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ACOUSTIC EFFECTS OF OIL PRODUCTION ACTIVITIES ON BOWHEAD AND WHITE WHALES VISIBLE DURING SPRING MIGRATION NEAR PT. BARROW, ALASKA--1989 PHASE:

SOUND PROPAGATION AND WHALE RESPONSES TO PLAYBACKS OF CONTINUOUS DRILLING NOISE FROM AN ICE PLATFORM, AS STUDIED IN PACK ICE CONDITIONS

by

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PROJECT ORGANIZATION

This contract was conducted by LGL Ltd., environmental research associates, assisted by two subcontractors: Greeneridge Sciences Inc. and BBN Systems & Technologies Corp. **LGL** organized the project as a whole, and conducted the biological aspects of the work. B. Würsig and M. Smultea of the Marine Mammal Research Program, Texas A & M University, worked with LGL on the biological components. **Greeneridge** was responsible for the physical acoustics portions of the fieldwork and for much of the acoustical analysis. **BBN** provided specialized acoustical modeling expertise. The affiliations of the authors are as follows:

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ABSTRACT

Previous studies of the reactions of bowheads to noise from oil industry operations have all been conducted during late summer or autumn. Concern has arisen about potential reactions of bowheads and white whales to oil industry noise in leads through which whales migrate around northern Alaska in spring. Hence, MMS funded an experimental study to determine physical acoustic conditions, especially rates of sound attenuation, in spring lead systems; and the short-term behavioral responses of whales to sounds from production platforms, icebreakers, and aircraft. The work must be done without interfering with subsistence whaling or other research. After consultation with local groups and other scientists, a study area centered ~60 km ENE of Pt. Barrow was selected. During the first field season, in 1989, priority was given to testing whale reactions to continuous noise recorded near a drillrig on a grounded ice pad.

The primary field procedure was to use an underwater sound projector to broadcast recorded industrial noise into the water such that the reactions of approaching whales could be observed. The projector was also used to broadcast various test sounds in order to measure sound attenuation rates. Between 29 April and 30 May 1989, a helicopter-supported crew conducted sound transmission loss experiments on five days and aircraft noise measurements on two days. They also projected drilling noise into the water for several hours on each of 11 days. On five of these days, whales were observed within the ensonified area. An aerial-observation crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations of whales on 10 days, and bowhead photogrammetry on 8 days. Because of difficult ice conditions, all ice-based work had to be done from the pack ice rather than the landfast ice edge, and sample sizes for most types of biological observations were smaller than desired.

During playback experiments, low-frequency (<300 Hz) drilling noise was projected into the water at a source level of ~164 dB re 1 μPa. This noise was strong within ~1 km of the projector, and faintly detectable out to at least 4-5 km (occasionally to 9-10 km). Underwater sound attenuated more rapidly under pack ice conditions NE of Pt. Barrow in spring than found previously in open waters of the Beaufort Sea during late summer.

During playbacks of drilling sound, several bowheads migrated NE within 1 km of the projector, well within the ensonified area; one whale swam within 120 m. However, one mother/calf pair swam *west* away from the projector, possibly exhibiting avoidance. These limited data show that some bowheads tolerated low-frequency drilling noise without interrupting or diverting their migration; others may have reacted strongly. It would be premature to generalize these few data to the whole population, or to other types of industrial sounds.

White whales migrating toward the projector traveled toward it until they came within a few hundred meters. Some then continued past it without apparent hesitation or turning. Others definitely reacted at distances on the order of 200-400 m; they slowed, milled and in some cases reversed course temporarily. However, within a few minutes, they continued past the projector, sometimes passing <50-100 m from it. We saw no evidence that white whales reacted at distances >200-400 m. Again, it would be premature to generalize these observations to other situations or other types of noise.

Although additional data are required before definite conclusions can be reached, the 1989 work provided useful results on sound propagation and whale responses, and demonstrated that it is possible to conduct a study of this type despite the logistical and other difficulties involved.

EXECUTIVE SUMMARY

Previous studies of the reactions of bowhead whales to noise from oil industry operations have all been conducted during late summer or early autumn, in open water or at most light ice conditions. Concern has arisen about potential reactions of bowheads to man-made noise in the leads through which bowheads migrate in spring. Particular concern has arisen about the possible effects of continuous noise from structures that might be used for oil production in or near spring lead systems.

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 of the study can be summarized as

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 1989 Objectives

Prior to the 1989 field program, it was decided that the study would include at least a second spring field season, in 1990. It was agreed that the highest priority during the initial 1989 field program was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. The basic field technique to be used for these tests consisted of underwater playbacks of recorded industrial sound. In 1989, all opportunities for playbacks were to be devoted to replication of a single type of experiment in order to obtain sufficient data to allow meaningful interpretation. However, as a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if that could be done on occasions when playbacks of drilling platform noise were impractical. The specific 1989 objectives were as follows:

1. To record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter.
2. To measure ambient noise levels and characteristics along the spring migration corridor of bowhead and white whales in the western Beaufort Sea.
3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of test tones and the continuous drilling platform sound recorded in (1).
4. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of the continuous drilling platform sound in (1).
5. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to helicopter overflights.
6. 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.
7. 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.
8. To analyze the data to test hypotheses concerning effects of the drilling platform sound recorded in (1) on movement patterns and behavior of bowhead and white whales visible along their spring migration corridor in the western Beaufort Sea.

Approach and Procedures

No oil production facilities have yet been constructed in or near the spring lead systems, so no recording of underwater sounds from such an operation exists. It was decided that sounds from one of the bottom-founded caissons used for exploratory drilling in the Beaufort Sea would be the most appropriate sounds to use. No recording of sounds from such a caisson operating in winter or spring ice conditions existed at the time of the 1989 field program. It had been hoped to record such sounds in the winter of 1988-89, but no caisson-based drilling was done in the Beaufort Sea during that season. Instead, as part of this project, sounds from drilling on a grounded ice platform were recorded near Prudhoe Bay in late March 1989. These sounds were used for all playback experiments in the spring of 1989.

The study had to be conducted in such a manner 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 where there is spring whaling, and the census is also done just north of Barrow. After consultation with the Barrow Whaling Captains' Association, the Alaska Eskimo Whaling Commission and the North Slope Borough's Dept of Wildlife Management, it was agreed that the most suitable location for playback experiments was about 60 km NE or ENE of Pt. Barrow.

It was hoped that much of the playback work could be done from the edge of the landfast ice. However, ice-based studies of bowheads have not previously been done much to the east of Pt. Barrow. It was realized that it might be impractical to work from the landfast ice edge in that area. Heavy pack ice commonly occurs adjacent to the landfast ice edge, and the whale migration corridor tends to be farther away from the landfast ice edge 60 km east of Pt. Barrow than it is near Barrow. In part because of these anticipated complications, a Bell 212 helicopter was dedicated to the project for the duration of the 1989 field season. This provided the flexibility to work from the pack ice rather than the landfast ice edge when necessary.

In fact, ice conditions east of Pt. Barrow in the spring of 1989 were severe. There was no nearshore lead along the landfast ice edge until 20 May, and there was little open water amidst the pack ice seaward of the landfast ice edge until mid-May. Even after 20 May, when the nearshore lead formed, most of the passing whales moved through the pack ice or along the offshore side of the nearshore lead. Hence, all playback attempts were from the pack ice rather than the edge of the landfast ice. The absence of a consistent whale migration corridor reduced the number of opportunities for observations of whales passing the sound projector. By the last week of May, when weather and ice conditions were greatly improved, few whales were passing. Nonetheless, useful data were obtained on the reactions of bowhead and white whales to drilling noise, and most of the desired physical acoustic data were collected. The availability of full-time helicopter support allowed us to work from different locations on the moving pack ice each day.

The field crew consisted of two teams. ► A helicopter-supported crew deployed a U.S. Navy J-11 underwater sound projector from ice pans, and used it to project recorded drilling platform 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. In addition, this crew measured the rate of attenuation of underwater noise with increasing distance from the source (in this case the projector). ► A second crew, in a Twin Otter aircraft, located whales and suitable projector sites, documented the behavior of whales as they swam toward and past the projector, and obtained known-scale vertical photos of bowheads in order to identify individuals and measure their sizes. The aircraft crew also used naval sonobuoys to monitor underwater sounds near whales exposed to projected drilling sounds.

Whale observations obtained by the two crews were complementary. The ice-based observers obtained more detailed data on the paths and speeds of some whales that passed within 1-2 km of the projector, and observed whales even when there were low clouds. The aerial observers could observe whales at any distance from the projector site, and could follow them for longer distances.

Aerial observers also had a better vantagepoint for viewing the details of behavior. However, aerial observations were only practical when the cloud ceiling was at least 457 m (1500 ft) above sea level, since bowheads sometimes react to a circling observation aircraft if it flies lower than that altitude.

The helicopter-supported crew worked from the ice on 18 days between 29 April and 30 May 1989. They conducted sound transmission loss experiments on five days, aircraft noise measurements on two days, and projected drilling noise into the water for several hours on each of 11 days. On five of these days, bowhead whales were observed within the area ensonified by the projector. On four days, white whales were also observed near the operating projector. Whales near the operating projector were observed from the ice on two dates, and from both the ice and the air on three dates. Overall, the aircraft crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations on 10 days, and photogrammetry on 8 days.

Physical Acoustics

Underwater noise from the *Karluk* drillsite, on a grounded ice pad, was concentrated below 300 Hz. Infrasonic components of the *Karluk* sounds--those below 10 Hz--were not studied, and may have been significant. Most components of the noise above 10 Hz had diminished below background levels after propagating only 2 km through the shallow (6-7 m), ice-covered waters. However, tones at 25 Hz and 294 Hz were still evident at that range.

Underwater noise from aircraft overflights was measured systematically by conducting a series of passes at several altitudes over a pair of hydrophones suspended 3 m and 18 m below the edge of an ice pan. As expected, helicopter noise contained more tonal components than did Twin Otter noise. Helicopter noise was usually stronger at 3 m depth than at 18 m, but this trend was not evident for the Twin Otter. Underwater noise increased and decreased more gradually when the aircraft was high than when it was low. The peak level, recorded when the aircraft was overhead, was higher when the aircraft was low than when it was high. All of these trends are consistent with theory and previous measurements. However, there was evidence that the presence of ice had a modifying influence on some of these trends.

Ambient noise was recorded in small to large open areas amidst the pack ice, and occasionally through thin ice covering recently-refrozen leads. No measurements were obtained during periods of strong wind. The ambient noise was usually dominated by ice noises, wave slap, and marine mammal calls. Bearded seal calls were ubiquitous and often strong; white whale calls were also heard commonly. Bowhead calls were less common. Most measurements of ambient noise were averaged over 8.5 s. Much of the variability in ambient noise, especially above about 500 Hz, was attributable to the variable occurrence and levels of marine mammal calls in these 8.5 s samples.

When no sounds were being projected, tonal sounds from the generator used to power the underwater projector were detectable underwater (18 m deep) at distances as great as 400 m, but not at 1 km. These tones consisted of a harmonic family with fundamental frequency 60 Hz. However, when the projector was in operation, the generator sounds were much less intense than the projected sounds at corresponding frequencies. Hence, the generator would not have been audible to whales during playbacks.

During playback experiments, *Karluk* drilling platform noise was projected into the water at a source level of about 164 dB re 1 μPa. Received levels of the projected drilling noise were strong at distances within ~1 km of the projector. The drilling sound was usually weakly detectable out to distances of about 4-5 km, and occasionally to 9-10 km but not farther than that.

Sound propagation experiments were done on five days, and four of these tests provided interpretable results. Three types of signals were projected using the J-11 projector: pure tones at eight frequencies ranging from 50 Hz to 10 kHz; frequency-modulated tones oscillating within 1/3-octave bands centered at seven frequencies from 50 Hz to 5 kHz; and samples of the *Karluk* drilling sound. During each propagation experiment, underwater sounds were recorded (at 18 m depth) at distances ranging from 100 m to 9 or 18 km. As expected, pure tones often were detectable about twice as far away as were the *Karluk* sounds (typically 9-18 km for tones vs. 4-10 km for *Karluk* sounds). This occurred because all of the projected power was concentrated at a single frequency when tones were projected, but not when broadband drilling sounds were projected. A special matched-filter signal processing technique was effective in measuring received levels of the oscillating tones at distances greater than those where they could be measured by conventional methods.

Semi-empirical Weston/Smith sound propagation models were fitted to the transmission loss data acquired during two propagation experiments. Bottom loss and ice scattering loss coefficients tended to increase with increasing frequency. At frequencies in the kilohertz range, volumetric absorption was also a factor. Underwater sound attenuated more rapidly under pack ice conditions northeast of Pt. Barrow in spring than had been found previously in largely open water conditions in the central and eastern Beaufort Sea during late summer. It is not known whether all of this difference can be attributed to the difference in ice conditions. It may also have been partly attributable to increased bottom loss in our study area. The propagation results from this study were generally consistent with those found during a previous late winter and summer study in the Chukchi Sea.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area throughout late April and May 1989, often through heavy pack ice conditions. Even in late May, when a nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 40-80 km ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead.

Bowhead calves and their mothers were seen only in the latter half of May in 1989, and constituted the majority of the bowheads present in the last week of May. They did not migrate as strongly or consistently eastward as did other bowheads. A few mother/calf pairs traveled *west* for at least a few kilometers, based on direct observations or photoidentification. One mother/calf pair traveled only 12 km in 44 h. 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. The calves apparently were pulled along by hydrodynamic forces created by the motion of the mothers. It is not known whether the animals touched one another during this "riding" behavior. Riding has not been seen in late summer or autumn, when the calves are older and larger.

One adult seen on 24 May 1989 was closely accompanied by a presumed yearling.

Photogrammetric data showed that the bowheads without calves present in mid and late May 1989 were mainly adults (>13 m long). The mothers that were measured were 13.9-15.9 m long (n=9); calves were 4.0-5.0 m long (n=8). Four individually-recognizable adults were photographed on two or three different days in May 1989 either by ourselves or by National Marine Fisheries Service personnel. At least four adults photographed by ourselves or NMML in May 1989 had also been photographed in earlier years, including two photographed as early as 1982. One of the latter had a calf in both 1982 and 1989.

Bowheads visible under undisturbed conditions in May 1989, mainly amidst the pack ice, were engaged in traveling (migration), socializing, and resting. Several behaviors that have been observed commonly in late summer and autumn were seen only infrequently in May 1989: pre-dive flexes, fluke-out dives, and aerial activities. A few bouts of sexual activity were observed. Many bowheads apparently migrated through the study area unseen during periods of heavy ice cover and poor weather. It is not known whether the observed frequencies of behaviors in visible whales were representative of frequencies in the population as a whole.

Drilling Noise Playbacks

Because of the difficult field conditions in 1989, there were only five days when we were able to observe bowheads that were exposed to projected drilling noise. All data had to be collected from holes and leads amidst the pack ice rather than along the landfast ice edge. The number of bowheads seen near the sound projector in 1989 was too small to allow detailed statistical analysis of acoustic effects on distribution or movements. However, some noteworthy data were obtained.

Several bowheads were observed migrating east past the projector while it was broadcasting continuous drilling sounds. The closest observation was on 19 May, when one bowhead swam almost directly toward the operating projector until it was only 100-120 m away. This whale then dove. The drilling noise :

ambient noise ratios 100-120 m from the projector were estimated to be S:N = 41 dB in the 20-1000 Hz band and S:N = 49 dB in the third-octave band centered at 200 Hz. On the same day, another bowhead swam almost directly toward the projector until it was 720 m away, whereupon it dove and disappeared. Two more bowheads swam past with a closest point of approach 1 km away. All of these positions were determined by theodolite. During this period the sounds received 1.1 km from the projector were monitored via a sonobuoy. The drilling sounds were quite prominent there, well above the natural background noise. Hence, it seems inevitable that all of these whales were able to hear the drilling sounds.

Similarly, on 14 May, at least three migrating bowheads passed as close as 500 m to the side of the projector while it projected continuous drilling sounds, and a fourth passed 900 m to the side. Two of these whales were observed from the circling aircraft for ~1½ hours as they swam NE and N, generally toward the projector. Again, the drilling sounds were monitored 1 km from the projector, and confirmed to be well above background noise levels there. S:N 500 m from the projector was ~13 dB in the 20-1000 Hz band and 24 dB in the third-octave band centered at 80 Hz.

The bowheads mentioned above were migrating NE past the operating sound projector, with no evidence of hesitation or diversion. However, other bowheads may have been diverted when they came that close. On 23 May, we saw a mother and calf swimming north and then west, directly away from the projector, while it emitted drilling noise. They were 1 km away when first seen, and were still heading away when last seen 5 km west of the projector. Below 350 Hz, the drilling noise was quite prominent 1 km from the projector. S:N 1 km from the projector was ~8 dB in the 20-1000 Hz band and 15 dB in the third-octave band centered at 200 Hz. However, it was barely detectable 5 km away, where the whales were still heading west away from the projector.

The westward travel by this pair of bowheads was inconsistent with the normal NE, E or SE movements of bowheads migrating in the study area in spring, and was suggestive of a disturbance reaction. However, we cannot be certain that these whales reacted to the sound projector. Other bowheads, particularly mothers and calves, occasionally traveled west in the absence of drilling noise. It is well known from previous studies that the sensitivity of bowheads to man-made noise varies. It is possible that there is additional variation in sensitivity in spring because some bowheads, before reaching our study area, are pursued by whaling crews. Thus, it would not be surprising if some individual whales migrated past the projector at relatively close distances while other bowheads showed avoidance reactions even to quite weak industrial sounds.

In summary, only limited data have been acquired to date on reactions of bowheads to noise playbacks in spring lead systems. However, some bowheads that were visible migrating through the pack ice east of Pt. Barrow in spring tolerated low-frequency drilling noise without interrupting or diverting their migration. Some bowheads tolerated levels of industrial noise as high as or higher than the levels that elicited avoidance reactions during playbacks to summering bowheads. Other individuals *may* have reacted strongly to drilling noise no stronger than that tolerated by certain bowheads. It would be premature to generalize these few observations. In particular, it should not be assumed that all bowheads migrating in spring would tolerate sounds as strong as those a few hundred meters from the projector. The ice present near all 1989 observation sites made it impossible to determine whether some whales were reacting at greater distances. Also, it should not be assumed that bowheads would behave in the same way when exposed to other types of industrial sounds differing in spectral characteristics or source level.

Aircraft Disturbance

Only a few opportunistic observations of reactions of bowheads to aircraft were obtained in 1989. Our preliminary impression is that bowheads are no more sensitive to fixed wing aircraft like the Twin Otter during spring migration through pack ice than they are in late summer in largely open waters. In the one observed case of repeated exposure to low-altitude helicopter passes, a mother and calf bowhead did not flee, but may have dived in response to some passes. No generalizations should be drawn from these preliminary data on reactions to helicopters.

White Whales

Movements and General Behavior

Sightings of white whales were much more numerous than those of bowheads in May 1989. As previous workers have reported, white whales tended to be more widely scattered and slightly farther offshore than bowheads, but their migration corridors overlapped broadly. Most of the white whales seen were amidst the pack ice, although in late May a few were traveling east on the offshore side of the lead bordering the landfast ice edge.

Most white whales were either migrating in a generally NE direction or resting on the surface. Migrating white whales tended to follow leads or cracks, changing heading as necessary to remain within the crack. 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.

Drilling Noise Playbacks

We observed migrating white whales close to the operating projector on four dates in May 1989. On three of these dates, at least a few white whales came within ~200 m of the operating projector, including a few within 50-75 m of the projector. White whales that were 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 to the projector continued past it without apparent hesitation or turning. However, others did react temporarily to the noise (or perhaps visual cues) at distances on the order of 200-400 m.

On 14 May, a substantial proportion of the white whales that came within 200-400 m of the projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was very obvious, but lasted only several minutes. Then the whales 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. We suspect that this was related to their poor hearing sensitivity at the low frequencies where the *Karluk* drilling sounds were concentrated. On most days during the study, received levels of the low-frequency drilling sounds (on a 1/3-octave basis) were less than the measured hearing sensitivity of white whales at all distances beyond ~200 m. This suggests that white whales may have been unable to hear the low-frequency drilling sounds at distances much beyond 200-400 m, even though the sounds were detectable by hydrophones (and audible to humans) up to several kilometers away.

These results provide preliminary evidence about the seemingly low sensitivity of white whales to the one type of continuous drilling sound used in the 1989 experiments. However, the sample sizes were small. Also, the results refer to a particular experimental situation. Some oil industry activities have higher source levels than we could simulate with a J-11 sound projector. Reaction distances are expected to be greater in such cases. Some other activities have lower source levels than did the J-11 projector.

Also, sensitivity of white whales to other types of oil industry sounds probably differs. The hearing sensitivity of white whales improves greatly with increasing frequency. Thus, reaction distances are likely to be greater in the cases of industry noises containing higher frequency components. In the Canadian high arctic, spring-migrating white whales react strongly to noise from vessels tens of kilometers away. To understand the effects of industrial noises related to oil production on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989.

Aircraft Disturbance

Only a few opportunistic observations of the reactions of white whales to aircraft overflights were obtained in 1989. *Twin Otter*: Two white whales rolled slightly and looked up at the Twin Otter as it flew over at altitudes of 260 and 457 m ASL. A group of seven white whales dove abruptly and steeply when it flew almost directly over them at 200 m. *Bell 212*: Two groups of white whales dove immediately when the helicopter flew over at altitudes of 152 and 457 m ASL. A single white whale dove rapidly and steeply when the helicopter flew 50 m to the side at 120 m ASL. Additional data are needed before conclusions can be drawn about reactions of white whales to aircraft overflights during spring migration through the study area.

Prior to the 1989 field season, doubts had been expressed about the feasibility of a study of this type, given the logistical problems and potential for interference with whaling or other research programs. The initial 1989 phase of the study demonstrated that it is possible to conduct an experimental study of noise effects on whales migrating through leads in spring, and to do so without interfering with spring whaling.

Of the four general objectives stated above, objectives 1-2 were partially met, but additional data are needed. Objective 3, involving coordination with other studies and local resource users, was met. Objective 4 concerned analyses and hypothesis tests; the 1989 data have been analyzed, but formal tests of hypotheses have been deferred because of the generally low sample sizes from the 1989 experimental work. Sample sizes were small because of the difficult ice and weather conditions encountered in 1989. In a year with different weather and ice conditions, considerably larger sample sizes might be obtained.

After additional data are collected, the results of this study should be useful in assessing the acoustic effects of oil exploration and development near spring lead systems on migrating bowhead and white whales. These results should help resolve questions about possible jeopardy to bowheads if oil development proceeds near spring leads.

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Mr. Mark Fraker	BP Exploration (Alaska), Inc.,
Dr. Roger Green	University of Western Ontario (1990 only),
Mr. Allen Milne	Sci. Rev. Board Chairman,
Dr. Byron Morris	Nat. Mar. Fish. Serv. (1989 only),
Mr. Ron Morris	Nat. Mar. Fish. Serv. (1990 only),
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INTRODUCTION

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 studies of the reactions of bowhead whales to oil industry operations in the Alaskan Beaufort Sea (e.g. LGL and Greeneridge 1987).

All of the bowhead disturbance studies done to date have 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 has 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 has been no systematic scientific study of the suggestion by Inupiat whalers that bowheads 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, *viz* aircraft and boat traffic, marine seismic exploration, drillships, and offshore construction. Only a very limited effort has been devoted to the reactions of bowheads to icebreaking, which is a particularly noisy activity (Richardson et al. 1983; Greene 1987a). Reactions of bowheads to sounds from an oil production platform have 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 recent Biological Opinions on lease sales in the Beaufort and Chukchi seas. NMFS believes 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). 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 Canadian high arctic. 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). Their responsiveness to underwater noise during the spring migration around western and northern Alaska has not been studied previously.

In order to answer some of these questions, MMS has funded this study. The main objectives are 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 is 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 are also to be determined when possible.

This report describes the first year of a continuing study. Fieldwork in 1989 provided useful data concerning several of the objectives. However, more data will be required before definite conclusions can be drawn about disturbance effects on spring-migrating bowheads and white whales.

Background

Spring Migration of Bowhead Whales

Bowhead whales spend the winter in and near the pack ice of the western Bering Sea from St. Lawrence Island south to St. Matthew Island and west to the USSR coast (Braham 1984). They leave their wintering grounds in March and follow the nearshore flaw lead ("NW Alaska Lead") through the Chukchi Sea to Point Barrow (Fig. 1; Ljungblad et al. 1985). Although a few sightings have been made at the Barrow ice-edge as early as March (Brower 1942; Dronenburg et al. 1983), the main migration usually does not begin until late April. The majority of bowheads pass Pt. Barrow and enter the Beaufort Sea during May but some stragglers continue passing until mid- to late June (Fig. 2). The early migrants tend to be small whales and the later migrants tend to be large ones, including mothers with newborn calves (Nerini et al. 1987).

In 1980, unusually severe ice conditions in the Bering Strait region apparently blocked the migration route of bowheads until mid May (Johnson et al. 1981). Although the first bowhead was not seen passing Pt. Barrow until 21 May (~1 month late), the majority of the whales had passed Barrow by early June--the normal end time of the migration past Barrow.

The direction of movement of bowheads appears to turn slightly from northeast to ENE or east after they pass Pt. Barrow (Marko and Fraker 1981; Braham 1984; Ljungblad et al. 1985; Rugh 1987). The turning point tends to be about 35 km beyond Pt. Barrow, where the landfast ice edge also tends to turn from NE to about east or ESE. Once east of Pt. Barrow, most bowheads follow the "E-W offshore shear zone" through the pack ice rather than the nearshore flaw lead along the edge of the landfast ice (Fig. 1, 3). The whales are more dispersed there than when they are southwest of Barrow, and bowheads are frequently found among the pack ice (Ljungblad et al. 1985). As bowheads move eastward their

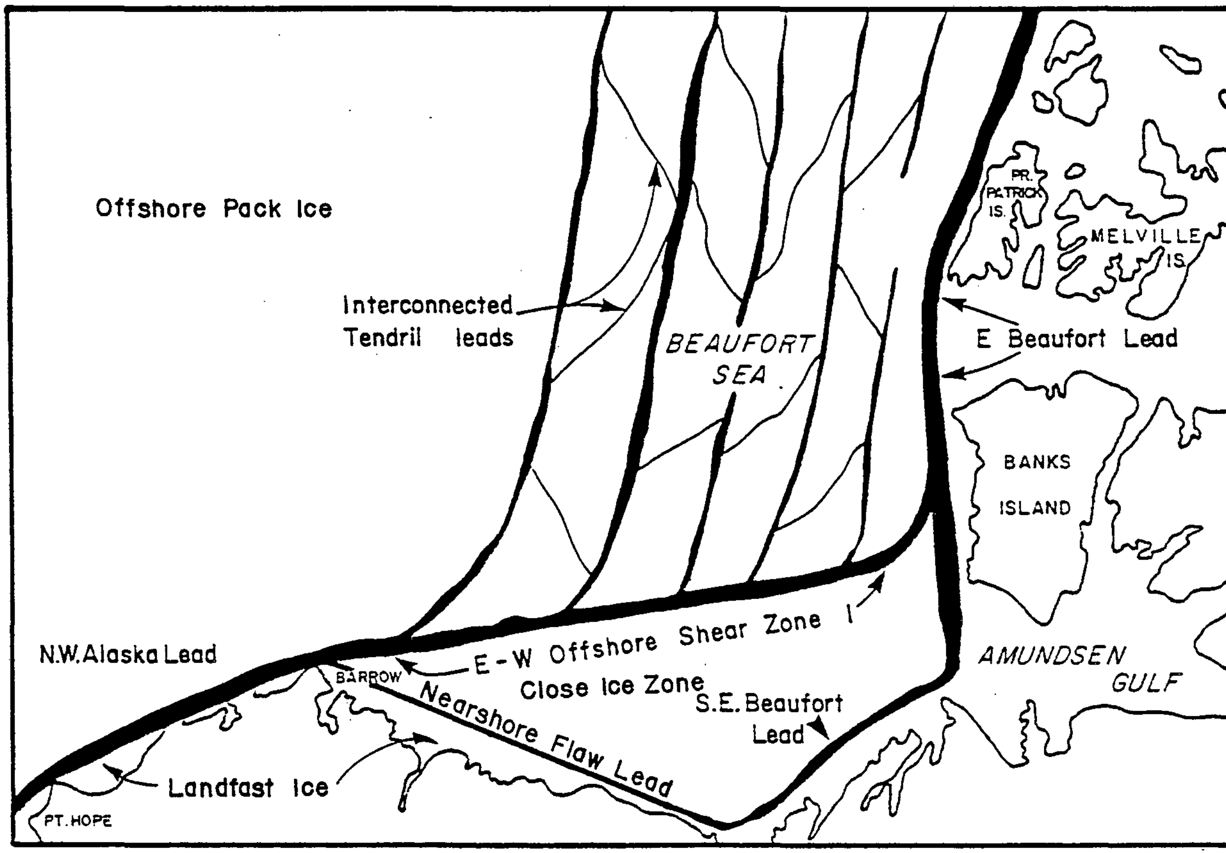


Fig. 1. Typical pattern of spring lead formation in the Beaufort Sea (modified from Marko and Fraker 1981).

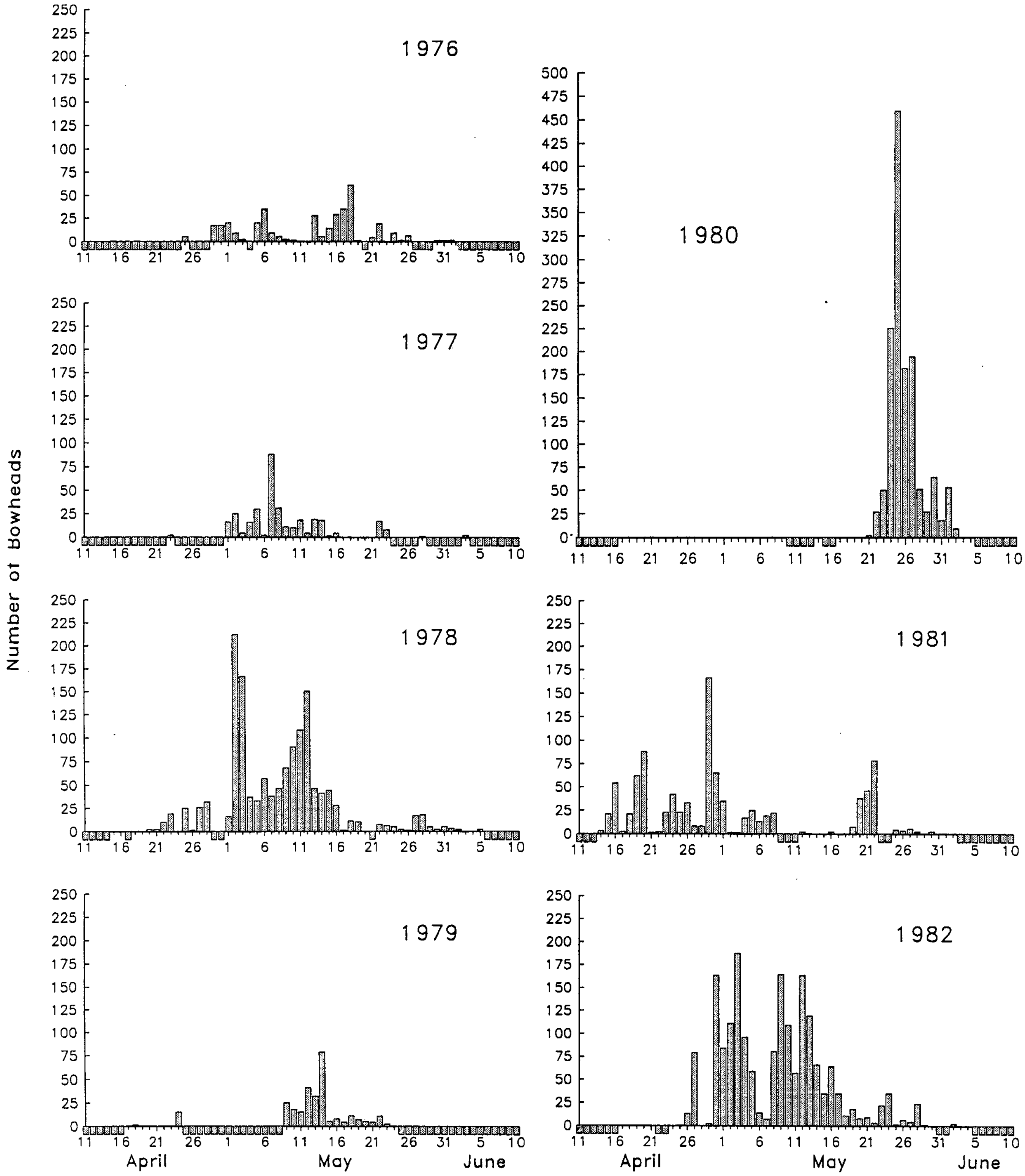
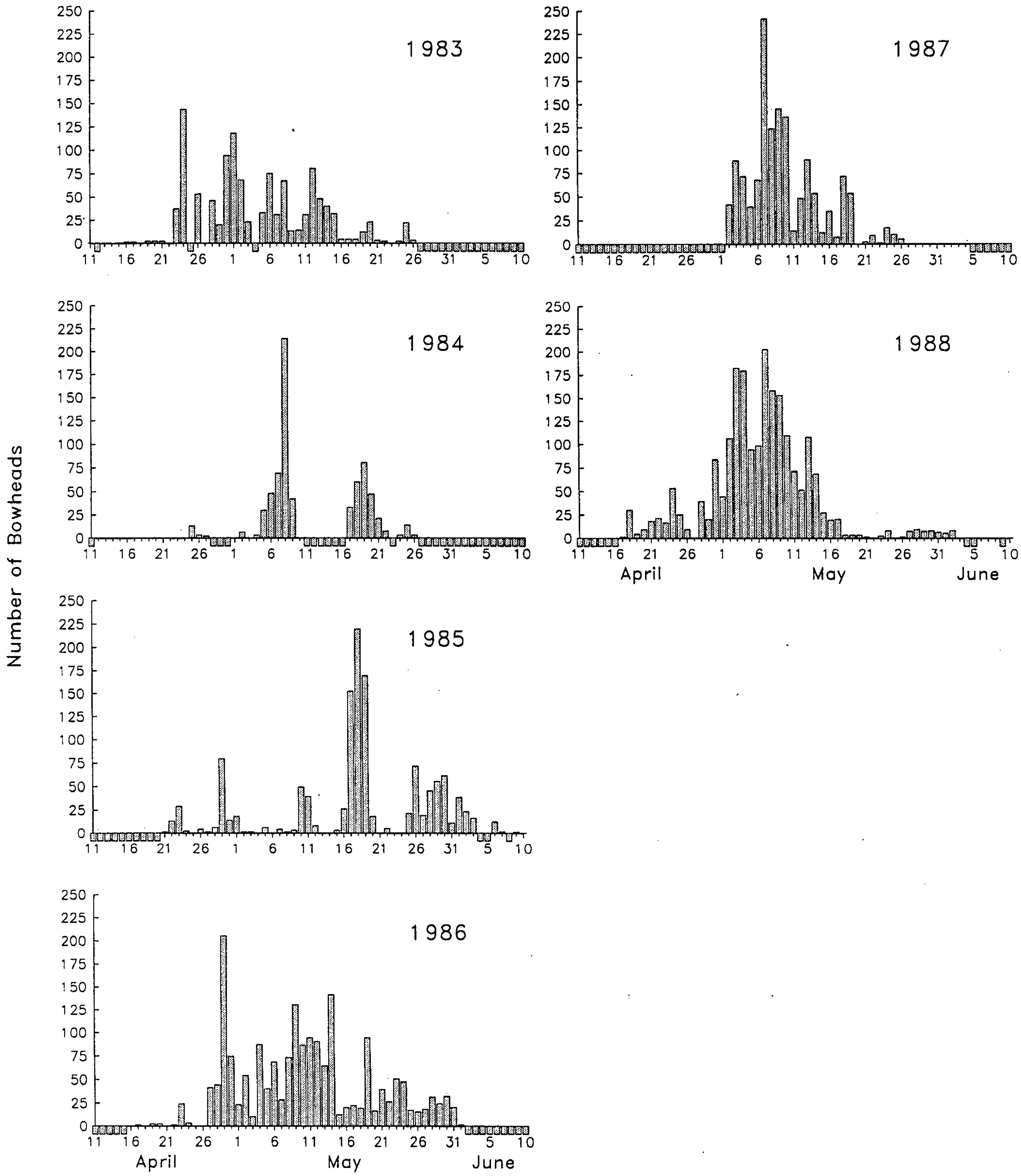


Fig. 2. Timing of the spring bowhead migration past ice-based census camps near Barrow, 1976-88. Days when no visual census was possible are shown by a mark below the date axis. Re-plotted from a data file provided by North Slope Borough Dept. of Wildlife Management, courtesy of J. C. George.



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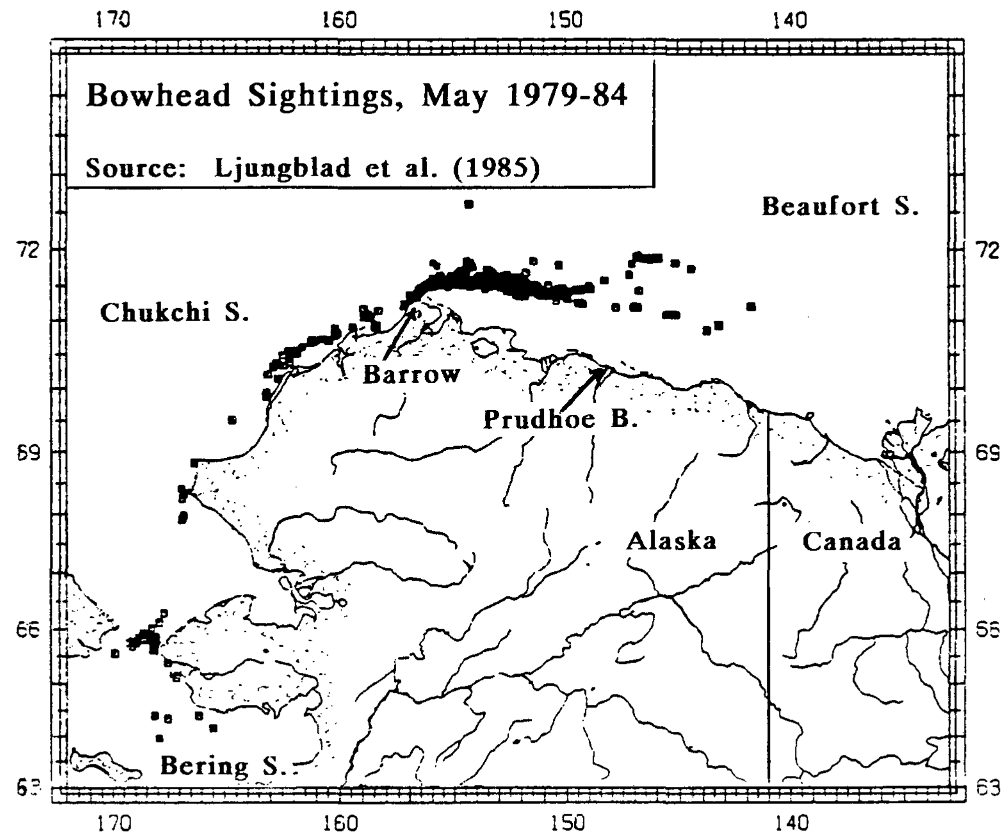


Fig. 3. Distribution of bowhead whale sightings during the month of May in 1979-1984 (modified from Ljungblad et al. 1985).

migration corridor becomes wider and they are more likely to be found amidst the pack ice both north and south of the main shear zone (Marko and Fraker 1981). Ljungblad et al. (1984) found the eastward migration route to be ~25 km wide at Barrow but ~50 km wide from north of Smith Bay to Harrison Bay.

The width of the spring migration route through the planned study area east of Pt. Barrow varies from year to year. Locations where bowheads were sighted during surveys flown by the U.S. National Marine Fisheries Service during the springs of 1985-87 are shown in Figures 4A-4C. The migration corridor in 1987 was narrower than the corridors in 1985-86. In 1987, the corridor was apparently less than 11 km wide even as much as 50 km east of Pt. Barrow (Fig. 4C). In each of these years, there was a concentration of bowheads along a route oriented ENE from Pt. Barrow, gradually turning to the right as the whales progressed eastward.

All available evidence indicates that few if any bowheads migrate in the "Nearshore Flaw Leads" that occasionally form along the landfast ice edge off the NE Alaska coast (Fig. 1). Almost all travel east through leads in the E-W offshore shear zone.

<u>Spring Migration of White Whales</u>

White whales winter among the pack ice of the Bering and southern Chukchi seas (Seaman et al. 1985). They begin their migration one to two weeks earlier than bowheads (Braham et al. 1984). The earliest recorded passage of white whales past Point Barrow was on 2 April, but white whales are known to utilize offshore leads during spring migration and it is possible that some pass Pt. Barrow unnoticed on earlier dates. Frost et al. (1988) suggest that they may pass Barrow as early as late March. The peak of the spring migration past Pt. Barrow occurs from late April to the third week of May, and varies according to ice conditions. The spring migration past Pt. Barrow may continue through at least early July (Oliver 1987).

White whales follow the nearshore flaw lead through the Chukchi Sea to Pt. Barrow (Ljungblad et al. 1985), and are more likely to move through the offshore pack ice than are bowheads (Braham et al. 1984). Once they have passed Pt. Barrow, white whales follow offshore leads in deep water northeast or east toward Banks Island (Fig. 1, 5; Fraker et al. 1978; Hazard 1988; Fraker 1979). They tend to migrate in waters north of the usual bowhead migration route, although there is some overlap. Ljungblad et al. (1984) referred to the distribution of the two species east of Pt. Barrow as "partially segregated" with white whales commonly seen farther north than bowheads. Braham et al. (1984) found white whales near the northern ends of survey lines flown north of Pt. Barrow in May 1976 (sightings near 72°10'N), and as far north as ~73°15' northeast of Pt. Barrow in late May 1977. The latter sighting was about 300 km north of the coast between Harrison and Prudhoe Bays. Farther east, in the Canadian Beaufort Sea, Fraker (1979) found white whales as far north as he flew (75°36'N), and he suggested that some white whales could move through waters as far north as 77°N. Frost et al. (1988) mapped spring white whale sightings in

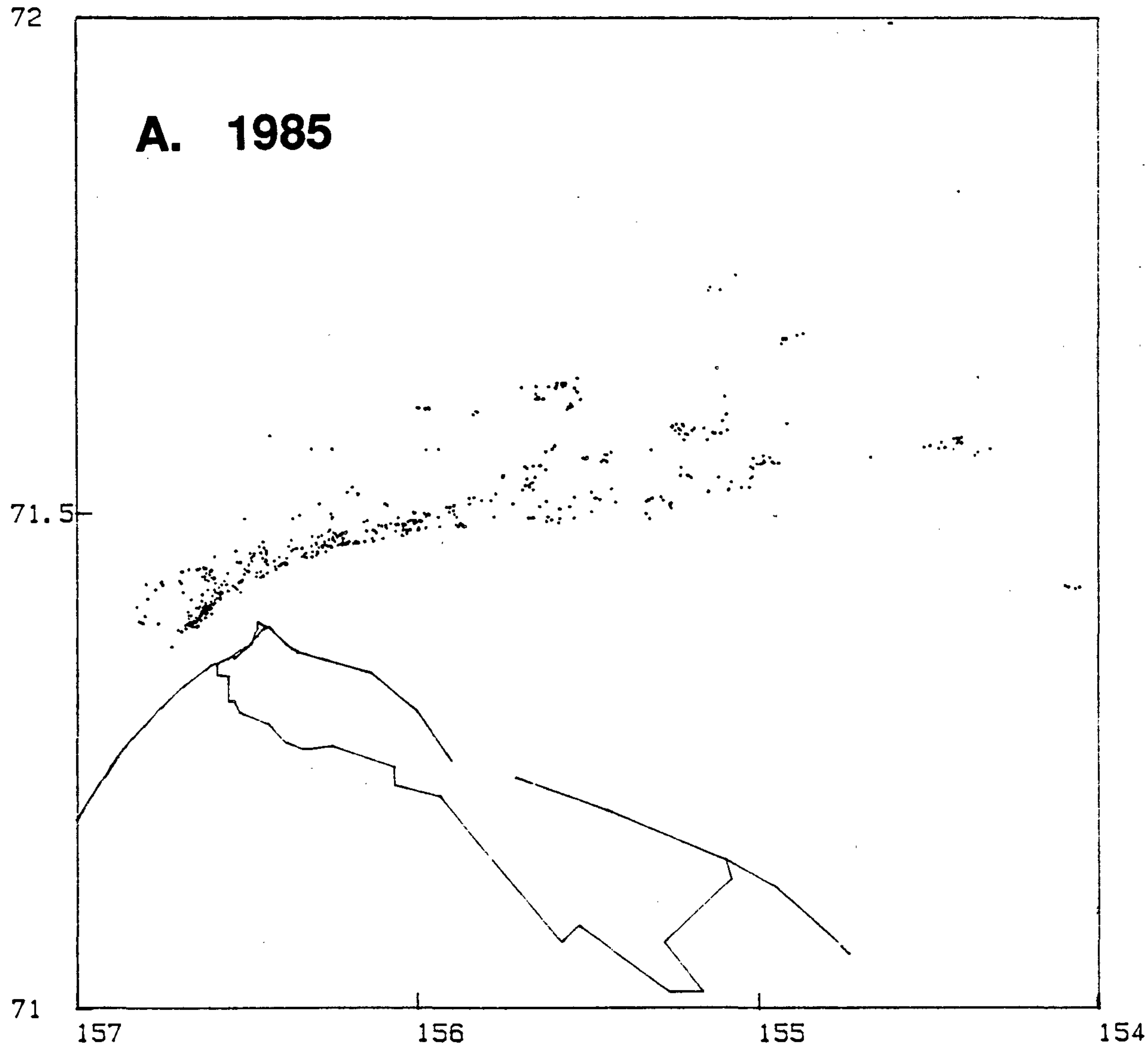
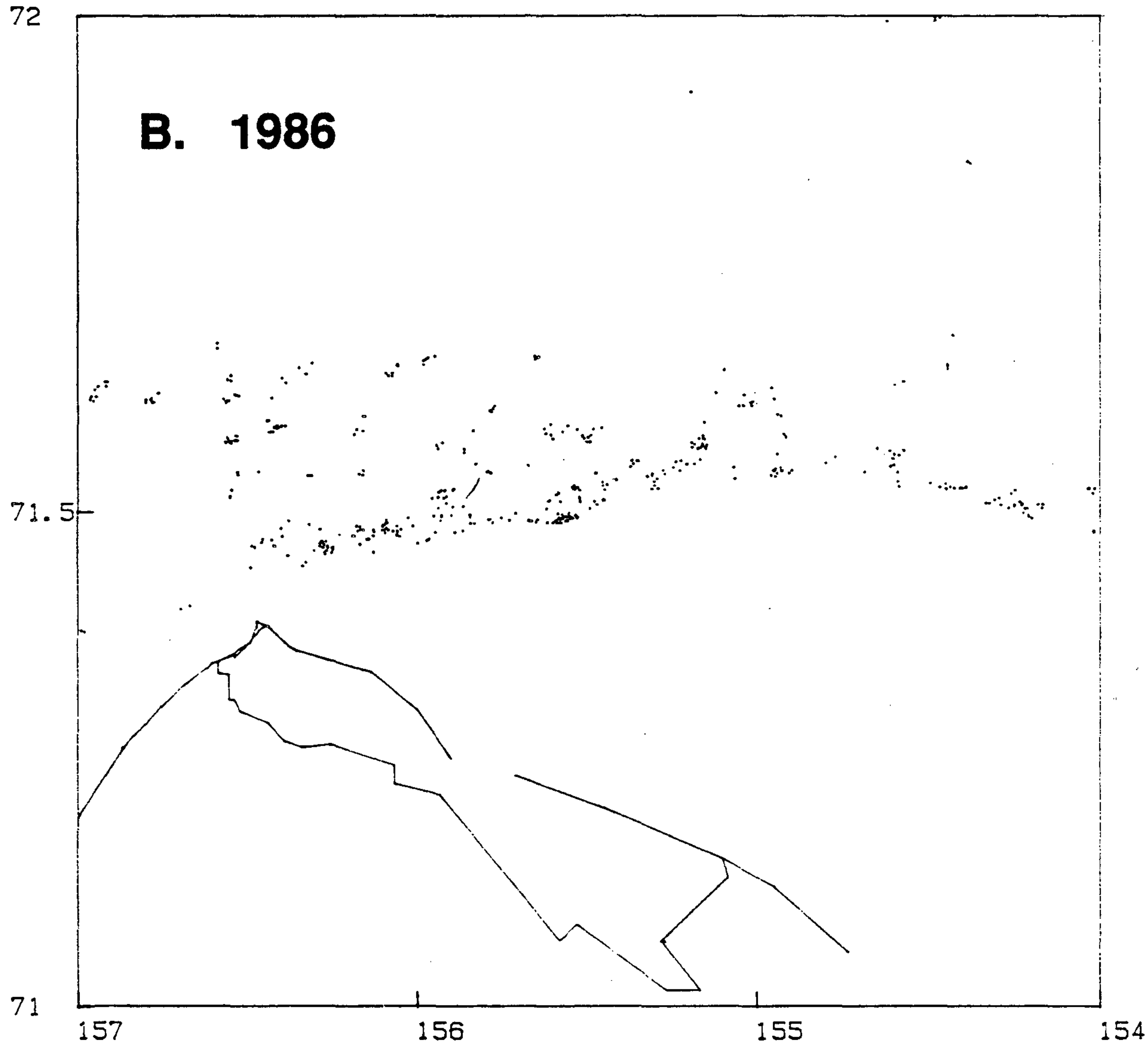


Fig. 4. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Fisheries Service in (A) 1985, (B) 1986, and (C) 1987 (NMFS unpubl. data).



