	54.3			
	500.0		36.6	39.5	49.1	55.7			
	630.0		33.8	37.4	46.8	46.8			
	800.0		32.2	40.9	46.7	47.9			
	1000.0		28.6	39.2	42.0	47.5			
	1250.0		27.9	30.9	44.9	47.3			
	1600.0		30.5	37.3	47.6	50.1			
	2000.0		30.8	33.8	44.9				

TABLE B-6. Transmission loss measurements by frequency and range for the tones, Karluk and icebreaker sounds during test #2 on 25 May 1994.

	Range (km) →	0	0.1	0.2
	Depth (m) →	178		
	Frequency (Hz)			
Tones	20.0		48.9	
	40.0		39.7	51.4
	50.0		35.1	45.4
	100.0		32.6	38.2
	200.0		35.3	34.9
	500.0		40.5	36.7
	1000.0			
	2000.0			
	5000.0			
	10000.0			
Karluk	10.0			
	12.5			
	16.0			
	20.0		52.5	53.5
	25.0		53.6	53.2
	31.5		52.7	51.7
	40.0		45.8	45.6
	50.0		40.8	39.9
	63.0		36.7	36.4
	80.0		35.8	33.8
	100.0		33.6	31.7
	125.0			
	160.0			
	200.0			
	250.0			
	315.0			
Icebreaking	10.0			
	12.5			
	16.0			
	20.0			37.8
	25.0			41.2
	31.5		44.8	42.1
	40.0		41.1	41.6
	50.0		39.3	39.7
	63.0		38.0	37.9
	80.0		38.2	37.4
	100.0		36.2	33.0
	125.0			
	160.0			
	200.0			
	250.0			
	315.0			
	400.0			
	500.0			
	630.0			
	800.0			
	1000.0			
	1250.0			
	1600.0			
	2000.0			

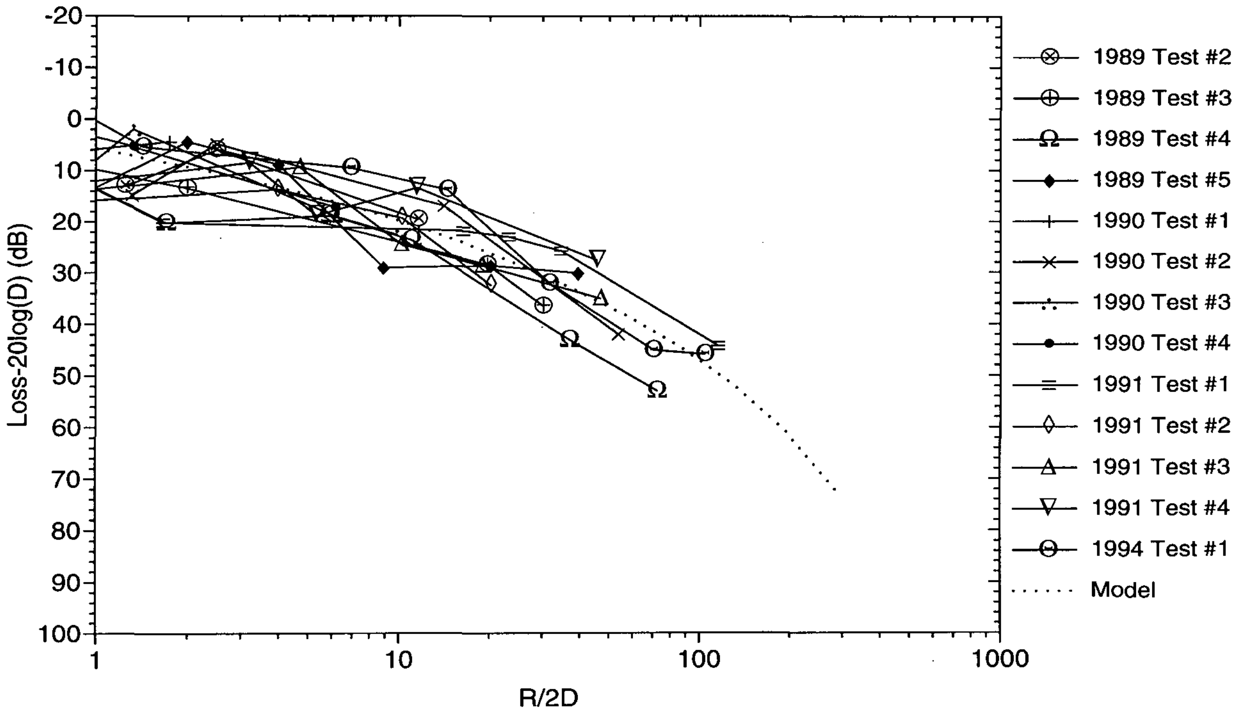


FIGURE B-1. TL-20log(D) vs. scaled distance for the 50 Hz tones measured during transmission loss tests.

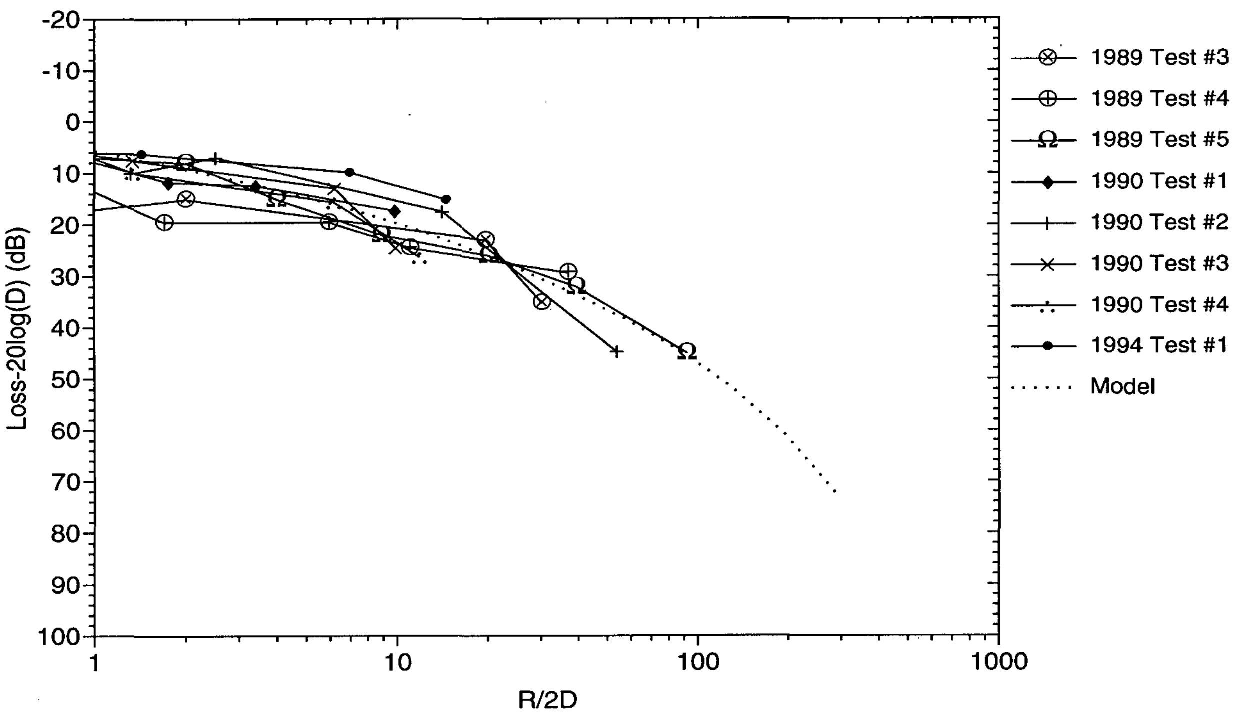


FIGURE B-2. TL-20log(D) vs. scaled distance for the 50 and 63 Hz 1/3 octave band levels of *Karluk* drilling sounds measured during transmission loss tests.

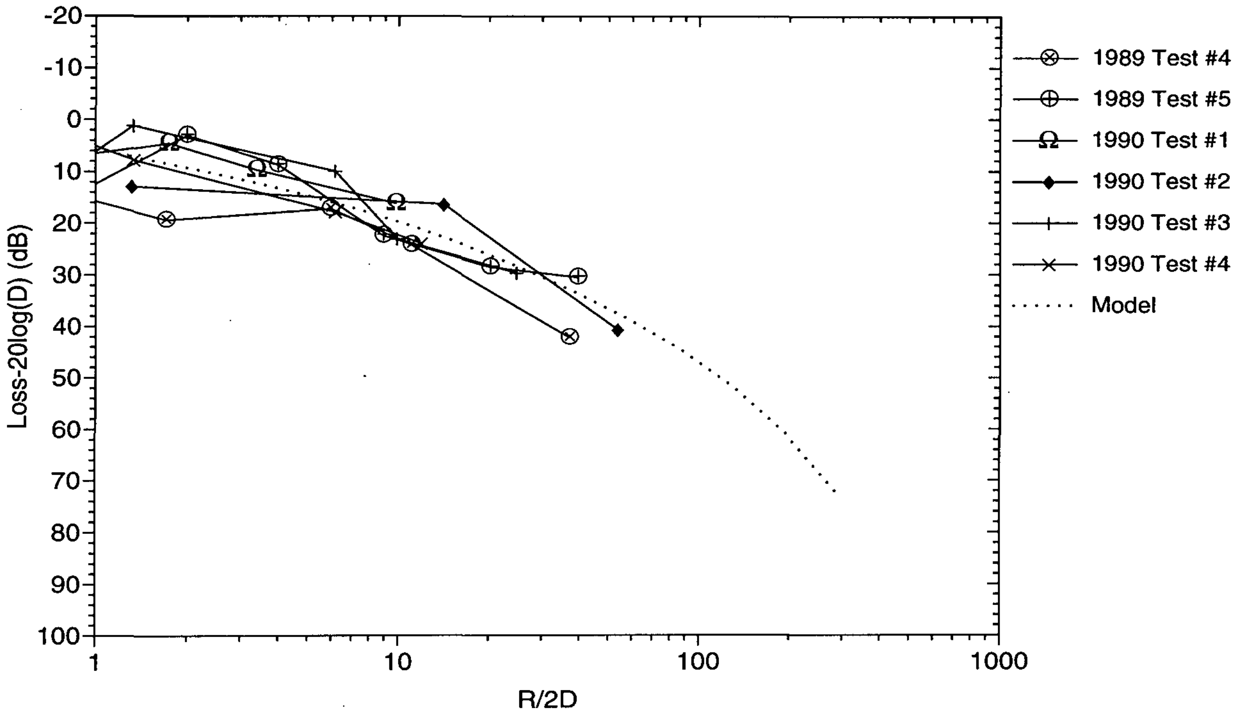


FIGURE B-3. TL-20log(D) vs. scaled distance for the 50 Hz FM sweeps measured during transmission loss tests.

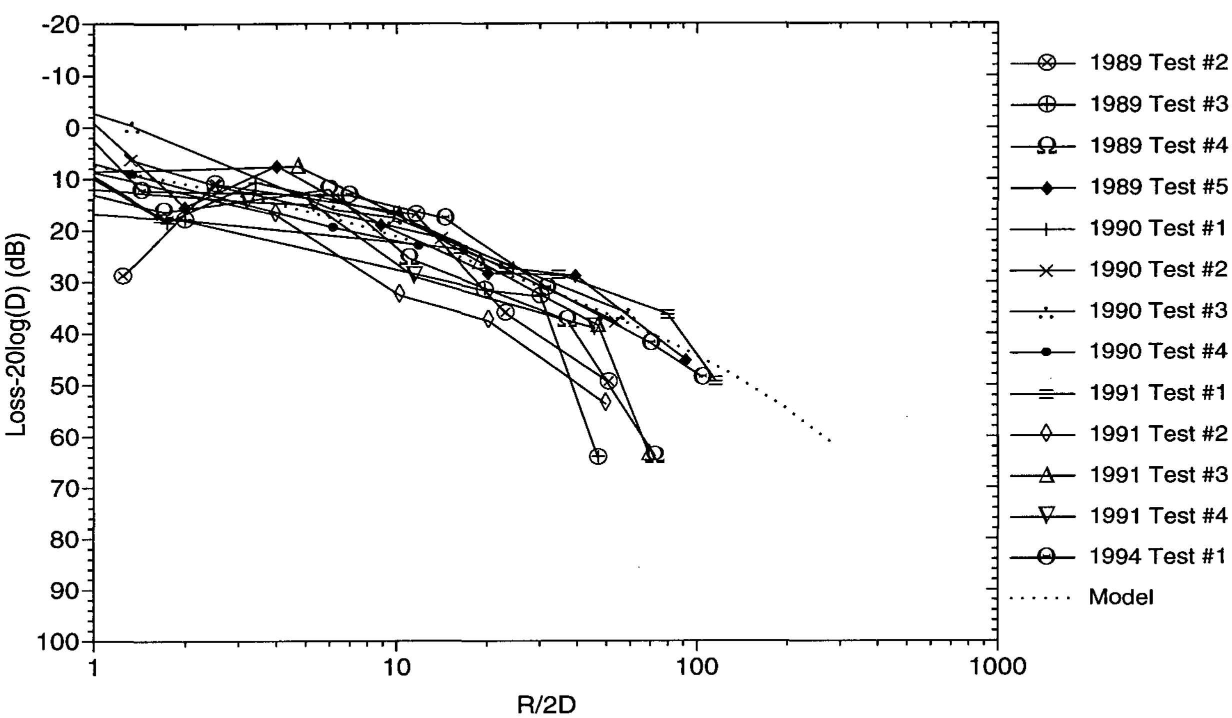


FIGURE B-4. TL-20log(D) vs. scaled distance for the 100 Hz tones measured during transmission loss tests.

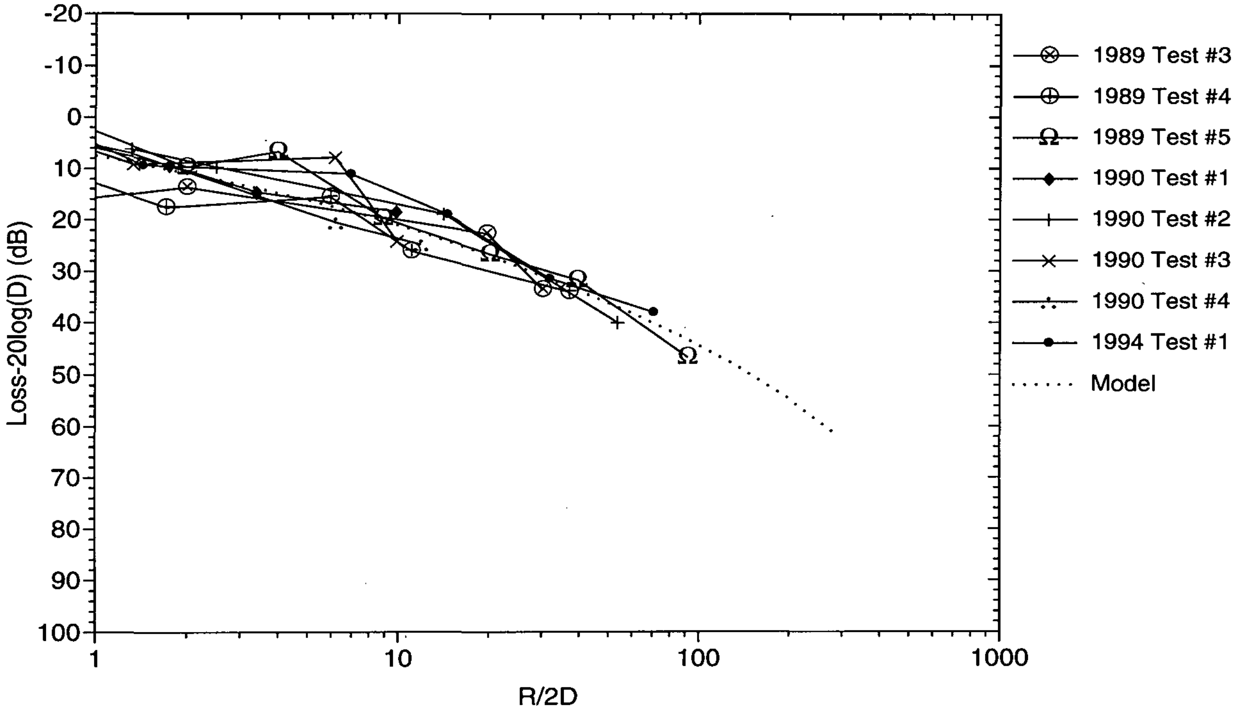


FIGURE B-5. TL-20log(D) vs. scaled distance for the 100 Hz 1/3 octave band levels of *Karluk* drilling sounds measured during transmission loss tests.

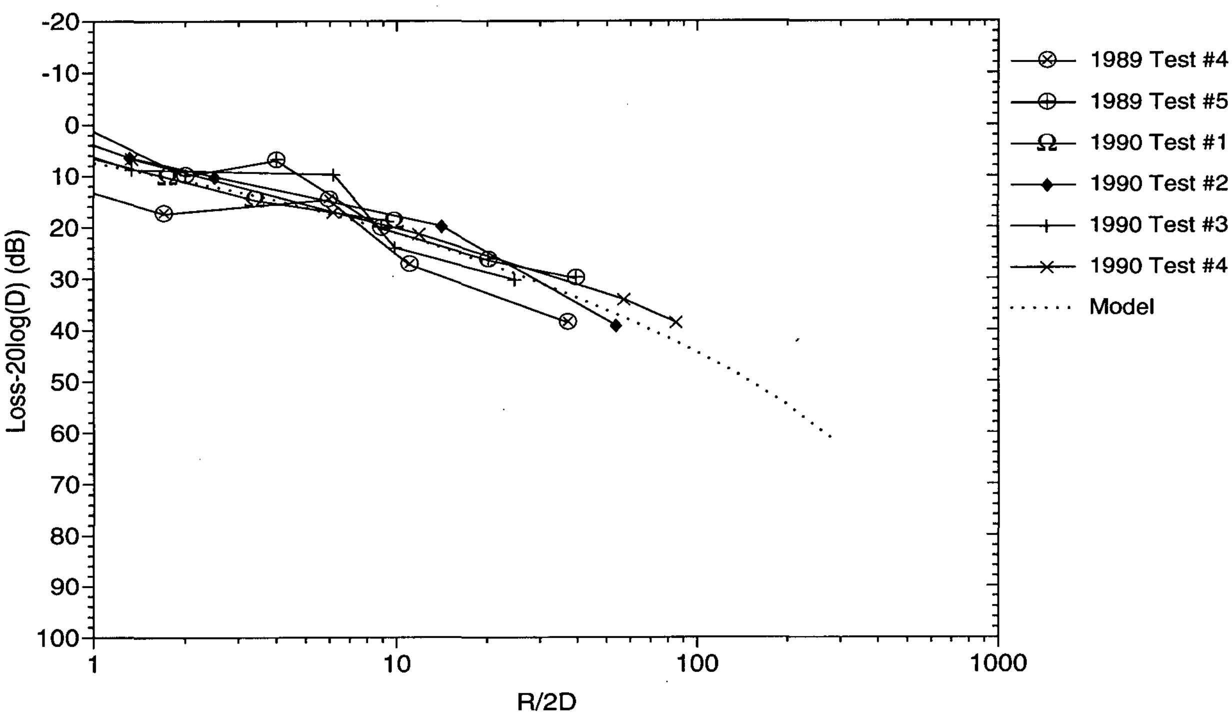


FIGURE B-6. TL-20log(D) vs. scaled distance for the 100 Hz FM sweeps measured during transmission loss tests.

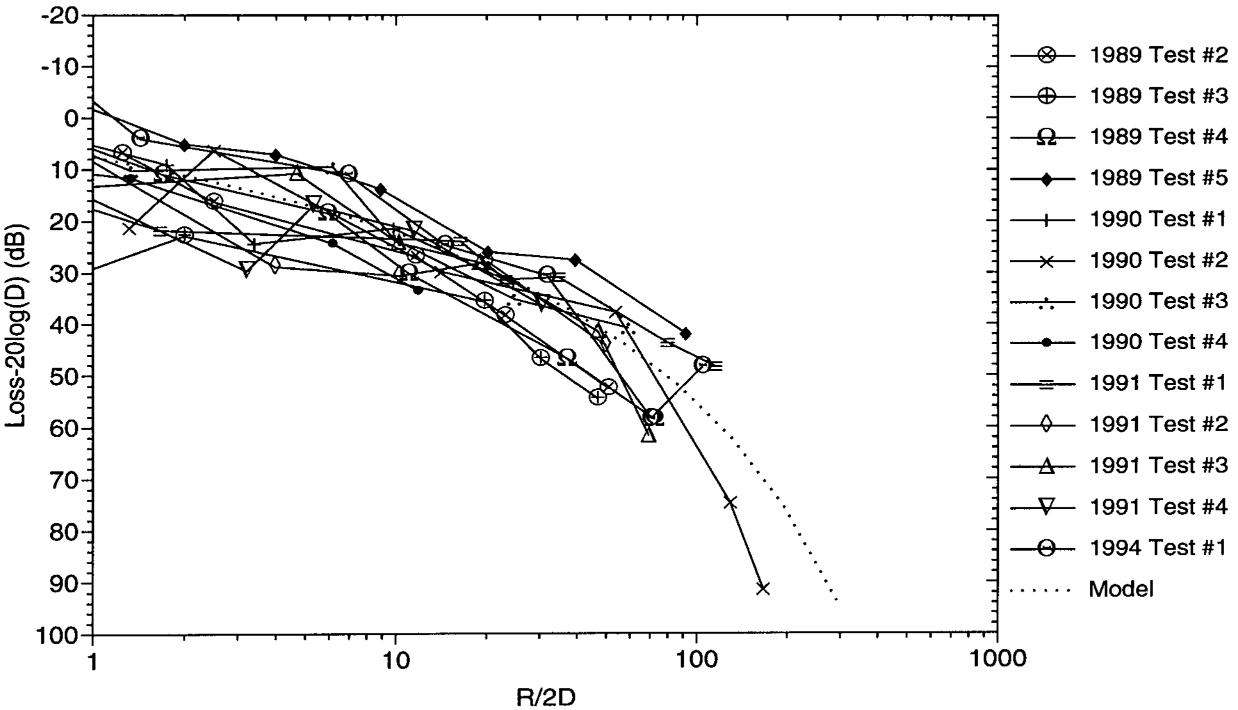


FIGURE B-7. TL-20log(D) vs. scaled distance for the 500 Hz tones measured during transmission loss tests.

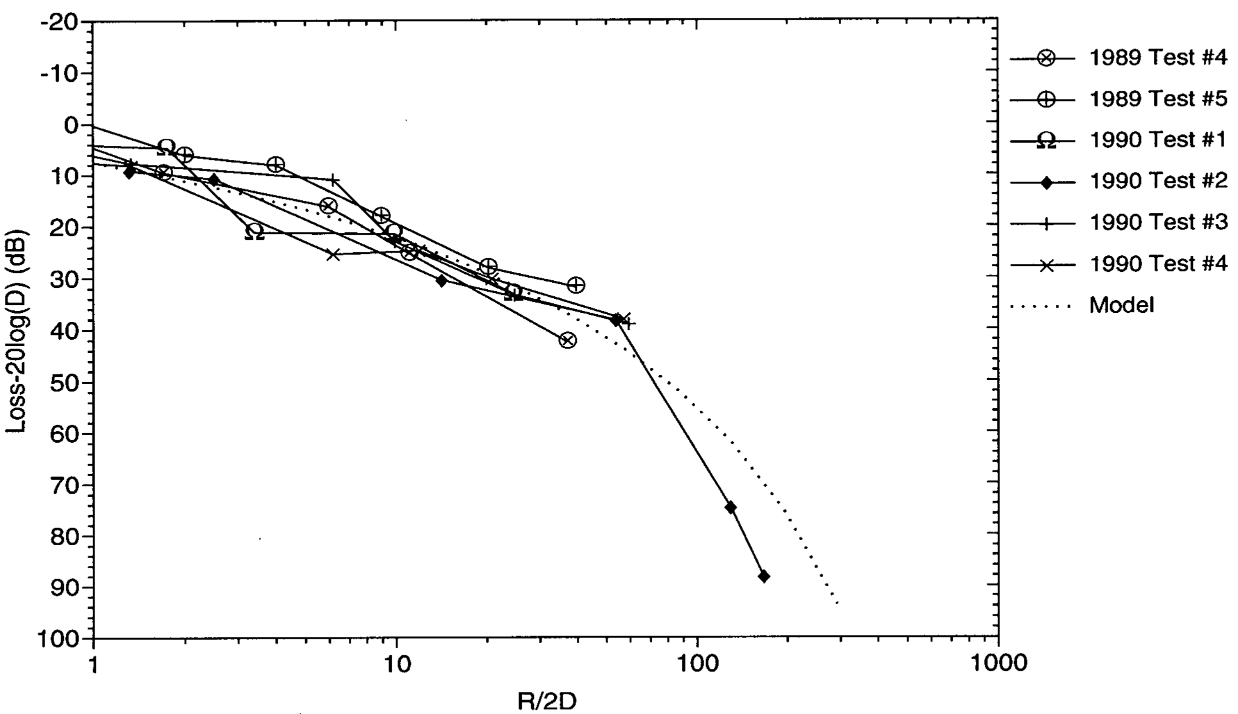


FIGURE B-8. TL-20log(D) vs. scaled distance for the 500 Hz FM sweeps measured during transmission loss tests.

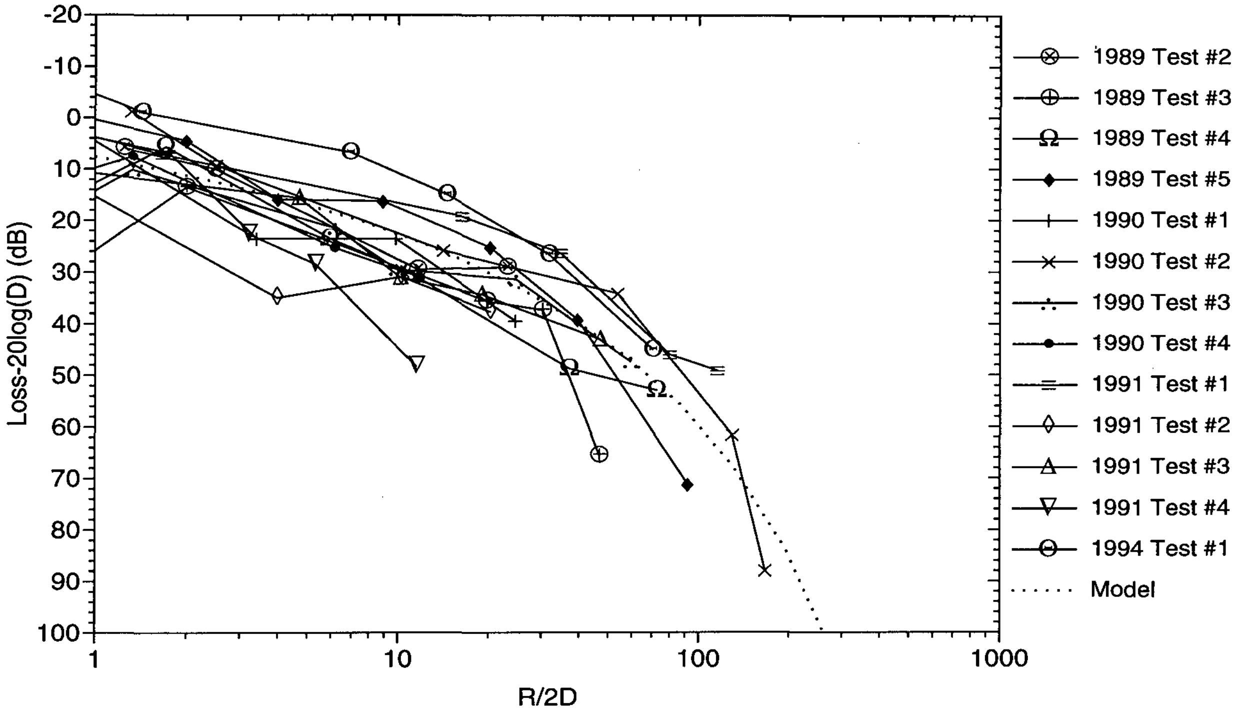


FIGURE B-9. TL-20log(D) vs. scaled distance for the 1000 Hz tones measured during transmission loss tests.

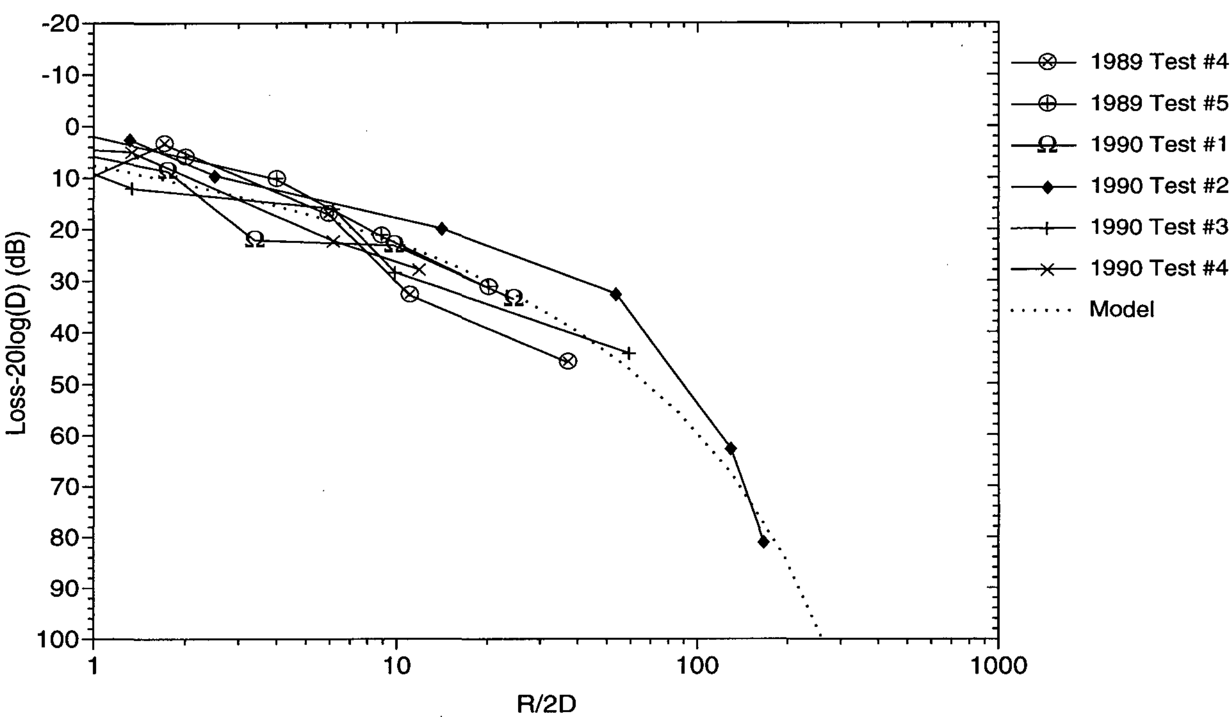


FIGURE B-10. TL-20log(D) vs. scaled distance for the 1000 Hz FM sweeps measured during transmission loss tests.

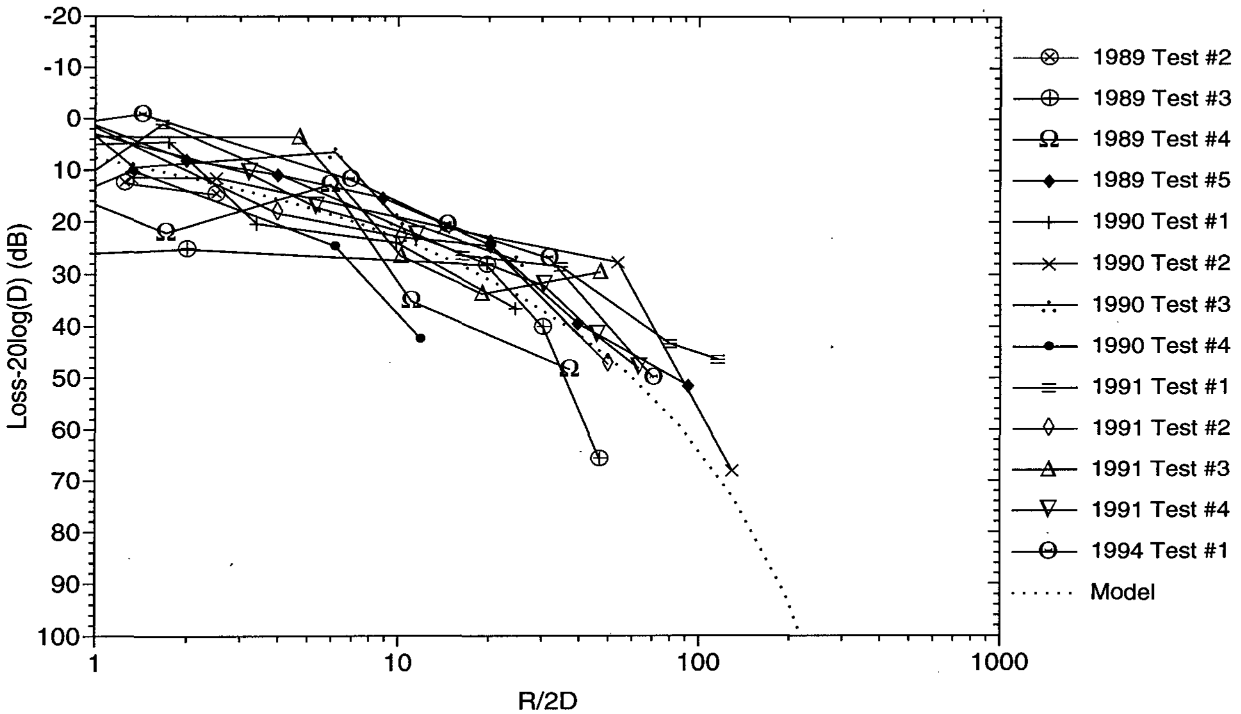


FIGURE B-11. TL-20log(D) vs. scaled distance for the 2000 Hz tones measured during transmission loss tests.

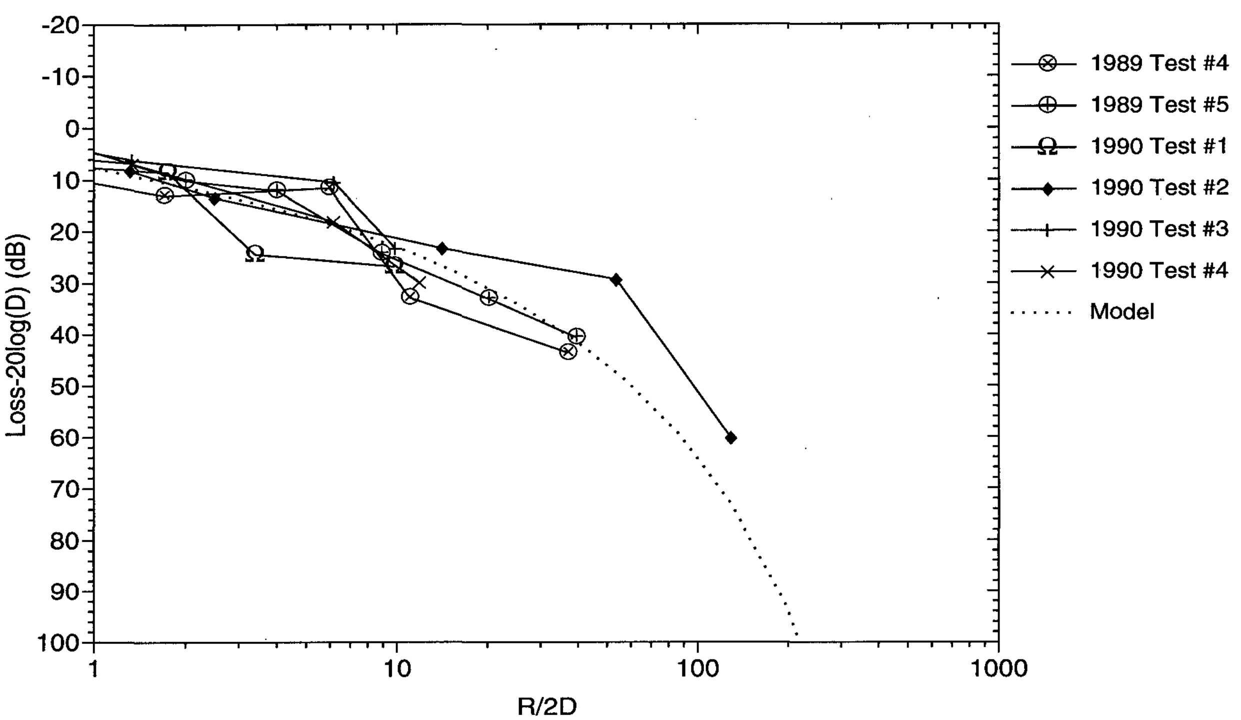


FIGURE B-12. TL-20log(D) vs. scaled distance for the 2000 Hz FM sweeps measured during transmission loss tests.

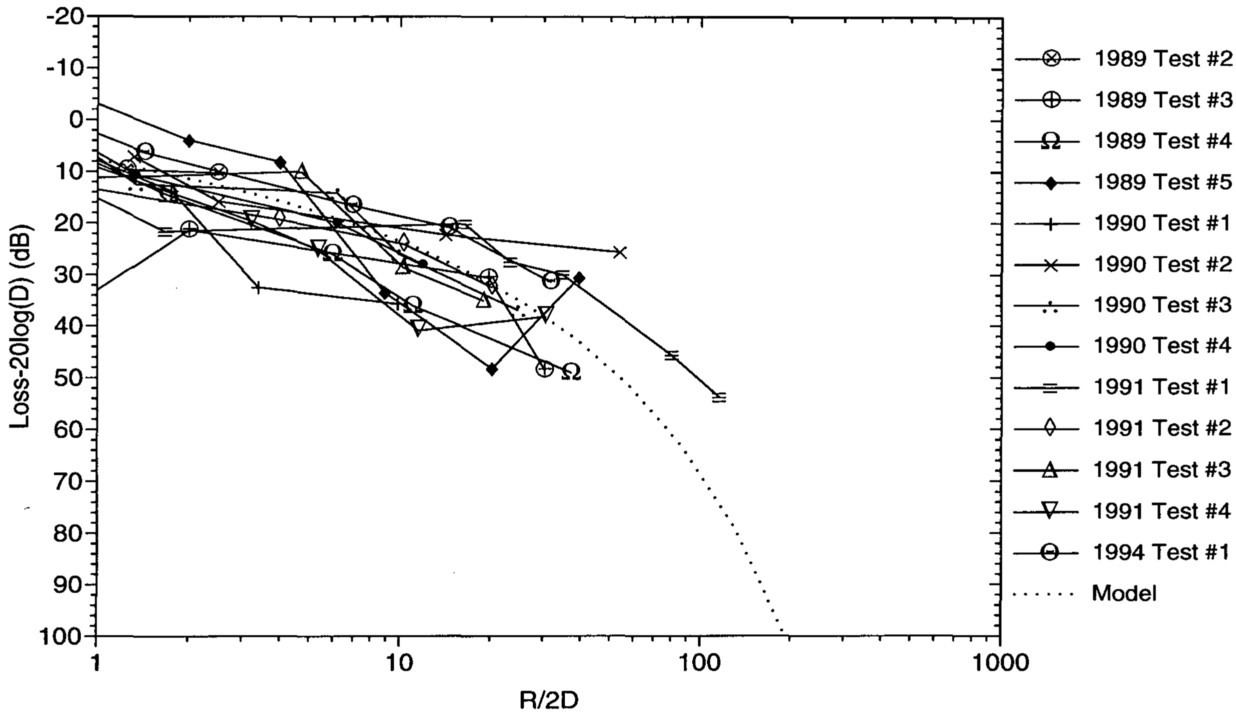


FIGURE B-13. TL-20log(D) vs. scaled distance for the 5000 Hz tones measured during transmission loss tests.

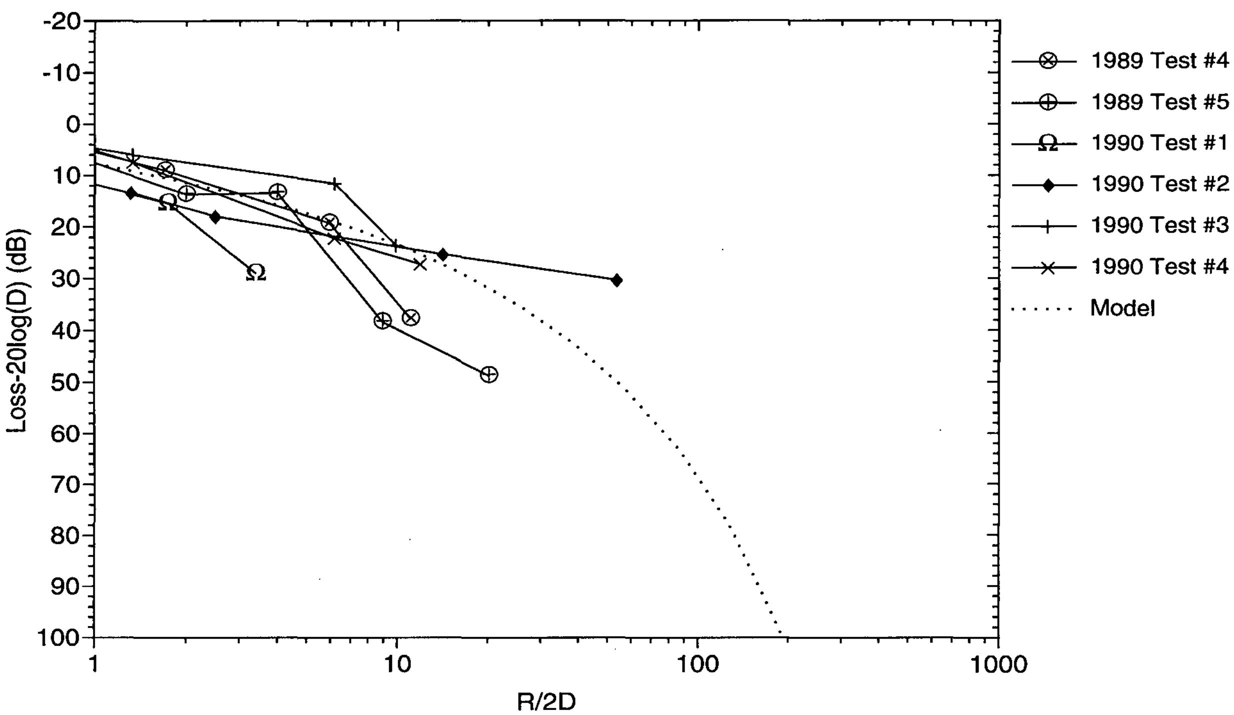


FIGURE B-14. TL-20log(D) vs. scaled distance for the 5000 Hz FM sweeps measured during transmission loss tests.

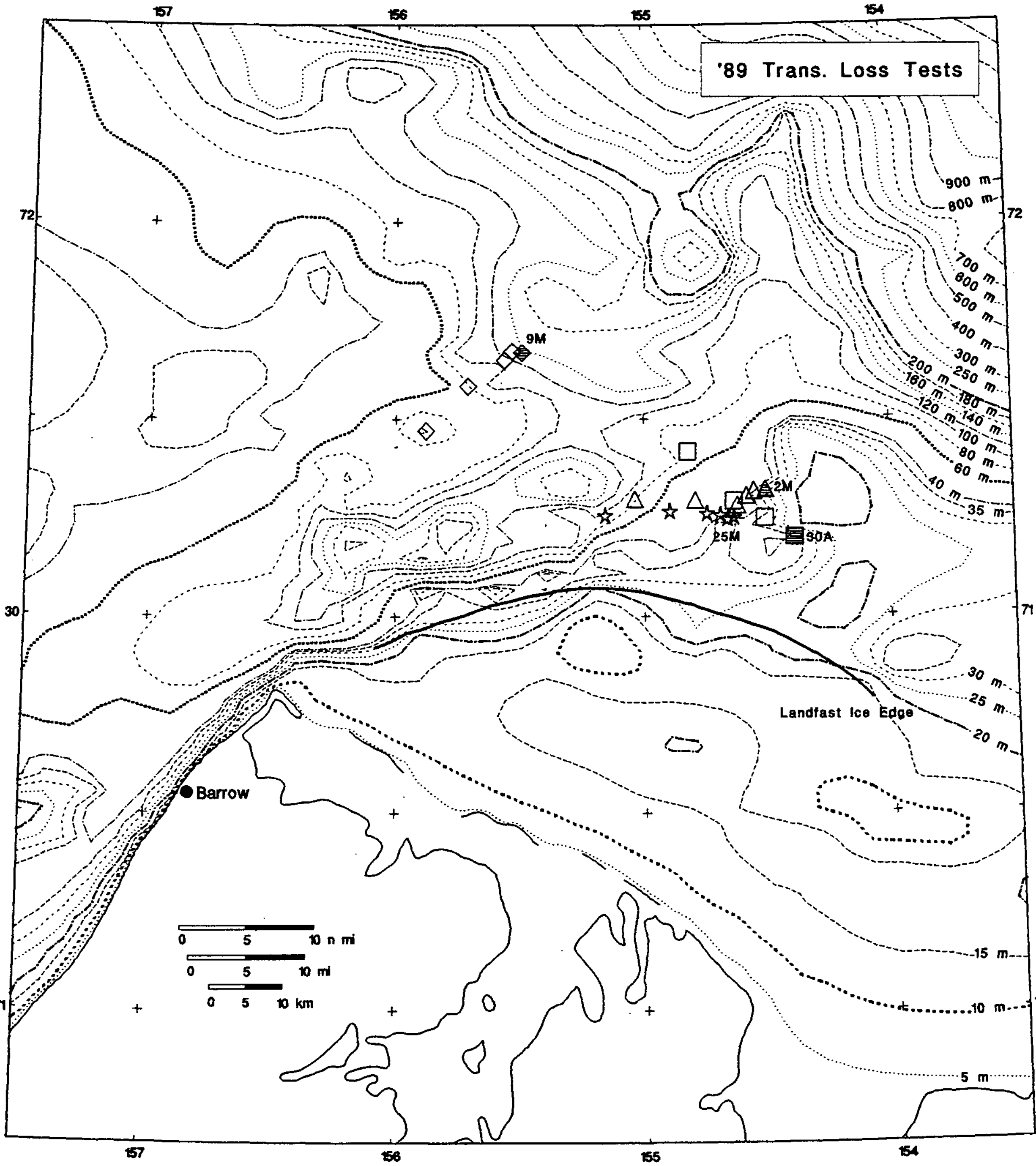


FIGURE B-15. Locations of four transmission loss tests in 1989. Solid symbols are the transmit stations on 30 April and 2, 9 and 25 May 1989. Corresponding open symbols are the more distant receive stations.

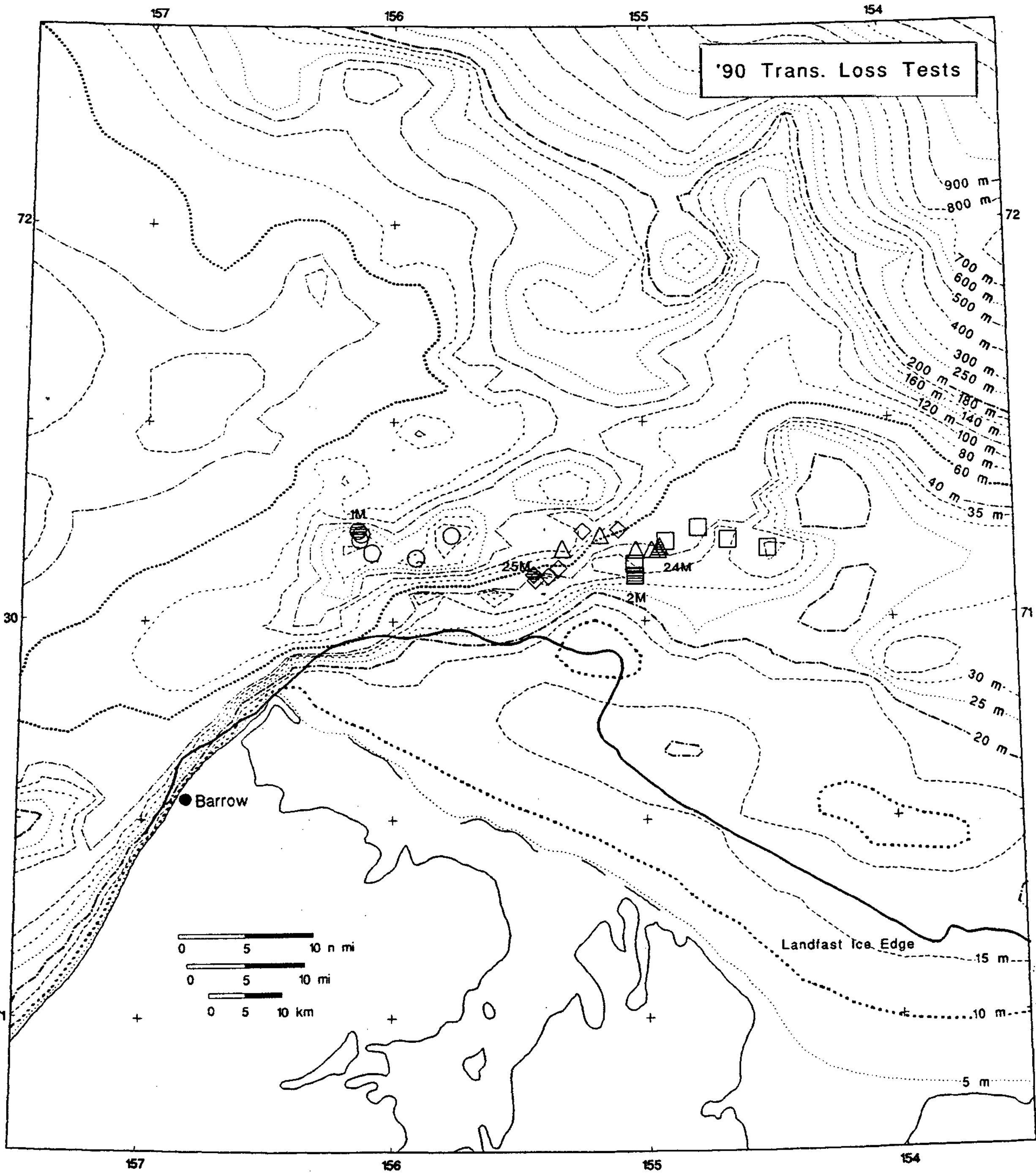


FIGURE B-16. Locations of four transmission loss tests in 1990. Solid symbols are the transmit stations on 1, 2, 24 and 25 May 1990. Corresponding open symbols are the more distant receive stations.

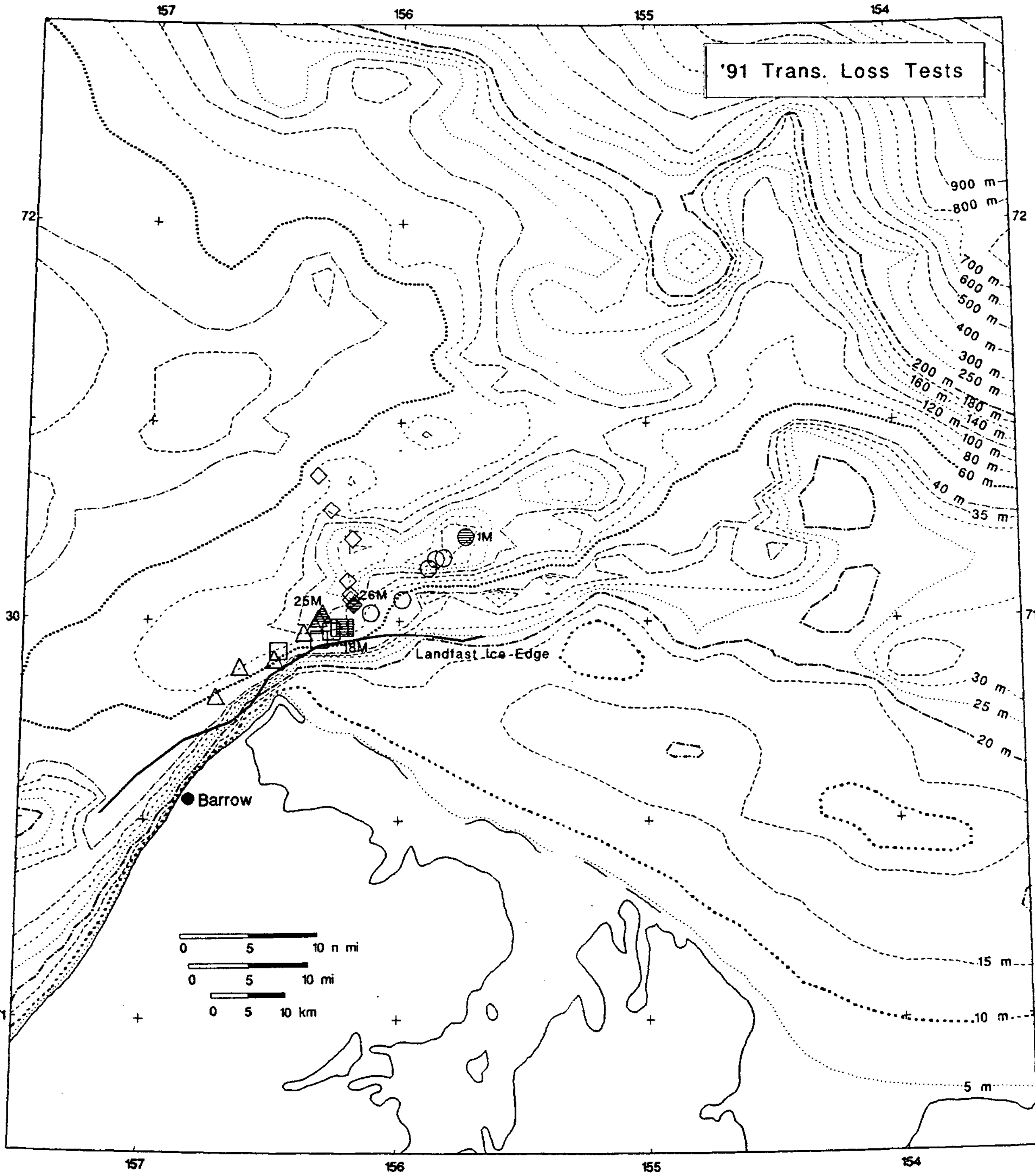


FIGURE B-17. Locations of four transmission loss tests in 1991. Solid symbols are the transmit stations on 1, 18, 25 and 26 May 1991. Corresponding open symbols are the more distant receive stations.

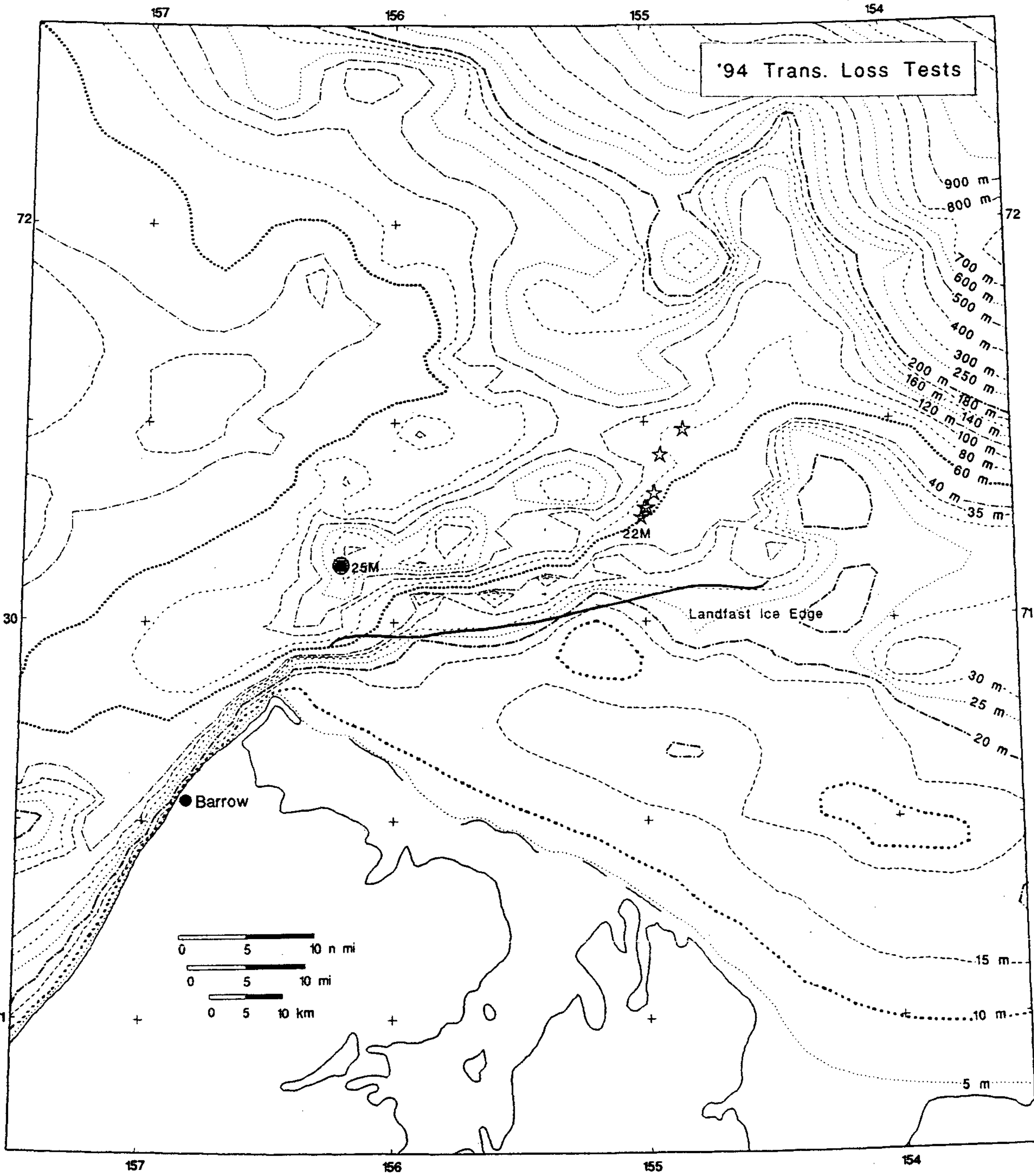


FIGURE B-18. Locations of two transmission loss tests in 1994. Solid symbols are the transmit stations on 22 and 25 May 1994. Corresponding open symbols are the more distant receive stations. The 25 May 1994 test was limited to short ranges.

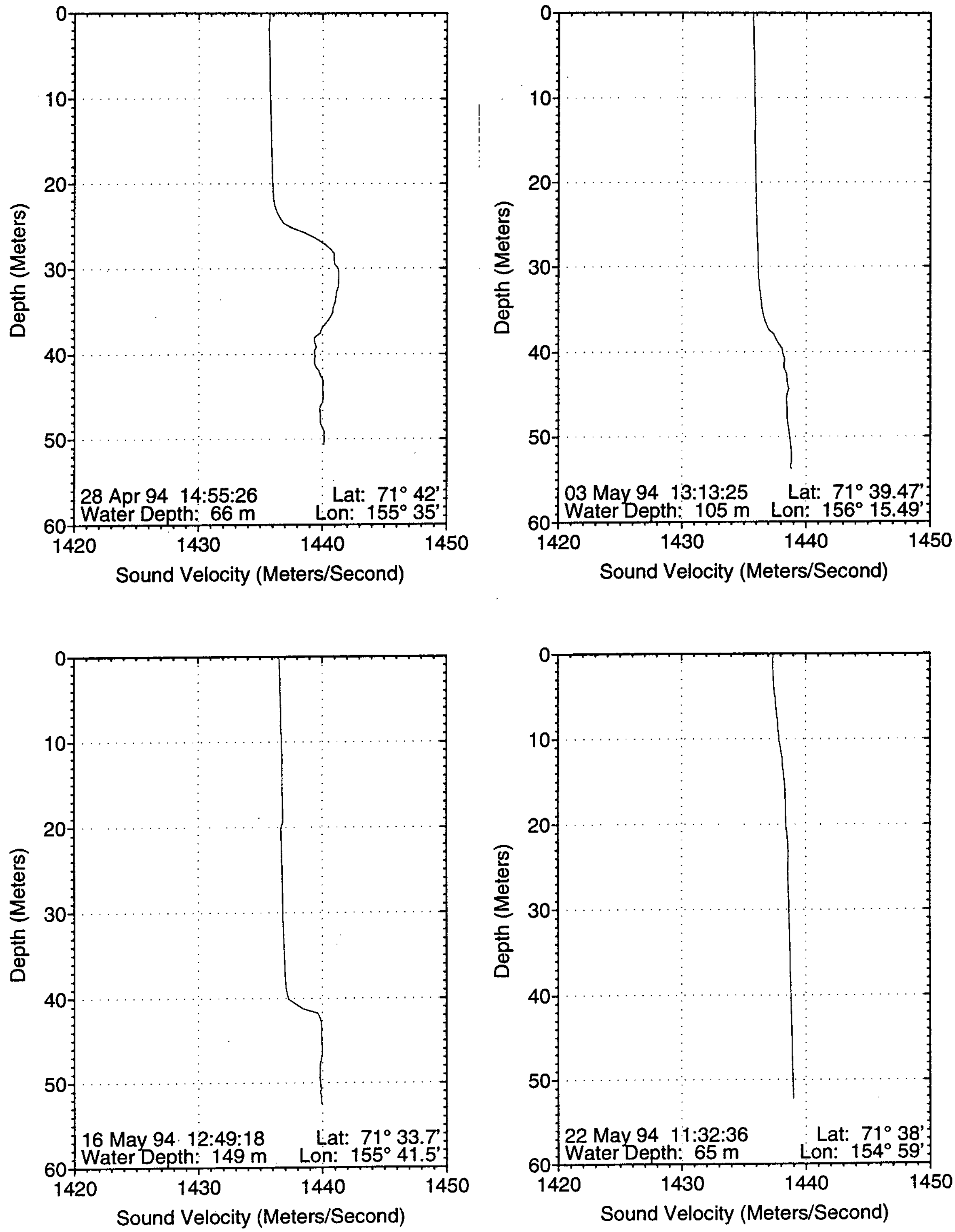


FIGURE B-19. Sound velocity profiles for four days in April/May 1994.