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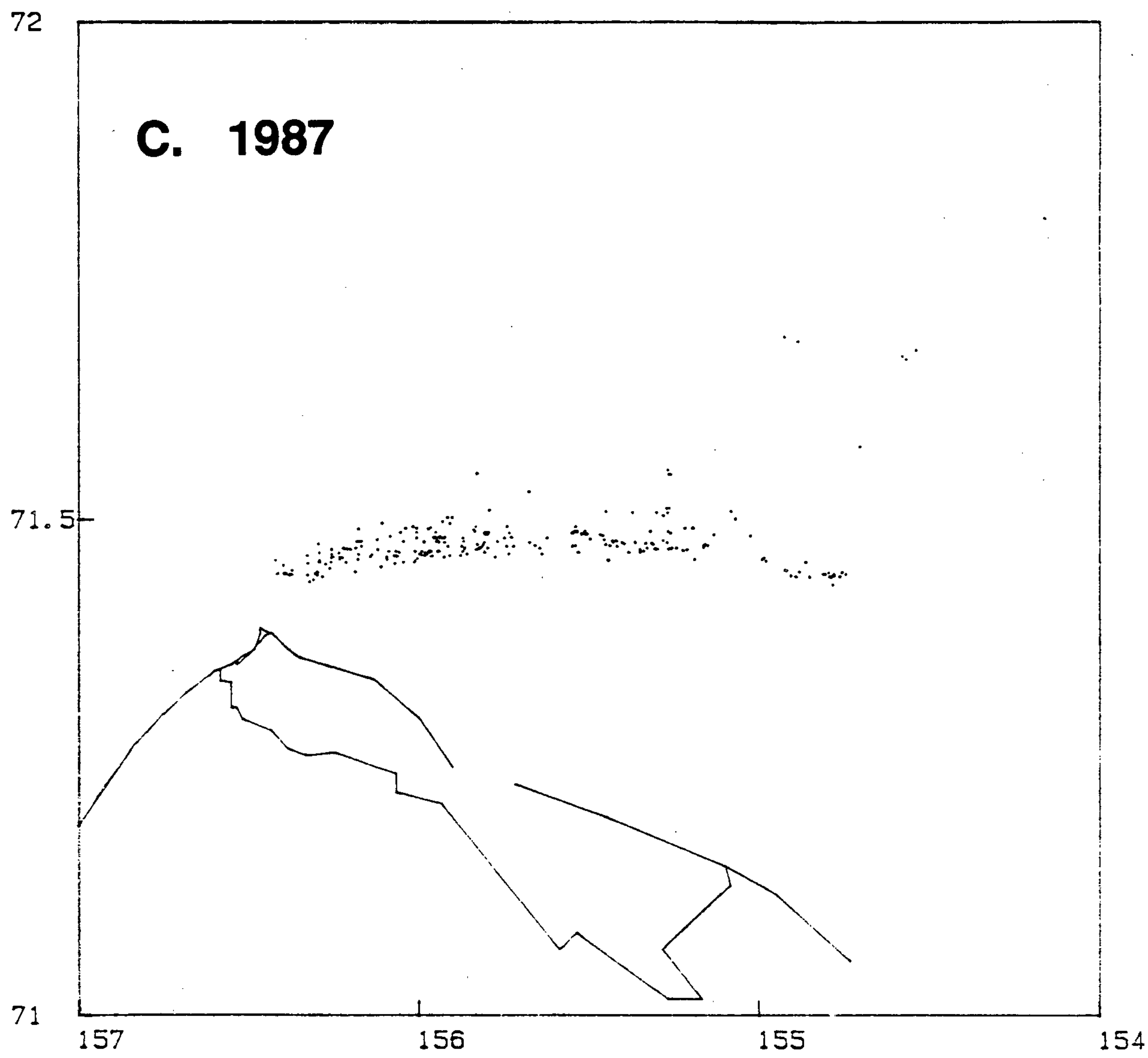

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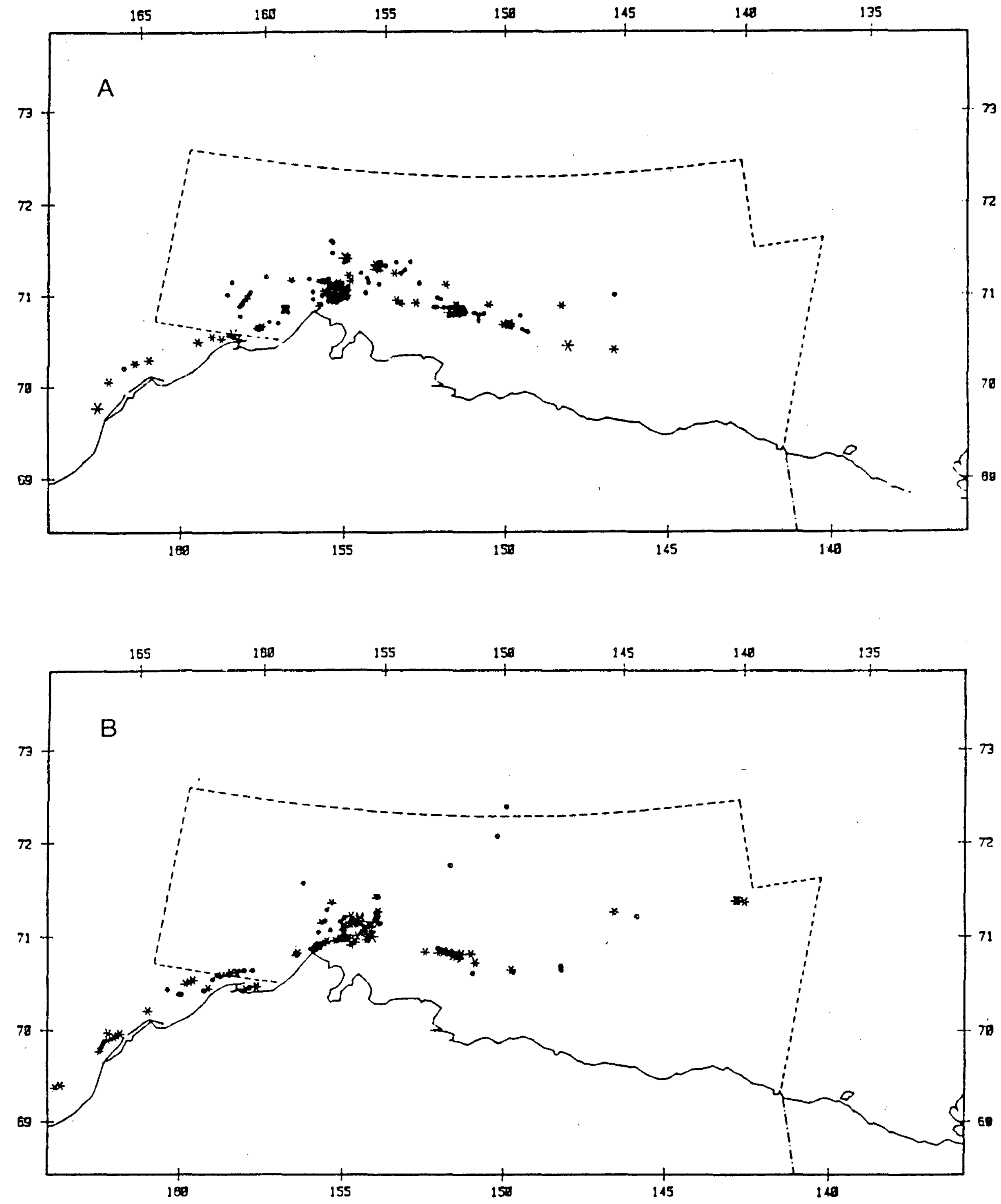

Fig. 5. Distribution of white whale sightings during (A) 1-15 May and (B) 16-31 May in the Alaskan Chukchi and Beaufort Seas (from Frost et al. 1988).

the Chukchi and Alaskan Beaufort Sea by two-week periods (Fig. 5). These maps also indicate a migration path somewhat farther north and more dispersed than the relatively narrow bowhead migration corridor. The scarcity of white whale sightings north of 72°N on Figure 5 may, in part, reflect little survey coverage in that area.

Disturbance Reactions of Bowhead Whales

The short-term behavioral reactions of bowhead whales to several types of oil industry activities have been studied on the summer feeding grounds in the eastern Beaufort Sea (Richardson et al. 1985a,b, 1986, 1990; Wartzok et al. 1989) and during autumn feeding and migration in the Alaskan Beaufort Sea (Reeves et al. 1984; LGL and Greeneridge 1987; Ljungblad et al. 1988). The major types of oil industry activities whose disturbance effects have been investigated are aircraft and vessel traffic (including, to a limited extent, icebreakers), marine seismic exploration, drillships, and offshore construction. These and other related studies have included work on the spectral characteristics, source and received levels, and propagation losses of the underwater noise from each of the main oil industry activities occurring in the Beaufort Sea during summer and autumn.

The summer/early autumn data from the eastern Beaufort Sea came from very different circumstances than those found in spring. The data came from areas of open water or, at most, loose pack ice, and involved whales that were remaining in specific feeding areas rather than actively traveling. However, the eastern Beaufort work is noteworthy in that it did involve controlled experiments on the reactions of bowheads to continuous industrial sounds. Recorded drilling and construction sounds were projected into the water, and the behavior of bowheads before, during and sometimes after the playbacks was compared (Richardson et al. 1985b, 1990; Wartzok et al. 1989). However, the durations of the experiments were limited to 30-105 min by logistical constraints, and the sound levels emitted during these tests were less than those of the actual industrial activities being simulated.

The bowhead disturbance data acquired during summer (up to 1985) have been used, along with data on underwater noise from oil industry activities, to predict the likely radii of audibility and responsiveness around various oil industry activities (Miles et al. 1987; Richardson et al. 1990). These predictions refer to late summer conditions in the Canadian Beaufort and early autumn conditions in the Alaskan Beaufort. The Miles et al. modeling study assumed that each industry activity operated during autumn, in turn, at each of six specific drillsites in the Alaskan Beaufort Sea.

The available data on disturbance reactions of bowheads during autumn migration may be the most relevant results with respect to spring migration. LGL and Greeneridge (1987) studied the reactions of bowheads to full-scale drilling operations involving a drillship and several support ships. Drilling activities of this nature may be more disruptive to whales than production activities from a single stationary platform. LGL and Greeneridge (1987) found that westward-migrating bowheads whose courses would have brought them within 10 km of the drillship altered course to pass more than 10 km north or south of the drillsite. By making such a diversion, they avoided exposure to strong industrial noise. Several migrating whales were observed 15-30 km from the drillsite. Their responses to the weaker noise at those ranges were described as none to mild. On one occasion, a bowhead altered its course repeatedly, apparently to divert around the drillsite. It remained 23-27 km from the drilling operation as it migrated westward past the operation. In spring, ice conditions might often prevent bowheads from undertaking similar diversions. In that case, it is unknown how the whales would react.

There have been a few late winter and spring observations of bowhead reactions to fixed wing survey aircraft (e.g. Ljungblad et al. 1984; Ljungblad 1986) and helicopters (Dahlheim 1981). With these few exceptions, there is virtually no information in the scientific literature concerning the reactions of bowheads to human activities and noise in spring.

Thus, previous disturbance studies of bowheads have been important in assessing potential short-term disturbance responses, at least in the open water and loose ice conditions common in summer and early autumn. However, available data are not sufficient for predicting short-term reactions of bowheads in spring when ice conditions and whale activities are very different. Existing data also are not sufficient for predicting the long-term consequences of continuous, stationary industrial activities at any season, and especially in spring.

Disturbance Reactions of White Whales

Davis and Thomson (1984) and Richardson et al. (1989) reviewed the available published and unpublished information on responses of white whales to disturbance. There is great variation in responses depending on the population involved, time of year, and other factors such as presence of potential food.

Populations that have been exposed to moderate to high levels of shipping in open water seem to have habituated to the shipping noise. White whales in areas with much vessel traffic (St. Lawrence estuary; Cook Inlet, Alaska; Churchill, Manitoba) are not displaced by nearby shipping or by oil production facilities (Davis and Thomson 1984). In the Bristol Bay area (Alaska), white whales were relatively insensitive to playbacks of taped drilling noise from a semi-submersible vessel, although they did "startle" when the playback started and stopped suddenly. However, white whales responded more noticeably to outboard motor noise, perhaps because whales are hunted from outboards (Stewart et al. 1982, 1983; Awbrey and Stewart 1983). Playbacks of drilling noise to captive animals caused little behavior change and no evidence of physiological stress even though received levels were as high as 153 dB re 1 μPa (Awbrey et al. 1986). The latter study, along with Johnson et al. (1989), also confirmed that hearing sensitivity below 1000 Hz, where industrial noise is concentrated, is quite poor even though white whales have very sensitive hearing at high frequencies (Fig. 6).

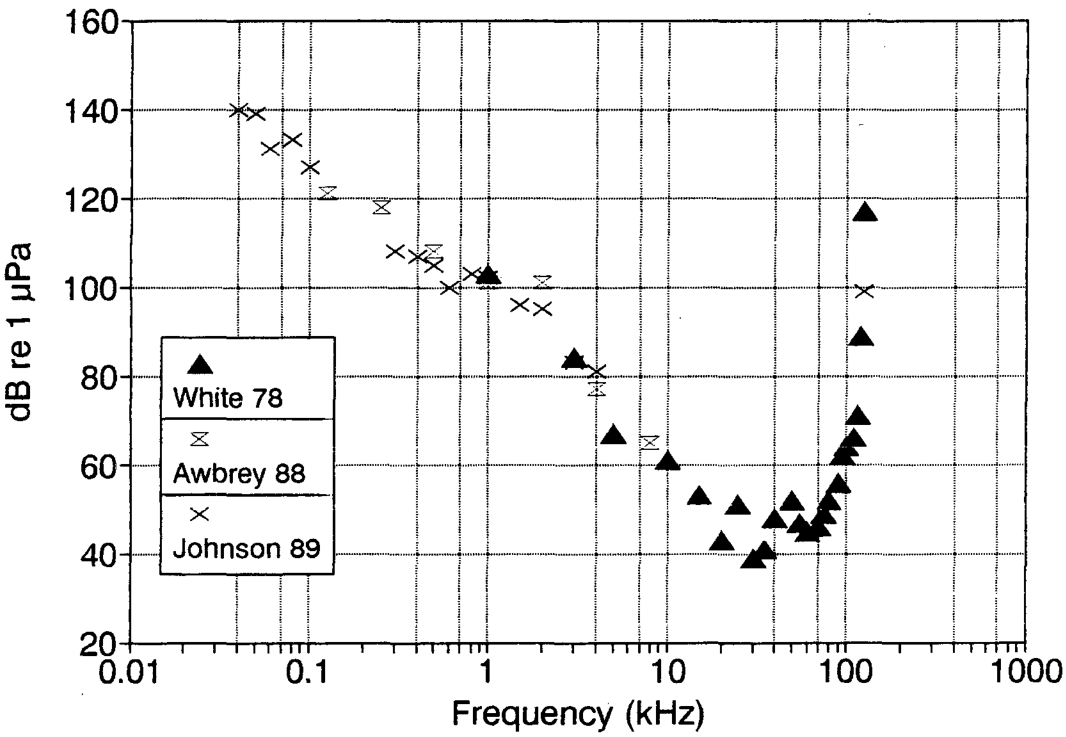

Fig. 6. Absolute hearing sensitivity of white whales listening underwater, plotted in relation to frequency. Data are from White et al. (1978, average of two animals), Awbrey et al. (1988, n = 3), and Johnson et al. (1989, n = 1).

In addition to general habituation, the activity of the animals may affect their response to disturbance. White whales actively feed on salmon in inner Bristol Bay in June and early July. The area contains a major salmon fishery with hundreds of fishing boats supported by high-powered tender boats and float planes. While feeding on the salmon, the whales consistently move among the boats and nets (Frost et al. 1983; L. Lowry *in* Davis and Thomson 1984). It appears that feeding white whales will sometimes tolerate large amounts of noise and disturbance.

Ice conditions apparently can influence the disturbance responses. In open waters of the Mackenzie estuary, white whales were relatively tolerant of stationary noise sources, although they did take evasive action at distances up to 2.4 km from moving vessels. White whales seemed more sensitive when in confined areas, such as leads in the ice, than when in open water. They also appeared to be more sensitive in shallow than in deeper water (Fraker 1977a,b, 1978; Fraker and Fraker 1979; Norton Fraker and Fraker 1982; M.A. Fraker *in* Davis and Thomson 1984).

In the Canadian high arctic, white whales of a different stock are very sensitive to ship noise when the first ship of the season approaches (LGL and Greeneridge 1986; Cosens and Dueck 1988). Alarm calls and fleeing responses were detected when the ship was still tens of kilometers away and its sound was barely detectable. These extremely large reaction distances may have been partly attributable to good sound propagation conditions in deep water. However, other reasons for the high sensitivity of the whales may have included the partial confinement of the whales by heavy ice cover in spring, and the novelty of industrial noise in that area and season. These last two possibilities might also apply in the Beaufort Sea in spring.

To summarize, available data show that reactions of white whales to man-made noise are highly variable. Based on these data, it is not possible to predict how white whales migrating through the ice near Barrow will respond to playbacks of industrial noise. Available data suggest that white whales whose movements are partly confined by ice in spring may be quite sensitive to industrial noise.

Sounds from Spring Production Activities

There are published data on the spectral characteristics and levels of underwater noise from many activities of the offshore oil industry. Many of these measurements were obtained in the Beaufort Sea or elsewhere in Alaskan waters. However, offshore oil production has not yet begun from arctic waters deep enough to be used by bowhead whales, so there are no data on noise from oil production activities in the arctic.

Sounds from production platforms were studied by Gales (1982), but the types of platforms that he studied are not at all typical of those that would be used in arctic waters. Future hydrocarbon production near the spring migration routes of bowheads and white whales in the arctic is likely to be from large, bottom-founded caissons or islands. These structures, unlike those studied by Gales, are expected to have large areas of contact with the bottom in order to withstand expected ice conditions. Sounds from bottom-founded exploration caissons have been recorded in the Canadian and Alaskan Beaufort Sea. Almost all published results concern the open water season (Greene 1985, 1987b; Miles et al. 1987; Hall and Francine 1990).

Existing bottom-founded drilling platforms used in the arctic (CIDS, Molikpaq, SSDC) are usually encircled by a grounded mass of ice when operating in winter. This ice is seeded by hoses from the platform in order to build up a thick barrier around the structure. This barrier provides additional protection against moving pack ice. The presence of this ice barrier may significantly reduce the amount of noise that radiates into the waters surrounding the drilling platform. Thus, sounds from summer drilling operations may be quite different than noise from winter/spring drilling operations even if conducted from the same platform.

The only data on sounds emitted by a bottom-founded platform surrounded by ice were recorded near the CIDS in late November 1989, after the present study was conducted (Hall and Francine 1990).[1] The received broadband levels in the 30-1000 Hz band were relatively low (~89 dB re 1 μPa at range 1.4 km). However, there was much more energy at frequencies below 30 Hz, including a strong tone near 1.5 Hz. That tone was interpreted as being the fundamental frequency of the rotary table on the drillrig. Other studies of noise from industrial activities in the Beaufort Sea have not considered sound components below 10 or 20 Hz. It is not known whether bowheads are sensitive to frequencies in this range (see p. 208-210). White whales almost certainly do not have useful sensitivity below 20 Hz, based on measurements from 40 Hz upward (Fig. 6).

Offshore production platforms typically support many directionally-drilled wells. Drilling of additional wells may continue long after production from the first well begins. Hence, it would be reasonable to study the reactions of whales to sounds from existing bottom-founded drilling caissons used in the arctic, even though these structures are not fully equivalent to anticipated production facilities.

The attenuation of received noise levels with increasing distance from industrial sources has received considerable attention in arctic waters. However, most of these data were acquired during seasons other than spring, and very few of the published propagation data were obtained near Barrow. Seasonal variations in ice conditions and water mass characteristics are known to have strong effects on underwater sound propagation in the arctic. A review and

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[1] Greeneridge Sciences was funded, under the present project, to obtain such recordings during the winter of 1988-89 if a caisson had been drilling in the Alaskan or Canadian Beaufort Sea at that time. However, there were no caisson-based drilling operations in the Beaufort Sea during that winter.

analysis by BBN Systems & Technologies Corp. during the planning phase of this project indicated that propagation conditions in and near spring lead systems vary widely, depending largely on variable ice characteristics (Appendix A).

Objectives

General Objectives

Given the above concerns and data gaps, 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 Seas 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."

Specific 1989 Objectives

Prior to the 1989 field program, it was decided that the study would include at least a second spring field season, in 1990. It was recognized that the overall objectives could not be met in a single season. The highest priority during the 1989 field program was to study the reactions of bowheads to noise from a bottom-founded drilling or production platform. When possible, reactions of white whales to this sound were to be determined as well. Underwater playback techniques were to be used to simulate the noise from an actual platform. As a lower priority, the reactions of bowheads and white whales to actual helicopter overflights were to be determined if opportunities allowed.

The specific objectives for the first field season, in 1989, were as follows:

1. To record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter.

2. To measure ambient noise levels and characteristics along the spring migration corridor of bowhead and white whales in the western Beaufort Sea.

3. To measure and model transmission loss of underwater sound along that part of the spring migration corridor, based on playbacks of test tones and the continuous drilling platform sound recorded in (1).

4. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of the continuous drilling platform sound in (1).

5. To measure the short-term behavioral responses of bowhead and (as possible) white whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to helicopter overflights.

6. 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.

7. 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.

8. To analyze the data to test hypotheses concerning effects of the drilling platform sound recorded in (1) on movement patterns and behavior of bowhead and white whales visible along their spring migration corridor in the western Beaufort Sea.

The 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 in 1989 were made more specific in four areas: (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 a platform. 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 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 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, LGL 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.

Approach

This is a complex study with many interrelated tasks or components. This section provides a brief description of the overall approach. This may be helpful in understanding the relationships among the various tasks. Methods are described in more detail in a later section (METHODS).

The general concept was that reactions of bowhead and white whales to industrial noises would be tested by using an underwater sound projector to introduce recorded noise into a lead through which whales were migrating. The movements and behavior of whales would be documented as they approached and passed the sound projector. Industrial sound levels reaching the whales at various distances from the projector were to be measured with sonobuoys or hydrophones, supplemented by acoustic modeling procedures. Reactions to helicopter overflights were to be determined using an actual helicopter rather than playback techniques.

LGL is responsible for the project as a whole, and for all biological components of the work. Subcontractor Greeneridge Sciences Inc. is responsible for providing and operating acoustical equipment, and for analyzing and reporting most of the physical acoustics results. Subcontractor BBN Systems & Technologies Corp. is responsible for sound propagation modeling.

The contract was awarded to LGL in the autumn of 1988. Funding was provided in two stages. Initial funding covered the planning phase (October 1988 to April 1989). After it was determined that the project likely would receive the necessary approvals and permits, incremental funding was provided for the 1989 fieldwork, analysis and reporting.

During the planning phase, we contacted and met with representatives of three local organizations: the North Slope Borough (NSB), Alaska Eskimo Whaling Commission (AEWC), and Barrow Whaling Captains' Association (BWCA). The purposes of these communications were (1) to obtain information about local conditions that would be helpful in planning the study, and (2) to avoid any actual or perceived interference with their ongoing activities, most notably whaling and the spring bowhead census. As part of this consultation process, project personnel attended a public meeting in Barrow in January 1989 and a meeting of the BWCA in February 1989. In addition, we contacted and met with representatives of the National Marine Mammal Laboratory (NMML) aerial photogrammetry group, who were also planning to work near Barrow in the spring of 1989.

Prior to the 1989 fieldwork, the acoustic environmental conditions near Pt. Barrow during spring were reviewed, modeled and interpreted (Malme et al. 1989; Richardson 1989). The main objective was to determine how far from Barrow this study would have to be conducted in order to avoid acoustic interference with whaling or the census near Barrow. (The report by Malme et al. (1989) is included as Appendix A of the present report.) In addition, Miller (1989) reviewed available literature on spring ice conditions and the spring whale migration near Barrow to assist in determining the best site for the fieldwork.

A study area was then selected based on all of the above mentioned discussions and considerations. It was decided that experimental work should be centered about 60 km northeast or east of Point Barrow. To confirm that sounds projected into the water in that region would not reach the whaling or whale census areas, two preliminary sound transmission loss tests were conducted there in late April 1989, prior to the main field season in May 1989. These tests were designed to check the acoustic predictions developed by Malme et al. (1989) and Richardson (1989).

At the end of March 1989, a trip was made to Prudhoe Bay to record the sounds produced by drilling on a grounded ice platform ("*Karluk*") in 6 m of water. Production platforms similar to those that might be used in or near spring lead systems have not been constructed, and no recording of sounds from an icebound concrete or steel drilling caisson were available. In the absence of recordings of such sounds, the under-ice noise from the *Karluk* platform was selected as having the most suitable characteristics for use during playback experiments during 1989. In order to maximize the sample size, it was decided to use this one type of industrial noise in all playback tests during 1989.

Plans for the 1989 fieldwork were reviewed and refined at a meeting of the project's Scientific Review Board (SRB) held in early April 1989. The SRB included representatives of the three concerned local groups (AEWC, BWCA and NSB) as well as independent biologists and acousticians (see Acknowledgements). MMS and project personnel also attended.

The main field program was conducted during May 1989 using two crews of researchers. One crew (aerial crew) conducted surveys and aerial observations of bowheads and white whales from a fixed-wing aircraft. This crew also dropped sonobuoys into the sea to document the underwater sounds near whales and other sites of interest. The second crew (ice-based crew) operated a sound projector to project recorded sounds into the sea and sound recording equipment to monitor those and other sounds. They also used a theodolite to track the movements of whales observable from the ice edge.

No open lead was present along the edge of the landfast ice NE of Barrow until 20 May, and openings in the pack ice seaward of the landfast ice edge were also scarce and small until about that date. As a result, until 20 May there was no persistent or predictable open water area, although there were transient areas of open water amidst the pack ice. Even after the nearshore lead opened on 20 May, most whales traveled through the pack ice or along the offshore side of the lead. Therefore, a suitable projector site on the pack ice had to be located each day by aerial reconnaissance. The ice-based crew spent the nights in Barrow, and used a helicopter to move to and from the chosen field location on each day when weather and ice conditions permitted.

After arriving on the pack ice each day, the ice-based crew deployed the sound projector and a monitor sonobuoy about 1 km away. Before beginning to project the drilling sounds into the sea, they recorded ambient noise levels. When the drilling sound was being projected, they monitored the transmitted sound level and recorded the noise received at the sonobuoy 1 km away. During sound playbacks, two of the ice-based observers watched for whales, documented behavioral observations, and used a theodolite to track whale movements. The highest available observation platform was usually an ice ridge, so the theodolite was only 2-5 m ASL (Above Sea Level). Because of the low elevation, ice-based observations were restricted to whales within ~1 km of the projector. In addition, even some of the whales within a few hundred meters of the projector could not be detected because of obstruction by intervening ice.

Whales approaching the projector from greater distances were observed from a fixed-wing aircraft (Twin Otter) circling at an altitude high enough to avoid disturbing the whales (457 m ASL). The aerial observers were able to document whale movements (albeit less precisely than via ice-based theodolite), observe behavior of individual whales, determine whale distribution relative to the sound projector, and drop and monitor sonobuoys to determine sound levels at whale locations. None of these tasks could be done adequately from the ice platform when the whales were beyond ~1 km from the theodolite site.

To provide more information concerning noise attenuation in the water under different environmental conditions, three more transmission loss experiments were conducted by the ice-based crew during the main field season in May 1989. These complemented the two similar propagation tests conducted in late April 1989. These data are used in modeling studies to estimate sound levels at various distances from noise sources under different ice conditions.

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 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 ENE 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) All sound propagation tests and behavioral observations in 1989 were necessarily performed in pack ice conditions or along the south side of the pack ice (north side of the nearshore lead). The applicability of these data to whales migrating along the south side of the nearshore lead, near the landfast ice, is not verified.
>
> (b) The applicability of the 1989 results to the Chukchi Sea is not verified, since all 1989 data were necessarily obtained well to the ENE of Pt. Barrow in the western Beaufort Sea. (However, see p. 148.)
>
> (c) Water depths at many of the 1989 study locations were greater than those where bottom-founded drilling or 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 data on reactions to noise were from whales migrating through open pack ice or along the north side of 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, p. 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. Based on the limited observations obtainable in the difficult ice conditions encountered in 1989, we could not determine what proportion of the bowheads approached within various distances of the noise source.

(c) Acoustic monitoring and localization methods, which have proven very valuable in studying the movements of whales migrating under the ice during spring migration past Pt. Barrow, are not nearly as useful in a study of this type. The noise emitted during playbacks would mask all but the strongest bowhead calls received near the projector site.

(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. In 1989, specifically, we assumed that playbacks of underwater sounds recorded near a drillrig on a bottom-founded ice pad were a useful method for testing the reactions of whales to an actual drilling operation of that type.

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, and it is uncertain how similar the sounds from an actual drilling/production platform will be to the *Karluk* sound used here. To date, neither drilling nor production have been done in or near spring lead systems off northern Alaska. Therefore, it has not been possible to record or study the sounds emanating from such an operation. It was desirable to conduct tests of the reactions of whales to simulated industrial activities prior to the start of actual industrial activities. There is some reason for optimism that 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. 1990). Nonetheless, any extrapolation of the 1989 playback results to situations involving other types of industrial sounds must be considered 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, 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.

(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 provided a reasonable simulation of the components of *Karluk* sound within the 50 to 12,000 Hz band. However, the playback system could not adequately reproduce components at frequencies much below 50 Hz (p. 99). White whales are not sensitive to these low frequency components unless their levels are very high (Fig. 6), so the inability to project them was not a problem during playback tests on white whales. It is not known whether bowhead whales are sensitive to these low frequency components. In summer, bowheads seem at least as sensitive to playbacks of drillship and dredge sounds as they are to actual drillships and dredges (Richardson et al. 1990). This suggests that playbacks can provide relevant data.

(4) It is assumed that the presence of the observers did not bias the results. Three potential problems existed (see items a-c, below), but these sources of bias were present during most control observations as well as during playbacks. Furthermore, the potential for bias of all three types is believed to be low:

Limitations: (a) Whales are known to react to aircraft overflights in some situations; most 1989 observations were obtained from an aircraft circling above the whales. Studies in summer and autumn have shown that an observation aircraft circling over bowheads causes no significant disturbance reaction provided that it remains at an altitude of at least 457 m (1500 ft) at a low power setting, and avoids passing directly over the whales (Richardson et al. 1985a,b). Anecdotal data suggest that white whales also tolerate aircraft at that height (reviewed by Richardson et al. 1989). Limited data from the 1989 study suggest that sensitivity to aircraft is no greater in spring than during summer or autumn (see p. 210 and 239). Given this, and the fact that we excluded observations from periods when the aircraft was below 457 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. Also, interpretation problems arising from any bias that does exist can be avoided by comparing behavior of whales passing the camp when the projector is operating vs. silent. (This type of control is scheduled for the 1990 field season.)

(c) It was necessary to operate a small gasoline-powered generator at the ice camp during playbacks and some control periods. This emitted some underwater noise. This noise was detectable underwater within a few hundred meters of the campsite during control (quiet) periods, but the generator noise was masked by the projected sound during playbacks (see p. 97).

(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 that they can be seen below the surface throughout part or all of a dive in open water.

(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 (see limitation 2b, above).

(e) This study concerns the short-term reactions of migrating whales to one source of industrial noise. The long-term consequences with respect to the well-being of individuals and the population are not addressed directly. However, data on the short-term reactions to one noise source may provide an indication of the likely severity of the long-term effects of one or more sources of that type of noise.

STUDY AREA

Selection Criteria

In choosing a study area, it was necessary to compromise between choosing (a) an area where many whales would be encountered 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, the Alaska Eskimo Whaling Commission, and the Barrow Whaling Captains' Association. Strong opposition would have occurred if the proposed study site were southwest of the northeasternmost of the spring whaling communities (Barrow). Whalers undoubtedly 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.

In addition, for more than a decade there has been an annual spring bowhead census near Pt. Barrow (Fig. 2). In 1988, a very intensive census effort was conducted, and in 1989 a scaled-down census effort was planned for late April and May. 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 procedures have become very precise and highly sophisticated. Present census and data analysis procedures depend on the consistent migratory behavior of the whales. Disturbance-related changes in whale behavior might include changes in swimming speeds, average distance from the ice edge, or the distribution of migration directions. Any one of these changes could significantly affect the results of the census. Also, acoustic monitoring techniques are now an important part of the census (Clark et al. 1986; Ko et al. 1986; Gentleman and Zeh 1987). If background noise levels 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 would have been 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 Location

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 the preceding "Background" section. Logistically, the most advantageous location for the study area and ice camp were expected to be along the landfast ice edge where a permanent camp could have been established. However, Miller (1989) noted that open leads are found infrequently along the landfast ice edge east of Barrow, and that the migrating bowheads start to move away from the landfast ice edge about 35 km ENE of Pt. Barrow. Beyond that point, the whales tend to follow the E-W offshore shear zone rather than the nearshore flaw lead along the landfast ice edge (Fig. 1). The white whale migration corridor is broader; it overlaps with the corridor used by bowheads but also extends farther offshore. Thus, few whales are found along the landfast ice edge more than about 35 km east of Barrow.

During most 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 along the E-W offshore shear zone NE 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, and logistic support becomes progressively more difficult.

Given the above, it was clearly 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 (Appendix A) and consultation with local Barrow organizations, individuals and scientific investigators. 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).

Because of the 60 km restriction, there were several days during the first half of the study when playbacks of drilling sounds could not be done even though open water and whales were present closer to Barrow. On some of these latter occasions we conducted aerial observations of bowhead behavior and/or aerial photogrammetry efforts within 60 km of Pt. Barrow. During these activities we remained at least 10 km from the traditional whaling sites. We also avoided overflying the whale census area, although ice conditions prevented an effective ice-based census in May 1989.

Ice Conditions

General

Sea ice dominates the Alaskan Beaufort Sea, with ice cover of almost 100% for 9 to 10 months each year (Norton and Weller 1984). There are three principal zones of ice cover in the Beaufort Sea: landfast ice, the shear zone, and the pack ice (Fig. 1).

The landfast ice forms gradually in fall and by late winter extends from 25 to 75 km offshore, depending on the position along the coast. During the initial phases of freeze-up, multiyear ice floes become grounded as they enter the nearshore region. As freezing continues, new ice locks these multiyear floes in place. These grounded multiyear floes, in turn, act to anchor new ice, contributing to its stability and shorefast tendency during spring breakup.

The pack ice is composed of floes of multiyear ice that are consolidated and supplemented by each year's annual ice. Multiyear ice in the Beaufort Sea averages 4 m in thickness and new ice can grow to 2.4 m in thickness during one winter season. Circulation patterns tend to move the pack westward along the Alaskan coast. This circulation is largely wind driven, and is less energetic in winter. During periods of westerly winds, the direction of ice drift can be reversed temporarily, becoming eastward.

Between the fast ice and the pack ice lies the shear zone. In this area pressure ridges form where shearing and compressive forces are exerted by the mobile pack ice on the less mobile pack ice and the fast ice. Pressure ridges may exceed 10 m in height (Tucker et al. 1984; Kovacs and Mellor 1974).

Marko and Fraker (1981) presented an idealized representation of spring ice cover in the Beaufort Sea showing typical locations of major leads (Fig. 1). The lead along the E-W offshore shear zone is an extension of the NW Alaska Lead, although the shear zone typically deviates 5-10° to the south at a point about 35 km east of Pt. Barrow. Marko and Fraker (1981) note that the lead along this shear zone does not coincide with the edge of the landfast ice at points more than about 35 km east of Pt. Barrow. Instead, it is situated well offshore amidst the pack ice. The E-W offshore shear zone is apparently the result of the shearing of the relatively mobile "Offshore Pack Ice" against the more stable "Close Ice" zone (Fig. 1).

Although the E-W offshore shear zone is the predominant area of lead formation in the Alaskan Beaufort Sea, leads also develop closer to shore, along or near the landfast ice edge that parallels the NE coast of Alaska. In general, this ice-edge is oriented WNW-ESE, and parallels the Alaskan coast from a point northeast of Pt. Barrow to the Mackenzie Delta. Based on the locations shown by Marko and Fraker (1981) for mid May, the fast-ice edge is ~25-55 km off the coast between Pt. Barrow and Cape Halkett in different years. The lead along this fast ice edge is the "Nearshore Flaw" shown in Figure 1.

The maps presented by Marko and Fraker (1981) for 20 April-10 June show that, in most years, there are periods when leads are present in our study area either in the E-W offshore shear zone or in both the shear zone and along the fast ice edge. Of the 8 years considered (1973-80), 1979 was the only year when leads were noticed only along the fast-ice edge. In 31 maps of ice features during various years and periods, there was a nearshore lead along the fast-ice edge in 13 cases (42%) and offshore leads in 29 cases (94%).

Marko and Fraker (1981) noted that few leads form in the Close Ice Zone (Fig. 1), and those that do form often subsequently close. This occurs because the prevailing easterly winds that tend to form leads elsewhere in the Beaufort Sea force the ice of the southwestern Beaufort Sea against the Alaskan coast, tending to consolidate it. Burns et al. (1980) found that leads were present in this zone only 26 to 43% of the time during the January to May period.

Lead locations and configurations can change markedly during a season (Marko and Fraker 1981). For example on 6 May 1978 there was a well developed lead east of Pt. Barrow in the E-W offshore shear zone (Fig. 7A). On 16 May this major lead was no longer evident and only some small leads well north of the 10 May lead location were present. The nearest open water north of Cape Halkett was about 100 km offshore on this date. By 30 May a major lead that extended from Pt. Barrow all the way into Amundsen Gulf was present in the E-W offshore shear zone. At this time the lead was within about 65 km of Cape Halkett. The data also show rapid shifts in lead positions between the E-W offshore shear zone and the fast ice edge, and lead configurations that were intermediate between the two "typical" locations.

Thus, leads in the southwestern Beaufort Sea tend to form offshore in the E-W offshore shear zone amidst the pack ice, and nearshore along the edge of the landfast ice. Because these two typical lead configurations form an acute angle with an apex east of Pt. Barrow, there is usually a lead in that area regardless of which lead configuration (offshore or nearshore) develops.

Farther east of Pt. Barrow, leads are also common in the E-W offshore shear zone. However, the maps presented by Marko and Fraker (1981) indicate that locations of leads within this zone vary considerably among and within years. The ice in this area is less stable than that near Pt. Barrow. Nearshore leads are uncommon along the fast ice edge off eastern Alaska, and those that do form are often short-lived. Thus, the area just east of Pt. Barrow is more favorable for the present study than is the area farther east.

1989 Ice Conditions

Ice conditions in 1989 were more closed than in the typical years described above.

When the study was initiated in late April, no major lead was present either along the fast ice edge or in the area where the E-W offshore shear zone usually forms. The overall ice cover was 98 to >99%. The few open water areas

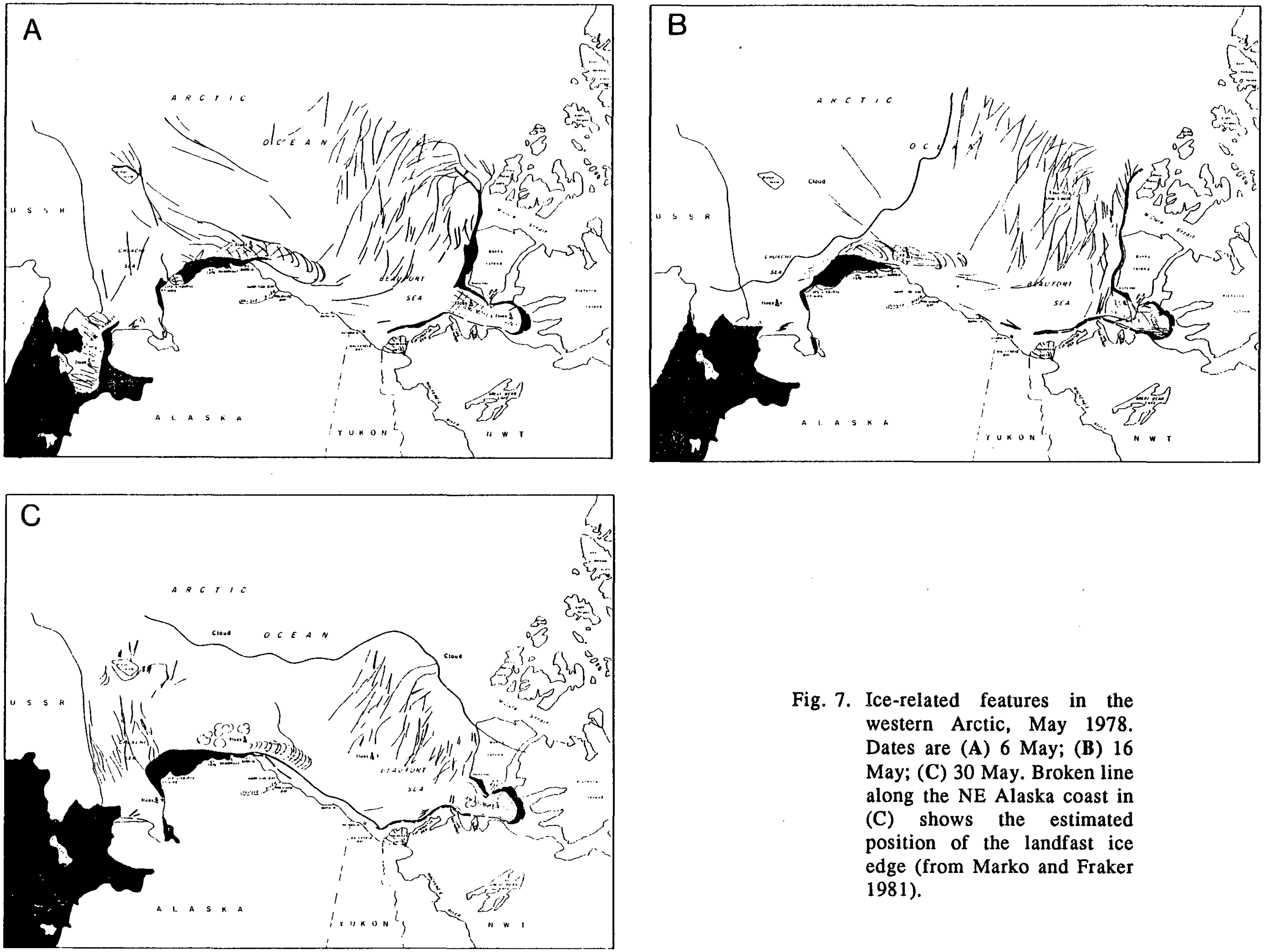

Fig. 7. Ice-related features in the western Arctic, May 1978. Dates are (A) 6 May; (B) 16 May; (C) 30 May. Broken line along the NE Alaska coast in (C) shows the estimated position of the landfast ice edge (from Marko and Fraker 1981).

consisted of small holes among pans plus narrow cracks and leads that tended to be oriented NW to SE. These conditions were maintained until 7 May. Minor shifts in the pack ice formed small holes, cracks and small leads at about the same rate as older ones were freezing. The amount of open water or thin newly-refrozen ice decreased as one went east from Pt. Barrow. In the area 60 km or more to the NE, ENE and E, there were no extensive leads or open areas, and indeed very little open water in any configuration. From 7 to 11 May slightly colder temperatures (-6 to -23°C offshore) and calm winds resulted in freezing of virtually all open water in the study area (Plate 1).

On 12 May moderate NNE winds (26 km/h) shifted the offshore pack ice and formed several minor leads oriented SW to NE. The overall ice cover recorded during the aerial survey on that date had decreased to 95%. Moderate NE winds continued for the next few days and the NW Alaska Lead finally developed along the fast ice edge as far north as several kilometers to the northeast of Barrow. However, this lead was farther offshore than usual and a broad shelf of rough, rubble ice between the stable landfast ice and the lead made access to the lead from Barrow almost impossible by snowmachine. Because of this, the ice-based whale census normally done by the North Slope Borough could not be conducted during our 1989 study period. In most years, the NW Alaska Lead is present off Barrow, at least intermittently, by mid-to-late April.

By 13 May no major leads had developed in our study area either along the fast ice edge or in the offshore shear zone, but the overall ice cover had decreased to 85%. The open water areas consisted of short leads up to 5 km in length and large irregular-shaped areas of open water amidst the pack ice. Although most of the short leads were oriented generally SW to NE, there was no well defined migration corridor for whales to follow.

On 15 May the wind decreased to 15 km/h and some of the open water areas began to freeze. On 16 May the wind was light (13 km/h) from the SW and the open water areas in the study area were further reduced to 5% by freezing and compression of the pack ice by the wind.

Ice conditions remained about the same until 20 May when the ice started to open up. The lead along the fast ice edge extended well east of Pt. Barrow for the first time, and ice cover in the study area decreased to 90%. Strong winds on 21 May further loosened the pack ice in the study area to 80% ice cover, and a lead 1-6 km wide developed along the landfast ice edge as far east as 60 km east of Pt. Barrow. This was a northeastward and eastward extension of the NW Alaska lead. The ice cover north of the lead was 90%; this pack ice contained open water areas having irregular shapes and no particular orientation.

From 22 to 29 May there were no major changes in ice conditions. The lead along the landfast ice edge widened slightly and extended farther east, to 85 km east of Pt. Barrow (Plate 2). However, no notable changes occurred in the pack ice north of the lead.

On 30 May the pack ice moved south and partially blocked the nearshore lead west of 155°30′ and east of 154°30′. The 35 km stretch of lead between these longitudes had widened. On that date, the last day of our field season, open water areas among the pack ice north of the lead had also expanded.

Specific information on ice conditions near each experimental site appears in the "Bowhead Results - Reactions to Playbacks" section. For each experiment, that section maps and describes the ice near the sound projector and the whales.

Weather

General

As part of the planning process, spring weather data from northern Alaska were reviewed. Weather was expected to have strong influences on project logistics and the feasibility of various field procedures. Weather data have not been collected systematically within our offshore study area. However, systematic data have been reported for May from two coastal stations near the study area (Barrow, 1948-74 period, and Lonely DEW site, 1957-75). Opportunistic weather observations in marine areas to the north and west of Barrow have also been summarized for May of 1872-1974 (Fig. 8; Brower et al. 1977).

The mean temperatures recorded in May at Barrow, Lonely and marine areas NW of Barrow were -7, -6.5 and -10.5°C. Temperatures appear to have been related only weakly to wind direction, but tended to be 2-4 C° warmer when winds were out of the S, SW or W (Fig. 9).

The predominant winds at all locations during May were out of the E and NE. At the two coastal stations, winds from the E or NE sectors occurred over 50% of the time during May. In the offshore area, these winds occurred over 40% of the time (Fig. 10). The mean wind speeds at Barrow, Lonely and offshore were, respectively, 18.7 km/h (10.1 knots), 14.8 km/h (8.0), and 19.2 km/h (10.4). The wind direction did not change with time of day at the two coastal sites, but there was a tendency for slightly lower wind speeds during the early morning (00:00 to 08:00 h) except at Lonely (Fig. 11, 12).

Precipitation was recorded at 37% of the May observation times at Barrow, 9% at Lonely and 25% offshore (Fig. 13). Most of this precipitation was in the form of snow.

Visibility and ceiling have direct influences on the feasibility of the aircraft operations necessary for the project. Horizontal visibility during May is surprisingly good according to Brower et al. (1977). Visibility was ≥9.3 km (5 n.mi.) about 70% of the time. The ceiling was ≥610 m (2000 ft) only ~34% of the time at Barrow, but it was 305-610 m an additional ~22% of the time[2].

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[2] Actual percentages may be as much as 4% higher, given the manner in which Brower et al. (1977) present the data.

Plate 1. NOAA Satellite imagery taken on 8 May 1989 showing the extensive offshore ice cover near Barrow, Alaska.

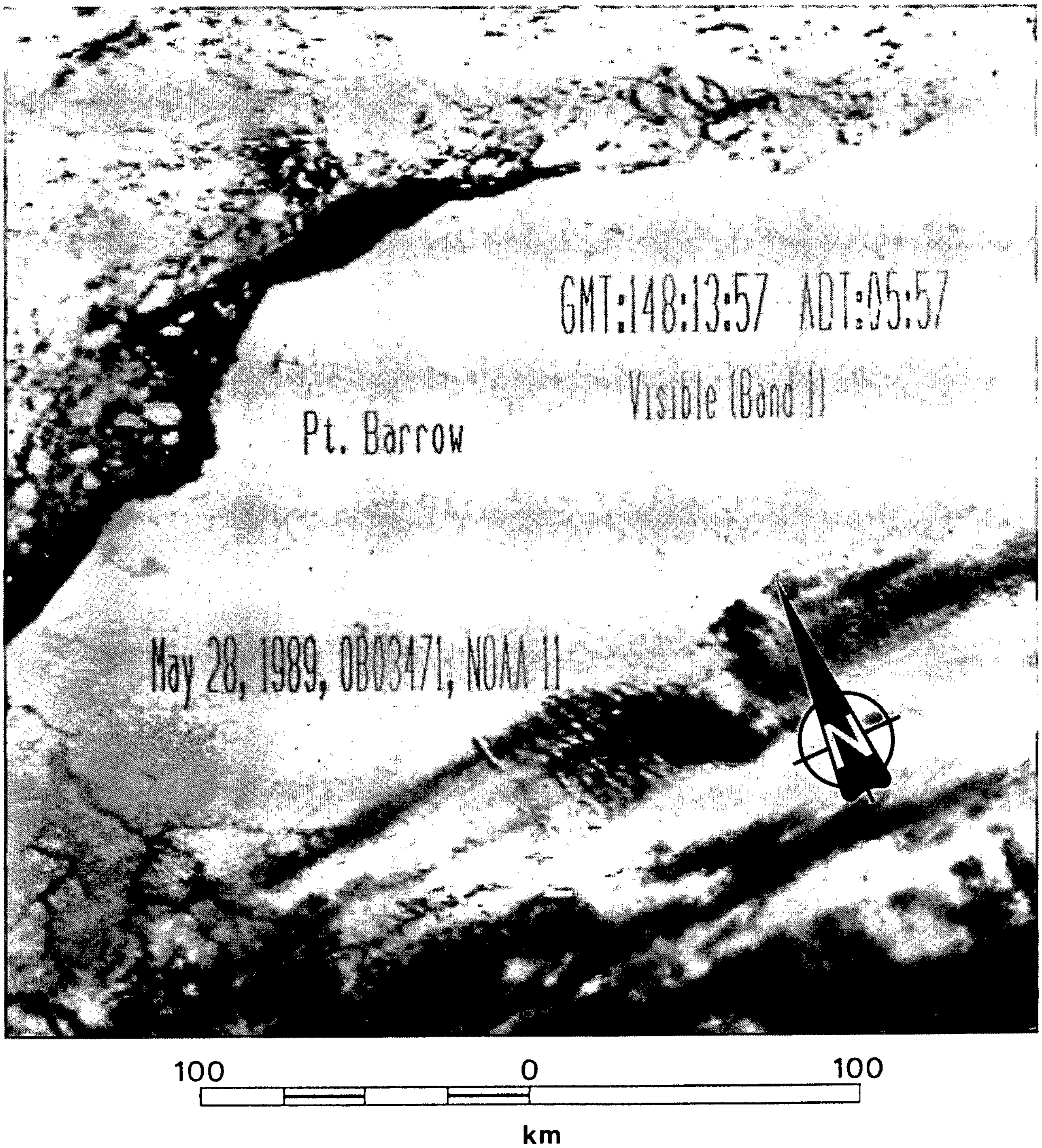

Plate 2. NOAA Satellite imagery taken on 28 May 1989 showing the NW Alaska lead and the extensive offshore ice cover near Barrow, Alaska.

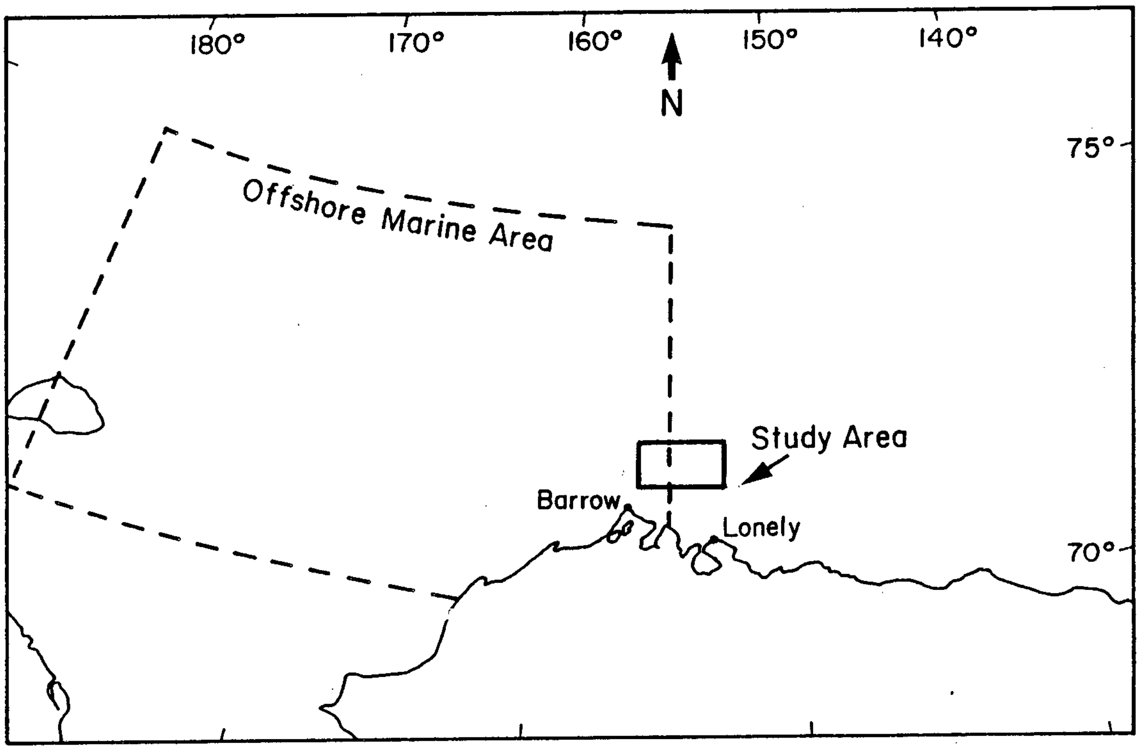

Fig. 8. Sources of weather information near the study area as summarized from Brower et al. (1977).

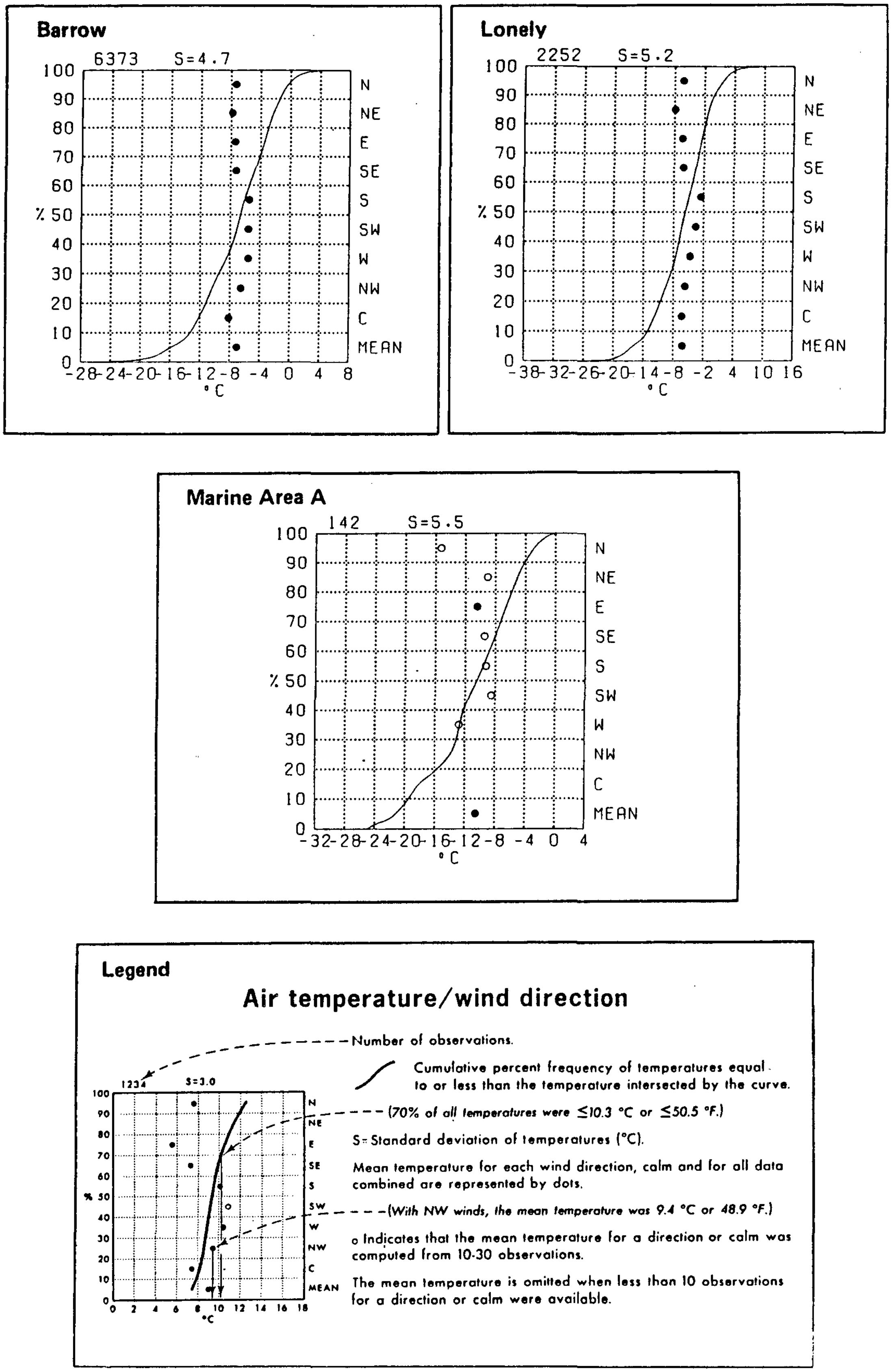

Fig. 9. Air temperature in relation to wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

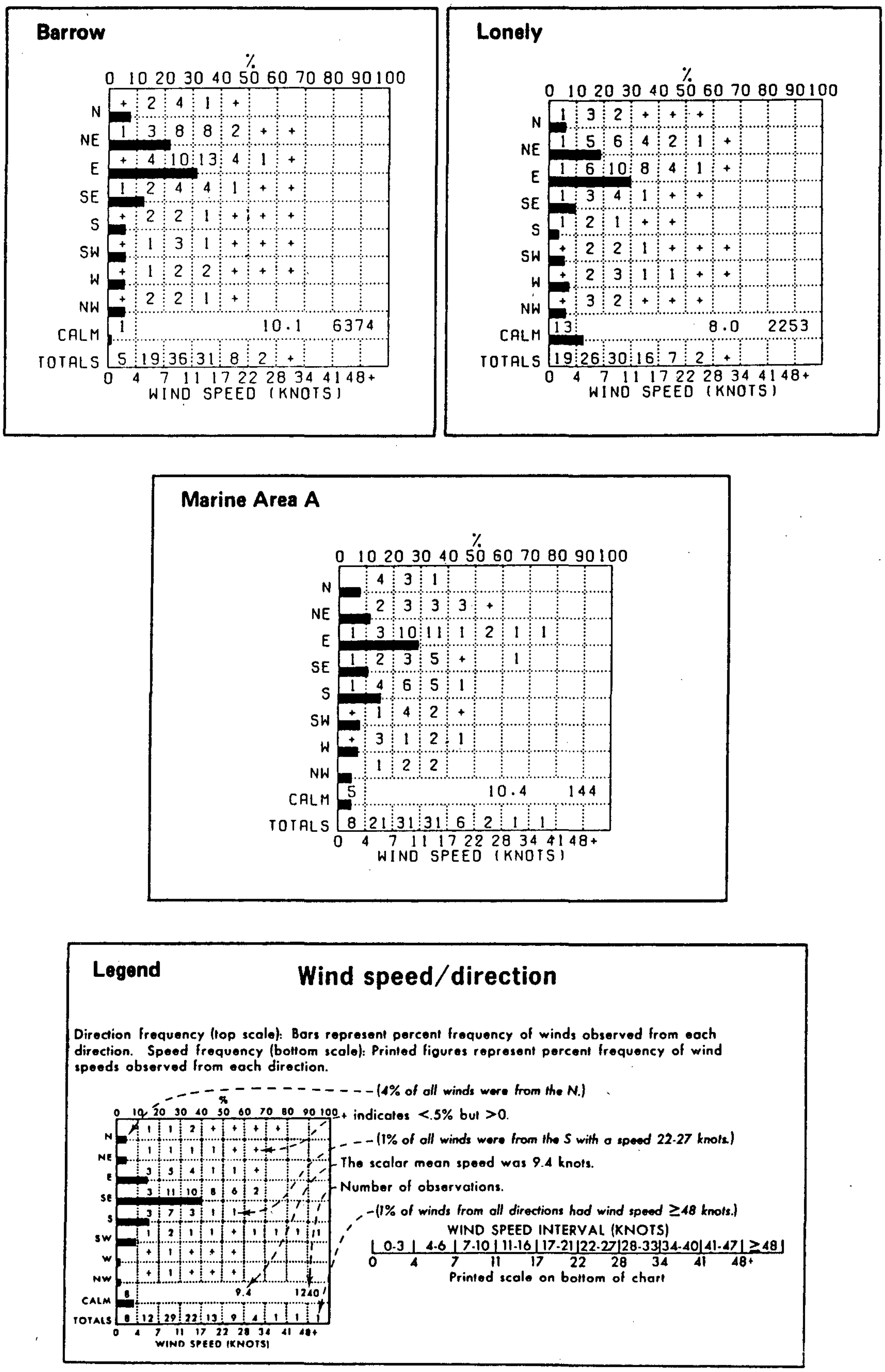

Fig. 10. Wind speed in relation to wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

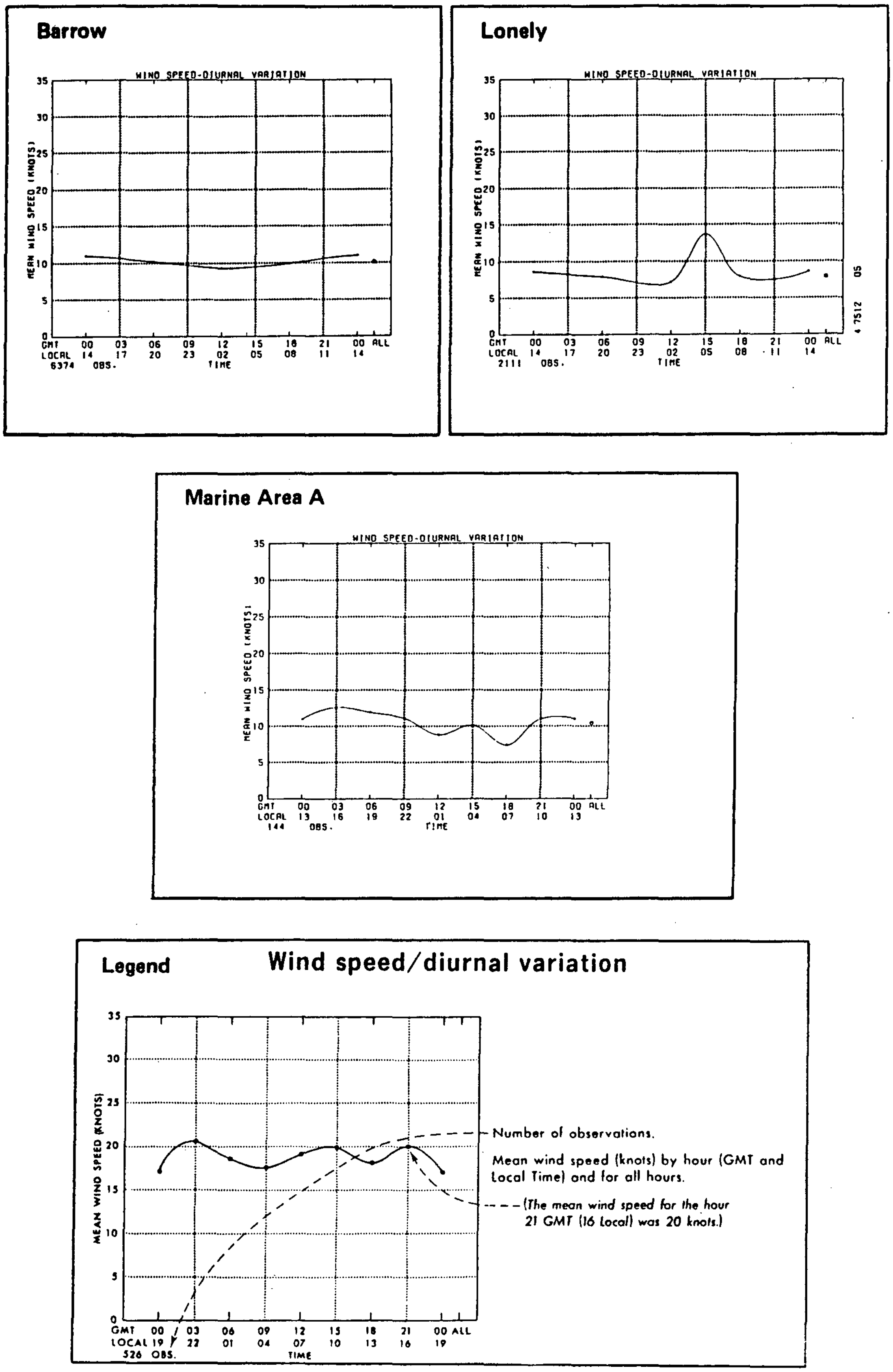

Fig. 11. Wind speed in relation to time of day at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

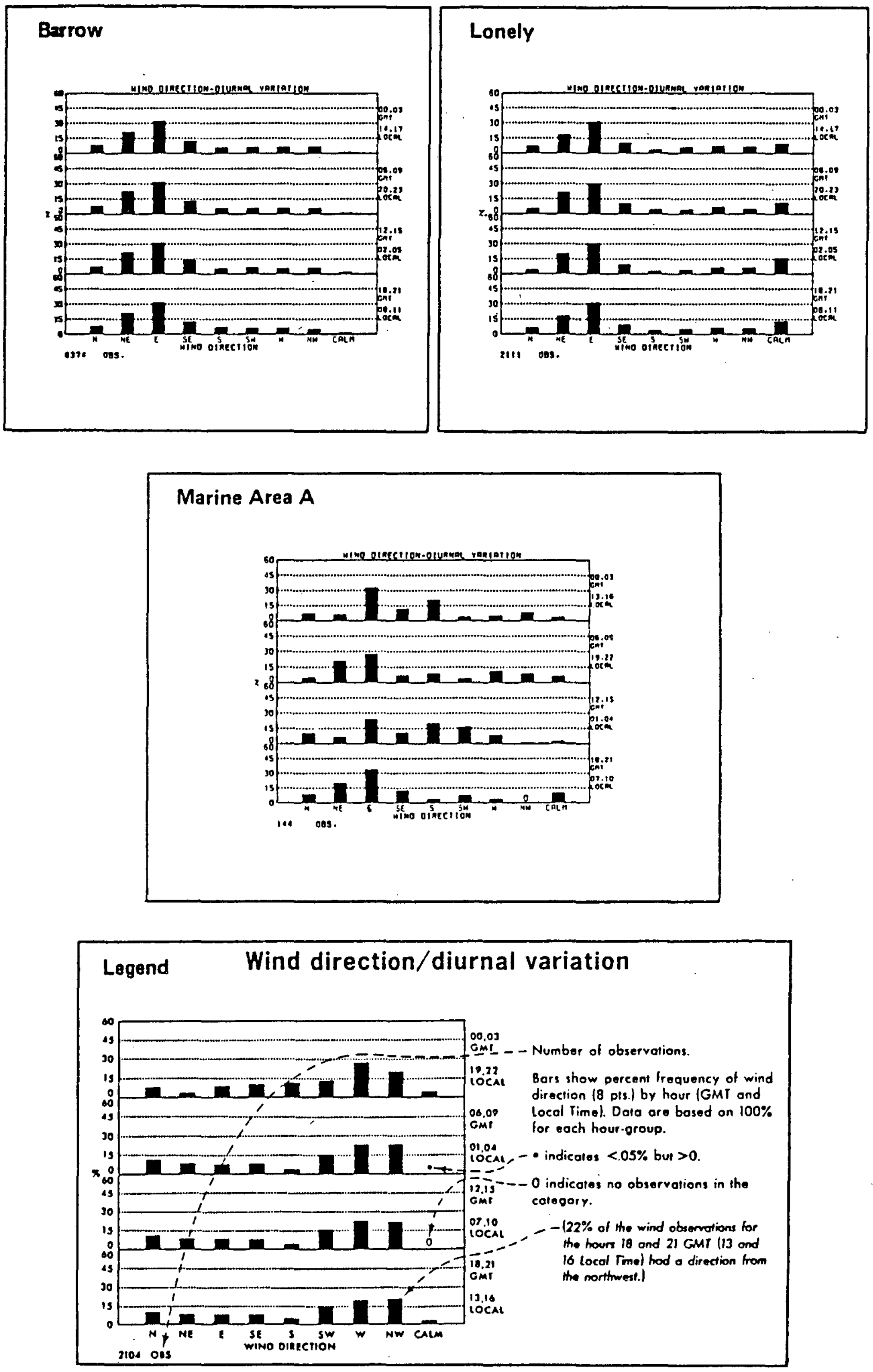

Fig. 12. Wind direction in relation to time of day at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

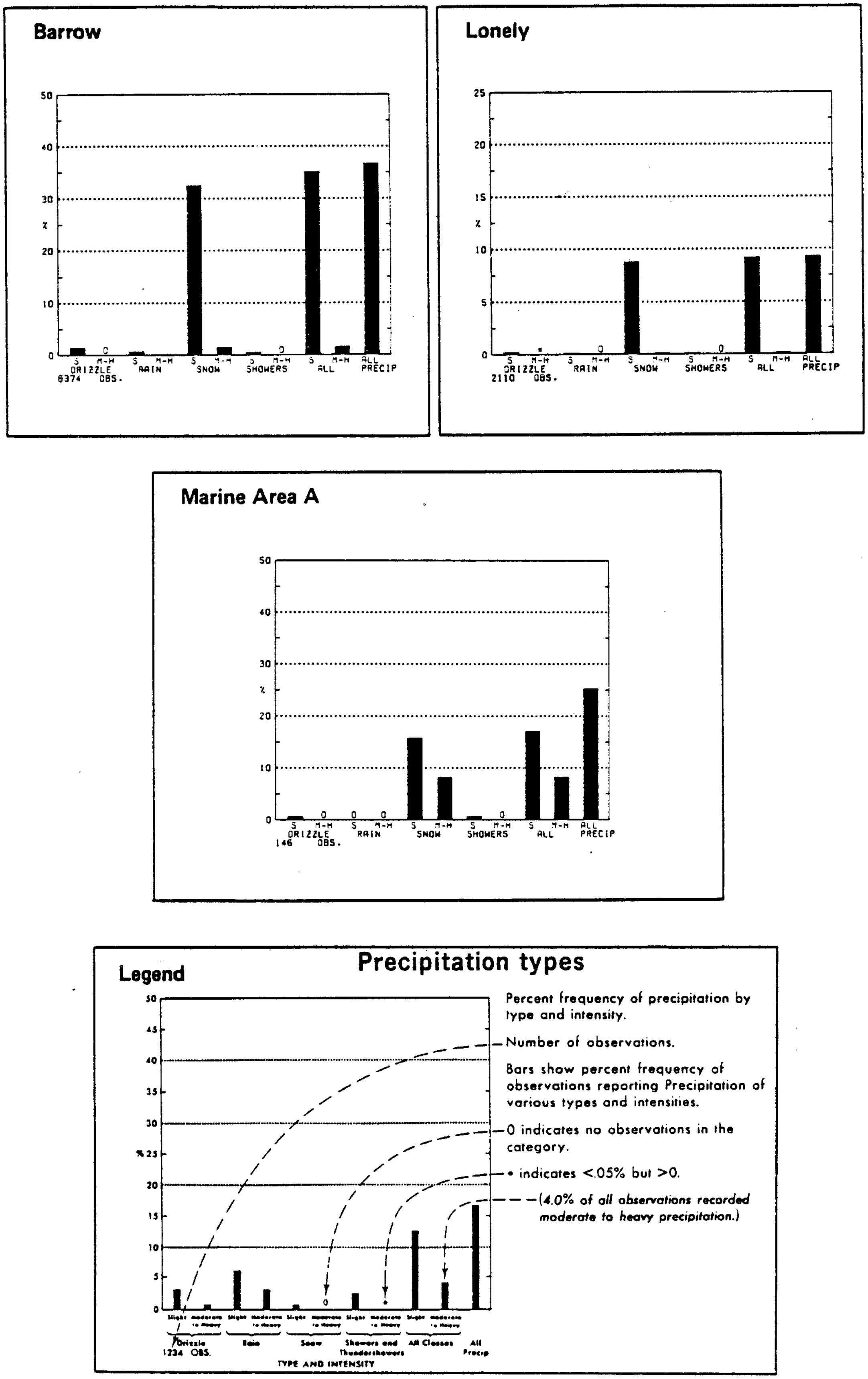

Fig. 13. Frequency of precipitation of various types at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

In offshore areas the reported ceiling tended to be much higher: ≥610 m 60% of the time and ≥305 m a full 79% of the time (Fig. 14). It should be noted that the accuracy of ceiling data is variable; some observations may be based on visual estimates of dubious reliability.

Fog was relatively infrequent during May (Fig. 15). Overall, it was reported only 12% of the time at Barrow and 18% of the time at Lonely. As expected, fog was most common during the early morning (18% of the time at Barrow during the 02:00-05:00 period) and rare during the afternoon (7% of the time at Barrow during the 14:00-17:00 period). Fog tended to be most common during periods of calm, E and SE winds.

1988 Weather

Additional weather data were provided by the North Slope Borough's Department of Wildlife Management, which recorded weather data by 2-h periods during their 1988 ice-based whale census near Barrow. Table 1 summarizes their cloud information for 1988.

Table 1. Proportion of days having clear (upper) or clear and partially cloudy (lower) weather near Barrow during the 1988 census period. Data provided by J.C. George, Dept of Wildlife Management, North Slope Borough, Barrow, AK.

	Clear ≥ 6 h	Clear < 6 h	No Clear Periods
26-30 April	0.33	0.00	0.67
1-15 May	0.53	0.20	0.27
16-31 May	0.06	0.00	0.94
1-10 June	0.67	0.00	0.33
26 April-10 June	0.35	0.08	0.58
	Clear or Partially Cloudy ≥ 6 h	Clear or Partially Cloudy < 6 h	No Clear or Partially Cloudy Periods
26-30 April	0.75	0.00	0.25
1-15 May	0.80	0.00	0.20
16-31 May	0.19	0.06	0.75
1-10 June	0.83	0.00	0.17
26 April-10 June	0.56	0.02	0.41

Behavioral observations would have been possible from an aircraft circling above whales during all periods with clear skies and most periods with partly cloudy skies. In addition, observations could be conducted during an unknown portion of cloudy periods, i.e. those when the ceiling was >460 m ASL. Based on the 1988 data, extended periods of observation from an aircraft would have

Barrow

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	+	+	1	16	6
50<80	+	+	+	+	1	1
35<50	+	0	0	+	1	+
20<35	+	+	+	1	5	1
10<20	+	1	1	4	15	1
6<10	+	1	1	4	16	1
3<6	1	1	1	3	6	+
1.5<3	+	+	+	+	+	0
0<1.5	4	1	+	+	+	+
					6365	

Lonely

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	1	+	1	9	14
50<80	+	0	0	0	1	1
35<50	0	0	0	0	+	+
20<35	+	+	+	1	4	4
10<20	1	2	2	4	22	7
6<10	1	2	2	2	6	1
3<6	1	1	1	1	2	+
1.5<3	+	+	+	+	+	0
0<1.5	3	+	+	+	0	0
					2245	

Marine Area A

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	1	0	0	1	13	28
50<80	1	0	0	0	0	2
35<50	0	0	0	1	1	1
20<35	1	0	1	1	3	5
10<20	0	1	1	1	15	1
6<10	2	0	1	2	3	0
3<6	2	1	1	2	1	0
1.5<3	0	1	1	0	0	0
0<1.5	5	0	0	0	0	0
					143	

Legend

Low cloud ceiling/visibility

VISIBILITY

LOW CLOUD CEILING	<1/2	1/2<1	1<2	2<5	5<10	≥10
NC	0	0	+	3	13	64
50<80	0	0	0	0	+	1
35<50	0	+	0	0	0	4
20<35	0	+	1	1	2	2
10<20	0	+	1	1	2	1
6<10	0	1	0	+	+	0
3<6	+	+	0	+	+	0
1.5<3	+	0	0	0	0	0
0<1.5	+	0	0	0	0	0
					334	

Percent frequency of simultaneous occurrence of specified low cloud ceilings (hundreds of feet) and visibilities (nautical miles).

Low cloud ceiling heights are estimated from the height of low clouds (h) when low cloud amount (N_h) is ≥5/8.

Obscurations are included under ceiling "0 <1.5"

"N C" (no ceiling) includes bases of clouds ≥8000 feet as well as occurrences of N_h <5/8.

(2% of all observations reported ceiling ≥1000 but <2000 feet simultaneously with visibility ≥5 but <10 nautical miles.)

+ indicates <.5% but >0.

Number of observations.

Fig. 14. Low cloud cover and horizontal visibility at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively, and data for offshore areas are from 1872-1974.

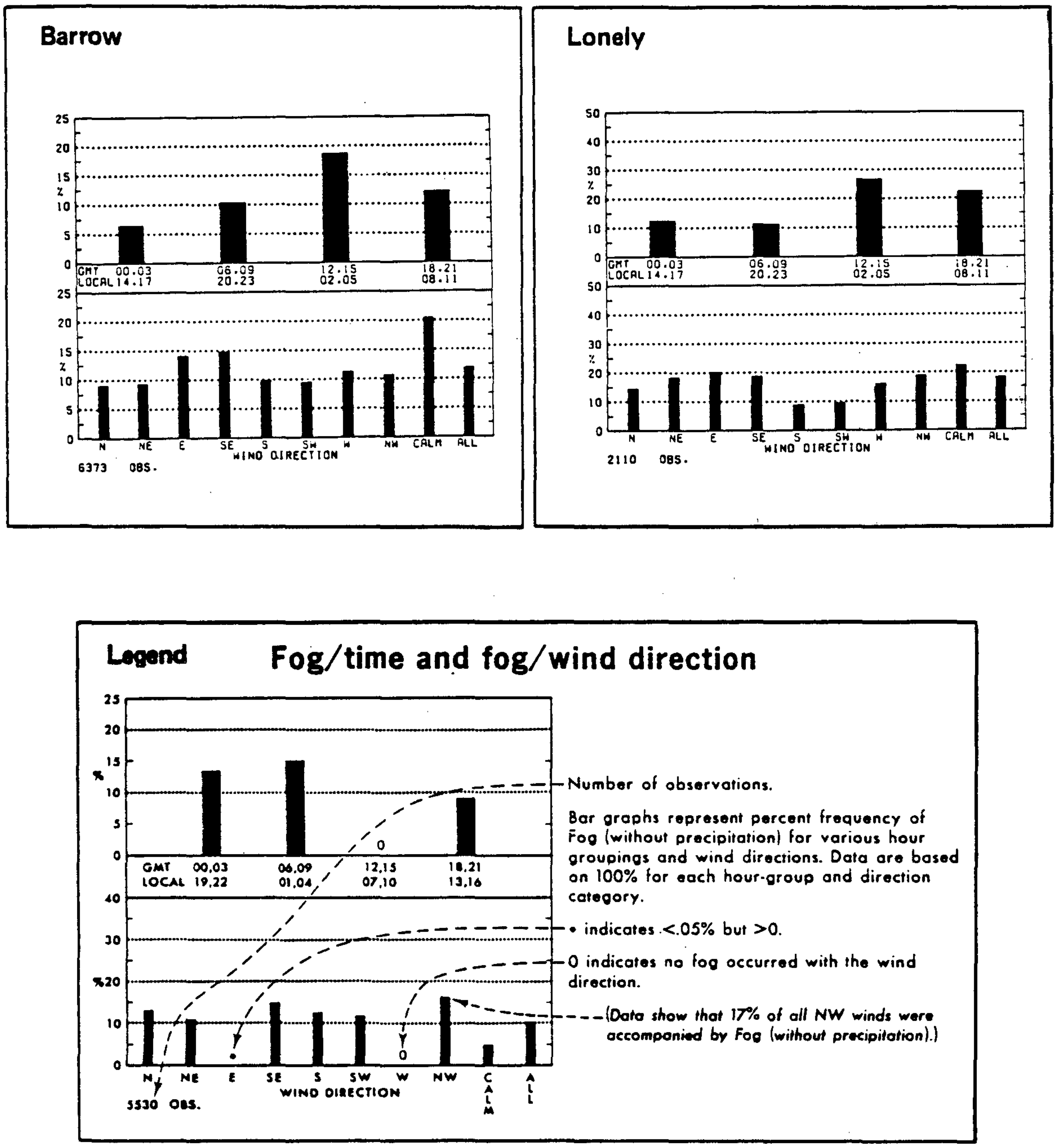

Fig. 15. Fog in relation to time of day and wind direction at selected locations near the study area in May (from Brower et al. 1977). Data for Barrow and Lonely are from 1948-1974 and 1957-1975, respectively; few data were obtained for offshore areas.

been possible during at least 35% of the days (Table 1). Brief periods of observation would have been possible on at least 43% of the days (0.35 + 0.08), and probably on at least 58% of the days (0.56 + 0.02). Additional observations probably would have been possible on some cloudy days--those when the ceiling was >460 m.

It appears that, in the spring of 1988, behavioral observations could have been conducted from an aircraft circling at 457 m ASL for parts of at least 60% of the days. This was so even though the spring of 1988 was a season with extensive open water, which would tend to cause fog and low cloud.

<u>1989 Weather</u>

We did not record weather conditions systematically during this study, but weather was recorded at the ice camp when it was set up on the pack ice, and at Barrow on a non-systematic basis.

The winds were from the WSW and SW during the last few days of April and first three days of May. This moved the pack ice in the northern Chukchi Sea northeastward. The closed ice conditions that resulted prevented formation of the NW Alaska lead southwest of Barrow. Except for periods of fog during the morning, skies were clear and weather conditions were suitable for observing whales had more open water been present.

From 5 to 8 May, the temperature was cold (lows of about -20 to -30°C) and the few open water areas amidst the offshore pack ice froze. During this period, winds were light and from the E to NE. Ceilings improved from low overcast on 4-6 May to partially cloudy and clear on 7 and 8 May. On 9 May, the temperature rose to -6°C in offshore areas, winds were light, and the sky was partly overcast--ideal conditions for observing whales. However, there was virtually no open water.

Weather conditions were poor during the 10-13 May period. Ceilings were low (<335 m) and visibility was poor in snow and fog. Winds were out of the NE quadrant but were light to moderate (<25 km/h). Consequently, some leads formed amidst the offshore pack ice.

The ceiling lifted temporarily to >460 m during the morning and early afternoon of 14 May. The temperature was warm (-7°C) and the winds were moderate (23-27 km/h) out of the NE.

The temperature, ceilings and visibility decreased on 15 May with snow flurries occurring throughout most of the day. Similar weather continued until 20 May. Ceilings varied between 150 and 460 m (occasionally to 670 m); winds were light to moderate, primarily from the NE sector; temperatures were -2 to -7°C and light snow and snow squalls were present much of the time.

The winds increased to 24-41 km/h on 20 and 21 May and the upper cloud layers thinned out. Fog and blowing snow reduced visibility to 1-9 km. The strong winds from the NE to SE started to open a lead along the fast ice edge north and NE of Barrow.

Low ceilings and poor visibility due to snow and fog persisted throughout 22 May and the morning of 23 May. Conditions improved on the afternoon of 23 May; winds were 19-26 km/h from the NE to SE, ceilings were 365-460 m and the temperature offshore was -2 to 4°C.

Low ceilings (with freezing rain on the morning of 24 May) and variable visibility persisted from 24 to 26 May. Winds were light from the SE and temperatures were -2 to 4°C.

The weather cleared early on 27 May and remained clear for the rest of the study. Winds were light from the S (27 May) and E (28 and 29 May), and air temperatures were +1 to +7°C. Ceilings were usually unlimited with occasional partially overcast periods.

In **summary**, weather and ice conditions in 1989 were worse than normal for conducting bowhead whale studies. Weather was clear at the end of April and early May, but little open water was present. Unusually cold weather from 5 to 8 May froze existing open water areas and consolidated the offshore pack ice. From 10 to 26 May, low ceilings, snow and fog prevented aerial observations from >460 m ASL most of the time. Observing conditions were ideal on 27-30 May, but most bowheads had migrated past Barrow by this time.

METHODS

Acoustical Field Methods

Industrial Noise

Specific objective 1 was to record and characterize the underwater noise from a drilling operation on a grounded ice pad in shallow water during late winter. At the end of March 1989, a trip was made to Prudhoe Bay to record the sounds produced by drilling on a grounded ice platform (*Karluk*). The site was at 70°19.5'N, 147°30.3'W, 8.1 km south of Narwhal Island (in the McClure Islands) and 38.7 km ENE of the Deadhorse airport at Prudhoe Bay. A drillrig was installed on an ice platform about 150 m in diameter. It had been built by spraying sea water into the air to form ice granules. In this construction method, the layer of ice formed by these granules gradually thickens until it rests on the bottom. The rig used a conventional rotary table and kelly to drive the drill-string. Recordings were made at six distances, ranging from 0.13 to 5 km, along each of two bearings from the drillrig: southeast and northwest. At each receiving station, a hole was drilled through the landfast ice and an ITC model 6050C hydrophone was lowered to mid-depth. Water depth was 6-7 m, ice thickness was close to 2 m, the wind was light, and the air temperature ranged from -25° to -17°C. Chevron U.S.A. provided full support in permitting us to make the sound recordings at *Karluk*. They also provided the drilling operation logs to permit us to determine the rig activity at the recording times.

Underwater sounds from a Bell 212 helicopter and a deHavilland DHC-6-300 Twin Otter were recorded by having the aircraft fly over a pair of ITC 6050C hydrophones suspended over the edge of an ice floe via faired cables. Both of these aircraft are powered by twin Pratt & Whitney Canada PT6 turbine engines: the Bell 212 by the PT6-T turboshaft and the Twin Otter by the PT6A-27 turboprop. Hydrophone depths were 3 and 18 m. The helicopter flyover sounds were recorded on 17 and 28 May; the Twin Otter sounds were recorded only on 28 May. For each aircraft and date, at least two passes were made (in opposite directions) at each of four altitudes. On 17 May, altitudes were 76, 152, 305 and 457 m (250-1500 ft). On 28 May, altitudes were 76, 152, 305 and 610 m (250-2000 ft) for the helicopter and 152, 305, 457 and 610 m (500-2000 ft) for the Twin Otter. The passes were oriented perpendicular to the ice edge along which the hydrophones were deployed. Helicopter passes were made at normal cruise speed (185 km/h). Twin Otter passes were made both at normal cruise speed (285 km/h) and at a lower power setting (185 km/h).

Sound Propagation

Specific objective 3 was to measure and model transmission loss of underwater sound. Sound propagation tests, also called sound Transmission Loss (TL) tests, were conducted on five dates: 29 and 30 April, and 2, 9 and 25 May 1989. Each test was conducted from a base camp on the pack ice at which a U.S. Navy J-11 sound projector was installed. The locations are shown as the five squares on Fig. 19, in the "1989 Chronology" section, p. 72. The projector was suspended from the edge of an ice pan at a depth of 9 m for TL tests 1 and 2, and 18 m for tests 3-5. Power was supplied by a 2.2 kW gasoline-powered Honda generator sitting on snow-covered ice, typically about 20 m back from the ice edge.

A cassette tape had previously been recorded with three types of sounds to be projected: tonal sweeps, pure tones, and sounds from the drillrig at *Karluk*. ► The tonal sweeps were special "hyperbolic frequency modulation" (HFM) signals synthesized by BBN (Rihaczek 1986). Each 5-s sweep spanned one-third octave at a center frequency of 100, 200, 500, 1000, 2000, or 5000 Hz. Each sweep was sent twice (TL tests 1-2) or four times (tests 3-5) with no pauses between sweeps. ► The pure tones were at 50, 100, 200, 500, 1000, 2000, 5000, and 10,000 Hz. Each tone was transmitted for 10 s (TL tests 1-2) or 20 s (tests 3-5), with 5 s between tones. ► The *Karluk* sounds were a 37-s (or longer) segment from the recording made 130 m away from the *Karluk* drillsite. The operator rewound the tape after each transmission ended.

The sound projected by the J-11 was monitored with an ITC model 1042 spherical hydrophone placed at a nominal distance of 0.8 m in front of the projector face. The actual distance was measured during each installation, and a correction term of 20 log (distance) was applied to the measured sound level to compute the source level at 1 m. The waveform from the monitor hydrophone was displayed on an oscilloscope to ensure that the projector was not overdriven to the point of distortion. The source level of the projector depended on the frequency content of the signal, but was typically near 165 dB re 1 μPa at 1 m.

The receiving/recording equipment consisted of an ITC model 6050C hydrophone, a 0-60 dB selectable gain postamplifier, and a Sony TC-D5M cassette recorder. The receiving station crew used a Rolotape distance measuring wheel to locate receiving sites at ranges 100, 200, and 400 m (if possible) along the edge of the ice pan. At each distance, the hydrophone was lowered on a faired cable to 18 m depth, and a recording of the ambient noise was made. The recording crew then radioed the base camp to request transmission of the taped signal. When transmissions ended, ambient noise was recorded again. During some tests, ambient noise was recorded at ranges 100-400 m 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.

More distant receiving stations were reached by helicopter. The crew attempted to find suitable recording stations at ranges 0.5, 1.0, 2.0, 5.0 and 10 n.mi. (0.9-18.5 km). Suitable sites were those along the edge of an ice pan bordered by open water or thin recently-refrozen ice. The helicopter's GNS-500 VLF navigation system was used for positioning. The GNS was not designed for such precise navigation, but GNS readouts of the relative positions of two stations overflown at short intervals normally are accurate within a few hundred meters. When there was doubt about the accuracy of the GNS, the helicopter returned to the ice camp in order to re-calibrate the GNS. This was also helpful in allowing for the rapid drift of the ice (and thus the projector) on some days. The absolute position of the ice camp was determined more accurately using a Si-Tex model A-310 satellite navigation system[3]. When beyond radio range, the base camp operator played the tape at prescribed times, generally at 10-min intervals commencing on the hour. The remote recording crew then knew when the signals were being transmitted even if the signals could not be heard.

About 4 h were required to measure received signals at eight ranges from 100 m to 18.5 km, exclusive of the time (4-5 h) needed to set up and remove the projection equipment.

Acoustical Monitoring During Playbacks

Manually-deployed Sonobuoys.--Prior to each drilling noise playback test, a sonobuoy was installed manually at a nominal distance of 1 km from the projector. The helicopter was used for transportation to this site. On most occasions, we used a Sparton Defense Electronics AN/SSQ-41B wideband sonobuoy that had been modified to use external batteries for longer life. Also, its cutoff mechanism had been disabled so as to allow operation for more than the usual maximum of 8 h. Hydrophone depth was 9 m. On some days, we used a Sparton AN/SSQ-57A sonobuoy that was standard except that the hydrophone depth was 12 m. Both types of sonobuoys provide useful data from 10 to 20,000 Hz. These buoys telemeter the received sounds on VHF frequencies 162.25-173.5 MHz. The distance of the sonobuoy from the ice camp was determined roughly via the helicopter's GNS system as described in the previous section. On most days this was checked via theodolite, as described on p. 59-60.

A calibrated L-tronics model LS44 receiver was set up at the base camp to monitor the sounds received at this sonobuoy. The same telemetered signals were often received and recorded aboard the project's Twin Otter aircraft. Sounds projected during playback experiments were monitored and recorded with this remote installation, thus providing received level data at one known range (~1 km) in addition to the known level at the projector.

Air-dropped Sonobuoys.--Sonobuoys were dropped from the Twin Otter aircraft during playback experiments and at certain other times. This allowed us to measure the levels and spectral characteristics of sounds reaching whale locations. It also allowed us to monitor whale calls. We used Sparton AN/SSQ-57A buoys; they were standard naval sonobuoys except that the hydrophone deployed only to 12 m depth. The signals were received via an RF preamplifier and calibrated Regency MX5000 wideband FM receiver on the aircraft. These signals were recorded on a calibrated Marantz PMD430 cassette recorder for later analysis. Sometimes the presence of faint *Karluk* drilling sounds could be detected by spectrum analysis of these recordings even if they could not be distinguished by listening. (To the human ear, bearded seal calls often tended to obscure the drilling sounds.)

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[3] A homing beacon left at the ice camp provided increased assurance that the camp could be re-located even in poor visibility or if other navaids failed.

Ambient Noise

Specific objective 2 was to measure ambient noise. During the five transmission loss tests, ambient noise was recorded at each range station before and after the tones and other signals were received. These data were recorded with an ITC 6050C hydrophone at 18 m depth. Each of these ambient noise recordings was typically 2-4 min in duration.

Ambient noise also was recorded at the beginning and end of each playback experiment. Most of these data were telemetered from the wideband -41B or -57A sonobuoys that were deployed manually about 1 km from the ice camp, as described above. Recordings usually were 2-4 min in duration.

When -57A sonobuoys were air-dropped near whales, the signals were generally recorded aboard the aircraft from splash-down until the aircraft departed the area. During some of these periods the sound projector was inactive or too far away to be audible, and aircraft sound was detectable only a minority of the time. These sonobuoy recordings provided additional ambient noise data.

Acoustical Analysis Methods

Industrial and Ambient Noise

The basic tool for sound analysis was a computer workstation programmed for narrowband spectrum analysis and for third-octave and one-octave band level computation. The tape-recorded sounds were filtered (passband from 5 Hz up to slightly less than half the sample frequency) and amplified as necessary. These signals were sampled and digitized (12 bit resolution) in blocks, usually 8.5 s in duration. The sampling rate varied depending on the frequency band to be analyzed, extending from 2048 samples per second for 10-1000 Hz analysis to 32,770 samples/s for 10-16,000 Hz analysis. Spectrum analysis was by an FFT (Fast Fourier Transform) algorithm using block sizes of 2048-8192 samples, Blackman-Harris windowing, 50% overlap of blocks, and averaging of results from all blocks within the 8.5 s sampling period. The various combinations of sampling rate, frequency range, and effective analysis resolution were as follows:

Sample Rate	Anal. Freq. Range	Eff. Analysis Width
1024 Hz	10 - 500 Hz	1.7 Hz
2048	10 - 1000	1.7
4096	10 - 2000	1.7
8192	10 - 4000	1.7
16384	10 - 8000	1.7
32770	10 - 16000	3.4

The averaged spectra for the tape recorder outputs were referenced to volts squared per Hz. These "raw" spectra were converted to spectra referenced to $\mu Pa^2/Hz$ by applying calibration corrections for the tape recorder, sonobuoys and their receivers (if involved), preamplifiers, postamplifiers and hydrophones. These corrections were frequency dependent.

The acoustical powers in the analysis cells were added appropriately to compute third-octave band levels, one-octave levels, and the 20-1000 Hz broadband level. The frequencies and levels of peaks in the spectrum were printed to aid in identifying tonal components and harmonic families of tones. Results from each spectrum analysis were printed, plotted, and saved in a disk file for further summarization.

In analyzing the sounds from aircraft overflights, just over a minute's signal was digitized at a rate of 1024 samples/s. Successive power spectra were computed from blocks 1024 samples long and overlapped 50%. These were normalized relative to the strongest spectral peak within the set of spectra (121) in order to derive a waterfall spectrogram spanning the 1 min segment of overflight sounds (see Fig. 27, p. 90). Graphs of the aircraft sound levels vs. time were prepared for each overflight, based on the levels in the 1-min sequence of spectra. Two levels were graphed: the level in the 20-500 Hz band level, and the level in the strongest one-third octave band.

Measured Propagation Loss

Data used to determine propagation loss were (1) the signals from the monitor hydrophone in front of the J-11 projector, and (2) the recorded signals received at distances 0.1 to ~18.5 km.

Signals from the monitor hydrophone were used to calculate source levels of the tones and the transmitted samples of *Karluk* drilling sounds. ► During TL tests 1 and 2, the J-11 monitor hydrophone signals were measured with an AC voltmeter (true rms meter) to determine the signal level at the monitor hydrophone. The distance of this hydrophone from the projector varied over the range 0.75-0.85 m from day to day. The spherical spreading model was used to determine the level at a standard distance of 1 m, the reference distance for all source levels quoted in this report. (The spherical spreading model assumes that sound level varies with the square of the distance.) ► For TL tests 3-5, the monitor hydrophone signals were tape recorded and later analyzed by computer. This procedure provided spectrum analysis of the emitted signals, 8.5 s averaging, and accurate determination of source levels. This procedure also provided source levels for each third-octave component of the broadband drilling sounds during TL tests 3-5.

The signals recorded at the various receiving stations were analyzed using the computerized spectrum analysis procedures described above, with 8.5 s of averaging. For each TL test and range, Greeneridge determined the received level of each of the eight pure tones, the sample of *Karluk* drilling sounds, and the ambient noise immediately before and/or after these sounds were projected. For TL tests 4 and 5, Greeneridge also determined the received levels of the audible HFM sweeps at each range. BBN repeated some of these measurements and, for the more distant receiving stations where the signals were inaudible, also applied a specialized cross-correlation signal processing technique in an attempt to detect and measure the HFM signals (see below).

The difference between the source level and received level of corresponding signals was the transmission loss. This difference was determined for each tone and for each of the prominent third-octave bands in the *Karluk* drilling noise. Thus, acoustic transmission loss was measured as a function of frequency and range on five occasions.

Matched Filtering of HFM Signals

The Concept.--Where background noise is high, a signal processing technique known as matched filtering can be used to obtain an estimate of signal energy (intensity) with better noise rejection than is possible with conventional methods. A common signal used for matched filtering is an HFM (Hyperbolically Frequency Modulated) sweep. HFM sweeps centered at 100, 200, 500, 1000, 2000 and 5000 Hz were projected during all transmission loss tests. The HFM signal is unique in that it is doppler invariant. Matched filtering can be performed without having to account for any doppler shift in the received signal. Any doppler shift is observed in the matched filter results as a shift in the apparent arrival time. Thus, the waveform forgoes arrival time accuracy in order to be doppler-insensitive (Rihaczek 1986).

Matched filtering is effectively a correlation operation between the received acoustic signal and a "replica". The acoustic signal is the signal received by a hydrophone. It contains a number of components including, for example, the signal transmitted by the underwater sound source (modified by transmission loss effects), ice cracking, wave slap, and biological noise. The purpose of matched filtering is to obtain a measure of the signal energy received from the underwater source without including the acoustic energy from the other noise sources. The measurement is obtained by correlating the acoustic signal with a "replica" of the signal transmitted by the source. The key difference between an energy estimate obtained from a matched filter and an energy estimate obtained by conventional methods is that the matched filtering process uses phase information in the replica to aid in discriminating signal vs. noise.