APPENDIX C: Sonobuoy Impact Sound

Introduction

An ice camp was established on 29 May 1989, latitude 71°41.1'N, longitude 154°51.7'W, water depth 90 m, to conduct a sound playback experiment. The project's Twin Otter aircraft deployed a sonobuoy at a distance of 800 m from the ice camp. Although the ice camp was on the edge of an ice floe, there was a reasonably ice-free path between the sonobuoy impact point and the ice camp. The sound of the water impact was recorded from hydrophones at depths 3 and 18 m. The playback experiment was in progress, so strong sounds of the drillsite *Karluk* were being projected from the J-11 projector at depth 18 m, distance 2-3 m from the 18 m hydrophone.

The sonobuoy impact sound is of interest because, on rare occasions, bowhead whales were seen to react when a sonobuoy was deployed in their vicinity (Richardson et al. 1990a:212).

Methodology

The sounds detected by the 3- and 18-m deep hydrophones (ITC model 6050C) were recorded on a Sony model TCD-5M audio cassette recorder. The recordings were analyzed with Greeneridge's PC-based analog-to-digital converter and analysis software.

The *Karluk* playback sounds dominate the recordings over the low frequency range up to ~500 Hz. Although the "slap" sound of the buoy impact can be heard in the presence of *Karluk* sounds, the acoustic pressure peaks of the impact cannot be discerned in time series graphs of the broadband sounds. Therefore, the recordings were high-pass filtered at 1 kHz before digitization and analysis. The sampling frequency was 32,768 Hz.

Results

Figure C-1 contains plots of times series for the impact sounds received at the 3- and 18-m deep hydrophones. Each hydrophone received two pairs of pulses. No sound velocity profile was measured at the measurement site, but profiles measured in the same area in late May five years later, with similar ice conditions, were essentially isovelocity at 1435 m/s. Each pair of arrivals consists of an upward-traveling sound followed by a surface-reflected sound. In the 3-m hydrophone signal, the arrivals in each pair are closer than they are in the 18-m hydrophone signal, as expected. The signals are stronger at the 18 m depth, which is accounted for by surface-release effects.

It is informative to calculate the sound ray arrival angles for the signals at the two hydrophones. The calculation is based on measuring the travel-time difference between the direct and surface-reflected arrivals and assuming parallel rays (plane waves). Assuming a sound velocity of 1435 m/s and that the measured hydrophone depths were accurate, the arrival angles (below horizontal) for the first pair of arrivals are 14° for the 3-m hydrophone and 13.3° for the

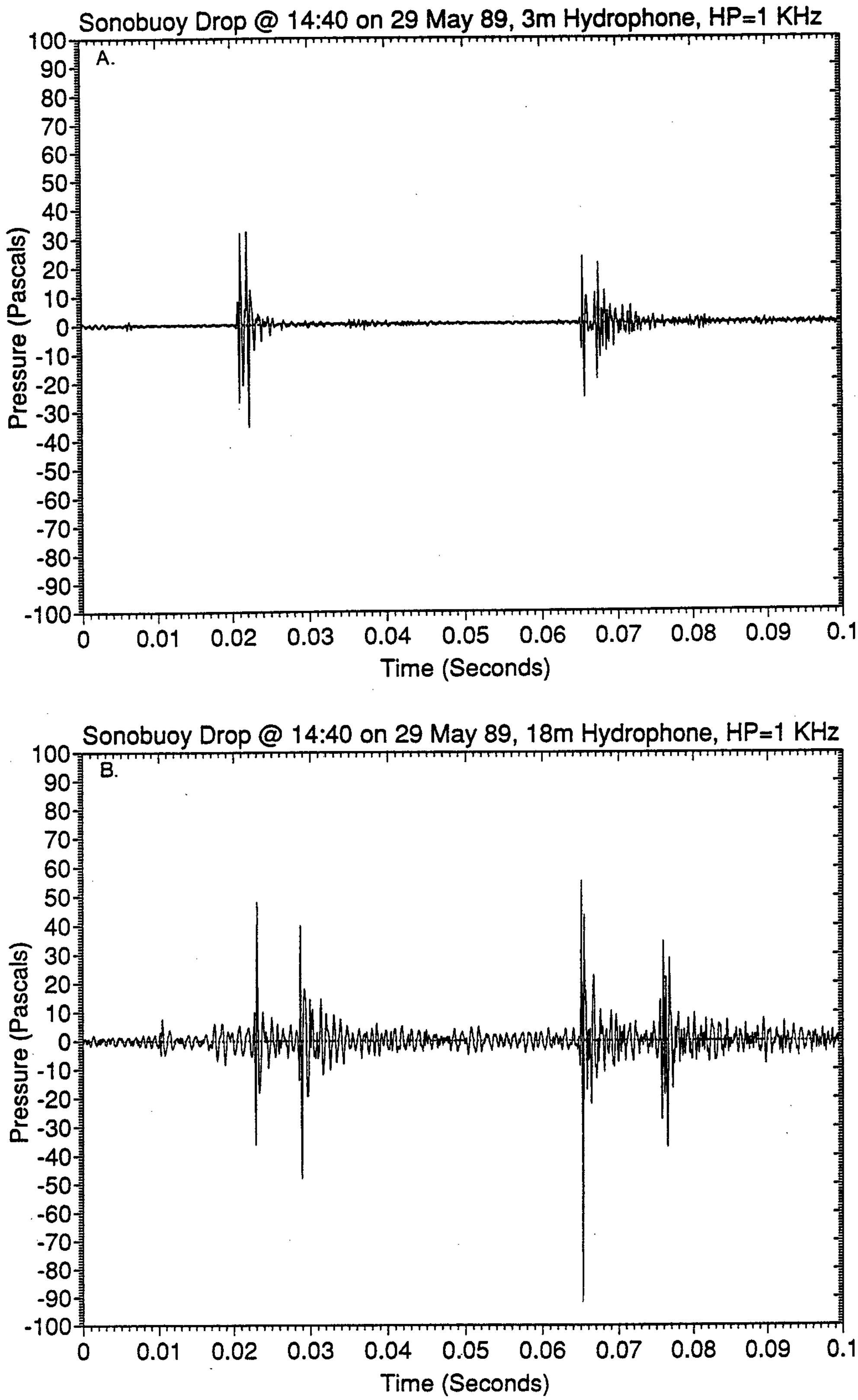


FIGURE C-1. Sonobuoy impact sound as received at two hydrophones 800 m from the impact. The sound was high-pass filtered at 1000 Hz to reject strong local interference (see text). *(A)* is for depth 3 m and *(B)* is for depth 18 m.

18-m hydrophone. The corresponding angles for the second pair of arrivals are 26.1° for the 3-m hydrophone and 25° for the 18-m hydrophone.

The simplest model for sound propagation is straight rays over the 800-m path, water depth 90 m, from the surface to the surface (a better approximation for the 3-m hydrophone than for the 18-m hydrophone). A direct (non-reflected) ray is not likely in isovelocity water. For the model (Fig. C-2), a single bottom bounce ray arrives at an angle of 12.7° and a two-bottom-bounce ray, including a surface reflection, arrives at an angle of 24.2°. The measured angles are ~14° and 26°, which are slightly larger than the predicted arrivals for the straight-line rays. Slight upward refraction would account for the slightly larger angles.

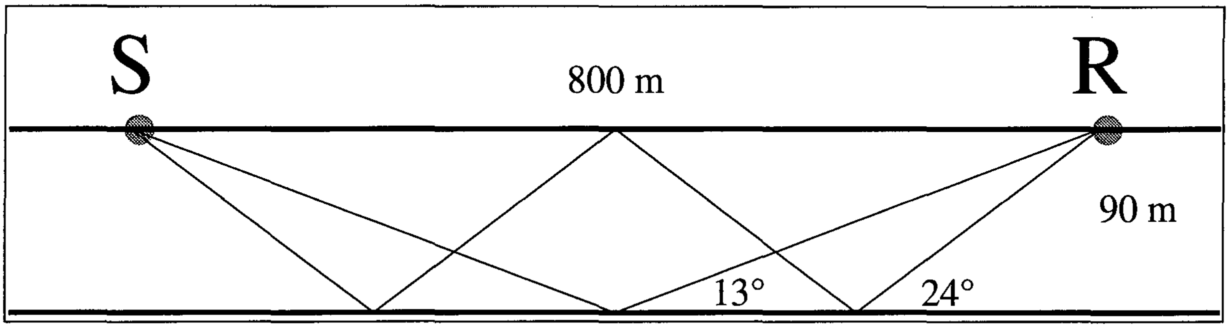


FIGURE C-2. Sound ray path model.

The geometric path length difference for the straight one- and two-bottom bounce rays, surface source to surface receiver, is 57.27 m. At 1435 m/s, 57.27 m corresponds to 40 ms; the measured time difference for the 3-m hydrophone is 44 ms and for the 18-m hydrophone, 42 ms. Small errors in sound speed, distance and water depth may account for the discrepancy.

Given the assumptions of accurate knowledge of water depth, hydrophone depths, sound speed and range from hydrophones to sonobuoy splash, the one- and two-bottom bounce hypothesis is plausible. A very weak signal may be seen at arrival times expected for a three-bottom bounce ray path. Its arrival angle, assuming the straight-line model, would be 34°. Such a steep angle ray may not be reflected well from the bottom, accounting for its weak presence in the received signal signature.

Figure C-3 presents an expanded graph of the pressure amplitude signal in the first (single bottom bounce, no surface reflection) arrival at the 18-m hydrophone. The acoustic impulse, calculated for the positive portion of the received pulse, is 0.00694 Pa-s (the positive signal duration is 0.26 ms). The peak pressure in this signal is 47 Pa, which corresponds to an acoustic peak pressure source level of 212 dB re 1 μPa-m assuming spherical spreading over a distance of 800 m. The acoustic impulse at distance 1 m from the source (assuming no positive pulse spreading and simply scaling the pressure for spherical spreading) is estimated to be 5.55 Pa-s. This is a very low value. The impulse from a 1 g TNT explosion underwater at depth 1 m, range 1 m, is calculated to be 61 Pa-s (Greene and Moore in press). Also, the rise time for the explosion would be orders of magnitude shorter than for a sonobuoy impact.

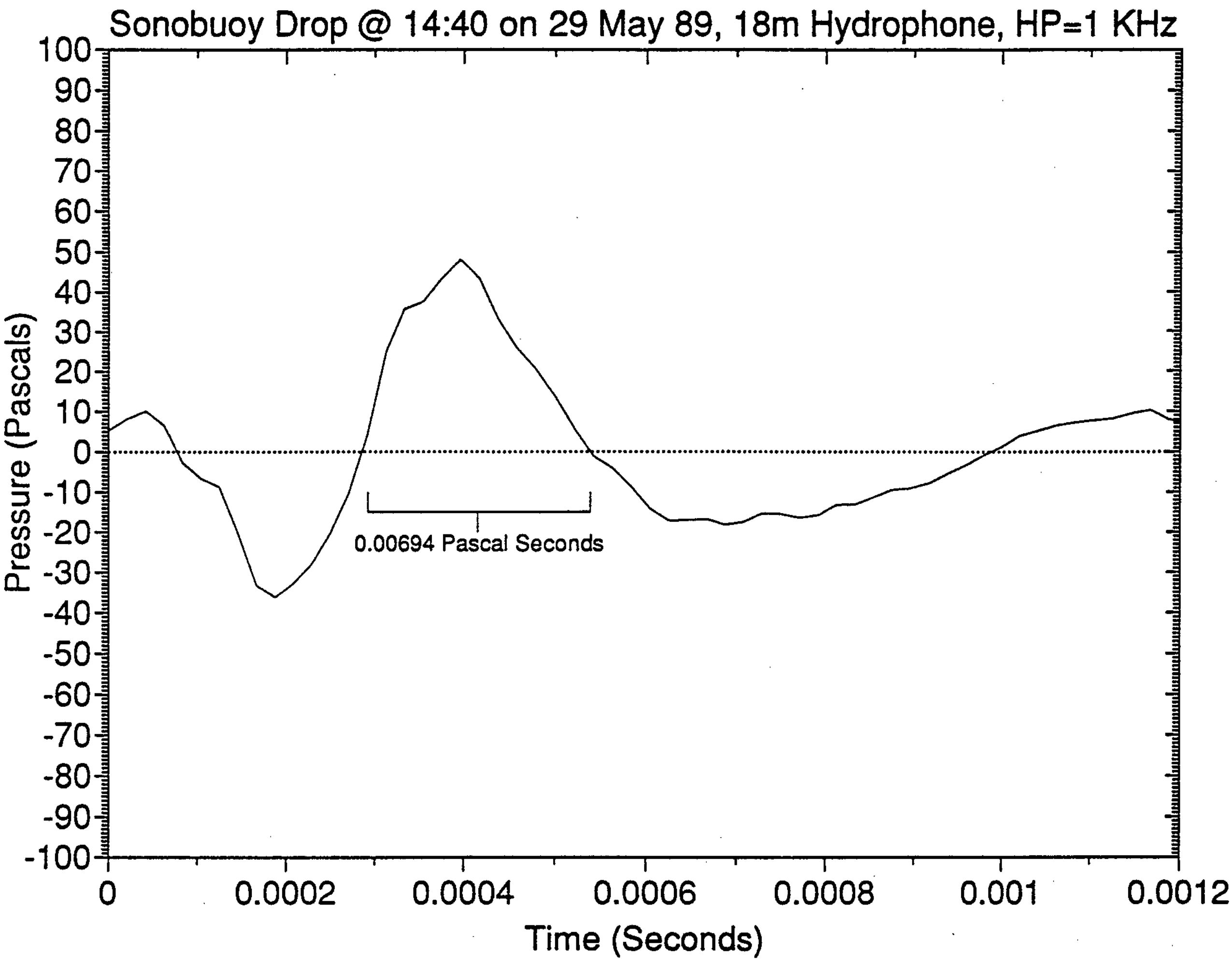
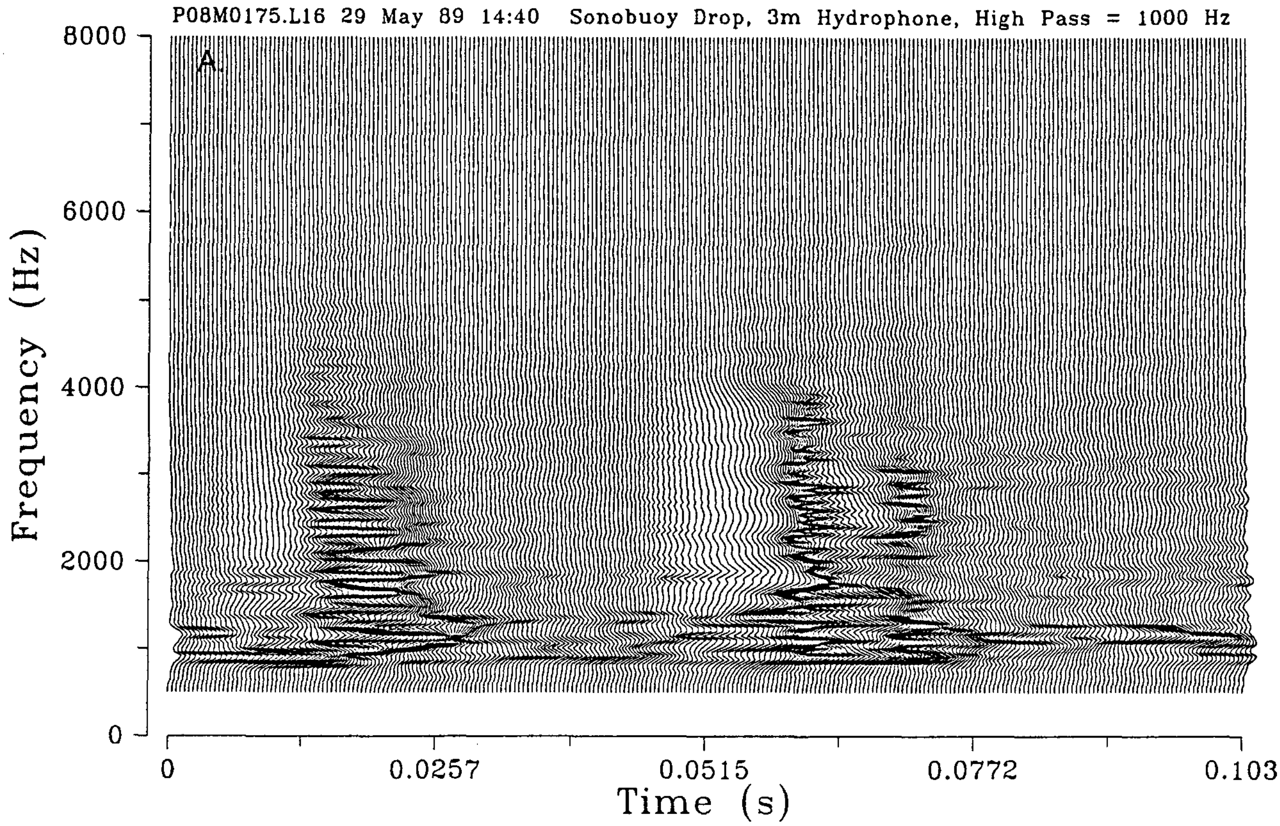


FIGURE C-3. Pressure-time signature of the single bottom bounce ray arrival at the 18-m hydrophone.

Figure C-4 presents waterfall spectrograms for the sonobuoy impact sound at the two hydrophones. Recall that the signals were high-pass filtered at 1 kHz before being sampled to reject most of the *Karluk* playback sounds present in the recording. The discrete Fourier transform length for these waterfalls is 256 samples, corresponding to a frequency bin spacing of 128 Hz and a bin width (frequency resolution) of 218 Hz. A high degree of overlap between transforms provides a waterfall display with relatively gradual changes with time, although the lengths of the signal pulses are very short.



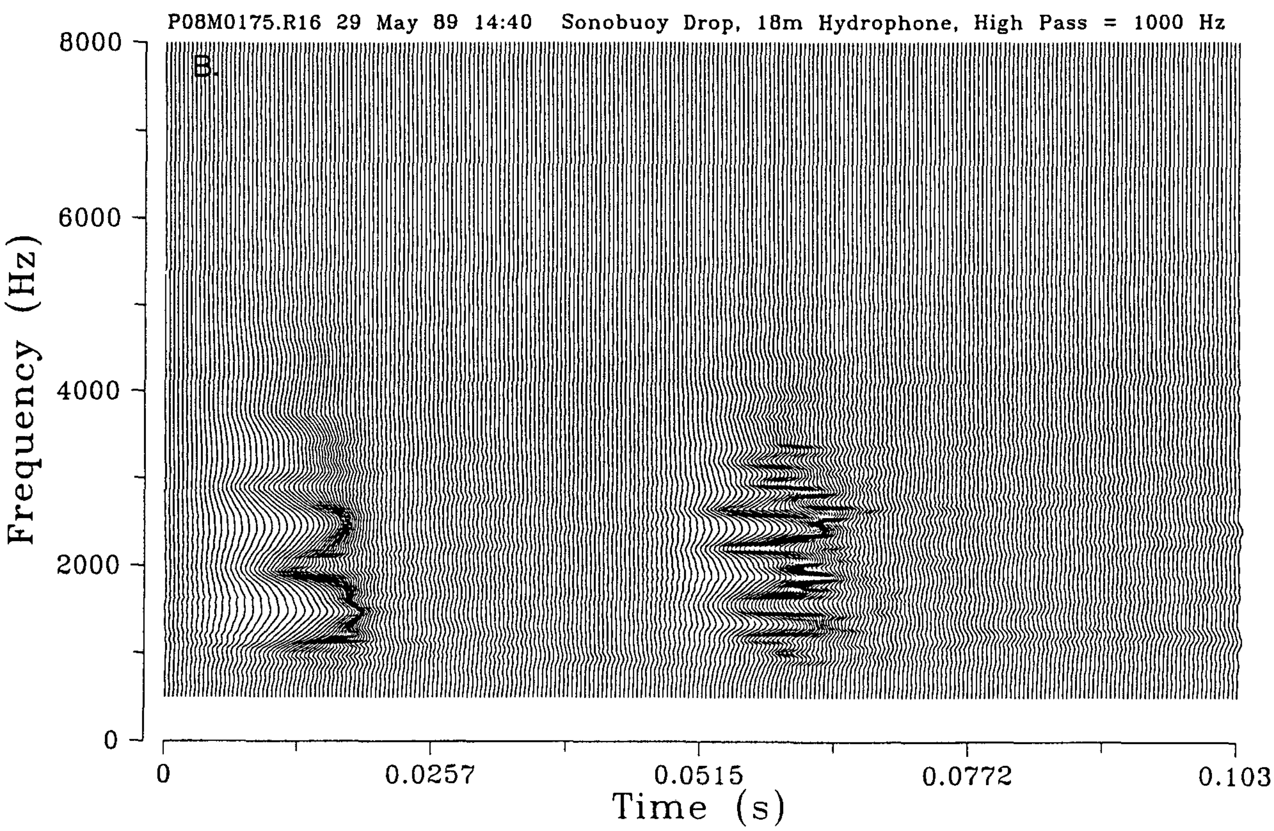


FIGURE C-4. Waterfall spectrograms for the pressure signatures at the two hydrophones. *(A)* is for depth 3 m and *(B)* is for depth 18 m.

APPENDIX D: Bowhead Distribution Maps, 1989-90

Appendix D shows all bowhead sightings during the present study by 10- or 11-day period in the springs of 1989 and 1990 (four maps per year). Each map shows all bowheads detected by observers in the Twin Otter aircraft (hatched symbols) and by observers in the helicopter or on the ice (open symbols). Mother-calf pairs of bowheads are shown with double circles. Headings toward which the whales were oriented when first seen are also shown.

Note that all search effort was non-systematic. The amount of effort varied greatly among different parts of the mapped area within any given 10- or 11-day period. The distribution of search effort also varied from one 10- or 11-day period to the next. The designated locations of the landfast ice edge are approximate.

Corresponding sighting maps for the 1991 and 1994 phases of the project appear in section 5.1 of this report.

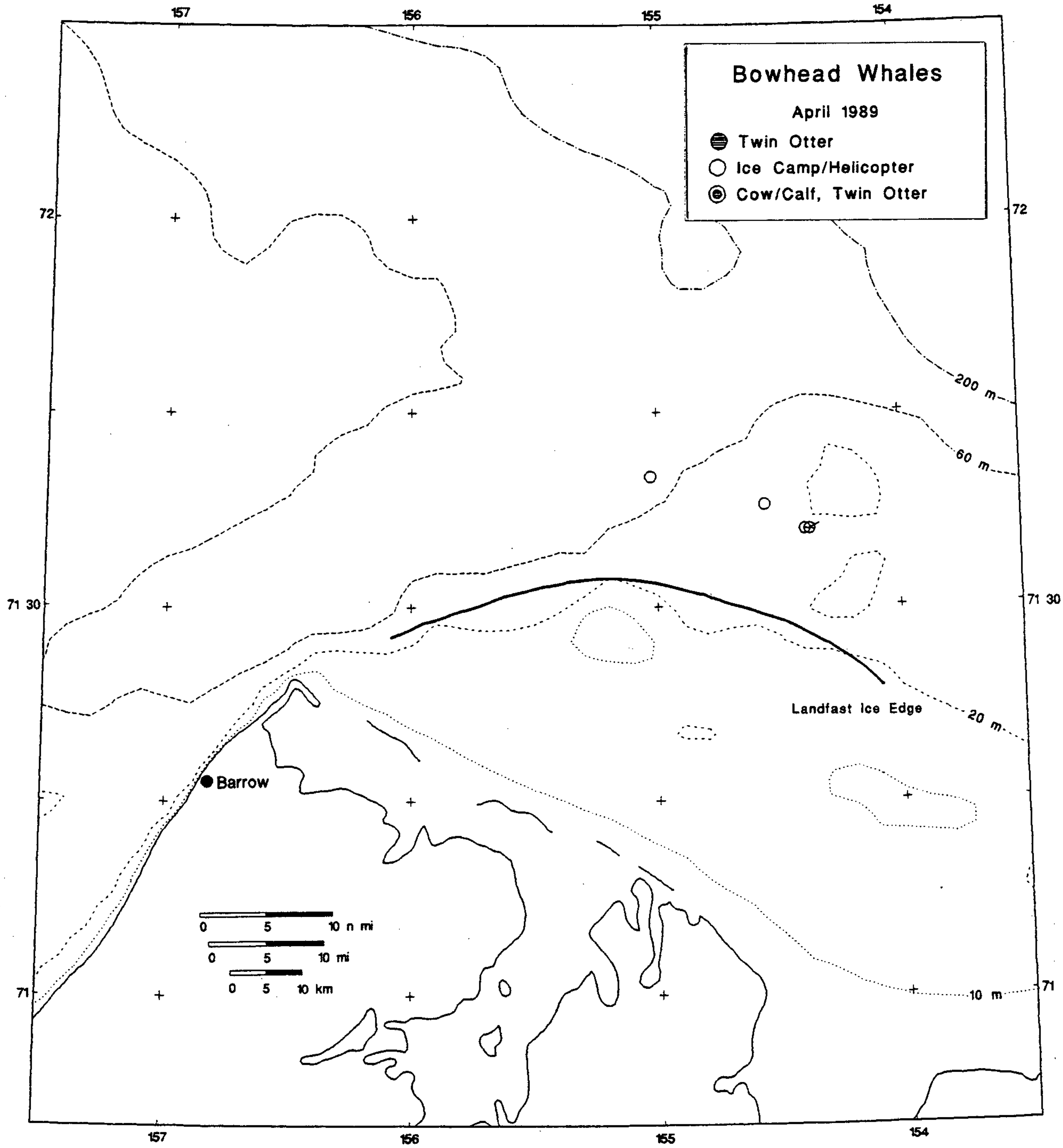


FIGURE D-1. LGL sightings of bowhead whales, late April 1989. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped.

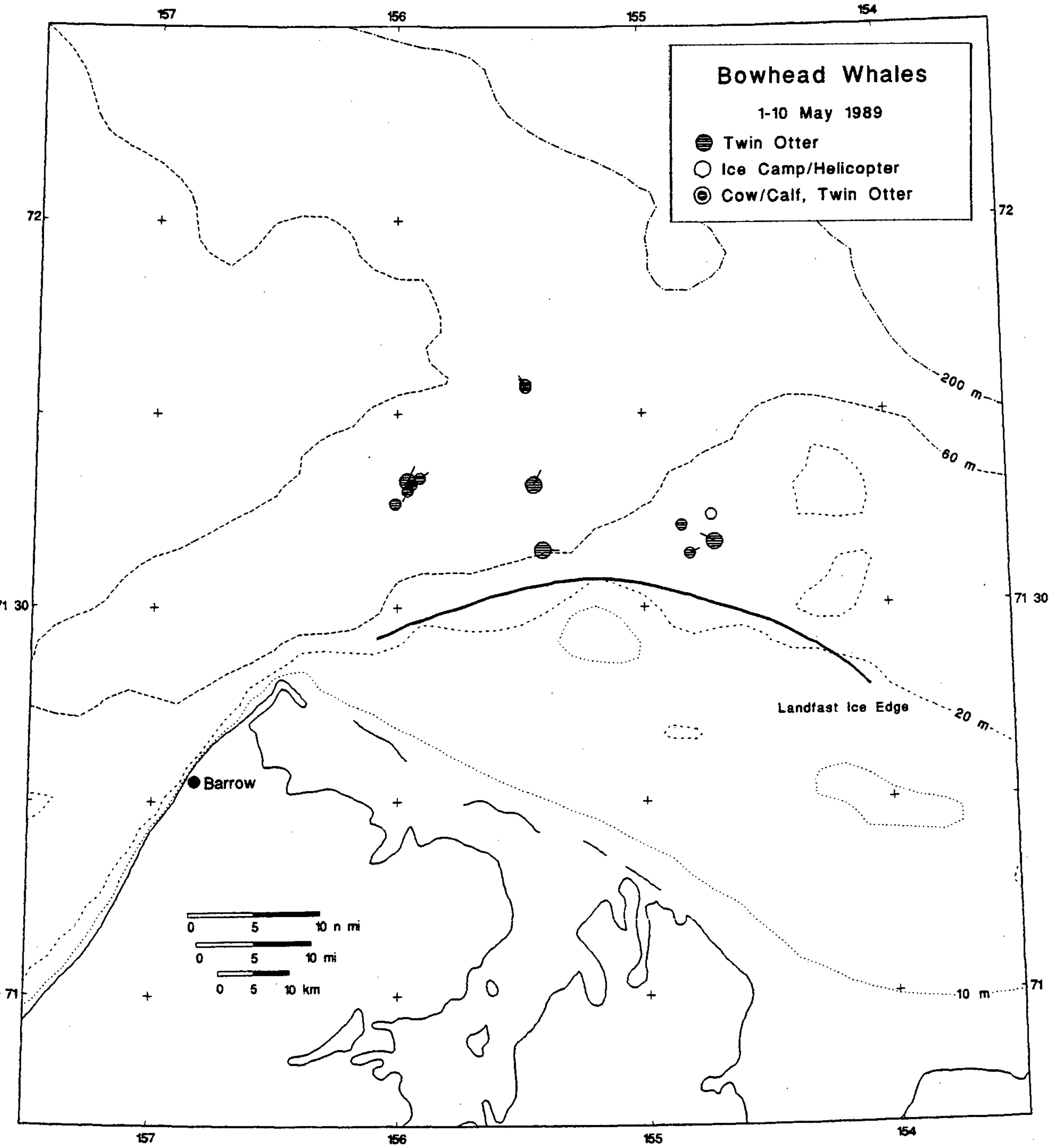


FIGURE D-2. LGL sightings of bowhead whales, 1-10 May 1989. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped.

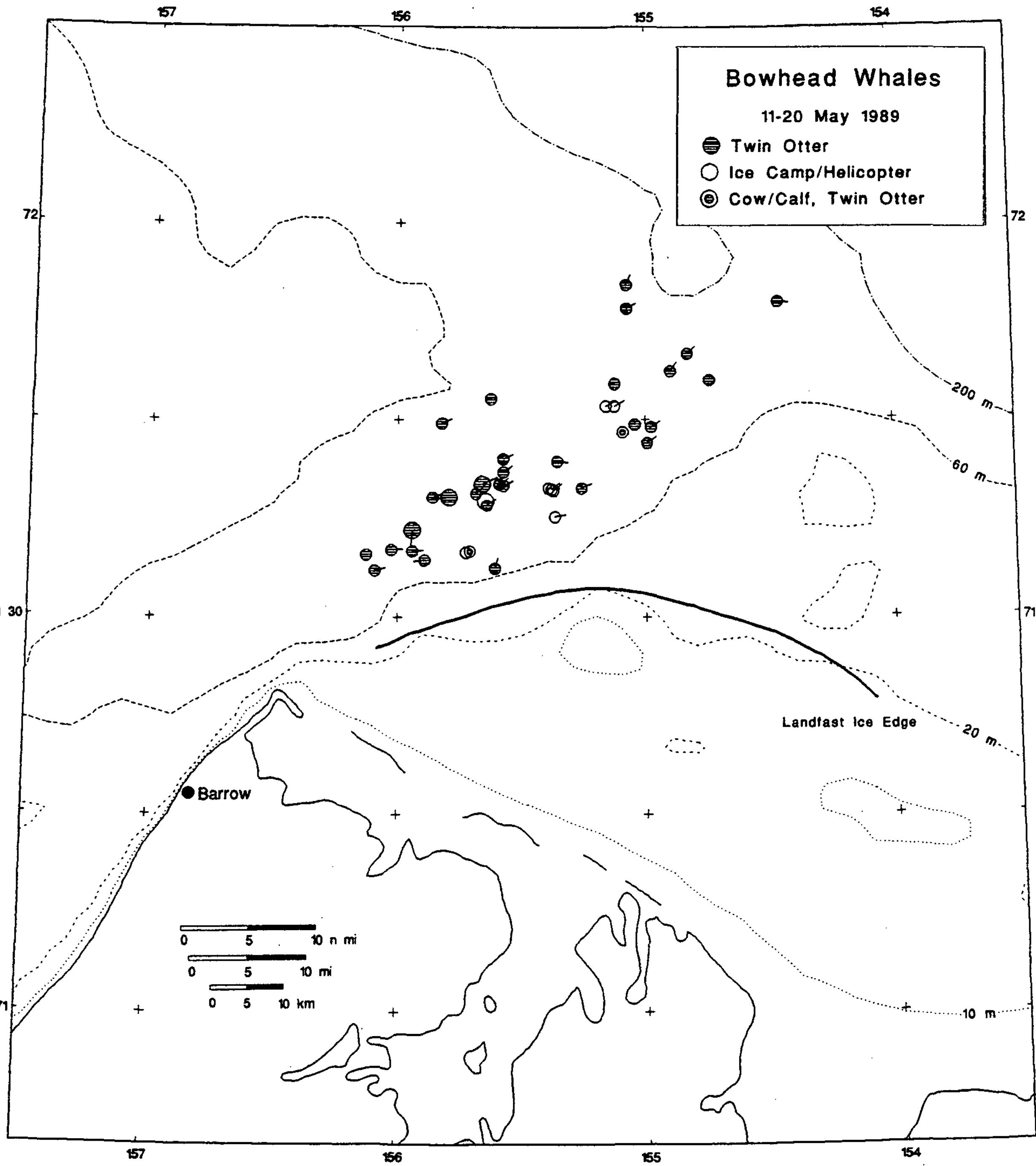


FIGURE D-3. LGL sightings of bowhead whales, 11-20 May 1989. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped.

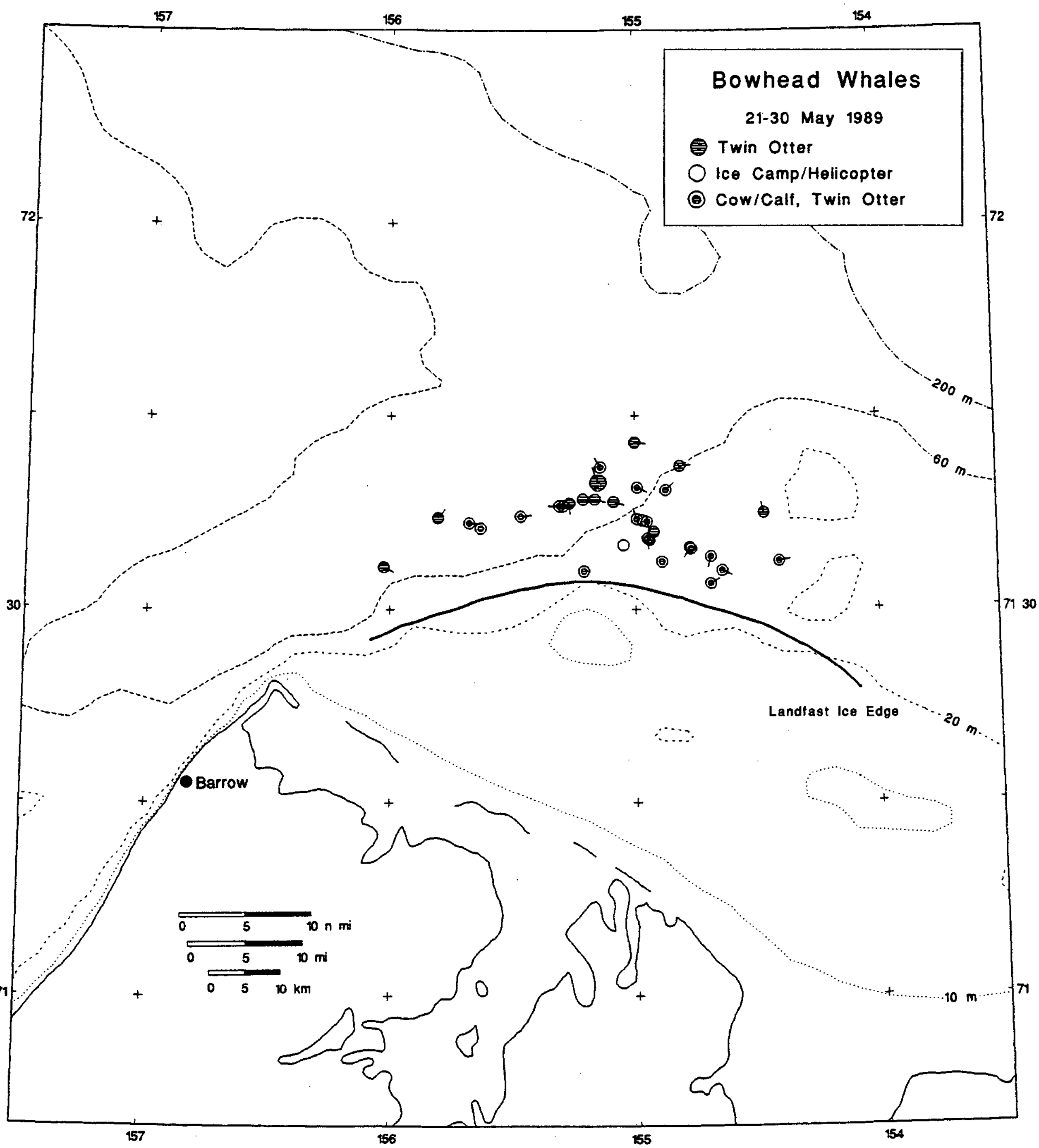


FIGURE D-4. LGL sightings of bowhead whales, 21-30 May 1989. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

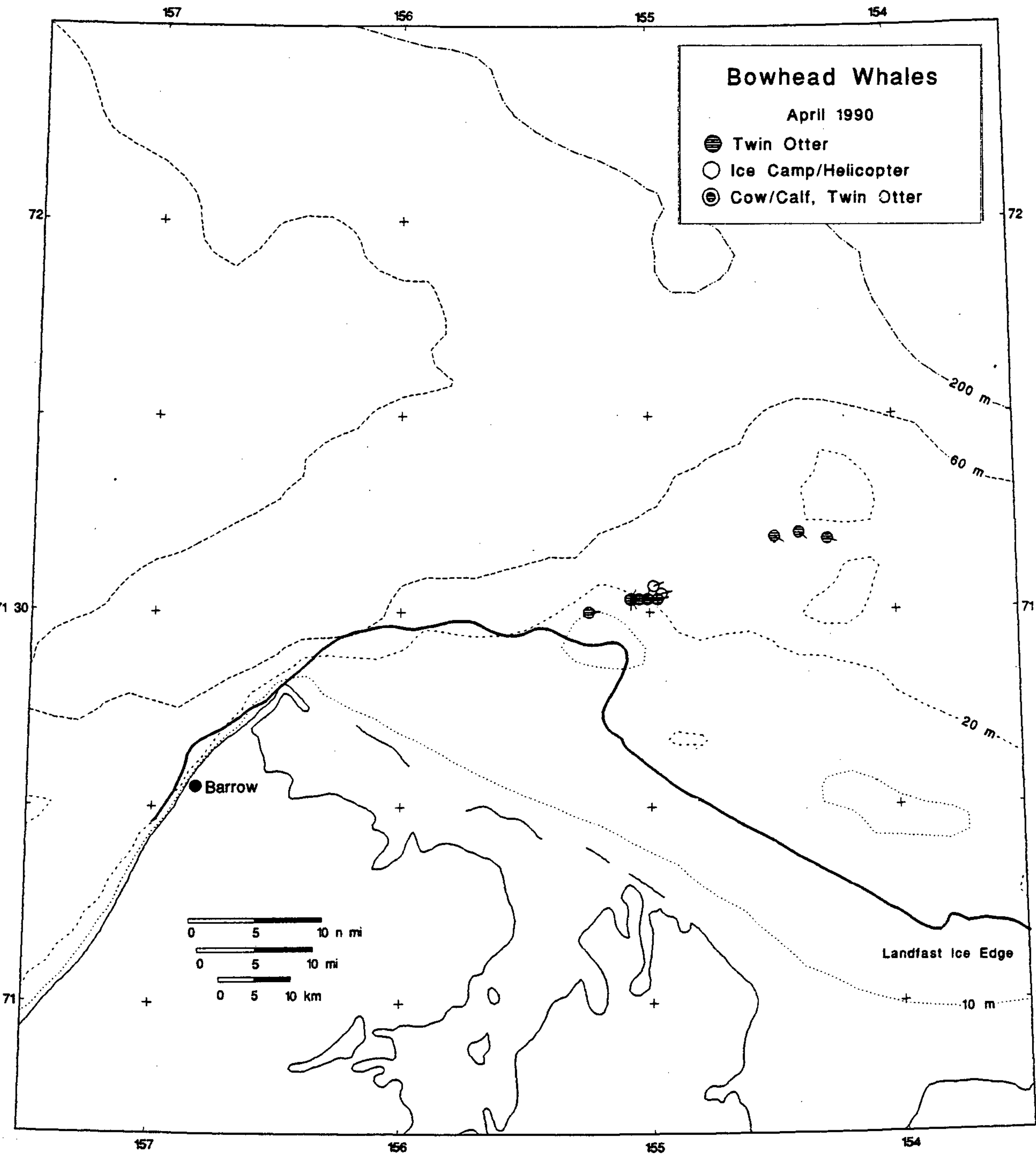


FIGURE D-5. LGL sightings of bowhead whales, late April 1990. Symbol type distinguishes sightings by the two crews, sightings of 1-2 vs. >2 bowheads, and sightings of mother/calf pairs vs. other bowheads. Headings toward which the whales were oriented when first seen are also shown when available. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

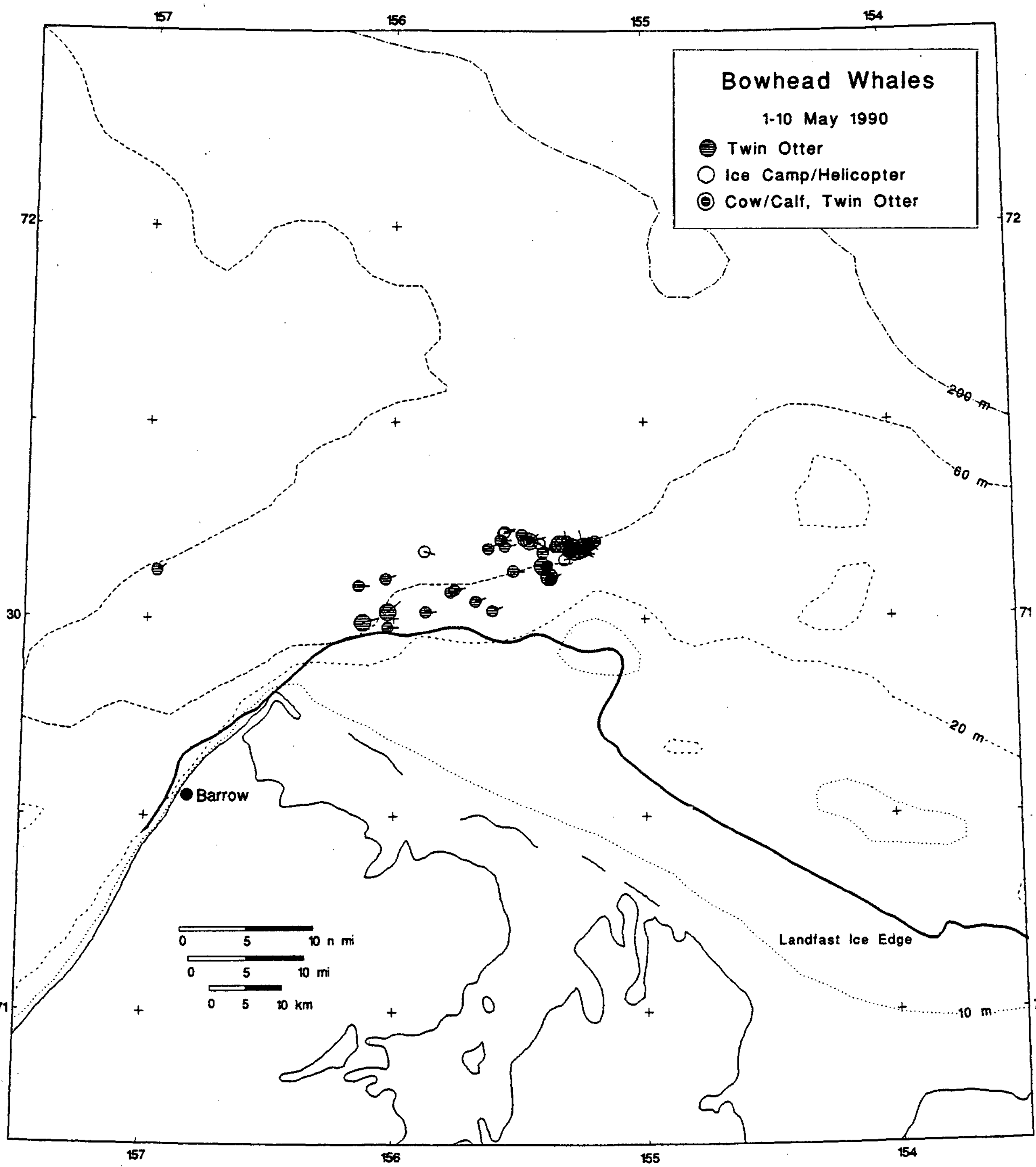


FIGURE D-6. LGL sightings of bowhead whales, 1-10 May 1990. Format as in Fig. D-5.

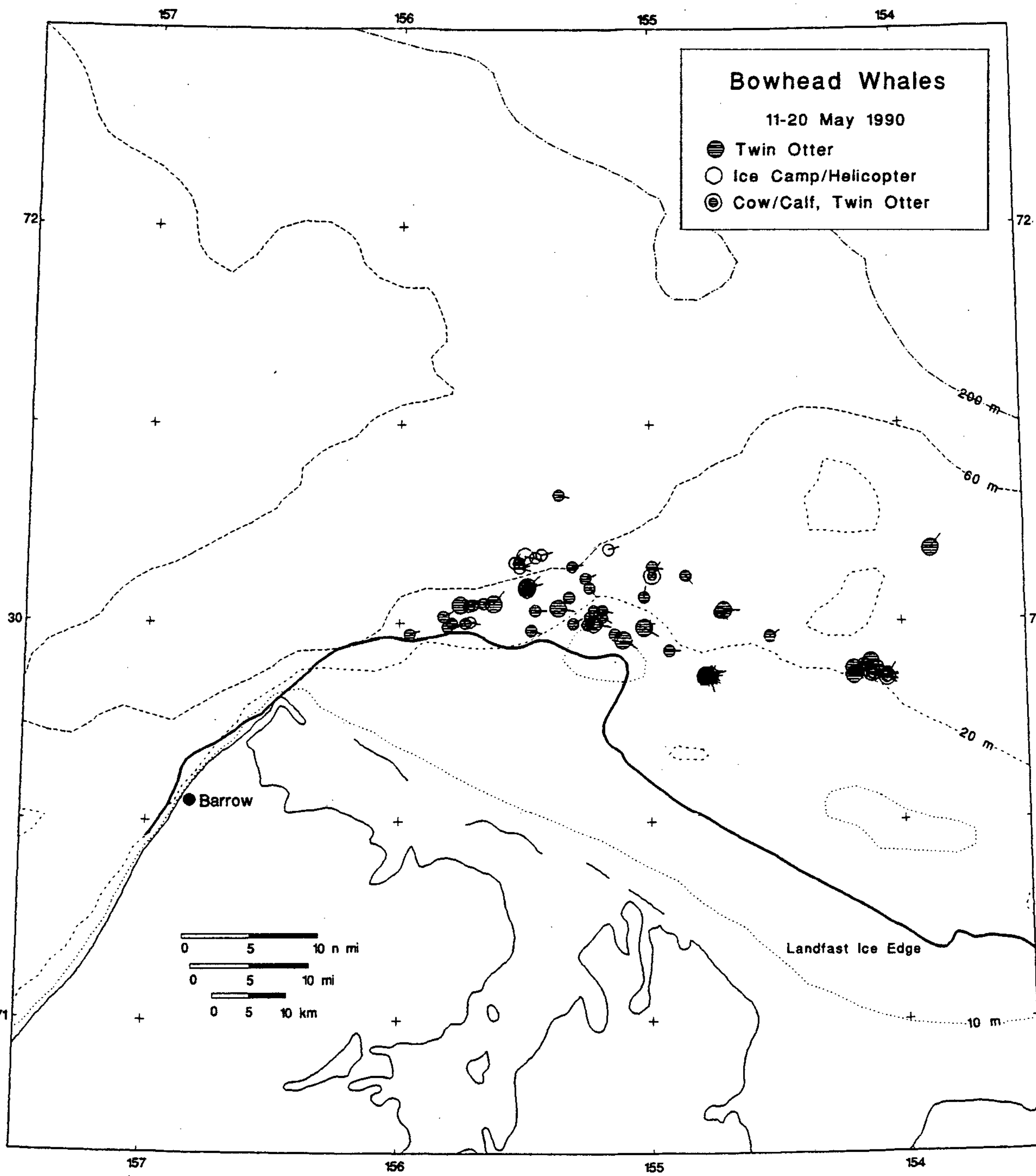


FIGURE D-7. LGL sightings of bowhead whales, 11-20 May 1990. Format as in Fig. D-5.

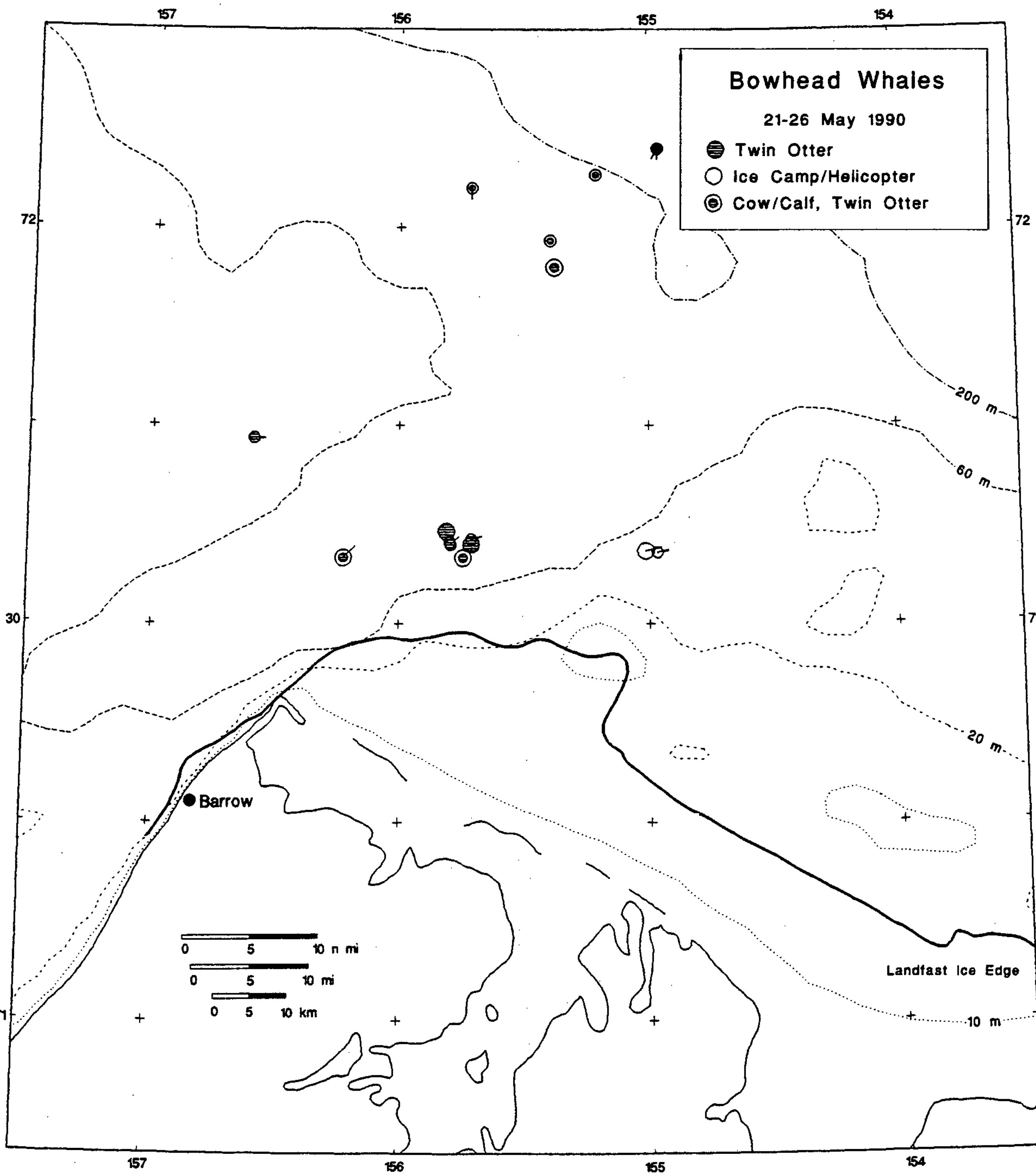


FIGURE D-8. LGL sightings of bowhead whales, 21-26 May 1990. Format as in Fig. D-5.

TABLE E-1. Details of NMML's 1989 between-year resightings of bowheads, various origins and years, to MMS study area, spring 1989. Originally listed (with less detail) in Koski et al. (1992).

Source of Photos[a]	Whale Number	Year	First Photographed: Date	Loc'n[b]	Latitude	Longitude	Resighting at Barrow: Date	Latitude	Longitude	Length in Year of Resighting (m)	Calf Present: First Sighting	Resighting
LGL-NMML	4	1981-89	1 Aug	NCA	~71°18.0'N	~121°48.0'W	7 May	71°35.6'N	156°23.1'W	15.8[c]	no	no
LGL-NMML	8	1981-89	1 Aug	NCA	~71°18.0'N	~121°48.0'W	2 May	71°39.2'N	155°25.7'W	13.6	no	no
LGL-NMML	49	1981-89	11 Sep	FB	70°39.2'N	127°42.3'W	29 Apr	71°36.6'N	155°36.9'W	14.1	no	no
LGL-NMML	1057	1982-89	16 Aug	HI	69°48.5'N	138°50.5'W	17,18 May	71°36.6'N	155°17.5'W	15.0	no	no
LGL-NMML	1112	1982-89	16 Aug	HI	69°48.5'N	138°49.1'W	27 May	71°37.0'N	155°33.3'W	15.8	no	no
LGL-NMML	1131	1982-89	16 Aug	HI	69°47.6'N	139°48.8'W	2 May	71°39.5'N	155°25.3'W	11.6[c]	no	no
LGL-NMML	1483	1982-89	24 Aug	DS	70°29.8'N	136°45.9'W	25 May	-	-	15.1	yes	yes
LGL-NMML	1576	1982-89	4 Sep	HI	70°08.5'N	139°06.2'W	21 Apr	71°30.3'N	156°01.0'W	11.8[c]	no	no
LGL-NMML	1617	1982-89	5 Sep	IF	69°39.2'N	138°01.5'W	17 May	71°34.8'N	155°53.3'W	14.0	no	yes
LGL-NMML	1576	1984-89	2 Sep	KP	69°22.5'N	138°41.8'W	21 Apr	71°30.3'N	156°01.0'W	11.8[c]	no	no
LGL-NMML	4020	1984-89	16 Aug	IF	69°24.8'N	137°12.3'W	6 May	71°38.5'N	155°59.0'W	13.8	no	no
LGL-NMML	4735	1984-89	2 Sep	IN	70°27.4'N	135°28.5'W	26 Apr	71°47.5'N	154°30.1'W	13.7[c]	no	no
NMML-NMML	2246	1985-89	26 May	BR	71°23.4'N	156°39.1'W	6 May	71°38.6'N	155°58.8'W	14.1	no	no
NMML-NMML	2247	1985-89	26 May	BR	71°23.9'N	156°38.0'W	17 May	~71°35.6'N	155°53.9'W	13.3[c]	no	no
NMML-NMML	2428	1985-89	6,7 Jun	BR	71°25.4'N	156°36.7'W	27 May	71°37.2'N	155°42.5'W	16.0	no	no
LGL-NMML	5286	1985-89	25 Aug	FB	69°38.7'N	126°11.4'W	7 May	71°36.0'N	156°23.6'W	13.4	no	no
NMML-NMML	4020	1986-89	11 May	BR	71°37.5'N	154°57.3'W	6 May	71°38.5'N	155°59.0'W	13.8	no	no
LGL-NMML	7035	1986-89	11 Sep	EA	70°22.7'N	143°49.0'W	23 Apr	71°28.3'N	156°16.1'W	14.5[c]	no	no
CRC-NMML	7728	1986-89	31 Aug	TPS	70°38.5'N	130°45.2'W	28 Apr	71°32.7'N	155°15.9'W	13.1	no	no
NMML-NMML	7946	1986-89	6 May	BR	71°38.4'N	156°04.3'W	3 May	71°35.8'N	155°21.1'W	13.3	no	no
NMML-NMML	8090	1986-89	14 May	BR	71°32.3'N	156°10.1'W	19 Apr	-	-	12.9	no	no
NMML-NMML	8135	1986-89	22 May	BR	71°29.7'N	155°50.9'W	21 Apr	71°30.4'N	156°01.2'W	13.1	no	no

[a] LGL - Photographic studies by LGL during summer (Davis et al. 1983, 1986a,b) and fall (Koski and Johnson 1987). NMML = Spring photographic studies by National Marine Mammal Laboratory. CRC = Summer photographic study by Cascadia Research Collective (Ford et al. 1987).

[b] NCA = North Central Amundsen Gulf, N.W.T., BR = Barrow Region, AK, FB = Franklin Bay, N.W.T., HI = Herschel Island, Y.T., DS = Mackenzie Delta Shelfbreak, N.W.T., IF = Mackenzie Delta Interface, Y.T., KP = King Point, Y.T., IN = Mackenzie Delta Industrial Area, N.W.T., FB = Franklin Bay, N.W.T., EA = Eastern Alaska, TPS = Tuktoyaktuk Peninsula Shelf, N.W.T.

[c] Approximate length.

APPENDIX F: Individual Playback Experiments, 1991/94[38]

Playback in 1991

17 May 1991 Playback

On 17 May 1991, the J-13 and F-40 projector system was set up along the edge of the landfast ice several kilometers northeast of Point Barrow (Fig. 3.6 on p. 72). Spring whaling at Barrow had ended by this date. As a result, it was possible to project icebreaker sound into the water closer to Barrow than had been possible earlier in 1991 or at any time during 1989-90.

All observations of whales near the projector site on 17 May 1991 were obtained by the ice-based crew stationed at the projector site. The landfast ice edge and the nearshore lead were oriented from west to east (True) in this area. The measured water depth at the projectors was 110 m. The main nearshore lead adjacent to the landfast ice edge was several kilometers wide and largely ice-free. However, a band of pack ice was drifting in the lead west of the ice camp (Fig. F-1A). This ice blocked the ice-based observers' view of the open nearshore lead farther west. This band of ice drifted closer to the camp as the day progressed (Fig. F-1A). Whales traveling east in the main nearshore lead swam under this ice. The crew was on the landfast ice edge from 10:46 through 20:59. Icebreaker sounds were projected into the lead from 12:42 through 18:01.

The Twin Otter crew made two flights on this date for purposes of whale reconnaissance and vertical photography, and with the hope of making behavioral observations. However, there was low cloud all day, plus patches of fog. This prevented us from circling at 460 m altitude to observe whales near the projector site or elsewhere. To avoid any possibility of aircraft disturbance to whales being observed by the ice-based crew, the Twin Otter remained a minimum of several kilometers away from the ice camp.

Ice-based Observations.—No bowheads were sighted from the ice during the period of pre-playback control observations. Five or six single bowheads plus two pairs were seen traveling east past the ice camp during or immediately after the icebreaker playback, i.e. a total of 9 or 10 whales in 7 or 8 groups. There were two additional "control" sightings of single bowheads well after the playback had ended.

Small numbers of bowheads traveled past the ice camp while icebreaker noise was projected into the lead. The closest observed distances of these whales relative to the projectors were 540-1360 m (Table F-1A). Some whales were apparently at or near their closest points of approach (CPA) when seen. However, others were approaching and/or moving away when seen at the surface, and were below the surface when they passed the projectors (Fig. F-1A). The closest estimated points of approach (CEPA) of the whales for which we have reliable measurements or estimates were ~450 to 1300 m (n=4 sightings; Table F-1A). Some or all of the other three single whales may have come closer than 450 m, but the CEPAs for those three whales (sighting numbers 4, 5, 7 in Table F-1A) are subject to considerable uncertainty.

Sightings during or immediately after the playback were as follows (see Table F-1A and Fig. F-1A):

1. At 14:34, a group of two bowheads was sighted twice traveling east at medium speed at a location 840 m west (True) of the operating projectors, and ~¼ of the way across the lead. The same group surfaced again at 14:50 when it was 1.87 km ENE of its 14:34 position and 1.24 km NE of the projectors (Fig. F-1A). A total of 11 position fixes were obtained from 14:50 to 14:55 as these whales traveled east at medium speed up the lead while remaining at the surface. If they traveled on a straight line from the 14:34 to the 14:50 position, their CPA to the operating projectors was ~450 m. It is unlikely that they diverted far from the straight line, given that their

[38] By W.R. Koski, N.J. Patenaude and M.A. Smultea, with R. Elliott, G.W. Miller and W.J. Richardson.

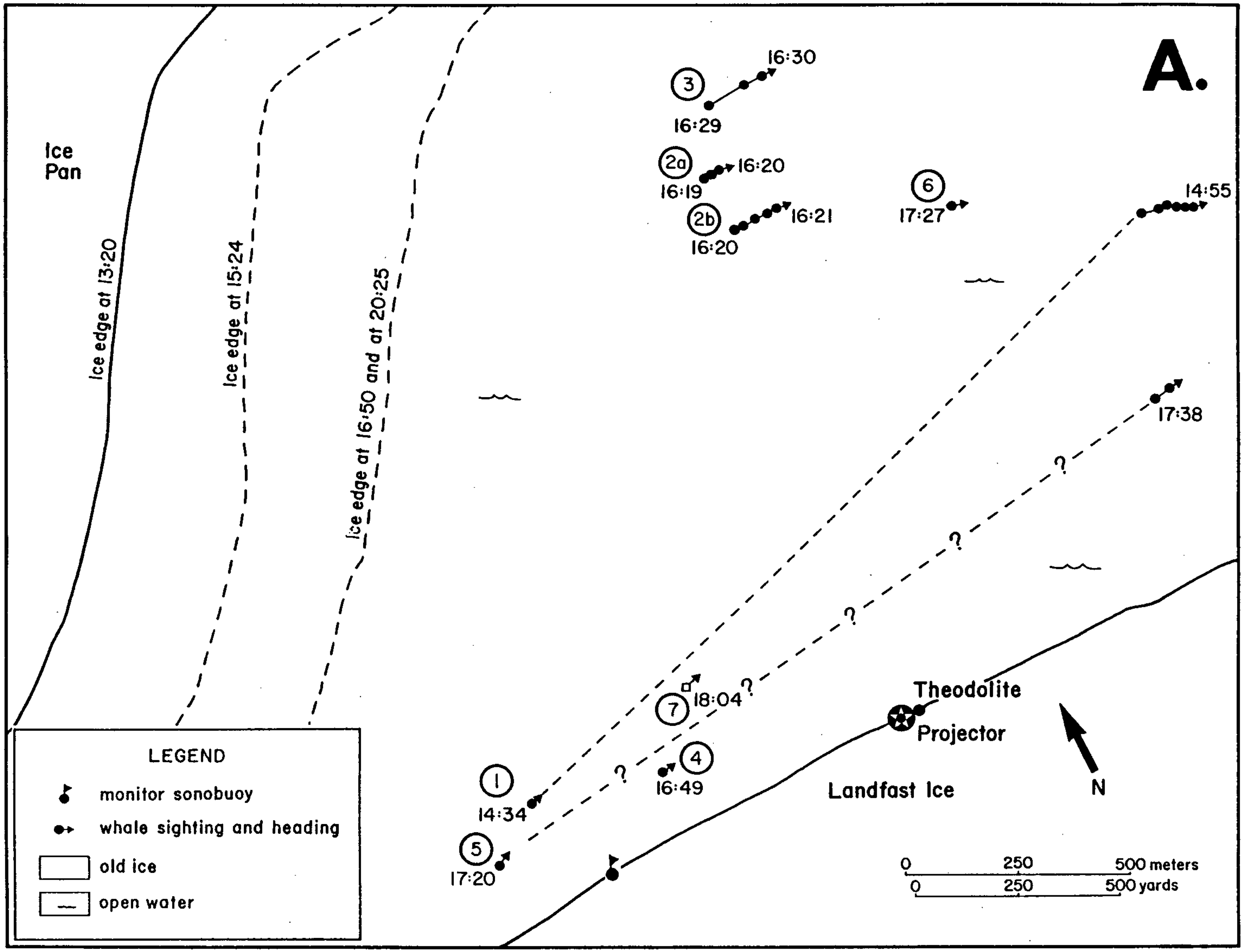


FIGURE F-1. Ice-based theodolite observations of bowhead whales that passed the ice camp along the landfast ice NE of Pt. Barrow, 17 May 1991. *(A)* Projectors broadcasting icebreaker sounds; *(B)* projectors silent. The projectors operated from 12:42 to 18:01; no bowheads were seen before 12:42. The whale seen at 18:04, 3 min after the end of the playback, is shown in *(A)* because it was exposed to icebreaker noise as it approached. Dashed lines represent presumed paths of whales while they were below the surface.

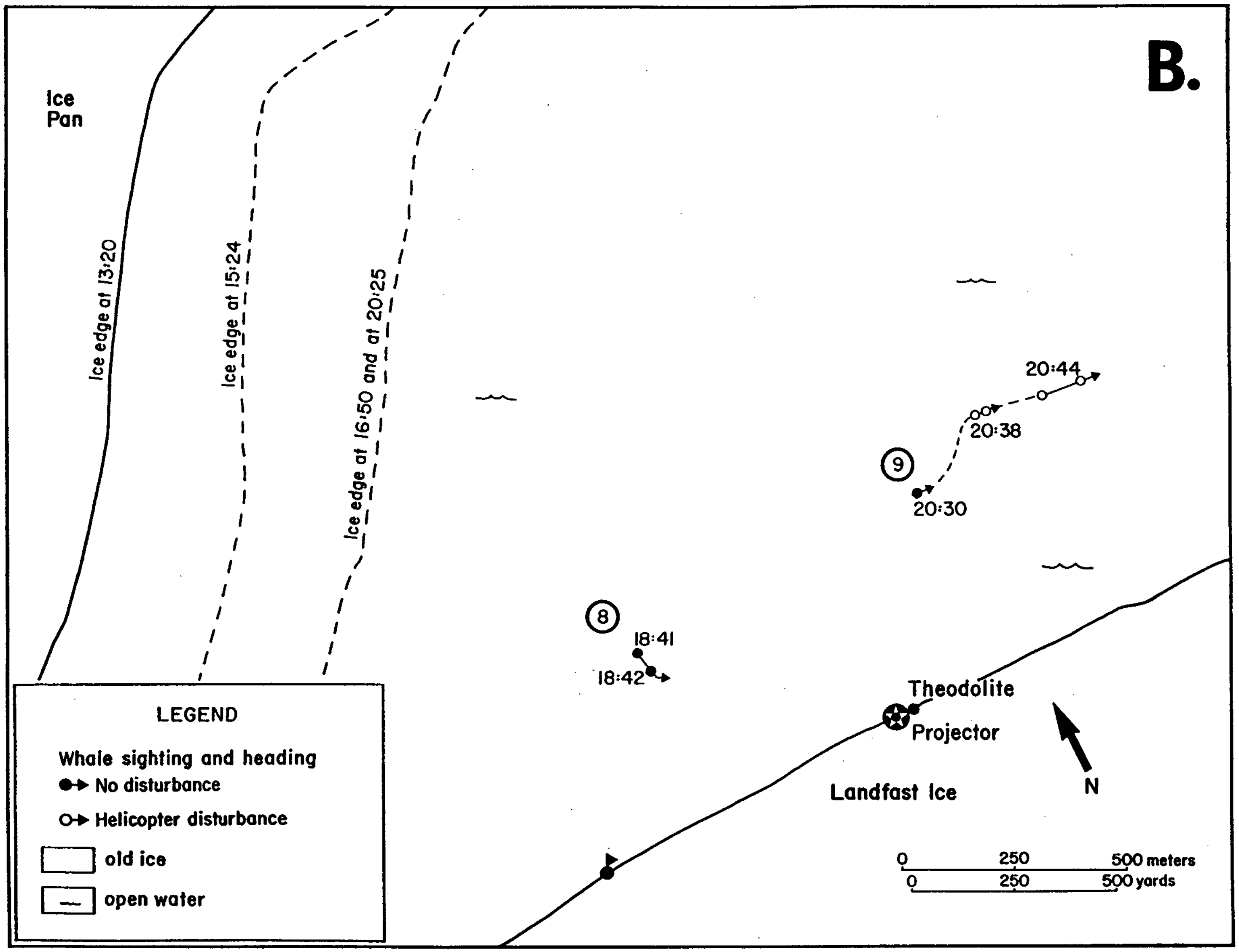


FIGURE F-1 (continued). Post-playback "control" observations, 17 May 1991.

TABLE F-1. Summary of sightings of bowhead whales seen passing the sound projector located on the landfast ice edge NE of Pt. Barrow on 17 May 1991 when the projectors were *(A)* broadcasting icebreaker sound and *(B)* silent. All observations were by the ice-based observers.

Sighting No.	Time	No. Bhds.	Closest Observed Distance (m)	CEPA		Estimated Sound Levels Near Whales (dB re 1 μPa): RL_{BB}		$RL_{1/3}$		$S:N_{BB}$		$S:N_{1/3}$		Nature of Track
				Distance	Method[a]	med	max	med	max	med	max	med	max	
A. Icebreaker Playback														
1.	14:34	2	840	~450	3	111	115	104	106	12	16	23	25	Passed operating projectors underwater; seen before and after CPA
2.	16:19	2	1100, 1250	1100, 1250	1	104 102	107 106	97 95	100 99	5 3	8 7	21 18	24 23	Seen once, at apparent CPA
3.	16:29	1	1360	1300	3	103	106	96	98	4	7	20	22	Seen once, just after apparent CPA
4.	16:49	1	540	<540	4	108	111	101	104	9	12	25	28	Seen once, approaching
5.	17:20/ 17:38	1	~1000/ 900	300?	4	103	106	98	101	4	7	21	24	Seen while approaching and after passing; same whale?
6.	17:27	1	1130	1100	3	91	94	85	86	-8	-5	9	10	Seen once, just after apparent CPA
7.	18:04	1	800	<800	4	97	100	91	92	-2	1	15	16	~800 m away and approaching at end of peak-level playback
B. Silent Projector														
8.	18:41	1	540	<540	4									Changed course, approaching
9.	20:30	1	500	~400	4									Seen after CPA

[a] 1 = measured by theodolite at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacing(s); 4 = estimate based on whale position(s) and heading(s) during sighting(s) distant from CPA position (possibly unreliable).

net speed between the two sighting locations was relatively high: 7.1 km/h (1.87 km in 0.262 h). Thus, the actual CPA distance was less than 840 m, and probably not much above 450 m.

2. At 16:19-16:21, two more eastbound bowheads were seen 1100 m and 1250 m north of the operating projectors. They were at their closest points of approach when they surfaced (Fig. F-1A). These whales were ~150 m apart and were traveling east at medium speed. We obtained three position fixes on one and five fixes on the other.

3. At 16:29, a bowhead traveling east at medium speed was seen 1360 m north of the operating projectors. It surfaced shortly after passing its apparent CPA position, ~1300 m from the projectors (Fig. F-1A). Three position fixes were obtained during a 1½-min interval.

4. At 16:49, another single whale 150 m away from the landfast ice edge was sighted as it traveled ENE at medium speed. It was 540 m west of the operating projectors when seen, but dove at that position. It would have passed within 200 m of the projectors if it did not change course, but we have no information about its actual CPA distance.

5. At 17:20, another single bowhead was seen close to the ice edge ~1 km west of the operating projectors (distance estimated). It was traveling ENE toward the projectors, swimming at medium speed. Actual CPA distance is unknown, but <1 km. A whale seen 900 m ENE of the projectors at 17:38, traveling ENE at medium speed, might have been the same one, based on distance, bearings and times (Fig. F-1A). If so, and if it swam on a straight line, its CEPA was ~300 m.

6. At 17:27, a single bowhead traveling east at medium speed was seen 1130 m NNE of the operating projectors. It was slightly past its apparent CPA position. The CPA distance would have been ~1100 m if this whale was traveling on a straight line (Fig. F-1A).

7. At 18:04, just after the end of the icebreaker noise playback, a single bowhead heading ENE at medium speed was seen 480 m WNW of the now-silent projectors. Assuming that it was swimming at 5 km/h, it would have been ~800 m WNW of the projectors at 18:00, when we started to reduce the playback level, and ~700 m away at 18:01:20 when the playback ended. Thus, this whale is treated as having a CEPA distance of <800 m relative to the projectors operating at full power.

There were two additional "control" sightings well after the end of the playback (Fig. F-1B; Table F-1B):

8. At 18:41, 40 min after the playback ended, a small bowhead—probably a calf or yearling—was first observed traveling SSE toward the landfast ice edge ~580 m NW of the projectors. It continued on this heading, toward the ice camp, until 18:43 (Fig. F-1B). It then turned to the ESE and was traveling at medium speed when last seen 540 m NW of the silent projectors.

9. At 20:30, a bowhead traveling east at medium speed was seen 500 m NE of the ice camp. It was sighted again at 20:38, 200 m ENE of its original position, and finally at 20:42. The helicopter landed at the ice camp during the interval between the last two sightings.

Noise Exposure.—Icebreaker sounds were projected into the lead by the J-13/F-40 projector system from 12:42 to 18:01. The 5th, median, and 95th percentile broadband (20-5000 Hz) source levels over the full 14-min cycle of the icebreaker sounds were 156, 161, and 167 dB re 1 μPa-m, respectively, from 12:42 to 16:49. After that time the source level was reduced by ~12 dB until the end of the session. Considering the dominant 1/3-octave band, the median source level was 155 dB re 1 μPa-m in the band centered at 80 Hz prior to 16:49, and 144 dB in the band centered at 80 Hz thereafter. Figure F-2 shows the variability in the sounds as projected (1-m source levels) and as received at 1 km range at 17:30, during the quieter period. The received level at 1 km in this figure, and the received levels in all similar figures, are estimated by the sound exposure model described in §2.3. There will be small differences between the received levels estimated by the model and those actually received at the specified distance and time. A discussion of the differences between the model and actual measured sound levels is presented in §4.3.

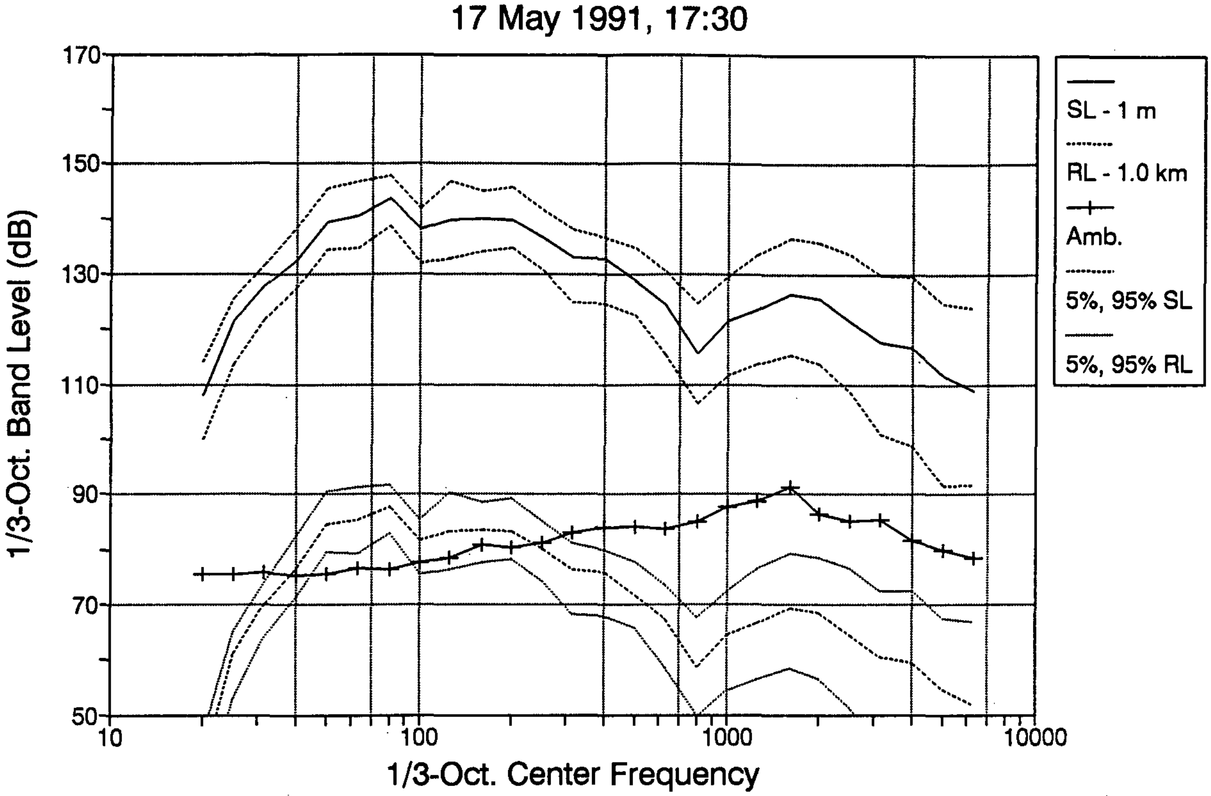


FIGURE F-2. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 17:16-17:30: variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). Plus signs show average ambient noise level after playback. ***Explanatory notes:*** *(1)* Source levels are dB re 1 µPa-m and ambient and received levels are dB re 1 µPa. *(2)* Because of projector limitations, components of the icebreaker sounds at low frequencies are underrepresented in the projector output relative to components at higher frequencies. *(3)* The tape of icebreaker sounds is repeated every 14 min. As illustrated by the 5th and 95th percentiles, the actual source or received level at any particular time can be substantially different than the median level, depending on the precise location along the 14-min loop that is being projected or received. *(4)* Source and ambient levels were measured; received levels at 1.0 km were estimated via an empirically-validated propagation model. *(5)* Received levels within a few meters of the surface will be lower than estimated here.

Ambient noise was measured at the monitor hydrophone near the projectors after icebreaker playbacks stopped. The average broadband ambient noise level was 99 dB re 1 µPa. The level in the dominant 1/3-octave band was 91 dB re 1 µPa in the band centered at 1600 Hz. Ambient noise in the 1/3-octave band centered at 80 Hz was 76 dB re 1 µPa; this band had the dominant source level of icebreaker sounds.

The projected icebreaker sounds varied in level, as shown in Figure F-2. On a 1/3-octave basis, the strongest projected sounds on 17 May 1991 were between 50 and 250 Hz (Fig. F-2). Projected levels diminished sharply with decreasing frequency in bands below 50 Hz, and diminished slowly with increasing frequency in bands above 250 Hz.

Figure F-2 also summarizes the variation in the 1/3-octave levels received 1.0 km from the projectors. The received levels fluctuated but, within the 50 to 80 Hz range, the medians were 9-10 dB above the

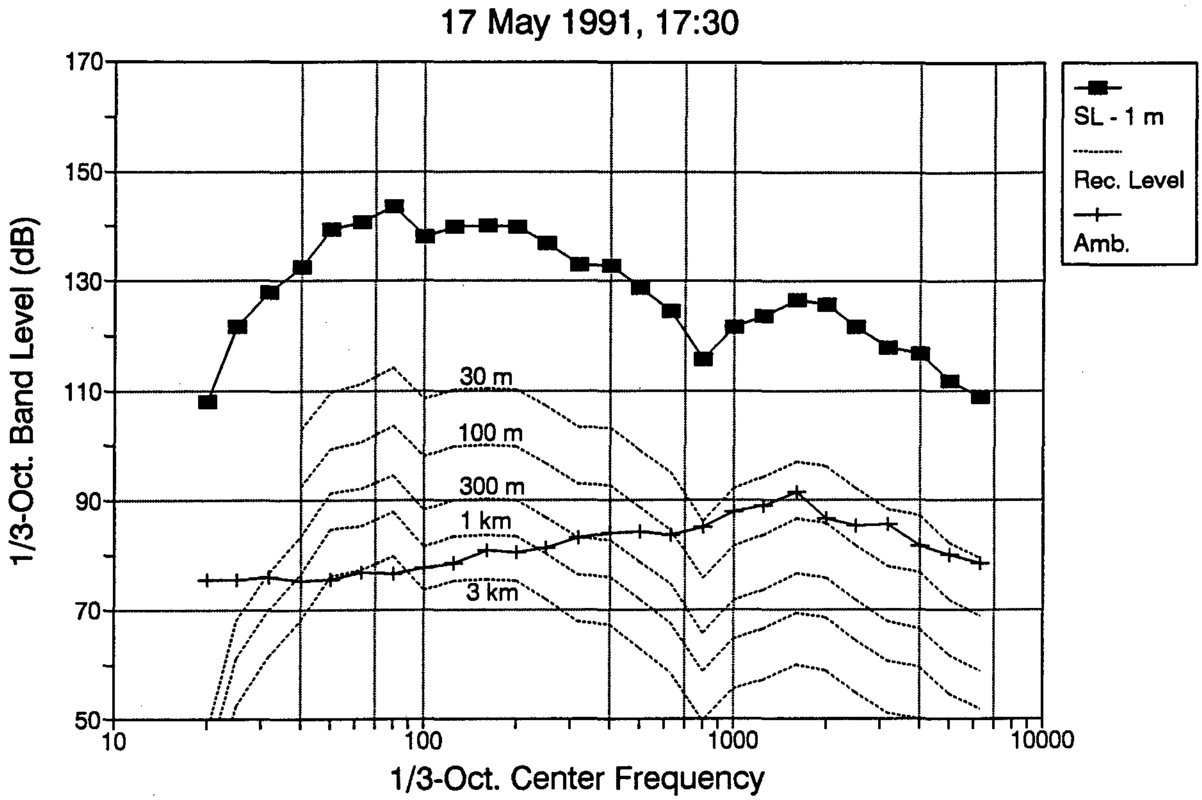


FIGURE F-3. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 17 May 1991, time 17:16-17:30: median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level after playback.

Explanatory notes: See notes to Fig. F-2. Figure F-3 shows median received levels at more ranges, but does not show 5th and 95th percentiles. Estimated received levels at 0.03 and 0.1 km assume spherical spreading; model of §2.3 was used to derive estimates for 0.3 to 3 km.

background ambient levels in the corresponding 1/3-octave bands. At some times and frequencies, the received level at range 1.0 km was 15 dB or more above the corresponding ambient noise level (Fig. F-2). At frequencies below 20 Hz and above 300 Hz, the received level of icebreaker noise was always below the ambient noise level. Figure F-3 shows the estimated median received levels at several standard distances during the period with the lower source levels.

To estimate the maximum noise level near whales passing the sound projectors, an estimate of the whales' closest point of approach to the projectors is required. Because whales are at the surface, and therefore visible to observers, only a fraction of the time, the closest observed distance often overestimates the actual closest point of approach (CPA). However, whale headings when they dive are not always a good indication of tracks that they will take or headings when they first surface are not always a good indication of tracks that they have followed to arrive at their position. In this study we calculated a ***Closest Estimated Point of Approach or CEPA*** that used all information collected for a whale to estimate its closest approach to the projectors. Calculation of the CEPA assumed that a whale sighted both as it approached and receded from the projector traveled in a straight line between consecutive sightings. The shortest distance between the assumed path and the projector was the CEPA (CEPA "A" in Fig. 6.1 on p. 254). For whales seen only as they approached or only as they receded from the projector, the CEPA was the closest observed distance from the projector (CEPAs "B" and "C" in Fig. 6.1). We did not assume a continuation of the last observed heading because some whales may have diverted after (if approaching) or before (if receding) they were sighted. Thus CEPA for a whale that was seen only as it approached or receded likely overestimates the actual closest point of approach, and therefore underestimates the maximum sound levels near that whale.

Levels of icebreaker sound received by every observed bowhead at its CEPA location were then estimated via the sound exposure model described in §2.3. This model produces many different measures of sound exposure. Those quoted in this section are estimated received levels in the 20-5000 Hz band ("broadband") or in the 1/3-octave band with highest received level ("dominant 1/3-octave band"). For both the 20-5000 Hz band and the dominant 1/3-octave, we refer to both the median and the maximum level in the 64-s period preceding the observation in question. These four estimates of received level are often abbreviated as $RL_{BB,med}$, $RL_{BB,max}$, $RL_{1/3,med}$, and $RL_{1/3,max}$. When the average ambient noise level in the corresponding band, as measured before and after the playback, is subtracted from one of these received levels, the result is the estimated icebreaker-signal to ambient-noise ratio, $S{:}N_{BB,med}$, $S{:}N_{BB,max}$, $S{:}N_{1/3,med}$, and $S{:}N_{1/3,max}$.

The closest CEPA of a traveling whale on 17 May 1991 was ~300 m (see 17:20 sighting above). By interpolation, this whale was near its CEPA to the projectors at ~17:29:30. At that time and distance the median broadband received level over a 64-s period ($RL_{BB,med}$) preceding CEPA was estimated as 103 dB re 1 µPa, and the maximum for any 8-s interval within that 64-s period ($RL_{BB,max}$) was 106 dB. The corresponding median and maximum levels in the dominant 1/3-octave band ($RL_{1/3,med}$ and $RL_{1/3,max}$) were 98 and 101 dB re 1 µPa in the band centered at 63 Hz. Thus for this closest whale at its closest point of approach, the median and maximum icebreaker noise to ambient noise ratios in the dominant 1/3-octave band ($S{:}N_{1/3med}$ and $S{:}N_{1/3max}$) were 21 and 24 dB (Fig. F-4).

Because of the variability in the source level with time and because of the change in source level at 16:49, the whales seen closest to the projectors were not the ones that were exposed to the strongest sound levels. The whale seen 540 m west of the projector at 16:49 was subjected to stronger sound levels when it dove toward the projectors. At that time and distance, the whale would have been subjected $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ of 25 and 28 dB. Because this whale was not resighted, we cannot estimate its actual CPA, but the whale probably approached closer than 540 m; thus it was probably exposed to stronger sound levels.

Summary.-On 17 May 1991, the projectors were set up along the edge of the landfast ice several kilometers northeast of Point Barrow. Spring whaling at Barrow had ended by this date, allowing work closer to Barrow than at previous times in 1989-91. All observations of whales near the projector site on 17 May 1991 were obtained by the ice-based crew because the cloud ceilings were too low for the aerial crew aboard the Twin Otter to observe bowhead behavior from an altitude of 460 m. The main nearshore lead adjacent to the landfast ice edge was several kilometers wide and largely ice-free. The crew was on the landfast ice edge from 10:46 through 20:59. Icebreaker sounds were projected into the lead from 12:42 through 18:01. The median broadband (20-5000 Hz) source level, measured over the full 14-min duration of the icebreaker playback cycle, was 161 dB re 1 µPa-m from 12:42 to 16:49; after that time the source level was reduced by ~12 dB until the end of the session. Because of variation in the source level associated with the icebreaking activities within the 14-min period of the tape, the source and received levels at certain times were 4-15 dB higher or lower than the median levels in corresponding 1/3-octave bands (Fig. F-2). Even with the reduced source level after 16:49, median levels of icebreaker sounds in the 1/3-octave band centered at 63 Hz were estimated to have exceeded ambient levels (Fig. F-3), and therefore were presumably audible to bowheads 3 km or more away from the projectors.

No bowheads were sighted from the ice during the period of pre-playback control observations. Five or six single bowheads plus two pairs were seen traveling east past the ice camp during or immediately after the icebreaker playback, i.e. a total of 9 or 10 whales in 7 or 8 groups. There were two additional "control" sightings of single bowheads well after the playback had ended.

The CEPAs of the whales for which we have reliable measurements or estimates were ~450 to 1300 m (n=4 sightings). A fifth whale seen on 17 May appears to have passed ~300 from the operating projectors; it was linked after an 18-min dive, although distinctive markings that would confirm the link were not seen

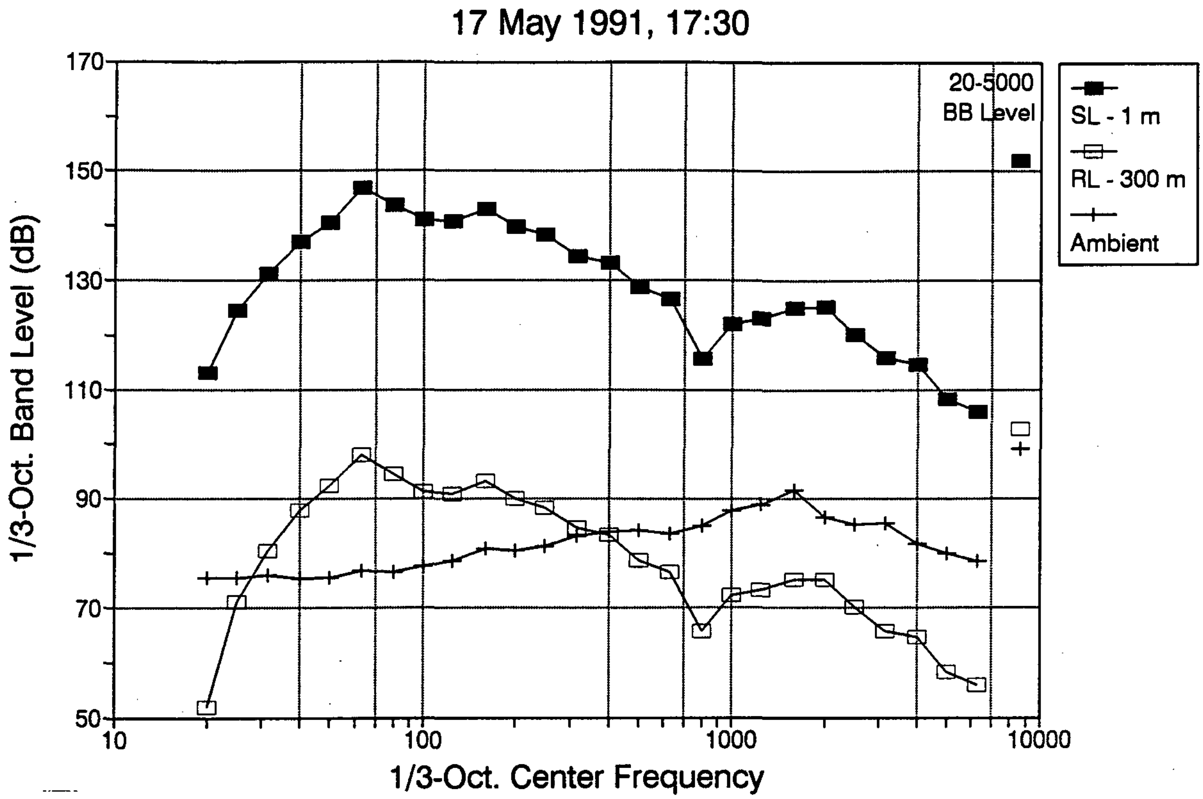


FIGURE F-4. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near a bowhead 300 m from the projector (median level over 1 min), 17 May 1991, time 17:30. Plus signs show average ambient noise level after playback.

Explanatory notes: *(1)* Source levels are dB re 1 μPa-m and ambient and received levels are dB re 1 μPa. *(2)* Because of projector limitations, components of the icebreaker sounds at low frequencies are underrepresented in the projector output relative to components at higher frequencies. *(3)* The tape of icebreaker sounds is repeated every 14 min. The 1-min values are estimated by determining the location on the loop that was projected at the selected time and summarizing the data for the preceding 1 min. *(4)* Source and ambient levels were measured; received levels at 300 m were estimated via an empirically-validated propagation model. *(5)* Received levels within a few meters of the surface will be lower than estimated here.

(Fig. 6.1). At their CEPAs, six of eight groups were exposed to icebreaker sounds 22-28 dB above the ambient noise level ($S:N_{1/3,max}$). No overt reactions to the sounds were observed by the ice-based crew.

Playbacks in 1994

7 May 1994 Playback

The ice camp and projectors were set up on the edge of the landfast ice about 45 km ENE of Pt. Barrow (Fig. 3.8, p. 77). The edge of the landfast ice was oriented NE-SW (Fig. F-5). The "nearshore" lead along the ice edge near the camp was 0.4-1.8 km wide and was constricted on the western end by a large ice pan and an outcropping of the landfast ice. This portion of the lead became congested with brash ice and pans during the latter part of the day. Aerial reconnaissance from 08:43 to 09:19 determined that a steady flow of bowhead whales were migrating NE along the main nearshore lead. Tones were projected from 14:14 to 16:03 and icebreaker sounds were projected from 16:07 to 20:01. The J-11 and one side of the Argotec 220 were operational. The source levels were adjusted on several occasions but were generally ~20 dB weaker (20-5000 Hz broadband level) before than after 18:09, when the source levels were increased. The measured water depth at the projectors was 37 m.

Ice-based Observations.—Large numbers of bowheads were migrating within view of the ice camp (<1500 m from camp) throughout the day. These whales approached from the SW and moved away to the NW. About 63 bowheads (~45 groups or singletons) were estimated to have passed the ice camp during the 13.3 h of observation. The number of sightings on this and later dates when numerous sightings were made is approximate because of uncertainties in discriminating "new" and "repeat" sightings, and because of the likelihood that some passing whales were missed. A steady stream of bowheads moved by the ice camp from 10:40 to 15:30 (Fig. F-5 to F-7). There was a lull from 15:30 to 17:27 when no whales were observed. Bowhead sightings were fewer and spaced at greater time intervals from 17:27 to 21:28 when the last bowhead was sighted (Fig. F-8, F-9). Observations ended at 23:03.

About 40 bowheads (~25 groups or singletons) were sighted during control observations (i.e., projectors silent) from 10:30 to 14:14. Most whales sighted during this control period were traveling NE or ENE at medium speed along the southern one-third of the lead (Fig. F-5, F-6). One bowhead showed no apparent reaction as the helicopter landed on the ice ~250 m away at 11:05. Another bowhead showed no apparent reaction to the helicopter engines operating at a distance of ~350 m from 11:41 to 11:43. Repeated surface activity (predominantly breaches) was exhibited by a group of 2-3 whales tracked from 13:44 to 14:05. Social and surface activity was observed among 5 groups or singletons. The closest approaches to the projectors during the control period were <76 and 110 m as measured by theodolite (Table F-2).

From 14:14 to 16:02, while the projectors were broadcasting tones, ~11 bowheads (~8 groups or singletons) were sighted by observers at the ice camp. As during the control period, most whales traveled NE or ENE at medium speed along the southern one-third of the lead and approached the projectors from the west (Fig. F-7). However, a group of two bowheads deviated from a general NE heading; the presumed path of this group was erratic from 15:04 to 15:11. At 15:11 they turned west almost directly away from the projectors; at this time they were 607 m west of the projectors. Another group of two bowheads hesitated near the ice edge before diving ESE under the landfast ice at 14:29. This sighting was the second closest by bowheads to the projectors (108 m, measured by theodolite) during playback of tones. The closest sighting was at range 77 m by a single bowhead at 14:25; the heading of this whale was eastward directly toward the projectors, indicating that its CPA was closer than 77 m.

During projection of icebreaker sounds from 16:07 to 20:01, ~8 singleton bowheads were sighted by observers at the ice camp (Fig. F-8). No whales were sighted from the ice camp until 17:27, although aerial observations (see below) indicated that some whales were approaching from the west during at least part of this time. Most bowheads observed during the playback period traveled NE or ENE at medium speed along the lead, as during preceding periods. However, sightings were farther from the projectors and more evenly distributed across the lead (Fig. F-8). The closest observed approaches to the projectors were 362 and 408 m (theodolite measurements). The CEPA of 362 m involved a bowhead first observed west of the projectors at 18:05. It was traveling fast (producing a large wake) to the north and away from the projectors. This whale also exhibited unusually long blow intervals (45 and 38 s, 3 blows). The same bowhead (presumably) was sighted again at 18:15, 700 m NW of the projectors. During the surfacing from 18:15 to 18:16 the whale turned from an initial northerly heading to the NE, apparently resuming NE movement. The projection of icebreaker sounds stopped briefly from 18:08:15 to 18:08:46, while this whale was underwater, and the source level of the icebreaker sounds was increased by ~20 dB at 18:08:46 when transmission resumed. Thereafter, the closest approach to the projectors was 578 m at 19:00 and 664 m at 18:48.

There were few sightings of bowheads by observers at the ice camp after 20:01 when the projectors stopped broadcasting icebreaker sounds. About four singletons were observed traveling ENE at medium speed in the northern two-thirds of the lead. Two of these whales were sighted <30 min after the playback ended. Observed CPAs were larger than during other periods on that date, and ranged from 763 to <1090 m

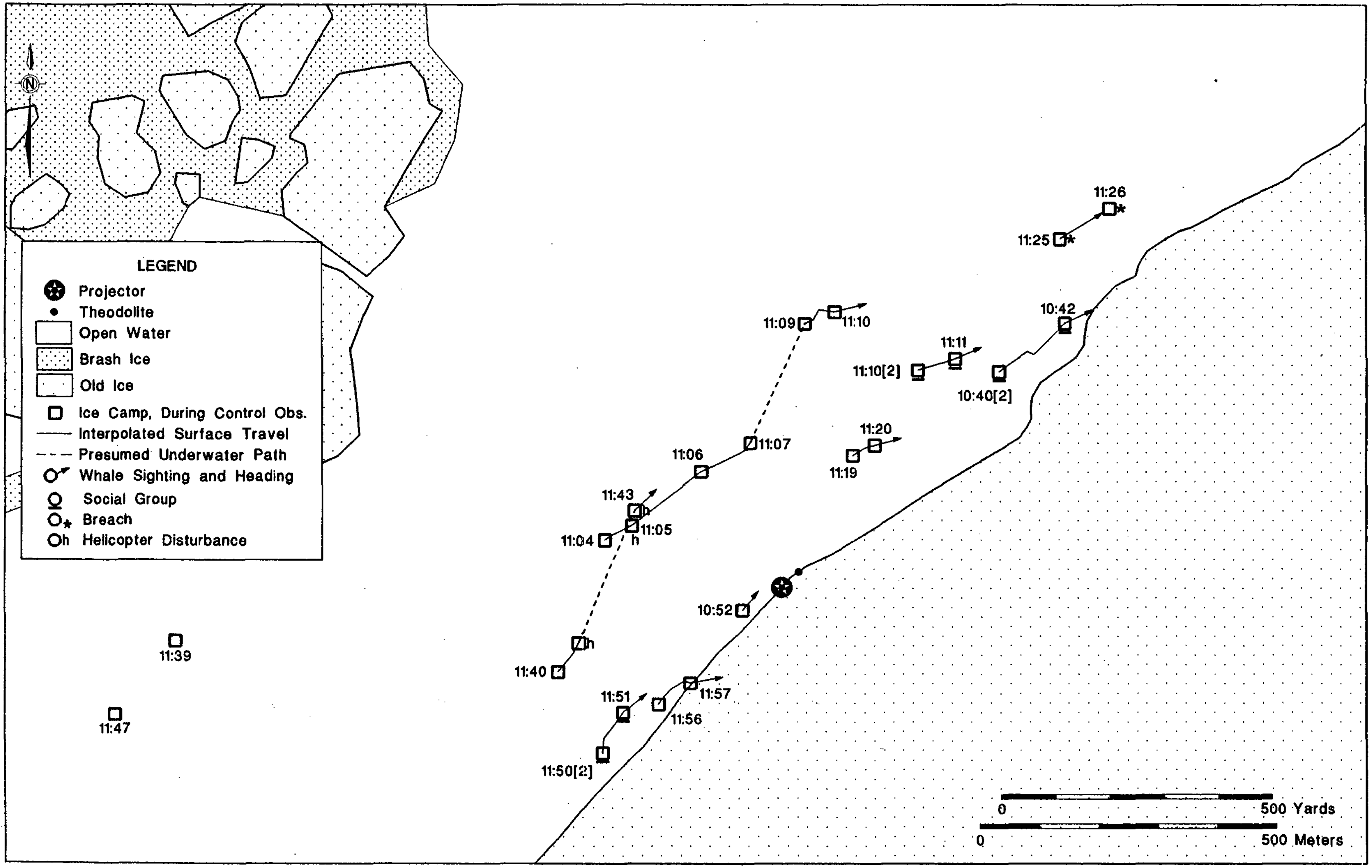


FIGURE F-5. Ice-based observations of bowhead tracks relative to the silent projectors (pre-playback) along the landfast ice NE of Pt. Barrow, 7 May 1994, times 09:42-11:57.

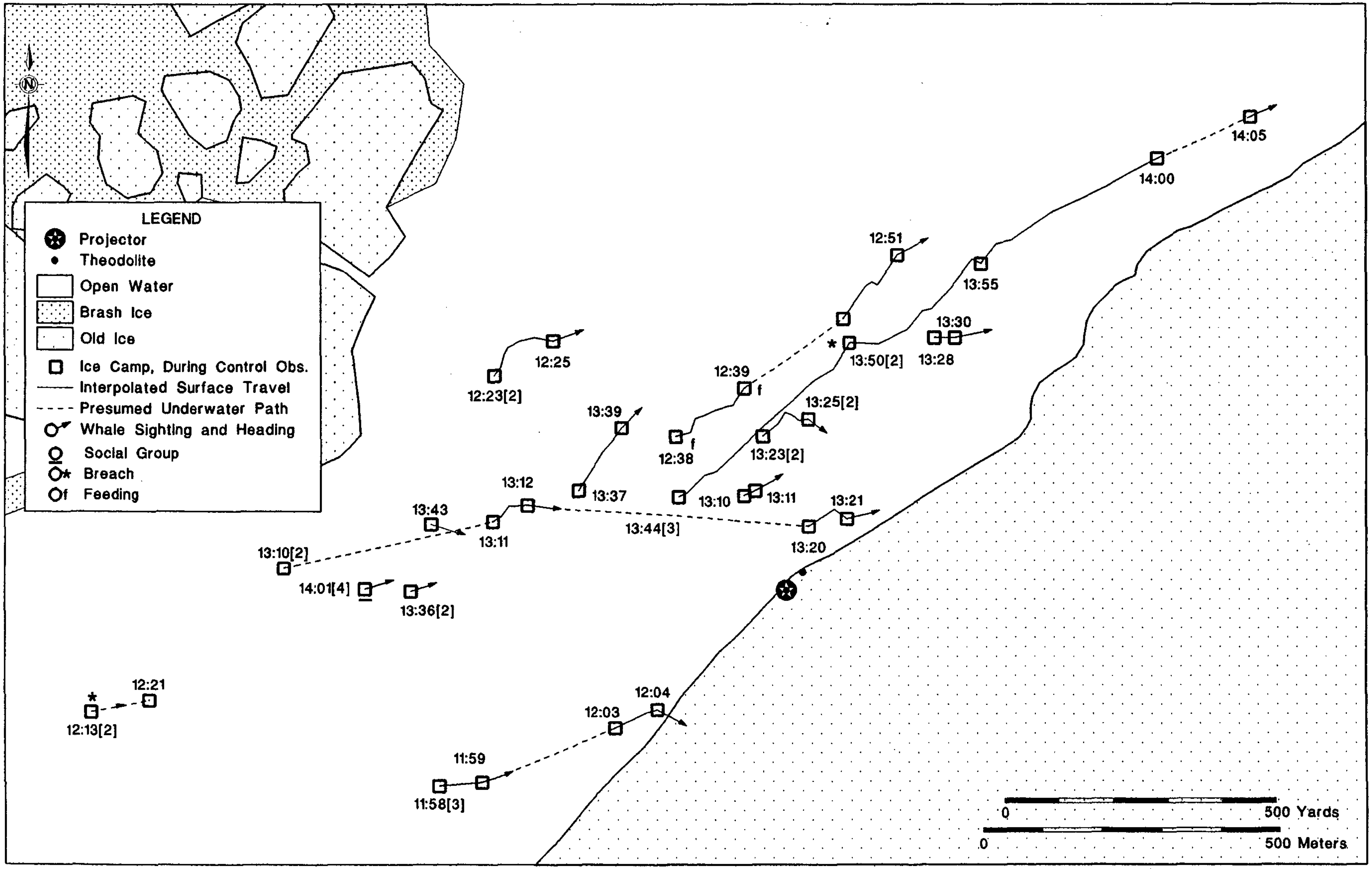


FIGURE F-6. Ice-based observations of bowhead tracks relative to the silent projectors (pre-playback) along the landfast ice NE of Pt. Barrow, 7 May 1994, times 11:58-14:13.

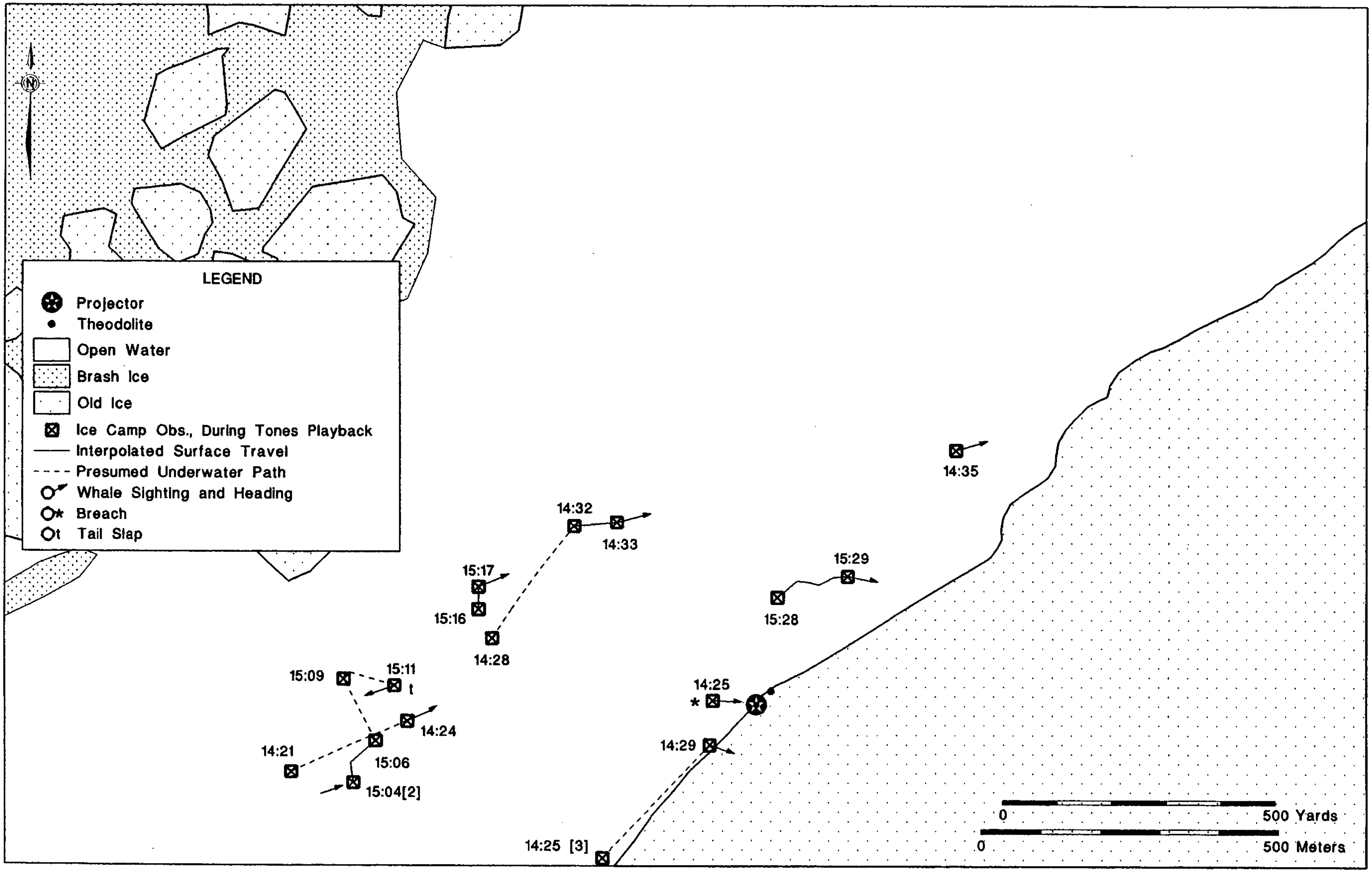


FIGURE F-7. Ice-based observations of bowhead tracks relative to the sound projectors broadcasting tones along the landfast ice NE of Pt. Barrow, 7 May 1994, times 14:14-16:05. Tones were projected from 14:14 to 16:02.

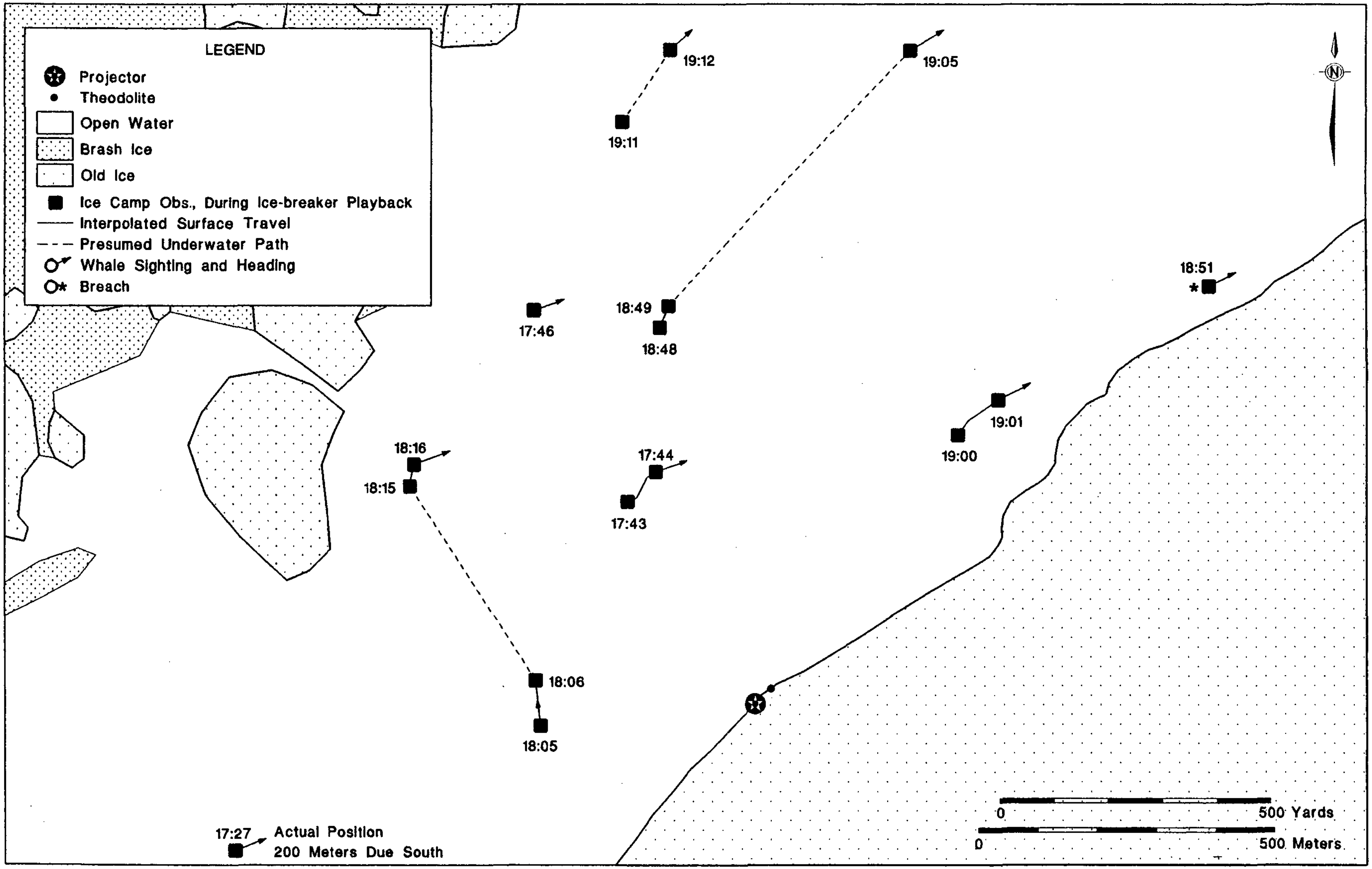


FIGURE F-8. Ice-based observations of bowhead tracks relative to the sound projectors broadcasting icebreaker sounds along the landfast ice NE of Pt. Barrow, 7 May 1994, times 16:06-20:01.

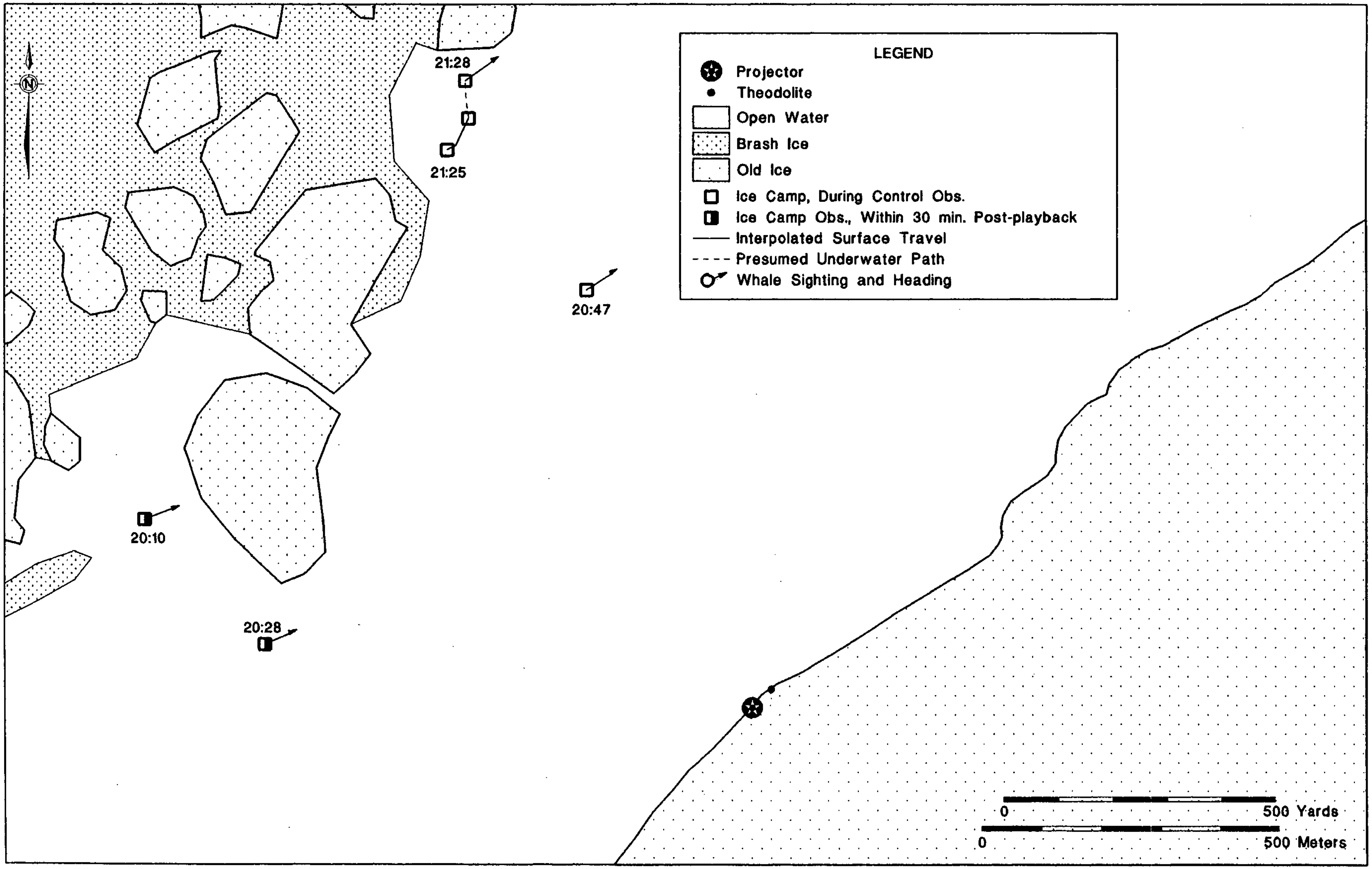


FIGURE F-9. Ice-based observations of bowhead tracks relative to the silent projectors (after icebreaker playback) along the landfast ice NE of Pt. Barrow, 7 May 1994, times 20:02-23:03.

TABLE F-2. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 7 May 1994.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S:N_{BB}$ med	$S:N_{BB}$ max	$S:N_{1/3}$ med	$S:N_{1/3}$ max	Nature of Track
A: Pre-Playback Control (09:42 to 14:13)															
10:40	2	+520 to +661	<520	10:39:48	1	IC									NE of projector heading ENE
10:49	1	single sighting	800	10:49:00	2	IC									Position and heading unknown
10:52	1	single sighting	<76	10:52:21	1	IC									SW of projector heading NE ~20 m from ice edge
11:04	1	-310 to +476	240	11:06:11	1	IC									WNW to NNE of projector heading ENE, heli. landed at camp at 11:05 (heli. disturb.)
11:10	2	+439 to +493	<439	11:10:16	1	IC									NE of projector heading ENE, 5 min. after heli. overflight
11:19	1	+261 to +290	<261	11:19:18	1	IC									NNE of projector heading ENE, 14 min after heli. overflight and 3 min before second overflight
11:25	1	+767 to +868	<767	11:24:54	1	IC									NE of projector heading NE, breached twice
11:39	1	single sighting	<1035	11:39:24	1	IC									WSW of projector, heading unknown
11:47	1	single sighting	<1159	11:47:20	1	IC									WSW of projector, heading unknown
11:40	1	-409 to -282	282	11:43:10	1	IC									SW to WNW of projector heading NE; heli. landed at camp at 11:41: no apparent reaction by whale
11:50	2	-416 to -346	<346	11:50:53	1	IC									SW of projector heading NE then ENE along ice edge
11:56	1	-299 to -226	<226	11:57:13	1	IC									SW of projector heading NE about 10 m from ice edge; dove E under ice edge, 14 min. after heli. overflight
11:58	3	-667 to -303	<303	12:03:55	1	IC									SW of projector heading ENE then dove ESE under ice edge
12:17	1	single sighting	<2000	12:17:53	2	A									W of projector heading ENE along brash ice
12:13	2	-1200 to -1100	<1100	12:20:45	1	IC									WSW of projector, heading unknown, breached
12:24	3	single sighting	<2500	12:23:51	2	A									WSW of projector heading ENE
12:23	5	single sighting	<2400	12:24:36	2	A									WSW of projector heading ENE
12:23	2	-617 to -583	583	12:25:05	1	IC									NW of projector heading NE
12:27	1	single sighting	<2500	12:27:19	2	A									WSW of projector heading NE
12:19	1	-1200 to +1000	615	12:31:00	4	A									W of projector heading NE
12:36	2	single sighting	<830	12:36:13	2	A									NNE of projector heading NE
12:38	1	single sighting	<1100	12:37:45	2	A									E of projector heading NE
12:38	1	-316 to +603	306	12:38:00	1	IC									NW to NNE of projector heading NE, flipper slaps
12:48	1	single sighting	<800	12:48:15	2	A									NE of projector heading NE along the ice edge
12:50	4	single sighting	<250	12:50:07	2	A									N of projector heading NE, social activity
13:10	1	-177 to -178	177	13:10:11	1	IC									NNW of projector heading ENE
13:10	2	-847 to +159	110	13:19:38	1	IC									W to NE of projector heading E

TABLE F-2. Continued.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S:N_{BB}$ med	$S:N_{BB}$ max	$S:N_{1/3}$ med	$S:N_{1/3}$ max	Nature of Track
13:23	2	-262 to +289	<262	13:22:59	1	IC									NNW to NNE of projector heading NNE then ESE
13:28	1	+498 to +516	<498	13:28:23	1	IC									NE of projector heading E
13:36	2	single sighting	<631	13:36:15	1	IC									W of projector heading ENE
13:43	1	single sighting	<613	13:43:08	1	IC									W of projector heading ESE
13:37	1	-395 to -390	385	13:38:00	1	IC									NW of projector heading NE
13:44	3	-240 to +1130	235	13:44:01	1	IC									NW to NE of projector heading ENE. Separated at 13:48 to a single and pair. Socialize and breach
14:01	4	-723 to -713	<713	14:02:20	1	IC									W of projector, socializing & tailslap, overall heading ENE
B: Playback of Tones (14:14 - 16:02)															
14:21	1	-795 to -587	<587	14:24:12	1	IC				Not Available					W of projector heading ENE
14:25	1	single sighting	<77	14:25:15	1	IC				Not Available					W of projector heading E, breached
14:25	3	-371 to -108	108	14:29:29	1	IC				Not Available					SW of projector heading NE along ice edge; hesitated at 14:29, 108 m from projector; dove ESE under ice edge
14:28	1	-463 to -392	392	14:32:41	1	IC				Not Available					W to NW of projector heading ENE
14:35	1	single sighting	<560	14:34:59	1	IC				Not Available					NE of projector heading ENE
15:04	2	-690 to -607	607	15:10:41	1	IC				Not Available					W of projector, reversed course ; heading ENE to NNW to ESE to W; tailslap 607 m from projector
15:16	1	-499 to -508	<499	15:15:42	1	IC				Not Available					NW of projector heading ENE
15:28	1	+185 to +275	<185	15:27:32	1	IC				Not Available					NE of projector heading E
C: Icebreaker Playback (16:07 - 20:01)															
16:52	1	single sighting	<2200	16:52:26	2	A	86	89	79	80	-9	-6	-3	-2	W of projector heading ENE
16:59	1	single sighting	<2400	16:58:57	2	A	82	86	74	77	-13	-9	-7	-4	WSW of projector heading ENE
17:01	1	single sighting	<2400	17:01:11	2	A	80	86	74	78	-15	-10	-7	-3	WSW of projector heading ENE
17:21	1	single sighting	<2100	17:21:15	2	A	87	89	80	81	-8	-6	-4	-2	W of projector heading ENE
17:27	1	single sighting	<1030	17:26:56	1	IC	89	92	82	83	-6	-3	1	2	SW of projector heading ENE
17:43	1	-408 to -432	408	17:42:45	1	IC	101	104	94	96	6	9	16	18	NW of projector heading ENE
17:46	1	single sighting	773	17:46:05	1	IC	95	100	88	93	0	4	8	12	NW of projector heading ENE
18:05	1	-362 to -706	362	18:04:56	1	IC	102	104	95	96	7	9	12	13	W then NW of projector; heading N fast away from projector at 362 m; headed ENE at next surfacing; long blow intervals
18:48	1	-664 to +1153	<664	18:48:14	1	IC	116	119	110	113	21	24	29	32	NNW then NNE of projector heading NE

TABLE F-2. Continued.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S:N_{BB}$ med	$S:N_{BB}$ max	$S:N_{1/3}$ med	$S:N_{1/3}$ max	Nature of Track
18:51	1	single sighting	<1052	18:50:45	1	IC	*110*	*116*	*105*	*111*	*15*	*21*	*24*	*29*	NE of projector heading ENE along ice edge, surface active including breach
19:00	1	+578 to +664	<578	18:59:32	1	IC	114	117	109	113	18	22	27	32	NE of projector heading ENE
19:11	1	-1023 to -1131	<1023	19:11:00	1	IC	112	116	104	109	17	21	20	26	NNW of projector heading NE
D: < 30 min After Playback (20:01 - 20:31)															
20:10	1	single sighting	<1081	20:10:11	1	IC									WNW of projector heading ENE
20:28	1	single sighting	<834	20:27:34	1	IC									WNW of projector heading ENE
E: Post Playback Control (>20:31)															
20:47	1	single sighting	763	20:47:08	1	IC									NNW of projector heading ENE
21:25	1	-1080 to -1090	<1080	21:25:02	1	IC									NNW of projector heading NE

Estimated Sound Levels Near Whales[d]

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] Data in italics are not included in analyses of traveling whales because this whale was engaged in aerial activities.