The processing gain G, which is the increase in signal-to-noise ratio obtained by the filtering process, is

$$G = 10 \log(W \cdot T)$$

where W is the bandwidth of the signal and T is the signal duration. The noise attenuation AN is

$$AN = 10 \log (W)$$

where W is the replica bandwidth.

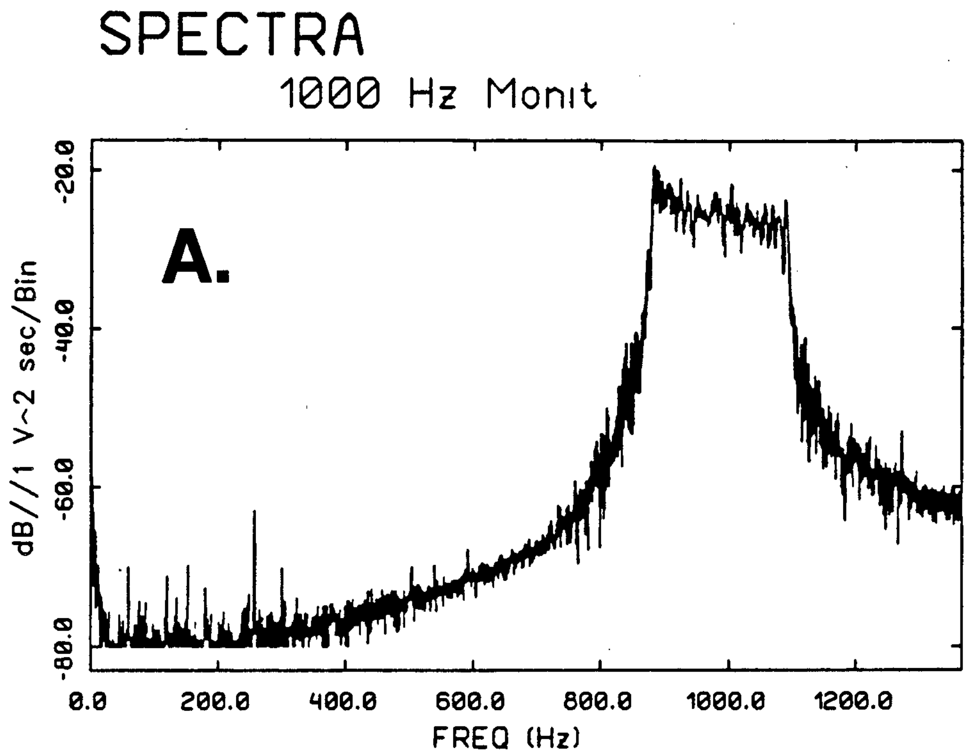
Signal Processing.--Processing of the received HFM signals involved two steps: digitization and matched filtering. Analog tape dubs of the signals received during transmission tests were played on a Sony Model M5D cassette tape recorder. The signal was filtered using antialiasing filters and digitized on a MASSCOMP 5500 data acquisition computer system. One HFM sweep was digitized for each range-frequency combination of interest. The specific sweep to be digitized was chosen based primarily on the amount of biological noise (mainly bearded seal calls). If the signal was not audible, digitization was begun based on the known time of the transmission. Matched filtering was performed on a general purpose VAX/VMS computer using existing software, which performed a frequency domain "fast convolution" and plotted the results (e.g. Fig. 16).

Two different signals were available for use as the replica for the matched filter: the signal monitored by the hydrophone <1 m from the projector, or an ideal replica representing the original HFM waveform. If the magnitude response of the projector is flat and its phase response is linear over the band of the signal, then the signal monitored in the water will be identical to that sent to the projector. In this case, either signal can be used as the replica with equal success. However, if these conditions are not met, or if the source distorts the signal through some non-linear process, then the filtering should be performed with a replica that represents the signal that was actually put into the water--i.e. the signal from the monitor hydrophone near the projector.

Preliminary analyses were conducted to compare the results obtained using these two types of replica signals. The original "ideal" HFM waveform proved to be a better replica than did the signal monitored by the hydrophone near the projector. The signals from the monitor hydrophone had apparently been degraded somewhat by tape speed flutter and multiple dubbing steps. Use of the ideal HFM waveform provided the greatest improvement in signal-to-noise (S:N) ratio. The following two subsections summarize our tests of the effectiveness of this procedure. Based on this analysis of effectiveness, the matched filter procedure was used to obtain measurements of received signal levels at some of the distant receiving stations during TL Tests 4 and 5.

<u>Test Results with Strong Signals</u>.--Figure 16 shows a matched filter analysis of a 1000 Hz HFM signal, as monitored near the projector, with itself as the replica. In this artificial case, the signal and replica are identical. The peak in the spectrum (Fig. 16A) is broad because the signal is a tone whose frequency oscillates within the 1/3-octave band centered at 1000 Hz. Because the signal and replica are identical, the matched filter produces a single "clean" cross-correlation peak (Fig. 16B). Based on the characteristics of that peak, the received level of the signal can be derived.

This is the ideal type of result that might be obtained from a matched filter analysis. However, in practical circumstances, the received acoustic signal is not identical to the replica, and the filter output is not as "clean" a peak as shown in Fig. 16B. It is common to see several peaks. This generally indicates that several components of the signal arrived along different propagation paths. If there is more attenuation along one propagation path than along another, the peak corresponding to the more attenuated component will be



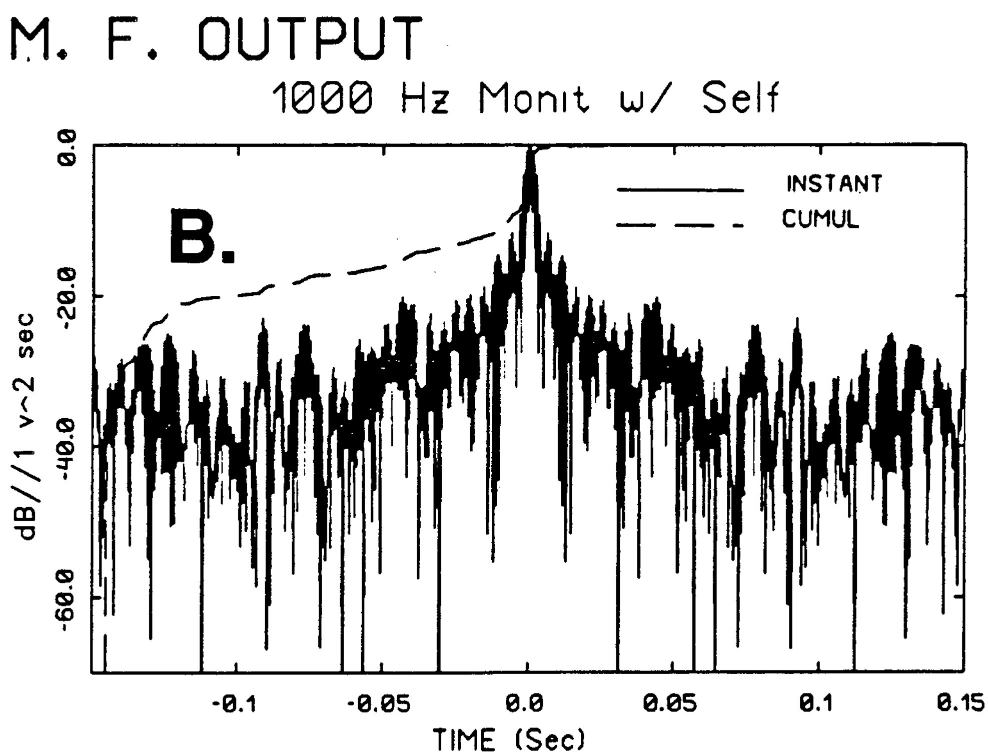


Fig. 16. Matched filter processing of projector monitor signal during transmission of 1000 Hz HFM signal, with itself as the replica. (A) Power spectrum. (B) Matched filter cross-correlation output.

lower. Sometimes the peak is smeared over a wider time interval; this is common in ducted environments where there is temporal spreading of the signal.

Figure 17 shows the results for the 1000 Hz sweep as received 100 m from the projector during TL Test #4. The ideal HFM waveform was used as the replica. Because the data were obtained only 100 m from the projector, the S:N ratio was high and the analysis produced a single sharp peak (Fig. 17B).

Representative Low S:N Data.--An example of the effectiveness of the matched filter method when the signal-to-noise ratio is low is given in Fig. 18. This analysis was based on the 2000 Hz sweep received at range 9.2 km during TL Test #5. Again, the ideal HFM waveform was used as the replica. The received level of this HFM sweep could not be measured by conventional methods at this range (see Table 11B, p. 122), although a pure tone at 2000 Hz was audible and measurable at this range (Table 12, p. 123).

The bandwidth for this 5 s sweep was 460 Hz, so the theoretical processing gain (G) was 33.6 dB and the noise attenuation (AN) was 26.6 dB. Based on conventional analysis methods, the measured RMS band-limited intensity for this waveform was -39.5 dBV. When the signal was passed through the matched filter, the noise level should have been reduced by 26.6 dB, so the average matched filter noise output intensity should have been -66.1 dBV. In fact, the matched filter output in Fig. 18B shows a peak occurring at time 0.07 s with signal energy of -48.8 dBV-s; the average noise intensity is around -65 dBV, as predicted. Thus the matched filter was able to extract a signal whose energy was about 16 dB below the noise energy in the corresponding band. The output S:N was 17 dB.

In conclusion, matched filter processing of the HFM waveforms was effective in improving the energy estimates of the signals received at distant sites where S:N ratios were low. The matched filter processing of the data worked better when the replica was the ideal waveform than it did with the monitored signal as the replica. This was attributable to tape speed flutter in one of several record and playback stages associated with the monitor hydrophone signals. The flutter problem presumably could be overcome in a future application of this method; ideally, a digital recorder should be used. However, even in the absence of a suitable monitored signal replica, the ideal waveform replica appeared to be adequate for the processing.

Received levels of pure tones generally were measurable using conventional methods at distances as great as those where HFM signals were measurable with matched filter methods (see Physical Acoustic Results, later). However, the HFM approach is expected to provide a better representation of the average transmission loss of sounds within a 1/3-octave band. The HFM signal oscillates across a 1/3-octave band, whereas a pure tone involves only a single frequency. Different frequencies within a single 1/3-octave can be attenuated differentially, so pure tone TL data do not necessarily apply to all frequencies within the associated 1/3-octave band.

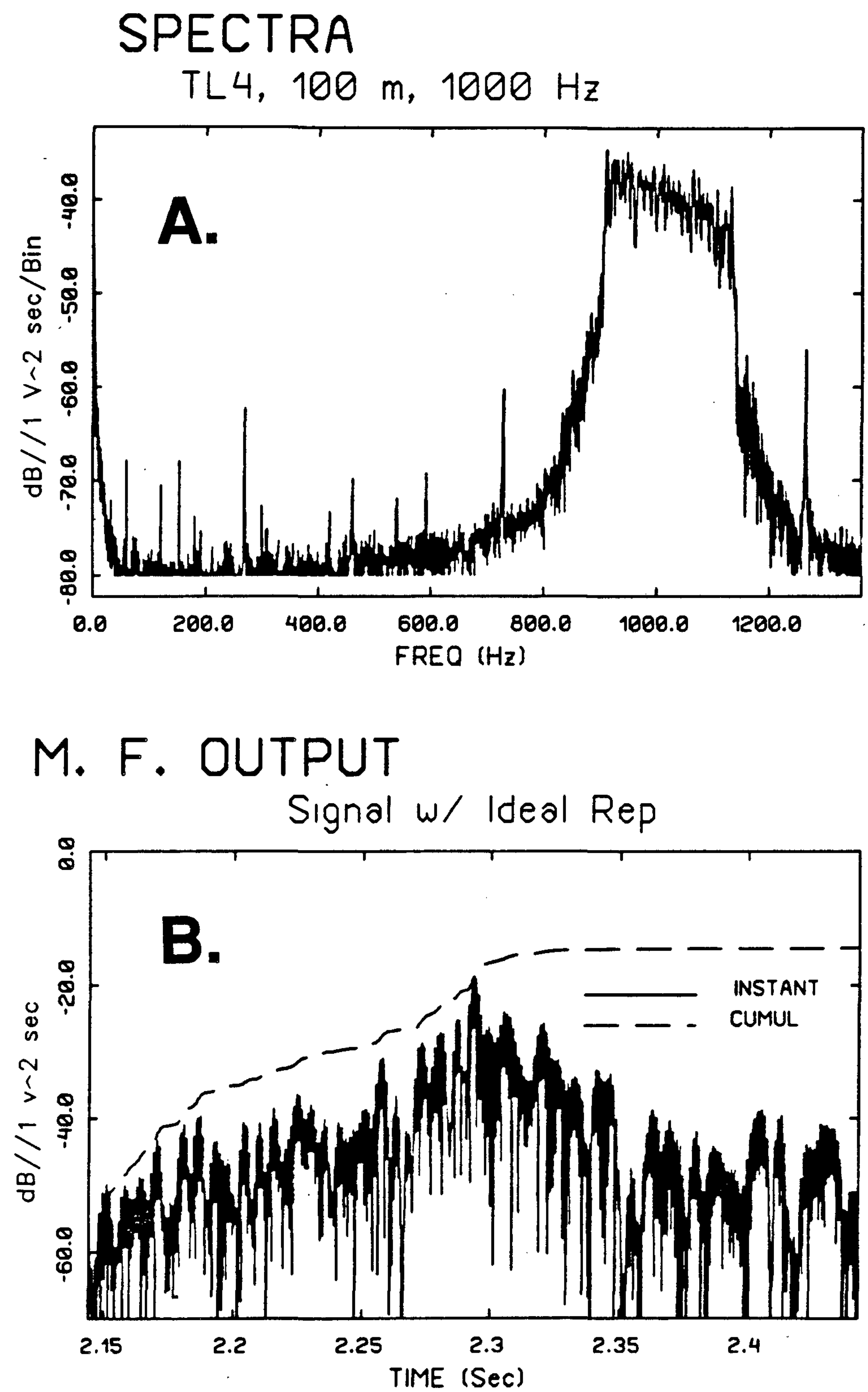


Fig. 17. Matched filter processing of signal received at 100 m range during transmission of 1000 Hz HFM signal with the ideal source waveform as the replica (high S/N ratio). (A) Power spectrum. (B) Matched filter cross-correlation output.

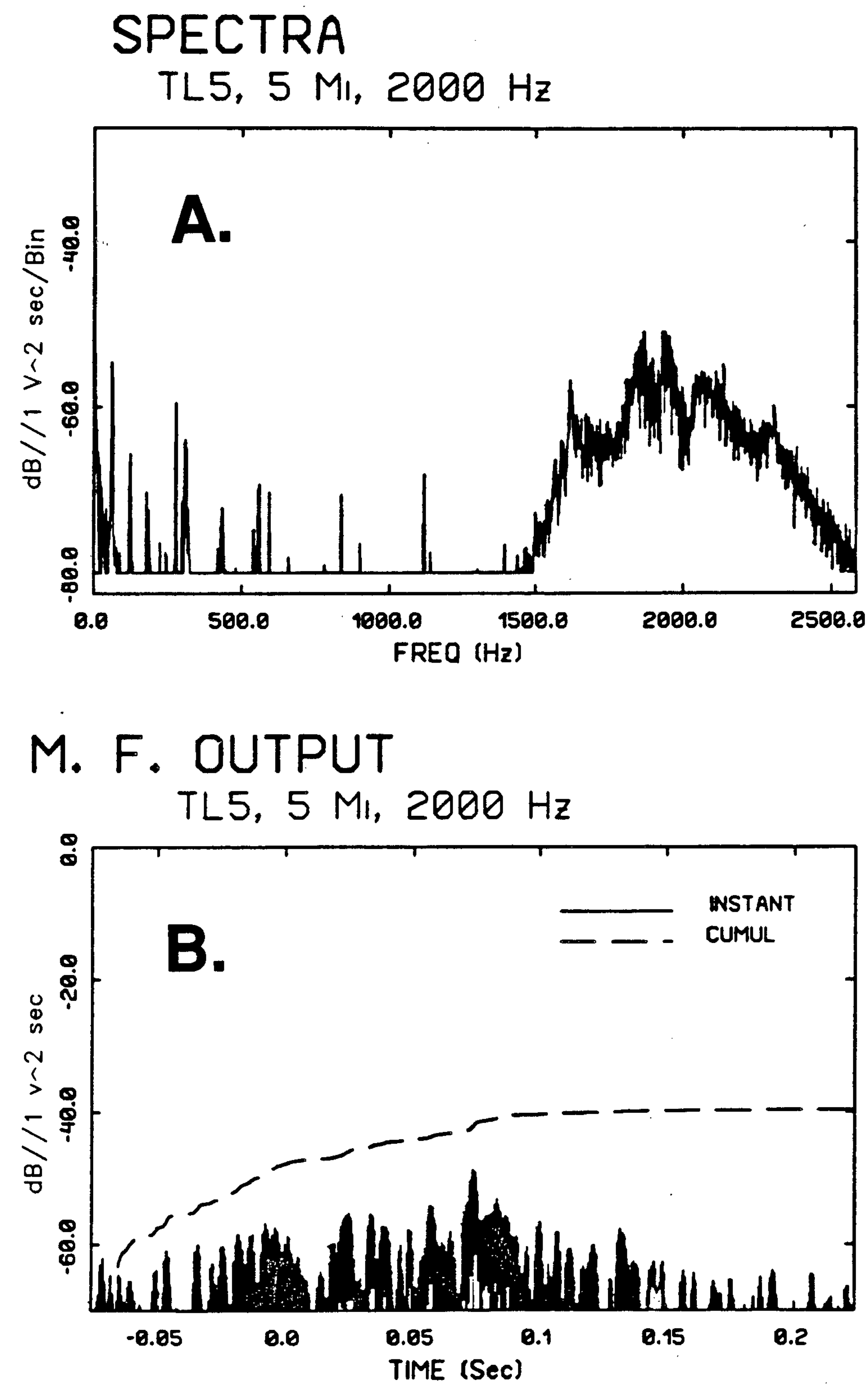


Fig. 18. Matched filter processing of signal received at 9.2 km range during transmission of 2000 Hz HFM signal, with the ideal source waveform as the replica (low S/N ratio). (**A**) Power spectrum. (**B**) Matched filter cross-correlation output.

Propagation Modeling

A version of the Weston/Smith sound propagation model was used to derive "best-fit" transmission loss curves, based on the TL data obtained by Greeneridge during TL Tests 4 and 5. When the TL data are obtained with a projector whose source level is known, as was the case in this study, it is possible to obtain the "true" transmission loss by subtracting the known projector source level from the measured received level. When a Weston/Smith model is fitted to such data, it is a semi-empirical model. Its predictions are partly controlled by theoretical considerations, but are strongly affected by coefficients derived from the empirical data.

The Weston/Smith model, as originally formulated by Weston (1976), Smith (1986) and Malme et al. (1986), was modified by incorporating a term that provides for the additional scattering loss incurred during sound transmission under ice (Milne 1967). Scattering loss is a function of the roughness of the underice surface. Scattering loss is also proportional to the average number of reflections along the transmission path, which is inversely related to the water depth. To minimize the influence of depth variations along different propagation paths on scattering parameters, a normalization factor was obtained by assuming that the average number of reflections (bounces) in the transmission path is proportional to R/H_{av}; H_{av} is the average water depth along the transmission path and R is the range.

A computer program was used to fit the Weston/Smith model to the empirical data by regression methods. The following coefficients were estimated:

b,	a parameter related to the bottom reflection coefficient
Sin ϕ_c,	the sine of the critical angle
L_s(eff),	the effective source level (includes site effects)
A_b,	the scattering term due to ice roughness (dB/bounce)

The difference (if any) between the known source level at 1 m, L_s, and the effective level estimated by the regression model, L_s(eff), represents the local transmission anomaly, in dB:

$$A_n = L_s(\text{eff}) - L_s$$

The local transmission anomaly results from the effect of the local bottom and surface conditions in producing a reverberant sound field near the source. This field may either be stronger or weaker than predicted by the transmission model, producing a positive or negative value for A_n.

The TL data obtained by Greeneridge included the results of conventional analyses of received HFM sweep tones, pure tones, and samples of the *Karluk* drilling noise analyzed by 1/3-octaves. The rms pressure average of these three test signals was determined at 50, 100, 200, 500, 1000, 2000 and 5000 Hz for each transmission range during TL Test 4, and separately for TL Test 5. These average TL values were then used in the regression analyses that determined the coefficients of the Weston/ Smith models. Above 200 Hz, only the pure tone and sweep tone data were used because the *Karluk* signals data did not contain significant energy above 315 Hz. BBN's matched-filter estimates of the received levels of HFM sweeps at certain long-range stations were considered when interpreting the Weston/Smith results, but were not included in the datasets used to develop those models.

The Weston/Smith models for different frequencies and for TL Tests 4 and 5 were compared to help evaluate the factors affecting transmission loss in the study area. In addition, the semi-empirical Weston/Smith results were compared with preliminary theoretical models of transmission loss that had been derived for the study area (see Appendix A) before any site-specific empirical data on TL were available.

Aerial Reconnaissance and Surveys

General Approach

Aerial reconnaissance and surveys were a necessary component of the work required to meet specific objective 4, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks...". Aircraft-based work was also important in addressing specific objective 6, "To document, as opportunities allow, other aspects of the movements, behavior, basic biology, disturbance responses and acoustic environment...".

Aerial surveys were necessary to determine the best location for the projector site each day and to determine the number and spatial distribution of whales moving east near the projector site. Because of the difficult ice conditions (see "Study Area--Ice Conditions"), it was not prudent to leave the ice-based crew on the ice overnight. There was no open lead along the landfast ice edge until late in the study period, and even then the whales were not moving along the nearshore side of the lead (see p. 149). Locations of open water amidst the pack ice varied from day to day. Consequently, the first priority each day was to determine a suitable location on the pack ice for the sound projector. Ideally, this location would have been a large multi-year ice pan along an open E-W lead through which bowheads and white whales were migrating.

Each day when conditions were suitable for flying, a reconnaissance survey of the study area was conducted to document ice conditions, including the locations and orientations of leads, and to determine the distribution, numbers, general activities and directions of movement of whales. The flight route depended on ice conditions. In general, a series of widely-spaced transects was flown initially to determine the overall ice conditions and the locations and orientations of leads. A location for the sound projector was then selected. While the projector was being set up, additional surveys were conducted as far as 20 km west and southwest of the projector site. These additional surveys followed any prominent leads that might bring whales to the projector site. On the few occasions when a more extensive area of open water was present, the survey consisted of a series of closely spaced parallel transects west of the projector site.

The need to avoid disturbing whales near Barrow necessitated setting up the projector ≥60 km east of Pt. Barrow (see specific objective 7 and "Study Area--Selection Criteria"). On several days during early and mid May 1989, there were no locations with suitable ice conditions or whales ≥60 km to the east. On these dates, aerial surveys were extended west, closer to Pt. Barrow, in order to find whales. When this was successful, behavior of undisturbed whales was documented and vertical photographs of bowheads were sometimes taken. We avoided flying over or west of the location where the North Slope Borough's whale census was to be based even though ice conditions prevented a census during May 1989.

Survey Methods and Data Recording

Aerial surveys were conducted from 1 to 30 May 1989 in a DHC-6-300 Twin Otter aircraft. The Twin Otter is a high-wing aircraft powered by two turbo-prop engines. The aircraft was equipped with an internal auxiliary fuel tank for extended endurance, a GNS 500A Very Low Frequency navigation system, a radar altimeter, an inverter for 120 V/60 Hz power, three bubble windows (right center, left center, left rear), a ventral camera port, and an intercom system for communication among the three observers and two pilots. The aircraft was flown at ~200 km/h airspeed and, when possible, at 305 m (1000 ft) or 457 m (1500 ft) above sea level (ASL). When ceilings were lower than 305-457 m, the maximum possible altitude below the cloud layer was maintained. During the midday periods when a NMFS/National Marine Mammal Lab crew was conducting low-altitude photogrammetric work with another Twin Otter in the same region, we normally either flew at 457 m altitude or stayed on the ground. This avoided some aircraft safety concerns, and fulfilled a condition of the research permit issued by NMFS for this project (see specific objective 7).

Three observers were present during all surveys. During surveys, they recorded observations onto audio cassette recorders. During surveys, one observer (right front) was in the co-pilot's seat and the other two were at bubble windows on the left and right sides of the aircraft two rows behind the pilot's seat. For each whale sighting, observers recorded the time, location, number, species, general activity, orientation, and ice conditions. Each observer also noted the ice conditions throughout the survey, particularly whenever a change in ice type or cover occurred. Aircraft position was recorded from the GNS and altitude from the radar altimeter whenever sightings were made, and whenever the aircraft changed course or altitude.

When a whale was sighted, the observer notified other members of the crew over the intercom. In most cases bowhead whales 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 usually were not circled, but large groups of white whales were circled to obtain more accurate counts and heading information.

No standardized surveys were conducted by helicopter. However, locations of bowheads seen from the helicopter during ferry flights were noted.

Behavioral Observations

Aerial Observations

On 17 occasions in May 1989, the aerial observation procedures of Richardson et al. (1985a,b) were used to observe the behavior of bowhead or white whales, as required to meet specific objectives 4 and 6. Three observers in the Twin Otter aircraft circled high above the whales. If possible, the aircraft circled at 457 m ASL, which has been found to be high enough to avoid significant aircraft disturbance to bowheads, at least during summer and autumn. (As noted on p. 210, sensitivity to the observation aircraft appeared to be no greater during this spring study than during previous summer and autumn work.) Airspeed during circling was 165 km/h. The 17 behavioral observation sessions ranged from 0.1 to 3.3 h in duration and totalled 25.6 h. During five of these sessions on four different days, 9.2 h of aerial observations were conducted near the ice camp in co-ordination with broadcasts of drilling platform sounds (see Fig. 19 on p. 72).

Throughout each observation session, two observers on the right side of the aircraft dictated standardized behavioral observations via the intercom into a single tape recorder. These observers were in the co-pilot's seat and the seat two rows behind it. During each surface/dive sequence by bowheads, they described the same behavioral attributes as were recorded in our previous behavioral studies (Würsig et al. 1984, 1985a; Richardson et al. 1985b, 1987b; Koski and Johnson 1987). For white whales, we recorded as many as possible of the same variables. However, blows by white whales often could not be seen while circling at 457 m altitude. For white whales, more emphasis was placed on recording direction and speed of movement relative to the ice edge and sound projector, and less emphasis was placed on recording respiration, surfacing and dive variables.

The third observer, also on the right side during behavioral observations, operated sonobuoy receiving equipment and, whenever whales were at the surface, an 8-mm video camera. The video camera was a Sony CCD-V11 with 12-72 mm lens and 2x teleconverter. The video camera was usually operated with manual focusing and 1/1000 s shutter speed to provide sharp images when viewed in stop-frame mode. On most occasions the behavioral dictation on the intercom was recorded onto the audio channel of the video tape recorder.

Behavioral data were transcribed from audiotape between flights, and the videotape was 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 for details). These records were hand checked, and then entered into an IBM-compatible microcomputer for computerized validation and analysis.

For bowheads, 380 surfacing and 242 dive records were obtained by aerial observers during 1989. Of these, 218 and 124 were obtained under "presumably undisturbed" conditions. Of the data obtained under "potentially disturbed" conditions, 90 surfacing and 69 dive records were obtained during playback of the drilling platform sounds. In addition, 44 surfacing and 23 dive records were obtained during periods when the observation aircraft was at an altitude <457 m and may have disturbed the whales.

For white whales, the aerial observers recorded 458 surfacing and no dive records. Of these surfacing records, 400 were obtained during playbacks of drilling sounds, and 23 during presumably undisturbed conditions. We recorded 451 orientations and 284 estimates of the relative speed of movement of individual whales.

Ice-based Observations

Observations of bowheads or white whales were conducted by ice-based observers on nine occasions from 30 April to 30 May 1989 to help meet specific objectives 4, 5 and 6. Two observers used binoculars and a land surveyor's theodolite to search for whales. The observation site was usually on an ice ridge 2-5 m ASL, and was ≤300 m from the sound projector. When whales were spotted, one observer watched the whales and dictated observations to the second observer, who recorded all relevant observations onto data sheets or into field notebooks.

The digital theodolite (Lietz/Sokisha Model DT20E, 20 second precision) was used to determine successive positions of whales and seals in relation to the sound projector. Upon arrival at the daily site, the theodolite was set up on the highest ice perch within ~300 m of the projector and ~20 m of open water. The height of the theodolite was determined each day by taking a horizontal reading from a vertical stadia rod at the projector location. Theodolite bearings were measured in degrees, minutes and seconds from the horizontal zero (referenced to magnetic north) and a vertical zero (referenced to the leveling device on the theodolite). Most ice ridges on which the theodolite was placed were less stable than desired. To control for error, the horizontal and vertical zeros were checked every 30 min (approx.) and after tracking episodes, and were reset if off by greater than one minute of arc.

The distances of whales from the theodolite were calculated by simple trigonometry (Felleman and Chumbley 1983). This calculation did not correct for the curvature of the earth, but this error is small for the combinations of perch heights and the short (<2 km) distances involved in the 1989 observations of whales (Table 2). A whale 500 m from the observers at an observation height of 2 m ASL would be 5 m farther than the distance calculated by the simple formula. Another potential error results from the refraction caused by temperature gradients in the air above the water (Sonntag and Ellison 1987). This error could be significant for low perch heights and whales more than ~1 km away when wind conditions are calm and air temperatures are low. However, the lack of reliable data on vertical temperature gradients in the air over a lead prevents an evaluation of refraction error.

Table 2. Underestimation of distances calculated from theodolite data (in m) when curvature of the earth corrections are not used*.

Perch Height	Distance from Perch (m) 100 m	500 m	1000 m	1500 m	2000 m
1 m	0.09	10.0	94.6	448	N/A
2 m	0.04	5.1	42.9	163	485
3 m	0.04	3.3	27.8	101	270
4 m	0.03	2.5	20.5	72.9	188
5 m	0.02	2.0	16.3	57.1	145
6 m	0.01	1.6	13.5	47.0	118

* Formula for curvature of the earth from Kewalo Basin Marine Mammal Lab., HI.

After the theodolite was set up, the relative locations of the projector, the manually-deployed sonobuoy, and the ice edge across the lead were documented by theodolite readings. Depending upon the width of the lead and the height of the perch, the waters within ~2-3 km of the theodolite were scanned intermittently with binoculars. When an animal was sighted, its bearing and depression angle were determined using the theodolite. Theodolite readings were recorded when the crosshairs were aligned with the waterline of the surfacing animal. An attempt was made to obtain a reading each time an animal surfaced for a blow. At each of these points, the time was also noted. Animals were tracked for as long as they remained in view.

Additional notes were made in real time of initial and final sightings of all animals, including estimated distance and magnetic bearing from the projector, group size and composition, general behavior, direction of movement and subsequent shifts in direction, blow times, sighting conditions, presence of other species, and any other occurrences of interest, including aircraft flying overhead. These notes were made whether or not the theodolite and/or projector were in operation.

Bowhead Photogrammetry and Photo-identification

We photographed bowhead whales using the calibrated vertical photography technique developed by LGL (Davis et al. 1983). Two types of information were obtained from the photographic images:

1. The sizes of individual whales were determined. This was important because whale behavior is expected to vary with the age and size of whales and because the timing of bowhead migration past Barrow is partially segregated according to size (Nerini et al. 1987).

2. Information on local movements and residence times of whales was obtained by photographing individual whales on more than one occasion. This information is important when interpreting potential effects of simulated industrial disturbance.

This work provided some of the information needed to meet specific objectives 4 and 6.

The acquisition of information on local movements and residence times of bowheads was enhanced by close cooperation between this study and the NMFS/NMML aerial photography project (specific objective 7). Before and after each flight, representatives of the two project teams met in Barrow and discussed their plans or findings. When both teams were flying, they maintained VHF radio contact. In this way it was possible to avoid having both groups photograph at the same location on the same day. In addition, we were able to direct the NMML crew to certain whales that were too far from the sound projector to be a priority for us, and the NMML crew occasionally pointed out situations that might afford us a useful research opportunity. Each crew benefited from weather reports provided by the other crew, given that there are no weather stations NE of Barrow.

Field Procedures

In 1989, we obtained vertical photographs at the conclusions of 5 of the 17 behavioral observation sessions and on 5 other occasions when behavioral observations were not conducted. During photography sessions, the aircraft descended to 145 m (475 ft) ASL. Because of the potential to disturb whales during photography from this low altitude, whales were not photographed if they could potentially be observed by the ice-based observers after the aircraft left, or if the aircraft might return to the same area to conduct further behavioral observations later the same day.

During photo sessions, the aircraft circled the location of the whales and flew directly over them at ~165 km/h when they surfaced. Photographs were taken with a hand-held Pentax 6x7 cm camera with a 105 mm *f*2.4 lens pointed directly downward through a ventral camera port. Ektachrome 200 color positive film was used for all photography. The firing of the camera was audible to all observers through the intercom system. As each photograph was taken, the pilot read the altitude from the analog display of the radar altimeter and the left observer recorded the time and radar altitude from a digital display in the rear of the aircraft. The altitude as read by the pilot was recorded by the right front observer. The two altitude records were later compared to ensure that no recording error had occurred. In addition, as the camera was fired the front observer recorded the time and position from the VLF navigation system. Two identical calibrated camera/lens systems were used; the system that was used was recorded for each roll of film.

Calibration photographs of a target of known dimensions were obtained to permit calculation of actual whale sizes from the photographs. The target was spread out on land in a "+" configuration, with a length and width of 20.0 m. Five photographs of the target were taken with each camera/lens system.

Size Measurements

Images of bowhead whales and calibration targets were measured directly from the processed film to the nearest 0.01 mm using a Zeiss binocular dissecting microscope and a stage micrometer. The average of three blind replicate measurements was used to calculate the dimensions of the target or whale using the following equation from Jacobson (1978):

$$\text{Calculated length} = \frac{\text{Altitude x Image size}}{\text{Focal length of lens}}$$

The dimensions calculated from the above formula were then corrected for distortion caused by the focal plane shutter in the camera (see Davis et al. 1986b).

Calculated target sizes (corrected as above) were regressed against the known target measurements to give the following regression equation:

$$\text{Actual length} = (\text{Calculated length} - 0.034)/0.99533$$

This equation corrects for systematic biases, e.g. in the altitude values derived from the aircraft's radar altimeter, and was used to convert calculated whale lengths to actual lengths. Recent studies (Koski and Johnson 1987; Nerini et al. 1987; Dave Withrow, NMFS, pers. comm.) have indicated that radar altimeters may give slightly different altitude readings over land and water. The observed differences appear to be consistent for a given individual radar altimeter. Altitude readings were ~1.3% lower over water than land, resulting in a slight underestimation of whale length (Nerini et al. 1987). However, it is not known whether the difference is the same for all altimeters made by the same manufacturer, or for altimeters made by different manufacturers. The lengths presented in this report are based on calibration data from targets photographed over land, with no correction for any land/water effect.

The quality of the measurements varied from one photograph to another because of the varying postures of the whales and changing sea state and lighting conditions. The repeatability of each measurement was assigned a grade from 1 to 6, following Davis et al. (1986b). A grade 1 measurement was the highest quality measurement.

Individual Identification

Koski and Johnson (1987), Richardson et al. (1987b) and Koski et al. (1988) have shown that vertical photographs can be used to document short-term (within day), medium-term (day-to-day), and long-term (year-to-year) movement patterns of bowhead whales. Photographs obtained by us and NMML, when combined, might provide information on rates of movement of bowheads subjected to playback experiments in comparison to those not subjected to playback experiments.

Individual whale images from this study were enlarged as 5x7 inch custom prints and labelled. Each whale image was assigned a re-identification grade, as in previous studies (Davis et al. 1983, 1986a,b). Photographs of whales that would be recognizable in another photo of similar or better quality taken in another year were grade A. Photos of whales that would be recognizable in a photo of similar or better quality taken the same day or within a few days were grade B. Photos of whales that probably would be unrecognizable in another photo of similar or better quality were grade C.

The grading of prints involved a subjective assessment of focus, resolution, lighting, glare, reflection, sea state and posture of the whale, as well as distinctiveness of the whale's markings. A poor quality photo of a very distinctively marked whale might be graded A while an excellent photo of a whale with no distinctive markings might be graded C. We have not considered grade C photographs in this analysis. Each grade A and B print was then assigned to one of 20 files depending upon the amount of white on the lower jaw and in the tail region (Davis et al. 1983; Braham and Rugh 1983).

Each whale image was compared to all others acquired in this study, and to all images that NMML obtained after 7 May 1989. Each grade A whale image was also compared to our collection of summer and autumn photos acquired since 1981 in the Canadian and Alaskan Beaufort Seas. In these inter-year comparisons, whale images were compared to all other images in the same file and in "adjacent" files containing images with similar characteristics.

Playback Experiments

Playbacks were conducted to meet specific objective 4, "To measure the short-term behavioral responses of ... whales ... to underwater playbacks of the continuous drilling platform sound...". Drilling platform sounds were projected from a mobile ice-based camp that was established on the pack ice each day when weather and ice conditions were suitable. Playbacks were conducted on 12 occasions. During seven of these sessions, no white whales or bowheads were seen while the projector was operating, although during two of these seven sessions (16 and 21 May) whales were observed before the projector was on. During one session (19 May) observations of whales were obtained only from the ice camp because low cloud cover prevented aerial observations from altitude ≥457 m. During the remaining four sessions (14, 23, 27 and 29 May) observations of whales were obtained by both the ice-based and aircraft-based crews.

Playback Equipment and Procedures

A single broadband J-11 projector was used for all playback experiments. The J-11 can produce a source level up to about 164-166 dB re 1 μPa-m without distortion. Its effective bandwidth is 20-12,000 Hz. It was powered by a 250 W Bogen MT250 power amplifier. The J-11 and its ancillary equipment were portable by helicopter, which allowed us to conduct "single-day" experiments at changing locations.

In order to operate the amplifier and other electronic equipment for a significant length of time, it was necessary to use a generator rather than batteries to provide power. The generator produced significant airborne noise, but little of this noise was transmitted into the water because of attenuation by the snow-covered ice. Noise levels produced by the 2.2 kW Honda gasoline-powered generator were low in comparison to those from the projector (see "Physical Acoustics Results", p. 97).

Each day when weather and ice conditions permitted, the ice camp was established on the pack ice along a lead near the east end of an open water area. When possible, the camp was placed to the east or northeast of whales located by aerial reconnaissance. The J-11 projector and ancillary equipment, the sound recording and monitoring equipment, and the theodolite were set up. This process normally required at least 2 hours after arrival at the site. The theodolite crew then watched for approaching whales, supported by the aerial crew whenever feasible. If no whales were seen close to the projector, it was started. (We did not plan to start the projector when whales were within a few hundred meters, since the sudden onset of industrial sound would not be typical of an actual oil-industry site, and might cause startle reactions that could confound interpretation of later behavioral observations.)

It was important to obtain the most accurate possible data on the relative positions of whales and the sound projector. These data were needed to plot whale movements and to estimate received sound levels when these were not measured directly by sonobuoys. When whales were within view of ice-based observers, the most precise positional data were obtained with the theodolite. However, for whales observed from the air, other procedures were necessary.

The absolute location of the ice camp was determined using the VLF navigation systems on the Twin Otter and helicopter (usually accurate within about 1-2 km) and using a Si-Tex model A-310 satellite navigation receiver at the ice camp (accuracy 0.1-0.2 km). The position of the ice camp often changed substantially during an experiment due to wind- and current-induced drifting of the ice. To account for this, all whale sightings and movements were plotted relative to the sound projector. To help determine whale positions relative to the ice camp, the observation aircraft was often flown from the location where whales had just dived to the ice camp. By flying directly over these two positions within a short interval, the aircraft's VLF navigation system provided accurate (±0.3 km) data on the whale-to-projector distance and bearing even though absolute position readouts from the VLF system were less precise. In addition, during playbacks we frequently recorded the position of the whale according to the aircraft's VLF navigation system, and we made visual estimates of the distance from the whale to the projector during most whale surfacings. Whale-to-projector bearings were estimated by reference to the aircraft's gyrocompass. Upon our return to the Barrow airport after each flight, we recorded the amount of drift in the absolute GNS readout during the flight. It was usually about 1 km.

Acoustical Monitoring

Sound levels reaching whales during playback experiments were measured and/or estimated using several techniques, as described in preceding subsections on "Acoustical Field Methods" and "Acoustical Analysis Procedures". By having a variety of monitoring capabilities, we were able to obtain the necessary data on sound exposure levels in a wide variety of field situations, including situations where some methods were impractical.

The transmission loss measurements described earlier, along with mathematical models of transmission loss, provided estimates of received level as a function of range under varying ice conditions. When direct measurements of sounds reaching the whales were impractical, the TL data and models were used to estimate the received levels.

The observation aircraft was equipped to drop sonobuoys near whales that were under observation from the aircraft, and to record the telemetered data on sounds being received by the whales. This permitted accurate measurement of sound levels received by some of the whales observed from the aircraft.

We also maintained a monitor sonobuoy about 1 km from the projector site during most periods when the ice camp was operating. (However, on 29 May an ice pan crushed the monitor sonobuoy, so these data were not available for much of that day.) The telemetered signals were monitored periodically at the projector site and also aboard the observation aircraft when it was in the area. These data provided a direct measurement of received industrial noise level at one distance from the projector. On 14, 19, 23 and 27 May, the monitor sonobuoy was positioned close to the point of closest approach of some of the whales that were observed, thus providing direct information about sound levels received by the whales. Even when the whales did not approach close to the monitor sonobuoy, the received sound levels there provided a calibration point for estimates made using propagation models.

Behavioral Observations

To maximize the power of the observations in assessing the hypotheses, we planned to use whales approaching the sound projector as their own controls. Our intent was to compare the behavior of the same whales when they were at various distances from the projector. 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 that they could not hear it or, at the least, were not likely to react to it. We then intended to observe their movements and behavior as they approached and passed the projector.

Because the projector had to be re-established on the ice each day, the projector often began operating while whales were already under observation from the aircraft. To eliminate observer expectancy biases, we attempted to prevent the two primary behavioral observers in the aircraft from knowing whether or not the sound projector was operating. This "blind" observation protocol was only imperfectly achieved because of difficulties in isolating the aerial observers from some radio communications. The behavioral observers usually did not know exactly when the projector was turned on or off. However, during the major part of each observation session near the projector site, they were aware that the projector was operating. This knowledge would affect few (if any) of the data collected. Estimated swimming speed was one variable that required a partly subjective judgement, and thus there is the possibility of observer expectancy bias in this case.

In addition to the aerial observations, the ice-based crew recorded whale behavior and movements with the aid of the theodolite during playback experiments. Because of the low vantage point from the ice, ice-based observers could not see whales unless they were within ½-2 km of the projector. The most valuable data obtained from the ice-based observations were data on the closest point of approach to the projector and on the precise tracks of whales that approached or passed the projector. More precise data of these types could be obtained by theodolite than by aerial observations. Also, ice-based observers sometimes were able to collect data when aerial observations were impractical because of low cloud ceiling or limited aircraft endurance.

Because of their proximity to the projector site, the ice-based observers were aware of projector status (on or off). However, most of their data were theodolite readouts, which do not involve subjective judgments. Thus, observer bias would not be a problem in these data.

To determine the reactions of whales to the drilling sounds, we planned to conduct three types of comparisons of whale movements and behavior: *(1)* For whales that approach and pass the operating projector, examine movements and behavior as a function of distance from the projector, allowing each animal or group to serve as its own control. *(2)* Compare the movements and behavior of whales passing the ice-based crew at times when the projector is operating vs. silent. *(3)* Compare the movements and behavior of whales seen near the operating projector vs. those seen at times and locations when the ice-based crew is absent. Because there were few opportunities for playbacks in 1989, we decided to operate the projector on each day when whales were passing it. Thus, few data of the type needed for comparison (2) were obtained in 1989. However, we recognize that this type of control information is needed to confirm that any observed changes in behavior are attributable to the noise rather than to the physical presence of the ice-based crew. The 1990 field program will include a number of control observation periods.

GENERAL CHRONOLOGY OF 1989 FIELD ACTIVITIES

Preliminary Sound Propagation Tests, 25-30 April

Plans called for preliminary sound propagation tests to be conducted from 25 to 30 April 1989. The main field program, including noise playback experiments, was to extend from 1 to 28 May. The purpose of the late April work was to determine whether the actual radius of detectability of the projected sounds was any greater than that predicted before the field season (*cf.* Appendix A). If not, the main field program could go ahead during May as planned.

The necessary research permit was issued by the National Marine Fisheries Service on 24 April, and fieldwork started on 25 April, as scheduled. The ice-based crew used the helicopter to conduct an initial ice reconnaissance ENE of Barrow. The purpose was to select prospective sites for the preliminary sound propagation tests (otherwise known as Transmission Loss or TL tests). Logistical constraints and poor weather prevented conduct of the first TL test until 29 April (Table 3).

TL tests were conducted on 29 and 30 April. There was no open water along the edge of the landfast ice, so the sound projector was set up on an ice pan alongside a small open-water area amidst the pack ice. The projector sites on the two days were 79 and 86 km, respectively, ENE of Barrow (Fig. 19). The projector was set up on the same ice pan on the two successive days, but the ice had drifted eastward several kilometers in the interim. Recording sites were to the west and northwest of the projector. Almost all of the region around the projector (>99%) was covered by pack ice. The ice was especially heavily ridged a few kilometers west of the projector site. Two bowheads were heard (but not seen) during the TL test on 29 April. Three bowheads were seen near the projector during the TL test on 30 April. One of these was observed just before and during broadcast of some of the test sounds.

The acoustic data from these two preliminary TL tests were analyzed in Barrow on 1 May to determine how far the drilling sounds were audible under the ice. Because the sounds attenuated rapidly with increasing distance and were inaudible within 5-10 km, it was concluded that the main field program could go ahead as planned.

Main Field Program, 1-30 May 1989

The Twin Otter and its crew were at Barrow by the evening of 30 April. On 1 May an aerial survey was conducted to determine the general ice conditions in the study area and to test the equipment aboard the Twin Otter. On 2 May the aerial crew conducted a survey ENE and NE of Barrow and found little open water and no bowheads. Because no bowheads were found, playback experiments were not practical. Hence, the ice-based crew conducted a third TL test amidst smoother ice slightly north of the first two TL test sites (Fig. 19).

Table 3. Summary of daily activities and weather and ice conditions, 25 April-30 May 1989.

	Ice-based Crew										Aircraft-based Crew					
				Number of										Number of		
												Behavior				
Date	Ferry Flights	Transm. Loss Test	Karluk Projec-tions	Bowheads	White Whales	Location	Other	Ice Conditi.	Overall Ceiling/ Visibility	Cloud Survey (h)	Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
25 Apr	1			0	0	ENE	Ice reconnaissance									
26 Apr	0								Poor visibility							
27 Apr	0						-35° with wind chill factor									
28 Apr	0								Poor visibility							
29 Apr	6	#1		2 heard	0	71°38' 154°34'	In hole among pack ice. Whales before transmission	>99%								
30 Apr	8	#2		3 (1)*	0(30)*	71°36' 154°25'	In hole among pack ice	>99%								Aircraft crew arrives at Barrow
1 May	0						Analyze TL data	>99%		1.7			Survey ENE of Barrow	0	0	
2 May	6	#3		0	0	71°39' 154°31'		>99% Narrow cracks	Fog until noon; clear, excellent visibility PM	1.9			Survey ENE of Barrow	0	22	Few open water areas
3 May	6		P1	0(1)	0(7)	71°44; 153°54'	Broadcast into area of thin ice	>99%	Fog until 12:00; clear, excellent visibility PM	2.5	2.5	0.3	71°33'-71°39' 155°28'-155°30'	25	53	Whales within restricted area (i.e. within 60 km of Barrow)
4 May	0								Low ceiling. Poor visibility							
5 May	0								Low ceiling. Poor visibility	2.4			Survey ENE of Barrow	0	36	
6 May	4		P2	0	0	71°37' 154°46'	Broadcast into open lead among pack ice	99% Small leads	Low ceiling E of 155° (~180 m). Clear at Barrow.	2.3	1.8		71°40' 155°57'	10	71	Bowheads within restricted area. Low ceilings E of 155°.
7 May	6		P3	0	0	71°37' 154°58;	Broadcast into refrozen lead among pack ice	>99%	Clear or high cloud	2.7	1.5		Survey ENE of Barrow 71°47' 155°29'	3	69	
8 May	0						No flight due to lack of open water	100%	Clear or high cloud	2.1			Survey ENE of Barrow	0	12	Virtually no open water, froze overnight

Continued....

Table 3. Continued.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projec-tions	Bowheads	White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
9 May	2	#4		0	0	71°50' 155°30'	TL conducted at thinly refrozen lead. Bowheads and white whales heard but not seen.	100%	Fog AM; clear PM	3.1			Survey ENE of Barrow	0	55	
10 May	0							100%	Low ceiling all day. Poor visibility in AM.							
11 May	0							>99% Narrow lead developing	Low ceiling. Poor visibility in snow, fog.							
12 May	0							95% Offshore leads developing	Low ceiling. Poor visibility in snow, fog.	1.9	0.1		Survey ENE of Barrow 17°55' 155°04'	4	68	
13 May	0							85% Large lead along ice edge E of Barrow	Low ceiling. Poor visibility in snow, fog.	1.5			Survey ENE of Barrow	1	31	
14 May	4		P4	5(3)	15(2)	71°46' 155°03'	Broadcast into open lead among pack ice	85% Offshore lead in pack ice	Good visibility. Ceiling >460 m until 15:00; 245-305 m after 16:00	2.3	5.5	0.4	Survey ENE of Barrow 71°38'-71°50' 154°45'-155°50'	26(1)**	160(8)	Projection experiment
15 May	0							85-90% Some new ice over night	Low ceiling. Poor visibility in snow	2.0		0.2	Survey ENE of Barrow 71°48' 155°08'; 71°54' 154°28'	5	133	
16 May	4		P5	2	13(6)	71°44' 155°08'	Broadcast into open lead among pack ice	90% Some new ice over night	Ceiling 180-305 m. Visibility good with occasional snow	2.2			Survey ENE of Barrow	0	22	

Continued....