[e] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

(measured by theodolite). However, one approaching whale sighted at 20:28 may have passed ~500 m from the projectors if it maintained its heading while underwater (Fig. F-9).

Aerial Observations.—Three behavioral observation sessions were conducted in the main nearshore lead SW, NE and W of camp on 7 May 1994. The first session was conducted from 09:20 to 10:38 ~7 km east of the ice camp location prior to the camp being set up. About 10 bowheads were observed as they traveled ENE at slow to medium speed. During the second session we followed 15 bowheads from 5 km SW to 6 km NE of the ice camp. Observations extended from 11:03 to 13:09, again with silent projectors. Whales observed during this period (15+ individuals) were actively socializing and/or traveling NE or ENE at slow to medium speed (Fig. F-10, F-11). Only one group was observed passing close to the ice camp (CEPA <250 m) at 12:50; it was a group of four socializing whales. Whales SW of camp traveled through a constriction created by a large ice pan and generally traveled in the center of the lead. Whales observed NE of camp were traveling along the landfast ice, maintaining the same general NE heading.

The third behavioral observation session near the camp was from 16:14 to 17:41 while icebreaker sounds were projected into the lead at a low source level. Observations were fragmentary and intermittent due to rapid incursion of low cloud and an uneven stream of whales. The western end of the lead became congested with brash ice and pans and was reduced to a small lead (100-200 × 1000 m); ~15 whales were observed traveling ENE at slow to medium speed. Several whales where observed traveling in heavy brash ice NW of the ice camp. A few whales (3-5 individuals) were observed traveling generally north in a small secondary lead oriented N-S about 3.2 km WNW of camp (Fig. F-12). No whales were seen in that area or with northerly headings during earlier aerial observation sessions on this date. Icebreaker sounds probably were not audible or barely audible at this distance and time, although some of these whales might have detected the sounds earlier when they may have been slightly closer to the projectors (see below).

The closest observed point of approach during this aerial observation session was 2.1 km. Bowheads were observed heading toward the projectors at that distance. Many of these whales would have passed the ice camp between 17:00 and 18:30 at distances <1 km if they had maintained their general headings and speeds (Fig. F-12). Few, if any, of these whales were seen by the ice-based crew (*cf.* Fig. F-8). Thus, it appears that on 7 May some whales were altering their tracks to avoid the projectors by >1 km. Some whales may have altered their paths at greater distances, given the observation at 16:43 of northbound whales in the small lead through pack ice.

Noise Exposure.—Icebreaker sounds were transmitted from 16:07 to 20:01 on 7 May 1994. The J-11 and one side of the Argotec 220 were operational. From 16:07 to 18:08 the median 14-min broadband (20-5000 Hz) source level was 146 dB re 1 μPa-m and from 18:09 to 20:01 it was 166 dB re 1 μPa-m. The corresponding median source level in the dominant 1/3-octave band was 139 dB re 1 μPa-m in the band centered at 80 Hz up to 18:08, and 159 dB re 1 μPa-m near 80 Hz thereafter. Figure F-13 shows the variability in the sounds as projected (1-m source levels) and as received at 1 km range during the two time periods. Figure F-14 shows the estimated median received levels at several standard distances for the two periods with different source levels.

On 7 May at 11:26 a 57A sonobuoy was deployed manually 1.77 km SW of the ice camp along the landfast ice. A 53B sonobuoy was air-dropped into the main near-shore lead 2.9 km SW of the projectors at 16:34. Ambient noise was measured with a hydrophone at the ice camp before and after projection of the icebreaker sounds. The average broadband (20-5000 Hz) ambient noise level was 95 dB re 1 μPa, and the ambient noise level in the strongest 1/3-octave was 86 dB re 1 μPa in the band centered at 200 Hz (pluses in Fig. F-13 to F-15). Ambient noise in the 1/3-octave band centered at 80 Hz was 82 dB re 1 μPa; this band had the dominant source level of icebreaker sounds.

The closest observed bowhead with respect to the operating projectors on 7 May was a whale seen 362 m from the projectors at 18:05. It was moving north, away from the projectors (Fig. F-8). At this time and horizontal distance, the median and maximum broadband received levels ($RL_{BB,med}$ and $RL_{BB,max}$) below the surface during the preceding 64 s were estimated to be 102 and 104 dB re 1 μPa. The median and

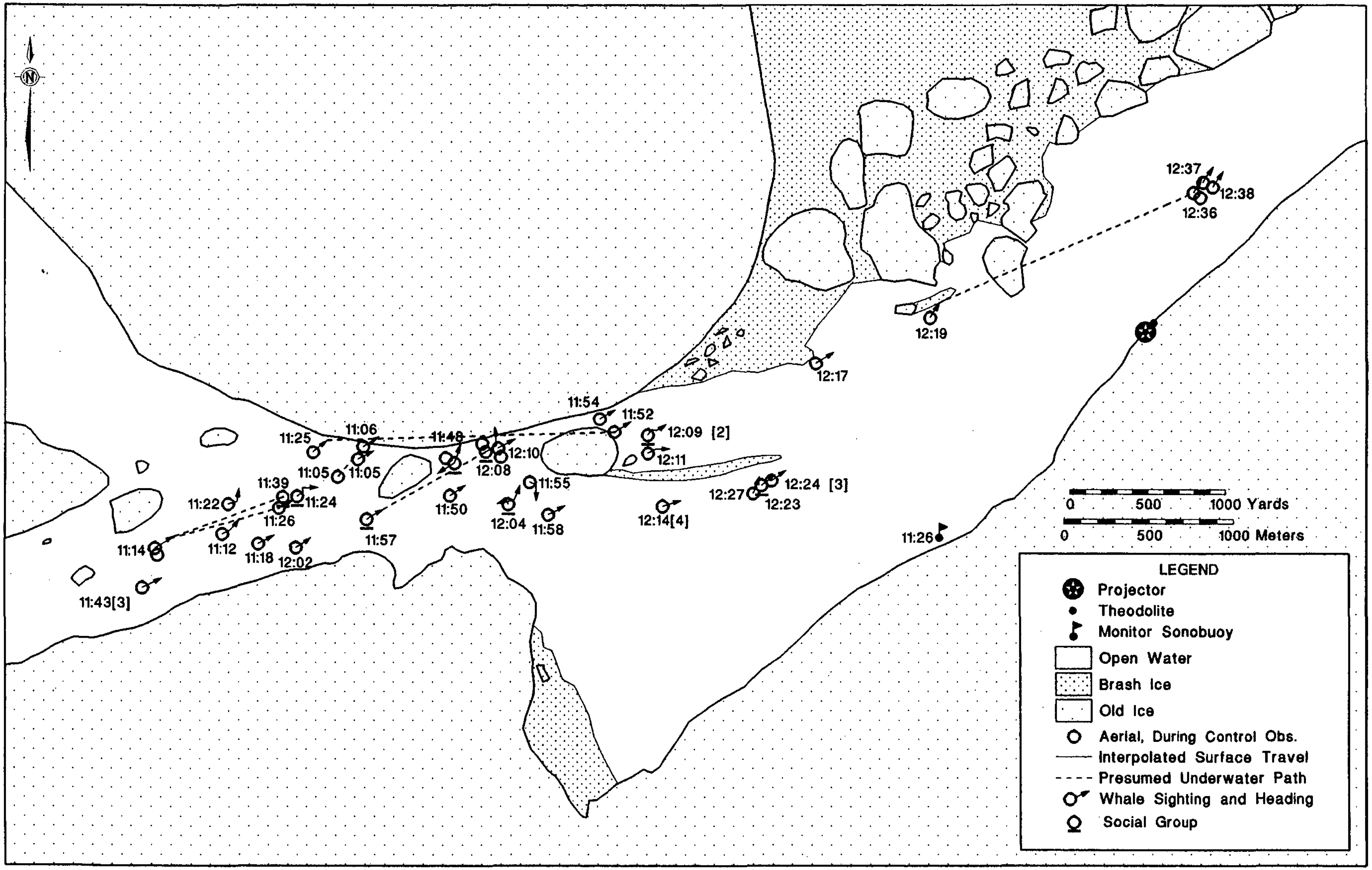


FIGURE F-10. Aerial observations of bowhead tracks relative to the silent projectors (pre-playback) along the landfast ice NE of Pt. Barrow, 7 May 1994, times 11:03-12:39.

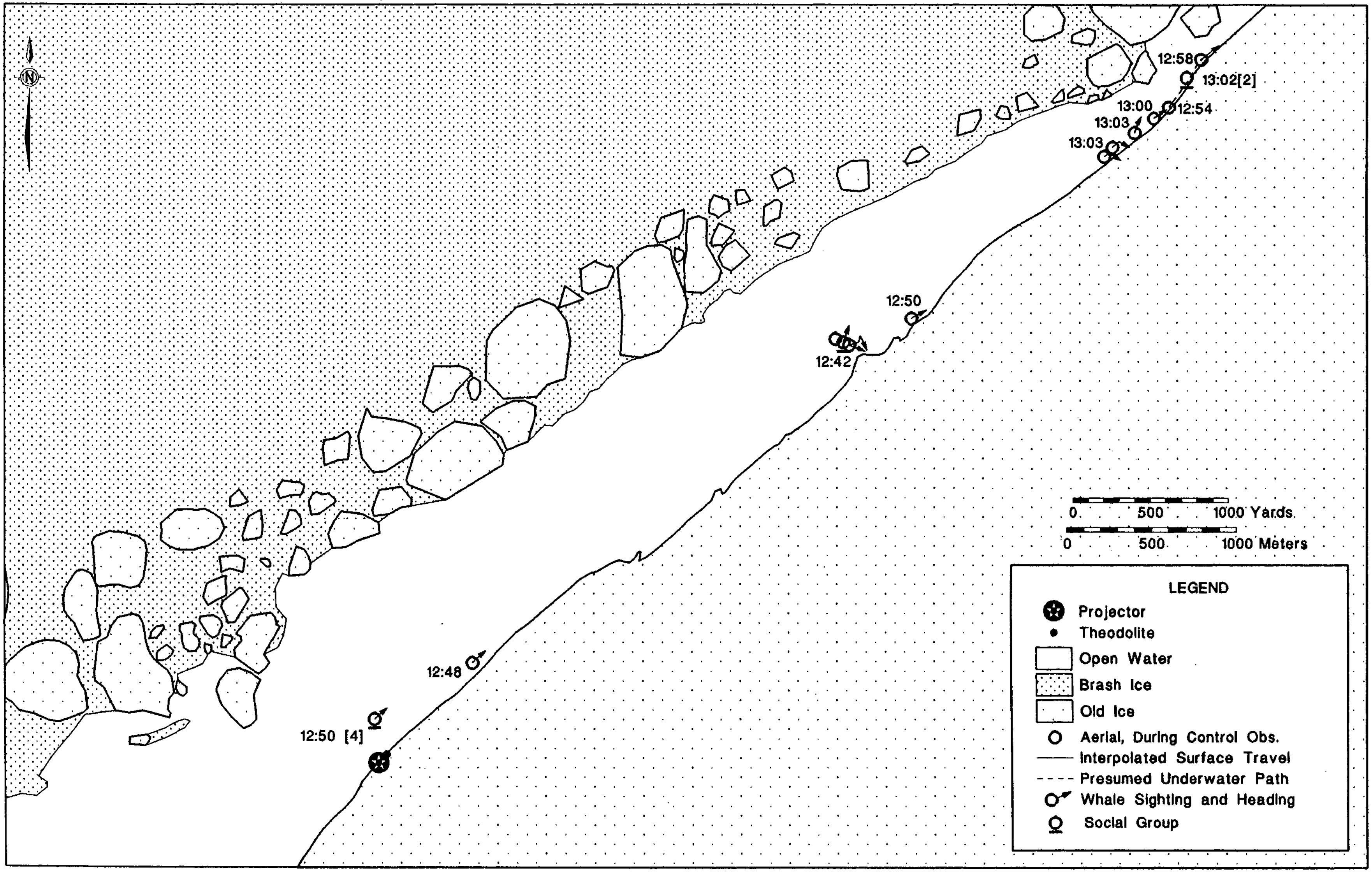


FIGURE F-11. Aerial observations of bowhead tracks relative to the silent projectors (pre-playback) along the landfast ice NE of Pt. Barrow, 7 May 1994, times 12:40-13:09.

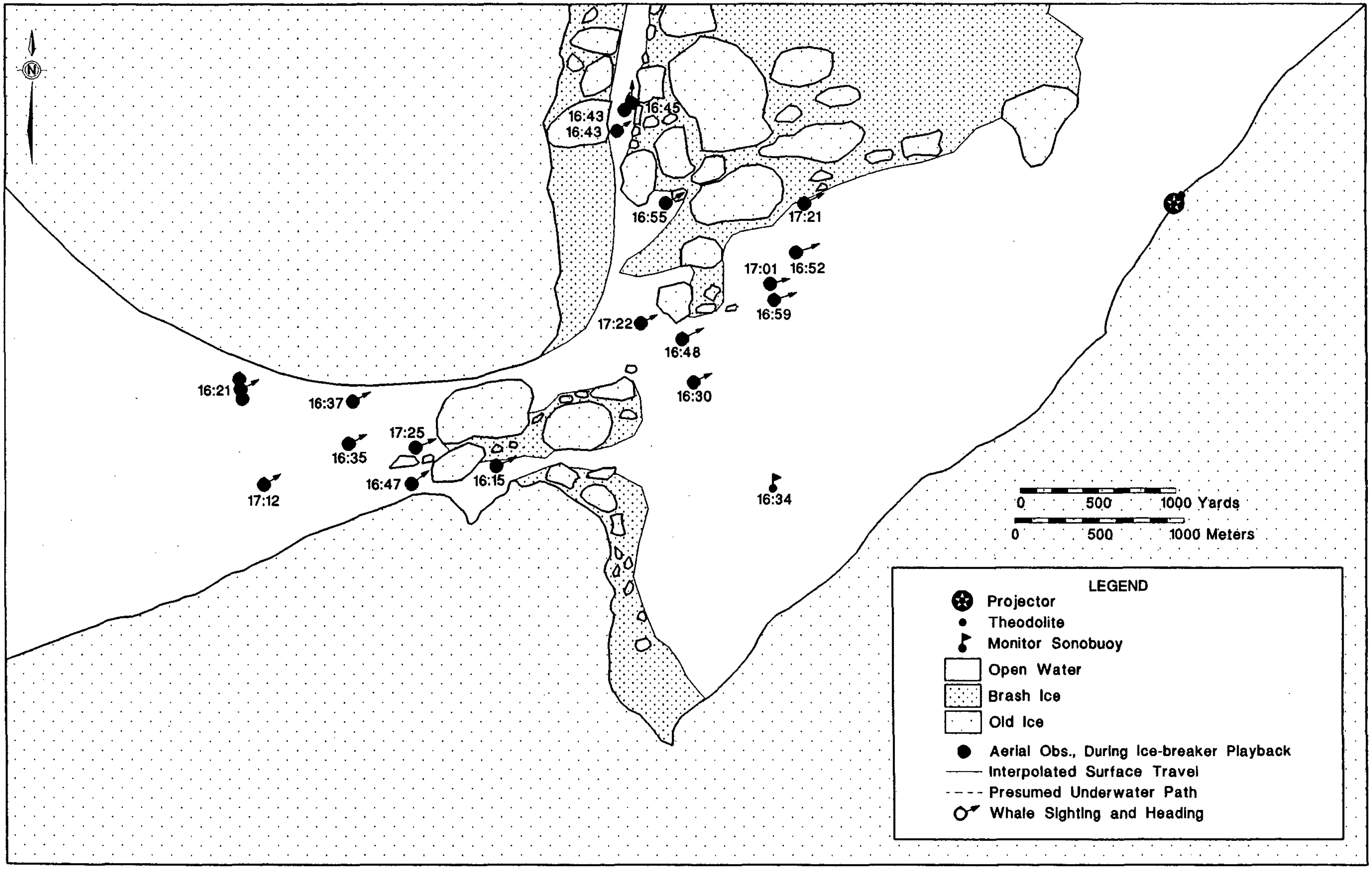


FIGURE F-12. Aerial observations of bowheads relative to the sound projectors broadcasting icebreaker sounds along the landfast ice NE of Pt. Barrow, 7 May 1994, times 16:14-17:41. Observations of each whale were brief and fragmentary due to buildup of low cloud below the aircraft.

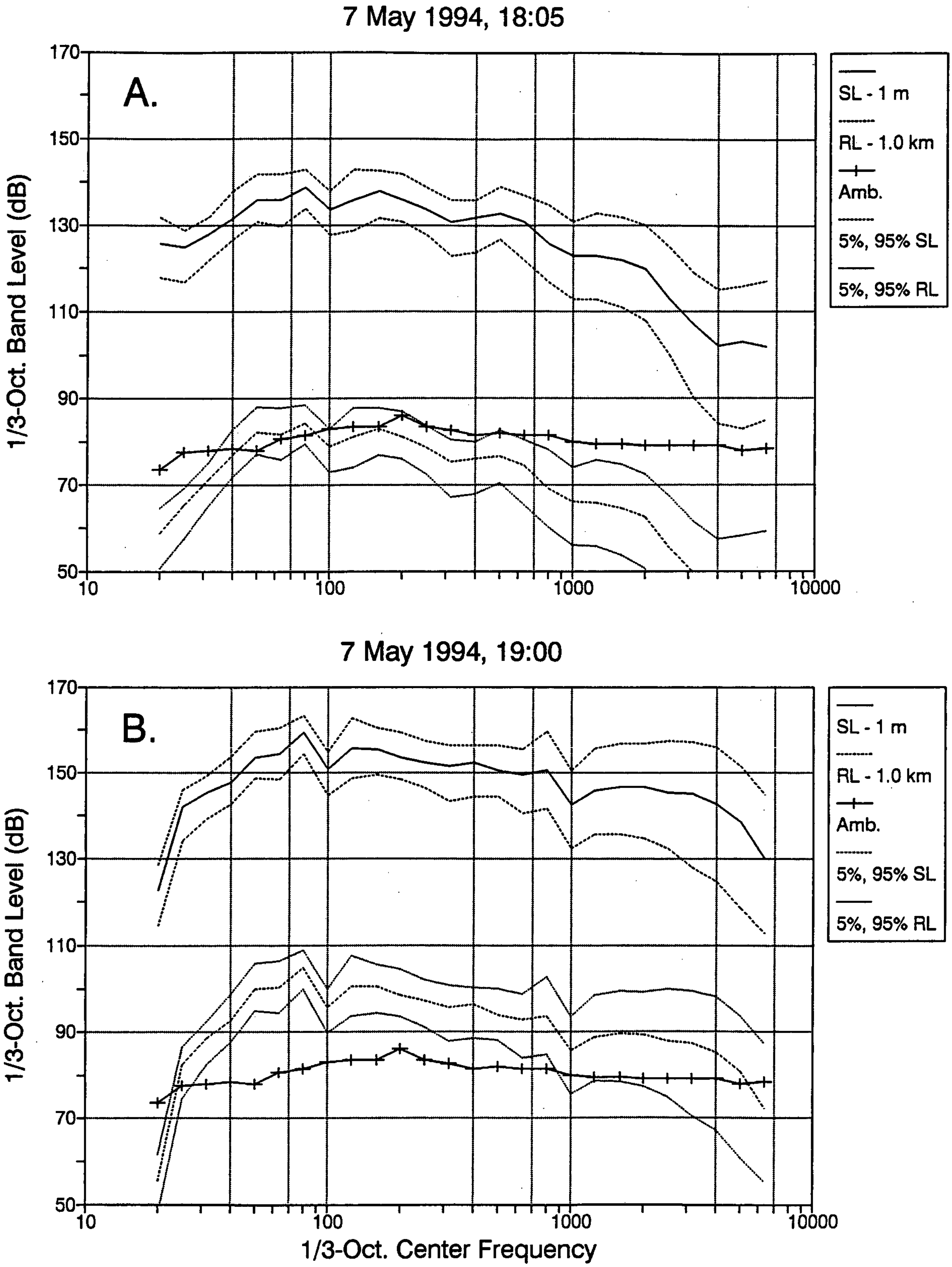


FIGURE F-13. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 7 May 1994: variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(A)* Time 17:51-18:05. *(B)* Time 18:46-19:00. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-2.

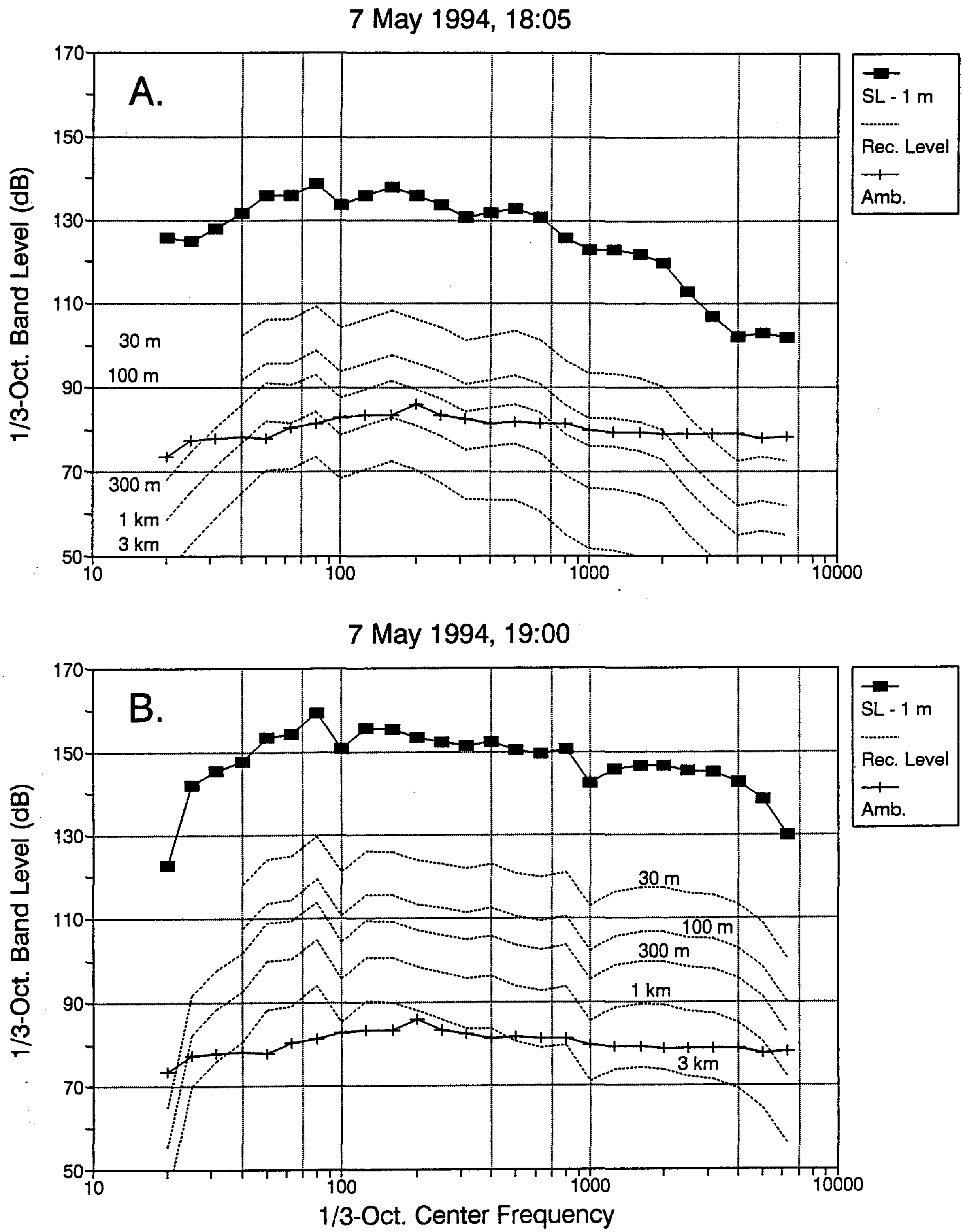


FIGURE F-14. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 7 May 1994: median levels at range 1 m (squares) and 30 m-3.0 km. *(A)* Time 17:51-18:05. *(B)* Time 18:46-19:00. Plus signs show average ambient noise level before and after playback. For additional explanation, see captions to Fig. F-2 and F-3.

maximum levels in the strongest 1/3-octave band ($RL_{1/3,med}$ and $RL_{1/3,max}$) were 95 and 96 dB re 1 µPa in the band centered at 160 Hz, with similar levels near 50 Hz (Fig. F-15). $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were 12 and 13 dB. Because the ambient noise level was lower at 50 than at 160 Hz, S:N near 50 Hz was higher: 16 dB for the median level over the 64-s period, and 18 dB for the maximum. This whale was at the surface at 18:05 and thus, at that specific time, was receiving lower sound levels than shown in Figure F-15 because of pressure release effects near the surface. The track of the whale suggests that it must have turned northward when it was below the surface previous to its 18:05 surfacing, at a distance similar to or perhaps slightly greater than its range at 18:05 (362 m). Thus, the whale apparently reacted to sound levels similar to or slightly lower than those estimated above.

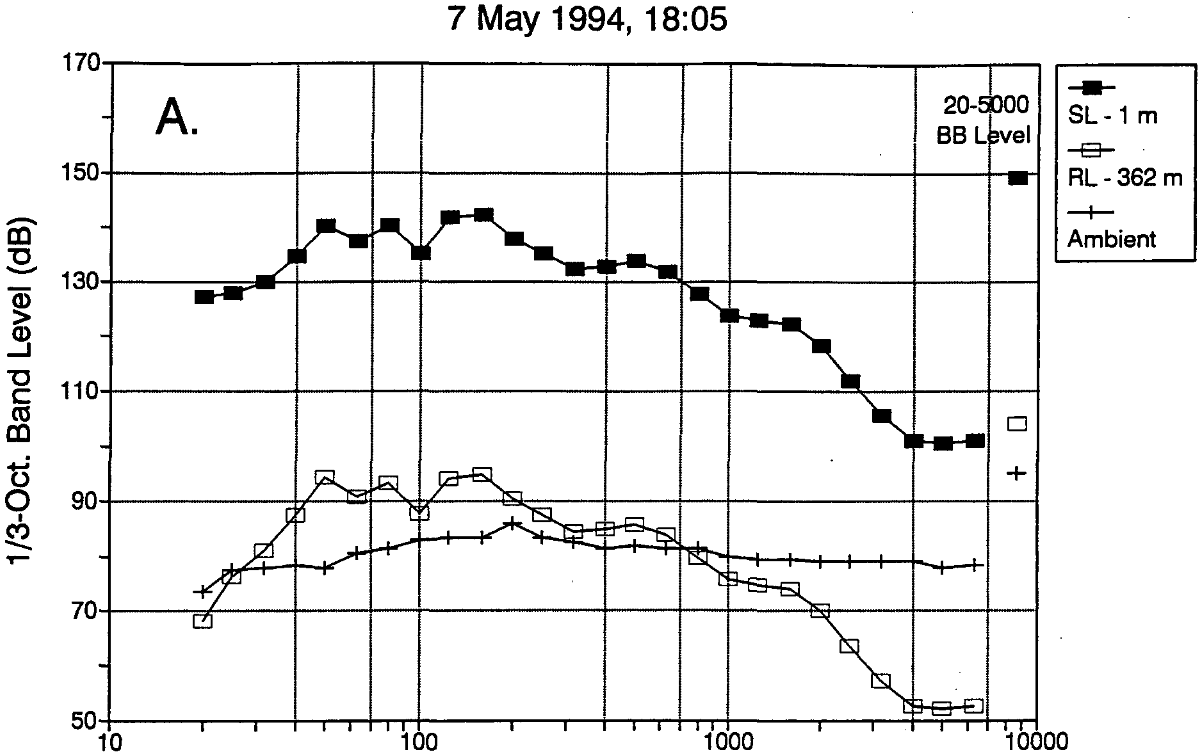
This same whale would have been subjected to sound levels that were considerably higher when the projectors were restarted at 18:09 at a higher source level. By interpolation between its positions at 18:05 and 18:15, the whale would have been ~500 m from the projectors and underwater at 18:09 when the stronger icebreaker noises were first projected. Because of the discontinuity in the projected signal, we are not able to estimate the received levels at that time. However, they would have been higher than the levels at 18:05; during its dive the whale may have been exposed to levels as high as those received by the whale described below at 19:00 (578 m from the projectors). When the whale surfaced at 18:15 it was still heading generally north away from the projectors; during its surfacing at 18:15-18:16 it turned toward the east.

The closest observation of a bowhead that approached or passed the projectors while they were projecting the strong icebreaker sounds was at 19:00. This whale was seen 578 m NE of the projectors and heading away. It is very likely that the whale passed the projectors at a considerably closer distance while underwater. In the 64-s period preceding the 19:00 surfacing, $RL_{BB,med}$ and $RL_{BB,max}$ 578 m from the projectors were estimated to be 114 and 117 dB re 1 µPa. $RL_{1/3,med}$ and $RL_{1/3,max}$ were 109 and 113 dB re 1 µPa in the band centered at 80 Hz. Thus, prior to surfacing, this whale that had just passed the projectors had been exposed to $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ of at least 27 and 32 dB in the strongest 1/3-octave band (Fig. F-15).

Several bowheads were seen traveling north or northeast in a thin lead more than 3 km WNW of the projectors from 16:43 to 16:55 (Fig. F-12). None were seen moving north or amidst the pack ice before icebreaker playbacks started. At that distance and time, the estimated $RL_{1/3,med}$ of icebreaker sound at the whales' location was below the ambient noise level even in the 1/3-octave bands with strongest icebreaker noise (Fig. F-14A). Peak levels in those bands at instants when the icebreaker sound was strongest probably were similar to the ambient noise, and some of these whales may have been exposed to slightly higher levels of icebreaker sound at an earlier time when they may have been slightly closer to the ice camp. Even so, if they diverted north in response to icebreaker sound, it appears that they did so at a long range (~3 km) and a low received noise level.

Summary.—On 7 May 1994, the ice camp was set up along the landfast ice edge about 45 km ENE of Pt. Barrow (Fig 3.8). Tones and later icebreaker sounds were projected into the nearshore lead adjacent to the landfast ice. Before the playback of tones and icebreaker sounds, large numbers of bowhead whales were sighted traveling NE at medium speed through the middle and southern third of the lead. Sighting rates were lower when tones were projected into the lead from 14:14 to 16:03, but the distribution and behavior of most whales seen then were similar to those during the preceding control period.

Bowheads continued to travel past the ice camp during the period of icebreaker playback from 16:07 to 20:01, but sighting rates were lower and some whales apparently diverted away from the landfast ice edge where the sound projectors were located. No bowheads were seen from the ice camp during the first 80 min of icebreaker projections and only a few whales were seen, all in the central and offshore sides of the lead, during the following 2½ hours of icebreaker playback. The broadband source levels were ~20 dB higher during the final 1.9 h of the playback than during the initial 2.0 h (Table 6.3 on p. 252). Aerial observations west of the projectors sighted large numbers of bowheads heading toward the projectors; few of them were later seen by ice-based observers. These whales apparently moved past the ice camp through the offshore side of the lead.



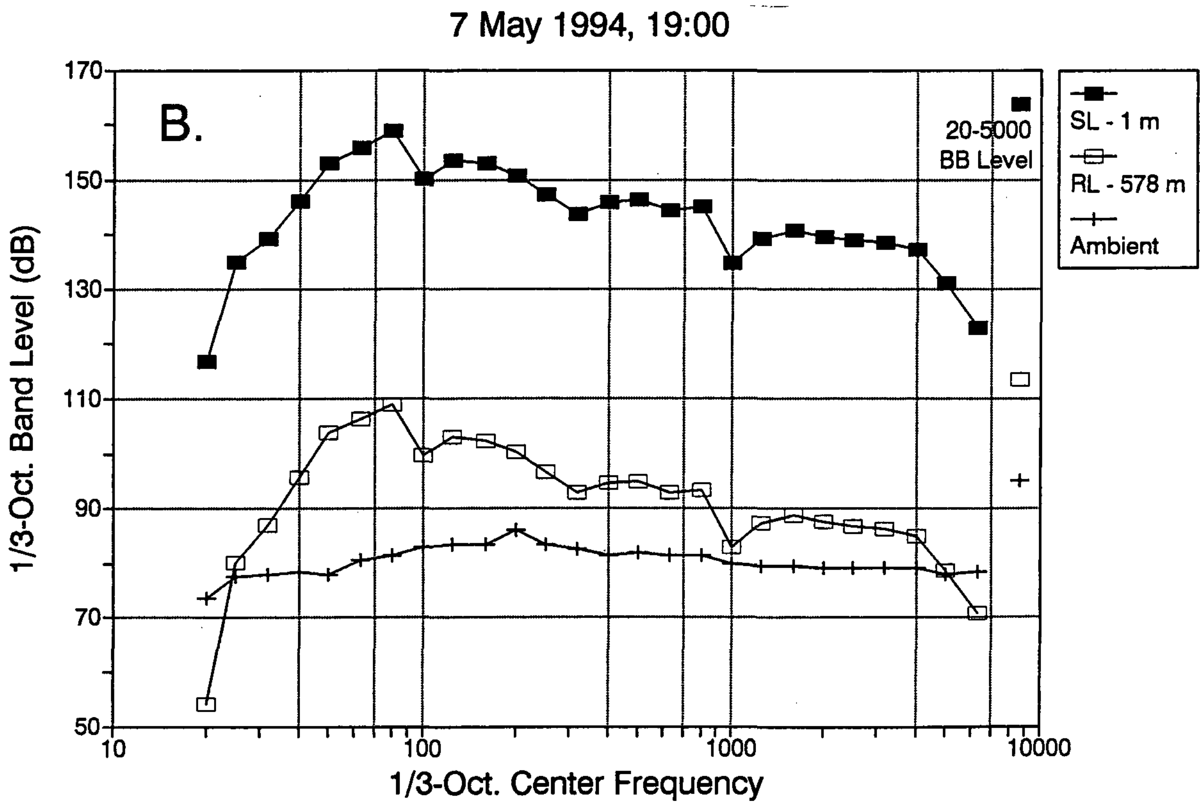


FIGURE F-15. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near bowheads *(A)* 362 m and *(B)* 578 m from the projector (median level over 1 min), 7 May 1994, times *(A)* 18:05 and *(B)* 19:00. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-4.

Some whales seemed to alter their paths at distances where icebreaker sounds in the strongest 1/3-octave bands were similar to the ambient noise levels in those bands and thus (presumably) barely detectable. The whale seen closest (362 m) to the operating projectors appeared to be detouring to the north to avoid a closer approach. It was seen during the first half of the projection experiment when source levels were low. This whale was exposed to an estimated $S{:}N_{1/3,max}$ of 18 dB when it started to detour (1/3-octave band centered at 50 Hz). However, not all bowheads diverted. One bowhead was seen that had apparently passed well within 500 m of the projectors on a normal northeasterly heading, tolerating $S{:}N_{1/3,max}$ well over 20 dB. Thus it appears that, on 7 May 1994, some whales altered their tracks to avoid the projectors by >1 km, but a few approached within a few hundred meters where they were exposed to $RL_{BB,max}$ as high as 119 dB re 1 µPa and $S{:}N_{1/3,max}$ as high as 32 dB.

9 May 1994 Playback

The ice camp was set up on the northern edge of the landfast ice along a major lead oriented NE-SW. The camp was ~2.5 km NE of the location where a playback was conducted on 7 May and where ice-based control observations were obtained on 8 May. The measured water depth at the projector was 40 m. NW of the ice camp the lead was ~2000 m wide and it narrowed to 250 m wide ~2.3 km NE of the camp (Plate 6.1). Aerial reconnaissance from 08:59 to 10:39 found that many bowheads were migrating NE in the main nearshore lead, which was ice-free within the first 3 km NE of the ice camp and discontinuous farther to the east. After the ice-based crew arrived at the site, 3.9 h of control observations were obtained from the ice. During this period 10 bowheads (not counting 2 bowheads potentially disturbed by the helicopter) were sighted. Then icebreaker sounds were projected into the lead adjacent to the landfast ice for 3 h via a J-11 projector; during that period 32 bowheads were observed from the ice and aircraft. There was a further 3-h period of observations after the playback ended, during which ~43 bowheads (excluding 1 potentially disturbed by the helicopter) were seen from the ice and aircraft.

The ice-based crew arrived at the camp site at 10:19, started behavioral observations at 10:28, and left the site at 20:29. Icebreaker sounds were projected into the lead from 14:22 to 17:30. During the first 40 min the source levels were ~9 dB stronger (20-5000 Hz broadband) than during the remainder of the period. The projection of icebreaker sounds was interrupted from 16:19:57 to 16:26:00. One bowhead surfaced 30 m from the ice camp less than 1 min before the sound playback was interrupted, swam to a position 17 m from the projector, and dove toward it a few seconds before the sound was interrupted. A number of whales were seen very close to the projector during the playback and post-playback periods; most of these whales were suspected to be feeding underneath the landfast ice. Aircraft-based behavioral observations were often fragmentary due to moderate-to-high sea states (3-6) throughout the day.

Ice-based Observations.—Many bowheads moved by within view of the ice camp. They approached from the SW and moved to the NE. Sightings were made throughout the day but the frequency of sightings varied during the day. During the first 3.9 h of control observations, 11 sightings (12 bowheads, including 2 singletons potentially disturbed by the helicopter) were made; during the 3 h of icebreaker playbacks, 20 sightings (26 bowheads) were made; during the first 2 h after playbacks, 16 sightings (19 bowheads, including 1 potentially disturbed by the helicopter) were made; and during the last 1 h only two sightings of three whales were made. In total, ~60 bowheads (~49 groups or singletons) were sighted from the ice during 10 h of observation. Most of these sightings were of traveling whales but 13 sightings (14 whales) were of small whales that appeared to be lingering (possibly feeding under the landfast ice) near the ice camp. There was no direct evidence of feeding, such as mud streaming from the mouths; however, these whales moved very slowly while at the surface, they turned frequently, they were seen diving under or surfacing from under the landfast ice, and one of the whales that had distinctive markings was reidentified from photographs taken at the ice camp 83 min apart. Thus, many of the sightings of whales lingering near the ice camp and along the landfast ice edge may be resightings of a few whales that could not be linked.

A total of ~12 bowheads (~11 groups or singletons) were sighted during pre-playback control observations from 10:28 to 14:21 (Fig. F-16, F-17). Most groups (9 of 11, 82%) were traveling NE or ENE at

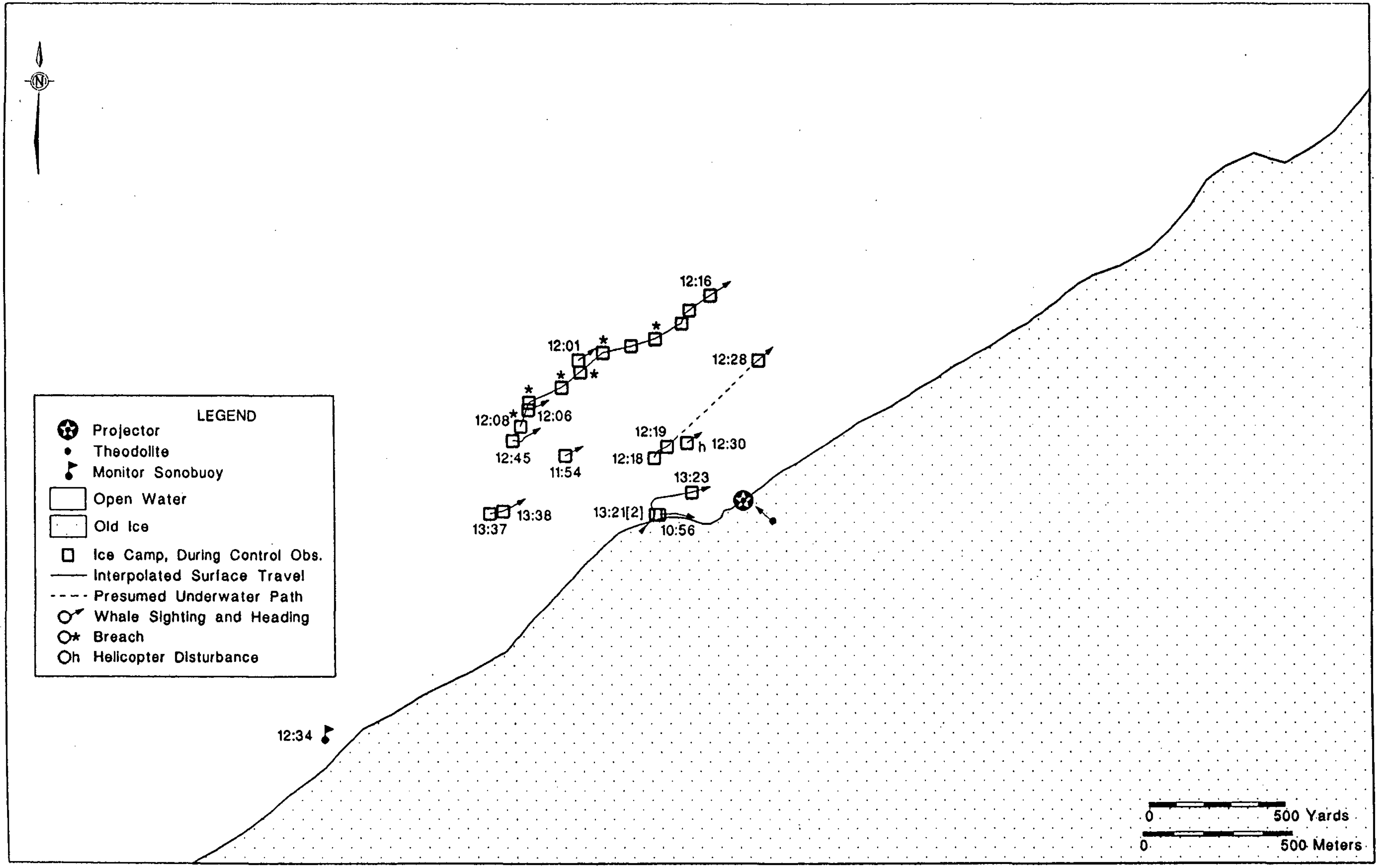


FIGURE F-16. Ice-based observations of bowhead tracks relative to the silent projector (pre-playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 10:28-14:21

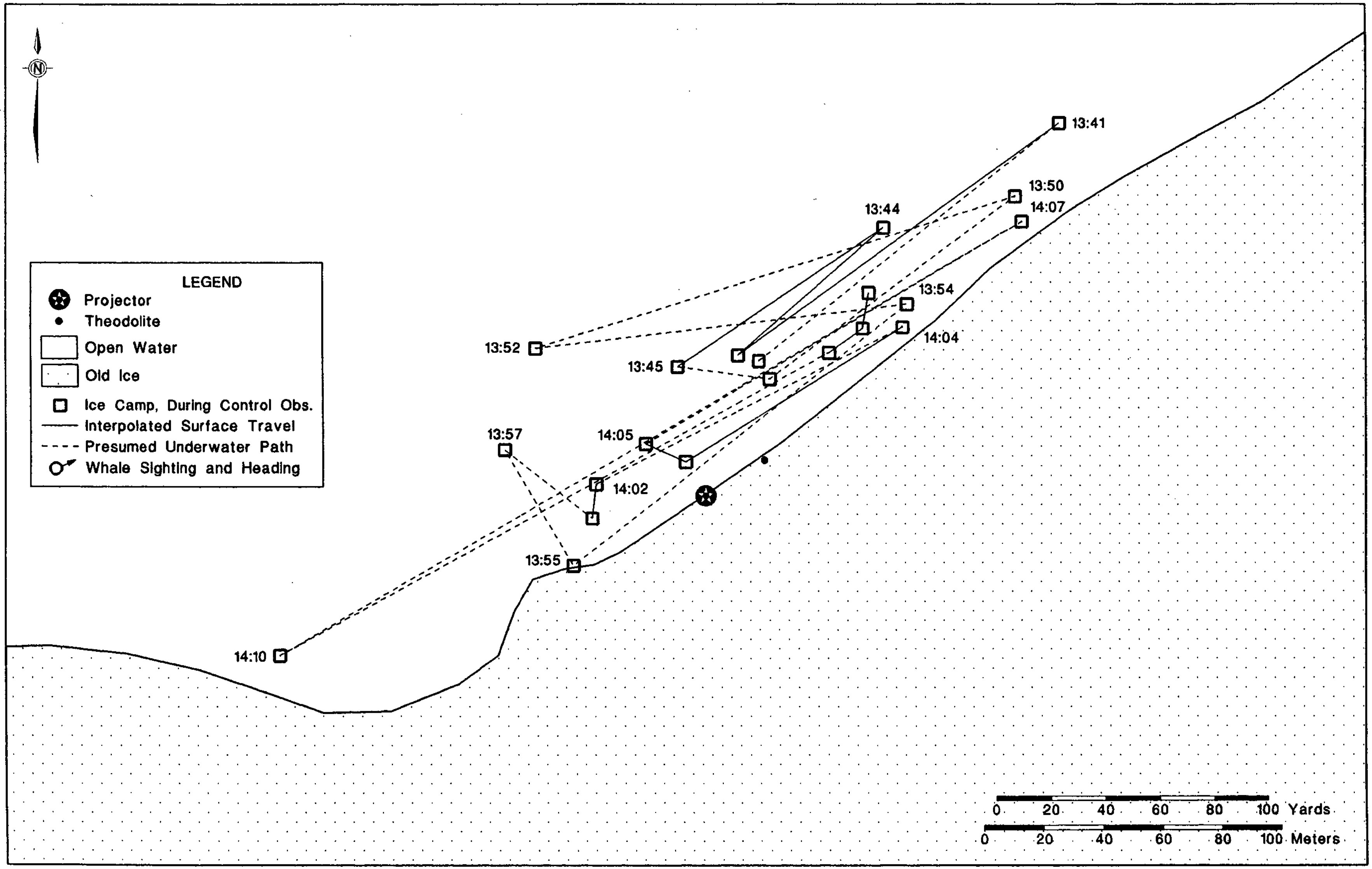


FIGURE F-17. Ice-based observations of a subadult bowhead relative to the silent projector (pre-playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 13:38-14:16. This subadult may have been attracted to the observers and equipment located at the ice edge.

medium speed along the lead (Table F-3). However, one small subadult milled in front of the camp from 13:38 to 14:16, repeatedly passing back and forth between the silent projector and the theodolite <30 m from the ice edge (Fig. F-17). This subadult may have been attracted to the observers and equipment located at the ice edge. However, similar sized whales were observed near the camp throughout the day; their behavior suggests that they may have been feeding under the landfast ice near the projector. The whale was observed as close as 5 m from the surface location above the silent projector (theodolite measurement of horizontal distance). This was the closest observed approach to the projector site throughout the day.

At 13:21 a group of two bowheads appeared to deviate briefly from a NE to a N, then NW, and then ENE heading when ~308 m west of the silent projector. A subadult bowhead apparently reacted to the helicopter engines operating on the ice ~230 m away at 12:30 by abbreviating its surface duration; the whale blew once and slipped under the water without an arch. A single bowhead breached six times from 12:08 to 12:16 while traveling ENE 628-792 m from the projector. The closest observed approaches to the projector during the control period were 5 m (see above), <185 m, and <243 m (theodolite measurements).

From 14:22 to 17:30, while the projector was broadcasting icebreaker sounds, ~26 bowheads (~20 groups or singletons) were sighted by observers at the ice camp. Two of these groups were seen during the 14:22 to 15:02 period when the projected icebreaker sounds were stronger. As during the previous control period, many bowheads (9 groups) traveled consistently NE or ENE along the lead at medium speed as they approached the projector from the west. However, more whales (10 of 19 groups with known headings) had other orientations during this period as compared to the previous control period (2 of 11 groups). Most of these "other orientations" may have involved feeding whales because most were sighted along the ice edge and their headings were generally toward the landfast ice and angling toward the projector (Fig. F-18).

Only two traveling whales passed within 400 m of the projector but seven presumed feeding groups were seen within that distance (see Fig. F-26, later). The closest approach by a traveling whale was by a single bowhead followed from 324 m west of the projector to 320 m east of it from 16:31 to 16:36. It is estimated that the whale passed ~60 m from the projector during the intervening dive, and there was no apparent change in the track of this whale as it passed the projector. However, some other traveling whales appeared to change their tracks in reaction to the operating projector. A single whale that surfaced 206 m NW of the projector at 16:50 turned to the north (from its previous NEward heading) as it surfaced. It traveled north until it dove at 16:52. Two whales sighted at 14:59 at a location 420 m west of the projector were observed heading slowly NNW away from the projector; they then turned to an ENE heading (see inset in Fig. F-18). The most distant apparent reaction seen from the ice camp was by a group of two traveling whales that appeared to alter their course when 940 m WSW of the projector at 17:26. They were initially sighted traveling slowly NNE, then turned east, and then SE (Fig. F-18). After the playback ended at 17:30, they turned and followed the landfast ice NE and were last seen 500 m WSW of the projector and heading NE (Fig. F-19). A group of two bowheads was sighted briefly at 14:36 as they traveled slowly ENE along the ice edge 390 m WSW of the ice camp. This group reversed course away from the projector and along the ice edge. They may have been feeding or they may have reacted to the projection of icebreaker sounds.

Three groups of presumed feeding whales were observed <100 m from the operating projector by personnel at the ice camp. The closest observed approaches by presumed feeding bowheads during the playback period were 17, 24, 43, and 130 m from the projector (theodolite measurements of horizontal distances). One of these whales moved SSW along and then under the ice edge away from the projector at a distance of 43 m; however, its actual CPA may have been <43 m before it surfaced. A subadult bowhead was sighted just before the projector was briefly turned off at 16:20; the subadult subsequently turned from an ENE heading and dove SE under the ice edge 17 m from the operating projector. The projector was turned off a few seconds after this whale dove. This same whale was resighted <20 m from the projector at 17:43 (~13 min after the end of the icebreaker noise playback), and may have been sighted several other times between these two times. The whale was reidentified from photographs taken at 16:20 and 17:43 by the ice crew; the whale had a pair of distinctive scars on its right side. The path of this whale was not "blocked" by icebreaker sounds. It was seen a few meters east of the projector at 16:19, it was

TABLE F-3. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 9 May 1994.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales[d] RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S{:}N_{BB}$ med	$S{:}N_{BB}$ max	$S{:}N_{1/3}$ med	$S{:}N_{1/3}$ max	Nature of Track
A: Pre-Playback Control (10:28 to 14:22)															
10:56	1	-298 to -243	<243	10:56:35	1	IC									W of projector heading ESE, 9 min. after heli. overflight
11:54	1	single sighting	<625	11:53:48	1	IC									WNW of projector heading ENE
12:01	1	single sighting	735	12:01:27	1	IC									NW of projector heading ENE
12:06	1	single sighting	<793	12:06:20	1	IC									NW of projector heading ENE
12:08	1	-792 to -705	628	12:13:06	1	IC									NW to N of projector heading ENE; 6 breaches
12:18	1	-342 to +488	325	12:18:52	1	IC									NW to N of projector heading NE
12:30	1	single sighting	285	12:30:18	1	IC									Subadult NW of projector heading ENE. Appeared to react to heli. idling on ice at ~230 m; blew once then slipped under without arch
12:45	1	-811 to -780	<780	12:45:31	1	IC									WNW of projector heading ENE
13:21	2	-308 to -185	<185	13:23:17	1	IC									W of projector heading NE; turned N when 308 m from projector, then NW, then ENE
13:37	1	-865 to -820	<820	13:37:37	1	IC									W of projector heading ENE
13:38	1	-90 to +100	5	14:04:40	1	IC									Subadult SW to NE of projector, heading variable. Milled near projector 13:38-14:16; rested once at surface, feeding?
B: Icebreaker Playback (14:22-17:30)															
14:36	2	-390 to -390	390	14:36:07	1	IC	*124*	*126*	*117*	*120*	*24*	*26*	*32*	*35*	WSW of projector heading slowly NE; reversed course when along ice edge 390 m SW of projector; feeding?
14:59	1	-430 to -420	420	15:00:10	1	IC	112	116	106	111	12	16	21	25	W of projector heading NNW then ENE
15:23	1	single sighting	<420	15:22:57	1	IC	*102*	*107*	*96*	*99*	*2*	*7*	*11*	*14*	W of projector heading SE under ice edge; feeding?
15:45	1	+495 to +540	<495	15:44:59	1	IC	102	109	95	100	2	9	10	15	NNE of projector heading ENE
15:57	3	single sighting	<2800	15:57:28	2	A	89	92	84	86	-11	-8	-1	1	WSW of projector heaidng ENE, social.
15:57	2	-472 to -442	<442	15:58:13	1	IC	102	105	95	98	2	5	8	10	W of projector heading NE
16:04	1	-370 to -251	<251	16:06:22	1	IC	*108*	*112*	*100*	*106*	*8*	*12*	*12*	*19*	Subadult NW to W of projector heading ENE then SE; feeding?
16:08	1	single sighting	<1275	16:08:12	1	IC	95	99	88	90	-5	-1	3	5	NW of projector heading ENE
16:14	2	single sighting	1700	16:14:17	1	IC	88	91	83	84	-12	-9	-2	-1	WSW of projector, heading unknown; breached
16:19	1	-30 to +17	17	16:19:56	1	IC	*128*	*132*	*121*	*123*	*28*	*32*	*36*	*38*	Subadult W to N of projector heading ENE. Playback interrupted. Dove SE under ice edge. Resighted at 17:43 W of projector heading ENE; feeding?
16:28	1	-985 to -946	<946	16:29:25	1	IC/A	105	107	99	101	5	7	14	16	W of projector heading ENE; breached
16:29	1	-34 to -24	24	16:30:22	1	IC	*132*	*135*	*126*	*129*	*32*	*35*	*41*	*44*	W of projector heading ENE, dove SE under ice edge; feeding?
16:31	1	-324 to +320	60	16:33:50	3	IC/A	115	117	108	109	15	17	23	24	W of projector heading ENE then E

TABLE F-3. Continued.

Time	Group size	Radial Distance Followed From Projector (m)[c]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales[d] RL$_{BB}$ med	RL$_{BB}$ max	RL$_{1/3}$ med	RL$_{1/3}$ max	S:N$_{BB}$ med	S:N$_{BB}$ max	S:N$_{1/3}$ med	S:N$_{1/3}$ max	Nature of Track
16:16	1	-2900 to +500	480	16:39:00	3	A	107	110	100	103	7	10	15	18	NW to N of projector heading NE. Dove NNE under brash with open water to ENE
16:46	1	single sighting	2000	16:46:21	2	A	93	99	86	93	-7	-1	2	8	WNW of projector heading N
16:50	1	-206 to +260	206	16:50:01	1	IC/A	114	118	108	111	14	18	23	26	NW to NNW of projector heading NNE. Adult
16:49	2	single sighting	<910	16:50:25	1	IC/A	104	107	98	102	4	7	14	17	WNW of projector heading ENE; tailslapped
16:52	1	single sighting	70	16:53:01	2	A	*119*	*122*	*114*	*115*	*19*	*22*	*29*	*30*	NE of projector, motionless, oriented ENE, turned SE, dove under ice pan. Subadult, feeding?
16:54	2	single sighting	1500	16:53:36	2	A	98	102	93	96	-2	2	8	11	ENE of projector heading ESE, dove under ice edge. Subadults
16:59	1	single sighting	<730	16:59:25	2	A	*107*	*110*	*101*	*103*	*7*	*10*	*16*	*18*	NNE of projector heading ENE, aerial activity
16:59	1	+730 to +804	<730	16:59:32	1	IC	106	109	100	103	6	9	15	18	NE of projector heading ENE
17:03	1	-58 to -43	43	17:03:52	1	IC/A	*124*	*128*	*116*	*122*	*24*	*28*	*31*	*37*	W of projector heading SSW under ice edge; feeding?
17:05	2	-366 to +890	281	17:06:12	1	IC/A	*108*	*113*	*101*	*104*	*8*	*13*	*16*	*19*	NW of projector heading ENE, social, aerial activity. Adult & subadult
17:06	1	single sighting	<1000	17:06:55	2	A	100	104	95	97	0	4	10	12	N of projector heading NNE
17:13	1	single sighting	<1500	17:12:50	2	A	101	104	96	99	1	4	11	14	NNE of projector heading E along brash ice
17:14	1	single sighting	<1600	17:13:36	2	A	101	103	95	96	1	3	10	11	NE of projector heading slowly ENE
17:19	1	single sighting	<850	17:18:40	2	A	105	108	99	102	5	8	14	17	NE of projector heading NNE, following group of 17:05
17:20	1	-140 to -130	130	17:21:13	1	IC	*114*	*117*	*108*	*110*	*14*	*17*	*23*	*25*	SW of projector heading slowly SW under landfast ice, rest/feeding?
17:22	1	single sighting	825	17:22:23	2	A	*103*	*107*	*97*	*101*	*3*	*7*	*12*	*16*	NE of projector, slowly heading NNW, turned S, dove steeply under ice pan. Subadult; feeding?
17:24	2	single sighting	<2100	17:24:28	2	A	94	97	88	90	-6	-3	3	5	NE of projector heading ENE in brash ice
17:25	1	single sighting	<750	17:25:37	2	A	102	106	96	103	2	6	11	18	NNE of projector heading NNE
17:27	1	single sighting	<1400	17:26:40	2	A	99	101	93	95	-1	1	8	10	NNE of projector heading NNE along brash ice
17:29	1	single sighting	1910	17:28:37	1	IC	*92*	*96*	*87*	*90*	*-8*	*-4*	*2*	*5*	WSW of projector, heading unknown; breached
17:26	2	-940 to -750	<750	17:30:05	2	IC/A	101	106	95	100	1	6	10	15	WSW of projector heading slowly NNE, then turned E, then SE. Playback ends. Whales then approach projector.
C: <30 min After Playback (17:30-18:00)															
17:33	1	100 to -50	17(*100*)	17:32:40	2	A	*113*	*119*	*107*	*113*	*13*	*19*	*22*	*28*	N to WSW of projector heading SSE, dove under ice edge. Yearling; feeding?
17:33	2	-750 to -500	<500	17:33:35	2	IC/A									WSW of projector heading ENE along ice edge. Followed during playback at 17:26 (See above)
17:36	1	+660 to +1400	<660	17:36:19	1	IC/A	102	107	96	101	2	7	11	16	NNE of projector heading NE across lead. CEPA during playback
17:37	1	single sighting	<850	17:36:44	2	A									NNE of projector heading NNE

TABLE F-3. Continued.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales[d] RL$_{BB}$ med	RL$_{BB}$ max	RL$_{1/3}$ med	RL$_{1/3}$ max	S:N$_{BB}$ med	S:N$_{BB}$ max	S:N$_{1/3}$ med	S:N$_{1/3}$ max	Nature of Track
17:43	1	single sighting	<20	17:43:19	1	IC									N of projector heading slowly SE, dove SSE under ice toward projector at 20 m. Sighted during plbk at 16:19; subadult, feeding?
17:42	1	single sighting	<650	17:45:23	2	A									WNW of projector heading E. Adult
17:48	1	-290 to +279	<279	17:49:04	1	IC									W of projector heading ENE
17:50	1	+142 to +168	<142	17:51:08	1	IC									NE of projector heading slowly SW along landfast ice edge toward projector; feeding?
17:52	2	single sighting	<1600	17:52:28	2	A									WNW of projector heading NE
17:54	1	single sighting	1100	17:55:21	2	A									NNW of projector heading E
17:56	1	-780 to -721	<721	17:56:55	1	IC/A									W of projector heading ENE
17:49	2	-1500 to -1300	1300	18:00:28	2	A									WNW of projector heading ENE; mother-calf ~30 min post-plbk
18:00	1	-295 to -244	<244	18:01:06	1	IC/A									W of projector heading ENE
D: Post Playback Control (>18:00)															
18:03	1	-750 to -742	<742	18:03:45	1	IC									W of projector heading ENE
18:02	1	-120 to +110	110	18:14:24	2	A									WSW of projector, dove under ice edge. Yearling; feeding?
18:20	1	single sighting	<720	18:21:01	2	A									WSW of projector, surfaced from under ice heading slowly NNE
18:23	1	single sighting	<600	18:23:19	2	A									WSW of projector heading SSW, dove under ice edge
18:27	1	-100 to +17	17	18:26:33	1	IC/A									N to SW of projector heading slowly WSW past projector; then dove SSE under ice edge. Resurfaced WSW of projector heading ENE, turned SE and dove under ice; feeding?
18:09	2	-1600 to +1500	283	18:27:00	3	IC/A									WSW to NE of projector heading ENE. Adults
18:30	1	+290 to +920	<290	18:29:50	1	IC/A									NE of projector heading ENE along ice edge. Subadult
18:47	1	single sighting	278	18:47:18	1	IC									W of projector heading NNE
18:52	1	single sighting	<2200	18:52:00	2	A									NNE of projector heading ENE
18:56	1	single sighting	<2300	18:55:45	2	A									ENE of projector heading NNE along ice edge
19:05	1	single sighting	1039	19:05:20	1	IC									NE of projector, heading unknown
19:14	2	-316 to -328	311	19:14:47	1	IC									NW of projector heading NE, 3 min. after heli.overflight
19:20	1	+959 to +1052	<959	19:20:09	1	IC									NE of projector heading ENE
19:24	1	+741 to +822	<741	19:24:02	1	IC									NE of projector heading NE
19:25	1	single sighting	<1500	19:25:40	2	A									W of projector heading slowly NE along brash ice
19:24	2	-1700 to -1600	<1500	19:27:11	2	A									WNW of projector heading ENE along edge of brash ice
19:31	1	+1300 to +1400	<1300	19:31:30	2	A									NW of projector heading NNE along brash ice, turned ESE
19:35	2	single sighting	<2700	19:36:45	2	A									WNW of projector heading NE in brash ice
19:39	2	single sighting	<1200	19:39:00	2	A									W of projector heading ENE

TABLE F-3. Continued.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales[d] RL$_{BB}$ med	RL$_{BB}$ max	RL$_{1/3}$ med	RL$_{1/3}$ max	S:N$_{BB}$ med	S:N$_{BB}$ max	S:N$_{1/3}$ med	S:N$_{1/3}$ max	Nature of Track
19:39	2	+750 to +885	<750	19:39:01	1	IC									NNE of projector heading NE; social travel/mill, flipperslap
19:37	1	single sighting	<2600	19:39:08	2	A									WNW of projector heading NE in brash ice
19:40	1	single sighting	<1400	19:40:42	2	A									NW of projector heading ENE in brash ice
19:40	1	single sighting	<1400	19:40:45	2	A									NW of projector heading ENE in brash ice
19:41	1	single sighting	<1400	19:41:25	2	A									WNW of projector heading ENE in brash ice
20:01	1	single sighting	524	20:00:54	1	IC									N of projector heading ENE

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] Data in italics are not included in analyses of traveling whales because these whales were socializing, feeding or engaged in aerial activities.