Table 3. Continued.

Date	Ice-based Crew: Ferry Flights	Transm. Loss Test	Karluk Projec-tions	Number of Bowheads	Number of White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Aircraft-based Crew: Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Number of Bowheads	Number of White Whales	Other
17 May	2			0(3)	24	71°35' 155°44'	Poor weather to east; helicopter overflight sound measurement	95% New ice formed over night	Ceiling 120-180 m to east. Visibility good to poor in snow	2.2			Survey ENE of Barrow	1	96	
18 May	1			0(1)	0		Flight aborted due to poor visibility	>90%	White-out conditions in some areas. Ceiling variable 150-460 m.	2.1		1.0	Survey ENE of Barrow 71°34'-71°36' 156°00'-156°15'	15	22	
19 May	4		P6	4	2	71°40' 155°23'	Broadcast into large open lead in pack ice	>90%	Ceiling 150 m. Visibility good (~18 km) except for occasional snow squalls.							
20 May	0							90% Lead formed along landfast ice edge	Variable, low ceilings and poor visibility	1.3			Survey ENE of Barrow	0	0	
21 May	8		P7	0	7	71°35.8' 155°16'	Broadcast along N side of main lead	85% Strong winds move ice	Very low ceiling (100 m) in blowing snow	1.5			Survey ENE of Barrow	0	22	
22 May	0							80%	Low ceiling. Poor visibility in snow and fog							
23 May	4		P8	3(3)	7(5)	71°37' 155°02'	Broadcast into large open lead among pack ice	80% Lead 8 km wide NE of Barrow	Variable ceiling 130-450 m. Good visibility	3.8	4.5		Survey ENE of Barrow 71°38' 155°07'; 71°42' 154°41'	5(2)	76(3)	Projection experiment
24 May	0							80% N of lead 90% pack ice	Low ceiling with icing in AM. Good visibility below 140-275 m later	1.4	1.1		Survey ENE of Barrow 71°36' 155°56'	6	59	Test difar sonobuoy. Major lead along fast ice edge NE of Barrow for rest of study.
25 May	4	#5		0	0(1)	71°37' 154°39'	Broadcast into small lead among pack ice N of main lead	80%	Low ceiling and poor visibility until late in day when ceiling lifts to 200-280 m	1.8		1.3	Survey ENE of Barrow 71°36' 155°38'; 71°33' 154°54'; 71°33' 155°12'	10	51	Aerial photogrammetry calibration

Continued....

Table 3. Concluded.

	Ice-based Crew									Aircraft-based Crew						
				Number of										Number of		
Date	Ferry Flights	Transm. Loss Test	Karluk Projections	Bowheads	White Whales	Location	Other	Overall Ice Conditi.	Cloud Ceiling/ Visibility	Survey (h)	Behavior Obser. Sess.	Photogr. (h)	Location	Bowheads	White Whales	Other
26 May	1			0	0		Flight aborted due to fog	80%	Ceiling and visibility variable in fog							
27 May	4		P9	0(1)	14	71°35' 154°34'	Broadcast among pack ice N of main open lead.	80%	Clear	3.8	5.5	0.9	Survey ENE of Barrow 71°33' 154°33'; 71°33' 154°42'	17	52(8)	Normal Behavior Projection experiment
	4		P10	0	0	71°35' 154°45'	Broadcast along N side of main lead.						71°38' 155°18'			Projection experiment
28 May	4		P11	0	0	71°35' 154°54'	Broadcast along N side of open lead. Helicopter and Twin Otter over-flight sound measurements.	80%	Clear AM. High cloud PM.	5.3	0.7	0.6	Survey ENE of Barrow 71°39' 155°00'	3	5	
29 May	4		P12	0(2)	2	71°41' 154°49'	Broadcast into small lead among pack ice on N side of main open lead	80%	Some high cloud. Good visibility.	3.9	2.5	0.3	Survey ENE of Barrow 71°42' 155°08'	4	77	Projection experiment
30 May	2			0	0		No projections due to unstable ice conditions	80% Lead partially blocked by pans	Clear	2.1			Survey ENE of Barrow	0	0	

* Numbers in parentheses indicate whales observed during ferry flights.
** Numbers in parentheses indicate additional whales seen from the aircraft that were also seen from the ice-based camp.

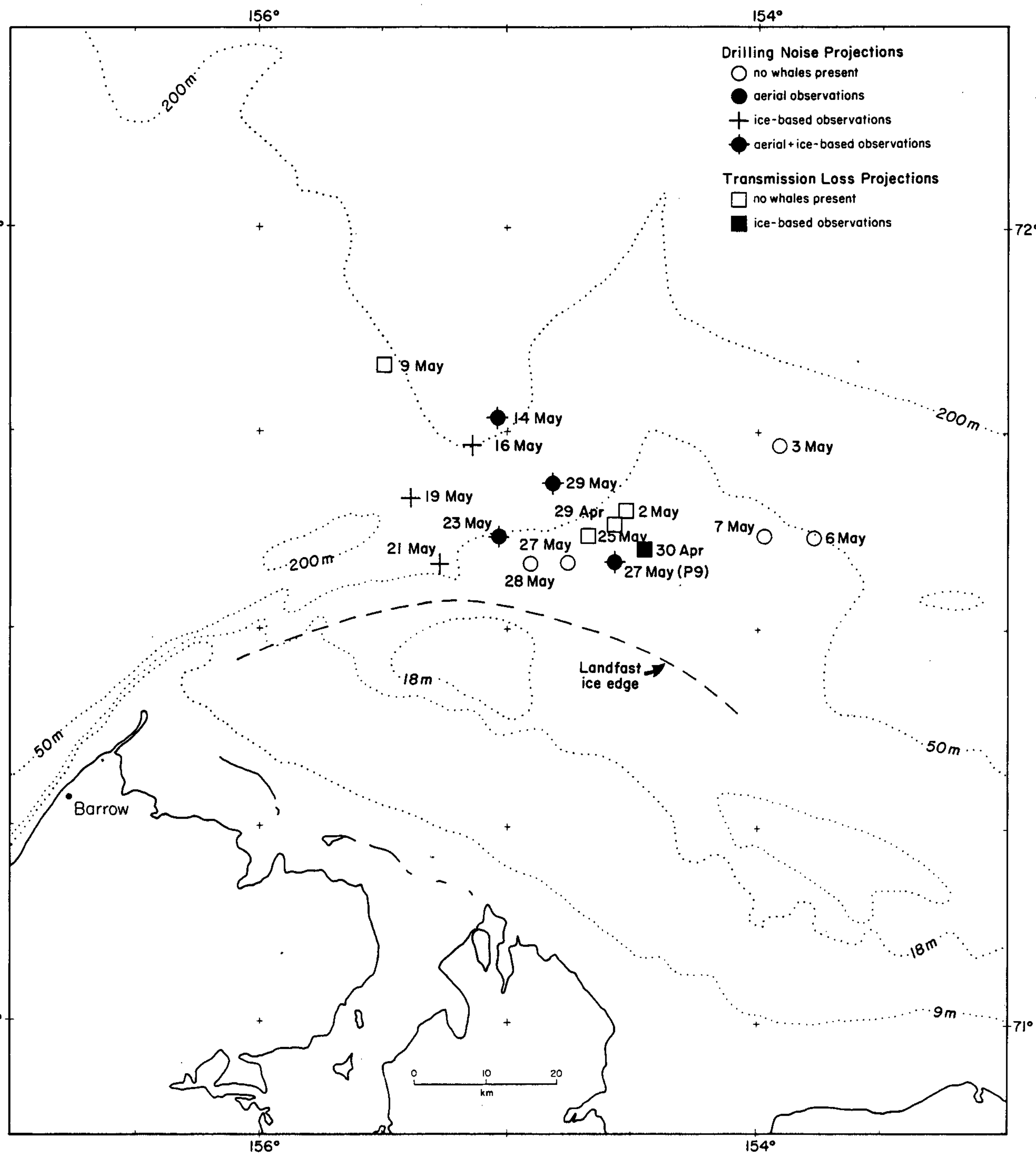


Fig. 19. Locations where ice-based crews conducted transmission loss tests or broadcast drilling sounds, 29 April-29 May 1989. Locations are approximate because of ice drift during the course of each day's work.

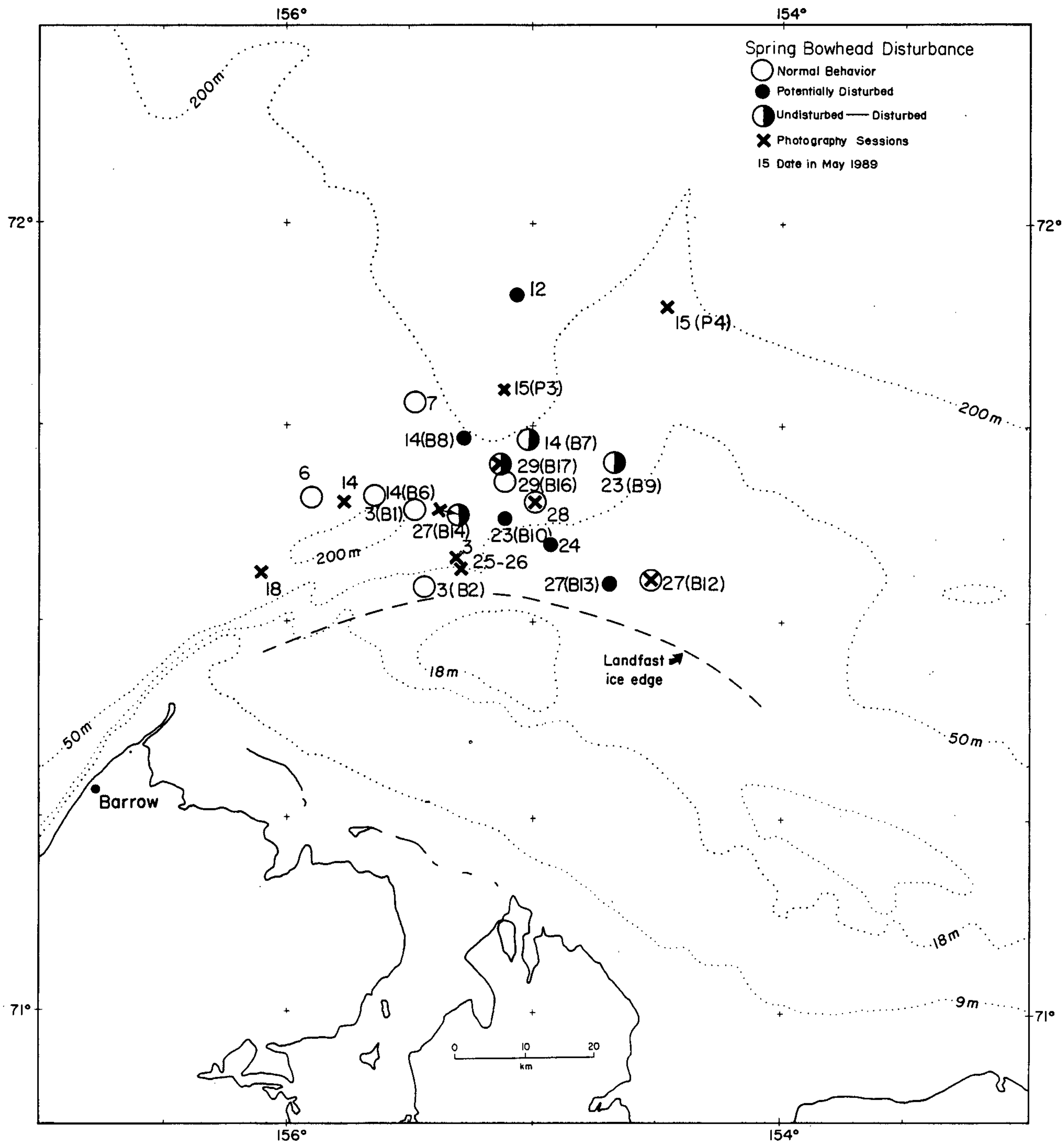


Fig. 20. Locations where behavior of bowhead whales was observed and vertical photographs were obtained by the aerial crew, 3-29 May 1989. Numbers outside parentheses indicate the date (in May 1989). Numbers in parentheses refer to behavior observation session numbers in Table 4 (prefixed by a B) or photo session numbers (P) where more than one occur on the same day.

On 3 May the ice-based crew projected drilling sounds into a recently refrozen lead found amidst the pack ice the previous day (Fig. 19). However, no whales were seen near the projector. After conducting extensive surveys near the projector site and not finding any bowheads, the aerial crew observed bowheads engaged in various activities closer to Barrow (Table 4, Fig. 20). About 25 bowheads were seen; this was the second-highest daily total for the entire field season. Most of the whales were migrating through narrow intermittent leads, which made it impossible for us to observe specific whales for prolonged periods. Playback experiments were not possible in this area because it was less than 60 km from Pt. Barrow.

Low ceilings and poor visibility prevented useful work on 4 and 5 May. However, on 5 May the aircraft crew conducted a low-level survey to monitor ice conditions and to select a potential site for an experiment the next day.

The weather cleared at Barrow on 6 May, but low cloud persisted east of longitude 155°W. The ice-based crew projected drilling sounds into an open lead amidst the pack ice and saw no whales. Because of the low ceilings at the projector site, the aerial crew conducted behavioral observations of bowheads closer to Barrow where the ceiling was higher but where drilling sounds could not be projected into the water.

The weather was clear and cold on 7 May and again little open water and few whales were found. The ice-based crew set up the sound projector along a refrozen lead in the pack ice, but saw no whales. After finding no whales near the projector, the aerial crew observed the behavior of three migrating and resting bowheads elsewhere.

Cold temperatures and light winds persisted on 8-10 May, and the few small open water areas that had been present froze. No bowheads were seen by the aerial crew on 8 or 9 May. The ice-based crew conducted a fourth TL test far offshore along a thinly refrozen lead. The ice was much smoother at this TL site than at previous sites.

From 11 to 13 May the weather was poor with low ceilings, fog and light snow. Leads were starting to develop in the offshore pack ice. Another lead started to develop near the edge of the landfast ice off Barrow, but did not extend east of Pt. Barrow. Few bowheads but numerous white whales were seen during surveys conducted by the aerial crew.

The weather cleared on 14 May, and the projector was set up along a long lead oriented NNE-SSW through the pack ice (Fig. 19). Large numbers of both bowheads and white whales were found in the vicinity. This was the first occasion when all of the factors necessary for a playback experiment were present at the same place and time, *viz* an area of open water 60+ km beyond Pt. Barrow, whales in that area, and cloud ceiling high enough (≥460 m) to allow behavioral observations from the air. The aerial crew observed two bowheads as they migrated from 4.7 to 0.5 and 0.9 km from the operating projector. Numerous white whales were also observed as they approached and passed the operating projector.

Table 4. Summary of aerial behavioral observation sessions, 1989.

Date 1989	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads: Circle	No. of Bowheads: Area	General Activity	Predominant Orientation	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice: in circle	% Ice: overall
3 May	1	71°33'-155°28'	16:13-17:36	3-5	15	some migrating slowly, some sexual activity	mostly E	slow	unknown	none	40	0	85	98
3 May	2	71°39'-155°30'	18:11-19:15	3	3	1 water-column feeding, 2 resting	variable	zero-resting	2 adults 1 small sub-adult	none	190	0	95	98
6 May	3a	71°40'-155°57'	15:53-16:34	4	9	probably migrating	NE	medium	unknown	none	120	0	95	99
	3b	71°40'-155°55'	16:55-17:05	2	9	probably migrating	NE and S	medium	unknown	none	130	0	95	99
	3c	71°39'-155°59'	17:12-18:10	3	9	sexual activity	variable	slow-medium	adults	none	150	0	95	99
7 May	4	71°47'-155°29'	15:58-17:25	3	3	migrating and resting	NNW	zero-medium	unknown	none	260	0	99	>99
12 May	5	71°55'-155°04'	12:55-13:01	1	1	migrating	NE	medium	unknown	potential aircraft	280	1	85	95
14 May	6	71°40'-155°40'	10:34-11:08	3	8	no forward motion-slow	NE to SW	zero-slow	unknown	none	205	1	80	85
14 May	7	71°44'-155°01'	11:29-14:47	3	6	migrating - one whale breaching	NE	medium	adults plus subadults	none to 11:58 *Karluk* play-back after 11:58	170	2	35	85
14 May	8	71°38'-71°50' 154°45'-155°50'	16:37-18:12	var.	var.	probably migrating	ENE	slow-medium	unknown	potential aircraft	160-233	1	90-95	85

Continued...

Table 4. Concluded.

Date 1989	Behavior Obs. Sess.	Location	Obs. Period	No. of Bowheads: Circle	No. of Bowheads: Area	General Activity	Predominant Orientation	Predominant Speed of Travel	Size Classes	Disturbance	Water Depth (m)	Sea State	% Ice: in circle	% Ice: overall
23 May	9	71°42′-154°41′	12:22-14:32	1	1	migrating	E	medium	unknown	aircraft to 12:40; post-aircraft to 13:10; then none; TL 13:59-14:09; then distant *Karluk* playback	72	1	90	80
23 May	10	71°38′-155°07′	15:40-18:02	1-3	4	2 migrating 2 local movement	W and SE	slow	3 adults 1 calf	*Karluk* playback	90-115	1	80	80
24 May	11	71°36′-154°56′	19:12-20:17	2	4	migrating	NE	slow-medium	1 adult, 1 calf 2 unknown	potential aircraft disturbance	42	0	85	80
27 May	12	71°33′-154°33′	9:22-11:47	4	6	migrating	variable NE to SE	slow-medium	2 adult-calf pairs	none	42	1	50	80
27 May	13	71°33′-154°42′	12:47-14:58	2	2	migrating	variable NE to S	slow-medium	adult/calf	*Karluk* playback Sonobuoy drop at 13:30	42	1	65	80
27 May	14	71°38′-155°18′	19:29-20:23	2	4	local movement	variable	slow	adult/calf	none to 20:11 Sonobuoy drop after 20:11	140	0	0	80
28 May	15	71°39′-155°00′	11:46-12:30	2	3	local movement	SW to NW	slow	adult/calf	none	95	1	80	80
29 May	16	71°42′-155°08′	10:28-10:46	2	2	local movement	SE to S and W	slow	adult/calf	none	160	1	85	80
29 May	17a	71°42′-155°08′	12:20 13:58	2	2	local movement	SE to SW	slow	adult/calf	none to 12:53; TL 12:53-13:02; then distant *Karluk* playback. Sonobuoy drop at 13:21	170	0	85	80
	17b	71°42′-155°08′	14:50-15:23	2	2	local movement	S to SW	slow	adult/calf	distant *Karluk* playback	160	1	85	80

The ice-based crew observed a single white whale by theodolite for 25 min as it approached and retreated from the projector. Several additional bowheads and white whales were observed for briefer periods by the aerial and ice-based crews. Aerial observations of whales passing the projector were curtailed when the cloud ceiling descended below 460 m during the afternoon. Even so, more bowheads and white whales were seen on this date than on any other (Table 3).

The ceilings were low and the visibility was poor for most of 15 May. In the evening, the visibility improved and the aerial crew conducted a reconnaissance ENE of Barrow. Five bowheads and 133 white whales were seen.

On 16 May, the visibility was generally good, but ceilings were too low for aerial observations. The ice-based crew observed a mother/calf bowhead and three white whales, which were potentially disturbed by the Bell 212 helicopter during deployment of equipment. White whales (n=16) were observed before the projector was started, but no whales were sighted while the projector was operating.

On 17 May, the ceiling was low 60+ km east of Pt. Barrow where we could conduct playback experiments. Therefore, the ice-based crew deployed hydrophones from an ice pan 55 km NE of Barrow to measure the levels and characteristics of underwater sounds from Bell 212 helicopter overflights at different altitudes.

On 18 May, the ceiling was again too low to conduct aerial observations of whale behavior. Leads through the offshore pack ice were starting to open again, but the only bowheads found during an aerial reconnaissance (n=15) were in the lead near the fast ice edge 30 km NE of Barrow. We took 13 vertical photographs of these whales.

The ceilings remained low on 19 May, again preventing aerial observations of behavior. However, the ice-based crew set up the sound projector on the pack ice and projected drilling sounds into an L-shaped lead. Four bowheads and two white whales were observed approaching the operating projector. A theodolite was used to track these whales. One bowhead approached to within 100-120 m of the operating projector.

From 20 to 22 May, the ceilings remained low and visibility was poor in snow and fog. Strong winds moved the offshore pack ice, resulting in more open water amidst the pack ice. The lead along the fast ice edge finally extended eastward into our study area. Aerial surveys on 20 and 21 May detected no bowheads and few (22) white whales. On 21 May, the ice-based crew set up the projector on the pack ice edge along the north side of the main nearshore lead between the pack and landfast ice. However, no bowhead or white whales were seen while the projector was operating.

On 23 May, the ice-based crew set up near the east end of an area of open water area amidst the pack ice a few kilometers north of the nearshore lead. Whales exposed to noise from the projector were observed from both the ice and the observation aircraft. A mother and calf bowhead heading north and west away from the projector were observed when the projector was broadcasting drilling sounds. Two additional bowheads were observed as close as 2.3 and 2.4 km from the operating projector, migrating eastward past it. About 50 white whales were watched as they migrated from 5 km WNW to 0.5 km NNE of the operating projector. They then hesitated for 12-20 min, dove under the pan supporting the projector, surfaced 300-600 m SSE to SE of the projector, and continued migrating E.

Low ceilings persisted throughout 24 May. The aerial crew conducted a low level survey ENE of Barrow and sighted numerous white whales and several bowheads. We tested the operation of a DIFAR (directional) sonobuoy from the Twin Otter near 4 bowheads and 11 white whales.

On 25 May, the ice-based crew set up the projector on the pack ice just north of the nearshore lead, but no whales were sighted nearby. Hence, a fifth sound transmission loss test was conducted along the north edge of the nearshore lead. The aerial crew sighted 11 bowheads (including 5 cow/calf pairs) and 51 white whales in or near the nearshore lead closer to Barrow. The cow/calf bowheads were all photographed. Low ceilings and fog prevented work on 26 May.

On 27 May, the projector was initially set up along a secondary lead ~4 km north of the main nearshore lead. The projector was again set up on the pack ice because the bowheads seen ~60 km beyond Pt. Barrow in mid-late May had all been either in the pack ice or along the north edge of the nearshore lead--none were on the south side of the nearshore lead. On 27 May, the ice-based crew saw 14 white whales but no bowheads pass the projector. All bowheads sighted by the aerial crew were moving along the north edge of the main nearshore lead, about 4 km south of the projector. Hence, during late afternoon the projector was moved to a large pan along the north side of the lead. In the evening, no whales were found near the projector operating at its new location, so the aerial crew observed a mother/calf pair ~20 km WNW of the projector. This same cow/calf pair was observed on 28 and 29 May (identity photographically confirmed).

Weather conditions were ideal on 28 May. The projector was set up on the pack ice near the north side of the main E-W nearshore lead. However, no whales approached the projector. The aerial crew observed the behavior of a mother/calf pair 13 km NW of the projector. Late in the day, the underwater sounds from both the Bell 212 helicopter and the Twin Otter were measured by flying at several altitudes over hydrophones deployed from the ice camp.

Fieldwork had been scheduled to end on 28 May. However, at that time the ice and weather conditions were improved from those in early and mid-May, and at least a few bowheads and white whales were still migrating through the study area. Hence, after consultation with MMS, we decided to continue fieldwork for two or three more days.

On 29 May, the weather was again good. The projector was set up on the largest available lead amidst the pack ice a few km north of the main nearshore lead. Two white whales passed the projector before it was operating, but no whales were seen near the projector afterwards. A mother/calf bowhead and 50 migrating white whales were observed about 10 km west of the projector, where drilling sounds were not detectable. The bowheads remained in that area through the day.

The weather was clear on 30 May, but it was windy and the ice conditions had changed dramatically. The main nearshore lead was partially blocked by large pans and the pack ice was shifting rapidly. The ice-based crew set up the projector on a large pan along the north side of the flaw lead. However, no whales were seen in the area by either crew. Because of the unstable and dangerous ice conditions, the ice-based crew returned to Barrow without projecting drilling sounds.

Summary of Field Activities

The helicopter-supported crew worked from the ice on 18 days between 29 April and 30 May. They conducted sound transmission loss experiments on five days, aircraft noise measurements on two days, and projected drilling noise into the water for several hours on each of 11 days (Table 3). On five of these days, we observed bowhead whales that were within the area ensonified by the projector: during the TL test on 30 April and the periods with drilling noise on 14, 19, 23, 27 May. On four days, white whales were also observed near the operating projector (14, 19, 23 and 27 May). Whales near the projector were observed from the ice on 30 April and 19 May, and from both the ice and the air on 14, 23 and 27 May. Overall, the aircraft crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations on 10 days, and photogrammetry on 8 days (Table 3).

The absence of a nearshore lead until 20 May in 1989, and the absence of a consistent whale migration corridor even after that date, reduced the number of opportunities for observations of whales passing the sound projector. By the last week of May, when weather and ice conditions were greatly improved, few whales were passing. All ice-based work had to be done from the pack ice rather than from the edge of the landfast ice. This was necessary because there was no lead along the edge of the landfast ice until 20 May, and even then the whales continued to migrate farther offshore. Nonetheless, useful data were obtained on the reactions of bowhead and white whales to drilling noise, and most of the desired physical acoustic data were collected. The availability of full-time helicopter support allowed us to work from different locations on the moving pack ice each day.

PHYSICAL ACOUSTICS RESULTS

Industrial Noise

Specific objective 1 was to record and characterize noise from a drilling operation on a grounded ice pad in shallow water during late winter. Specific objective 5 required study of noise received during helicopter overflights, and objective 6 required analyses of other components of the acoustic environment of whales during spring. Underwater noise from three sources was recorded and studied during fieldwork in 1989: noise from drilling on the *Karluk* artificial ice island near Prudhoe Bay, noise from a Bell 212 helicopter flying over pack ice, and noise from a deHavilland Twin Otter flying over pack ice.

Drilling Noise from *Karluk* Ice Platform

Noise from the *Karluk* drillsite (described under "Methods", p. 44) was recorded on 30-31 March at distances ranging from 0.20 to 5 km southeast and 0.13 to 2 km northwest of the drillrig. These underwater recordings were obtained by drilling through the stable fast ice surrounding the grounded ice pad on which the rig was operating.

The sound energy was strongest at frequencies below about 300 Hz (Fig. 21A, 22A). The received level of the sounds was greatly reduced by the time they had propagated 2 km from the rig through the shallow (6-7 m), ice-covered (2 m) inshore water (Fig. 21B, 22B). At 2 km, the only noise components that were well above the natural background level were a strong tone at 25 Hz and a weaker tone at 294 Hz. The source of the 25 Hz tone is unknown. It appeared in all spectra of drilling sounds except those at 130 and 200 m--the shortest ranges. The 294 Hz tone did not appear in the spectra for other ranges.

Figure 23 is a waterfall spectrogram of a three-minute segment of *Karluk* drilling sounds recorded 130 m northwest of the rig. This was the 3-min segment projected during playback experiments. Although the energy is generally concentrated at the same frequencies throughout the 3-min period, the spectrum levels vary with time. Note, for example, the increase in amplitude of the strongest tone, at 83 Hz, near the end of the 3-min segment. The consistent lack of significant energy at frequencies above 320 Hz is notable. For comparison, Figure 24 presents a waterfall spectrogram of a 3-min segment of icebreaker sounds. The *Karluk* drilling sounds were much more consistent over time, and were confined to lower frequencies (Fig. 23 vs. 24).

The *Karluk* data were collected with a recording system whose response diminishes severely at frequencies below 20 Hz. We calibrated our system down to 10 Hz and applied correction factors to compensate for the variable frequency response. However, the accuracy of the results below 20 Hz is uncertain, and we have no data below 10 Hz. The spectra of the *Karluk* sounds indicate that the sound level did not diminish at frequencies down to at least 20 Hz. The tape recorder and hydrophone responses limit knowledge of infrasonic sound energy at frequencies below 10 Hz. Some machinery on the rig has operational periodicities at much lower frequencies, e.g. pumps with piston rates near 1 or 2 Hz. These infrasonic components may be strong. They are not expected to propagate through the shallow water around the *Karluk* site, but propagation through the bottom might make such sounds detectable at significant distances from the rig. In future, it will be desirable to use a hydrophone and recording equipment that can provide calibrated measurements of infrasounds. However, the inability to record low-frequency (<10 Hz) components in 1989 did not affect the playbacks. The main factor limiting playback fidelity was the inability of any practical projector to project significant sound energy below about 20 Hz.

The overall level of the drilling sounds diminished rapidly with increasing range from the *Karluk* rig (Fig. 25). The broadband (20-1000 Hz) level diminished to about the background ambient level within ~2 km. On the SE leg, the received level at range 5 km was 2 dB higher than that at 2 km (Fig. 23), indicating that broadband measurements at both ranges were dominated by the background noise, not the drillrig. The recordings southeast of the rig, and some of those to the northwest, were made on one afternoon. Other recordings on the northwest leg were made during the following morning. Weather conditions, water depths and ice conditions were about the same and the rig was drilling on both occasions. However, there might have been some changes in the machinery operating at various times.

Received levels 0.13 to 1 km from the rig were used to derive a simple equation for broadband received level (20-1000 Hz) vs. range. We merged the data from the SE and NW legs, excluding the "rig not drilling" data. The best-fit equation including only a logarithmic spreading loss term is as follows:

$$\text{RL (dB re 1 } \mu\text{Pa)} = 96.7 - 31.0 \log R$$

where R is the range in km. If simple spherical spreading were occurring, the logarithmic term would be 20 log R. The higher loss rate seen near *Karluk* is the result of the low frequencies in shallow water and the shallow hydrophone.

<u>Aircraft Noise</u>

Measurements of underwater noise during flyovers by a Bell 212 helicopter were made on 17 and 28 May. On the latter date, similar measurements were made for the Twin Otter fixed-wing aircraft used for aerial observations of bowheads. The objectives were to investigate the effects of

- aircraft type,
- aircraft altitude,
- flight direction relative to orientation of ice edge, and
- receiving hydrophone depth

on measurements of

- the spectral characteristics and levels of underwater noise,
- the rate of change of the sound levels as the aircraft approached and flew away, and
- the duration of audibility of the sounds.

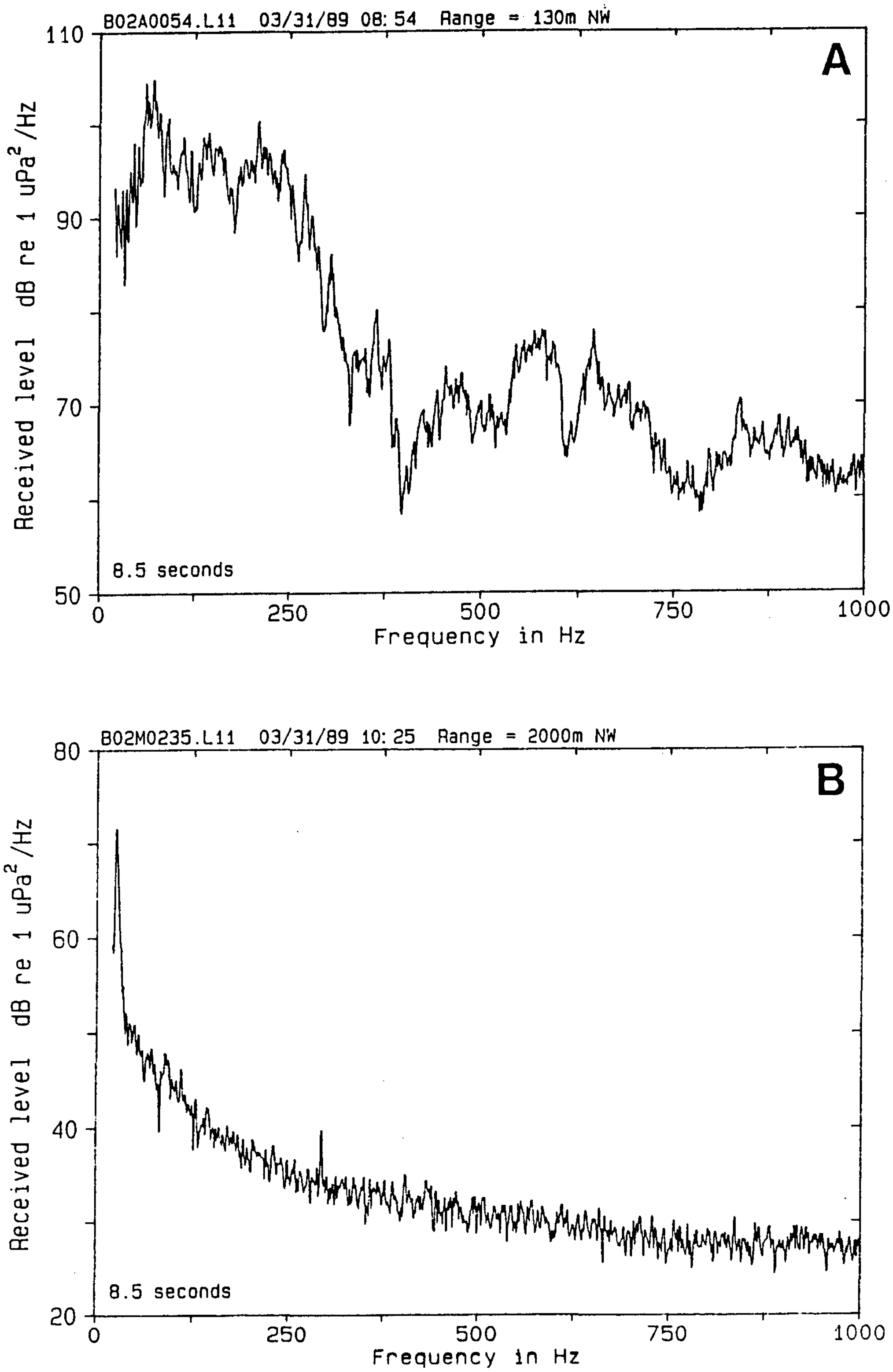


Fig. 21. Low frequency spectra (10-1000 Hz) of drilling sounds received at ranges 130 m (**A**) and 2000 m (**B**) from the actual *Karluk* drillsite. The tones in the 2000 m spectrum are at 25 and 294 Hz. See following Figure for 10-4000 Hz spectra.

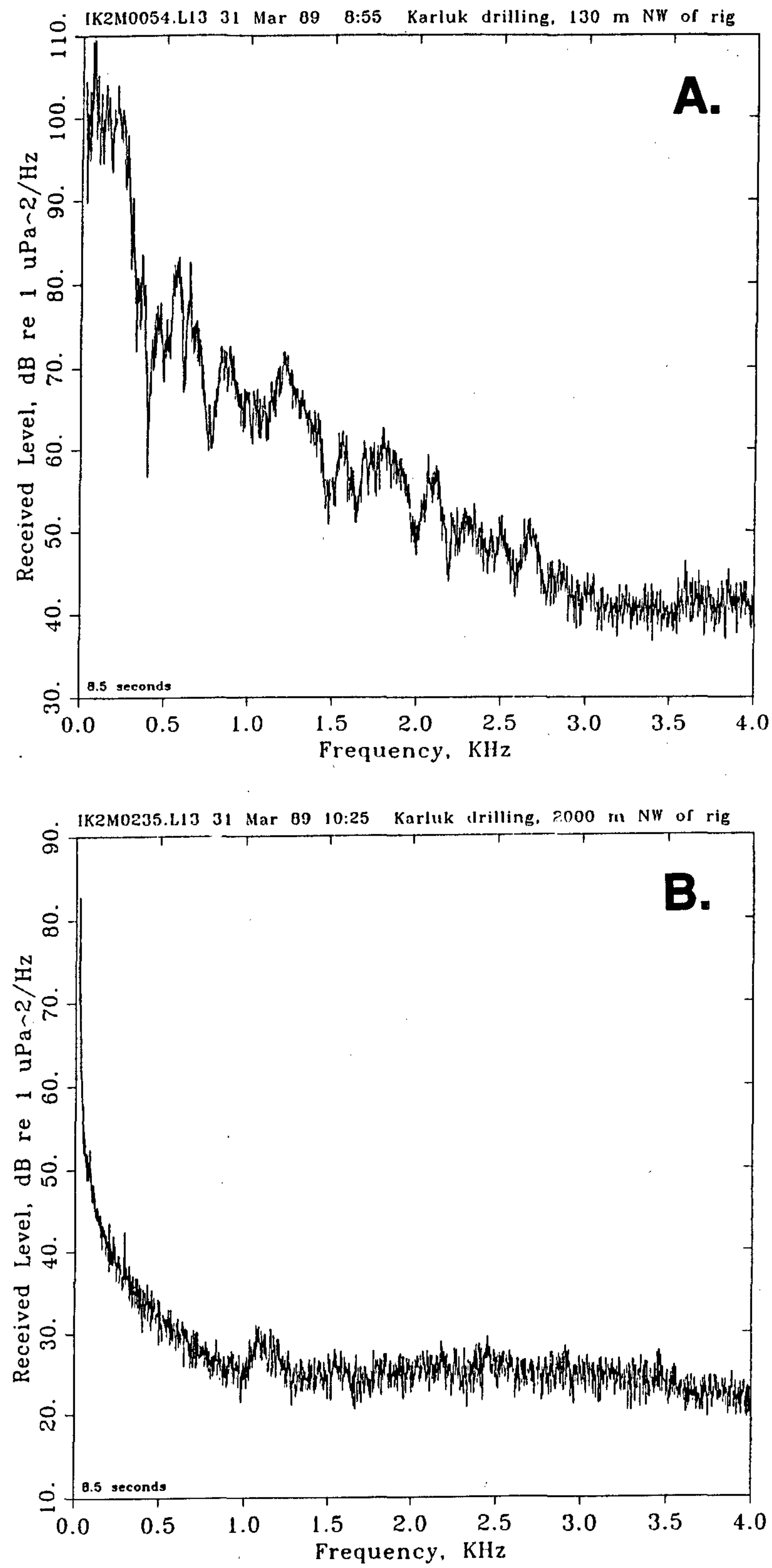


Fig. 22. Spectra (10-4000 Hz) of drilling sounds received at ranges 130 m (A) and 2000 m (B) from the actual *Karluk* drillsite. The respective 20-1000 Hz broadband sound levels were 125 and 87 dB re 1 μPa. See previous Figure for details at low frequencies.

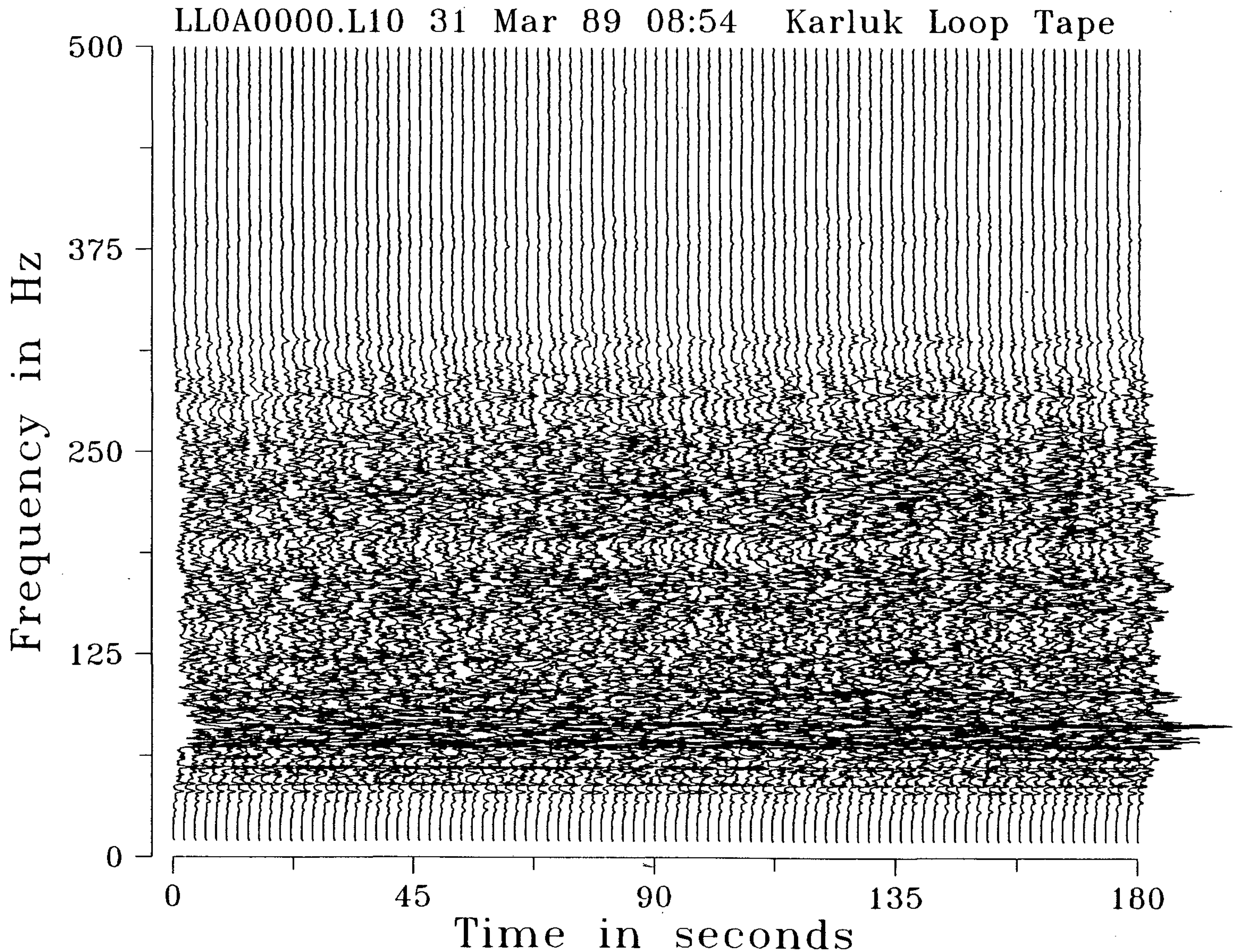


Fig. 23. Waterfall spectrogram for a 3-min segment of *Karluk* drilling sounds recorded 130 m NW of the rig, 31 March 1989. This was the 3-min segment used during playback experiments.

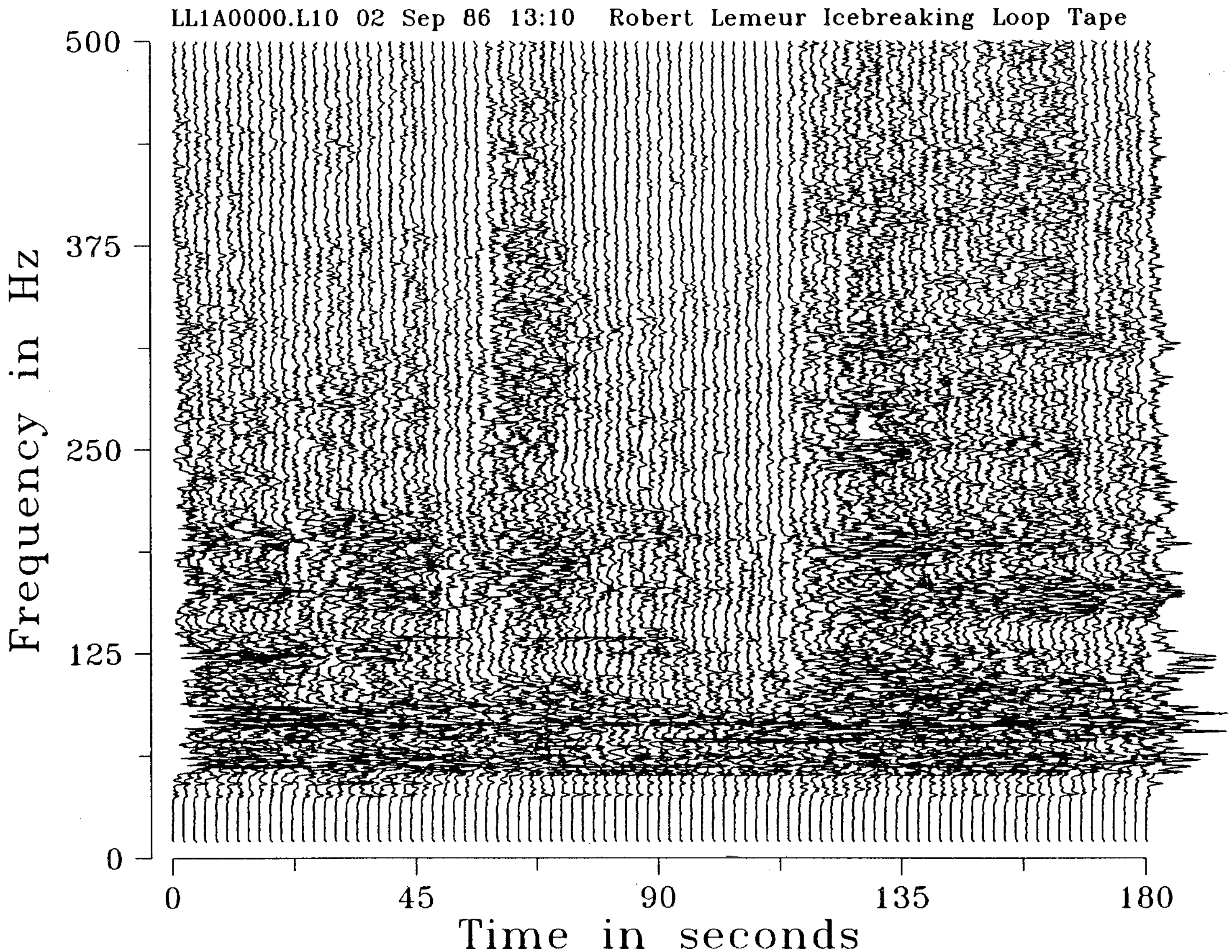


Fig. 24. Waterfall spectrogram for a 3-min segment of icebreaker noise, based on a recording of sounds from *Robert Lemeur* alternately backing up and ramming forward at range 460 m; hydrophone depth 18 m (data of Greene 1987a).

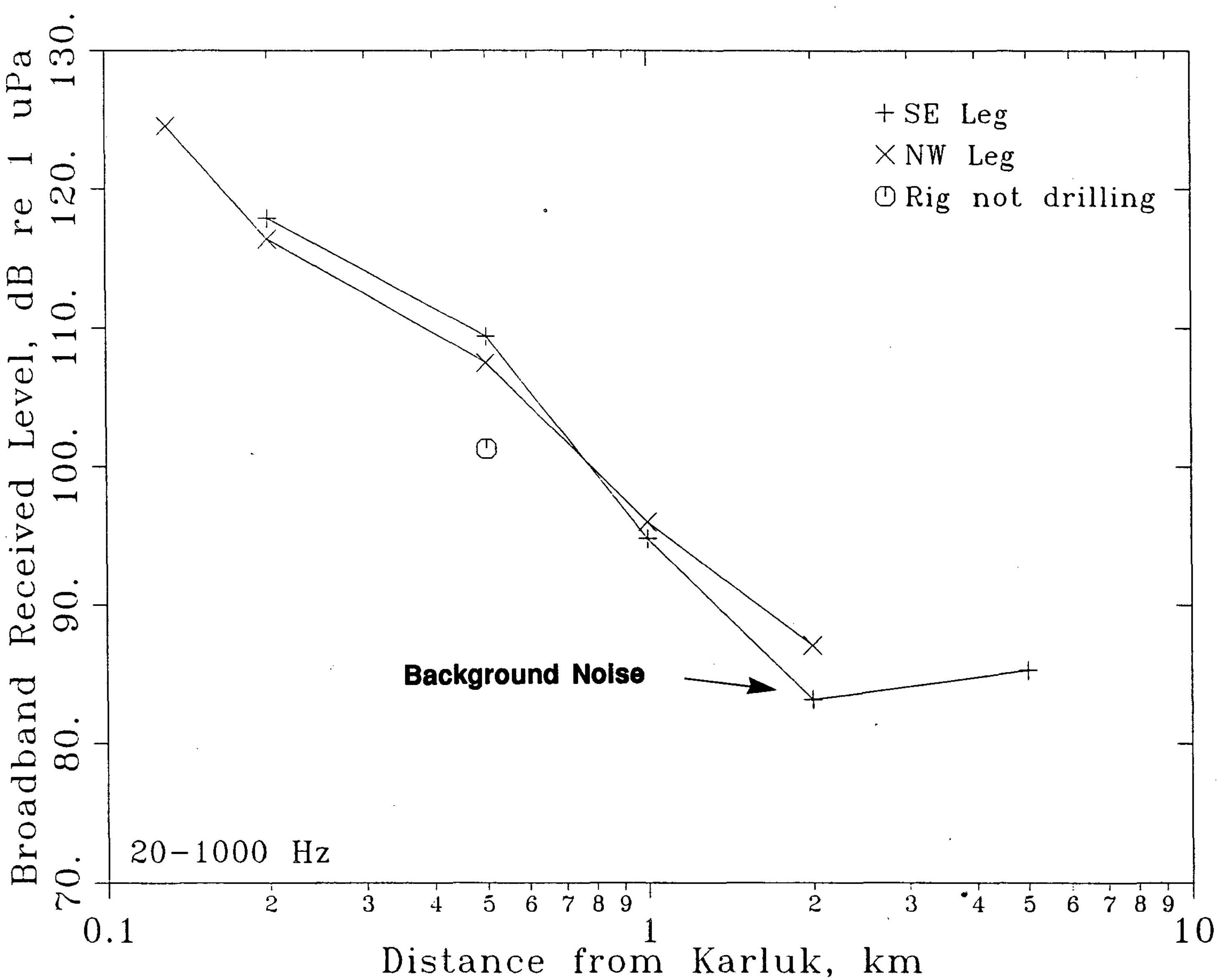


Fig. 25. Broadband (20-1000 Hz) received level vs. range from the *Karluk* drillsite engaged in drilling (+, x) and not drilling (o).

Bell 212 Helicopter.--This twin-turbine aircraft has a two-bladed main rotor turning at 324 rpm and a two-bladed tail rotor turning at 1650 rpm. The corresponding fundamental shaft frequencies are 5.4 Hz and 27.5 Hz; the fundamental blade frequencies are thus twice as high, 10.8 and 55 Hz. The blade frequencies, and to a decreasing degree their harmonics, are expected to have high sound levels. Figure 26A shows the sound spectrum for a 9-s period while the helicopter flew directly overhead at altitude 1,500 ft (460 m). Some of the peak sound levels and their frequencies were as follows:

Frequency (Hz)	Level (dB re 1 μPa)	Source of Tone
22.0	97	Main rotor blade, 2nd harmonic
32.0	88	Main rotor blade, 3rd harmonic
44.5	84	Main rotor blade, 4th harmonic
55.0	81	Main rotor blade, 5th harmonic and tail rotor blade, fundamental
57.0	85	Unknown

There are tones at various higher frequencies, but some of them appear in Figure 26A as narrow bands of frequencies. There are two reasons: Doppler shift during the 9-s analysis period spreads each of the higher-frequency tones across a noticeable range of frequencies. Also, the similar but not identical harmonic frequencies of the tail and main rotors produce closely-spaced tones, each smeared by Doppler shift. The 20-500 Hz band level for the Bell 212 sound spectrum shown in Figure 26A was 103 dB re 1 μPa.

Figure 27 shows waterfall spectrograms for overflights of the Bell 212 at low altitude (150 m, Fig. 27A,B) and higher altitude (460 m, Fig. 27C,D). Figure 27C,D depicts the same overflight as in Figure 26A. The upper and lower spectrograms show the sounds received simultaneously 3 m and 18 m below the water's surface. These graphs show the spectral composition and relative levels of the sounds over a 60-s period as the helicopter approached, flew directly overhead (at time 30 s), and flew away. The tonal sounds were stronger and detectable longer 3 m below the surface than 18 m deep, as predicted by theory (Urick 1972). It is interesting that the sounds ahead of the aircraft were stronger than those following it. Significantly more rotor blade sound energy is radiated ahead than behind. However, it may also be important that the helicopter was flying over open water while it was approaching, and over ice as it moved away. A pronounced Doppler shift in the frequencies of the tones was also evident as the helicopter passed overhead (Fig. 27). As expected, apparent frequencies decreased as the helicopter passed overhead.

The temporal characteristics of underwater sounds received from the passing helicopter depended strongly on its altitude, also as expected. The apparent duration of the sound increased as helicopter altitude increased, at least up to 1000 ft or 305 m (Fig. 28A,B). During a helicopter pass at 76 m ASL, its noise was not evident underwater until about 15 s before it passed overhead.

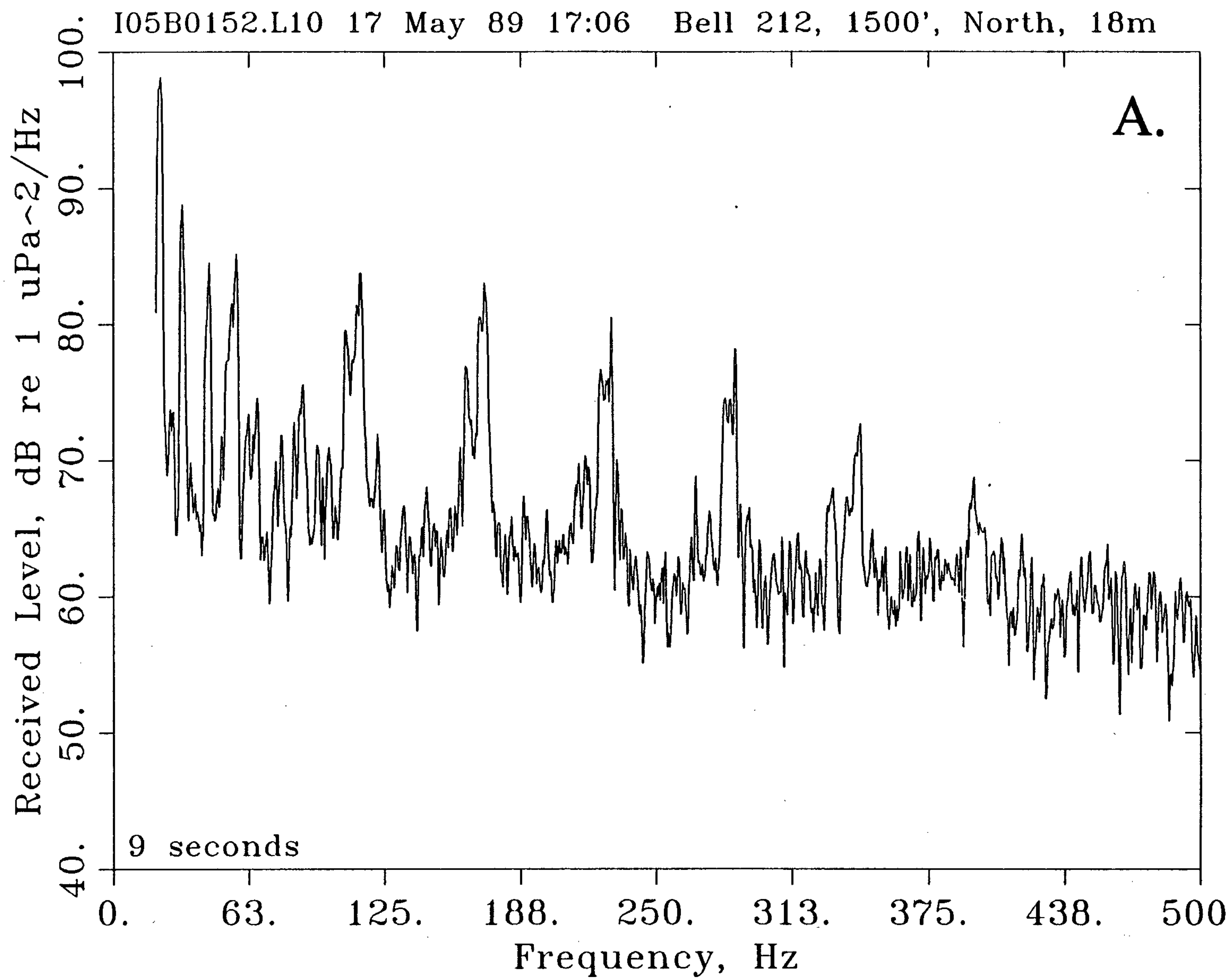


Fig. 26. Power spectrum for (A) Bell 212 helicopter and (B) Twin Otter, both flying at altitude 460 m (1500 ft) over a hydrophone at depth 18 m. Frequency resolution 0.5 s.

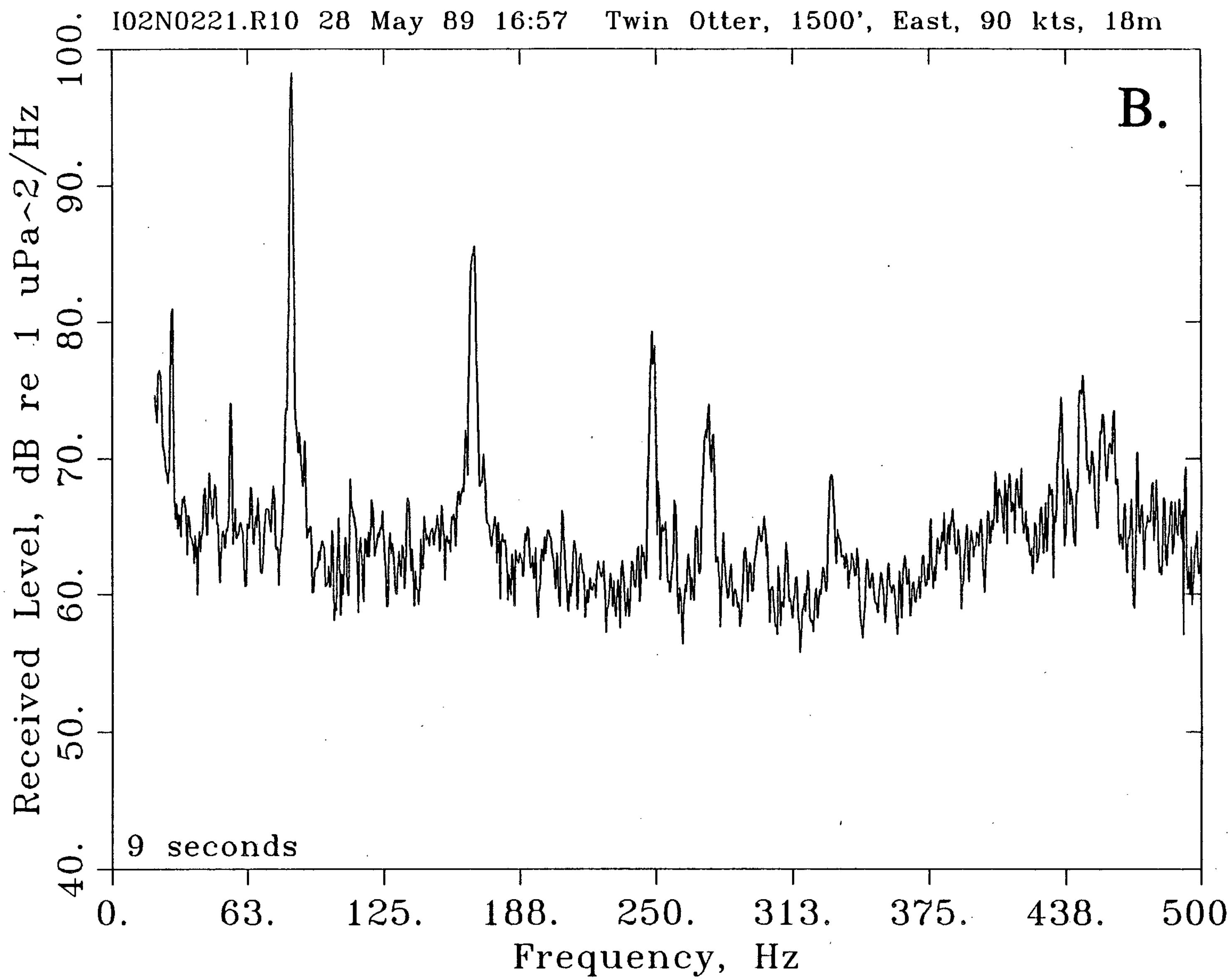
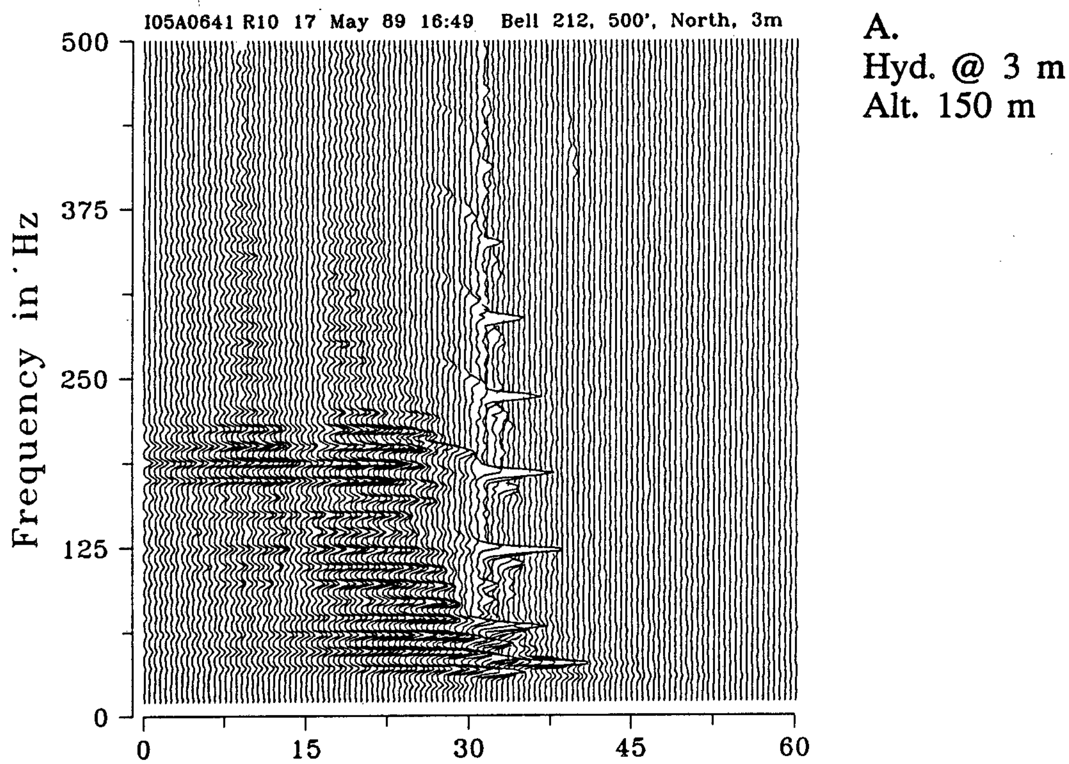


Fig. 26. Concluded.



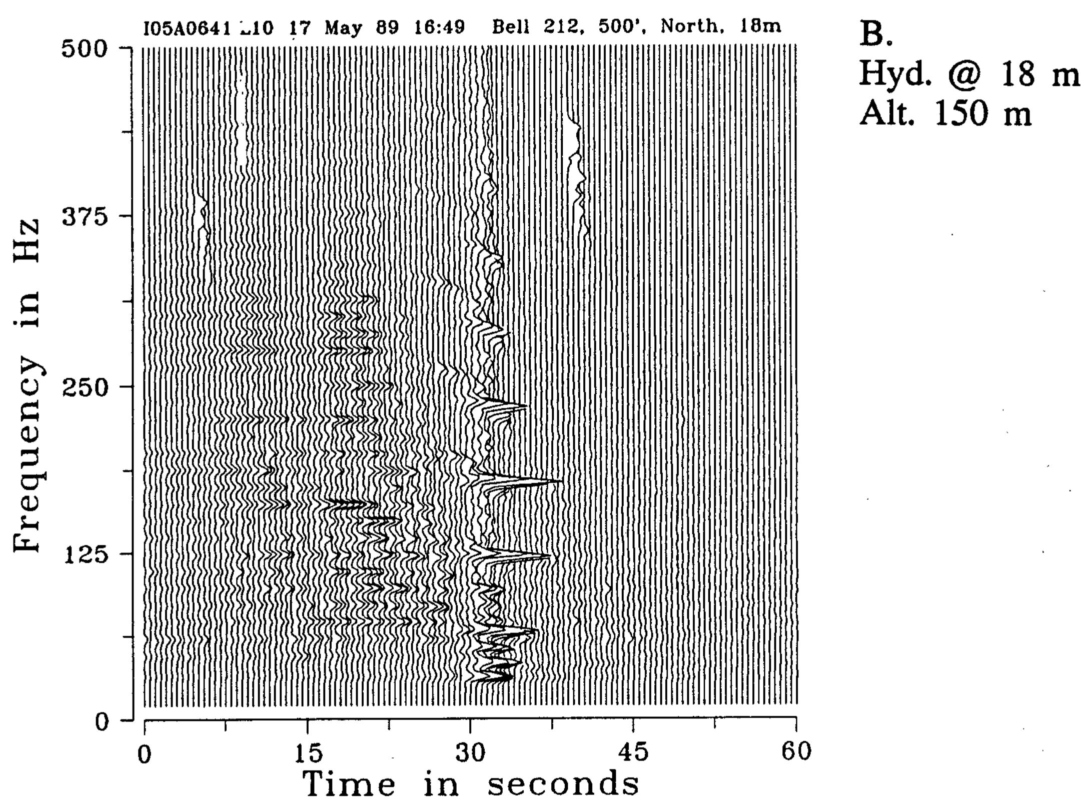
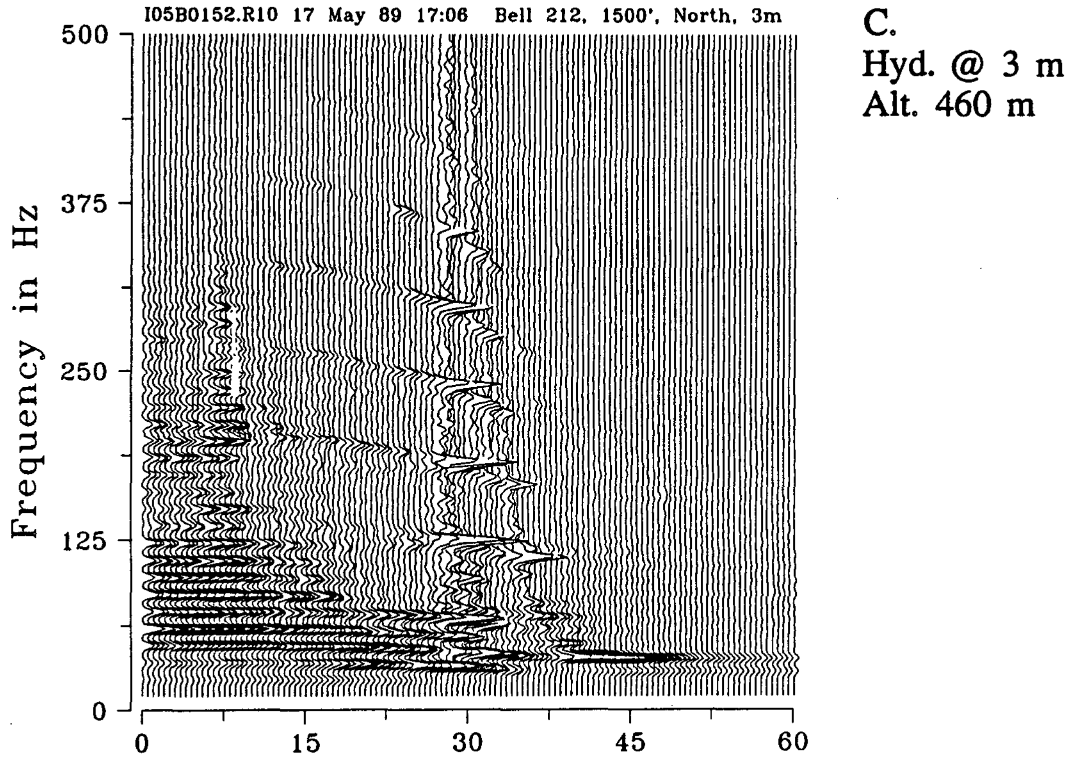
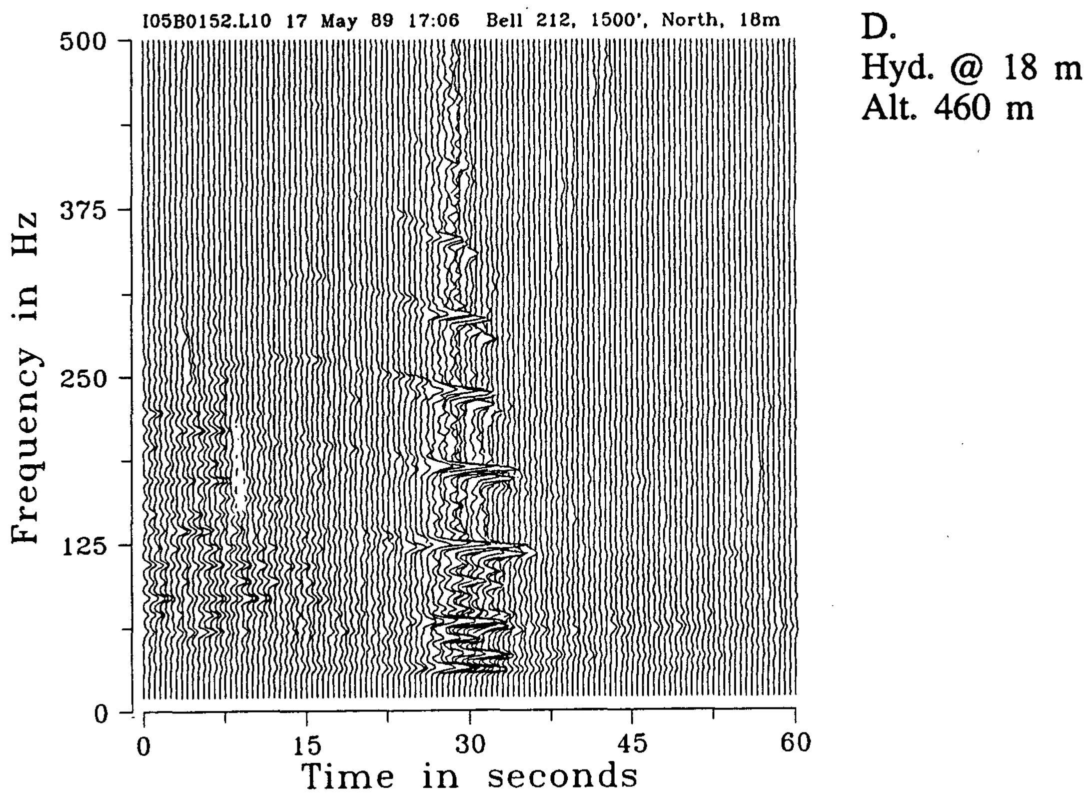


Fig. 27. Effect of receiver depth (3 vs. 18 m) and aircraft altitude (150 vs. 460 m) on the underwater sounds received from a Bell 212 helicopter flying towards, over, and away from the receiver, 17 May 1989. Water depth was ≈170 m.





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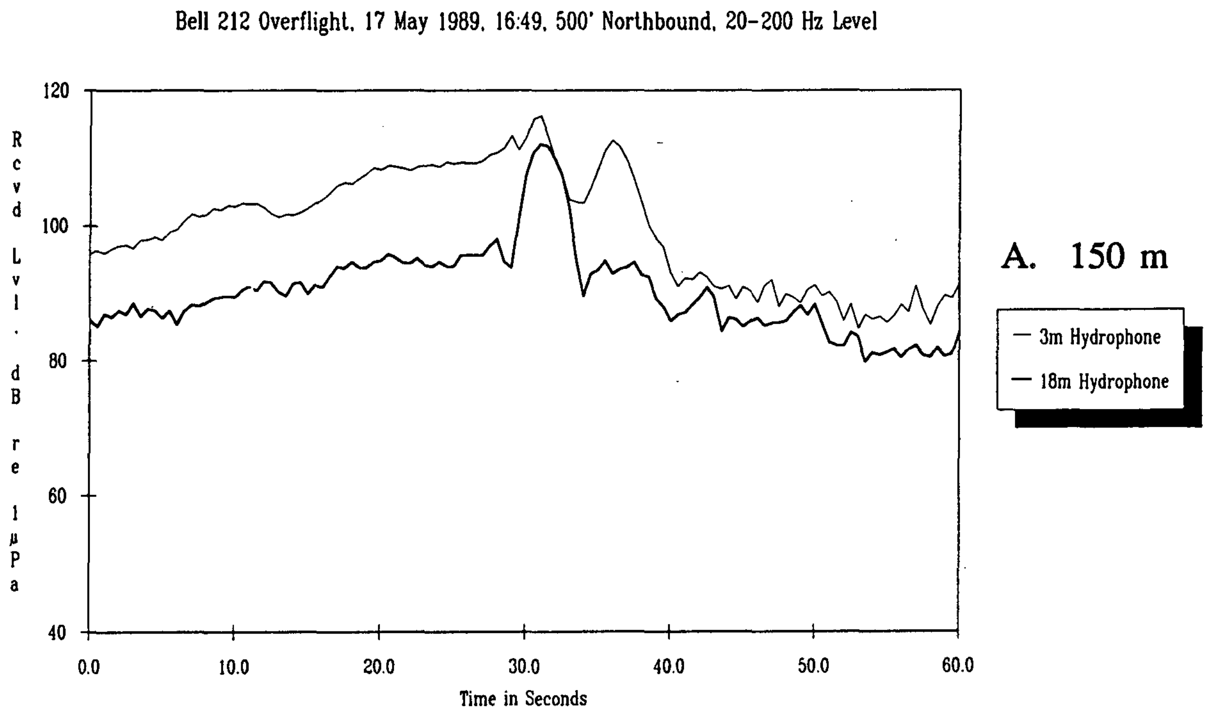


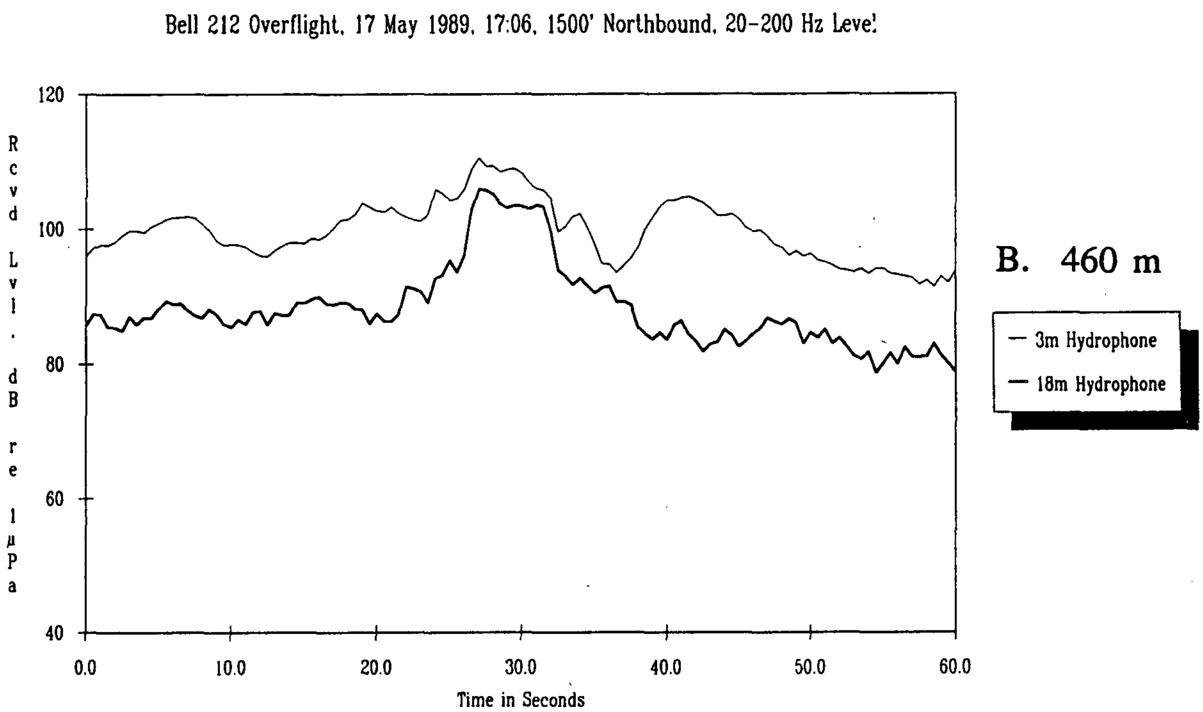


Fig. 28. Received levels of Bell 212 helicopter sound at depths 3 and 18 m as a function of time during overflights at altitudes (A) 150 m and (B) 460 m. Water depth was ≈170 m. The apparent anomalies are due to animal calls or ice sounds.

During passes at 150 and 305 m ASL, the received sound level was already elevated slightly about 30 s before the helicopter passed overhead.

Received levels at 3 m depth were higher than those at 18 m depth for most of each helicopter pass. However, the 3 m vs. 18 m difference was smaller or absent when the helicopter was directly overhead than when it was approaching or moving away (Fig. 28). The peak level, when the helicopter was directly overhead, was higher during the pass at 150 m ASL than during the pass at 460 m. The peak level tended to decrease with increasing aircraft altitude.

Most of these trends are consistent with expectation from theory and with the few measurements of underwater noise from aircraft published in the open literature (Urick 1972; Greene 1985; Greene *in* Richardson et al. 1989).

<u>Twin Otter</u>.--Twin Otter sounds contained fewer prominent tones than did Bell 212 helicopter sounds (Fig. 26B vs. A). This is partly explained by the presence of two sets of blades operating at widely different speeds on the helicopter. The Twin Otter is pulled along by two turbine-powered three-bladed propellers. The strongest tones from the Twin Otter, based on the analysis shown in Fig. 26B, were as follows:

Frequency (Hz)	Level (dB re 1 μPa)	Source of Tone
83.0	98	Blade rate, fundamental
165.5	84	Blade rate, 2nd harmonic
248.0	79	Blade rate, 3rd harmonic
273.0	72	Unknown
330.5	68	Blade rate, 4th harmonic

For a blade-rate fundamental at 83 Hz, the propeller shaft rate would be 1660 rpm. This is close to rates previously reported for Twin Otters (1625 and 1670 rpm, Greene 1982, 1985).

The 20-500 Hz band level for the Twin Otter spectrum in Figure 26B was 100 dB re 1 μPa, as compared to 103 dB for the corresponding Bell 212 sound (*cf.* Fig. 26A). Thus the helicopter was somewhat noisier than the Twin Otter.

The fundamental 83 Hz tone was at least faintly detectable for at least 30 s preceding and following Twin Otter overflights at both 150 and 460 m altitude (Fig. 29). Doppler shift was again evident. Some tones seemed slightly more prominent at 3 m than at 18 m depth. However, in contrast to the Bell 212 results (Fig. 28), overall received levels (20-200 Hz band) were similar at 3 and 18 m depth at most times during the Twin Otter overflights (Fig. 30). This may have been related to the stronger background noise levels during the Twin Otter overflights. The level when the Twin Otter was directly overhead was slightly higher when received at 18 m than at 3 m depth. As in the case of the Bell 212, the peak received level was slightly higher during the low altitude pass (150 m ASL) than during the higher pass (460 m).

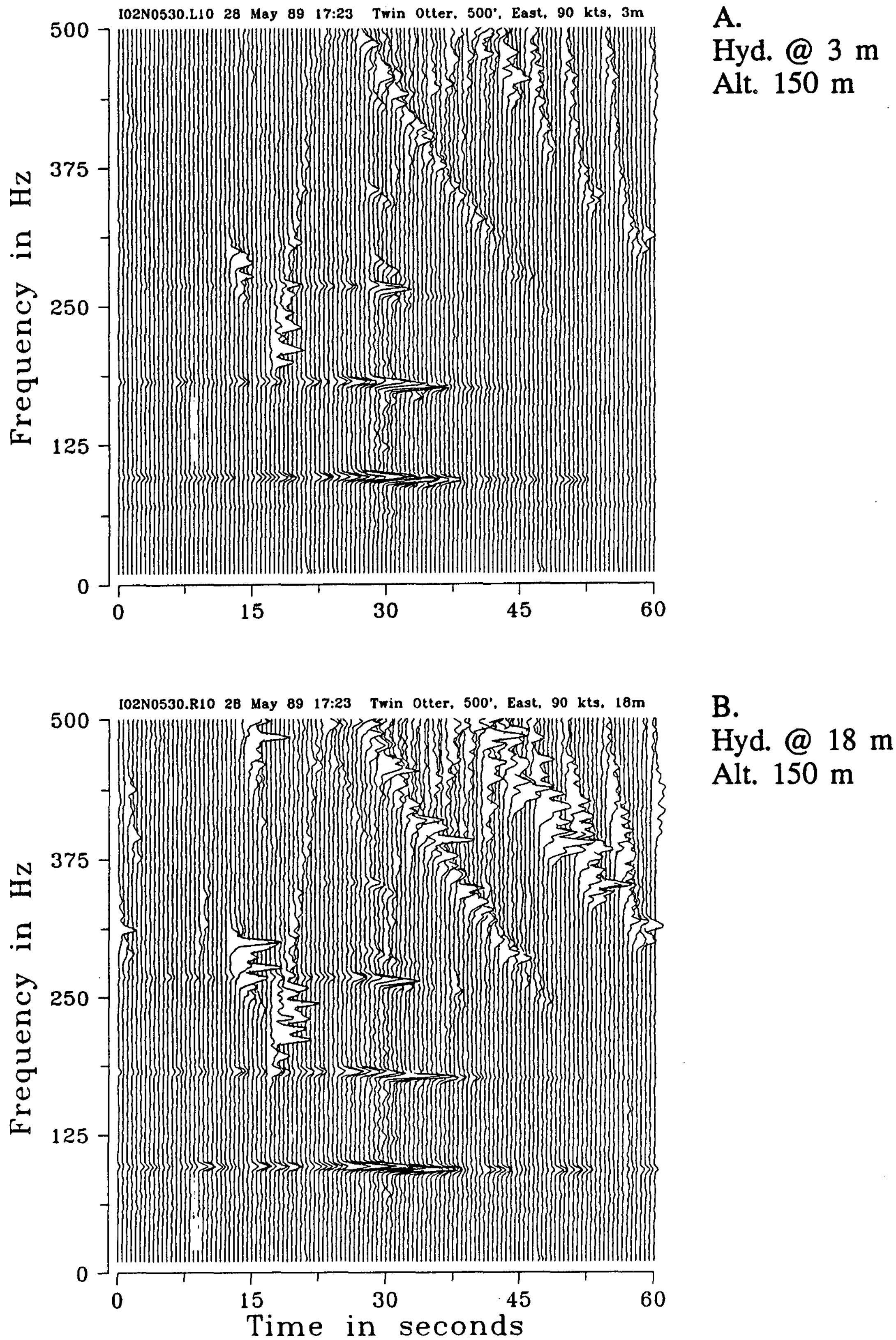
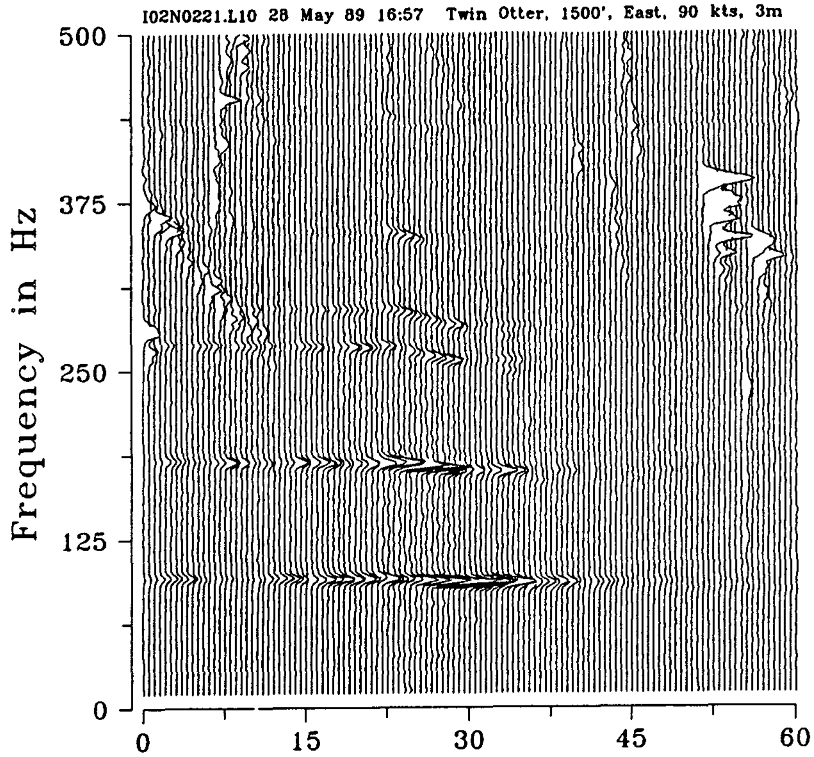
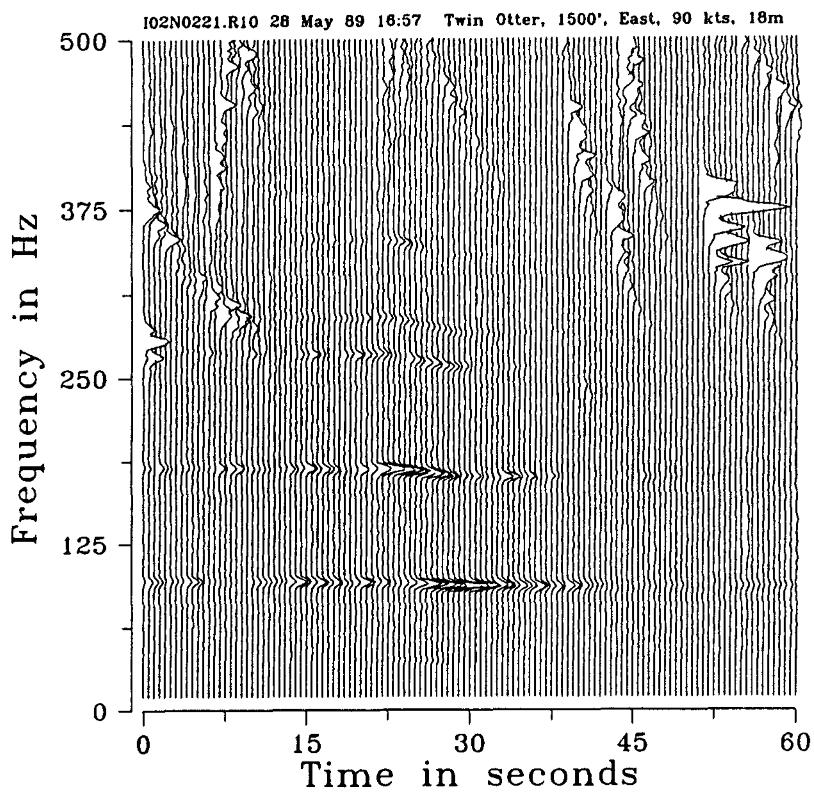


Fig. 29. Effect of receiver depth (3 vs. 18 m) and aircraft altitude (150 vs. 460 m) on the underwater sounds received from a Twin Otter aircraft flying towards, over, and away from the receiver, 28 May 1989. Water depth 34 m. The descending frequency sweeps above 300 Hz are bearded seal calls.

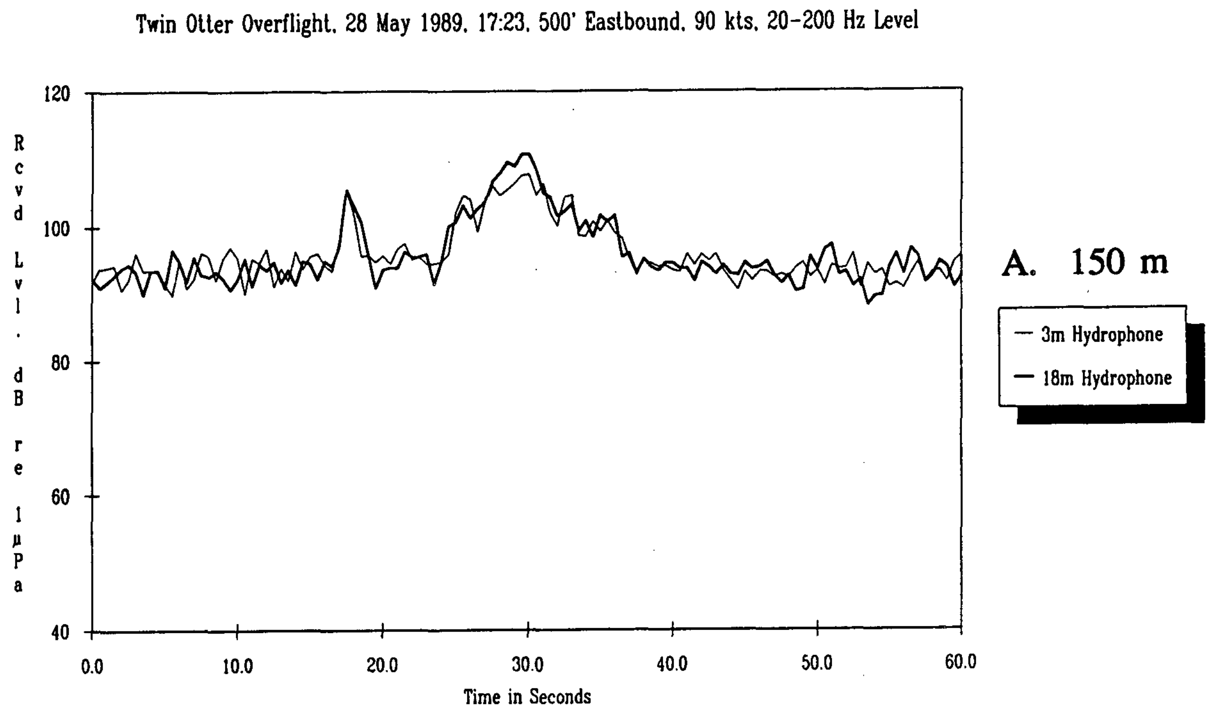


C.
Hyd. @ 3 m
Alt. 460 m



D.
Hyd. @ 18 m
Alt. 460 m

Fig. 29. Concluded.



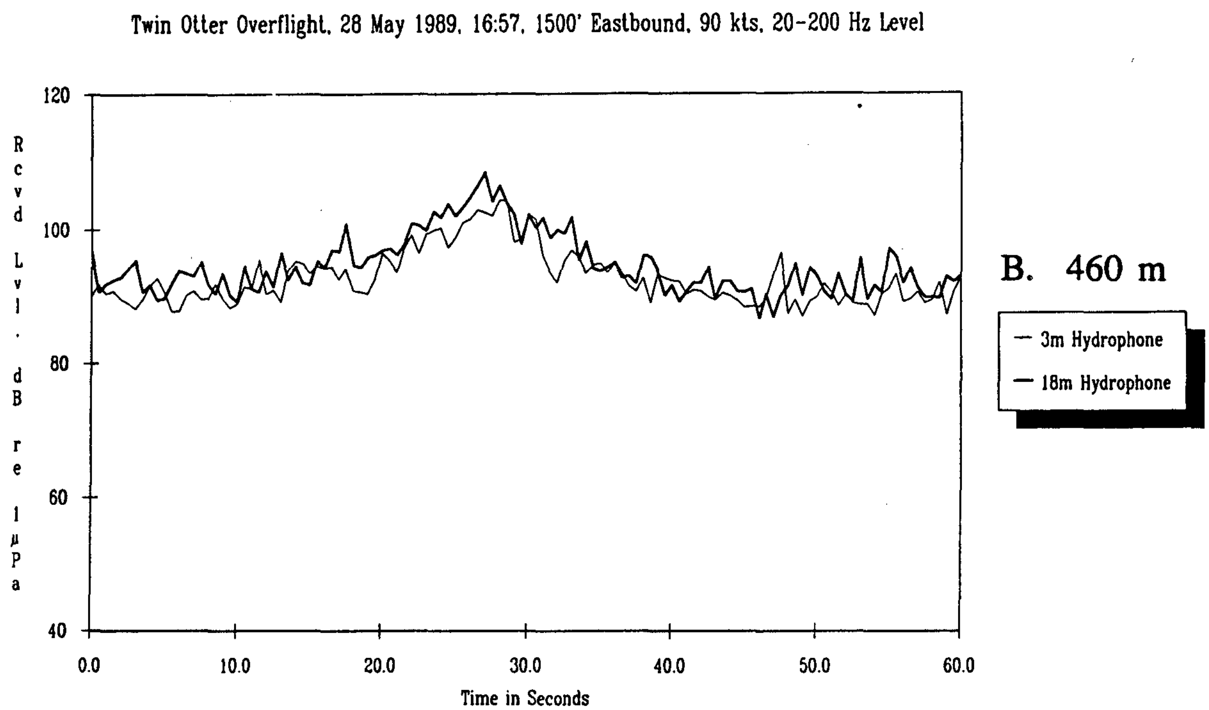


Fig. 30. Received levels of Twin Otter sound at depths 3 and 18 m as a function of time during overflights at altitudes (**A**) 150 m and (**B**) 460 m. Water depth 34 m. The apparent anomaly at the 18 sec point in Figure 30A is due to a strong sound (not from the Twin Otter) near 200 Hz (*cf*. Fig. 29A,B).

Ambient and Drilling Noise During Playbacks

Measurements of ambient noise were required by specific objective 2. The ambient noise was expected to vary considerably with time, since it is influenced heavily by ice activity, wind, and animal calling. We include some specific examples of ambient noise spectra for periods just before or after playback experiments. These natural sounds are compared with sample spectra for periods when *Karluk* drilling noise was being transmitted into the water. Most of the sounds described below were recorded via sonobuoys deployed about 1 km from the sound projector. Additional measurements of sound levels received near whales before, during and after playback experiments are summarized later ("Bowhead Results: Reactions to Playbacks"). Measurements of the levels of projected drilling sounds received near whales were needed to interpret the behavioral responses of whales to playbacks of drilling noise (specific objective 4). To help interpret the sounds received near whales, we also examined the sounds emitted by the generator that powered the sound projector, and we evaluated the fidelity with which the projector reproduced the drilling sounds.

Generator Noise

A potentially important constituent of the background sound during playbacks was sound from the gasoline generator running at the ice camp to power the amplifier for the J-11 projector. Examination of the data showed that, during playbacks, generator sounds would not have been detectable at any range from the projector. In the absence of masking noise from the projector, generator sounds were detectable at 18 m depth within a few hundred meters.

Two generators were used, both of which could provide up to 2.2 kW of electrical power. The first was a new, relatively quiet generator used through 14 May. Measurements of its sounds during an otherwise-quiet period showed three relatively weak tones (63, 126, 189 Hz) at range 100 m. These were the fundamental frequency of the power frequency and its first two harmonics. One very weak tone was evident at 63 Hz at range 200 m, and there were no detectable tones at range 410 m. The second generator, which was older and subjectively noisier, had to be used from 16 May onward. Measurements made on 25 May showed three strong tones at range 200 m and six strong tones at range 400 m (Fig. 31). These tones were at frequencies from 60 to 300 Hz. Most of them represented the power frequency and its harmonics, but there was also a tone at 3.5 times the power frequency. These tones were not evident in the ambient noise signals received at sonobuoys ~1 km from the ice camp while the generator was running but the projector was silent.

During playbacks of drilling noise, the spectrum levels of the *Karluk* sounds were about 30 dB stronger than the levels of the generator tones at corresponding frequencies (e.g. Fig. 31 vs. Fig. 32). The generator noise measurements were made with a hydrophone at depth 18 m. A shallower hydrophone would be expected to reveal moderately higher levels of generator noise at short ranges. However, with the possible exception of shallow depths directly below the generator,

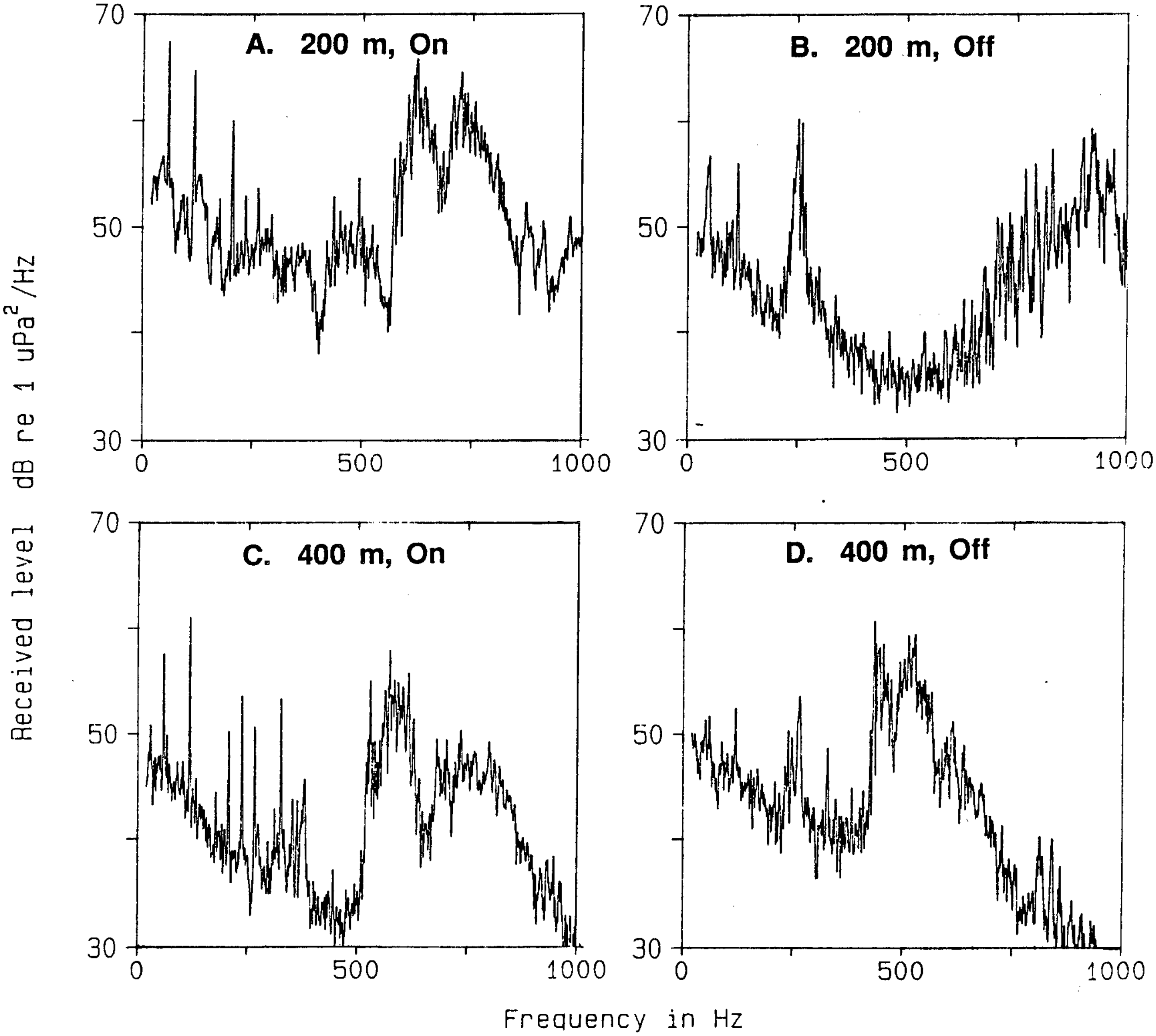


Fig. 31. Generator noise: spectra of received underwater noise at depth 18 m at distances (**A**) 200 m and (**C**) 400 m from a 2.2 kW generator operating on the ice, as compared with (**B**), (**D**) noise at corresponding distances with the generator turned off. Note the presence of additional tones at 60-300 Hz when the generator was on. All data from 25 May 1989, 8.5 s/sample.

generator noise would not have been detectable at any depth or at any distance from the projector during the noise playbacks.