[e] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

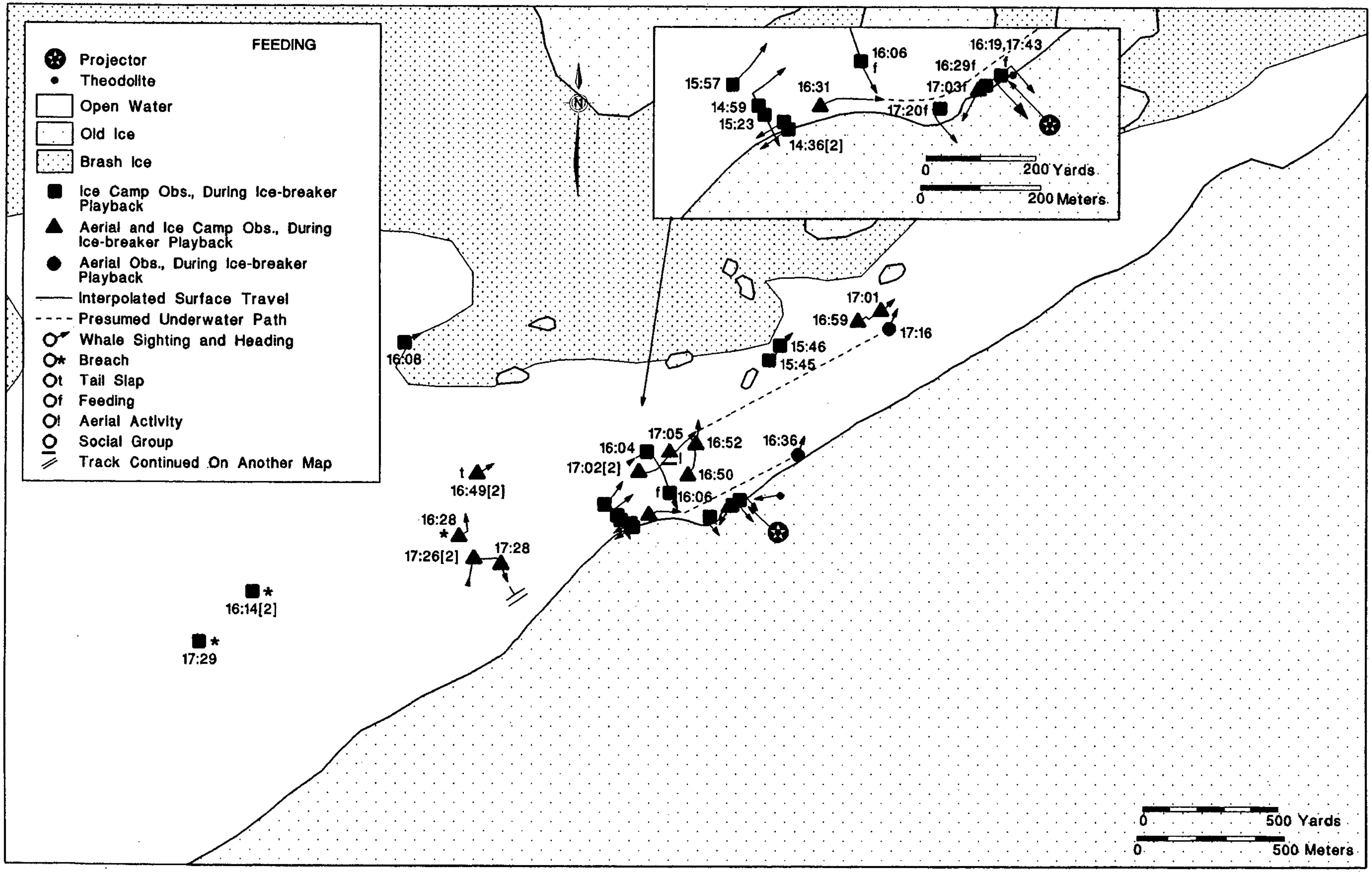


FIGURE F-18. Ice-based observations of bowhead tracks relative to projector broadcasting icebreaker sounds along the landfast ice NE of Pt. Barrow, 9 May 1994, times 14:22-17:30. Aerial observations are included where they concern bowheads observed from both the ice and the aircraft.

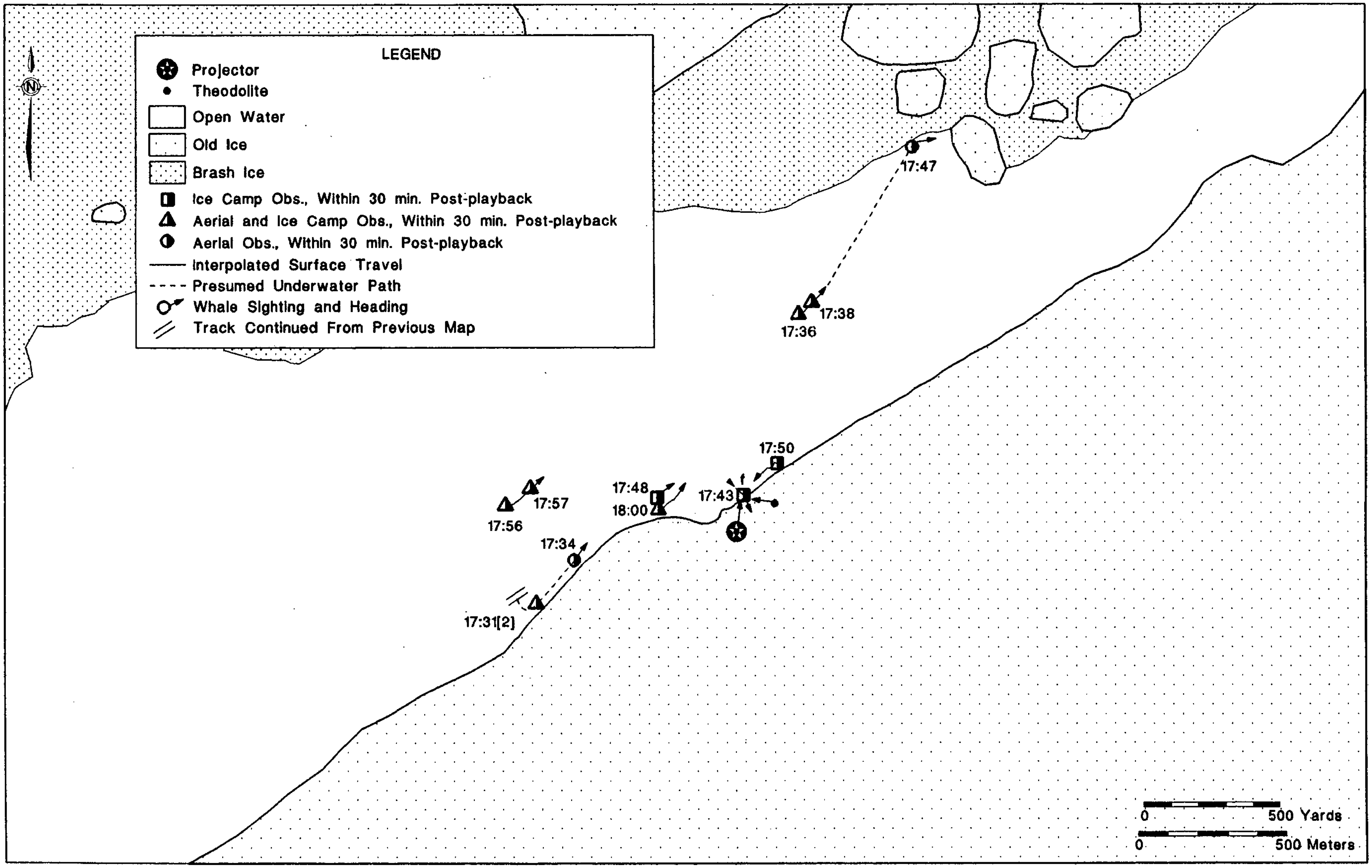


FIGURE F-19. Ice-based observations of bowhead tracks relative to silent projector (<30 min after icebreaker playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 17:31-18:01. Aerial observations are included where they concern bowheads observed from both the ice and the aircraft.

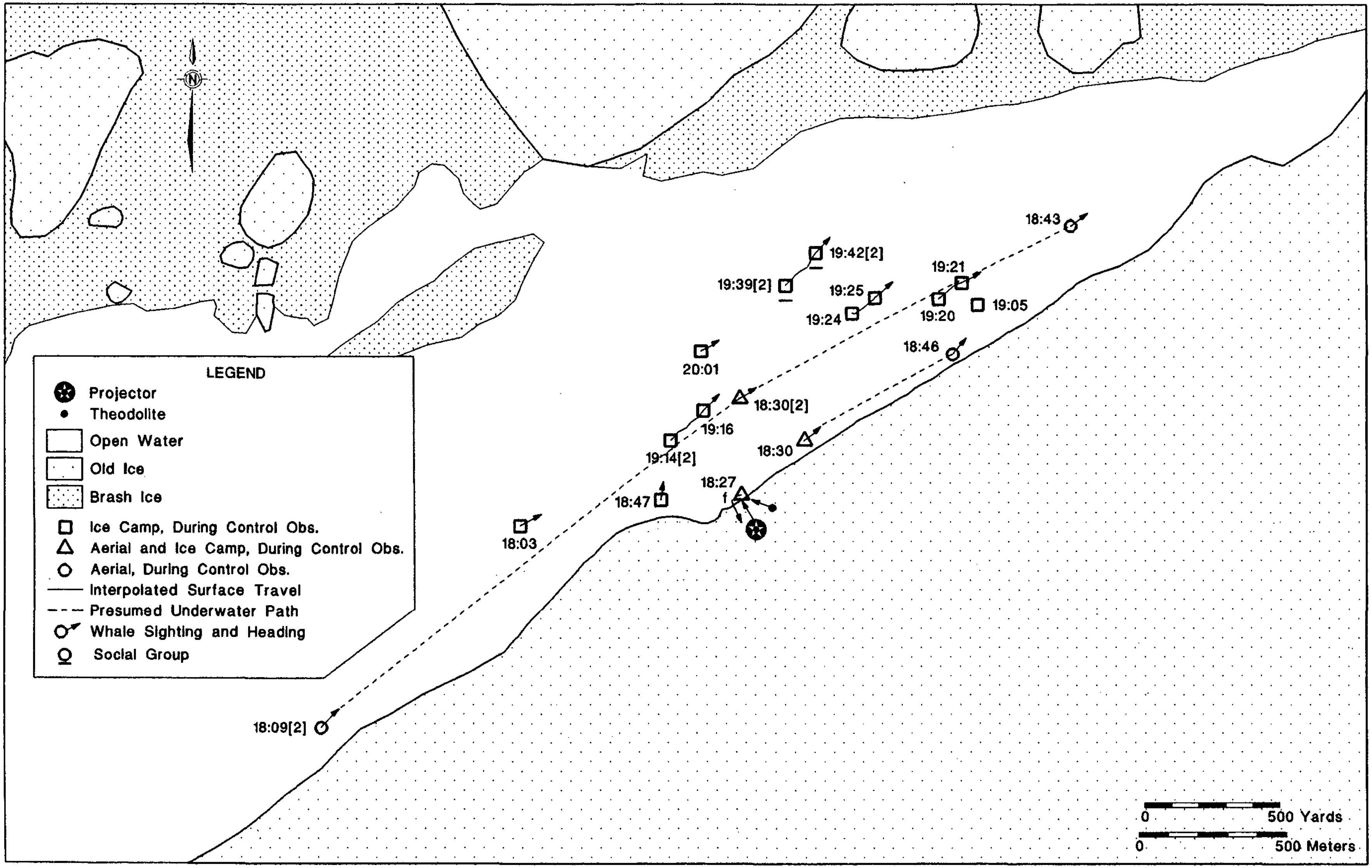


FIGURE F-20. Ice-based observations of bowhead tracks relative to silent projector (>30 min after icebreaker playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 18:02-20:29. Aerial observations are included where they concern bowheads observed from both the ice and the aircraft.

probably seen SW of the projector from 16:29 to 17:20, and it was photographed 20 m N of the projector at 17:43 (13 min after the projector was turned off).

There were ~22 bowheads (~18 groups or singletons) sighted by observers at the ice camp after the projector stopped broadcasting icebreaker sounds. Three of these sightings may have been of one or more feeding whale(s) near the ice camp (Fig. F-19, F-20). Their headings deviated from NE or ENE. These three groups also had the closest observed approaches to the now-silent projector during the post-playback period: 17, <20, and <142 m. About half of the whales (53% of 17 groups) sighted during the post-playback period were <500 m from the projector (Fig. F-19). Only one group was sighted during the last 45 min of observation from the ice camp, when aerial observers were seeing large numbers of whales traveling along the north side of the lead, beyond the visual range of ice-based observers. It is not known why this change in distribution across the lead occurred at this time, 2 h after the end of the playback.

<u>Aerial Observations.</u>—A large number of bowheads (~66) were observed by the Twin Otter crew during 4.7 h of observation on 9 May 1994. Many of these whales may represent repeat sightings of the same whales that could not be recognized because of rough sea conditions. Whales were observed during the playback, post-playback, and subsequent control periods. A low cloud ceiling prevented aerial observations during the pre-playback period.

From 15:11 to 17:30, while the projector was broadcasting icebreaker sounds, bowheads were generally traveling NNE to ENE along the lead at slow to medium speed (Fig. F-21). They approached the projector from the west or WSW. Bowheads followed during the early part of the session (15:11-16:20) included many whales engaged in social and aerial activities. Because of these behaviors, many of these whales had headings other than the NNE heading that would be expected of migrating whales. Many of the whales observed from the air were migrating east near the pack-ice edge along the north side of the lead.

Aerial observers saw ~27 bowheads approach within 1 km of the projector during the playback period. The closest of these were also seen by the ice-based observers and are described above under "Ice-based Observations". There is circumstantial evidence that a few additional whales seen from the aircraft may have altered their headings in response to the icebreaker playbacks. One well-marked traveling whale was initially seen heading ENE 2.9 km west of the projector at 16:16. It was resighted 500 m north of the projector along the south edge of brash ice. When it dove, it headed NNE under the brash ice although it could have continued ENE along the lead without passing under the ice (Fig. F-21). Another single bowhead, seen briefly 2 km NW of the projector at 16:45, was traveling slowly directly away from the projector. It turned slowly to the right and dove oriented north into the pack ice (Fig. F-21). Finally, a whale seen 660 m NE of the projector at 17:36, some 6 min after the projector stopped transmitting icebreaker sounds, was heading NNE (Fig. F-22). The expected heading along the lead would have been ENE. This whale would have been near its CPA to the projector when the projection stopped. It apparently continued its NNE heading after it dove and it resurfaced along the edge of the brash ice 1.4 km NNE of the projector. It then turned and followed the ice edge eastward (Fig. F-22).

In addition to the whale seen presumably feeding near the ice camp, aerial observers saw presumably feeding bowheads along the ice edge ENE of the camp. One subadult whale that was 825 m NE of the ice camp appeared to be feeding. It surfaced close to the ice edge heading NNW, turned slowly south, then dove sharply under the landfast ice edge. Two subadults 1.5 km NE of camp were also observed diving under the landfast ice edge heading ESE.

A group of 4-5 whales was engaged in social/sexual behavior ~5.0 km WSW of camp during the playback from 15:27 to 16:14. One whale repeatedly breached and lunged near the group. Another bowhead 4.6 km W of the ice camp was possibly disturbed by the observation aircraft when the aircraft passed almost directly over the whale at 16:20 (actual lateral distance unknown). Initially the bowhead was traveling ENE; it turned sharply, almost stopped, and then dove with a final heading of WNW.

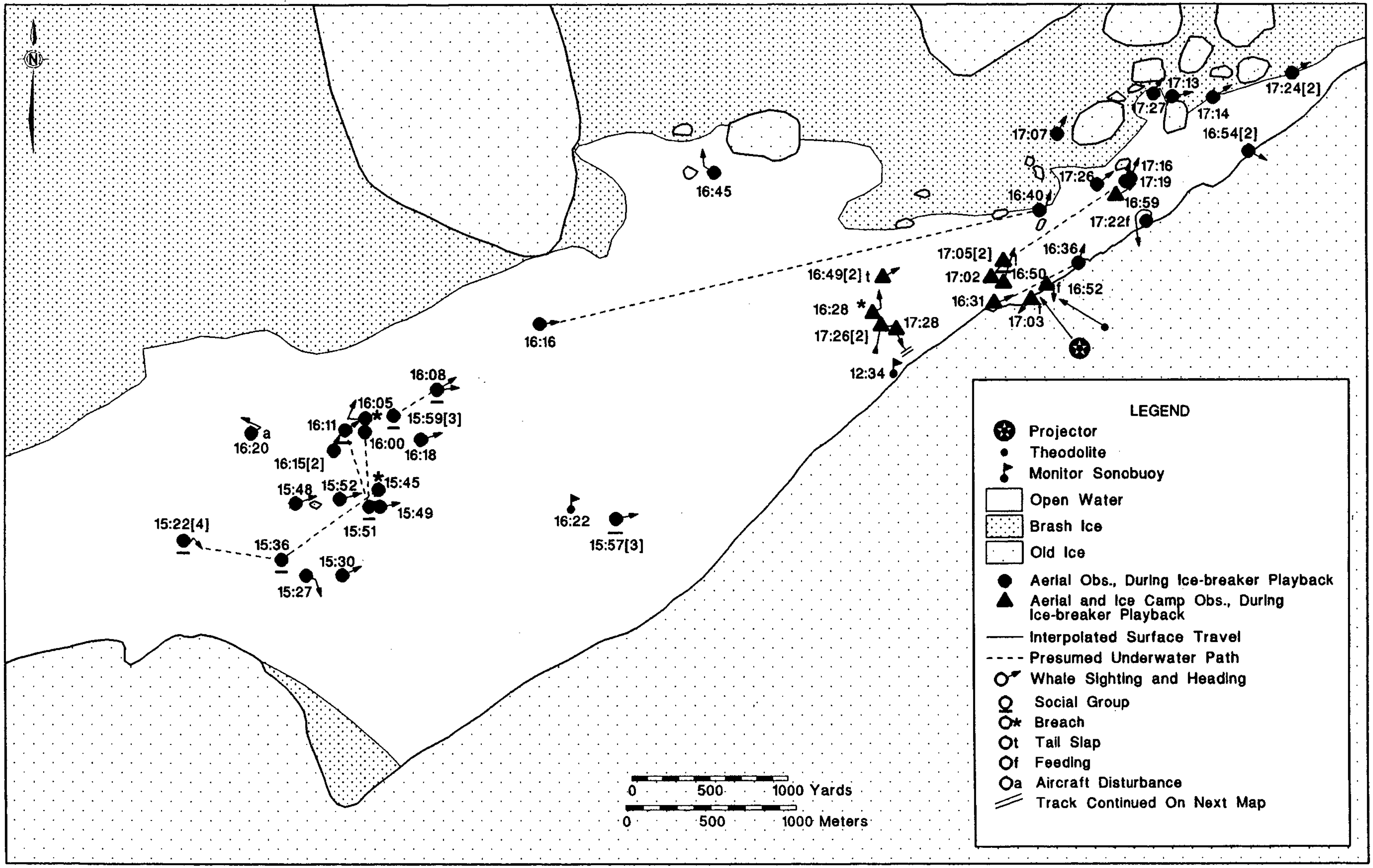


FIGURE F-21. Aerial observations of bowhead tracks relative to the projector broadcasting icebreaker sounds along the landfast ice NE of Pt. Barrow, 9 May 1994, times 15:11-17:30.

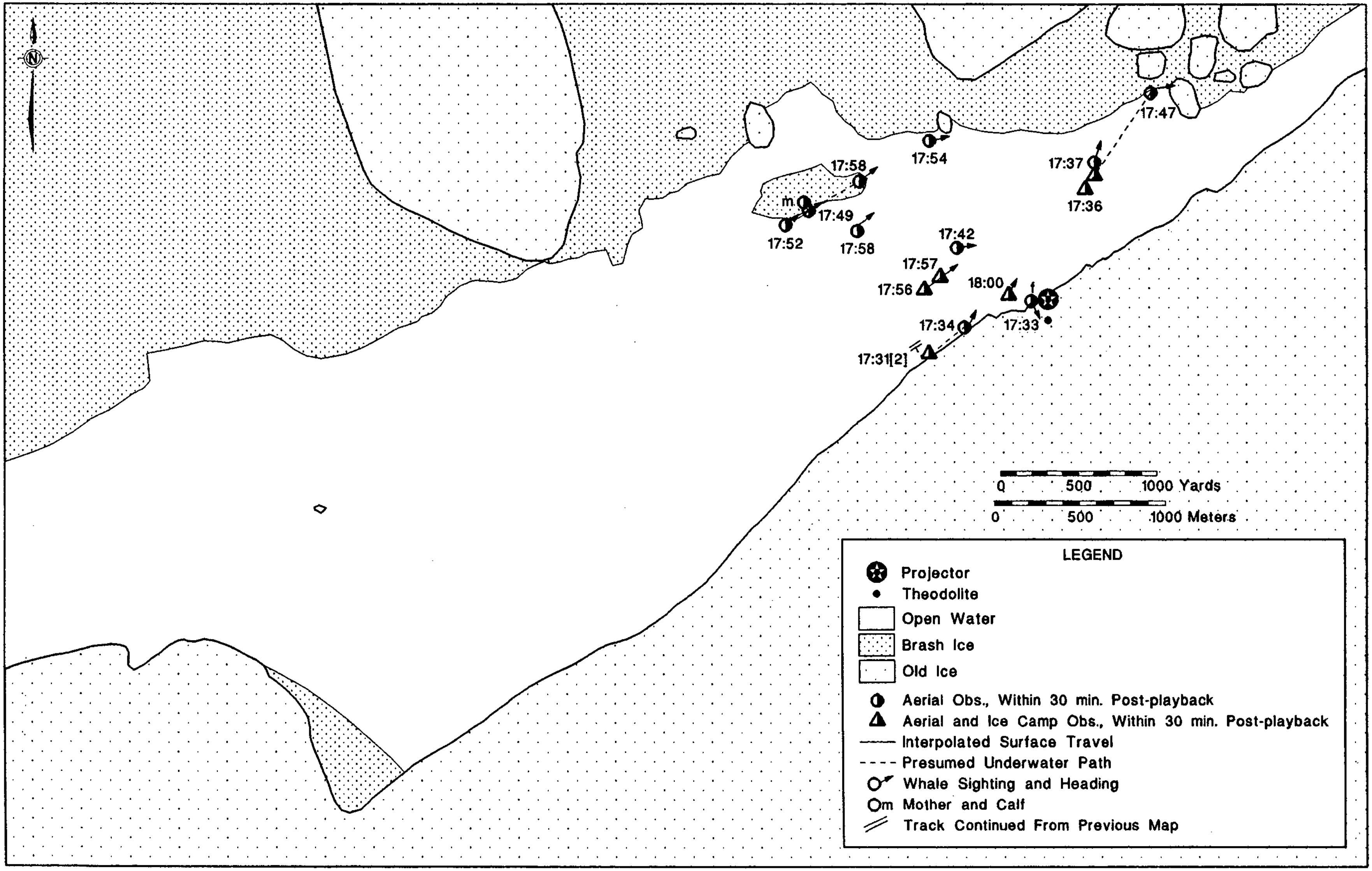


FIGURE F-22. Aerial observations of bowhead tracks relative to the silent projector (<30 min after icebreaker playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 17:31-18:01. Ice-based observations are included where they concern bowheads observed from both the aircraft and the ice. aircraft.

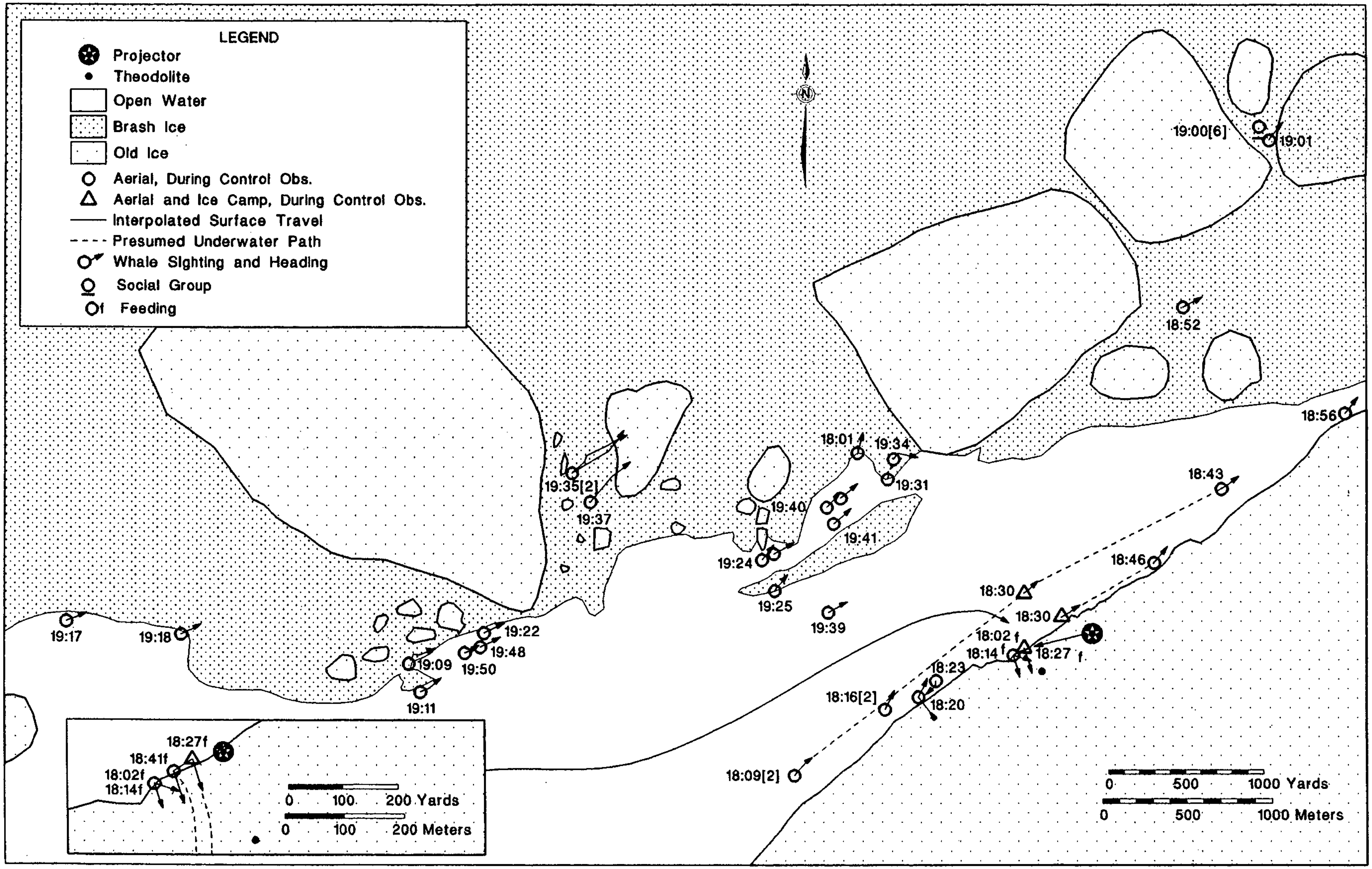


FIGURE F-23. Aerial observations of bowhead tracks relative to the silent projector (>30 min after icebreaker playback) along the landfast ice NE of Pt. Barrow, 9 May 1994, times 18:02-19:54.

A bowhead mother and calf were observed 1.5 km WNW of camp during the 30 min post-playback period. The pair traveled at medium speed heading NE along a row of brash ice. The calf was seen 'riding' (Fig. F-22). This was the only mother and calf observed during this study in 1994.

Approximately 3/4 of the bowheads observed during more than 30 min after the end of the playback period (18:01 to 19:54) were traveling ENE along the north side of the lead, generally parallel to the edge of brash ice or pack ice (Fig. F-23). Most of the other whales seen during this period traveled ENE along the landfast ice edge, but one small whale was seen 600 m WSW from camp heading SSW away from the ice camp at very slow speed. Seven whales (6 groups or singletons) were seen within 1 km of the silent projector. The CEPA was 17 m (theodolite measurement, see "Ice-based Observations" above). This same whale surfaced 100 m WSW of the ice camp 13 min later and subsequently it again dove under the ice edge. A subadult (possible yearling) was also observed twice ~110 m WSW of the ice camp. It was stationary while at the surface, and when it dove it went under the ice edge. Like several whales seen by the ice camp, this lingering whale may have been feeding along the landfast ice edge.

Noise Exposure.—Icebreaker sounds were projected into the lead from 14:22 to 17:30 using only the J-11 projector. The median broadband (20-5000 Hz) source level of icebreaker sounds ($RL_{BB,med}$) was

- 162 dB re 1 µPa-m from 14:22 to 15:02,
- 153 dB from 15:02-16:20, and
- 156 dB from 16:26-17:28.

Corresponding source levels for the dominant 1/3-octave bands were 157 dB near 500 Hz, 146 dB near both 315 and 400 Hz, and 149 dB near 200 Hz. Figure F-24A shows, for the last of these three periods, the variability in the sound levels as projected (1-m source levels) and as received at 1 km range. Figure F-24B shows the estimated median received levels at several standard distances at the same time.

At 12:34 on 9 May 1994, a 57A sonobuoy was deployed manually 890 m WSW of the ice camp along the edge of the landfast ice. A 53B DIFAR sonobuoy was air-dropped in the main lead 3 km WSW of the ice camp at 16:22. Ambient noise measurements were obtained from the monitor hydrophone near the projector and from the 57A sonobuoy. The average broadband (20-5000 Hz) ambient noise level was 100 dB re 1 µPa, and ambient noise levels in 1/3-octave bands were relatively uniform across a wide frequency range (84-87 dB, pluses in Fig. F-24).

Traveling Whales: Because of the variability in the source levels of the projected icebreaker sounds over time, the closest traveling whales to the projector were not necessarily exposed to the highest received levels (Table F-3). The highest maximum 20-5000 Hz broadband signal (118 dB re 1 µPa) was estimated for a whale that was 206 m from the projector at 16:50. The highest median broadband signal over 1 min (at least 115 dB) was estimated for a whale that was estimated to be 60 m from the projector at 16:34, based on interpolation of positions (Fig. F-21, F-25). A whale sighted 206 m west of the projector at 16:50 was subjected to the highest maximum icebreaker:ambient ratio in the strongest 1/3-octave band (26 dB), and the whale whose CPA was estimated as 60 m from the projector was subjected to the highest median ice-breaker:ambient ratio in the strongest 1/3-octave band (Fig. F-25). Traveling whales were exposed to substantially lower signal:noise ratios than some feeding whales, given the close CEPA distances of some feeding whales (Fig. F-26).

Feeding Whales: The closest observed bowheads to the operating projector on this date were feeding whales. These whales have not been included in our analyses of the CEPA distances or behavior of traveling whales, presented in sections 6.2 and 6.3. The closest of these whales to the projector was sighted 17 m from the projector at 16:20; at that time the whale dove toward the ice edge, angling toward but to the side of the projector. During that minute, the median and maximum broadband received levels at a horizontal distance of 17 m from the projector were estimated as 128 and 132 dB re 1 µPa. The median and maximum levels in the dominant 1/3-octave band were 121 and 123 dB in the band centered at 250 Hz. Thus, median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were 36 and 38 dB. Another

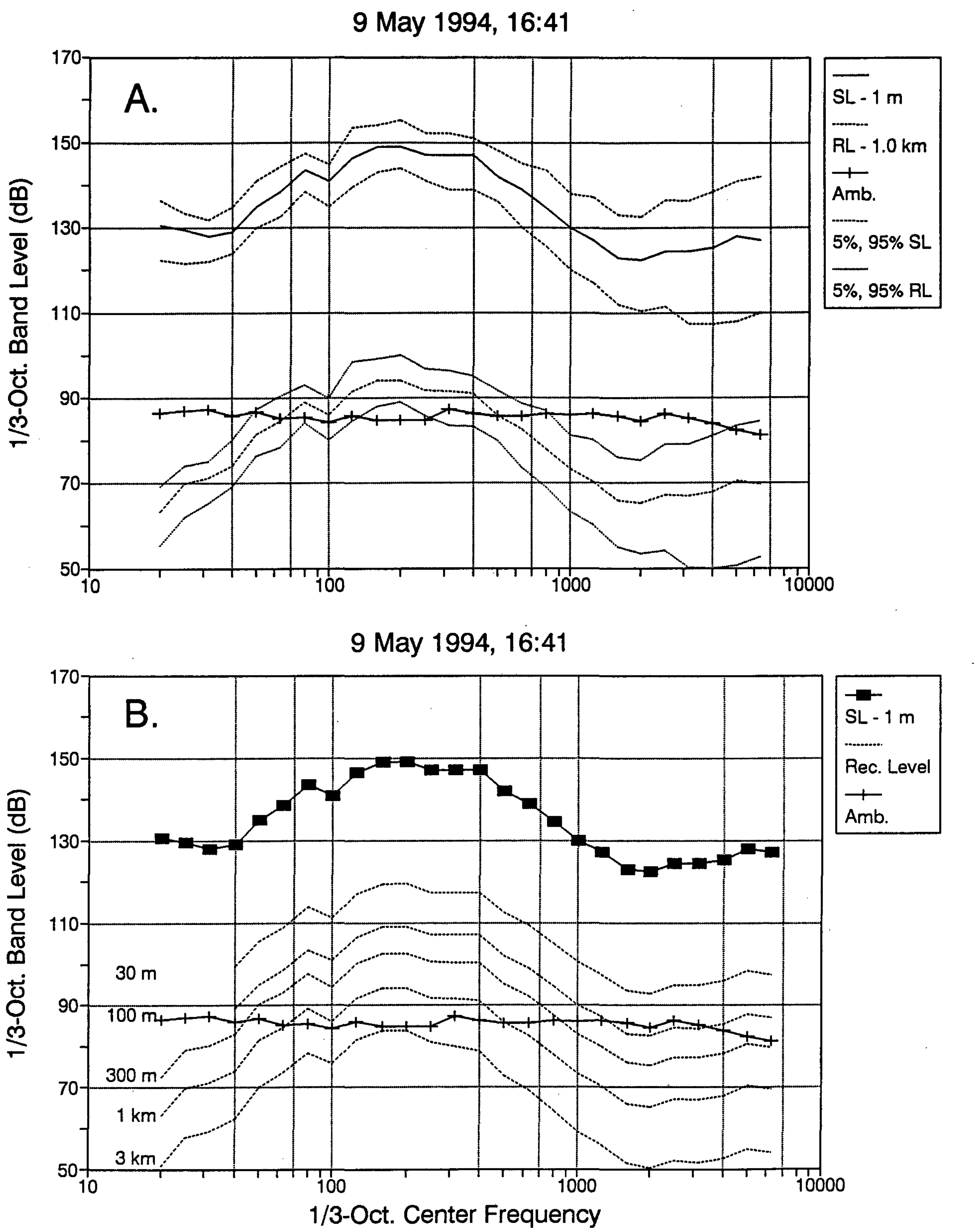


FIGURE F-24. Third-octave levels of projected icebreaker noise vs. distance from projector and ambient noise, 9 May 1994, time 16:27-16:41. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-2 or F-3.

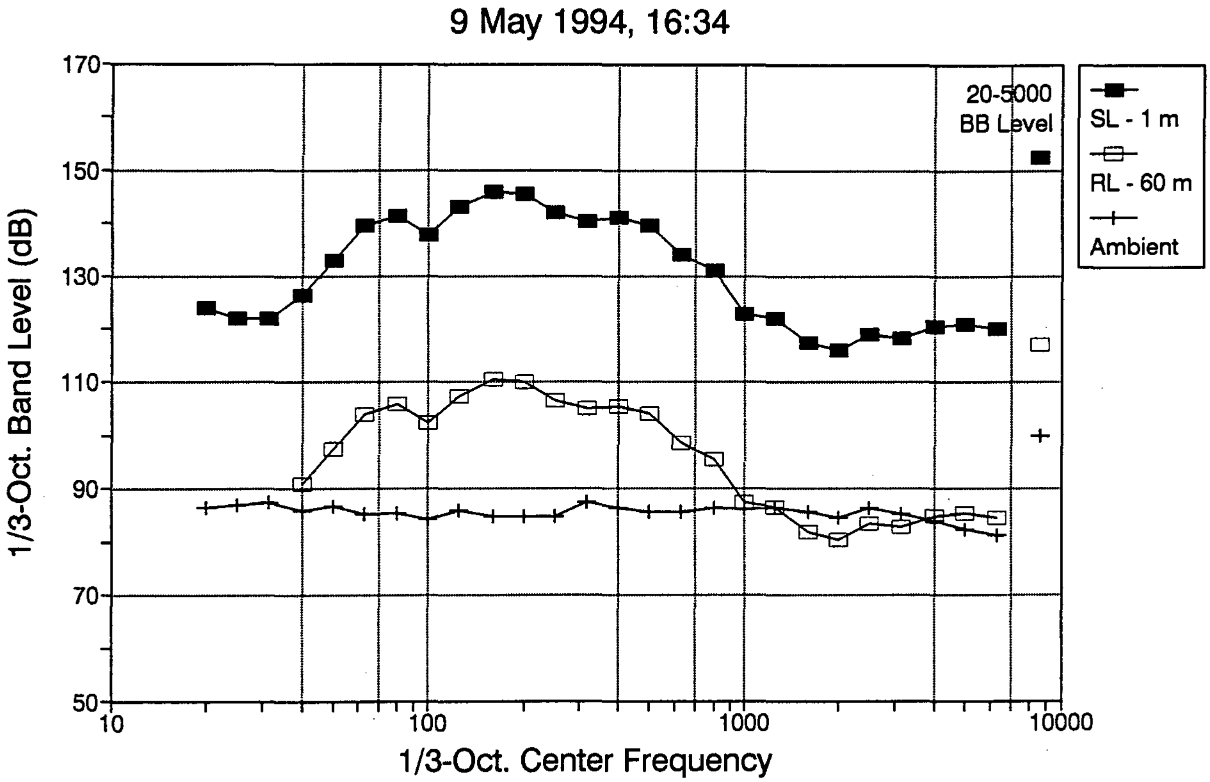


FIGURE F-25. Third-octave levels of projected icebreaker noise 1 m from the projector (closed squares) and near a bowhead 60 m from the projector (median level over 1 min), 9 May 1994, time 16:34. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-4. However, because of the short range, received levels at 60 m were estimated from source levels assuming spherical spreading.

feeding whale sighted 24 m from the projector at 16:29, which also dove under the ice edge angling toward the projector, was subjected to even higher noise levels before it surfaced:

- broadband: 132 dB re 1 µPa median and 135 dB maximum;
- strongest 1/3-octave (near 200 Hz): 126 dB median and 129 dB maximum
- icebreaker:ambient in strongest 1/3-octave band: 41 dB median and 44 dB maximum.

Several other feeding whales sighted at various distances from the projector were subjected to similar icebreaker:ambient ratios (Table F-3, Fig. F-26).

<u>Summary</u>.—On 9 May 1994, the ice camp was set up along the landfast ice edge about 2.5 km northeast of the 7 May location, and 3.9 h of pre-playback control observations were obtained from the ice. During this period 10 presumably undisturbed bowheads were sighted. Then icebreaker sounds were projected into the lead adjacent to the landfast ice for 3 h, during which 32 bowheads were observed from the ice and aircraft. There was a further 3-h period of observations after the playback ended, during which ~43 bowheads were seen from the ice and aircraft. Interpretation of the distribution and heading data was complicated by lingering whales that were probably feeding under the landfast ice near the ice camp.

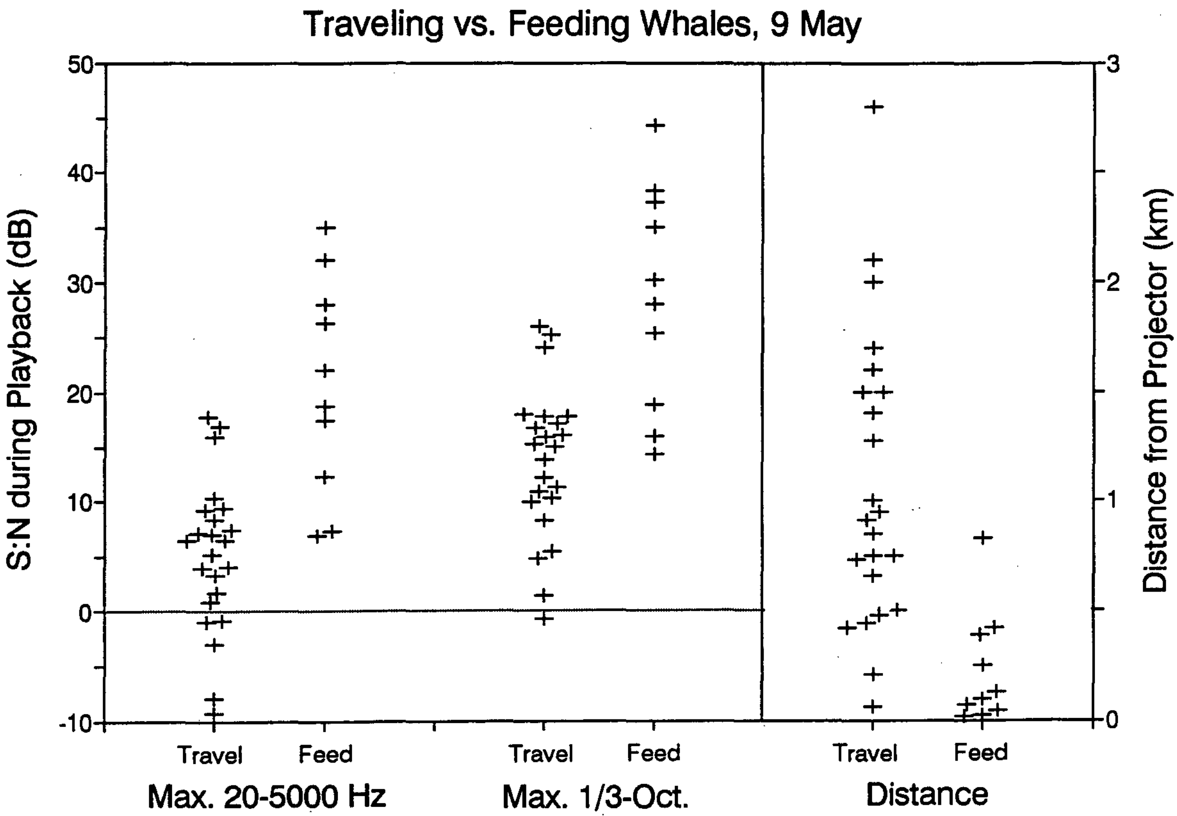


FIGURE F-26. Estimated signal-to-noise ratios (S:N) for icebreaker sound vs. ambient noise at the "CPA distances" of presumably feeding and traveling bowheads seen within 3 km of the ice camp on 9 May 1994. Maximum broadband (20-5000 Hz) and maximum 1/3-octave received levels during the 1-min period previous to the CPA were used to compute the S:N ratio for each whale. Many CPA distances are overestimated, so S:N values are often underestimated. Also shown on the right side of the panel are the CPA distances for which the S:N ratios are computed.

During all periods, bowheads traveled predominantly NE or ENE along the lead. A few whales sighted from the ice camp and aircraft may have altered their headings to avoid closer approaches to the projector (see Table 6.5 on p. 274), but other whales that appeared to be feeding headed generally south toward the landfast ice and projector. Two bowheads seen 940 m WSW of the operating projector at 17:26 appeared to temporarily modify their path at that time and distance in response to the icebreaker playback. They resumed traveling toward the ice camp a few minutes after the projector was turned off at 17:30. Another group reversed course WSW away from the projector; that group may have been feeding. Some whales sighted WSW to N of the ice camp during the playback had northerly rather than NEerly headings, suggesting that they may have been altering their tracks to avoid closer approach to the projector. However, during the post-playback period, bowheads did not resume traveling along the landfast ice near the ice camp; after the playback more bowheads traveled along the pack-ice edge forming the north (far) side of the nearshore lead than along the landfast ice, in contrast to the situation before and during the playback.

On 9 May 1994, traveling whales at their CEPA were exposed to $RL_{BB,max}$ as high as 118 dB re 1 µPa, $RL_{1/3,max}$ as high as 111 dB re 1 µPa, $S{:}N_{BB,max}$ as high as 18 dB, and $S{:}N_{1/3,max}$ as high as 26 dB. The group sighted 940 m from the projector at 17:26 appears to have modified its path at $RL_{BB,max}$=107 dB re 1 µPa, $RL_{1/3,max}$=101 dB re 1 µPa, $S{:}N_{BB,max}$=7 dB, and $S{:}N_{1/3,max}$=16 dB.

There were no clear differences in the distribution or behavior of presumably-feeding bowheads during the control versus playback periods. Bowheads that were apparently feeding near the projector while it was silent continued to do so, sometimes within a few tens of meters of the projector, while icebreaker sounds were transmitted. The strongest levels received by feeding whales exceeded 130 dB re 1 µPa ($RL_{BB,max}$); the highest icebreaker:ambient ratio was >40 dB ($S{:}N_{1/3,max}$). These whales appear to have tolerated levels 15-20 dB higher than did the closest traveling whales on this date.

14 May 1994 Playback

The ceiling on 14 May was low, preventing aerial observations of bowhead behavior. The Twin Otter crew conducted a reconnaissance survey (from 08:55 to 10:12) to help the ice-based crew find a suitable ice camp location where bowheads were present. The ice camp was set up 70 km ENE of Point Barrow on the landfast ice edge along a major lead oriented E-W (Fig. 3.8, p. 77). North of the ice camp the lead was ~3-4 km wide. Small pieces of brash ice were scattered throughout the lead. The crew arrived on the ice at 09:51 and remained there until 21:34. Very weak test-tones were projected from 13:24 to 14:08; these were considered too weak to be disturbing. Strong tones were projected from 14:08 to 15:45. Icebreaker sounds were projected from 15:50 to 19:00 with a brief interruption from 17:52:02 to 17:52:31. One side of the Argotec projector plus the J-11 projector were used on this date. The measured water depth at the projectors was 40 m.

Ice-based Observations.—About 30 bowheads (~24 groups or singletons) were estimated to have moved by within view (<1800 m) of the ice camp during 11.8 h of observation. One-half of the groups were observed before the projectors began broadcasting sounds. Few (3) groups were sighted after the playback, and these three groups were seen ≤30 min after playbacks ended.

A total of ~17 bowheads (~13 groups or singletons) were observed during control observations from 09:49 to 14:08; sightings during projection of very weak tones were considered control observations. Many of these groups were engaged in activities other than traveling, i.e., socializing and possibly feeding. As a result, the headings of whales were variable and even the headings of traveling whales may have been influenced by the activities of these non-traveling groups (Fig. F-27). The closest observed approach to the silent projectors was <50 m (visual estimate, Table F-4). This group of 3 whales did not appear to react to the helicopter as it landed at the camp ~150 m away. The next closest CEPAs were <232 and 282 m. Nine groups (64%) were observed <500 m from the projectors.

While the projectors were broadcasting strong tones from 14:08 to 15:45, ~6 bowheads (5 groups or singletons) were sighted by observers at the ice camp. All whales were headed ENE or ESE up the lead at medium speed. Most groups (83%) were observed >1000 m from the projectors at or near their probable CPA while tones were being projected.

From 15:50 to 19:00, while icebreaker sounds were being projected, ~3 singletons were sighted by observers at the ice camp. The two whales with known headings were traveling ENE up the lead at medium speed. The other whale was briefly engaged in aerial activity (tail slapping at 18:35, Fig. F-28). The closest observed approach to the projectors was 509 m (theodolite measurement). The other two bowheads were each observed once ≥1900 m from the projectors (Fig. F-28).

During the post-playback period from 19:00 to 21:34, ~3 single bowheads were sighted by observers at the ice camp, all ≤30 min after the playback ended. All were traveling ENE at medium speed at or near their CEPA to the ice camp. The CEPAs were ~650 m (visual estimates) by two singletons. The third whale passed the projectors at a distance of ~1760 (theodolite measurement; perch height 4.65 m).

Noise Exposure.—From 15:50 to 19:00, icebreaker sounds were projected into the lead using the J-11 and one side of the Argotec 220. There were a few brief periods when source levels were reduced by ~6 dB, but for most of the period the median broadband (20-5000 Hz) source level of icebreaker sounds was 157 dB re 1 µPa-m, considering the full 14-min cycle of the icebreaker sound. The corresponding source level for the dominant 1/3-octave band was 151 dB near 80 Hz. Figure F-29A indicates the variability in

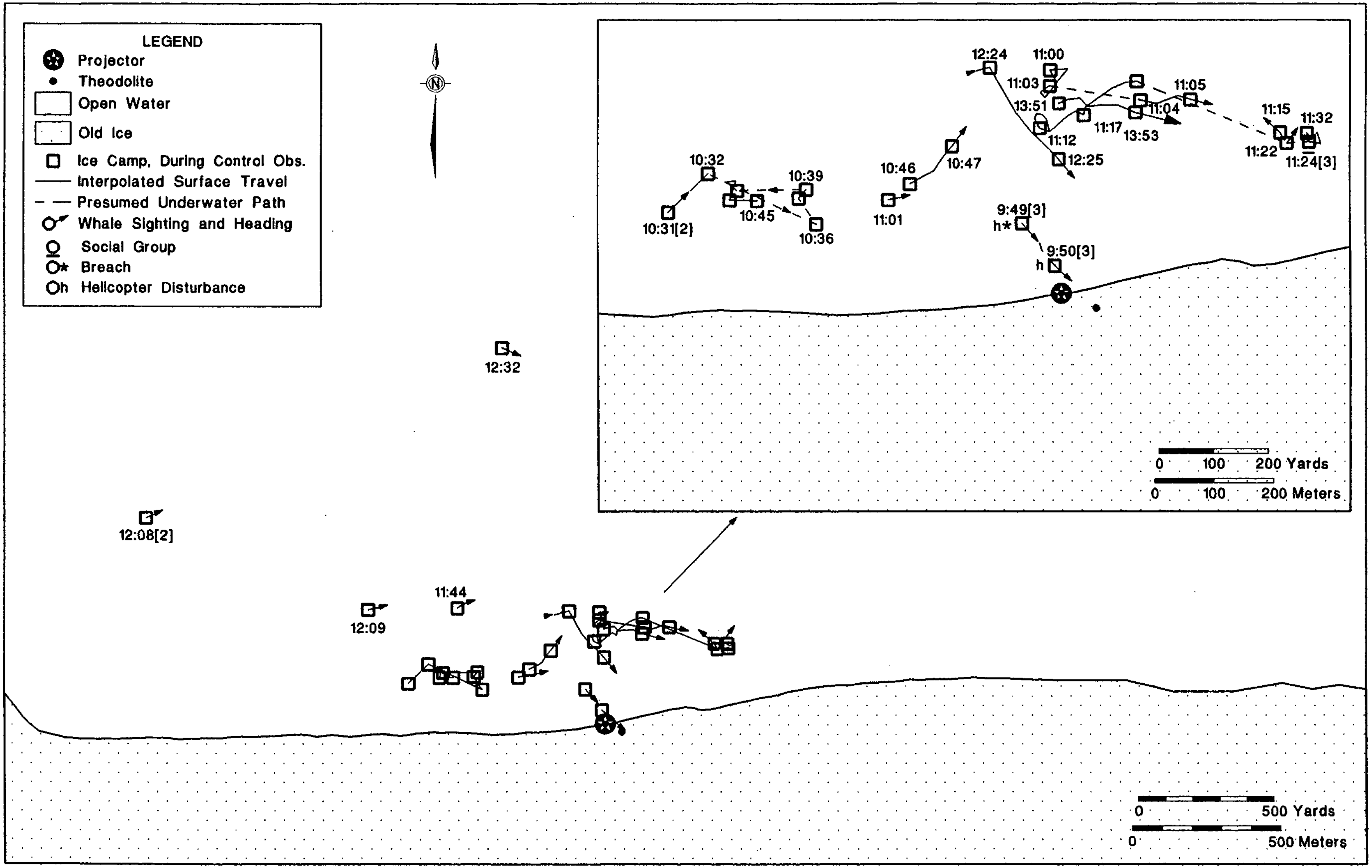


FIGURE F-27. Ice-based observations of bowhead tracks relative to the silent projectors (pre-playback) along the landfast ice NE of Pt. Barrow, 14 May 1994, times 09:49 to 14:07.

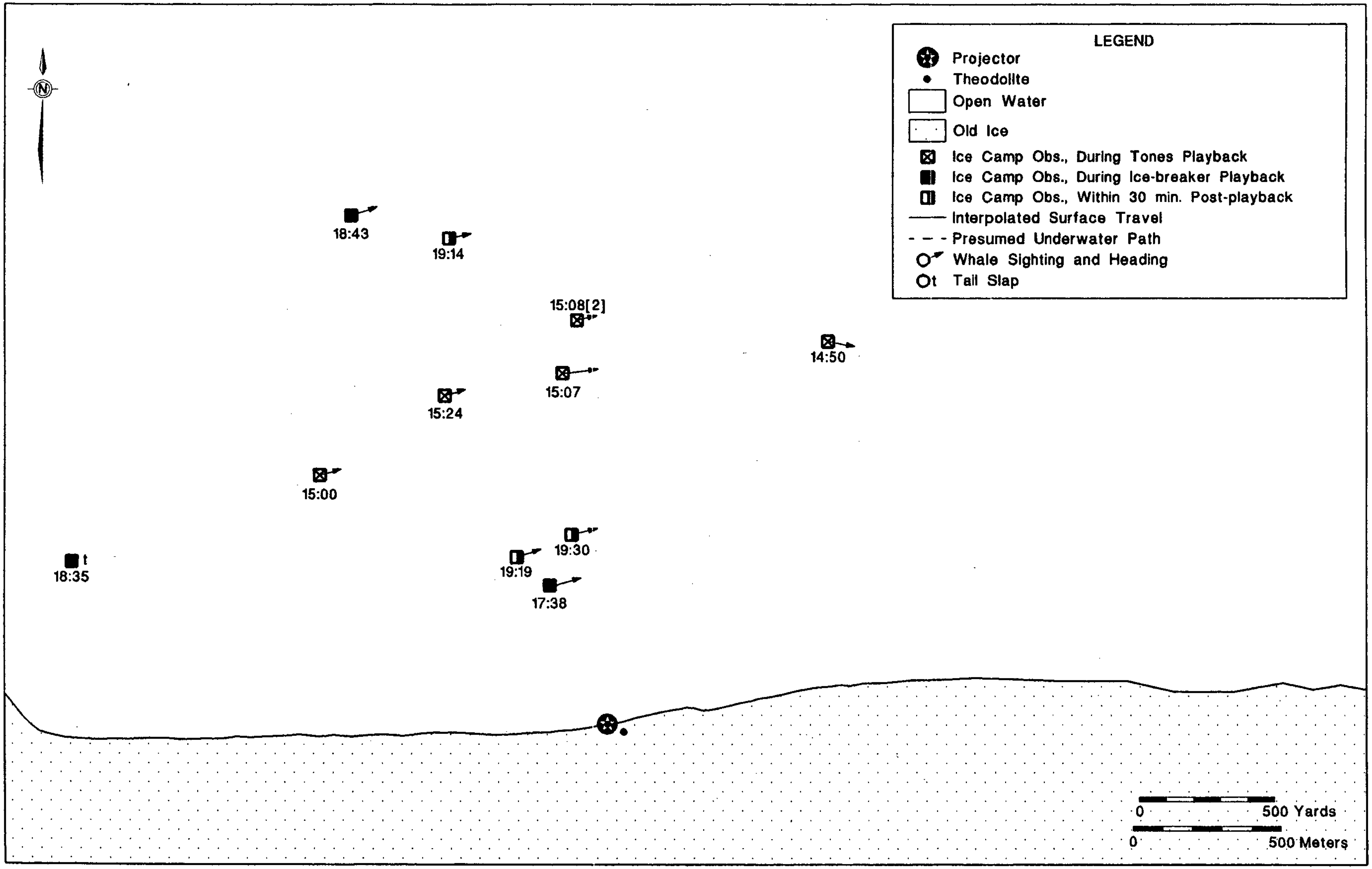


FIGURE F-28. Ice-based observations of bowhead tracks relative to the sound projectors along the landfast ice NE of Pt. Barrow, 14 May 1994, times 14:08-21:34. The projectors broadcasted tones from 14:08 to 15:45 and icebreaker sounds from 15:50 to 19:00.

TABLE F-4. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 14 May 1994.

		Radial Distance	CEPA[a]		Sight-		Estimated Sound Levels Near Whales[d]								
	Group	Followed From	Distance		ing		RL_{BB}		$RL_{1/3}$		$S:N_{BB}$		$S:N_{1/3}$		
Time	size	Projector (m)[e]	(m)	Time	ethod	Crew	med	max	med	max	med	max	med	max	Nature of Track
A: Pre-Playback Control (09:51 to 14:08)															
09:49	3	-150 to -50	<50	09:49:00	2	IC									N of projector heading SE; social. No apparent reaction to heli. ~150 m S of whales, 1 whale breached, others remained at surface as heli. turned then landed on ice at 9:50. Whales dove under ice edge ~20 s after heli. landed
10:31	2	-680 to -433	433	10:36:00	1	IC									NW of projector, heading variable/social mill; spyhop, feeding?
10:46	1	-320 to -312	300	10:46:25	1	IC									NW of projector heading NE
11:00	1	+350 to +398	340	11:02:02	1	IC									N to NE of projector, heading variable/slow mill
11:01	1	single sighting	<334	11:00:56	1	IC									NW of projector heading ENE
11:12	2	-290 to +510	282	11:12:21	1	IC									N to NE of projector, slow mill with overall heading to NE. Joined group below at ~11:24, socialize and aerial
11:15	1	+465 to +510	460	11:15:21	1	IC									NE of projector heading NNW. Joined group above at ~11:24
11:44	1	-636 to -631	<631	11:44:19	1	IC									NW of projector heading ENE
12:08	2	single sighting	<1710	12:08:20	1	IC									NW of projector heading ENE
12:09	1	single sighting	<895	12:09:05	1	IC									NW of projector heading ENE
12:24	1	-408 to -232	<232	12:25:24	1	IC									Subadult, N of projector heading ENE then SE, 13 min after heli. overflight
12:32	1	single sighting	<1335	12:31:34	1	IC									NNW of projector heading ESE
13:51	1	+327 to +329	327	13:51:08	1	IC									N of projector heading ESE
B: Playback of Tones (14:08 to 15:45)															
14:50	1	single sighting	1510	14:50:00	1	IC									NE of projector heading ESE
15:00	1	single sighting	<1295	15:00:15	1	IC									NW of projector heading ENE
15:07	1	-1212 to -1210	1210	15:07:11	1	IC									N of projector heading ENE
15:08	2	single sighting	1390	15:08:19	1	IC									N of projector heading ENE
15:24	1	single sighting	<1250	15:24:24	1	IC									NW of projector heading ENE
C: Icebreaker Playback (15:50 to 19:00)															
17:38	1	-515 to -510	509	17:37:49	1	IC	107	109	98	99	9	11	11	12	NNW of projector heading ENE
18:35	1	single sighting	1900	18:35:00	1	IC	*98*	*102*	*93*	*95*	*0*	*4*	*14*	*16*	WNW of projector, heading unknown; tail slaps
18:43	1	single sighting	1950	18:43:12	2	IC	104	109	101	103	6	11	22	24	NW of projector heading ENE

TABLE F-4. Continued.