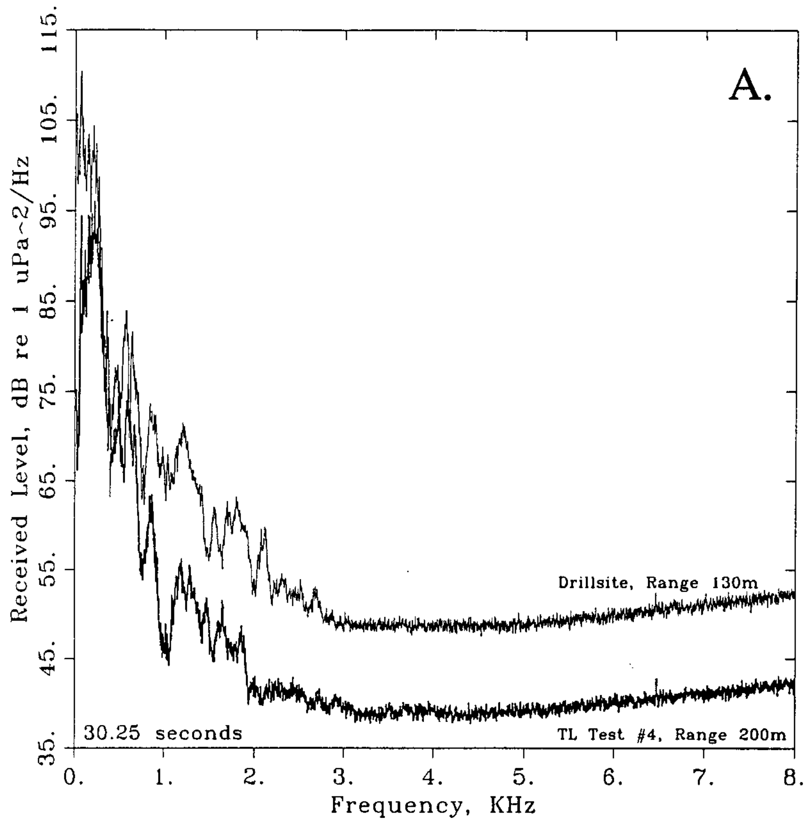
Fidelity of Drilling Noise Playbacks

To evaluate the adequacy of playbacks in simulating noise from the drillsite, we compared the *Karluk* sounds as originally received near the drillrig with the sounds received at similar distances from the projector system. Some changes in sound characteristics are expected because of (1) limitations in the recording and playback systems, and (2) environmental differences between the original drillsite vs. the projector site. The original drillsite was in shallow water (6.8 m), whereas all playback sites were in considerably deeper water. Hence, sound propagation during playbacks would not be expected to be directly comparable to that at the *Karluk* drillsite. Given this, it would not be reasonable to compare the signals received at long distances. We restrict most comparisons to short distances (but see Fig. 34, later).

The original recording used for all playbacks was recorded at range 130 m. For comparison, we considered sounds recorded 200 m from the projector during a transmission loss test on 9 May 1989. The water depth at the *Karluk* drillsite was 6.8 m, ice thickness was 2.1 m, and hydrophone depth was 3.2 m. At the 9 May projector site, the water depth was 142 m, ice thickness varied from 0.2 to 3 m, and the hydrophone (and projector) depths were 18 m.

We compared the narrowband spectra (Fig. 32) and third-octave spectra (Fig. 33). The sound energy near both sources was concentrated in the frequency range 50-350 Hz. Because the hydrophone was slightly farther from the projector than from the actual drillsite, the received spectrum near the projector would, ideally, be parallel to but a few decibels lower than that near the actual drillsite. This was generally true between about 200 and 750 Hz. However, there were three principal differences in the two spectra. **(1)** Levels at frequencies <50 Hz were markedly higher near the drillsite than near the projector (Fig. 32B). This difference is attributed to the reduced output from the J-11 projector at frequencies below 50 Hz, even though it is rated as being capable of projecting some energy at frequencies as low as 20 Hz when operated near 30 m depth. **(2)** Spectrum levels between 60 and 250 Hz were relatively constant near the actual drillsite but increased with frequency near the projector. This is attributed to interference effects associated with surface reflections over the 200 m path between the projector and the receiving hydrophone. **(3)** At frequencies >400 Hz, the differences between the received levels near the actual drillsite and projector increased with increasing frequency.

Apparent sound levels at frequencies above 3 kHz (Fig. 32A, 33) represent system noise rather than underwater sound. Underwater sound levels at these high frequencies would have been even lower than the low levels shown in Fig. 32A. The seemingly higher levels of high-frequency noise near the actual drillsite than near the projector reflect different recorder settings rather than different sound levels. Note that the system noise spectrum levels are >57 dB



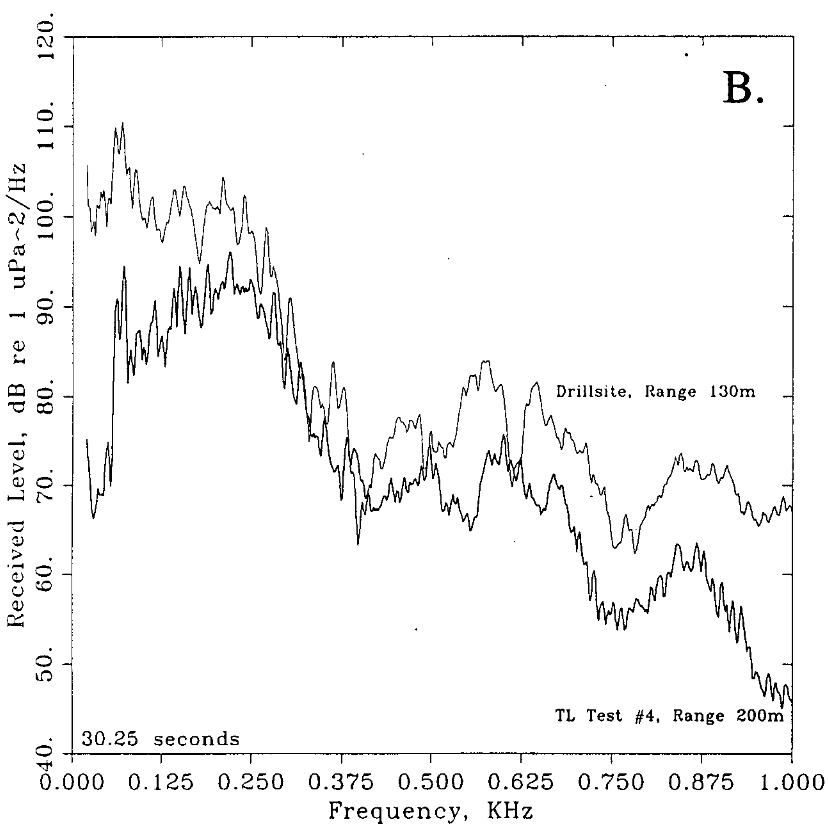


Fig. 32. Spectra of *Karluk* drilling sound as received near the original *Karluk* drillsite (range 130 m) and the J-11 projector during a playback of that sound (range 200 m, 9 May 1989). **(A)** 20-8000 Hz. **(B)** 20-1000 Hz.

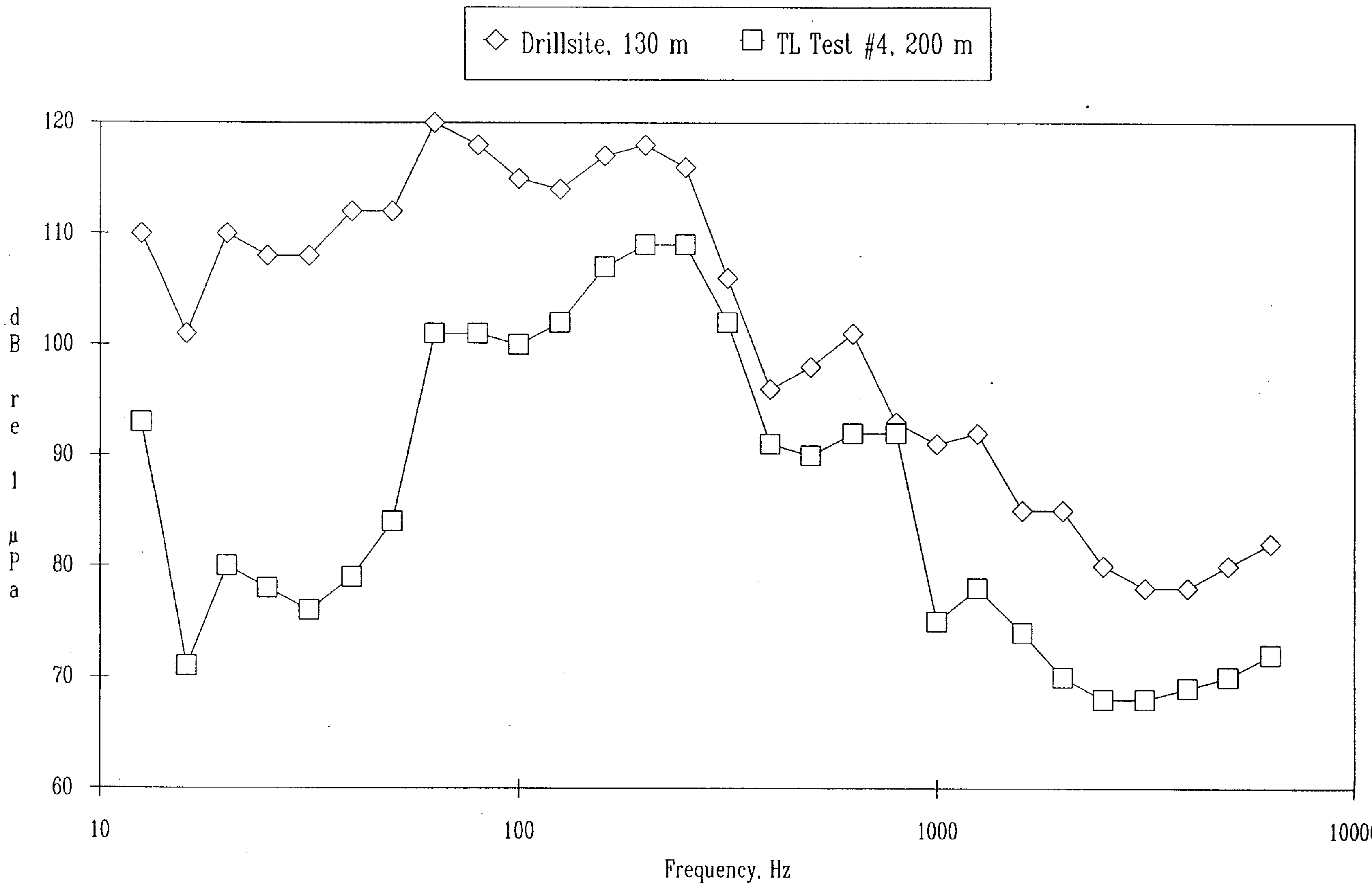


Fig. 33. One-third octave band levels of *Karluk* drilling sound as received near the original *Karluk* drillsite (range 130 m) and the J-11 projector during a playback of that sound (range 200 m, 9 May 1989).

below the strongest *Karluk* spectrum levels (Fig. 32A). Hence, very little energy was received or projected at these high frequencies.

A comparison of the distance-dependence of the received noise levels near the drillsite and the projector sites is of somewhat doubtful relevance. The water depths were much greater at the projector sites, and bowheads would not occur anywhere near the *Karluk* drillsite in spring. (The drillsite was inside the barrier island chain and surrounded by landfast ice.) However, the overall received levels of drilling noise (20-1000 Hz band) apparently were higher within ~200 m of the actual drillsite than at corresponding distances from the projector when it was broadcasting the drilling sound (Fig. 34). At intermediate distances, on the order of 200-500 m, received broadband levels were similar near the drillsite and the projector (Fig. 34). At distances greater than ~500 m, received levels were higher near projector sites. Thus, the rate of sound attenuation with increasing distance was higher near the actual drillsite. This was to be expected, given the rapid attenuation of low-frequency sounds in shallow water. At distances greater than ~200 m, levels near the projector were as high as or higher than those near the actual drillsite.

It is emphasized that these comparisons refer to sounds above 20 Hz. The drillsite emitted strong sound at frequencies as low as 10-20 Hz, and probably lower; the sound projector did not (Fig. 32B). If data on received levels at frequencies below 20 Hz were available and included in Figure 34, levels near the actual drillsite would be higher by an unknown but significant amount; levels near the projector would be essentially unchanged from those shown in Fig. 34.

Sounds During Specific Playback Tests

Figure 35 shows the spectrum for ambient sounds recorded via a sonobuoy 1 km from the ice camp immediately after the end of the playback experiment on ***14 May 1989***. This is an unremarkable spectrum, typical of situations when there was no especially prominent ice noise and when there were no prominent animal calls. The gradual decrease in received spectrum levels with increasing frequency is typical of such situations.

For comparison, Figure 36 shows spectra of sounds recorded a few minutes earlier while the *Karluk* drilling noise was being projected. Figure 36A shows the spectrum of the drilling noise as it was emitted from the projector, whereas Figure 36B shows the spectrum received at the sonobuoy 1 km away. As expected, the sounds emitted from the projector were similar in spectral characteristics to those recorded near *Karluk* itself, but the projector output at low frequencies was reduced (Fig. 36A vs. 21A; note the differences in horizontal scales). The effects of transmission loss and background noise on the sounds received 1 km from the projector are clear from Figure 36A vs. 36B. Above ~500 Hz, where there was little drilling noise energy, projection of the drilling noise had no obvious effect on sound levels 1 km away (Fig. 36B vs. Fig. 35). Below about 350 Hz, *Karluk* sounds were obvious 1 km from the projector. However, the shape of the low-frequency spectrum recorded 1 km away differed from the shape of the emitted

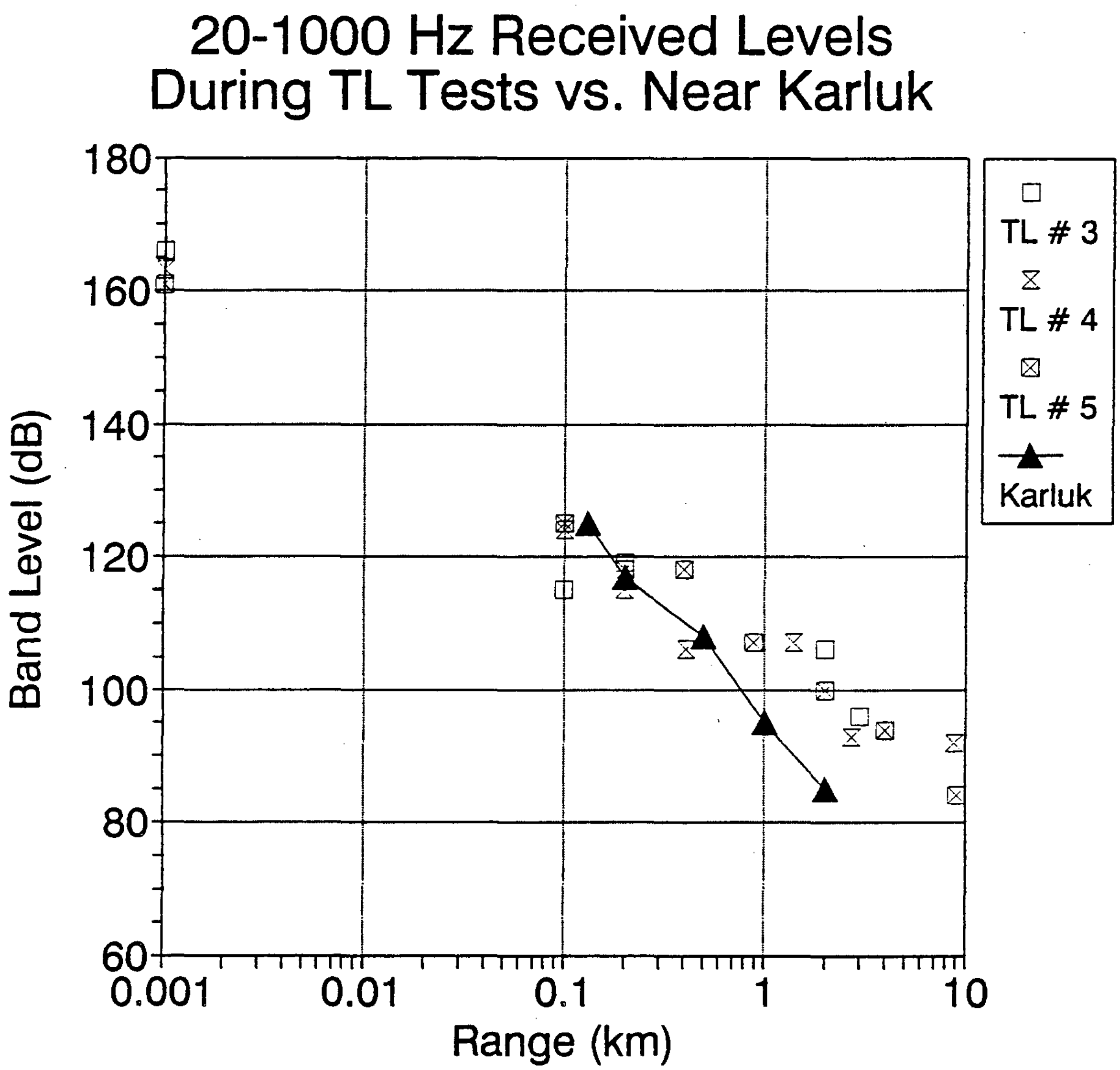


Fig. 34. Received levels of *Karluk* drilling sound, 20-1000 Hz band, as a function of distance from the actual drillsite (black triangles) and the sound projector during three transmission loss tests (open symbols).

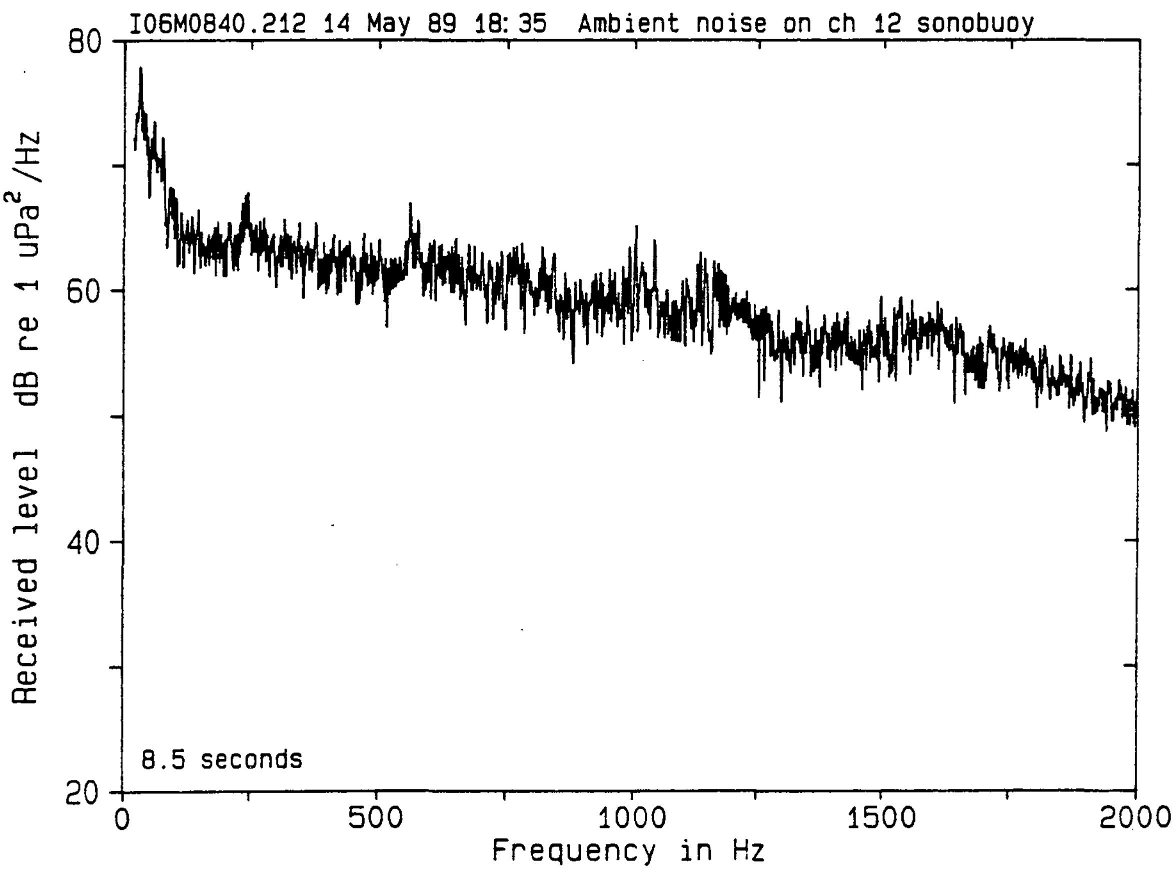


Fig. 35. An ambient noise spectrum for the background sounds received after the playback period at a sonobuoy about 1 km from the ice camp where the J-11 sound projector was operated on 14 May 1989. The 20-1000 Hz broadband level for this sample is 94 dB re 1 μPa.

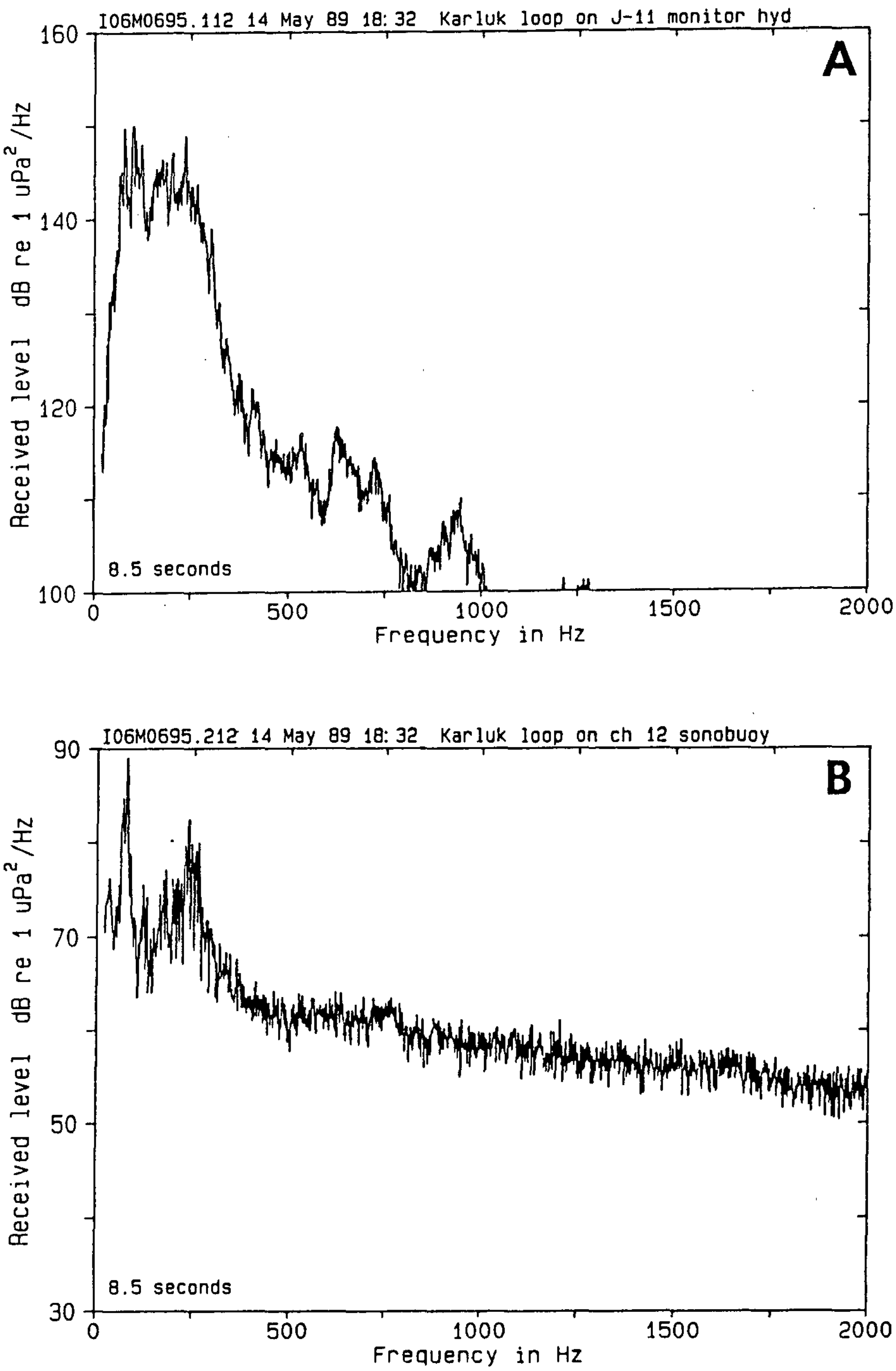


Fig. 36. A sample spectrum for the *Karluk* drilling platform sounds on the loop tape transmitted during the playback experiment on 14 May 1989. (A) is the spectrum recorded 0.74 m from the J-11 projector; its 20-1000 Hz band level is 168 dB re 1 μPa, corresponding to 165 dB at 1 m range. (**B**) is the spectrum of the signal received at a sonobuoy 1 km away; its 20-1000 Hz band level is 101 dB. The significant signal energy is in the frequency band 60-350 Hz; at higher frequencies the spectrum levels correspond closely to those of the ambient spectrum in the previous Figure. The low frequency portions of spectra (A) and (B) differ in shape because they are not exactly the same segment of the recorded drilling signal and because of propagation loss effects en route to the sonobuoy.

spectrum. The differences occurred, at least in part, because of frequency-dependent variations in transmission loss between the projector and sonobuoy.

Figure 37 compares ambient noise before a playback on ***19 May 1989*** with the combined drilling and ambient noise received at the same sonobuoy (1.1 km from the projector) while drilling noise was being projected. Again, drilling sounds were prominent 1.1 km from the projector at frequencies below about 350 Hz. The many peaks in Figure 37B above 300 Hz are spaced at varying intervals of 16-23 Hz. Their source is unknown.

Figure 38A vs. B is a similar comparison of ambient noise vs. drilling plus ambient noise received at a sonobuoy 1.1-1.3 km from the projector on ***23 May 1989***. Drilling sounds were prominent below ~300 Hz; the strong components above 1000 Hz are bearded seal (*Erignathus barbatus*) sounds (Fig. 38B). In general, bearded seal calls were extremely common and often very intense at frequencies above 1000 Hz. The same loud bearded seal calls were often detected simultaneously at sonobuoys located several km apart. Figure 39 shows additional examples of the strong effects that animal calls can have on ambient noise spectra.

Variability in Ambient Noise

An overview of the variability in ambient noise is given in Figure 40, which displays the 20-1000 Hz band levels of received noise vs. date. This graph excludes measurements contaminated by man-made sounds. No measurements were made during storms, when we were not on the ice. Thus, there may well have been, at certain times, higher sound levels than any of those shown in Figure 40. However, even on the days when measurements were made, there was considerable variability in ambient noise levels. There was much ice noise at some locations where ambient noise was measured during transmission loss tests. At times, there also were high ambient levels because of the presence of animal calls, including white whale and bowhead calls as well as bearded seal calls.

Three major factors influence ambient noise in the arctic: ice activity (pressure ridging, fracturing), wind, and animal calls. These factors influence the ambient noise in different frequency regions. Pressure ice noise tends to be at low frequencies whereas thermal cracking in ice tends to create high frequency noise. Wind noise can be at all frequencies. Animal calls vary in frequency. Most bowhead calls are at low frequencies (<400 Hz), white whales calls are at high frequencies (>5000 Hz), and bearded seal calls are intermediate in frequency.

Sound Propagation

Specific objective 3 for the 1989 program was to measure and model transmission loss of underwater sound in the study area based on playbacks of test tones and the *Karluk* continuous drilling platform noise. The results from transmission loss (TL) tests 2-5 are presented in this report. Test 1, conducted on 29 April, was not successfully completed and is not discussed. Results from tests 2-5 are presented individually.

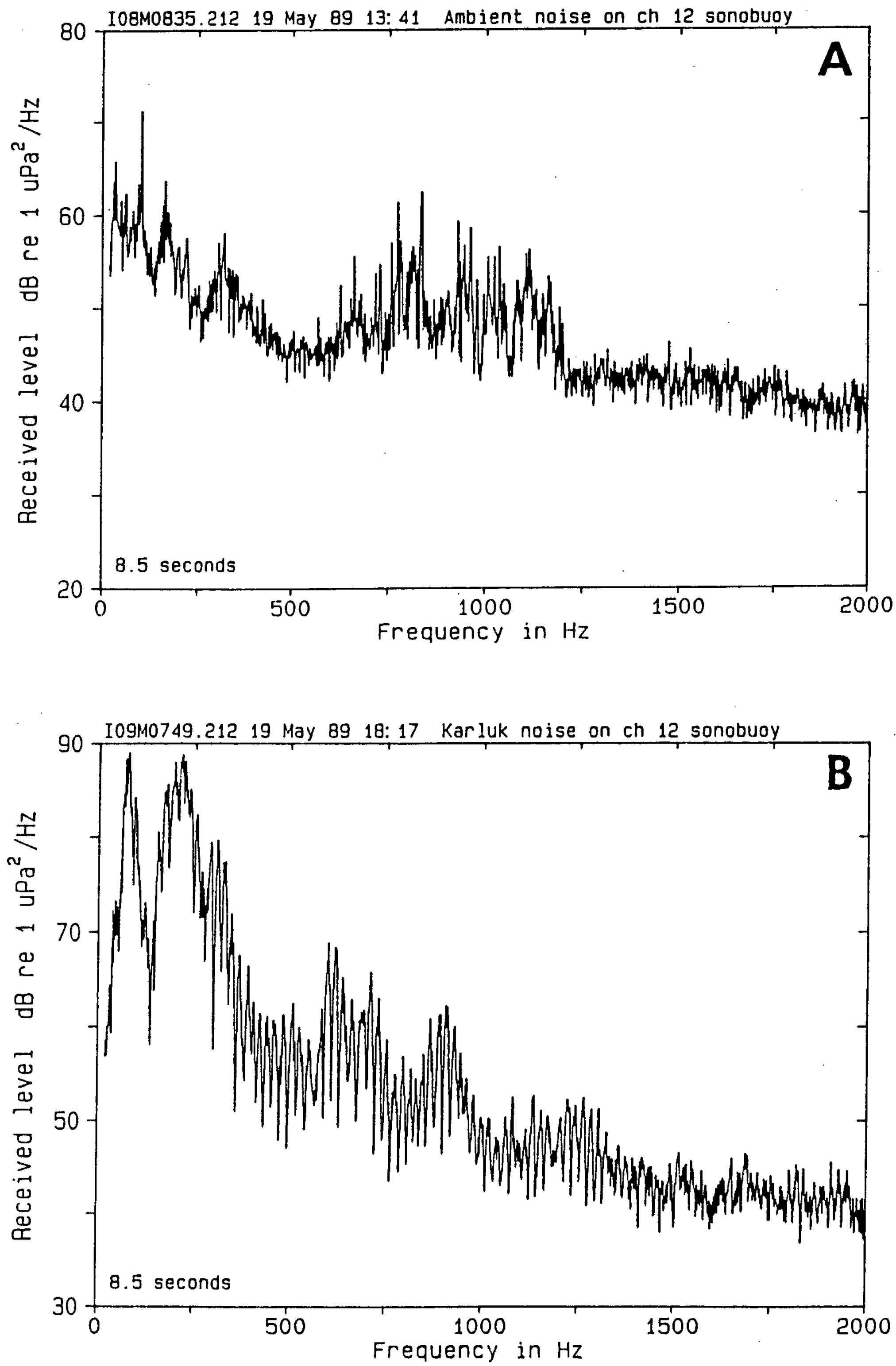


Fig. 37. Spectra for sounds received at the sonobuoy 1.1 km from the projector on 19 May 1989. (**A**) is an ambient noise spectrum--the isolated tone at the left is the propeller blade line from a Twin Otter aircraft, and the elevated levels at 700-1200 Hz are from an animal call; the 20-1000 Hz broadband level is 84 dB re 1 μPa. (**B**) is a spectrum for *Karluk* drilling sounds; the 20-1000 Hz broadband level is 106 dB.

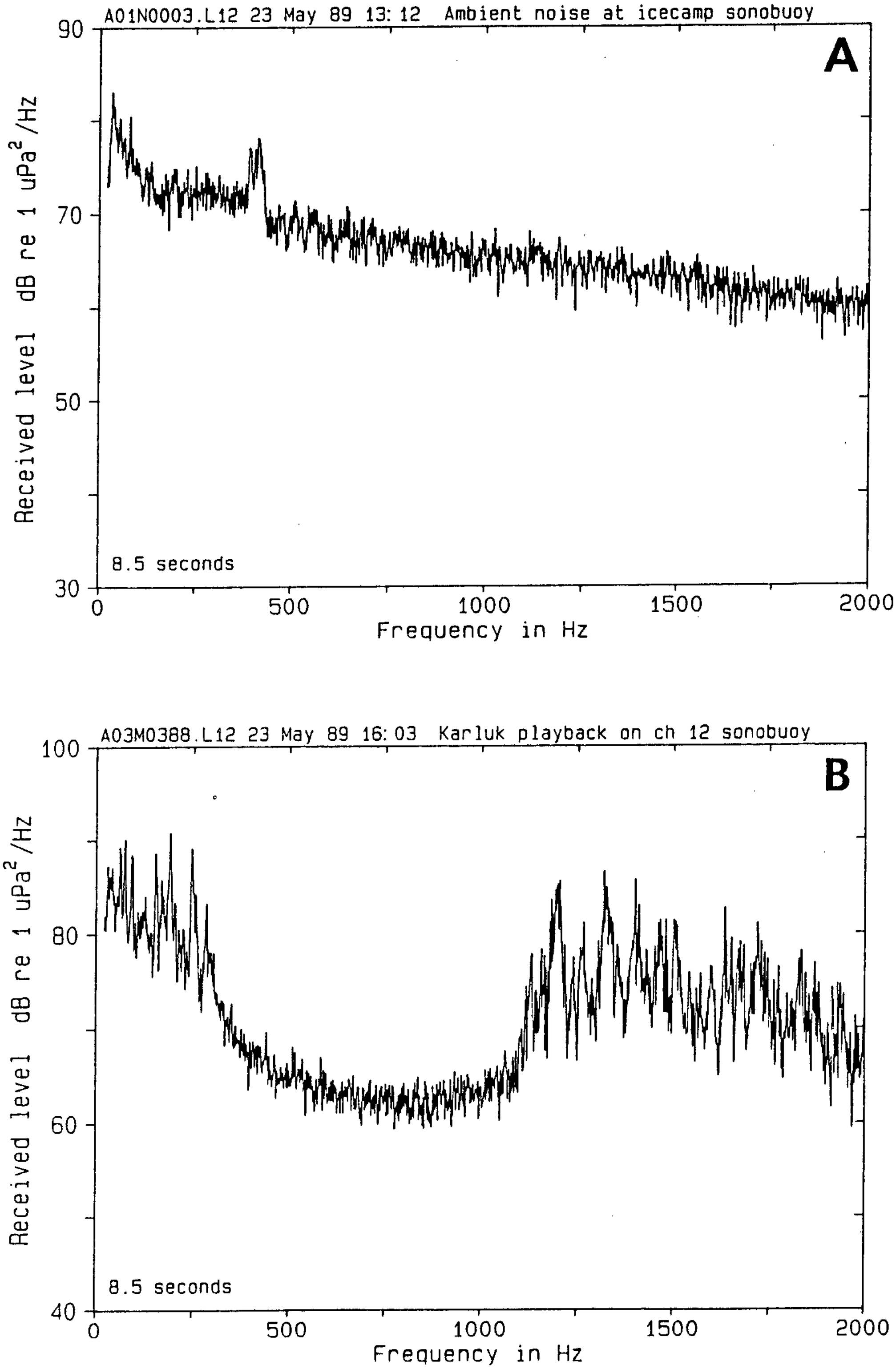


Fig. 38. Spectra for sounds received at the sonobuoy ≈1 km from the projector on 23 May 1989. (**A**) is for a segment of background sounds; 20-1000 Hz broadband level 102 dB re 1 μPa. (**B**) is a segment of *Karluk* drilling sounds; 20-1000 Hz level 107 dB. Animal sounds are manifest at frequencies above 1200 Hz.

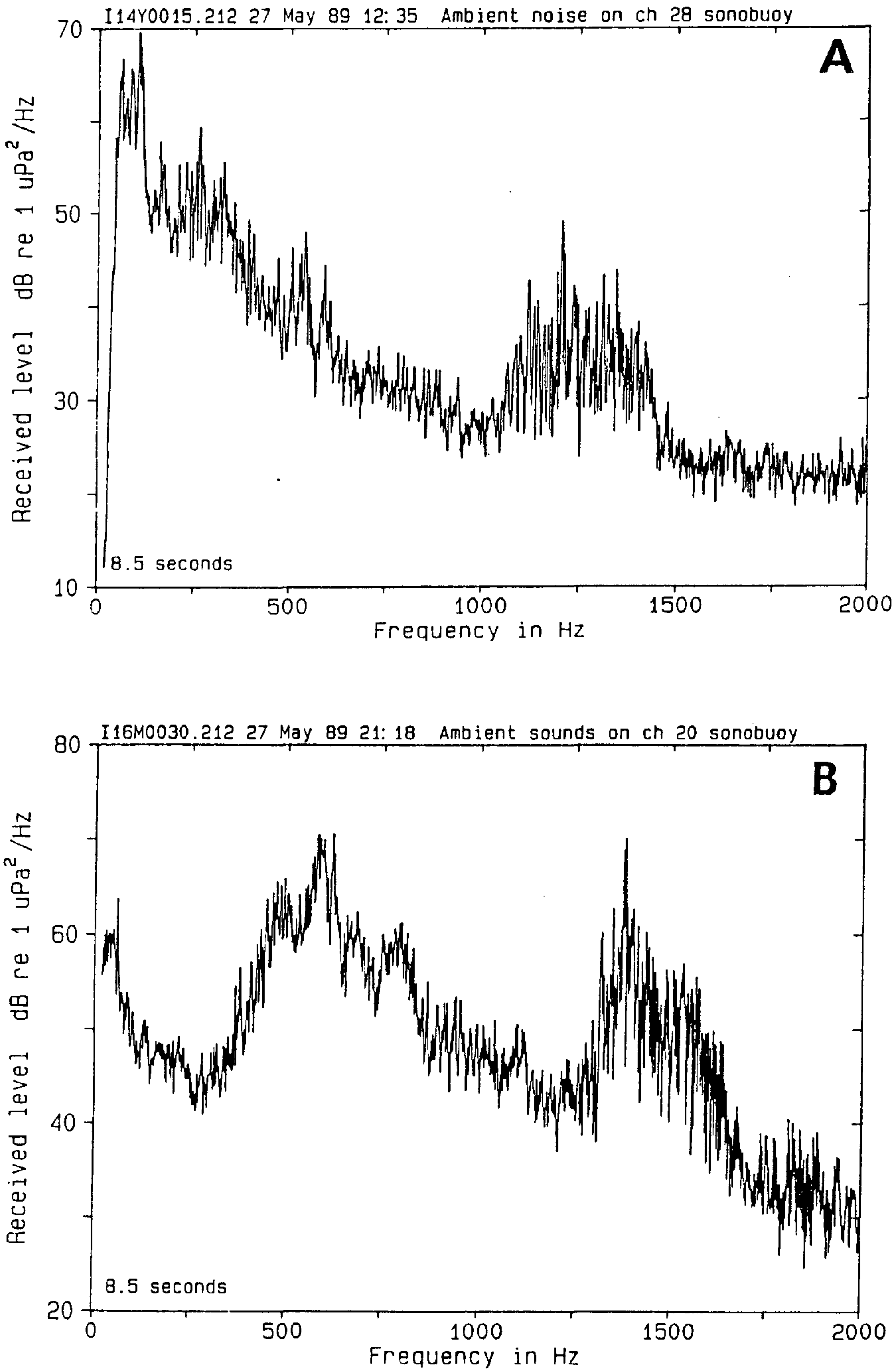


Fig. 39. Ambient noise spectra for sounds at two sonobuoys on 27 May 1989. (**A**) shows an animal call; the sonobuoy was 1.1 km from the ice camp before the playback period. (**B**) includes an animal call after the playback period; the 20-1000 Hz band level is 94 dB re 1 μPa.

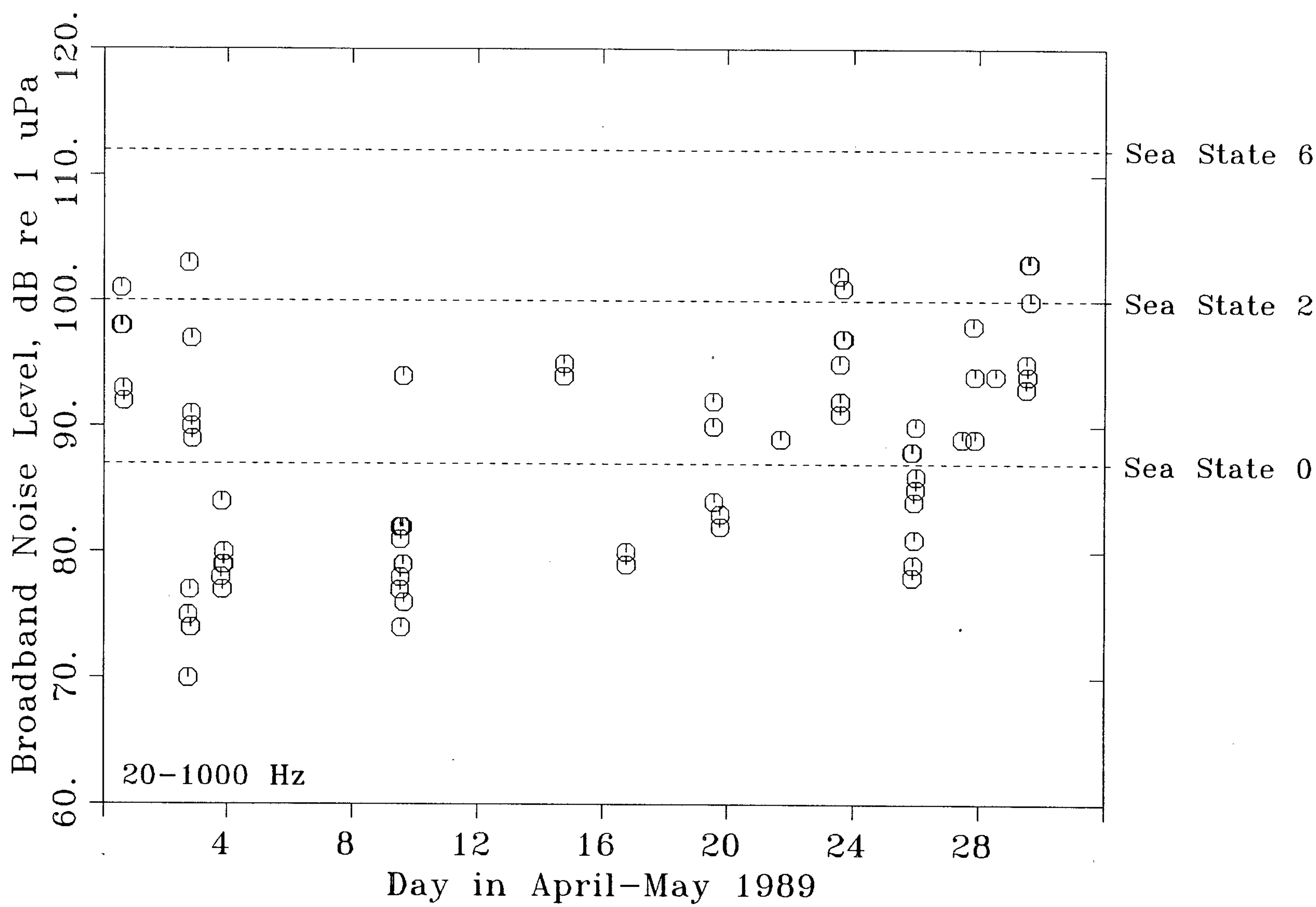


Fig. 40. Broadband ambient noise levels (20-1000 Hz) measured on numerous occasions during the 1989 field season. When several measurements were made on the same day, the vertical scatter indicates the variability in the broadband levels over relatively short periods. Variable ice noise and intermittent animal calls account for much of the variability. No measurements were made during storms or in the presence of man-made noise. Dashed horizontal lines show expected ambient noise levels (20-1000 Hz band) at sea states 0 (calm), 2 (light wind) and 6 (storm), from Greene (1987a).

Field Data

TL Test #2.--The second TL test was conducted on 30 April 1989 amidst pack ice (see Fig. 19 on p. 72 for projector location). The receiving stations were 100 m to 18 km west and northwest of the projector, with heavy pack ice between the projector and the more distant receiving stations. Water depth was 40-95 m. Table 5A shows the received levels of the eight tones (50-10,000 Hz) as a function of distance, along with their source levels 1 m from the projector. All tones at or below 1000 Hz were detectable as much as 1.85 km away. The 100-500 Hz tones also were detected 4.1 km away. Table 5A shows the received levels at various ranges, and Table 5B shows the corresponding transmission losses relative to the known source level at 1 m. The transmission loss values are plotted vs. range in Figure 41.

Table 6 shows the received levels of the sample of *Karluk* drilling sounds as a function of range. The overall source level was 164 dB re 1 μPa, but source levels by third-octave could not be determined on this date. Hence, TL values for *Karluk* sounds could not be determined on a third-octave basis for this date.

TL Test #3.--The third TL test was conducted on 2 May 1989 amidst pack ice (Fig. 19). Water depths were 49-63 m. Tables 7A,C present, respectively, the received level and transmission loss data for pure tones; Figure 42A shows the same data. For most frequencies, the tones were detectable as much as 4.7 km from the projector, and the 200 Hz tone was detectable 10.4 km away.

Tables 7B,D show the received levels and transmission losses for the sample of *Karluk* drilling sounds in relation to range. The measurements are presented by third-octave bands, considering those bands within which *Karluk* sounds were strong (the bands centered at 63-315 Hz; see also Fig. 42B). At certain frequencies, the *Karluk* sounds were still evident at range 4.7 km, but there was no evidence of these sounds at ranges 10.4 or 18.9 km. (In contrast, the 200 Hz tone was evident at 10.4 km.) It was expected that the drilling sounds would not be detectable as far away as the pure tones. When pure tones were projected, all of the projector output was concentrated at one frequency; when broadband drilling sounds were projected the overall source level was similar but less power was emitted at each particular frequency. Table 8 presents the *Karluk* received level data for all 1/3-octave bands from 20 to 1600 Hz, along with ambient noise data collected at corresponding ranges. These data show how the level of drilling sounds in each band approaches the ambient level in that band at distances ranging from about 3 to 10 km. (Related data are plotted in Fig. 81, p. 228.)

For certain frequencies, transmission loss was determined using both pure tones and the sample of *Karluk* drilling sounds. In these cases, there was fairly good agreement (Fig. 42A vs. B).

TL Test #4.--The fourth TL test was conducted on 9 May on smoother pack ice well to the northwest of the locations of previous TL experiments (Fig. 19).

Table 5. Sound propagation loss data from a transmission test (TL #2) with single frequency tones, 30 April 1989.