Time	Group size	Radial Distance Followed From Projector (m)	CEPA[a] Distance (m)	CEPA[a] Time	Sighting ethod	Crew	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S:N_{BB}$ med	$S:N_{BB}$ max	$S:N_{1/3}$ med	$S:N_{1/3}$ max	Nature of Track
D: <30 min After Playback (19:00 to 19:30)															
19:14	1	single sighting	1760	19:14:29	1	IC									NNW of projector heading ENE
19:19	1	single sighting	650	19:19:00	2	IC									NW of projector heading ENE
19:30	1	single sighting	650	19:30:30	2	IC									N of projector heading ENE
E: Post Playback Control (>19:30 – No whales were observed)															

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] Data in italics are not included in analyses of traveling whales because this whale was engaged in aerial activities.

[e] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

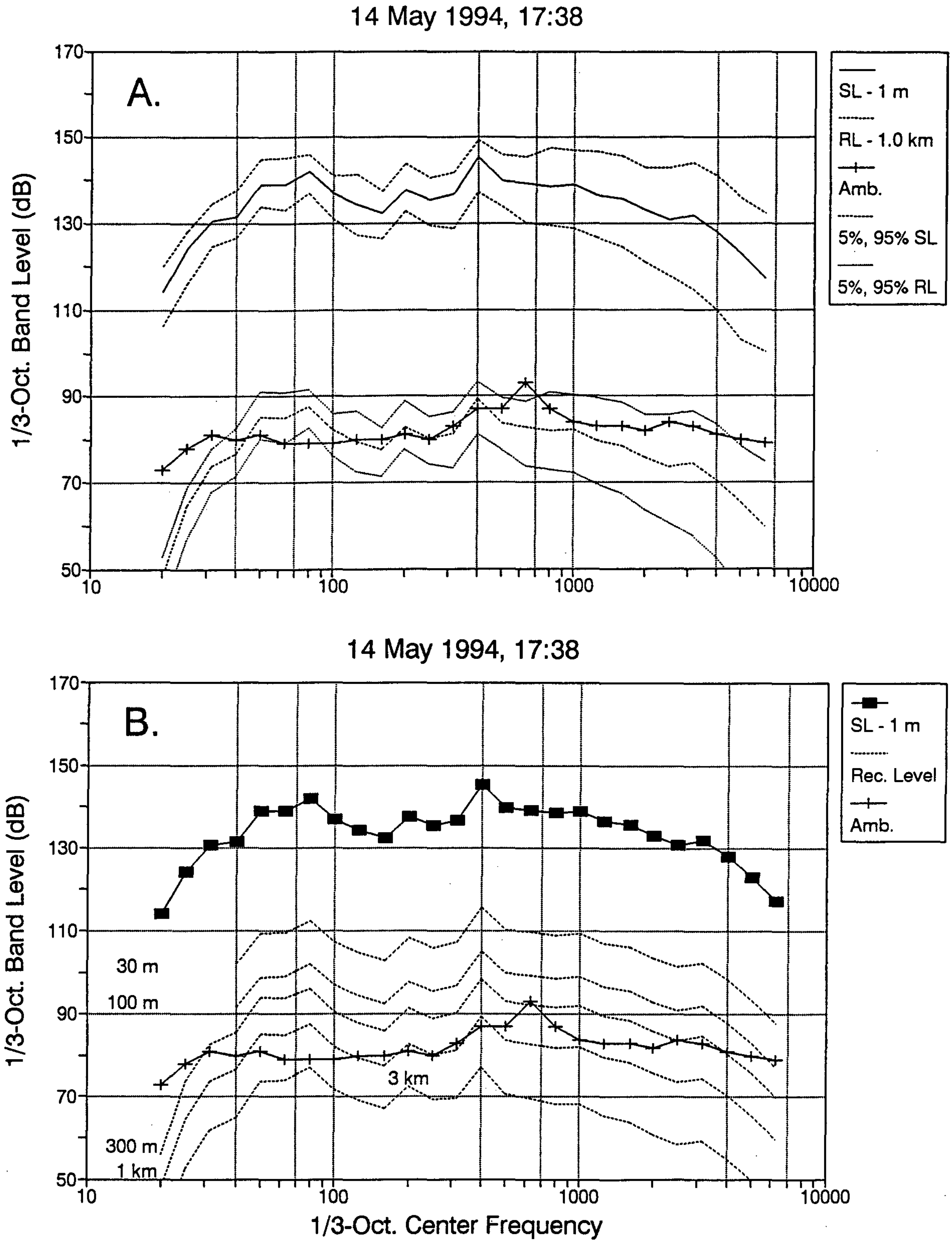


FIGURE F-29. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 14 May 1994, time 17:24-17:38. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level after playback. For additional explanation, see caption to Figure F-2 or F-3.

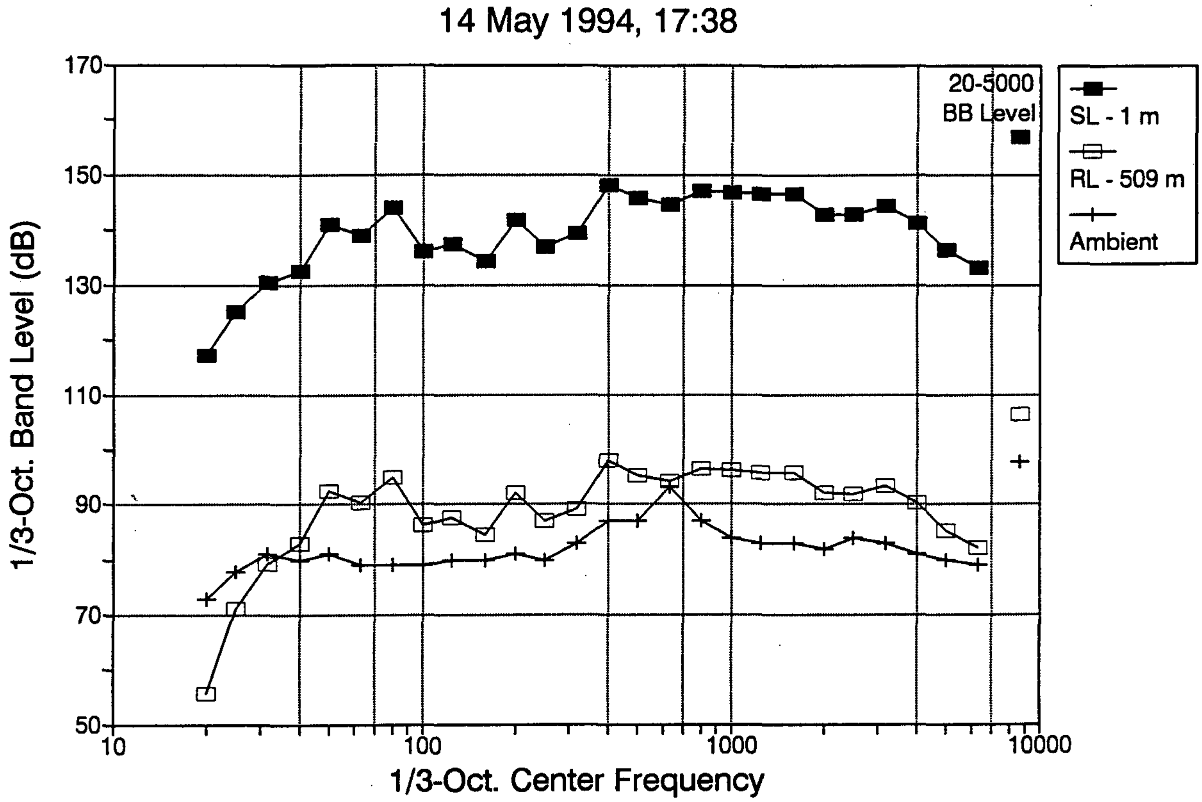


FIGURE F-30. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near a bowhead 509 m from the projector (median level over 1 min), 14 May 1994, time 17:38. Plus signs show average ambient noise level after playback. For additional explanation, see caption to Figure F-4.

the sounds as projected (1-m source levels) and received at 1 km range. Figure F-29B shows the median received levels at several standard distances at the same time.

Ambient noise was measured from the monitor hydrophone after the playback experiment. The ambient noise level was 98 dB re 1 µPa broadband (20-5000 Hz) and 93 dB for the strongest 1/3-octave band (centered at 630 Hz). Ambient noise in the 1/3-octave band centered at 80 Hz was 79 dB re 1 µPa; this band had the dominant source level of icebreaker sounds.

The closest whale to the operating projectors on this day was sighted 509 m away at 17:38 (Fig. F-28); the whale was traveling tangential to the projectors and dove at approximately the same distance. In the preceding 64-s period, the median and maximum broadband received levels at that distance were estimated as 107 and 109 dB re 1 µPa. The median and maximum 1/3-octave levels were 98 and 99 dB in the band centered at 400 Hz. Thus the median and maximum icebreaker:ambient ratios in the strongest 1/3-octave bands were 11 and 12 dB. However, the icebreaker:ambient ratios in the band centered at 80 Hz were 16 and 17 dB, respectively, given that the ambient noise was weaker in that 1/3-octave band (Fig. F-30). The only other two whales sighted during the playback were ~1900 m from the projectors at 18:35 and 18:43. The median and maximum received levels at that distance at 18:43 were 104 and 109 dB re 1 µPa broadband and 101 and 103 dB in the 1/3-octave near 80 Hz, on the usual 64-s basis. The median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were 22 and 24 dB.

Summary.—On 14 May 1994, the ice camp was set up on the landfast ice edge 70 km ENE of Pt. Barrow (see Fig. 3.8 on p. 77) along a 3-4 km wide nearshore lead. All observations were from the ice because low ceilings prevented behavioral observations from the aircraft. A total of 17 bowheads (13 groups) were observed during 4.3 h of pre-playback observation while the projectors were silent. Nine of these groups were seen relatively close (<500 m) to the silent projectors. The closest CEPA relative to the ice camp was ~50 m, during the pre-playback control period. During playbacks of tones (for 1.6 h) and icebreaker sounds (for 3.2 h), five and three groups, respectively, were sighted. They were all >500 m from the projectors; the closest sighting was 509 m away during the icebreaker playback. Three other groups sighted <30 min after the playback ended were also >500 m from the projectors. Thus the distribution of whales relative to the ice edge appears to have changed during the day. The closest whale observed during the icebreaker playback was exposed to an estimated $S{:}N_{1/3,max}$ of 17 dB. One whale seen farther from the projectors at a time of higher source level was exposed to $S{:}N_{1/3,max}$ = 24 dB. During the pre-playback control period, many of the whales seen were socializing and perhaps feeding, but during and after playbacks only traveling whales were observed.

16 May 1994 Playback

The ice camp was set up on the north side of a large elongated ice pan that had broken off the landfast ice edge. The lead bordering the north side of the pan was a secondary (offshore) lead amidst the pack ice. The main nearshore lead was south of the elongated pan. The ice camp was ~8 km north of the landfast ice edge. The secondary (offshore) lead was oriented ENE-WSW. The width of the secondary lead directly north of the ice camp was ~3 km. The lead contained scattered brash ice and was covered with slush ice that froze during the day. A large pan SW of the ice camp pan rotated counterclockwise during the day such that, in the afternoon, it extended diagonally across the inner lead south of the ice camp pan. This rotating pan had originally been part of the ice camp pan.

Aerial reconnaissance from 08:14 to 09:37 showed that many bowhead whales were traveling along the offshore lead far to the east of the area described above. However, a few whales were traveling in the offshore and nearshore leads in the described area. Given the prevailing logistic, ice and weather conditions, it was decided to attempt a playback at the site described above. The ice-based crew was present from 09:56 to 19:00. Tones were projected from 12:50 to 12:59 and icebreaker sounds from 13:03 to 17:13. The projector configuration included one side of the Argotec 220 plus the J-11. The measured water depth at the projectors was 149 m.

Ice-based Observations.—A total of ~4 bowheads (3 groups or singletons) moved by within view of the ice camp (<1500 m) during 9.1 h of observation (Table F-5). All sightings occurred while the projectors were broadcasting icebreaker sounds. The closest observed approach to the ice camp was 570 m (theodolite measurement; Fig. F-32). This bowhead was observed at 14:25 resting at the surface for <30 sec and oriented NE. The other two CEPAs were at 840 and 775 m. The first of these was a pair of bowheads sighted NW of the projectors and traveling NE along the lead at slow speed from 14:28 to 14:29. The second was a singleton that rested at the surface for at least 6 min while oriented WSW in a hole in the consolidated slush ice. The singleton reoriented to the ESE when it slipped below the surface at 15:54.

Aerial Observations.—Two aerial observation sessions were conducted on 16 May 1994. During the first session, bowheads were followed from 4.8 km SW of camp at 12:17 to 5.9 km SE of camp at 14:21 (Fig. F-31, F-32). Two whales were observed WSW of the ice camp traveling NE along the south side of the offshore lead. One group of five individuals was actively socializing in the same area. One identifiable whale was followed from 12:53 to 14:17 while tones (12:50-12:59) and then icebreaker noise (13:03-17:13) were projected into the lead (Fig. F-31, F-32). After the icebreaker playback started (13:03), this focal group and all other whales observed from the circling Twin Otter diverted from the offshore lead through a narrow crack in the elongated pan. This crack provided a route into the inner lead. The focal group then passed 2.0-2.3 km SSW of the projectors along the south side of the ice camp pan, i.e. the north side of the inner lead. The CEPA of the focal whales was during the icebreaker playback. Given the earlier sightings

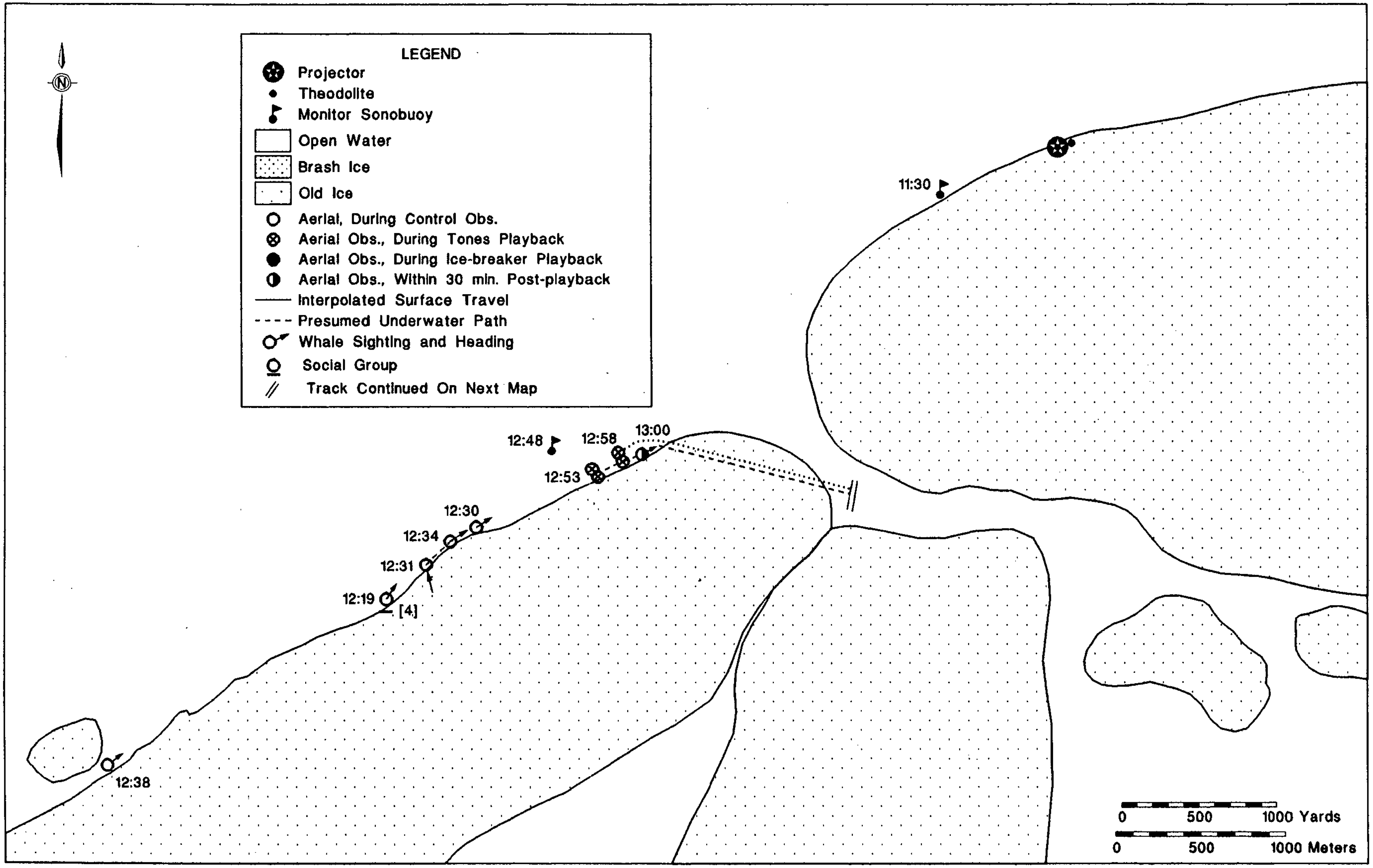


FIGURE F-31. Aerial observations of bowhead tracks relative to the sound projectors amidst the pack ice NE of Pt. Barrow, 16 May 1994, times 12:17-13:01. The projectors broadcasted tones from 12:51 to 12:59.

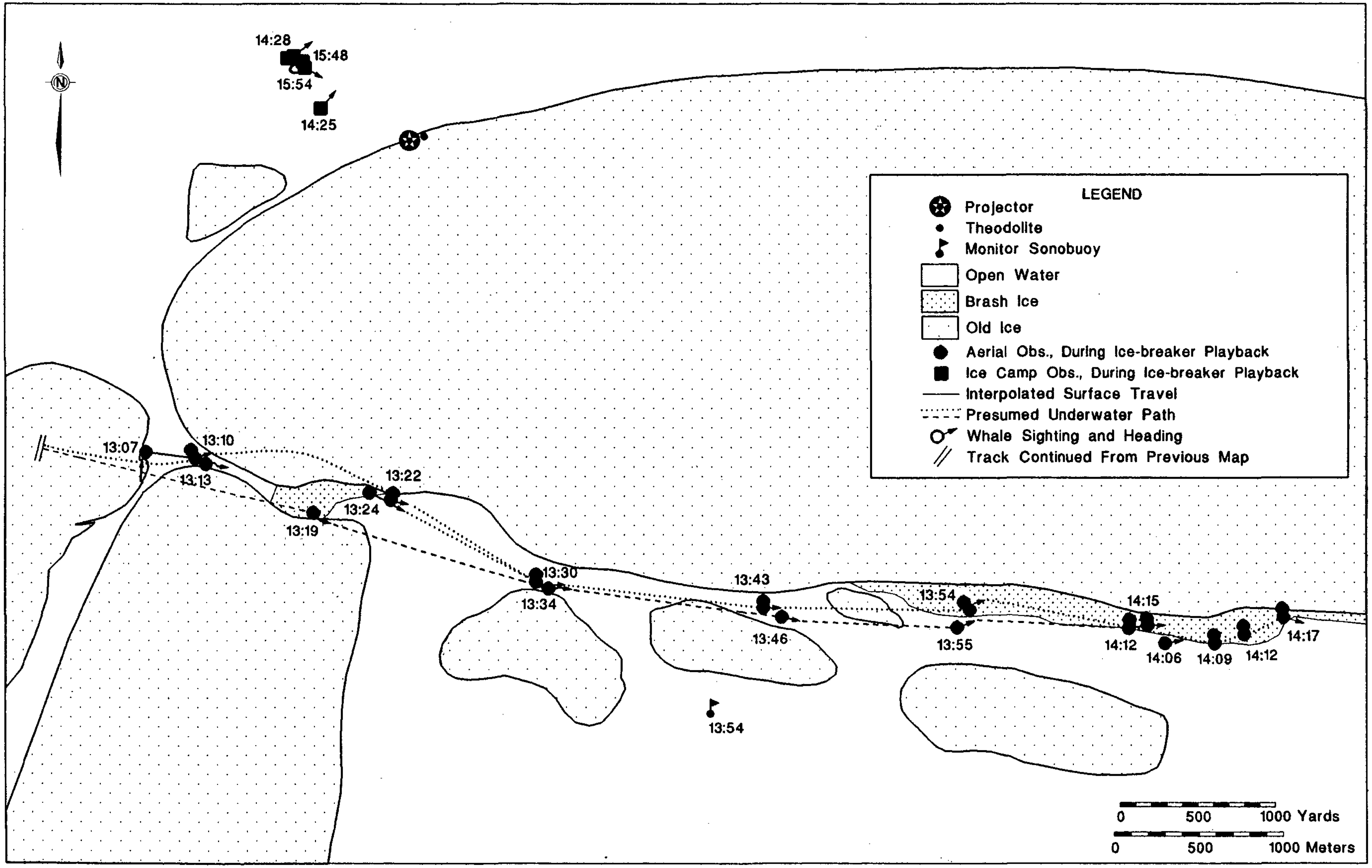


FIGURE F-32. Aerial and ice-based observations of bowhead tracks relative to the sound projectors amidst the pack ice NE of Pt. Barrow, 16 May 1994. The projector broadcasted icebreaker sounds from 13:03 to 17:13. Aerial observations of bowhead tracks are shown for the period 13:02-14:21. Ice-based observations of bowhead tracks are shown for the period 13:02-17:13.

TABLE F-5. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 16 May 1994.

Time	Group size	Radial Distance Followed From Projector (m)[d]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S:N_{BB}$ med	$S:N_{BB}$ max	$S:N_{1/3max}$ med	$S:N_{1/3max}$ max	Nature of Track
A: Playback of Tones (12:50 to 12:59)															
12:53	2	-3300 to -3150	3150	12:58:45	2	A									SW of projector heading NE along ice edge, turned ESE. Whales resighted during playback
B: Icebreaker Playback (13:03 to 17:13)															
13:13	1	-3150 to +5900	2300	13:13:14	2	A	106	109	100	102	17	20	22	24	SSW of projector heading SSE, then E along S edge of pan with projector. 1 of 2 above whales, appears to have diverted from initial NNE heading
13:07	2	-2420 to +4200	2000	13:14:00	4	A	105	109	98	103	16	20	22	27	2 adults SSW of projector following S edge of pan with projector
13:19	1	-3150 to +5100	2250	13:18:45	2	A	105	107	98	99	15	18	24	25	S of projector heading SSE then E along S edge of pan with projector. 1 of 2 whales initially described at 12:53, appears to have diverted from initial NNE heading
14:25	1	single sighting	570	14:25:09	1	IC	110	115	102	107	20	26	26	30	NW of projector resting at surface oriented NE
14:28	2	-855 to -840	840	14:29:12	1	IC	108	113	101	104	19	24	27	29	NW of projector heading slowly NE
15:48	1	-805 to -775	775	15:53:40	1	IC	114	119	108	110	24	30	34	36	NW of projector resting for 6 min at surface oriented WSW then NE in hole in consolidated slush ice

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

of whales along the south side of the outer lead, it is possible that the whales diverted southward to avoid closer approach to the projectors broadcasting tones and then icebreaker sounds. However, changes in the ice configuration, i.e. the opening of a route into the nearshore lead, could also have contributed to or caused the observed diversion from the outer to the inner lead.

The second aerial observation session was conducted 9 km SW of the ice camp at the SW end of the outer lead from 14:31 to 16:22 (Fig. F-33). Five bowheads were observed actively socializing or traveling slowly eastward. Most whales dove under the large consolidated ice pan SW of camp and moved into the inner lead south of the ice camp pan. The projectors were broadcasting icebreaker noise throughout. The eastward movements were not expected given the general NE movement of whales earlier in the day. Earlier in the day whales were following the NW side of the large consolidated pan toward the ice camp. During this session one whale actually traveled SE from 15:11 to 15:25 (Fig. F-33). However the large consolidated pan had rotated ~45° counterclockwise since the morning, and the changes in the paths of the whales may have been due to the changes in ice configuration, which now provided routes from the outer lead to the inner lead.

Noise Exposure.—From 13:03 to 17:13 icebreaker sounds were projected into the lead using the J-11 and half of the Argotec 220. Source levels were adjusted up and down by 2-3 dB during the projection period, but for most of the period the median broadband (20-5000 Hz) source level over a full 14-min cycle of icebreaker sounds was 166 dB re 1 μPa-m. The corresponding source level for the dominant 1/3-octave was 158 dB for the band centered at 80 Hz. Figure F-34A indicates the variability in the sounds as projected (1-m source levels) and received at 1 km range. Figure F-34B shows the median received levels at several standard distances at the same time.

A 57A sonobuoy was manually deployed 715 m WSW of the ice camp along the southern edge of the outer lead at 11:30. The aircraft crew deployed two sonobuoys along the path of the whales followed by the aircraft crew (Fig. F-31, F-32). The first was dropped 3.4 km WSW of the ice camp at 12:48 in the outer lead. The second sonobuoy was dropped 3.8 km SSE of the projectors in the inner lead south of the ice camp pan at 13:54. Ambient noise was measured by hydrophone at the ice camp before and after the playback experiment, from the first sonobuoy before and after the experiment, and from the second sonobuoy after the playback experiment. The average broadband (20-5000 Hz) ambient noise level was 89 dB re 1 μPa, and the ambient noise levels in the 1/3-octave bands centered at 400 and 80 Hz were 79 and 75 dB (Fig. F-34).

The closest whale to the operating projectors on this day was sighted 570 m away at 14:25 (Fig. F-32). The whale was resting at the surface oriented NE. When it dove, it would have approached slightly closer to the projectors. At that time and horizontal distance, the median and maximum broadband received levels were estimated as 110 and 115 dB re 1 μPa in the previous 64-s period. The median and maximum 1/3-octave levels were 102 and 107 dB in the band centered at 500 Hz. Thus the median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were 26 and 30 dB (Fig. F-35).

A whale sighted 775 m from the projectors at 15:54 may have been subjected to stronger sounds. The median and maximum broadband received levels were estimated to be 114 and 119 dB re 1 μPa (over 64 s), and the median and maximum 1/3-octave levels were 108 and 110 dB near 80 Hz. The median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were 34 and 36 dB.

The CEPA of the whales followed by the aircraft-based crew was ~2.0 from the projectors at 13:14 while it was broadcasting icebreaker noise. At that time and horizontal distance, the median and maximum broadband received levels were estimated as 105 and 109 dB re 1 μPa (64-s basis). The median and maximum 1/3-octave levels were 98 and 103 dB in the band centered at 500 Hz. Thus the median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were estimated to be 22 and 27 dB.

Icebreaker sounds apparently were clearly audible to bowheads seen during the second aerial observation session that was conducted ~9 km southwest of the operating projectors, given the comparatively high source level and low ambient level on this date. A bowhead that was observed at 15:11 turned sharply from

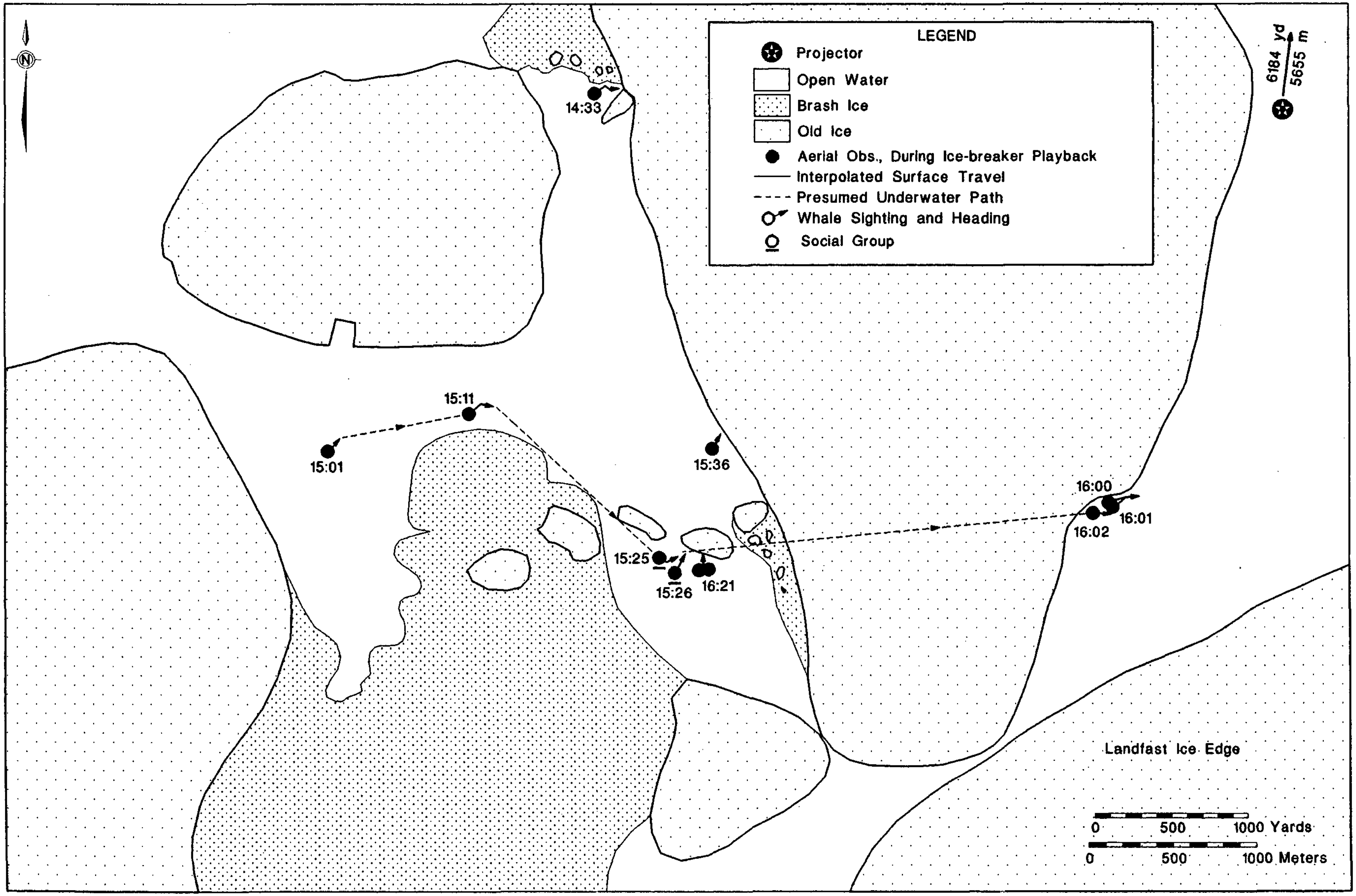


FIGURE F-33. Aerial observations of bowhead tracks relative to the sound projectors broadcasting icebreaker sounds amidst the pack ice NE of Pt. Barrow, 16 May 1994, times 14:31-16:22.

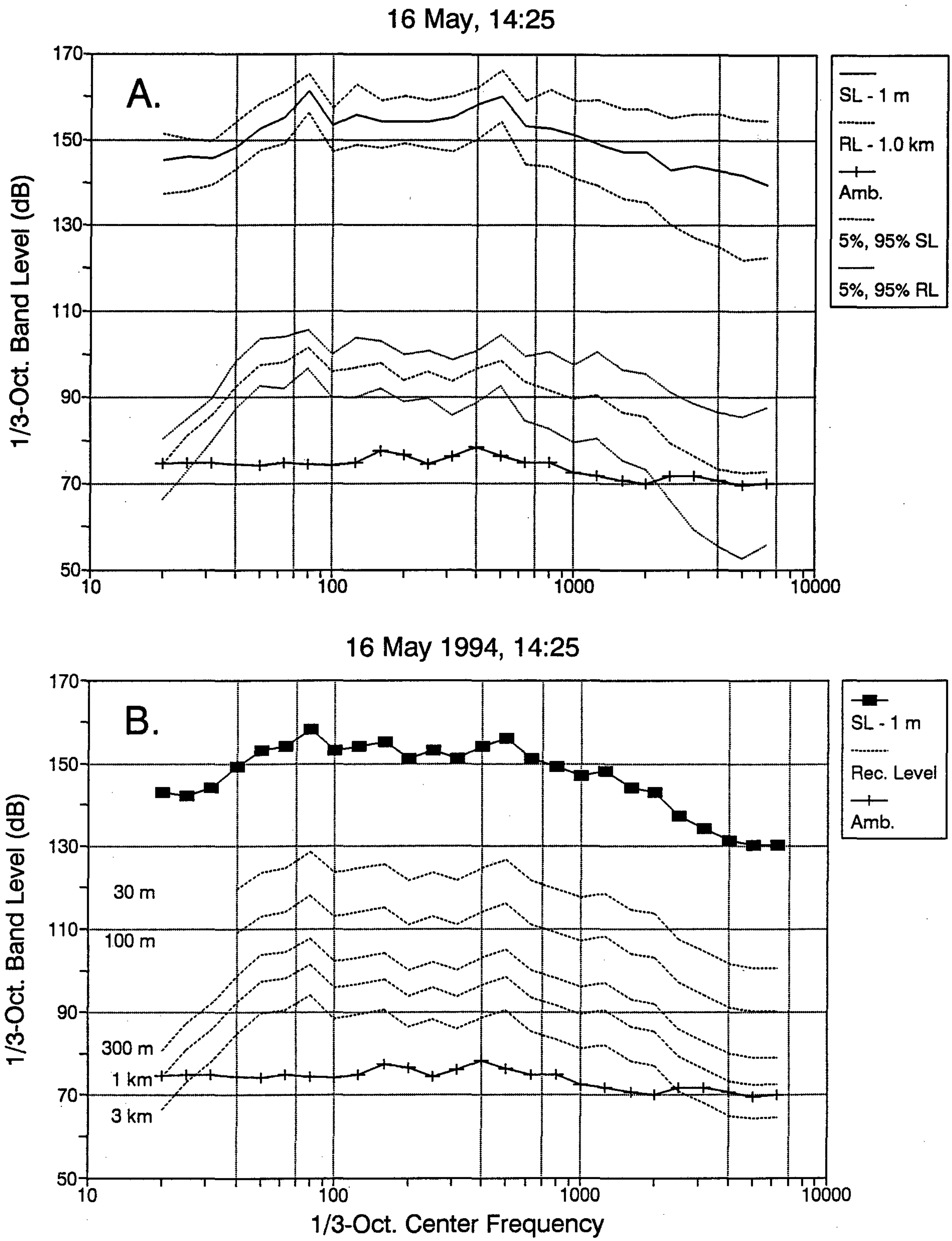
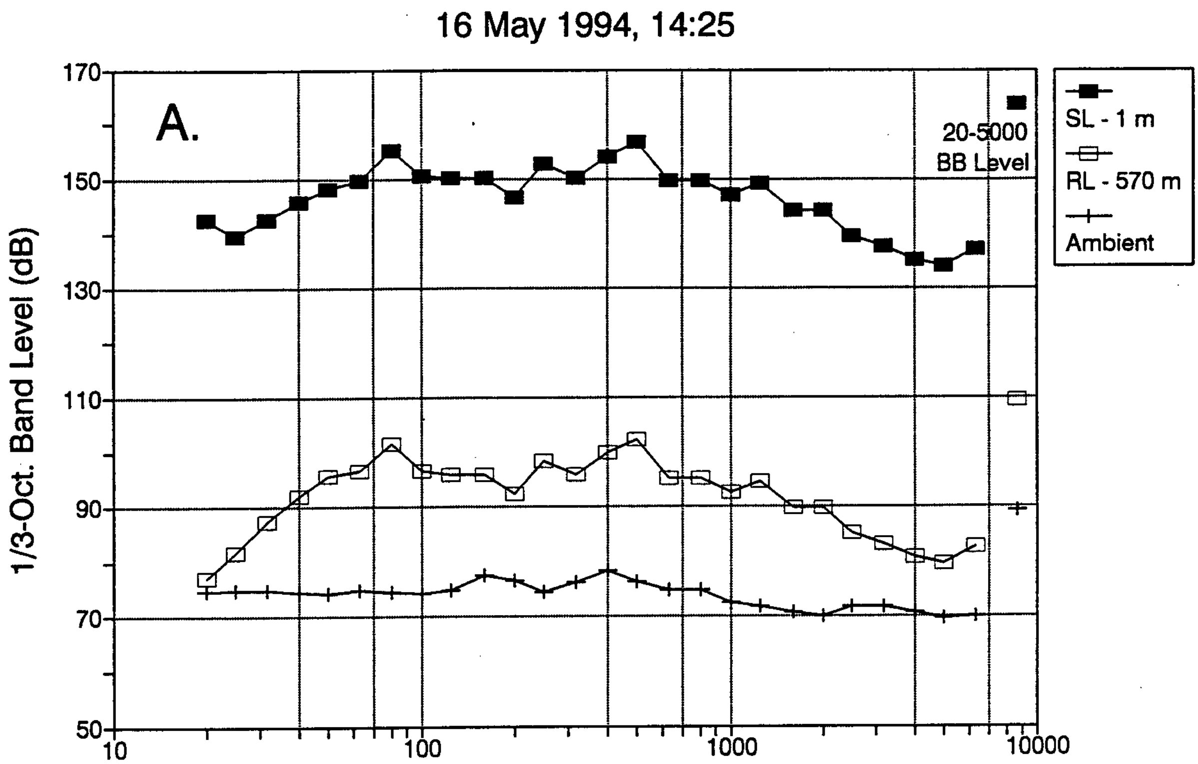


FIGURE F-34. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 16 May 1994, time 14:11-14:25. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-2 or F-3.



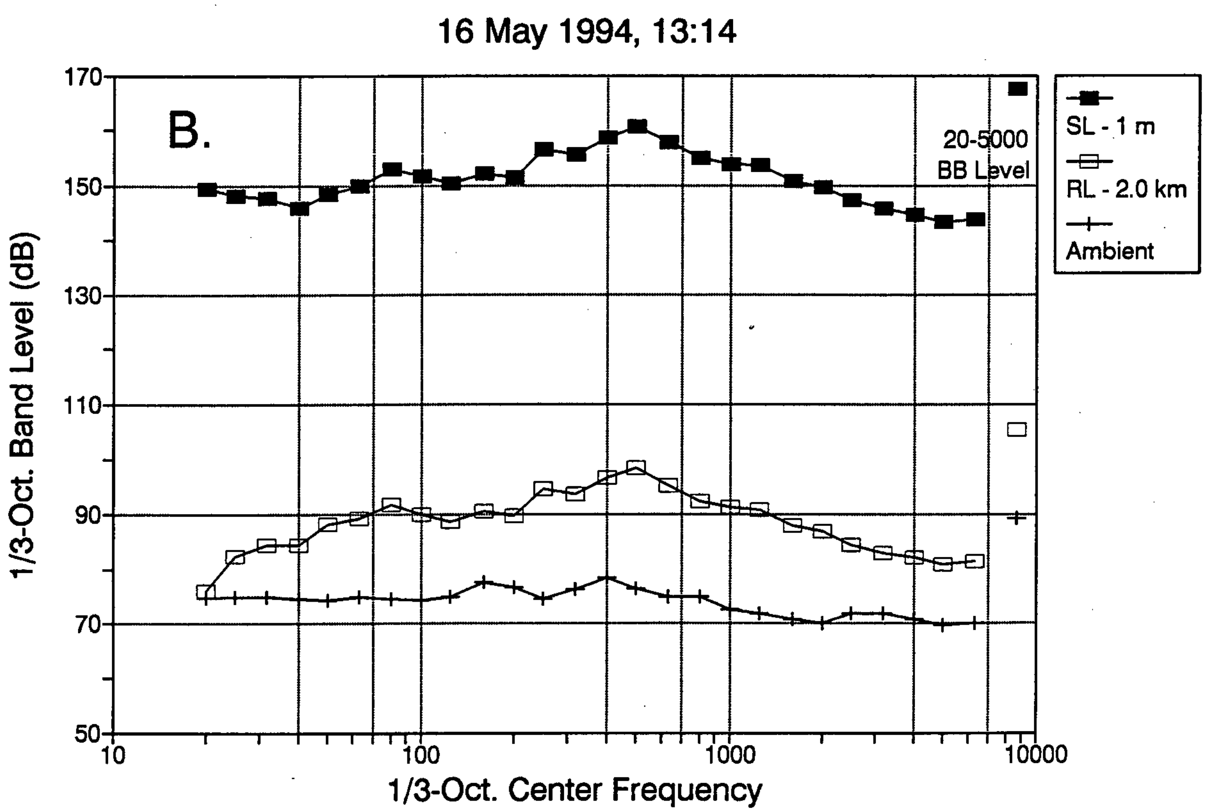


FIGURE F-35. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near bowheads *(A)* 570 m and *(B)* 2000 m from the projector (median level over 1 min), 14 May 1994, times *(A)* 14:25 and *(B)* 13:14. Plus signs show average ambient noise level before and after playback. For additional explanation, see caption to Figure F-4.

a NE heading to a SE heading while it was 9.2 km from the projectors. At that time and horizontal distance, the median and maximum received levels (over 64 s) were estimated as 93 and 99 dB re 1 μPa broadband, and 89 and 91 dB in the strongest 1/3-octave, centered at 80 Hz. Thus the median and maximum signal:noise ratios in the strongest 1/3-octave band were estimated as 14 and 16 dB. The sonobuoy dropped in the outer lead 3.4 km WSW of the camp showed received levels several decibels higher than those predicted by the model. Therefore, received levels near the whales 9.2 km southwest of the projectors may also have been higher than those estimated above.

Summary.-The ice camp was set up about 35 km NE of Pt. Barrow (Fig. 3.8 on p. 77) on the north side of a large elongated ice pan along a secondary (offshore) lead oriented ENE-WSW ~8 km north of the landfast ice edge. The ice camp was present from 09:56 to 19:00, and icebreaker sounds were projected from 13:03 to 17:13. On this date the median broadband (20-5000 Hz) source level of icebreaker sounds was ~166 dB re 1 μPa-m (relatively high) and the average broadband (20-5000 Hz) ambient noise level was 89 dB re 1 μPa (relatively low; Table 6.3 on p. 252).

Only ~4 bowheads (3 groups or singletons) moved by within view of the ice camp. All sightings there occurred while the projectors were broadcasting icebreaker sounds. The closest observed approach was to 570 m. The other two CEPAs were at 840 m and 775 m. These whales were exposed to strong icebreaker sounds (up to $S{:}N_{1/3,max}$ = 29-36 dB) but no obvious reaction was noted.

During one aerial observation session, bowheads were followed from 4.8 km SW of camp at 12:17 to 5.9 km SE of camp at 14:21. After the icebreaker playback started at 13:03, these whales diverted SE from the offshore lead through a narrow crack into the inner lead. They passed 2.0-2.3 km SSW of the operating projectors and continued east along the south side of the pan along whose north edge the ice camp was located. At CEPA, $RL_{BB,med}$ and $RL_{BB,max}$ were ~105 and 109 dB re 1 μPa, and $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were 22 and 27 dB. It is possible that the whales diverted SE to avoid closer approach to the projectors broadcasting tones and then icebreaker sounds. However, given the rapidly-changing ice configuration at the time, this "diversion" may have been related to ice conditions instead of (or in combination with) the man-made noise.

A second aerial observation session was conducted 9 km SW of the operating projectors, at the SW extent of the outer lead, from 14:31 to 16:22. Five bowheads were observed socializing or traveling slowly eastward. During this session, one whale turned from a NE to a SE heading when 9.2 km from the projectors and traveled SE. At that time and distance, $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were at least 14 and 16 dB. The unusually high icebreaker:ambient ratio for a range of 9.2 km was related to the high source level and low ambient noise on this date (Fig. F-34). Again, it is uncertain whether the SEward diversion was related to the icebreaker sounds, to changing ice conditions, or both.

17 May 1994 Playback

The ice camp was set up amidst pack ice on the south-west tip of an ice pan, at the eastern end of the main nearshore lead. The ice camp pan was bordered to the north and south by secondary leads oriented NE-SW and ENE-WSW, respectively. The width of the secondary lead south of camp increased from 200 m to 2.5 km throughout the day as ice pans drifted apart. Aerial reconnaissance from 08:39 to 09:40 showed that many bowhead whales were traveling along the main nearshore lead into the narrow ENE-WSW branch. The ice-based crew conducted observations from 11:20 to 17:15. Icebreaker sounds were projected by the J-11 projector from 12:48 to 17:02. The measured water depth at the projector was 39 m. The playback was interrupted briefly from 16:52:21 to 16:53:26. High sea states throughout the day (SS 3-6, depending on proximity of ice) limited the ability of the aerial observers to resight whales. The ice-based crew left the ice at 19:47 due to deteriorating ice and rough sea conditions.

Ice-based Observations.—Only one bowhead was sighted from camp during 5.9 h of observation. It traveled ENE up the northern lead at 13:01 as icebreaker sounds were projected (see Fig. F-38 later). Its closest observed position was 210 m from the projector. However, based on the whale's heading, its actual

CPA was probably slightly closer. The high sea state, combined with sun-glare when looking south toward across the southern lead, were at least partly responsible for the lack of ice-based sightings of bowheads in the southern lead. Bowheads continued to migrate into that lead through the day (see below).

Aerial Observations.—Five observation sessions were conducted on 17 May 1994. The first was conducted ~3.0 km SW of the silent projector from 09:41 to 10:40. Approximately eight whales were traveling ENE at slow to medium speed along the edge of some brash ice in the main nearshore lead (Fig. F-36, Table F-6). Whales were moving toward the southwest point of a large ice pan bordering the south side of the secondary lead SW of camp. A non-focal group of 3-5 bowheads was actively socializing along the south side of this point and may have attracted whales traveling along this lead. This socializing group was 2.8 km SW of camp in a small embayment formed by ice. One whale was repeatedly observed swimming in tight circles and is presumed to have been injured (09:55 and 10:29, Fig. F-36).

During the second observation session (also pre-playback control) the aerial crew followed ~8 whales from 3.8 km SW to 3.3 km ENE of the ice camp from 10:58 to 12:44. As during the previous session, whales approached the ice camp from the SW, heading for the SW point of the large ice pan south of the ice camp (Fig. F-37). They then traveled past the ice camp (CEPA distance 0.76 to 1.1 km) along the south (far) side of the southern lead. Two subadult whales 1.1 km ESE of camp were presumed to have briefly stopped to feed. They were motionless near the ice edge and then dove steeply ESE under the large ice pan bordering the S edge of the lead. One of these subadults resurfaced 100 m from where it dove 3 min earlier. Whales farther NE emerged from under the large ice pan bordering the south side of the secondary lead and then traveled more or less parallel to the ice edge, heading NE. Whales observed during this period passed 750 to 1000 m from the silent projector (visual estimates). There was no observable response from whales when a helicopter flew over the observation area at 11:37:39.

The third aerial observation session was from 13:10 to 15:05 while icebreaker sounds were being projected. The width of the secondary lead south of the camp had increased to ~1.8 km. Bowheads (~6) appeared to have followed the same general path as had the whales observed during the previous control period. They approached through the brash ice along the main lead SW of the ice camp, and then appeared to have traveled along the southern (far) edge of the secondary lead south of camp. However, the route that they followed past the projector is not known for certain. A very small whale (presumed to be a yearling) and an adult (presumed to be its mother) appeared to reverse course and may not have followed this general course. The mother and yearling were first observed SW of the ice camp, traveling ENE at medium speed, at 13:35 (Fig. F-38). The pair dove under the large pan bordering the southern edge of the secondary lead and resurfaced ~100 m farther NE. They then reversed course at slow speed and dove under the ice pan heading south at 14:44. We circled the area to the NE until 15:05 and did not resight them; they probably continued their southward path after 14:44 but, because they were not resighted, their actual route cannot be confirmed. The assumed CPA distance to the operating projector for this pair was 2400 m (visual estimate). The other ~4 bowheads may also have altered their paths when south of the projector. Two whales were heading ENE along the south side of the lead (14:34 and 14:48, Fig. F-38) when we last sighted them and another was heading SE under the ice (14:51) on the south side of the lead. As mentioned above, we circled the area east of there until 15:05 without sighting any of them. During the third observation session, the closest bowhead CPA to the projector was 1700 m (visual estimate).

The fourth aerial observation session was conducted ~4 km ESE of camp beginning 8 min after the end of the icebreaker playback at 17:02. Thus, observations began <30 min after the playback ended, and extended into the >30 min post-playback control period. Seven bowheads traveled at slow to medium speed heading NE along the secondary lead south of the ice camp. The locations and headings of all of these whales suggest that they passed the projector during the playback of icebreaker sounds, although none were seen by the ice-based observers. Contrary to the situation during the previous session, whales did not travel along the ice edge south of the ice camp but generally traveled in the center of the lead (Fig. F-39). The closest bowhead sighting to the ice camp was 1600 m (visual estimate) SW and heading toward it. The paths followed past the projector by bowheads seen from 17:35 to 18:09 is unknown.

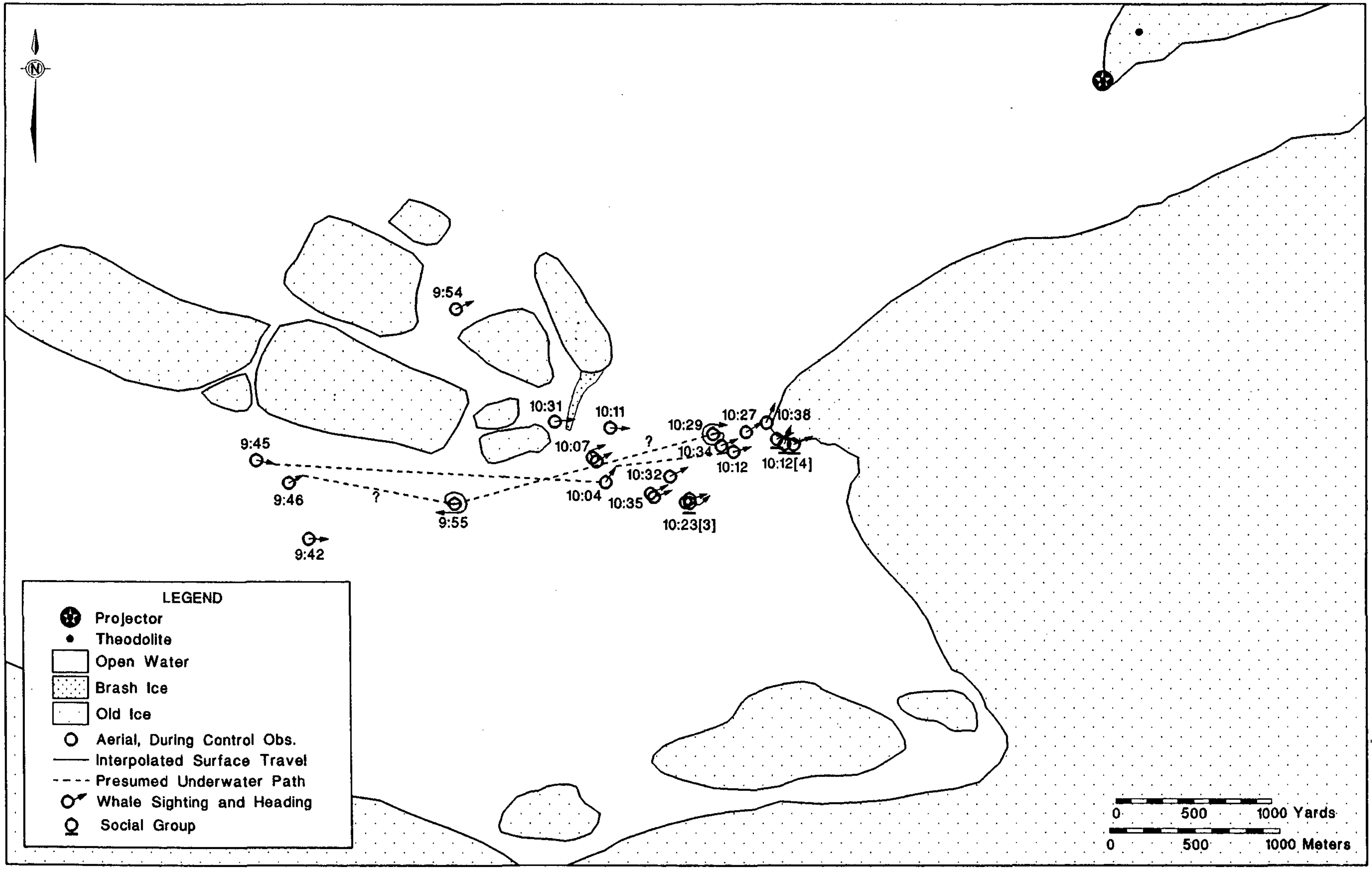


FIGURE F-36. Aerial observations of bowhead tracks relative to the silent projector (pre-playback) amidst the pack ice NE of Pt. Barrow, 17 May 1994, times 09:41-10:40.

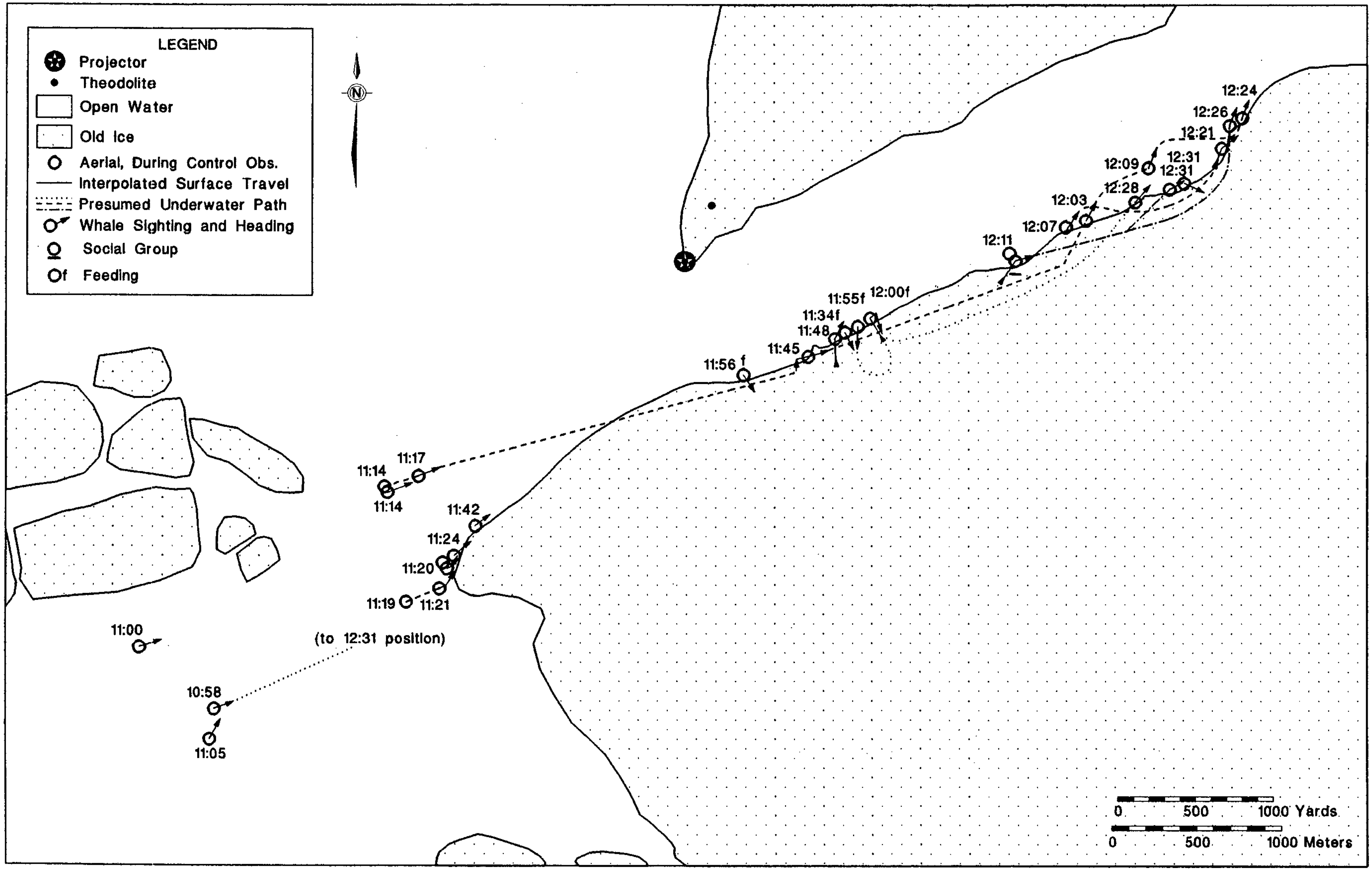


FIGURE F-37. Aerial observations of bowhead tracks relative to the silent projector (pre-playback) amidst the pack ice NE of Pt. Barrow, 17 May 1994, times 10:58-12:44.

TABLE F-6. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 17 May 1994.

Time	Group size	Radial Distances Followed From Projector (m)[d]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S{:}N_{BB}$ med	$S{:}N_{BB}$ max	$S{:}N_{1/3}$ med	$S{:}N_{1/3}$ max	Nature of Track
A: Pre-Playback Control (09:41 to 12:48)															
10:12	3	single sighting	<2800	10:11:42	2	A									SW of projector heading NE, dove under pan
9:45	1	-5400 to -3000	<3000	10:12:22	2	A									WSW of projector heading E then ENE
10:38	1	single sighting	<2800	10:37:32	2	A									SW of projector heading NNE, dove under ice pan
11:14	1	single sighting	<2200	11:15:27	2	A									SW of projector heading E
11:20	2	single sighting	<2300	11:21:21	2	A									SW of projector heading ENE, turned NNE to parallel ice edge
11:19	1	-2600 to -2500	<2200	11:21:45	2	A									SW of projector heading ENE, turned NNE to parallel ice edge
11:24	1	single sighting	<2200	11:26:52	2	A									SW of projector heading NE along ice edge
11:34	1	single sighting	1000	11:34:03	2	A									ESE of projector, resting along ice edge on S side of lead, dove under large pan heading SSE, feeding?
11:17	1	-2200 to +3300	800	11:41:00	3	A									SW of projector heading ENE, dove under large pan resurfaced SE of camp, dove under pan, resurfaced E of camp
11:47	1	single sighting	980	11:47:56	2	A									ESE of projector, surfaced from under large ice pan heading NE
11:55	1	+1100 to +2700	1100	11:54:42	2	A									ESE of projector, motionless against ice edge, dove steeply under ice edge, resurfaced ENE of projector dove under ice edge and resurfaced E of projector, feeding?
11:56	1	single sighting	<755	11:56:23	2	A									SSE of projector heading SSE, dove under large pan
12:07	2	+2300 to +3200	<2300	12:07:25	2	A									E of projector heading NNE along ice edge
12:11	2	+1900 to +3300	<1900	12:11:08	2	A									E of projector, surfaced from under ice pan, dove under ice pan
10:58	1	-3800 to +3000	<3000	12:30:34	2	A									SW of projector, resighted E of projector heading ENE, dove under ice pan
B: Icebreaker Playback (12:48 to 17:02)															
13:01	1	single sighting	<210	13:01:27	1	IC	119	123	112	117	19	24	22	26	NNE of projector heading ENE
14:33	1	single sighting	<2300	14:34:16	2	A	94	97	87	90	-8	-5	-4	-1	SSW of projector heading NE along ice edge
13:34	2	-5900 to -2400	2400	14:43:46	2	A	94	99	86	92	-7	-2	-5	1	Adult-yearling WSW to S of projector heading ENE. Appeared to reverse course, but were not seen again. Last seen traveling S.
14:47	1	single sighting	<2200	14:50:24	2	A	96	98	90	92	-6	-3	-1	1	S of projector heading NE along ice edge on S side of lead
14:51	1	single sighting	1700	14:51:10	2	A	99	101	93	95	-3	0	2	4	SSE of projector heading NNE, turned SE, dove under ice pan

TABLE F-6. Continued.

Time	Group size	Radial Distances Followed From Projector (m)	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales: RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S{:}N_{BB}$ med	$S{:}N_{BB}$ max	$S{:}N_{1/3}$ med	$S{:}N_{1/3}$ max	Nature of Track
C: <30 min After Playback (17:02 to 17:32)															
17:10	1	single sighting	<1600	17:10:04	2	A									SW of projector heading ENE
D: Post Playback Control (>17:32)															
17:35	1	single sighting	<2650	17:34:35	2	A									E of projector heading NE
17:37	1	single sighting	<3100	17:37:16	2	A									ESE of projector heading ENE
18:57	1	single sighting	<3000	18:58:11	2	A									WSW of projector heading NNE
19:00	1	single sighting	<2800	19:01:08	2	A									WSW of projector heading ESE, turned to parallel ice edge
19:08	1	single sighting	<2780	19:09:20	2	A									WSW of projector heading E
19:11	1	single sighting	<2100	19:12:56	2	A									SW of projector heading ENE
19:24	1	single sighting	<1400	19:25:27	2	A									WSW of projector heading N
19:27	1	single sighting	<1800	19:28:19	2	A									SSW of projector heading NE

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

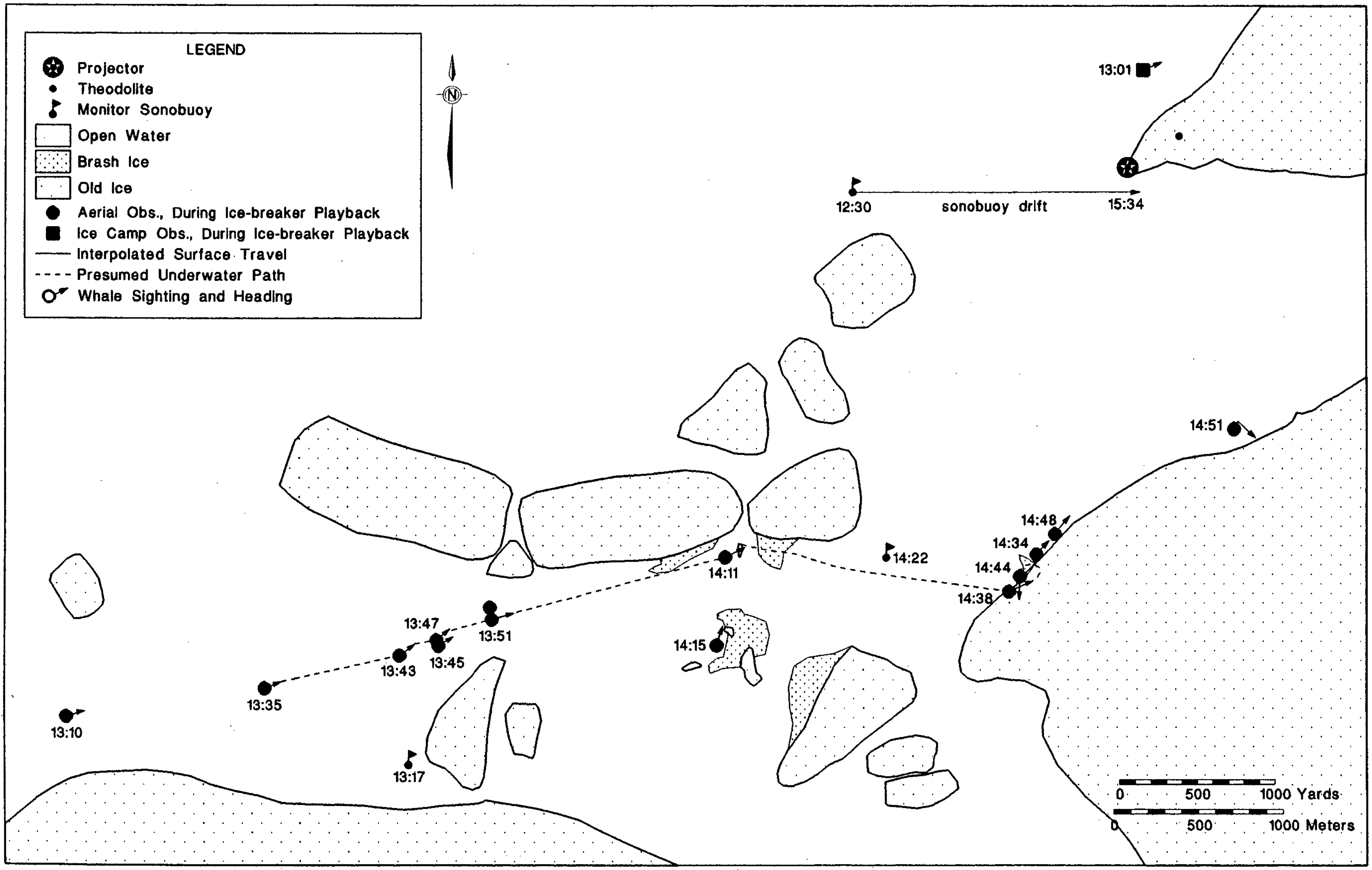


FIGURE F-38. Aerial and ice-based observations of bowhead tracks relative to the sound projector broadcasting icebreaker sounds amidst the pack ice NE of Pt. Barrow, 17 May 1994, times 12:48-17:02. Observations were conducted from 13:10-15:05 (aerial) and 12:48-17:02 (ice-based).

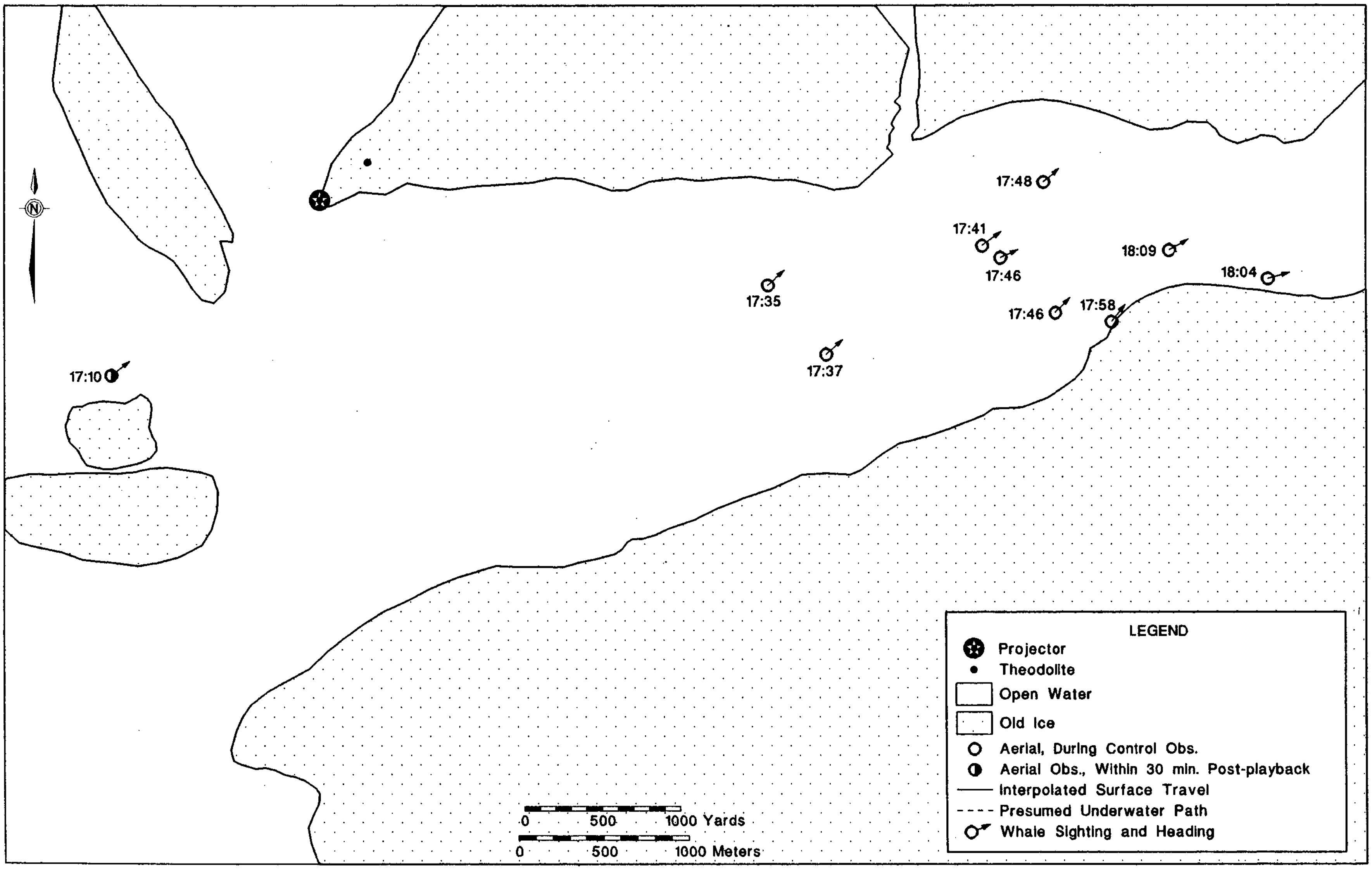


FIGURE F-39. Aerial observations of bowhead tracks relative to the silent projector (after icebreaker playback) amidst the pack ice NE of Pt. Barrow, 17 May 1994, times 17:10-18:12. The playback ended at 17:02.

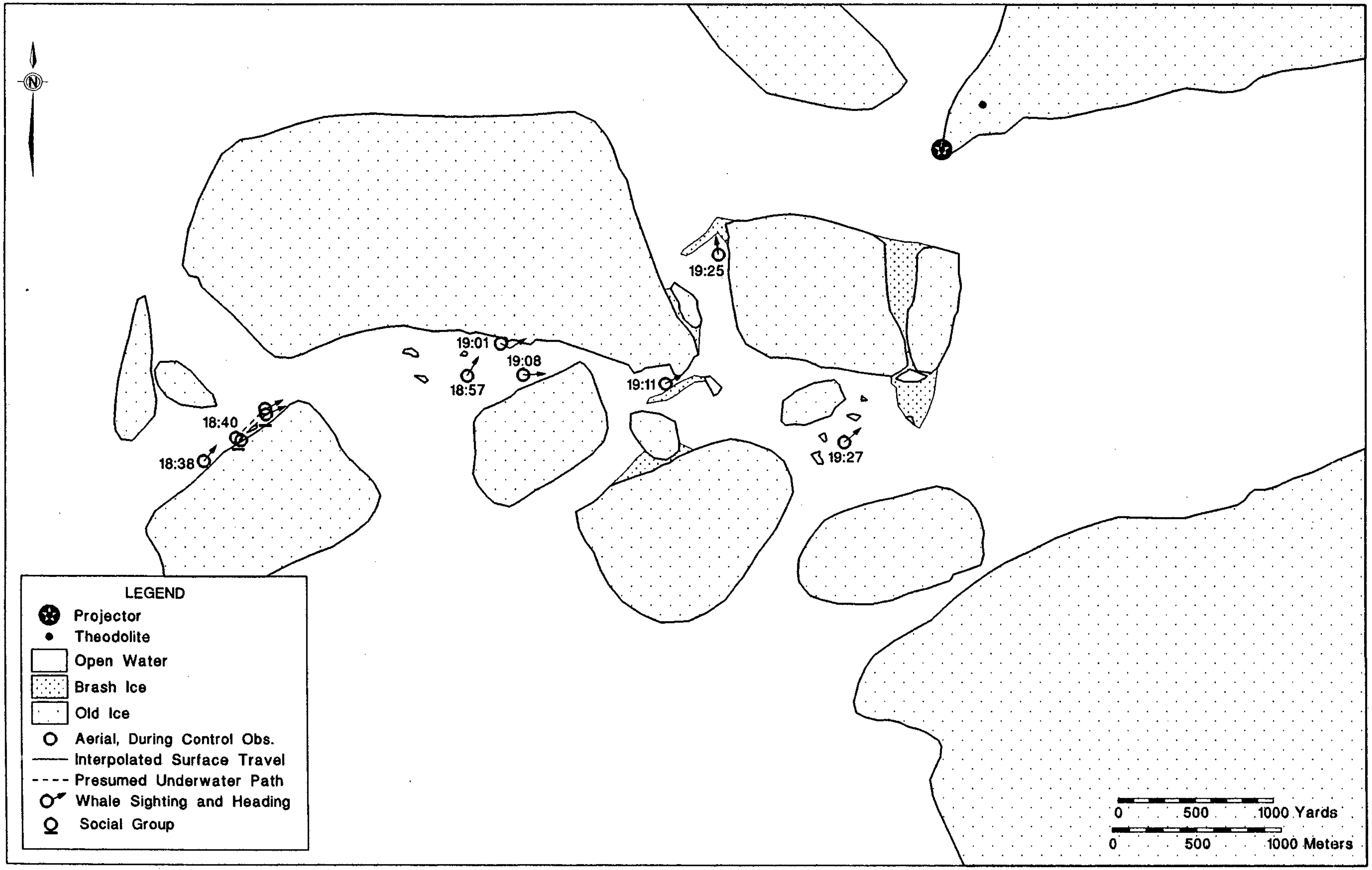


FIGURE F-40. Aerial observations of bowhead tracks relative to the silent projector (after icebreaker playback) amidst the pack ice NE of Pt. Barrow, 17 May 1994, times 18:37-19:32.

The fifth aerial observation period (control) was conducted near the ice camp from 18:37 to 19:32. Approximately five whales were traveling slowly NE or ENE amidst pack ice in the main lead SW of the ice camp (Fig. F-40). Low clouds and high sea states limited our ability to resight whales. A presumed mother and yearling were observed 4.5 km from camp traveling parallel to a large pan and heading NE. The closest whale sighting to camp was 1400 m away (visual estimate). Most of these whales would have passed 0.5-1.5 km from camp if their pattern of movement remained the same after observations stopped.

Noise Exposure.—From 12:48 to 17:02 icebreaker sounds were projected into the lead using only the J-11. It was projecting the higher-frequency components of the icebreaker sound. The Argotec 220 was in the water to project the low-frequency components but, unknown at the time, was not operating. A crossover network was in use to direct low-frequency energy to the Argotec 220. Therefore, icebreaker components below ~500 Hz were underrepresented, and little energy was projected below ~200 Hz on this date (Fig. F-41; *cf.* Fig. F-34). Source levels were adjusted during the projection period, but for most of the period the median broadband (20-5000 Hz) source level projected by the J-11 over the 14-min icebreaker cycle was ~160 dB re 1 μPa-m. The corresponding median source level for the dominant 1/3-octave was 154 dB for the band centered at 400 Hz. Figure F-41A shows the variability in the sounds as projected (1-m source levels) and as received at 1 km range. Figure F-41B shows the median received levels at several standard distances.

On 17 May 1994, a 57A sonobuoy was manually deployed 1.62 km west of the ice camp at 12:30. That sonobuoy drifted eastward, passing 50 m from the ice camp at 15:00. The distance of the drifting sonobuoy from the projector at various times was determined by cross-correlating the sounds received by a monitor hydrophone near the projector with those received by the sonobuoy. A 57B DIFAR buoy was air-dropped into the main lead 5.5 km SW of the ice camp at 13:16. A second DIFAR buoy was air-dropped 2.7 km SSW of the ice camp at 14:21 to replace the first one, which had failed. Ambient noise was measured from a monitor hydrophone at the ice camp and from the manually-deployed sonobuoy before and after the icebreaker projections. Because of gradually increasing winds during the day, the ambient noise levels increased throughout the period of playback. The average broadband (20-5000 Hz) ambient noise level was 98 dB re 1 μPa before icebreaker sounds were projected and 107 dB after the end of the playback. The latter value was higher than on any other playback day in 1991 or 1994. The ambient noise in the 1/3-octave centered at 400 Hz, where the strongest icebreaker sounds occurred, varied from 90 (before) to 93 dB (after). We estimated ambient noise levels near whales during the playback period by linear interpolation between the pre- and post-playback measurements.

The aerial observers' closest observation of a bowhead to the operating projector involved a whale 1700 m south of the projector at 14:51. The median and maximum received levels of icebreaker noise at the whale while underwater at that distance and time were estimated as 99 and 101 dB re 1 μPa broadband (64-s basis) and 93 and 95 dB in the strongest 1/3-octave band, centered at 400 Hz. At this time, the ambient noise was estimated as 101 broadband and 91 in the 1/3-octave band near 400 Hz. Thus the median and maximum icebreaker:ambient ratios were -2 and 0 dB on a broadband basis, and 2 and 4 dB in the strongest 1/3-octave bands (Fig. F-42A). Given the usual variation in source levels and ambient noise levels, the whales may have encountered slightly higher icebreaker:ambient ratios at certain times, but none of the whales under observation by aerial observers were subjected to strong icebreaker sounds.

The whale sighted closest to the operating projector was seen 210 m north of it by observers at the ice camp at 13:01. At that time and horizontal distance, the median and maximum broadband received levels (over 64 s) were estimated as 119 and 123 dB re 1 μPa. The median and maximum levels in the dominant 1/3-octave band were 112 and 117 dB in the band centered at 500 Hz. At this time, the ambient noise level was estimated by interpolation as 99 dB broadband and 90 dB in the 1/3-octave band near 500 Hz. Thus the median and maximum icebreaker:ambient ratios were 19 and 24 dB on a broadband basis, and 22 and 26 dB in the strongest 1/3-octave band (Fig. F-42B).

Summary.—On 17 May 1994, relatively large numbers (35+) of bowheads were observed as they passed within 3 km of a projector set up in the pack ice at the east end of the main nearshore lead, some

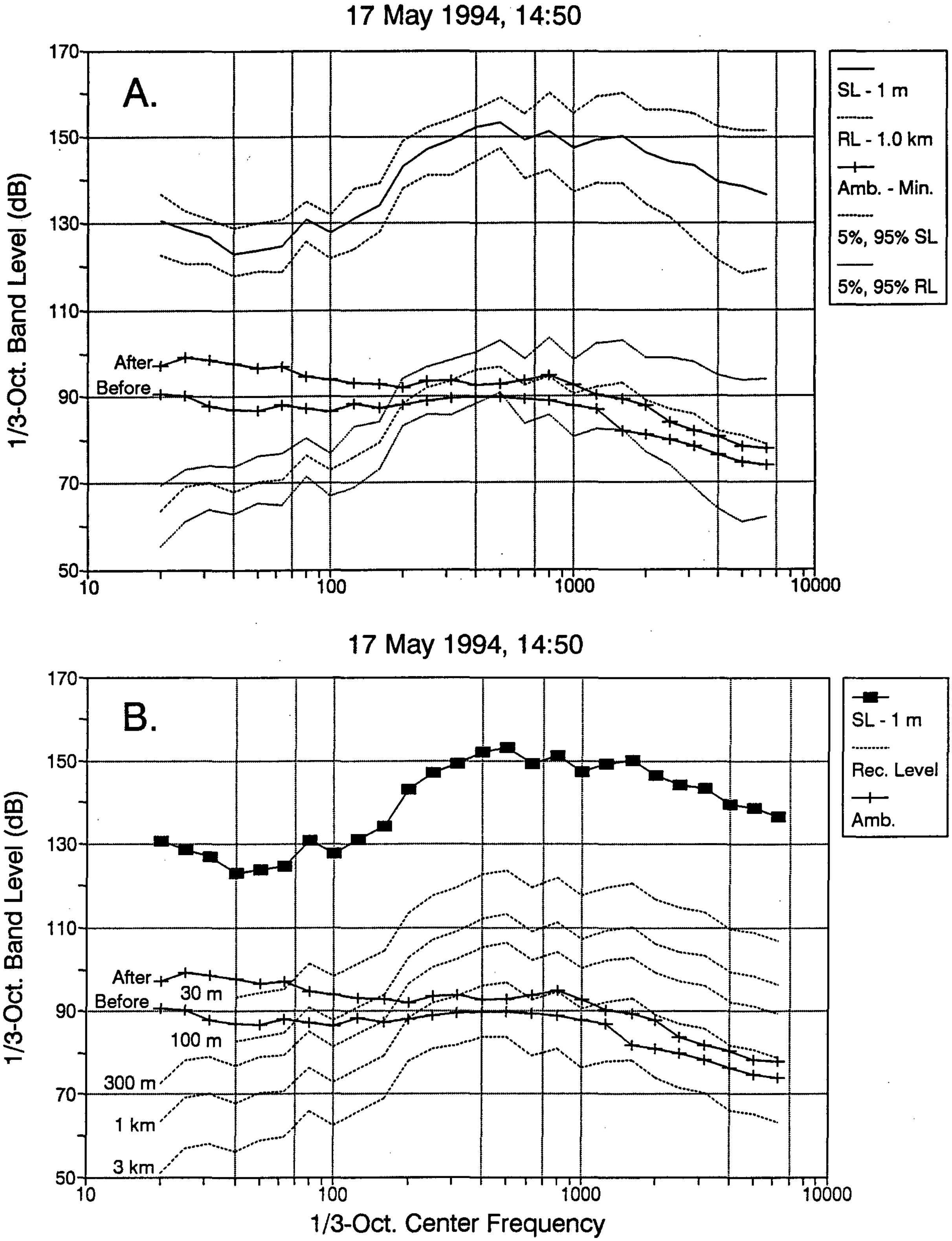


FIGURE F-41. Third-octave levels of projected icebreaker noise vs. distance from projector and ambient noise, 17 May 1994, time 14:36-14:50. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise levels before and after playback. For additional explanation, see caption to Figure F-2 or F-3.

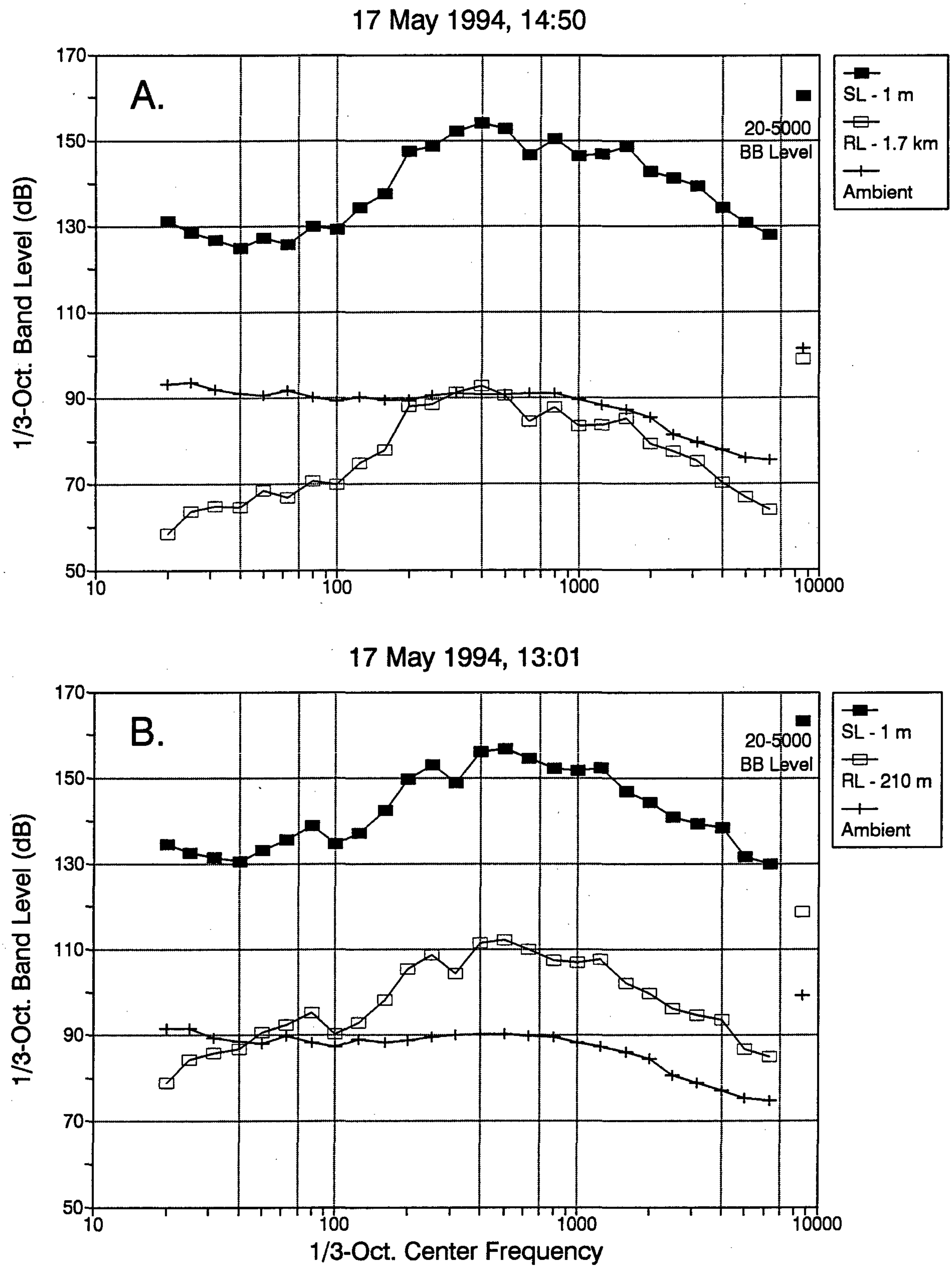


FIGURE F-42. Third-octave levels of projected icebreaker noise 1 m from the projector (closed squares) and near bowheads *(A)* 1700 m and *(B)* 210 m from the projector (median level over 1 min), 17 May 1994, times *(A)* 14:50 and *(B)* 13:01. Plus signs show estimated ambient noise levels for those times. For additional explanation, see caption to Figure F-4.

70 km ENE of Pt. Barrow (Fig. 3.8 on p. 77). High sea states hindered both ice-based and aerial observations, and caused high ambient noise levels. Also, the source level of the projected sounds was low, and the low-frequency components were largely missing, because only the J-11 projector was operating on this date. Throughout the day bowheads approached the projector from the WSW through a major lead. Most appeared to continue NE along a secondary lead extending NEward south of the projector. Only one bowhead was seen by the ice-based observers. It was seen 210 m north of the operating projector and would have been exposed to estimated $RL_{BB,med}$ and $RL_{BB,max}$ of 119 and 123 dB re 1 μPa before it surfaced. At this location and time, the icebreaker:ambient ratio in the strongest 1/3-octave band (near 400 Hz) was up to ~26 dB ($S{:}N_{1/3,max}$).

There were five aerial observation sessions. During the first two sessions (projector silent), whales traveled NE along a path that came as close as 600-800 m south of the projector, along the southern (distant) side of the secondary narrow lead. During the third session, when icebreaker sounds were being projected, some whales continued to follow that path. However, the secondary lead had by then widened to 1.8 km and icebreaker sounds were barely detectable, if detectable at all, at 1.8 km distance ($S{:}N_{1/3,max}$ ~4 dB). Two whales, a suspected mother/yearling pair, approached to 2400 m from the operating projector and then appeared to reverse course to the SW. However, it is doubtful that they could have detected icebreaker sounds at that distance, except for very briefly and weakly, because the estimated $S{:}N_{1/3,med}$ and $S{:}N_{1/3,max}$ were -4 and +2 dB.

<u>20 May 1994 Playback</u>

The ice camp was set up on the NW edge of a very large ice pan that abutted the landfast ice edge to the south, blocking the nearshore lead. There was extensive open water to the west (nearshore lead) and north. Aerial reconnaissance from 08:29 to 09:42 found that various bowhead whales were traveling eastward or socializing in the large open area SW and W of the large pan. Bowheads migrating eastward in the nearshore lead were constrained to detour north or south along the edge of this large ice pan, and any that detoured south would soon reach the landfast ice edge. The ice camp was present from 10:00 to 20:20. Icebreaker sounds were projected by the Argotec 220 (one side) plus J-11 from 12:38 to 17:17. The measured water depth at the projectors was 42 m. On this date, the source level of the projected sounds was high and the ambient noise level was low.

<u>Ice-based Observations</u>.—About 19 bowheads (~17 groups or singletons) were estimated to have passed within 3250 m of the ice camp during 10.3 h of observation. Six sightings occurred during the pre-playback control period; the remainder occurred during the playback of icebreaker sounds. No whales were sighted during a post-playback control period from 17:17 to 20:20.

Eight bowheads (6 groups or singletons) were sighted during pre-playback control observations from 10:00 to 12:38 (Table F-7). Most traveled NE or ENE at slow to medium speed as they approached the ice camp from the WSW (Fig. F-43). Two whales that were near the ice camp when the ice-based crew arrived were headed ESE or east directly under the large ice pan. One of these whales (10:02 on Fig. F-43) showed no apparent reaction to the helicopter as it landed at the ice camp ~500 m away. It is not known whether these two bowheads diverted around the pan to the north or to the south. The closest sightings to the ice camp during the control period were <20, <55, and <68 m from the (silent) projector site. The whale that approached to <55 m did so even though the helicopter had landed at the ice camp 3 min earlier <100 m from where the whale surfaced. The longest observed track was for a group of 3 whales followed for ~1 h. The group traveled slowly and socialized as it moved ENE until 11:27 when it dove under the large pan 460 m SSW of the projectors. Based on the group's heading, its CPA to the projectors was probably ~280 m. The group was resighted ~20 min later traveling north ~1000 m north of the ice camp.

In addition to the potential helicopter disturbances mentioned above, a subadult whale sighted at 12:11 showed no apparent reaction to the helicopter as it lifted off from the ice camp ~200 from the whale.

TABLE F-7. Summary of sightings of bowhead whales observed by ice-based and aerial observers, 20 May 1994.

Time	Group size	Radial Distance Followed From Projector (m)[e]	CEPA[a] Distance (m)	CEPA[a] Time	Method[b]	Sighting Crew[c]	Estimated Sound Levels Near Whales[d] RL_{BB} med	RL_{BB} max	$RL_{1/3}$ med	$RL_{1/3}$ max	$S{:}N_{BB}$ med	$S{:}N_{BB}$ max	$S{:}N_{1/3}$ med	$S{:}N_{1/3}$ max	Nature of Track
A: Pre-Playback Control (09:43 to 12:38)															
9:46	1	+2000 to +3600	2000	9:47:50	2	A									ENE of projector heading E. Aerial activity
10:02	1	-50 to -20	<20	10:02:00	2	IC									NW of projector heading SE toward ice camp. No apparent reaction to heli. as it landed ~500 m away; whale remained at surface for 5-6 blows and maintained SE heading
10:07	1	single sighting	<55	10:07:29	1	IC									NW of projector heading ESE, 3 min. after heli. overflt
11:00	1	-1200 to +2800	350	11:17:00	4	A									SW of projector heading ENE at slow speed. Resighted NNE of projector heading NE along ice edge, 13 min after heli. overflt
9:44	1 of 3	-5300 to +2140	280	11:31:30	3	IC/A									W of projector heading E, turned S and joined 2 whales below
11:00	2 of 3	-2555 to +2140	280	11:31:30	3	IC/A									SW to NE of projector; social + travel, breach; overall movement to NE at slow speed. Dove NE under pan S of ice camp, resurfaced NNE of camp heading NNE along ice edge
11:28	1	-520 to -68	<68	11:41:42	1	IC/A									Small whale SSW of projector heading slowly ENE along ice edge, dove under ice edge, resurfaced near projector, dove under ice pan outcrop heading N
11:49	1	+685 to +705	<685	11:48:35	1	IC									NE of projector heading ENE along ice edge
12:11	1	+190 to +210	190	12:11:05	1	IC									Subadult, NE of ice camp heading NW, surfaced from under pan, turned NE along ice edge, heli. landed at camp 1 min earlier
B: Icebreaker Playback (12:38 to 17:17)															
13:31	1	-2230 to -1760	<1760	13:35:08	1	IC	110	114	106	109	24	28	36	39	NW of projector heading ESE
13:32	1	-2030 to -1485	<1485	13:37:59	1	IC	112	115	107	108	26	28	39	40	NW of projector heading ESE
13:41	1	+3750 to +3250	3250	13:41:54	1	IC	102	107	97	100	16	21	27	30	N of projector heading NE
14:20	1	single sighting	<725	14:20:00	2	IC	114	118	110	112	28	32	42	44	WSW of projector heading SE then ESE
14:35	1	-600 to +1225	600	14:35:13	1	IC	112	116	105	108	26	29	35	38	NNW then NE of projector heading ENE
14:40	1	single sighting	930	14:40:00	2	IC	*107*	*113*	*101*	*109*	*21*	*27*	*31*	*39*	WSW of projector, heading unknown, breach
14:43	1	single sighting	800	14:43:00	2	IC	121	123	116	117	35	37	48	49	Heading NE, unknown position relative to projector
15:30	1	single sighting	500	15:30:03	1	IC	123	128	119	121	37	41	51	53	SSW of projector near ice edge, heading unknown
15:39	1	-115 to -58	58	15:39:47	1	IC	132	138	125	131	46	50	57	63	WSW of projector heading slowly ENE along ice edge toward projector then turned NNW away from projector at CPA
16:00	1	single sighting	<1275	16:00:28	1	IC	112	115	108	109	26	29	40	41	N of projector heading NE
16:09	1	single sighting	<920	16:09:27	1	IC	119	122	115	117	33	36	47	49	SW of projector heading ESE

[a] CEPA = Closest Estimated Point of Approach. See text for description of estimation procedures.

[b] 1 = measured by theodolite at CPA; 2 = visual estimate at CPA; 3 = estimate based on theodolite measurement(s) to nearby surfacings; 4 = estimate based on whale position(s) and heading(s) during sightings distant from CEPA (possibly unreliable).

[c] IC = ice-based crew; A = aerial crew.

[d] Data in italics are not included in analyses of traveling whales because this whale was engaged in aerial activities.

[e] "-" indicates that whales were approaching, generally from the SW or W; "+" indicates that whales were moving away, generally to the NE or E.

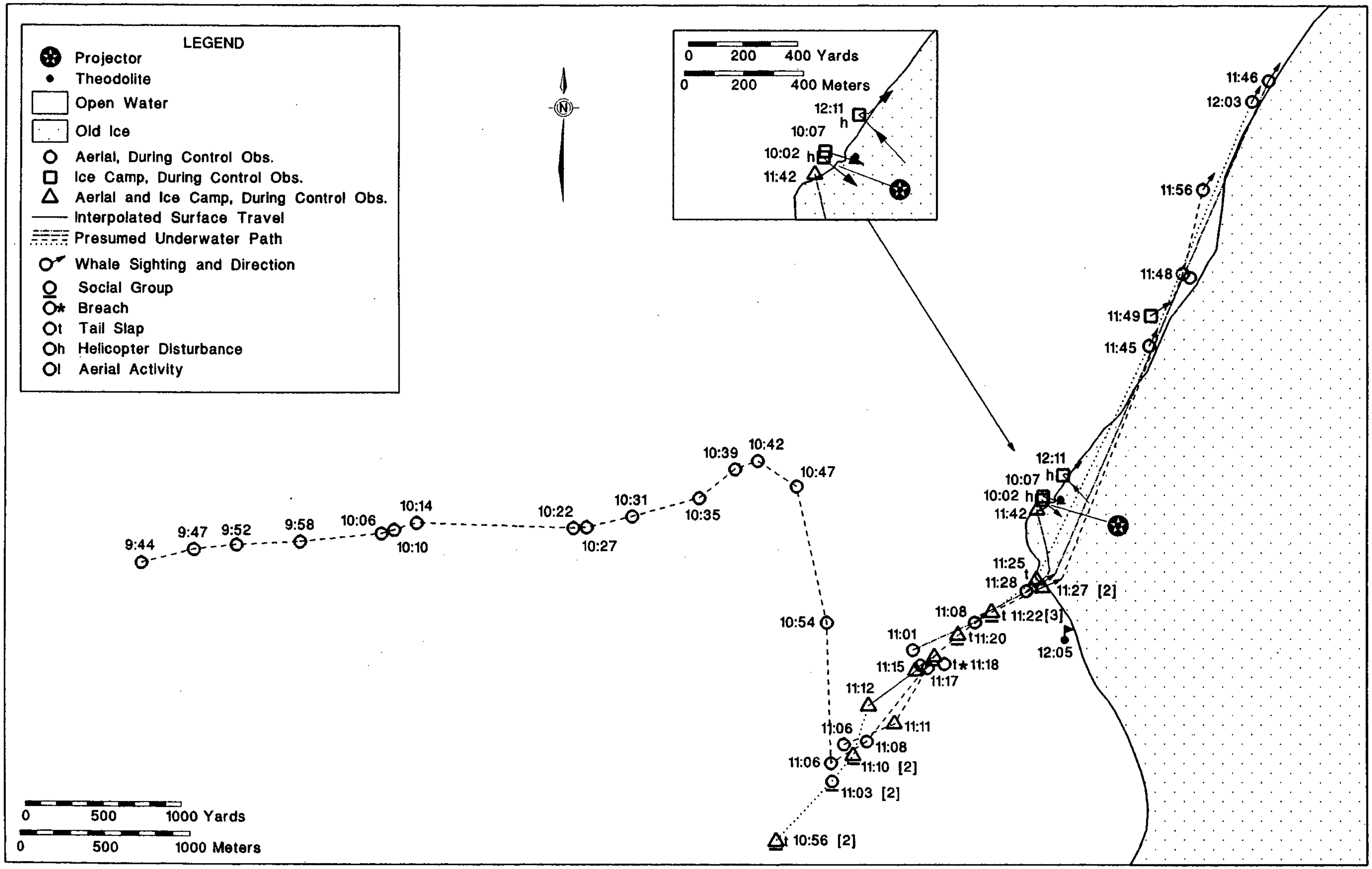


FIGURE F-43. Aerial and ice-based observations of bowhead tracks relative to the silent projectors (pre-playback) amidst the pack ice NE of Pt. Barrow, 20 May 1994, times 09:43-12:37. Aerial observations ended at 12:18.

From 12:38 to 17:17, while the projectors were broadcasting icebreaker sounds, ~11 single bowheads were sighted by observers at the ice camp (Fig. F-44, Table F-7). A lower proportion of the groups were sighted ≤500 m from the projectors during the playback period (33%) than during the control period (75%). This is evident by comparing Figures F-43 and F-44; note that the scale of Fig. F-44 is the same as that of the inset in Fig. F-43. As during the control period, most whales (7 of 8 groups with known headings) traveled generally eastward. However, one bowhead approached the camp along the ice edge to the SW and then turned sharply to the NNW away from the projectors at a distance of 58 m. This was the closest sighting to the projectors during the playback of icebreaker sounds on this date.

During the post-playback period from 17:17 to 20:20 no bowheads were sighted.

Given the consistent pattern of sightings close to the ice camp during the control period, the more distant locations of most sightings during the playback suggest that bowheads were altering their tracks to avoid the projectors. Except for the whale that approached to 58 m, the closest sightings to the operating projectors were 500-600 m away. Several whales seen 500-600 m SW of the projectors during the playback would have been expected to continue to approach the ice camp, based on observations during the control period. However, they apparently did not do so.

Aerial Observations.—Most of the bowheads observed from the ice camp during the pre-playback period were also observed over much longer distances by observers in the circling aircraft. Whales were followed from 5.3 km west of the ice camp at 09:43 to 8.3 km NNE of the camp at 12:18. A single bowhead 5.3 km W of the projectors traveled westward and then turned south to join a group of two socializing bowheads. As described above, these three whales then headed ENE and dove under the large ice pan 460 m SSW of the projectors. This group resurfaced NNE of camp and continued to travel NNE along the ice edge. The presumed CPA of their underwater track, based on general headings and locations of distant surfacings, was 280 m. It was not possible to conduct aerial observations during the playback period because, by then, low cloud had moved into the area.

Noise Exposure.—From 12:38 to 17:17, icebreaker sounds were projected into the lead using the J-11 and one side of the Argotec 220. Source levels were relatively uniform during the projection period. The median broadband (20-5000 Hz) source level of icebreaker sounds was ~170 dB re 1 μPa-m over the 14-min icebreaker cycle. The corresponding source level for the dominant 1/3-octave band was 163 dB in the band centered at 80 Hz. Figure F-45A indicates the variability in the sounds as projected (1-m source levels) and as received at 1 km range. Figure F-45B shows the median received levels at several standard distances at the same time.

On 20 May 1994, a 57A sonobuoy was manually deployed along the ice edge 765 m south of the ice camp at 12:05. Ambient noise was measured from that sonobuoy before the icebreaker projections. The broadband (20-5000 Hz) ambient noise level was 86 dB re 1 μPa, and the ambient noise in the 1/3-octave band centered at 80 Hz, where the strongest icebreaker noise occurred, was 68 dB (Fig. F-45).

The closest whale to the operating projectors was seen 58 m WSW of it by observers at the ice camp at 15:39. The whale turned to the NNW and dove away from the projectors, so it was at the surface at its CPA. At that minute and horizontal distance, the median and maximum broadband received levels below the surface were estimated as being at least 132 and 138 dB re 1 μPa. The median and maximum 1/3-octave levels were at least 125 and 131 dB in the band centered at 80 Hz. Thus the median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were at least 57 and 63 dB (Fig. F-46A). The whale would not have been exposed to levels quite this high because received sound levels, especially for low-frequency components, are lower near the water surface. However, in the minute before the approaching whale surfaced 115 m from the projectors, the median and maximum 1/3-octave levels 120 m from the projectors were estimated as 125 and 128 dB re 1 μPa, the same as or only 3 dB lower than those quoted above for range 58 m. Thus the maximum noise level to which this whale was exposed was apparently ~60 dB above the ambient level in the strongest 1/3-octave band.

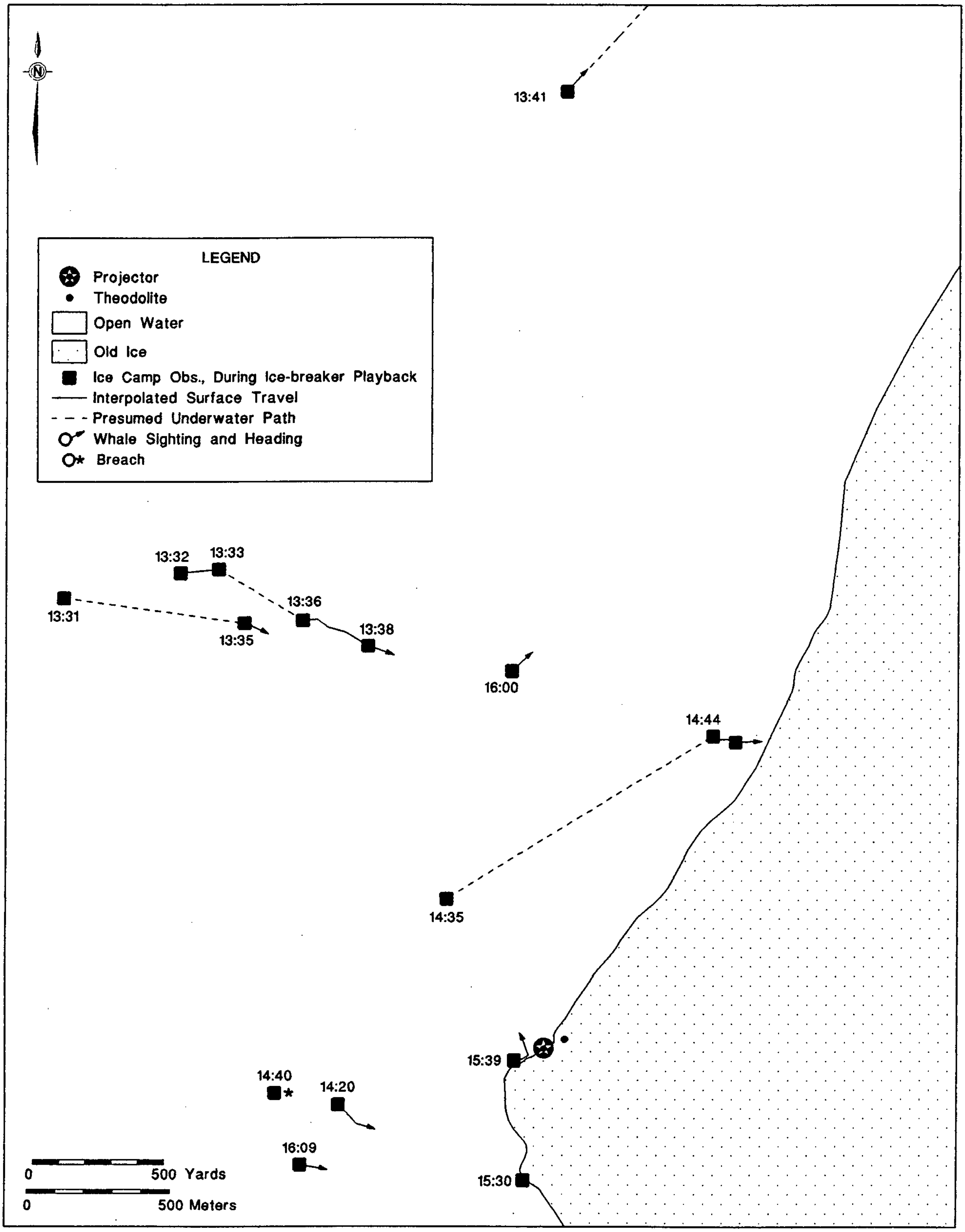


FIGURE F-44. Ice-based observations of bowhead tracks relative to the projectors broadcasting icebreaker sounds amidst the pack ice NE of Pt. Barrow, 20 May 1994, times 12:38-17:17.

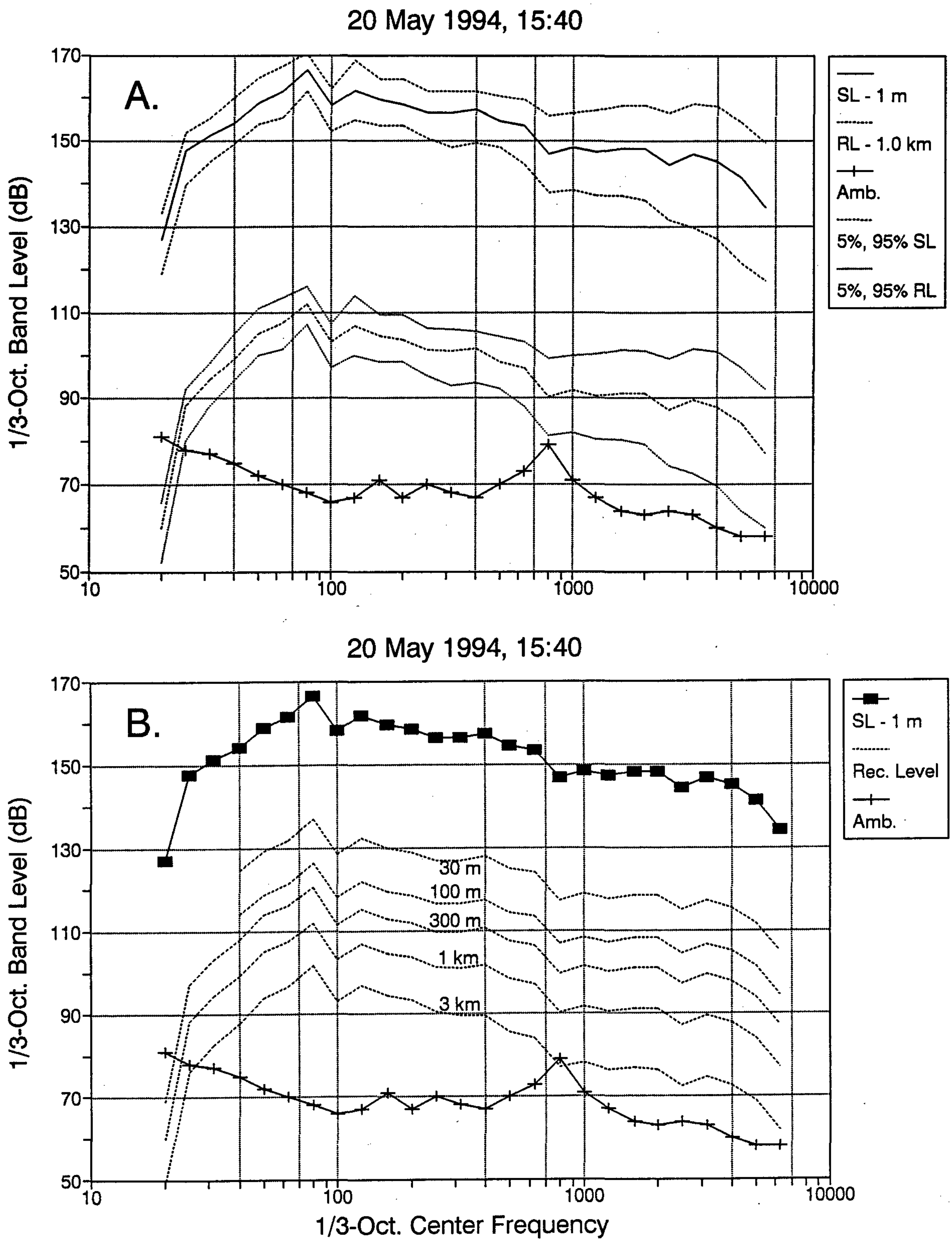


FIGURE F-45. Third-octave levels of projected icebreaker noise vs. distance from projectors and ambient noise, 20 May 1994, time 15:26-15:40. *(A)* Variability over 14 min at ranges 1 m and 1.0 km (median, 5th and 95th percentiles). *(B)* Median levels at range 1 m (squares) and 30 m-3.0 km. Plus signs show average ambient noise level before playback. For additional explanation, see caption to Figure F-2 or F-3.

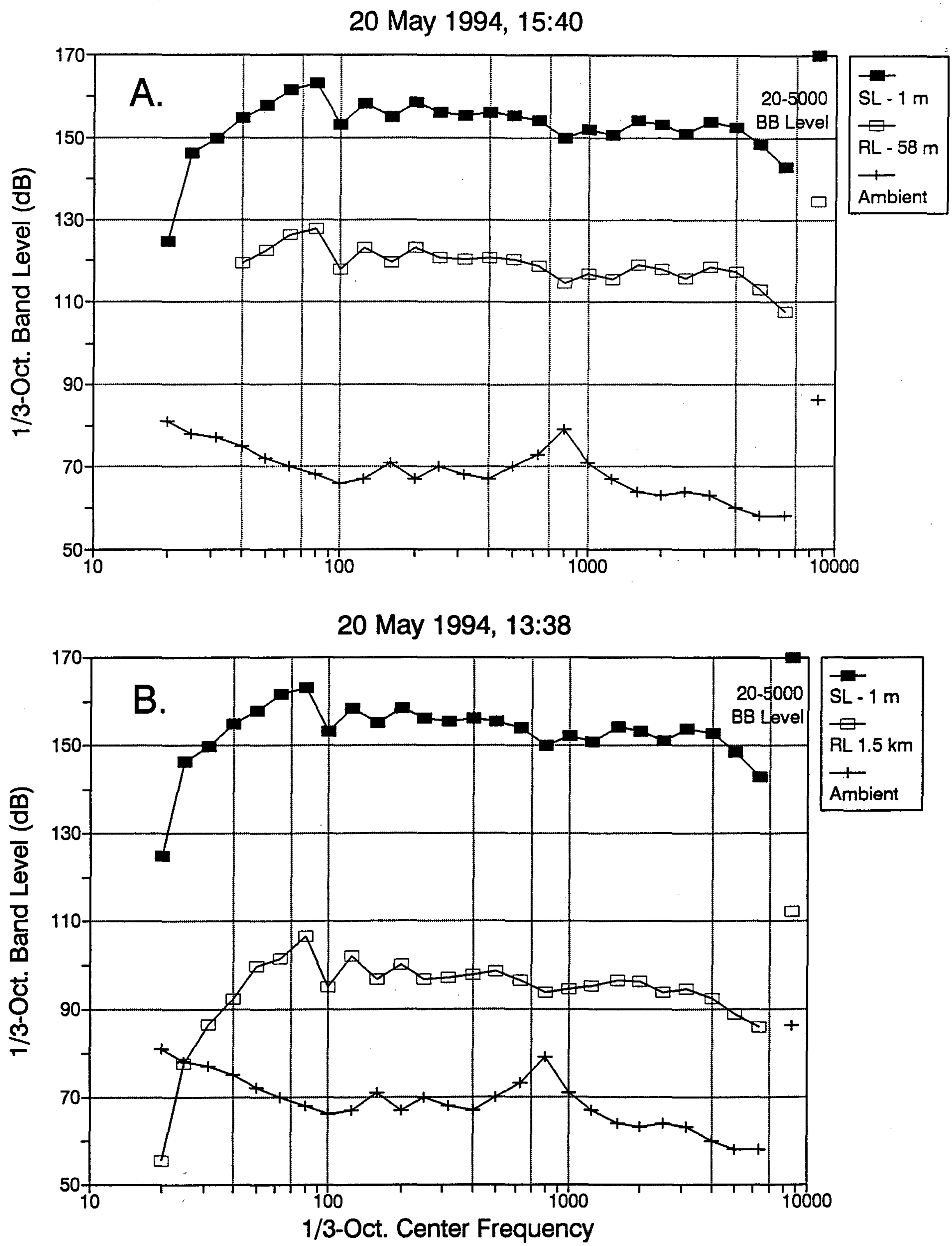


FIGURE F-46. Third-octave levels of projected icebreaker noise 1 m from the projectors (closed squares) and near bowheads *(A)* 58 m and *(B)* 1.5 km from the projector (median level over 1 min), 14 May 1994, times *(A)* 15:40 and *(B)* 13:38. Plus signs show average ambient noise level before playback. For additional explanation, see caption to Figure F-4. In (A), because of the short range, received levels at 60 m were estimated from source levels assuming spherical spreading.

The second closest observation of a bowhead to the operating projector was a whale 500 m south of the projectors at 15:30. The median and maximum 64-s broadband received levels of icebreaker noise at the whale while underwater were estimated as 123 and 128 dB re 1 μPa. The median and maximum 1/3-octave levels were 119 and 121 dB in the band centered at 80 Hz. Thus the median and maximum icebreaker: ambient ratios in the strongest 1/3-octave bands were ~51 and 53 dB.

Even the most distant whales that could be seen by the ice-based observers during the playback period on this date were exposed to strong icebreaker signals. The median and maximum icebreaker:ambient ratios in the strongest 1/3-octave band were estimated as 39 and 40 dB at a whale observed 1485 m from the projectors at 13:38 (Fig. F-46B). This distance was near the limit of the range where whales could have been reliably seen from the ice platform.

Summary.—On 20 May 1994, the projectors were set up on the NW side of a large pan that blocked the nearshore lead 40 km ENE of Pt. Barrow (Fig. 3.8 on p. 77). During control observations from both the circling aircraft and the ice camp, bowheads were observed as they approached the projectors from the west and WSW. They arrived at the large ice pan near and south of the projectors, turned northward, and followed the edge of the pan north and east. Six of eight groups of bowheads came within 400 m of the ice camp during the control period.

On this date the icebreaker sounds were projected at a high source level, and the ambient noise level was low. Only ice-based observations were obtained during the playback due to formation of low cloud. Bowheads continued to approach the projectors from the west and WSW. However, the patterns of movement of most of the whales when they came within several hundred meters of the ice camp were different during the playback than during the preceding control period. During the playback, they seemed to divert both to the north and south of the projectors. Only one whale approached the projectors closely during playback (1 of 11 groups were seen within 400 m); it turned sharply away from the projectors when 58 m from them. (A whale that surfaced at the same location during the control period dove toward the ice camp.) The whale that approached closely during the playback voluntarily approached even though $S{:}N_{1/3,max}$ was near 60 dB. At the observed CPAs of other whales that came within 500-1000 m, $S{:}N_{1/3,max}$ values were ~40-50 dB. The proportion of whales that diverted, and the actual distances when diversions began, are unknown because of the limited viewing area from the ice and because low cloud prevented aerial observations during this playback.

APPENDIX G: White Whale Distribution Maps, 1989-94

Appendix G shows all white whale sightings during the present study by 10- or 11-day period in the springs of 1989, 1990, 1991 and 1994 (four maps per year). Each map shows all white whales detected by observers in the Twin Otter aircraft (hatched symbols) and by observers in the helicopter or on the ice (open symbols). Headings toward which the whales were oriented when first seen are also shown.

Note that all search effort was non-systematic. The amount of effort varied greatly among different parts of the mapped area within any given 10- or 11-day period. The distribution of search effort also varied from one 10- or 11-day period to the next. The designated locations of the landfast ice edge are approximate.

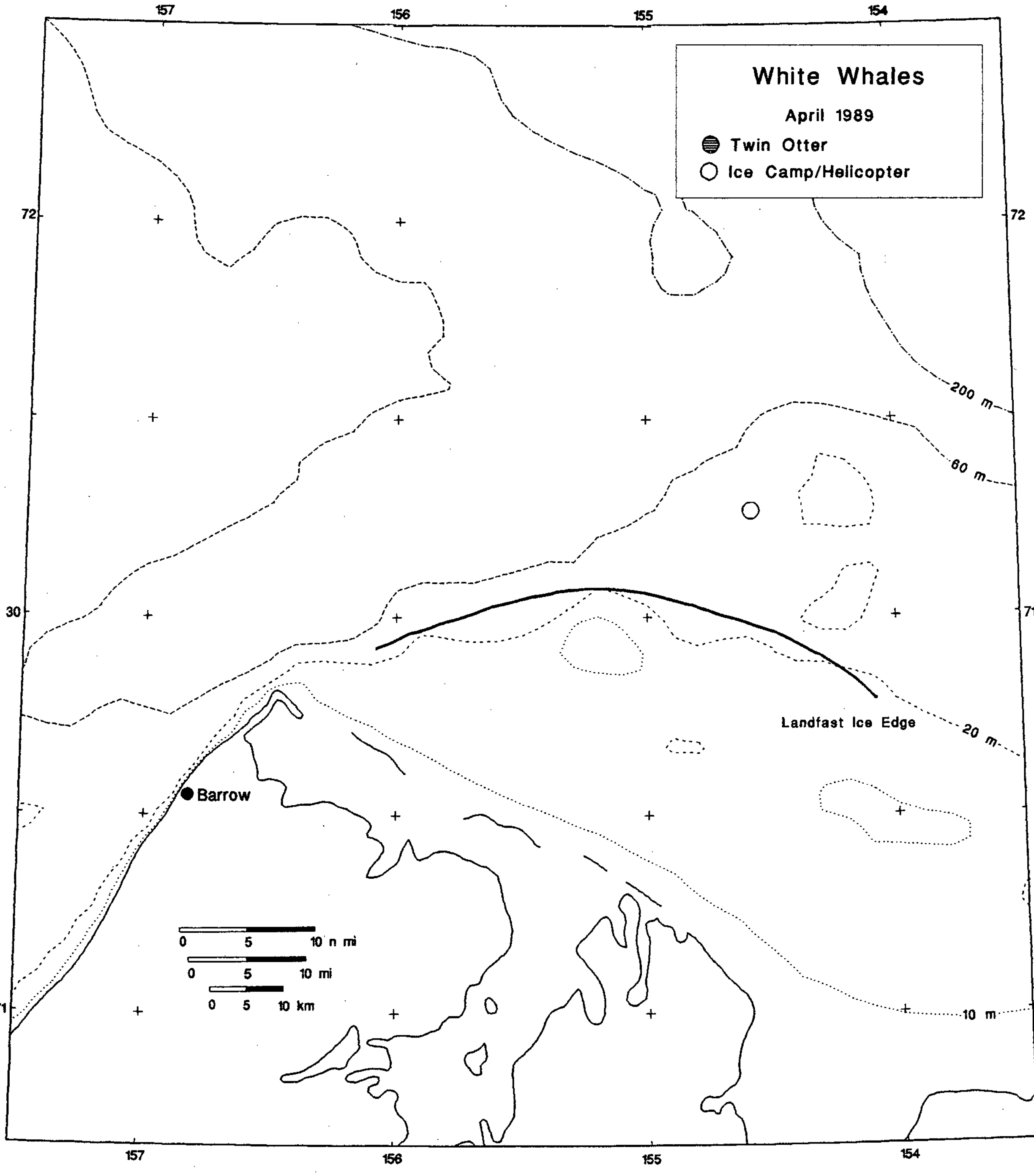


FIGURE G-1. LGL sightings of white whales, late April 1989. Symbol type distinguishes sightings by the two crews and sightings of 1-14 vs. 15+ whales. Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped.

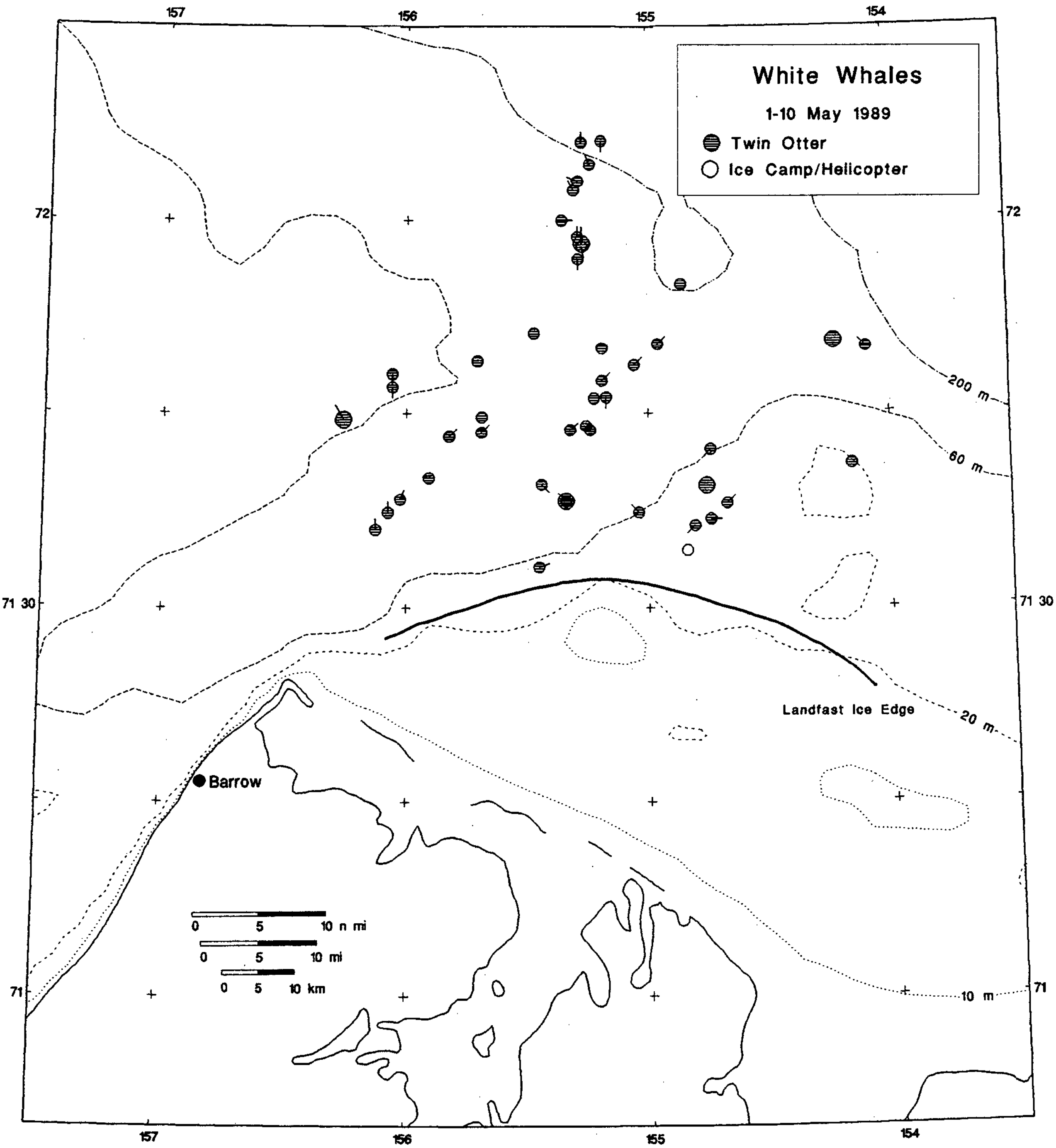


FIGURE G-2. LGL sightings of white whales, 1-10 May 1989. Symbol type distinguishes sightings by the two crews and sightings of 1-14 vs. 15+ whales. Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped.

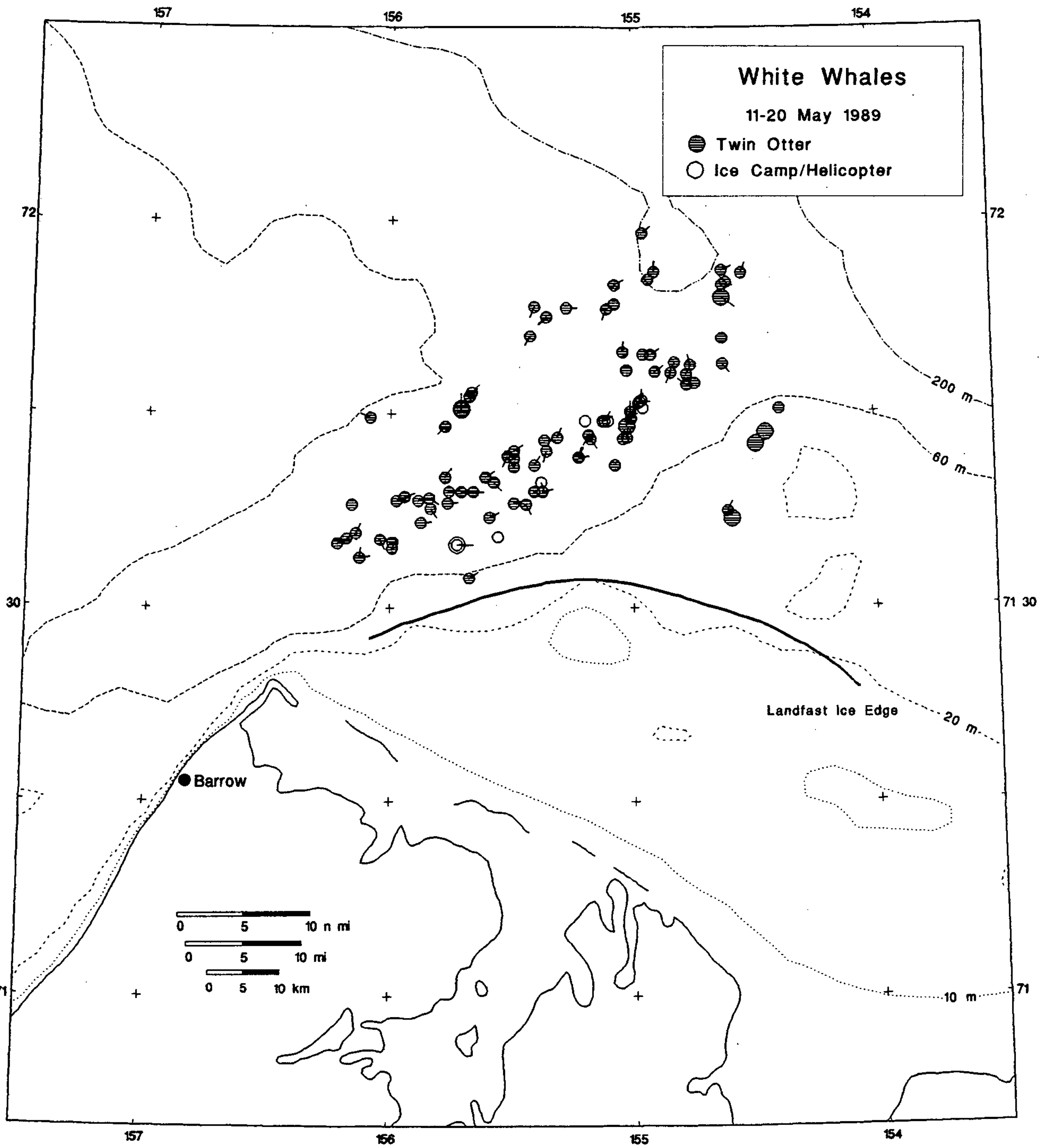


FIGURE G-3. LGL sightings of white whales, 11-20 May 1989. Symbol type distinguishes sightings by the two crews and sightings of 1-14 vs. 15+ whales. Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped.

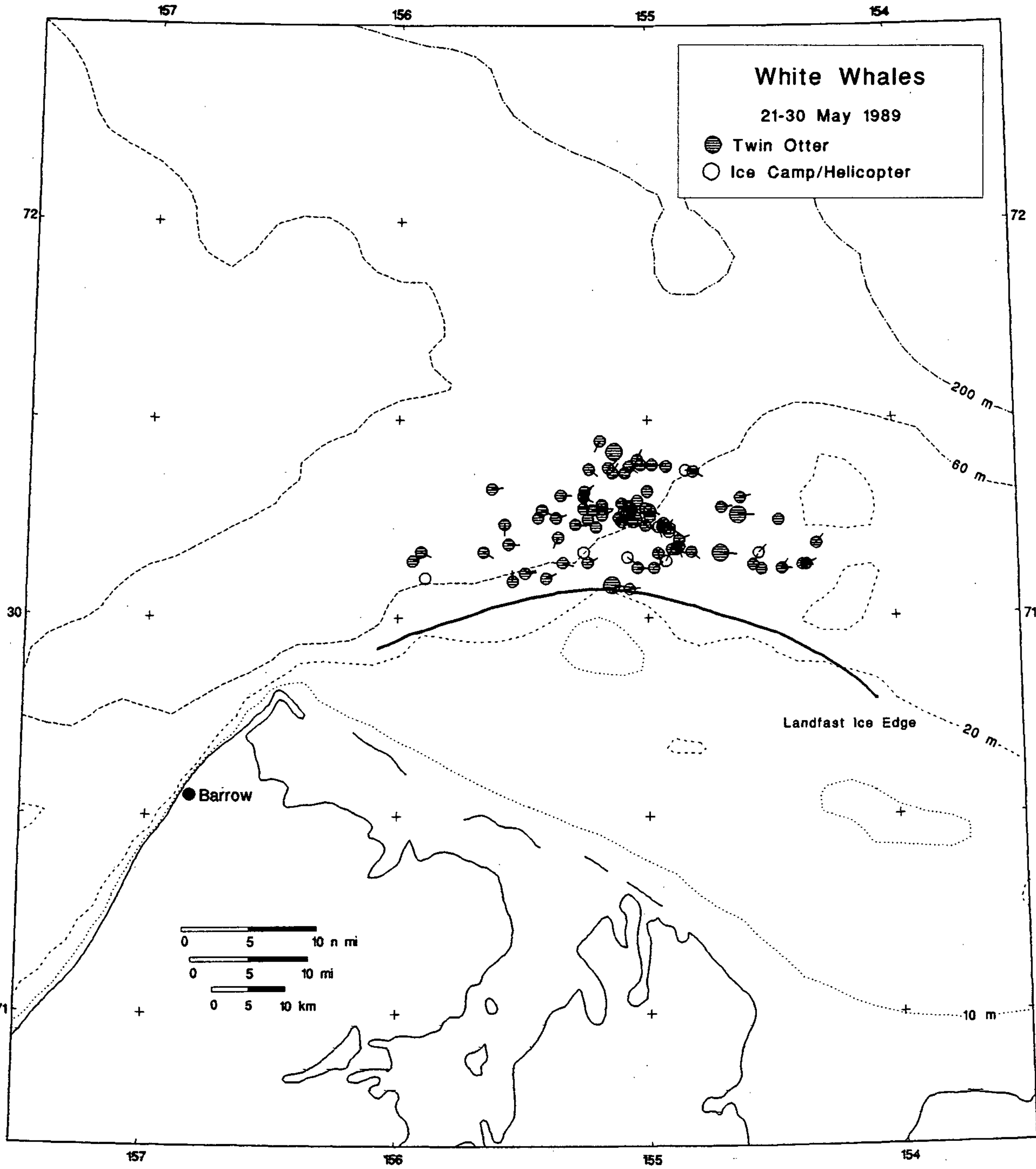


FIGURE G-4. LGL sightings of white whales, 21-30 May 1989. Symbol type distinguishes sightings by the two crews and sightings of 1-14 vs. 15+ whales. Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

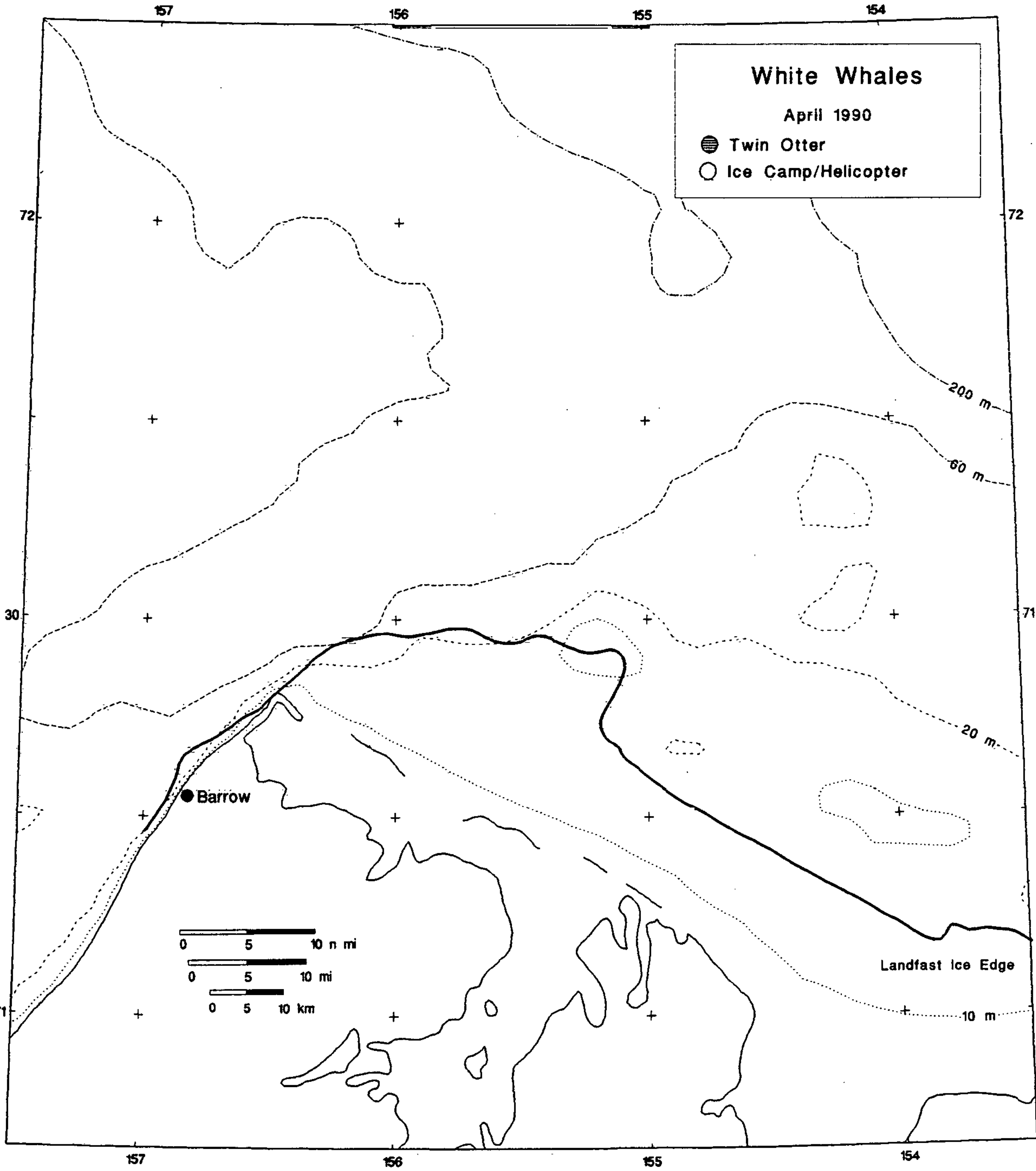


FIGURE G-5. LGL sightings of white whales, late April 1990. Symbol type distinguishes sightings by the two crews and sightings of 1-14 vs. 15+ whales. Headings toward which the whales were oriented when first seen are also shown. Survey effort was not uniform across the area mapped; the most intense effort was in the nearshore lead just north of the landfast ice.

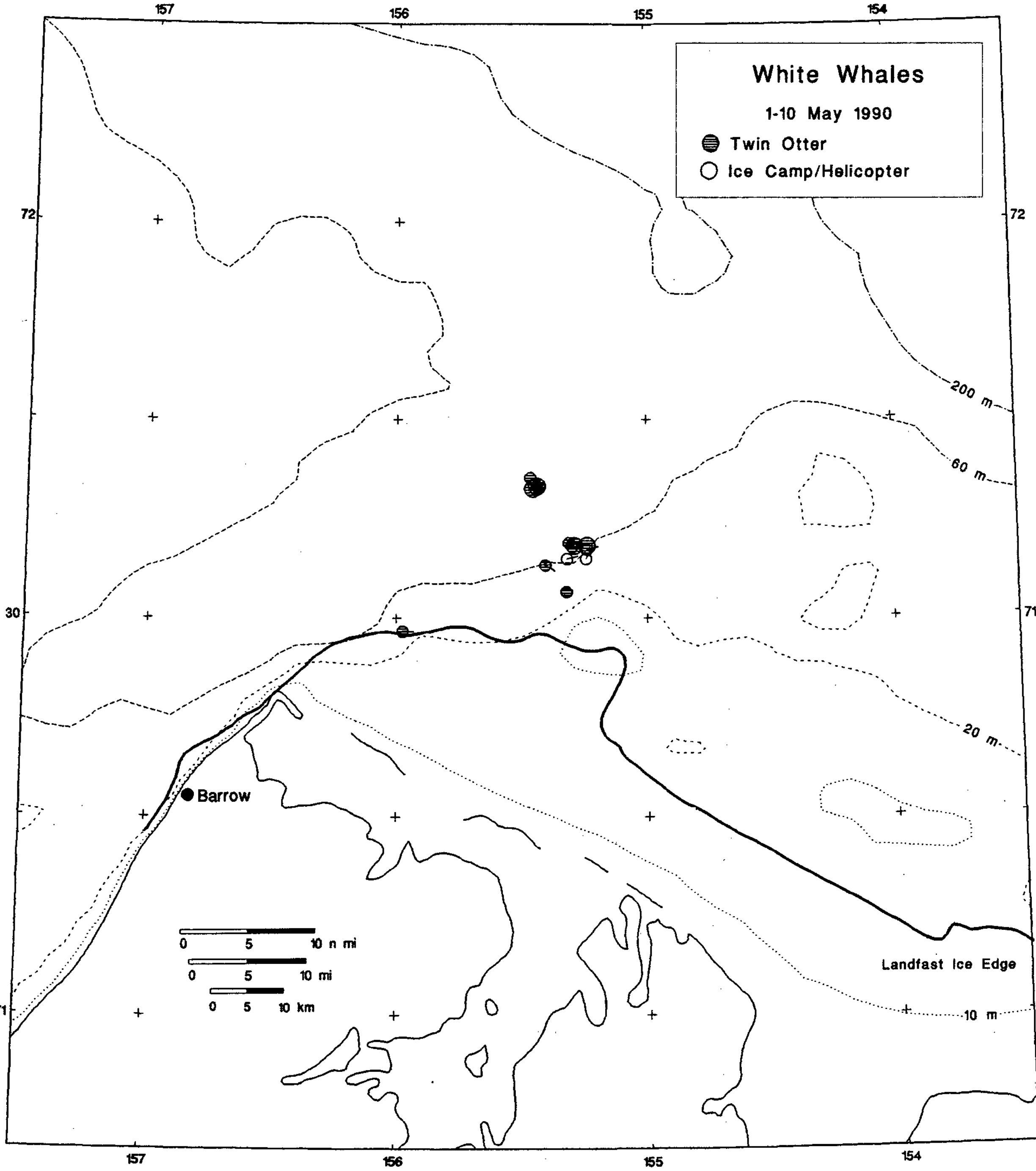


FIGURE G-6. LGL sightings of white whales, 1-10 May 1990. Format as in Fig. G-5.

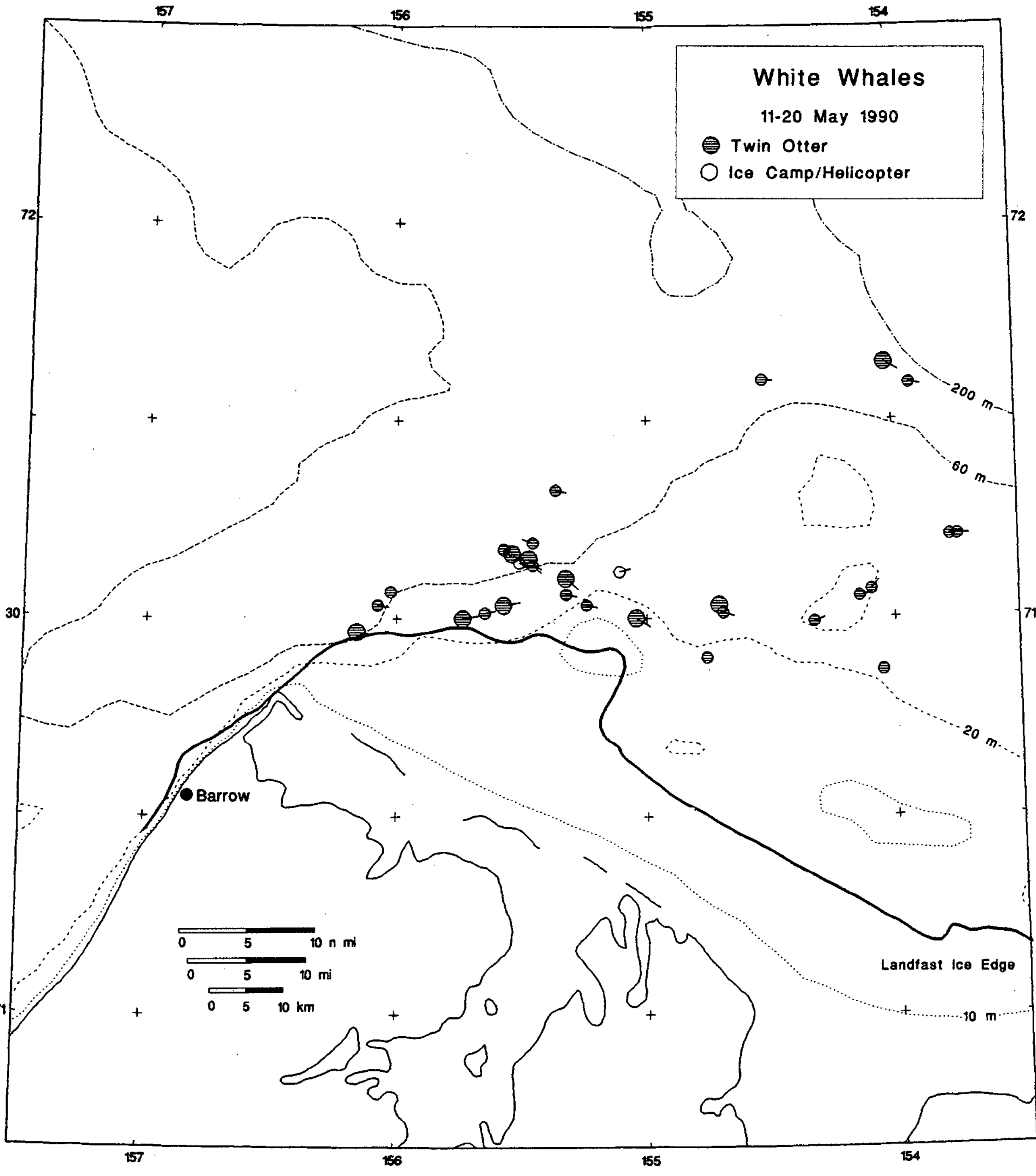


FIGURE G-7. LGL sightings of white whales, 11-20 May 1990. Format as in Fig. G-5.

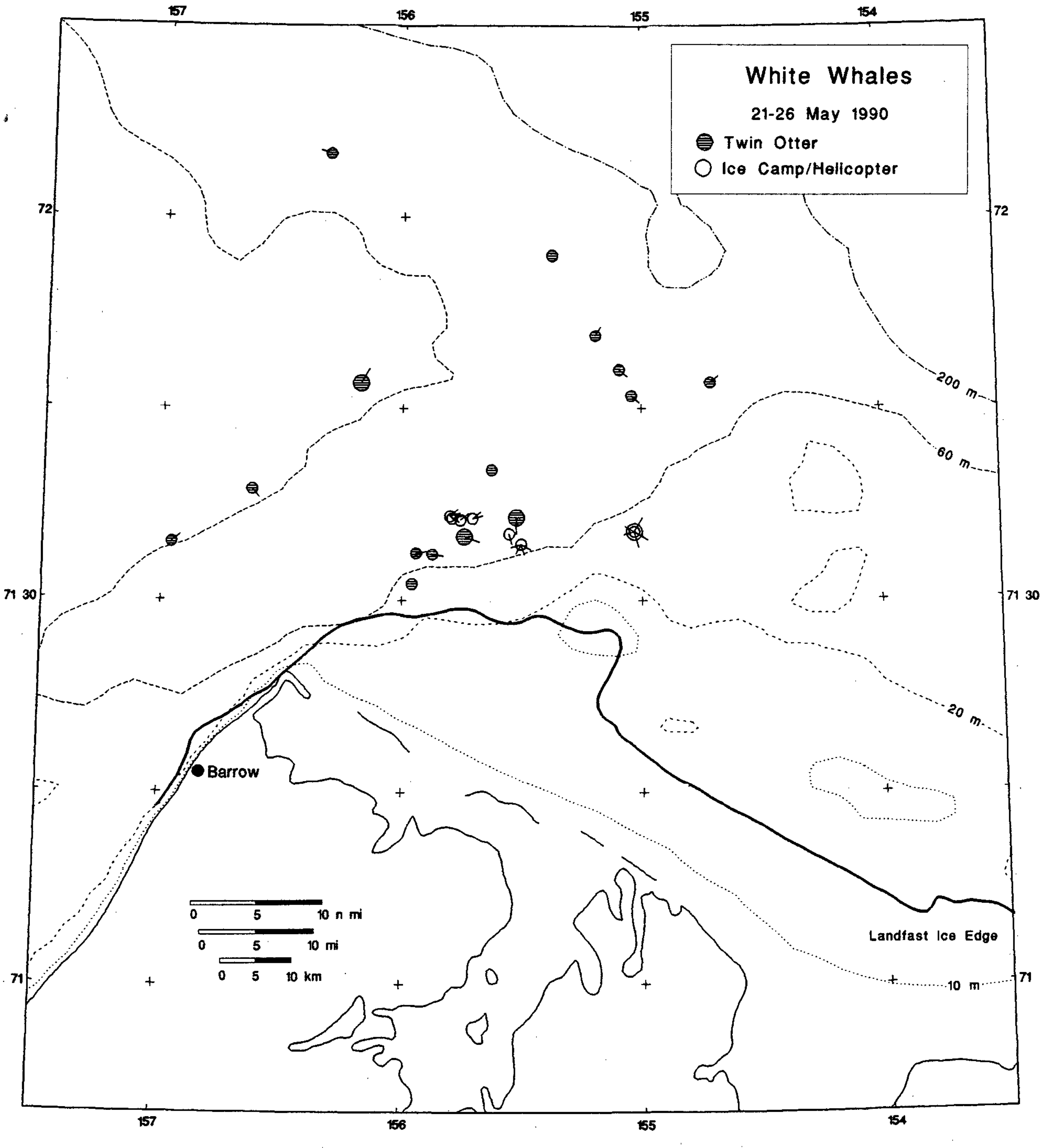


FIGURE G-8. LGL sightings of white whales, 21-26 May 1990. Format as in Fig. G-5.

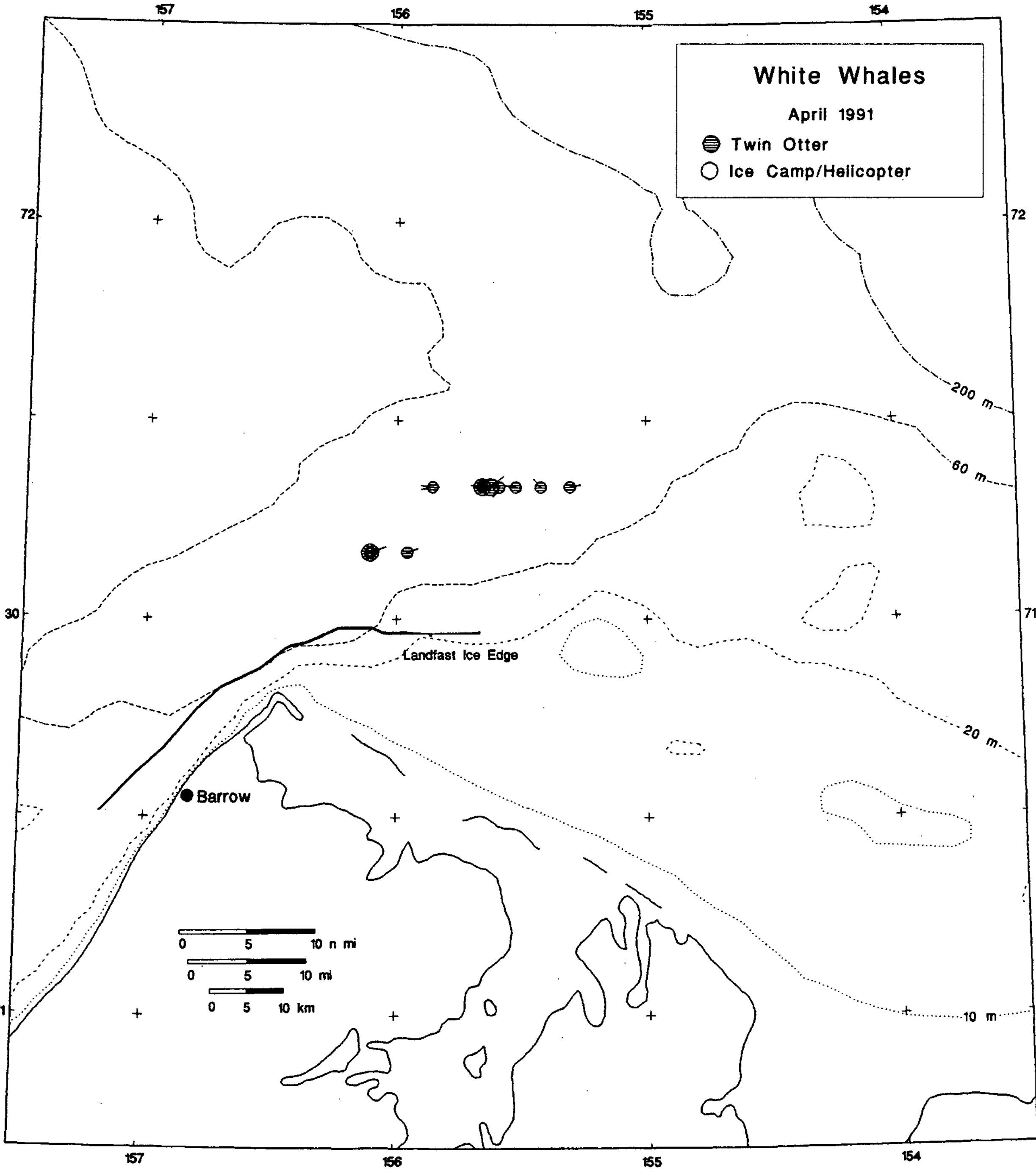


FIGURE G-9. LGL sightings of white whales, late April 1991. Format as in Fig. G-5.

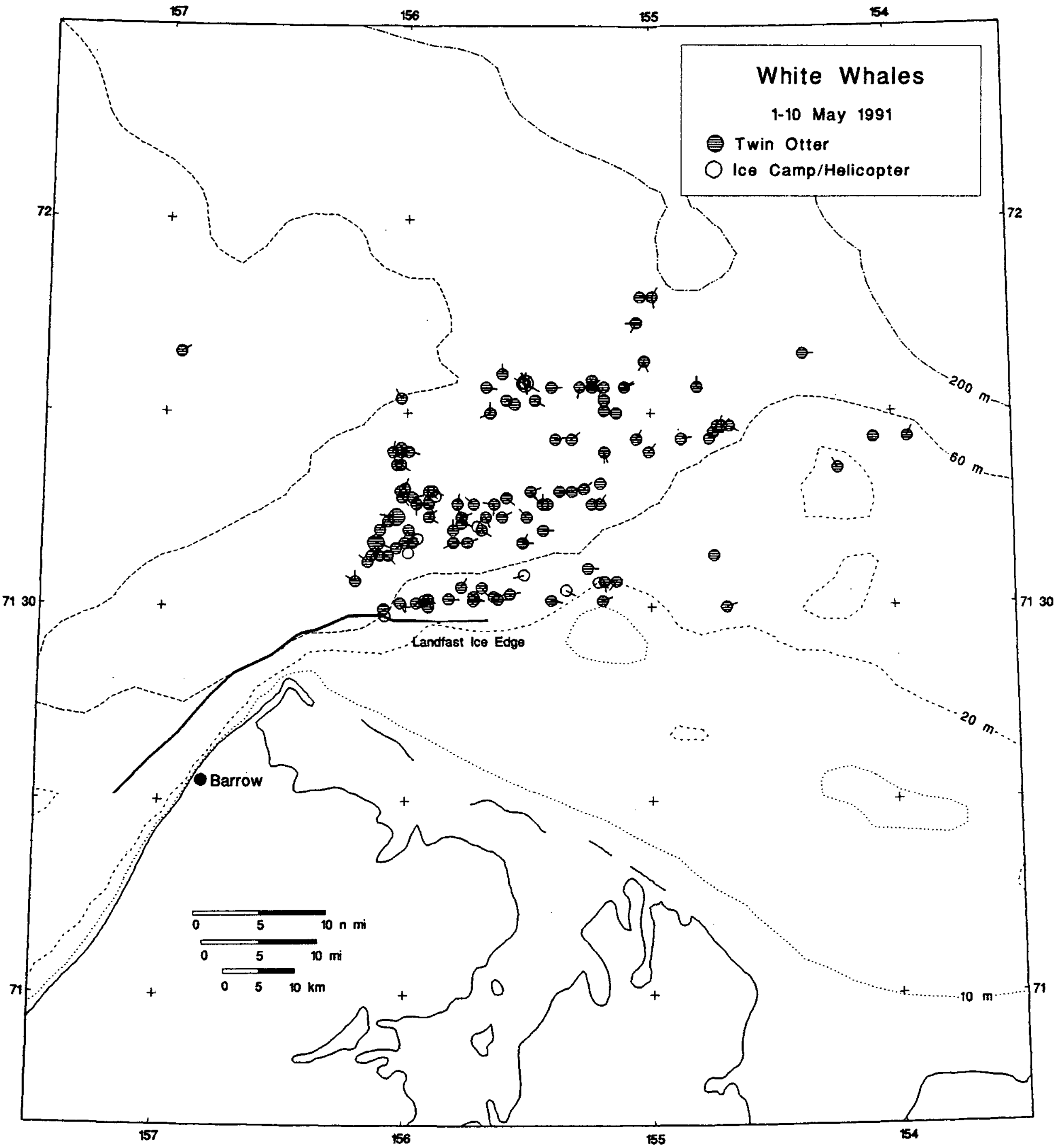


FIGURE G-10. LGL sightings of white whales, 1-10 May 1991. Format as in Fig. G-5.

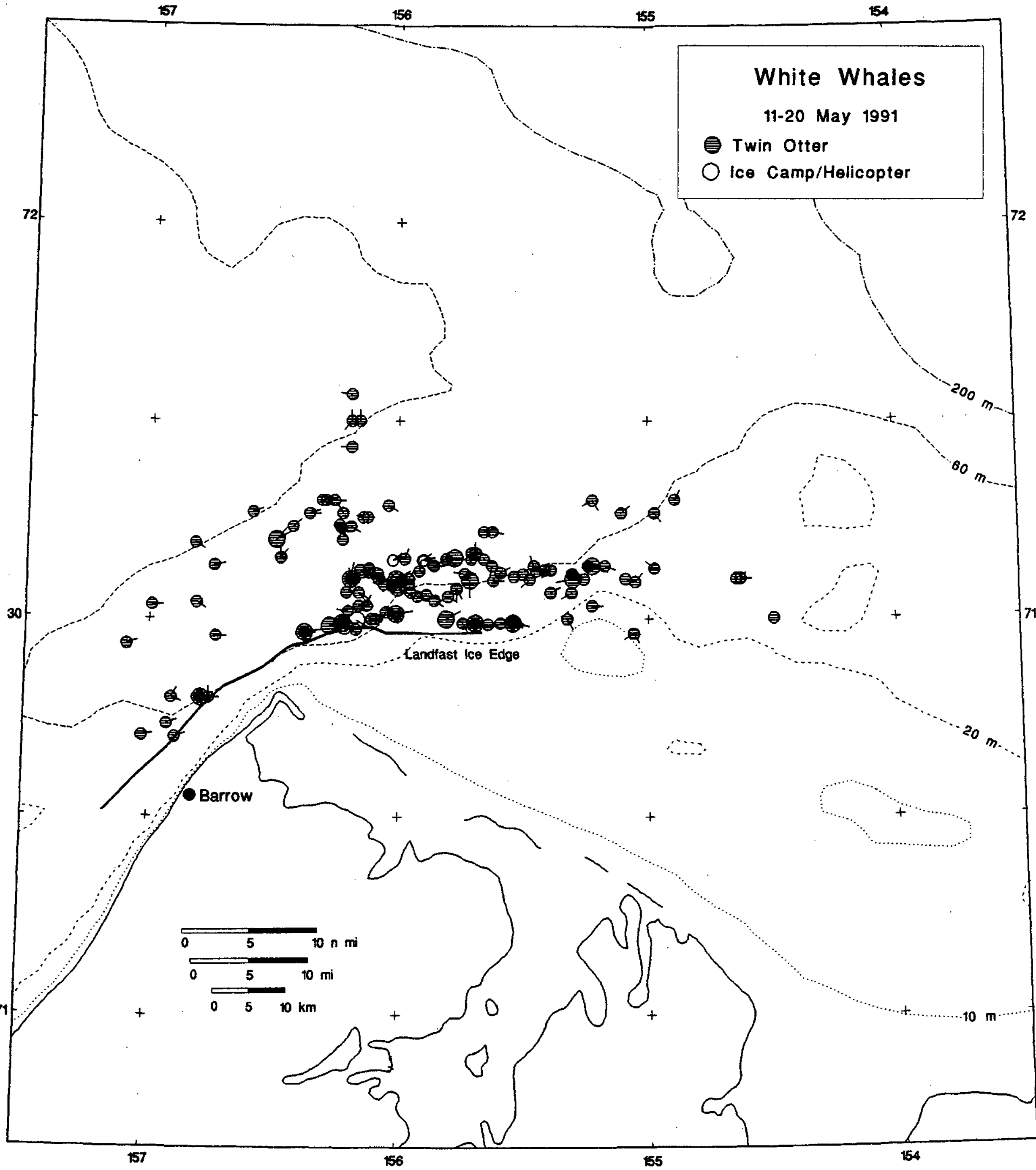


FIGURE G-11. LGL sightings of white whales, 11-20 May 1991. Format as in Fig. G-5.

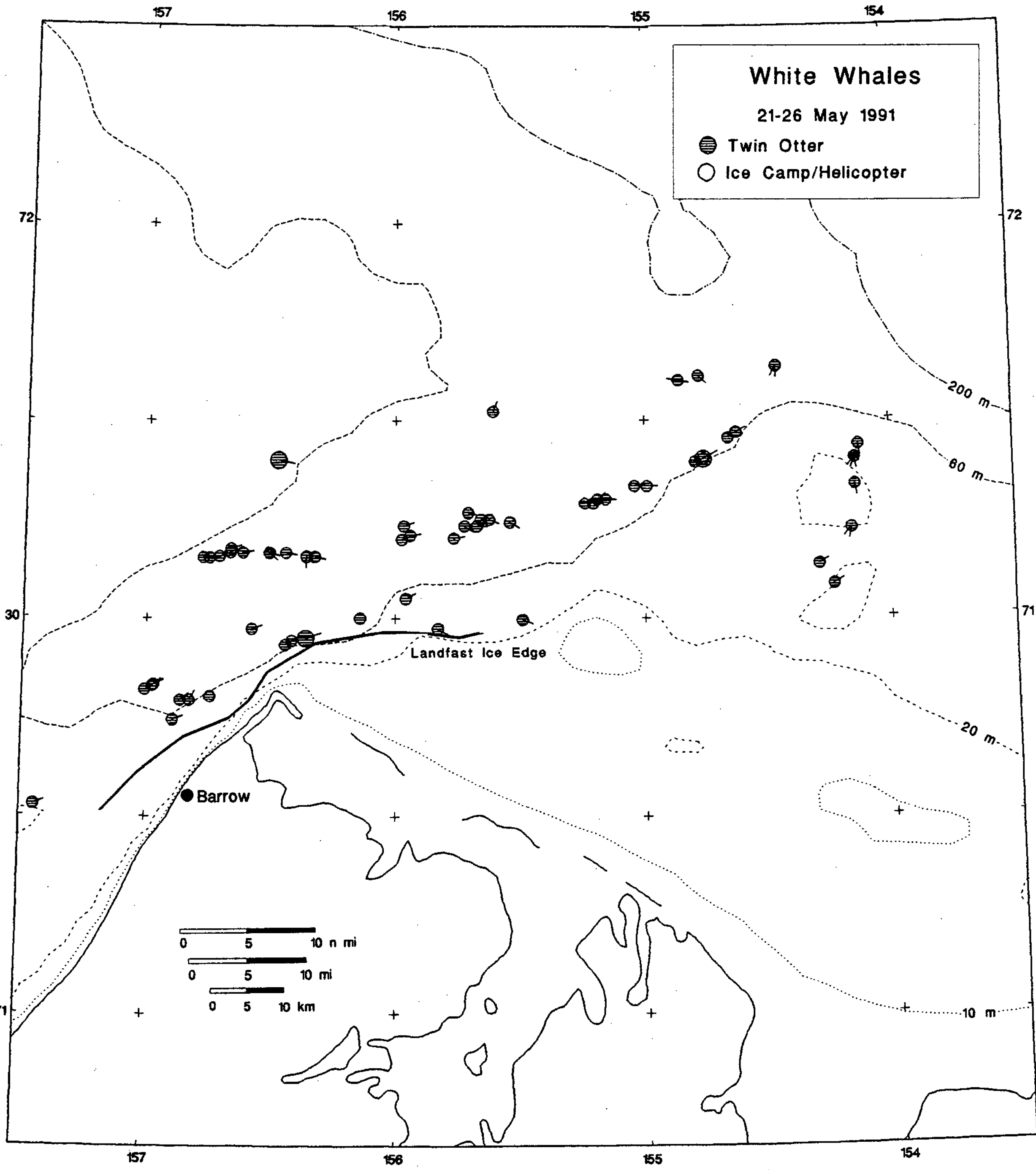


FIGURE G-12. LGL sightings of white whales, 21-26 May 1991. Format as in Fig. G-5.

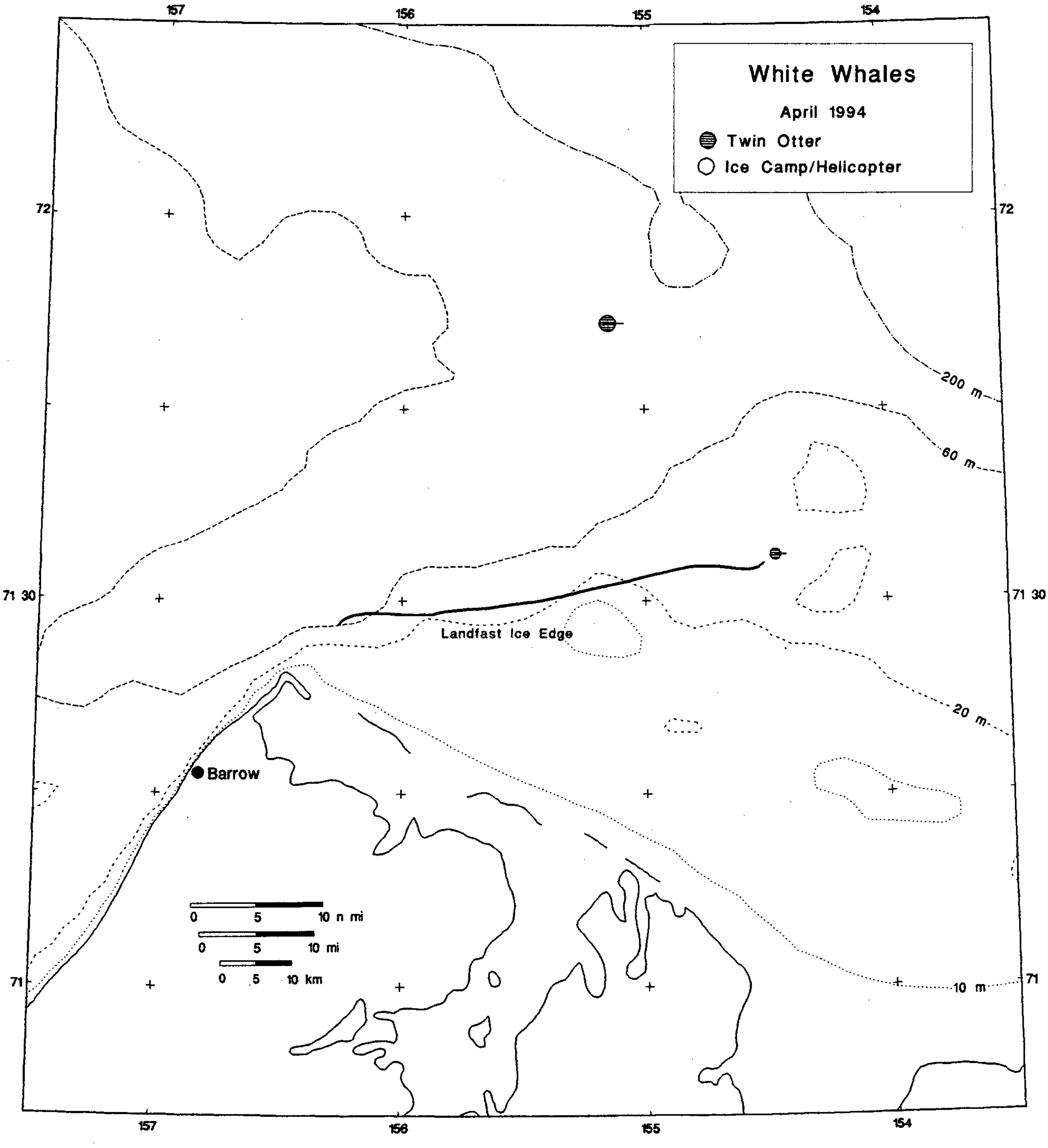


FIGURE G-13. LGL sightings of white whales, late April 1994. Format as in Fig. G-5.

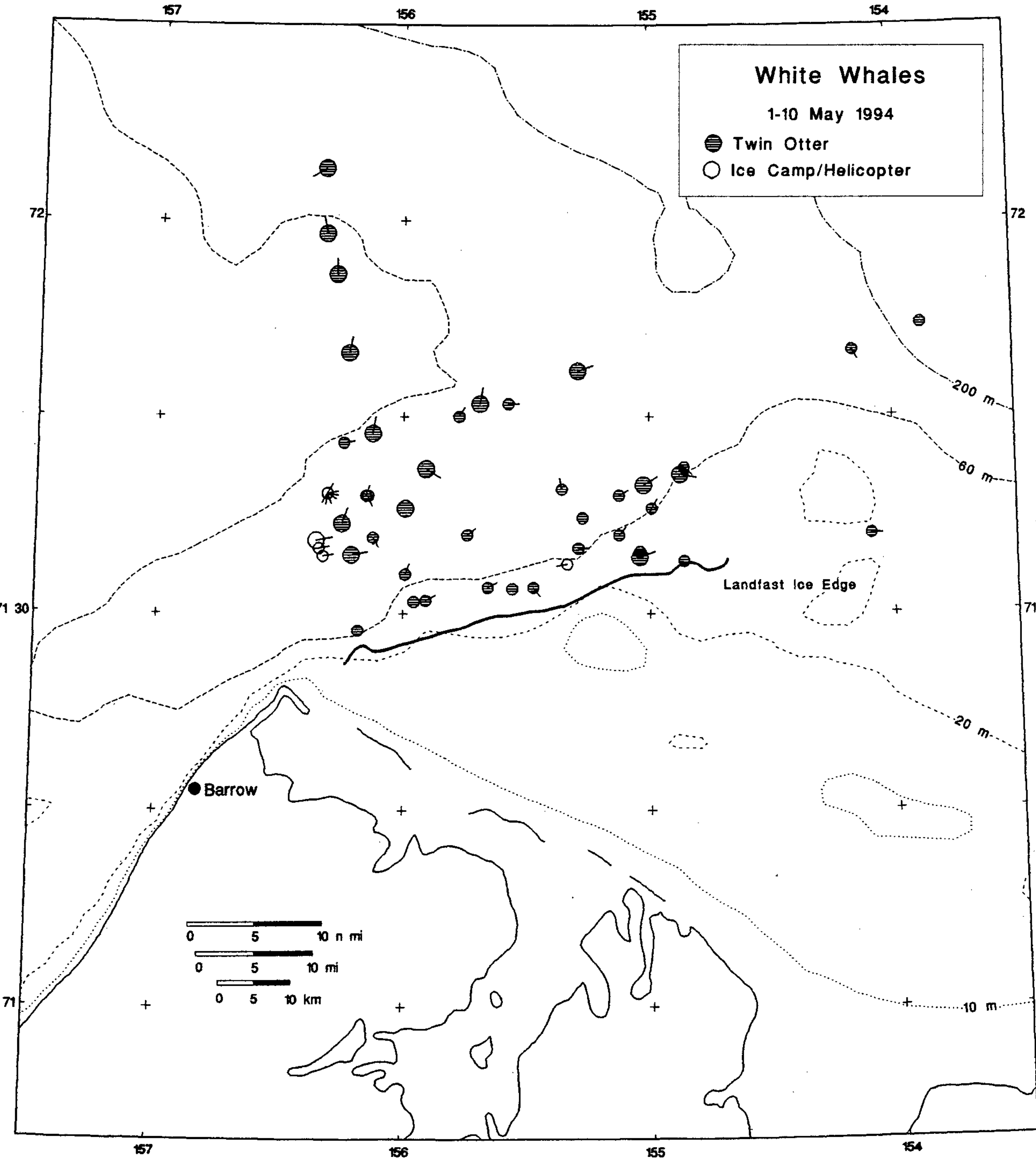


FIGURE G-14. LGL sightings of white whales, 1-10 May 1994. Format as in Fig. G-5.

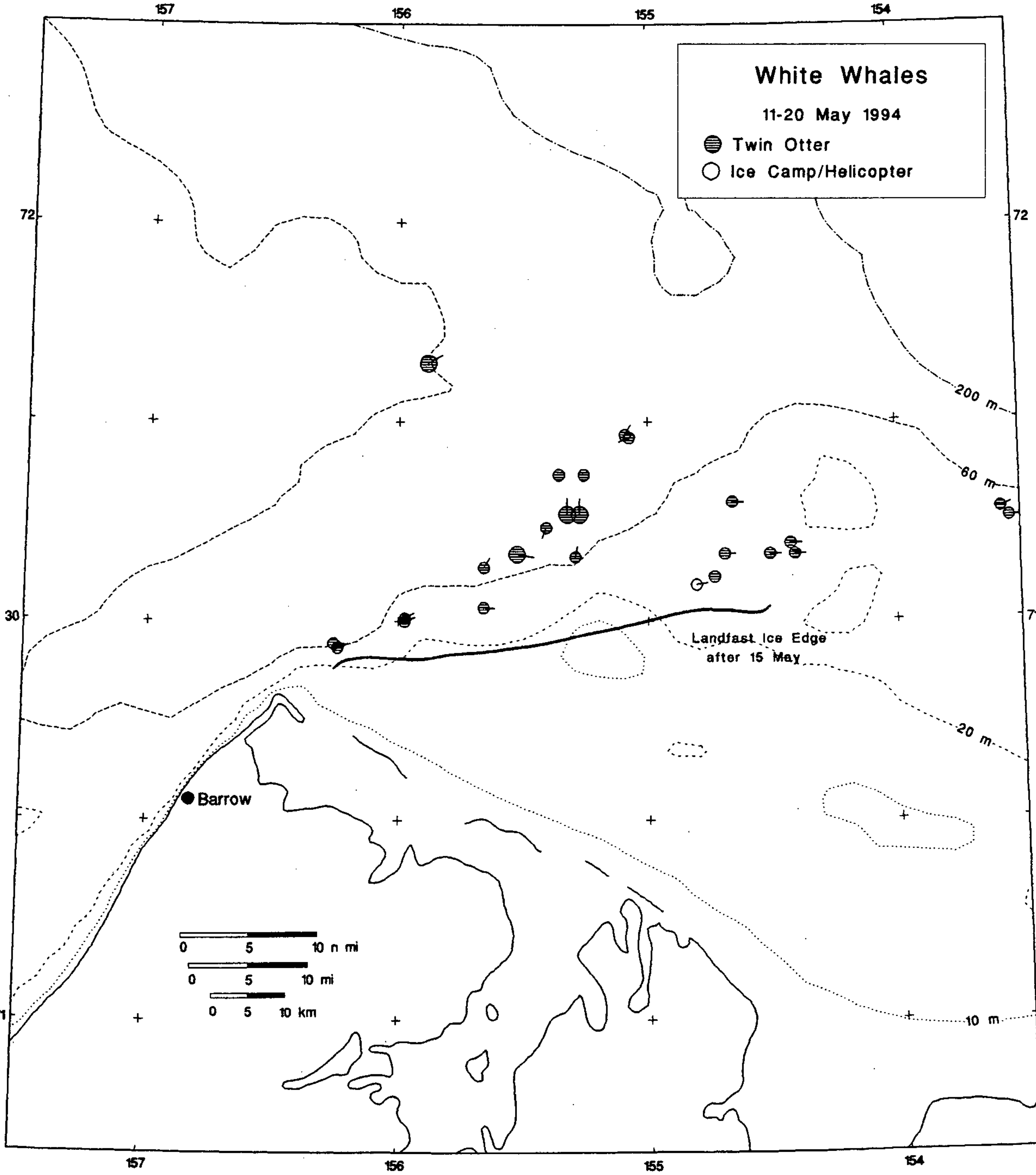


FIGURE G-15. LGL sightings of white whales, 11-20 May 1994. Location of ice edge changed on 15 May (*cf.* Fig. G-14). Format as in Fig. G-5.

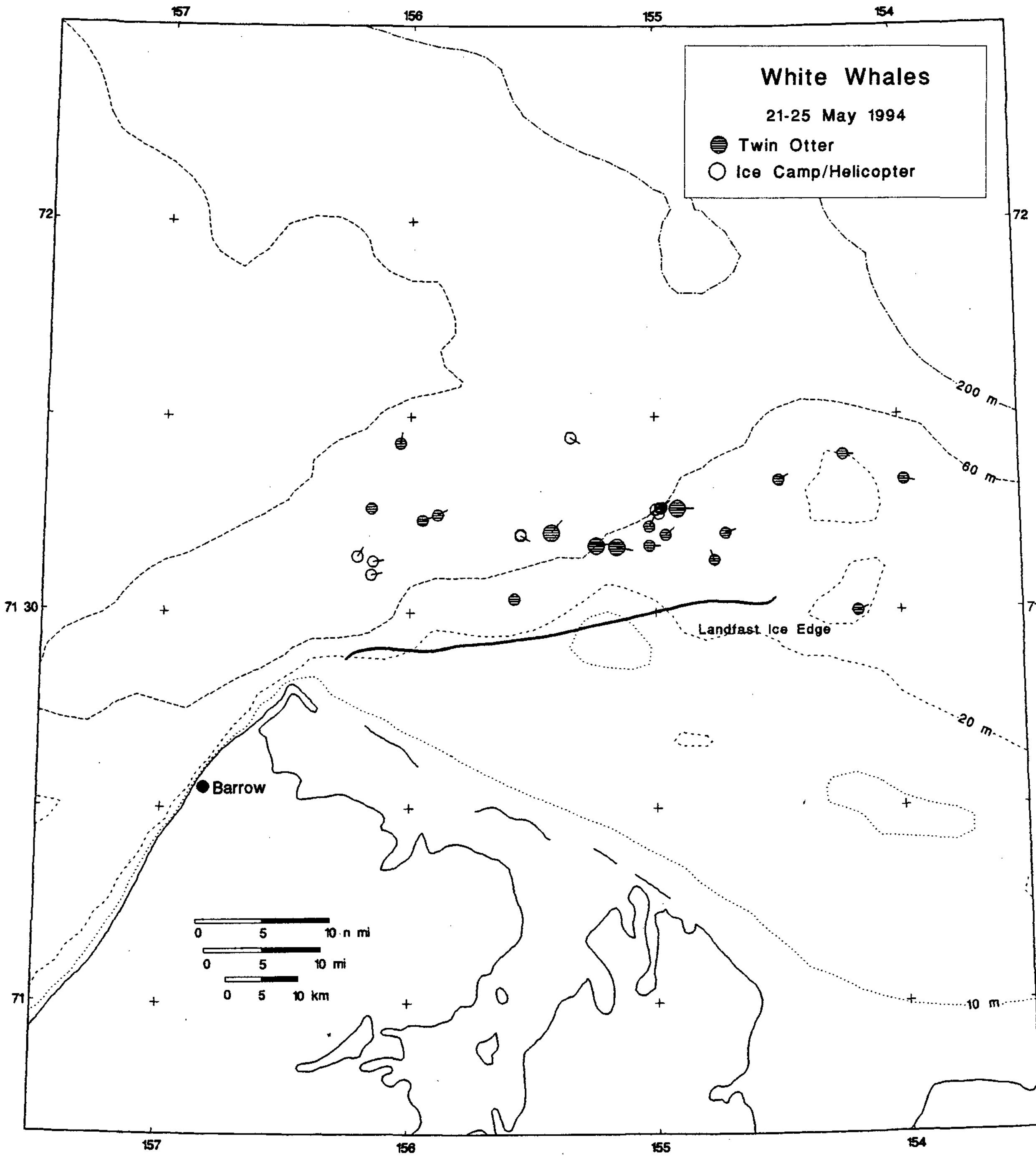


FIGURE G-16. LGL sightings of white whales, 21-25 May 1994. Format as in Fig. G-5.

APPENDIX H: SSDC Drilling Sounds in Winter

Introduction

With the cooperation of ARCO Alaska, a physical acoustician went to Canadian Marine Drilling Ltd's SSDC/MAT (a mobile arctic drilling caisson) during drilling operations about 30 miles east of Barrow, Alaska, in January 1992. The purpose of the trip was to record the drilling sounds at different distances from the structure. It was thought that the sounds might be appropriate for use in playback experiments during spring whale migration.

Methodology

The planned approach was to use battery-powered, portable equipment (an ITC model 6050C low-noise, wideband hydrophone, an ITC model 1032 spherical hydrophone for infrasonic sound transduction, and a TEAC model RD-101T digital audio tape recorder) for recording the drilling sounds. An ice auger was to be used to drill through the ice at each recording site, permitting the hydrophones to be lowered into the water for sound recordings. Analyses were based on 8.5 s averaged Fourier transform spectra spanning frequencies from 1 to 4000 Hz.

The recordings were made on 11 January 1992. Air temperature was -21°C; wind speed measured about 12 m above the ice was 20 knots. (It was somewhat lower at the ice surface.)

Results

Recordings were made successfully at only one range, on the starboard side at distance 115 m from the drillrig position on SSDC. The tape froze in the recorder transport after operating for 10 s, but data from this 10 s segment were usable (Fig. H-1). The 20-1000 Hz broadband level was 111 dB re 1 μPa, but the sound spectrum appeared to be only very low ambient noise at frequencies above 700 Hz. Prominent tones appear in the spectrum at 149 Hz (106 dB re 1 μPa) and at 447 Hz (92 dB re 1 μPa). (Note: These tone levels are 5.3 dB higher than the corresponding apparent peak levels in Figure H-1; the latter must be adjusted upward by 10 log(3.4) to allow for the 3.4 Hz effective filter bandwidth used in deriving Fig. H-1.) There was a weak tone at 20 Hz (97 dB re 1 μPa) but there was no evidence of infrasonic tones (at frequencies less than 20 Hz). The sounds had the dull quality of droning machinery.

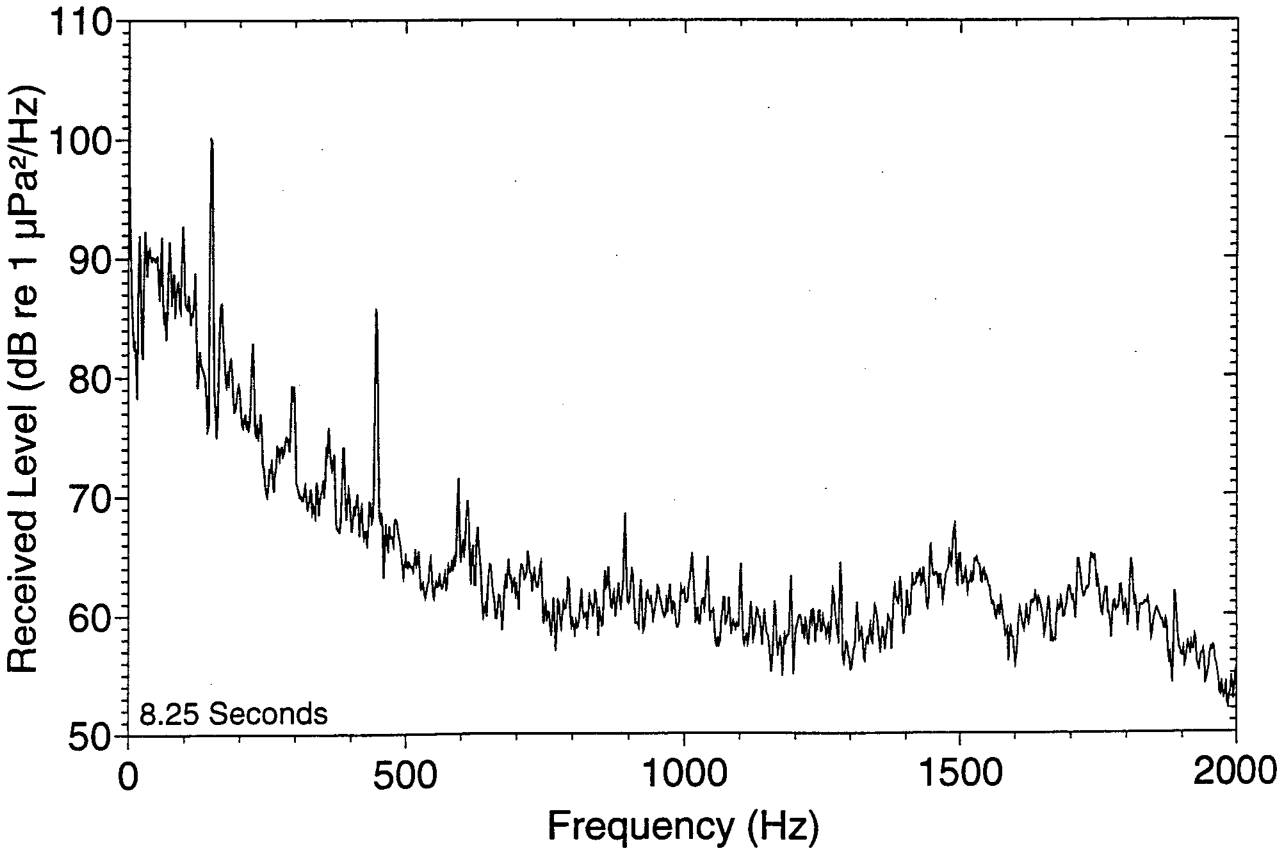


FIGURE H-1. Received signal pressure density spectrum of underwater sounds 115 m from the drillrig on SSDC during drilling operations. The effective analysis filter bandwidth was 3.4 Hz.