Range, km	0.001	0.1	0.2	0.93	1.85	4.07
50 Hz	158.0	113.0	120.0	106.4		
100 Hz	168.0	107.0	125.0	119.0	99.9	86.4
200 Hz	169.0	123.8	120.3	112.8	96.1	80.4
500 Hz	165.0	126.1	116.7	106.1	94.5	80.3
1000 Hz	159.0	121.0	116.9	97.4	97.8	
2000 Hz	162.0	117.4	115.2			
5000 Hz	162.0	120.3	119.6			
10000 Hz	171.0	118.7	122.4			
50 Hz	0.0	45.0	38.0	51.6	158.0	
100 Hz	0.0	61.0	43.0	49.0	68.1	81.6
200 Hz	0.0	45.2	48.7	56.2	72.9	88.6
500 Hz	0.0	38.9	48.3	58.9	70.5	84.7
1000 Hz	0.0	38.0	42.1	61.6	61.2	
2000 Hz	0.0	44.6	46.8			
5000 Hz	0.0	41.7	42.4			
10000 Hz	0.0	52.3	48.6			

A. Received level, dB re 1 uPa.

B. Trans. Loss, dB re 1 m.

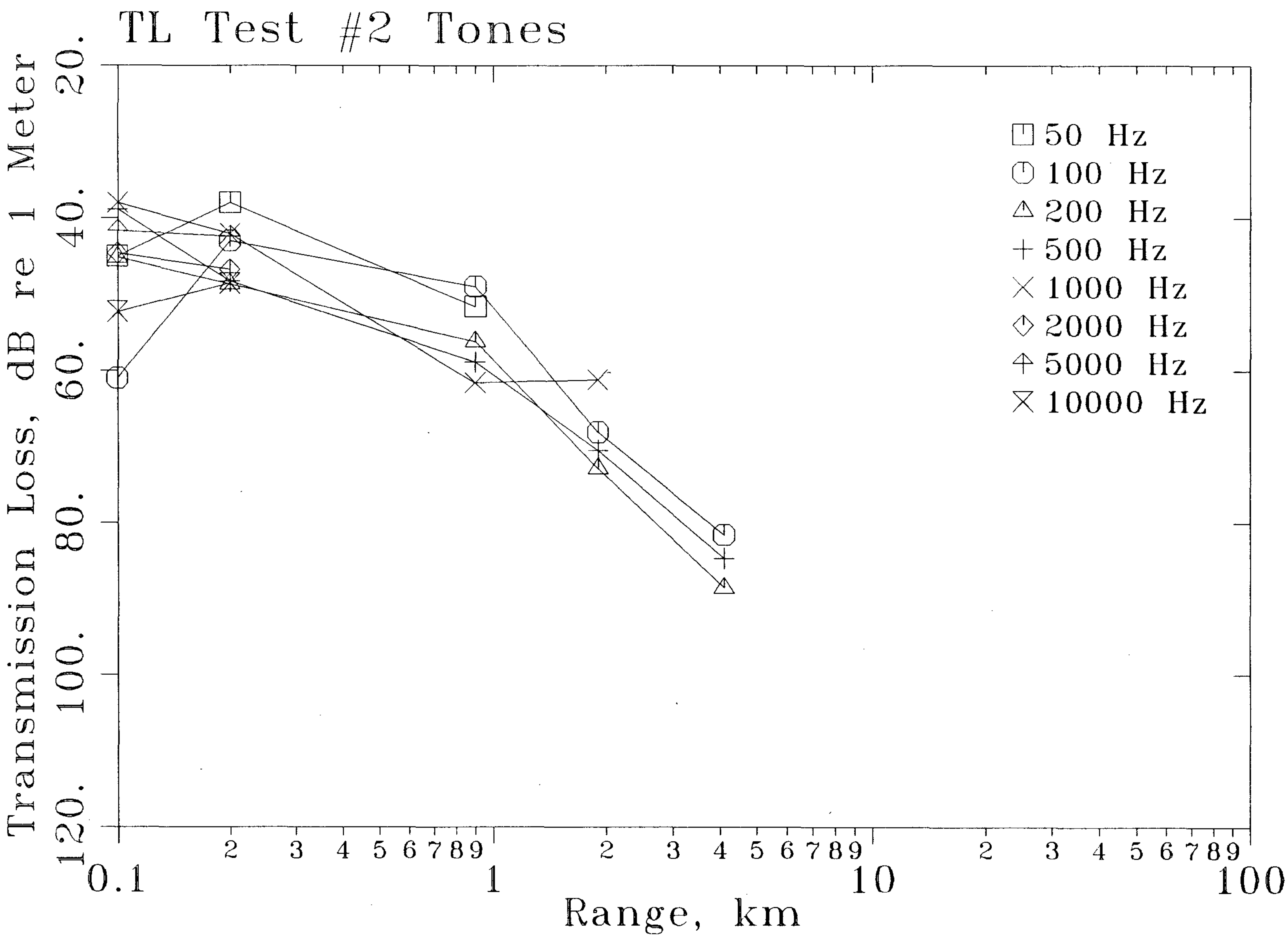


Fig. 41. Transmission loss vs. range for the eight pure tones transmitted during Test #2 on 30 April 1989. The corresponding values are presented in Table 5.

Table 6. Received levels in third octave bands (dB re 1µPa) vs. range for the transmitted *Karluk* drilling sounds, Transmission Loss Test #2, 30 April 1989.

Center Fr.	0.100 km	0.200 km	0.93 km	1.85 km	4.07 km
20.0	89.6	88.3	91.4		
25.0	89.0	86.0	89.9		
31.5	90.5	85.7	85.6		
40.0	94.5	93.0	85.1		
50.0	100.2	100.3	87.5		
63.0	115.5	110.5	102.7		
80.0	115.7	114.5	105.1	93.2	
100.0	105.3	115.7	103.3	94.1	
125.0	110.4	114.7	105.5	97.0	
160.0	119.5	108.2	100.4	98.5	
200.0	117.9	114.0	106.1	94.5	
250.0	116.9	110.8	107.6	91.1	
315.0	107.2	105.4	93.8	89.0	
400.0	97.5	93.5	84.1	82.5	
500.0	97.9	95.0	81.9	76.6	
630.0	99.2	94.8	81.5		
800.0	83.6	88.6	75.1		
1000.0	87.1	85.1	74.8		
1250.0	87.1	84.5	73.8		
1600.0	79.4	76.7	70.9		
2000.0	80.5	78.4	70.8		
20-1000	124.7	121.8	113.4	104.4	

Table 7. **Sound propagation loss data from a transmission test (TL #3) with (A, C) single frequency tones and (B, D) *Karluk* drilling noise, 2 May 1989.**

Range, km	0.001	0.1	0.2	1.97	3.03	4.68	10.39	
50 Hz	159.0	115.2	111.6	96.6	88.5			A. Received Levels, Tones. dB re 1 uPa.
100 Hz	169.0	118.2	117.0	103.4	102.2	70.8		
200 Hz	170.0	116.7	121.1	108.2	99.8	88.2	71.9	
500 Hz	165.0	101.9	108.2	95.3	84.1	76.4		
1000 Hz	161.0	101.2	113.5	91.3	89.5	61.1		
2000 Hz	157.0	97.0	97.8	94.5	82.4	56.6		
5000 Hz	154.0	87.0	98.6	88.7	70.3			
10000 Hz	168.0			88.7	68.1			
63 Hz	153.0	101.9	103.9	95.9	83.8			B. Received Levels, Karluk 3rd Octave Band Levels, dB re 1 uPa.
80 Hz	155.0	105.2	101.2	94.2	87.7			
100 Hz	156.0	106.3	108.3	99.3	88.4			
125 Hz	158.0	100.1	112.1	95.1	85.5			
160 Hz	159.0	107.9	112.9	99.9	87.0	74		
200 Hz	161.0	107.6	111.6	98.6	91.2	79		
250 Hz	158.0	106.5	108.5	93.5	85.8	73		
315 Hz	149.0	101.4	99.4	90.4	78.0			
50 Hz	0.0	43.8	47.4	62.4	70.5			C. Trans. Loss for Tones, dB re 1 m.
100 Hz	0.0	50.8	52.0	65.6	66.8	98.2		
200 Hz	0.0	53.3	48.9	61.8	70.2	81.8	98.1	
500 Hz	0.0	63.1	56.8	69.7	80.9	88.6		
1000 Hz	0.0	59.8	47.5	69.7	71.5	99.9		
2000 Hz	0.0	60.0	59.2	62.5	74.6	100.4		
5000 Hz	0.0	67.0	55.4	65.3	83.7			
10000 Hz	0.0			79.3	99.9			
63 Hz	0.0	51.1	49.1	57.1	69.2			D. Trans. Loss for Karluk 3rd Octave Band Levels, dB re 1 m.
80 Hz	0.0	49.8	53.8	60.8	67.3			
100 Hz	0.0	49.7	47.7	56.7	67.6			
125 Hz	0.0	57.9	45.9	62.9	72.5			
160 Hz	0.0	51.1	46.1	59.1	72.0	85.0		
200 Hz	0.0	53.4	49.4	62.4	69.8	82.0		
250 Hz	0.0	51.5	49.5	64.5	72.2	85.0		
315 Hz	0.0	47.6	49.6	58.6	71.0			

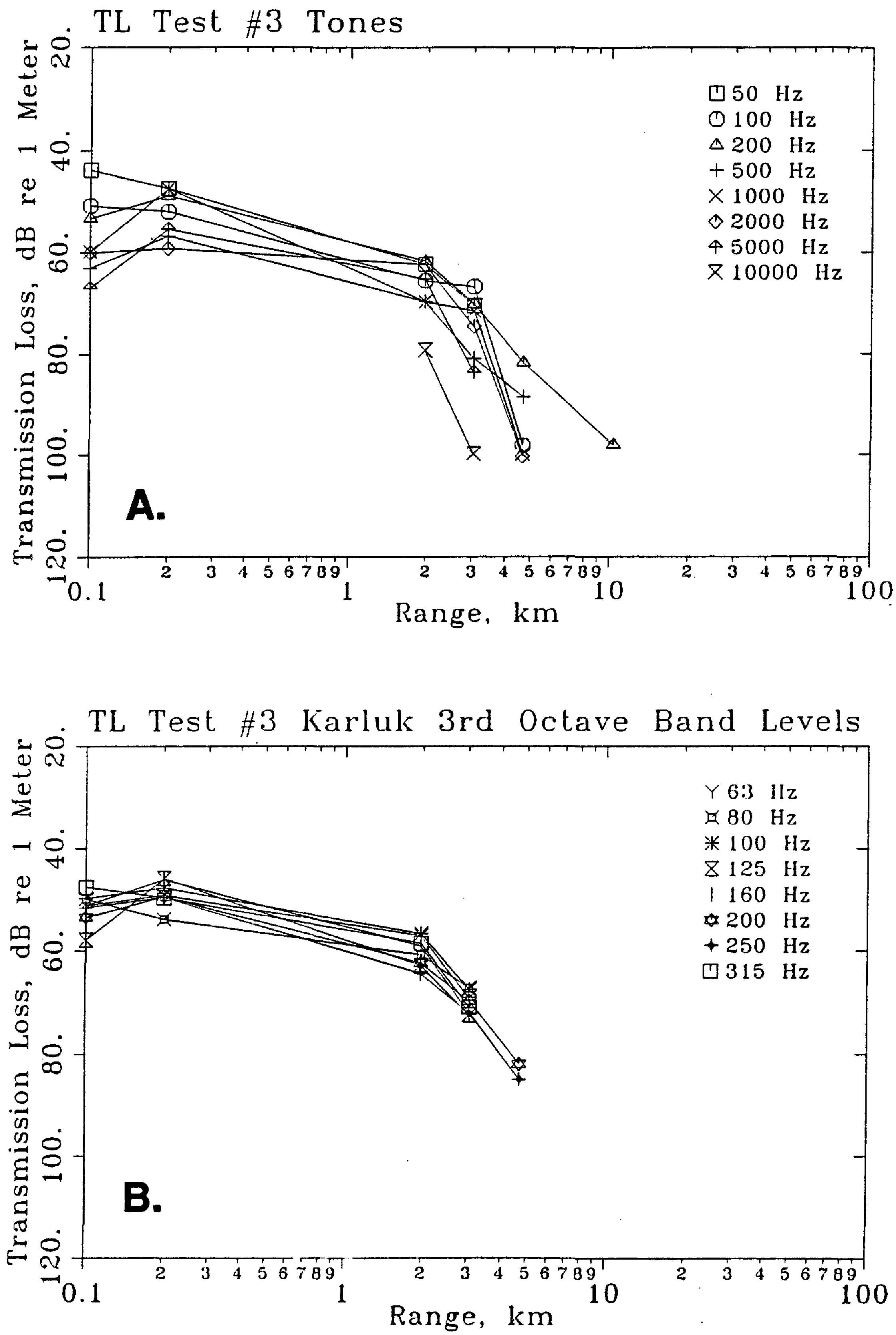


Fig. 42. Transmission loss vs. range for (A) pure tones and (B) *Karluk* sounds during Test #3 on 2 May 1989. The corresponding values are presented in Table 7.

Table 8. Received levels in third octave bands (dB re 1 µPa) vs. range (m) for (A) the transmitted *Karluk* drilling sounds and (B) the ambient noise at the various receiving stations, Transmission Loss Test #3, 2 May 1989.

Source	A. Karluk	Karluk	Karluk	Karluk	Karluk	B. Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient
Range (m)	100	200	1970	3030	4680	100	100	200	1970	3030	4680	10390	18930
20 Hz	75	102	67	71		64	64	98	71	68	88	91	84
25 Hz	78	96	68	70		65	64	97	72	69	85	91	83
31.5 Hz	80	94	70	66		64	62	95	69	65	81	90	82
40 Hz	91	95	76	69		61	60	94	65	63	78	90	79
50 Hz	96	97	79	74		60	59	92	66	63	78	87	79
63 Hz	102	104	96	84		73	58	91	66	61	76	85	75
80 Hz	105	101	94	88		59	57	89	66	62	72	84	76
100 Hz	106	108	99	88		57	57	87	65	60	76	82	74
125 Hz	100	112	95	86		58	56	88	64	60	74	79	74
160 Hz	108	113	100	87	74	58	56	84	65	61	68	79	73
200 Hz	108	112	99	91	79	55	55	82	60	60	68	77	72
250 Hz	107	109	94	86	73	55	54	81	60	58	67	76	71
315 Hz	101	99	90	78		53	53	79	58	56	66	75	68
400 Hz	87	87	79	75		53	52	75	58	57	65	72	66
500 Hz	86	87	75	84		53	51	72	60	57	64	71	67
630 Hz	87	88	77	82		52	50	72	59	56	62	70	64
800 Hz	74	84	71	78		52	49	73	56	55	59	69	63
1000 Hz	70	78	66	62		52	48	72	54	53	60	68	61
1250 Hz	75	78	62	59		51	48	72	54	52	58	66	60
1600 Hz	63	73	59	56		51	48	72	54	52	56	65	58
20-500 Hz	115	119	106	96		75	70	103	78	74	90	97	89
20-1000 Hz	115	119	106	97		75	70	103	78	74	90	97	89

The water was deeper, diminishing from 142 m at the projector site to 113 m at the most distant receiving station 17.4 km to the southwest. Tables 9A,C present the received level and transmission loss data for pure tones (see also Fig. 43A). Most tones were clearly detectable at range 8.9 km, and some were weakly evident at 17.4 km as well. Tones were detectable farther away on this day than during other TL tests. This was primarily because the ambient noise levels at the distant receiver sites were lower for this test than for the others. Also, the deeper water, and correspondingly fewer bottom and ice interactions for the spreading sound rays, may have contributed a reduced rate of sound attenuation.

The corresponding data for the sample of *Karluk* drilling sounds are shown in Tables 9B,D, and in Figure 43B. These sounds were clearly detectable at ranges as great as 8.9 km but, in contrast to some tones, not at 17.4 km. The transmission loss data derived from analysis of drilling sounds vs. pure tones are not in good agreement for ranges beyond 1.4 km (Fig. 43A vs. B). Table 10 presents the full range of 1/3-octave band levels for the drilling and ambient sounds at the various receiving stations (see also Fig. 81, p. 228).

The received levels of the HFM frequency sweeps were also determined for TL test 4 (Table 11A). Greeneridge's standard analysis procedures were applied for all combinations of frequency and range at which the sweep was audible. Transmission losses measured with tones and sweeps can be compared. At ranges 8.9 and 17.4 km, the differences for seven measurements were 0.5-4.7 dB, averaging 2.3 dB (Table 9C vs. 11A). At low frequencies (≤200 Hz), the differences were less than 2 dB.

<u>TL Test #5</u>.--The fifth TL test was done on 25 May along the north edge of the nearshore lead separating the landfast ice from the pack ice. Water depths increased from 42 m at the projector to 111 m at the most distant receiving station. Transmission loss estimates based on tones and *Karluk* sounds were in good agreement for the frequencies in common (Table 12C vs. D; Fig. 44A vs. B). Several tones and drilling sounds in several 1/3-octave bands were detectable as far as 9.2 km away. Table 13 presents the full range of 1/3-octave band levels for the drilling and ambient sounds at the various receiving stations (see also Fig. 81, p. 228).

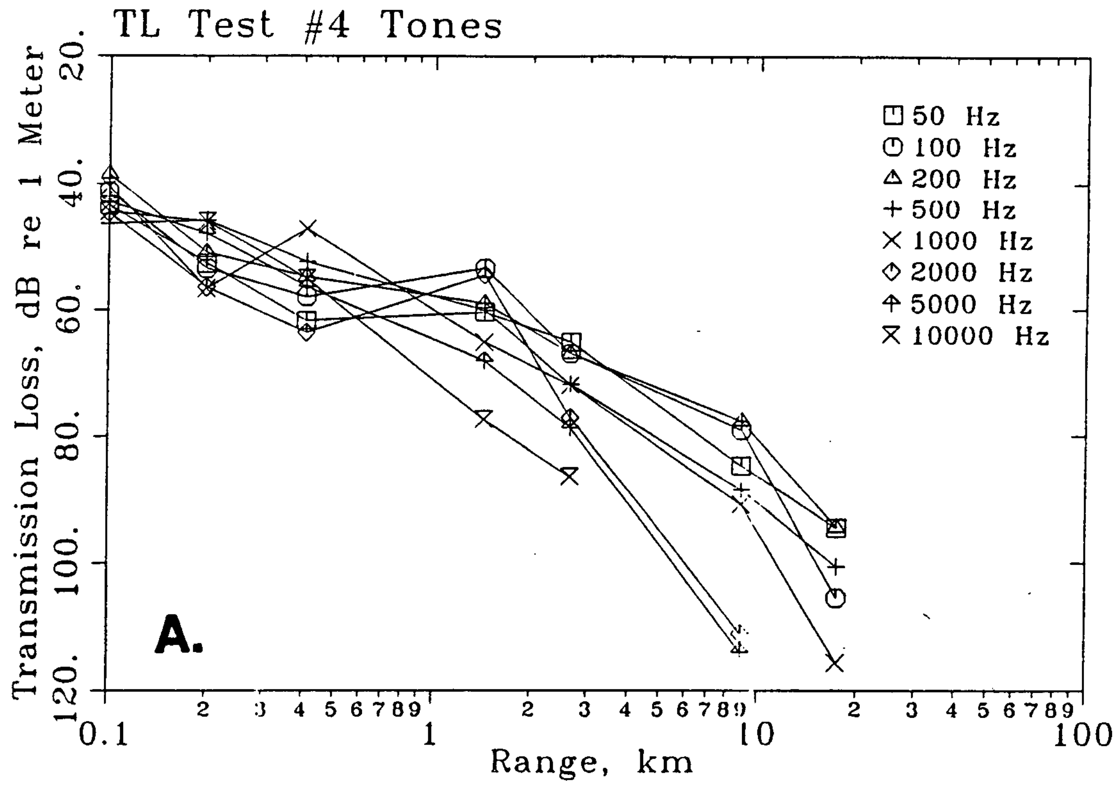
The received levels of the HFM frequency sweeps were also determined for TL test 5 (Table 11B). Figure 45 is a waterfall spectrum of the four successive HFM sweeps near 1000 Hz as received at range 890 m. The concluding low frequency portion of a typical descending-frequency bearded seal call appears at frequencies <500 Hz. At range 3.95 km, transmission losses measured with tones and sweeps differed by 0.4-4.3 dB; the average difference for 5 frequencies was 1.6 dB (Table 12C vs. 11B). At low frequencies (≤200 Hz) the differences again were less than 2 dB.

<u>Propagation Models</u>

Major factors influencing sound propagation in the study area during spring include water depth, sound speed profile, roughness of the underice surface,

Table 9. Sound propagation loss data from a transmission test (TL #4) with (A, C) single frequency tones and (B, D) *Karluk* drilling noise, 9 May 1989.

Range, km	0.001	0.1	0.2	0.41	1.43	2.65	8.9	17.4	
50 Hz	158.5	115.0	105.7	96.7	98.1	93.3	73.8	63.9	A. Received Levels for Tones. dB re 1 uPa.
100 Hz	163.2	122.0	109.6	105.2	109.6	96.2	84.1	57.7	
200 Hz	166.5	128.0	115.4	111.6	107.5	99.5	88.8	72.0	
500 Hz	162.2	115.8	116.3	109.6	102.1	90.4	73.6	61.6	
1000 Hz	158.5	118.0	101.8	111.2	93.3	86.5	67.6	62.8	
2000 Hz	156.5	111.8	100.0	92.8	101.9	79.4	65.4		
5000 Hz	153.4	110.5	105.4	97.0	85.3	74.7	59.4		
10000 Hz	159.0	114.5	112.9	103.8	81.6	72.6			
63 Hz	151.1	107.2	97.9	89.9	89.9	84.9	80.1		B. Received Levels, Karluk 3rd Oct. Band Levels, dB re 1 uPa.
80 Hz	153.1	109.2	99.2	97.2	94.2	84.2	79.8		
100 Hz	152.5	110.8	99.6	93.3	95.3	84.8	76.9		
125 Hz	152.2	112.9	102.1	92.1	97.1	80.1	76.0		
160 Hz	154.5	116.8	106.9	94.9	93.9	84.9	76.0		
200 Hz	156.5	119.7	110.6	101.6	100.6	87.6	77.5		
250 Hz	156.2	117.0	109.5	98.5	103.5	82.5	76.9		
315 Hz	147.8	107.1	101.4	92.4	89.4	75.4	71.2		
50 Hz	0.0	43.5	52.8	61.8	60.4	65.2	84.7	94.6	C. Trans. Loss for Tones, dB re 1 m.
100 Hz	0.0	41.2	53.6	58.0	53.6	67.0	79.1	105.5	
200 Hz	0.0	38.5	51.1	54.9	59.0	67.0	77.7	94.5	
500 Hz	0.0	46.4	45.9	52.6	60.1	71.8	88.6	100.6	
1000 Hz	0.0	40.5	56.7	47.3	65.2	72.0	90.9	95.7	
2000 Hz	0.0	44.7	56.5	63.7	54.6	77.1	91.1		
5000 Hz	0.0	42.9	48.0	56.4	68.1	78.7	94.0		
10000 Hz	0.0	44.5	46.1	55.2	77.4	86.4			
63 Hz	0.0	43.9	53.2	61.2	61.2	66.2	71.0		D. Trans. Loss for Karluk 3rd Oct. Band Levels, dB re 1 m.
80 Hz	0.0	43.9	53.9	55.9	58.9	68.9	73.3		
100 Hz	0.0	41.7	52.9	59.2	57.2	67.7	75.6		
125 Hz	0.0	39.3	50.1	60.1	55.1	72.1	76.2		
160 Hz	0.0	37.7	47.6	59.6	60.6	69.6	78.5		
200 Hz	0.0	36.8	45.9	54.9	55.9	68.9	79.0		
250 Hz	0.0	39.2	46.7	57.7	52.7	73.7	79.3		
315 Hz	0.0	40.7	46.4	55.4	58.4	72.4	76.6		



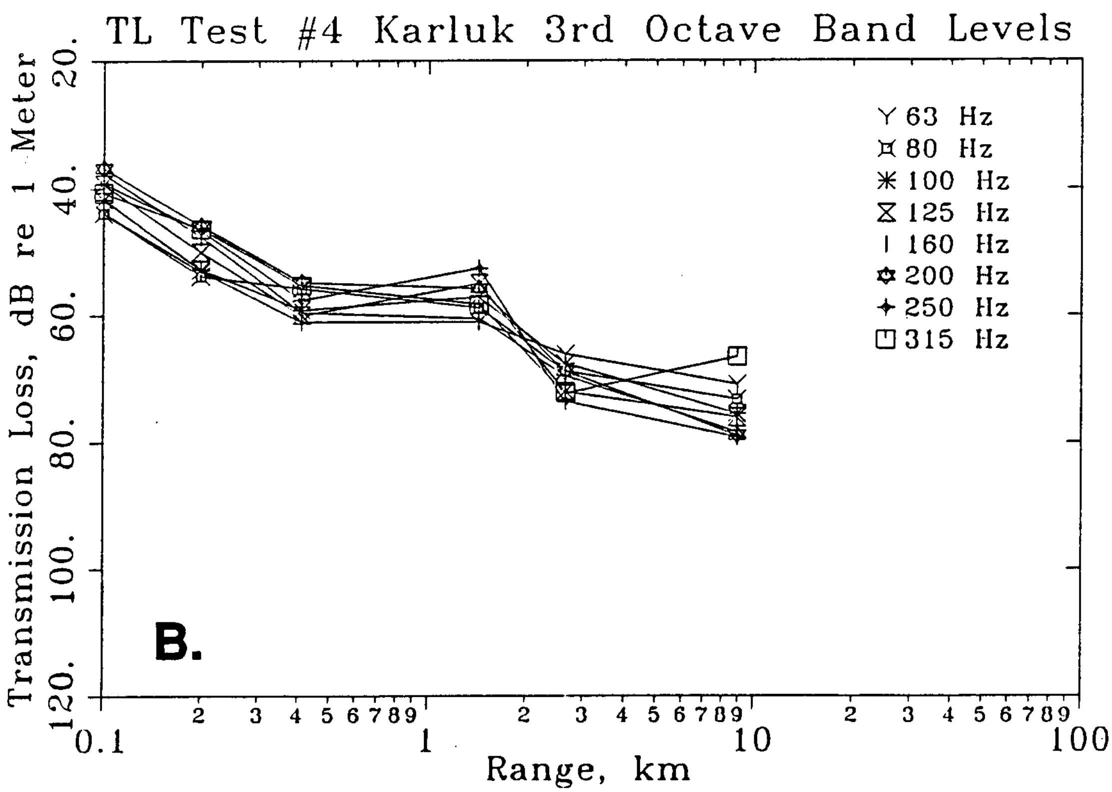


Fig. 43. Transmission loss vs. range for (A) pure tones and (B) *Karluk* sounds during Test #4 on 9 May 1989. The corresponding values are presented in Table 9.

Table 10. **Received levels in third octave bands (dB re 1 μPa) vs. range (m) for (A) the transmitted *Karluk* drilling sounds and (B) the ambient noise at the various receiving stations, Transmission Loss Test #4, 9 May 1989.**

	A.						B.									
Source	Karluk	Karluk	Karluk	Karluk	Karluk	Karluk	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient
Range (m)	100	200	410	1430	2650	8900	100	100	200	410	410	1430	1430	1430	2650	8900
20 Hz	80	73	70	73	72	85	68	70	70	74	68	69	74	70	70	67
25 Hz	79	73	69	74	72	85	69	70	72	79	66	69	76	72	72	66
31.5 Hz	81	73	74	72	69	83	64	70	69	73	61	68	76	69	69	64
40 Hz	88	76	79	78	73	82	61	68	69	73	60	70	72	70	70	63
50 Hz	92	82	79	81	74	80	61	69	68	72	60	69	71	73	72	62
63 Hz	107	98	90	90	85	80	65	71	69	70	59	68	71	68	68	63
80 Hz	109	99	97	94	84	80	61	66	67	67	58	66	69	66	66	62
100 Hz	111	100	93	95	85	77	62	66	68	67	59	63	69	65	65	61
125 Hz	113	102	92	97	80	76	61	62	69	65	63	64	67	65	65	60
160 Hz	117	107	95	94	85	76	66	62	71	64	65	63	67	62	62	65
200 Hz	120	111	102	101	88	78	69	63	73	64	66	63	67	61	61	66
250 Hz	117	110	99	104	83	77	62	61	69	63	59	62	66	61	61	65
315 Hz	107	101	92	89	75	81	63	59	69	59	55	60	62	58	58	63
400 Hz	90	91	82	75	67	79	62	59	67	57	54	59	61	56	56	59
500 Hz	91	91	83	77	68	75	57	59	68	56	52	57	59	56	56	58
630 Hz	95	92	86	80	72	64	56	58	66	55	50	54	57	57	57	56
800 Hz	90	82	83	73	63	61	54	56	64	53	49	52	55	52	52	55
1000 Hz	88	74	82	69	59		54	55	62	52	50	50	54	54	54	
1250 Hz	83	78	80	70	60		58	55	60	50	51	50	52	51	51	
1600 Hz	80	74	70	67	57		56	52	61	49	47	48	52	50	50	
20-500 Hz	124	115	106	107	93	92	76	78	81	82	74	78	82	79	79	75
20-1000 Hz	124	115	106	107	93	92	76	78	81	83	74	78	82	79	79	75

Table 11. Sound propagation loss data, in dB re source level at 1 m, based on HFM sweeps received during (A) transmission test 4 on 9 May 1989 and (B) transmission test 5 on 25-26 May 1989.

A. TL test #4, 9 May 1989.

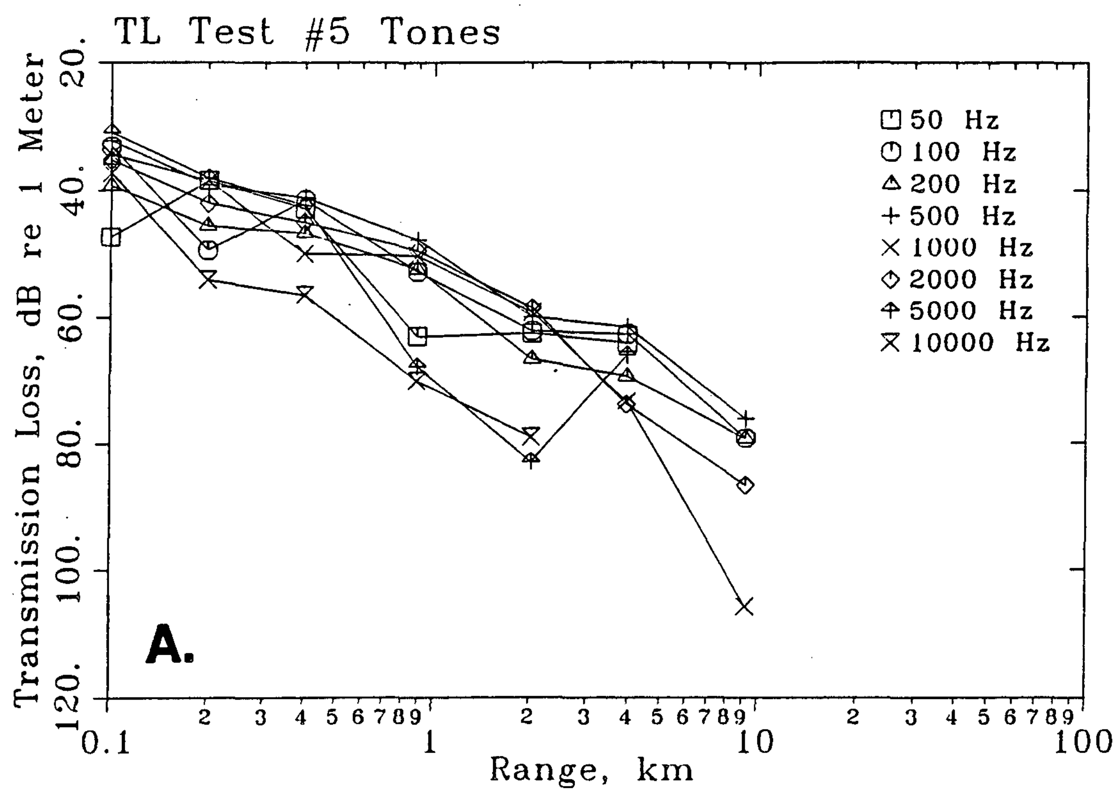
Center Fr.	0.001 km	0.1 km	0.2 km	0.41 km	1.43 km	2.65 km	8.9 km	17.4 km
50 Hz	0.0	46.6	56.1	61.0	58.9	65.8	83.8	
100 Hz	0.0	41.3	53.6	59.0	56.3	68.9	80.2	
200 Hz	0.0	37.5	48.3	56.7	58.1	68.3	79.5	94.0
500 Hz	0.0	43.0	44.5	51.2	57.8	66.9	84.3	
1000 Hz	0.0	38.5	53.3	45.1	58.8	74.6	88.0	
2000 Hz	0.0	42.2	51.3	54.7	53.3	74.8	86.4	
5000 Hz	0.0	42.1	45.9	50.8	61.4	80.4		

B. TL test #5, 25-26 May 1989.

Center Fr.	0.001 km	0.1 km	0.2 km	0.4 km	0.89 km	2.02 km	3.95 km
50 Hz	0.0	46.4	37.0	42.7	56.4	62.5	64.5
100 Hz	0.0	35.3	44.0	41.0	54.2	60.4	64.0
200 Hz	0.0	38.8	47.4	46.3	53.7	64.3	68.5
500 Hz	0.0	34.3	40.1	42.1	52.1	62.1	65.9
1000 Hz	0.0	36.0	40.1	44.3	55.4	65.5	
2000 Hz	0.0	38.6	44.1	46.1	58.4	67.3	75.1
5000 Hz	0.0	41.6	47.8	47.6	72.7	83.5	

Table 12. Sound propagation loss data from a transmission test (TL #5) with (A, C) single frequency tones and (B, D) *Karluk* drilling noise, 25-26 May 1989.

Range, km	0.001	0.1	0.2	0.4	0.89	2.02	3.95	9.21	
50 Hz	156.0	108.7	117.6	113.2	93.0	93.4	91.9		A. Received Levels for Tones, dB re 1 uPa.
100 Hz	160.0	126.8	110.6	118.6	107.2	97.8	97.3	80.8	
200 Hz	164.0	124.7	118.5	117.4	111.6	97.3	94.6	84.7	
500 Hz	153.0	120.7	113.9	111.9	105.2	93.0	91.4	76.9	
1000 Hz	148.0	113.6	109.5	98.1	97.7	88.7	74.6	42.2	
2000 Hz	145.0	109.7	103.0	100.1	95.5	86.4	71.1	58.3	
5000 Hz	140.0	109.0	102.0	97.7	72.2	57.0	74.0		
10000 Hz	145.0	107.7	91.0	88.6	74.9	65.9			
63 Hz	150.0	108.9	107.9	100.9	93.9	89.9	83.9	70.9	B. Received Levels, Karluk 3rd Oct. Band Levels, dB re 1 uPa.
80 Hz	152.0	111.2	104.2	108.2	95.2	89.2	80.2	72.2	
100 Hz	150.0	113.3	106.3	109.3	96.3	89.3	84.3	69.3	
125 Hz	150.0	117.1	111.1	109.1	92.1	91.1	85.1	70.1	
160 Hz	153.0	120.9	109.9	108.9	97.9	88.9	85.9	73.9	
200 Hz	156.0	116.6	109.6	108.6	102.6	91.6	87.6	77.6	
250 Hz	153.0	114.5	110.5	112.5	98.5	93.5	86.5	75.5	
315 Hz	144.0	111.4	105.4	105.4	88.4	83.4	72.4	67.4	
50 Hz	0.0	47.3	38.4	42.8	63.0	62.6	64.1		C. Trans. Loss for Tones, dB re 1 m.
100 Hz	0.0	33.2	49.4	41.4	52.8	62.2	62.7	79.2	
200 Hz	0.0	39.3	45.5	46.6	52.4	66.7	69.4	79.3	
500 Hz	0.0	32.3	39.1	41.1	47.8	60.0	61.6	76.1	
1000 Hz	0.0	34.4	38.5	49.9	50.3	59.3	73.4	105.8	
2000 Hz	0.0	35.3	42.0	44.9	49.5	58.6	73.9	86.7	
5000 Hz	0.0	31.0	38.0	42.3	67.8	83.0			
10000 Hz	0.0	37.3	54.0	56.4	70.1	79.1			
63 Hz	0.0	41.1	42.1	49.1	56.1	60.1	66.1	79.1	D. Trans. Loss for Karluk 3rd Oct. Band Levels, dB re 1 m.
80 Hz	0.0	40.8	47.8	43.8	56.8	62.8	71.8	79.8	
100 Hz	0.0	36.7	43.7	40.7	53.7	60.7	65.7	80.7	
125 Hz	0.0	32.9	38.9	40.9	57.9	58.9	64.9	79.9	
160 Hz	0.0	32.1	43.1	44.1	55.1	64.1	67.1	79.1	
200 Hz	0.0	39.4	46.4	47.4	53.4	64.4	68.4	78.4	
250 Hz	0.0	38.5	42.5	40.5	54.5	59.5	66.5	77.5	
315 Hz	0.0	32.6	38.6	38.6	55.6	60.6	71.6	76.6	



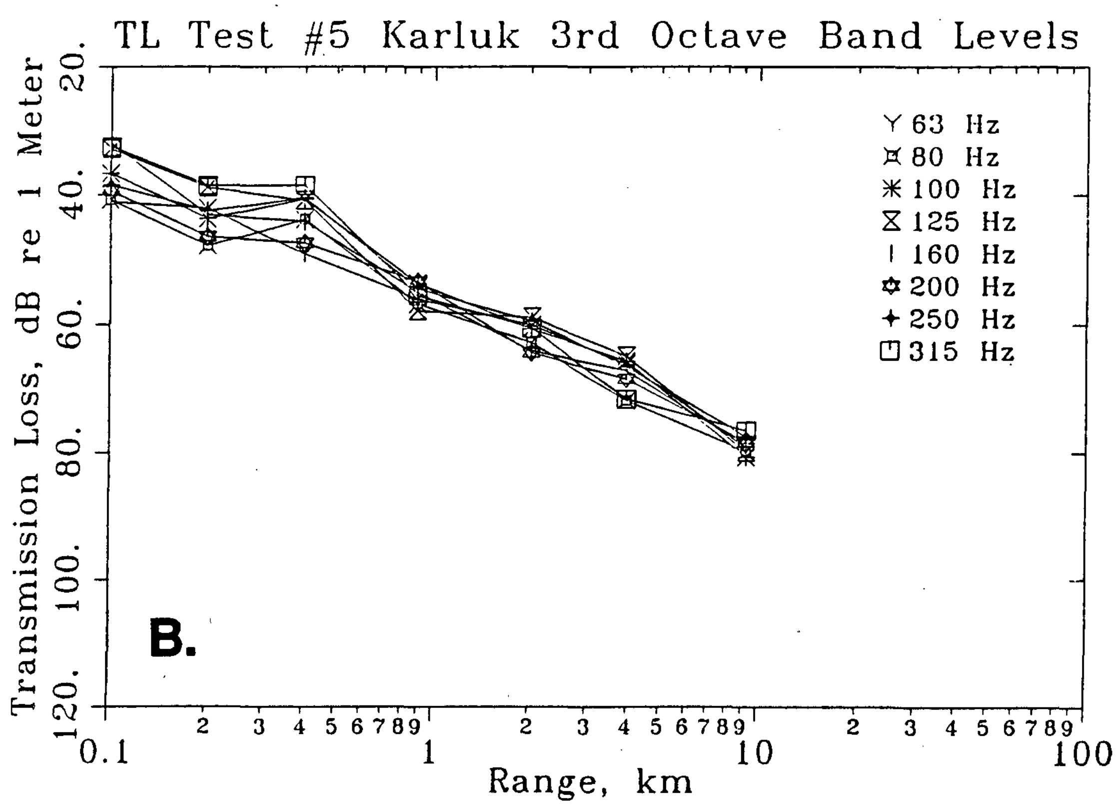


Fig. 44. Transmission loss vs. range for (A) pure tones and (B) *Karluk* sounds during Test #5 on 25-26 May 1989. The corresponding values are presented in Table 12.

Table 13. Received levels in third octave bands (dB re 1 µPa) vs. range (m) for (A) the transmitted *Karluk* drilling sounds and (B) the ambient noise at the various receiving stations, Transmission Loss Test #5, 25-26 May 1989.

A. **B.**

Source	Karluk	Karluk	Karluk	Karluk	Karluk	Karluk	Karluk	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient
Range (m)	100	200	400	890	2020	3950	9210	100	200	400	890	2020	2020	3950	3950	9210
20 Hz	79	77	78	74	68	66	68	69	65	75	70	76	68	65	71	69
25 Hz	82	78	80	76	70	68	70	69	66	74	70	72	67	67	73	71
31.5 Hz	89	85	82	75	71	66	70	68	64	73	69	68	67	65	66	67
40 Hz	87	97	92	77	74	68	70	67	67	76	70	70	69	68	65	70
50 Hz	91	100	93	82	77	74	69	66	68	73	70	75	74	73	66	68
63 Hz	109	108	101	94	90	84	71	68	63	71	70	75	72	70	63	68
80 Hz	111	104	108	95	89	80	72	69	62	74	69	68	67	66	62	73
100 Hz	113	106	109	96	89	84	69	64	63	72	68	73	66	70	62	67
125 Hz	117	111	109	92	91	85	70	62	64	72	70	72	66	68	64	68
160 Hz	121	110	109	98	89	86	74	63	60	71	70	71	68	66	64	66
200 Hz	117	110	109	103	92	88	78	62	60	69	69	72	67	64	67	66
250 Hz	115	111	113	99	94	87	76	73	72	72	70	72	72	71	74	67
315 Hz	111	105	105	88	83	72	67	69	60	82	80	71	68	72	73	76
400 Hz	98	96	90	87	89	75	66	72	57	82	71	71	69	69	68	80
500 Hz	98	91	91	99	75	77	68	86	57	66	78	70	66	63	67	77
630 Hz	102	93	94	89	79	73	70	80	62	66	81	70	66	73	67	66
800 Hz	96	96	86	78	76	66	71	77	72	74	86	79	66	80	72	68
1000 Hz	88	94	82	86	76	79	68	60	77	78	87	83	69	81	67	65
1250 Hz	78	86	80	82	84	71	60	54	68	74	78	79	83	77	68	61
1600 Hz	77	77	73	83	89	58	57	51	59	60	74	78	85	68	71	59
20-500 Hz	125	118	118	107	100	94	83	85	77	88	84	84	81	80	80	84
20-1000 Hz	125	118	118	107	100	94	84	88	79	88	90	86	81	85	81	85

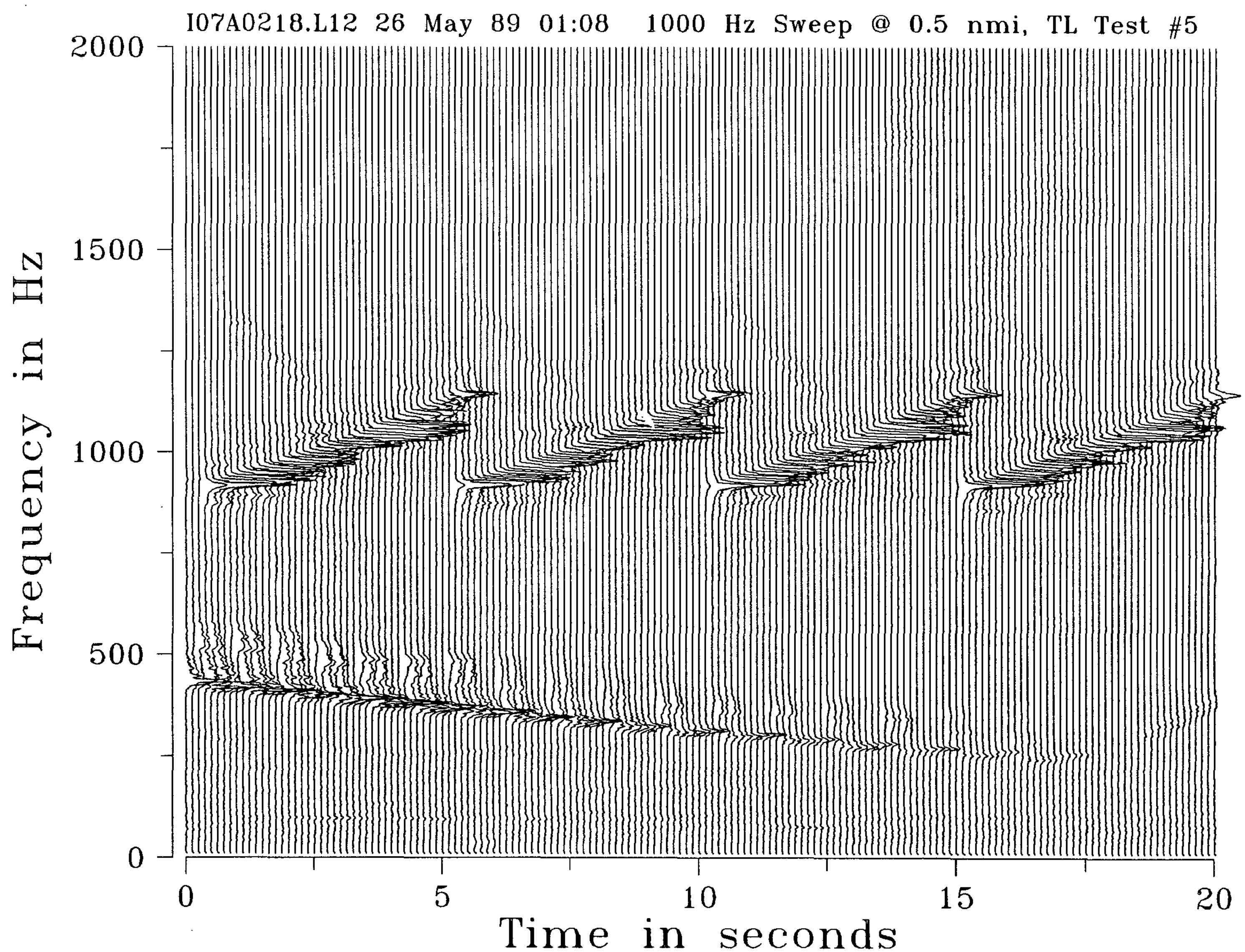


Fig. 45. Waterfall spectrogram for four HFM sweeps near 1000 Hz, as received at range 890 m during TL Test #5, 26 May 1989. The descending-frequency sound below 500 Hz is part of a bearded seal call.

bottom composition, and sound frequency. The water depth, being generally shallow, limits low frequency propagation. However, depths at different locations in the study area vary greatly (Fig. 19). This will cause local variations in propagation. Sound speed usually varies with depth in the water column, and under ice the sound speed tends to increase with increasing depth. This causes sound rays to be refracted upward, whereupon they are reflected by the ice.

The rough underice surface scatters sound, especially at higher frequencies. This scattering results in sound attenuation whose magnitude is linearly related to range. This attenuation is additional to the usual spreading losses that are logarithmically related to range. The amount of scattering loss caused by the underice surface is related to ice roughness, with greater losses under rough ice than under smoother ice.

The effects of ice roughness on scattering loss are frequency dependent. Sound wavelength is inversely related to frequency, and it is the relationship between ice roughness and wavelength that determines the amount of scattering loss. At high frequencies (kilohertz range), volumetric absorption of sound by seawater also becomes an important factor in long-distance sound propagation.

<u>Weston/Smith Propagation Models for 1989 Data</u>.--Semi-empirical Weston/Smith sound propagation models were fitted to the transmission loss data acquired during TL Tests 4 and 5, as described in the "Methods" section. These models assume that there is a spherical spreading region near the sound source, cylindrical spreading at somewhat greater ranges, a third "mode stripping" region, and--at the longest ranges--a fourth "lowest mode" region. The models allow for gradual changes in water depth along the propagation path and for volumetric absorption of high-frequency sounds. However, they do not allow for vertical changes in sound speed within the water column.

The empirical components of the Weston/Smith models are the several site-specific terms that are derived by regression analysis of TL data measured in the field (see Methods). Table 14 shows the results of the regression analyses of the data for TL Tests 4 and 5.

The bottom loss values (b) in Table 14 were comparable for the two test areas (except at 2 kHz). In both areas, b tended to increase with increasing frequency. This suggests that bottom composition in the two test areas is similar.

The ice scattering loss A_b was frequency dependent, becoming larger with increasing frequency. This was expected. The under-ice roughness produces greater scattering when the sound wavelengths become shorter.

The local anomaly values (A_n) shown in Table 14 are negative for most transmission loss measurements. This was likely caused by the relatively high values of scattering loss from the ice layer. Previous measurements in coastal regions of the Alaskan Beaufort Sea during open water conditions often showed positive transmission anomalies (Miles et al. 1987).

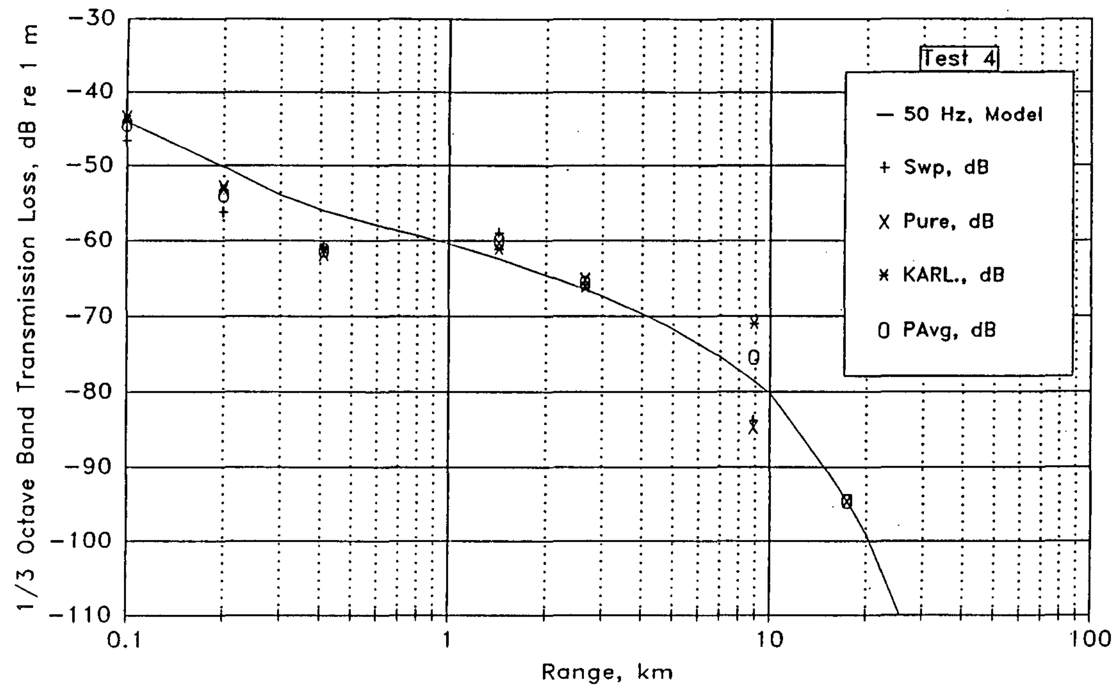
Table 14. Parameters for Weston/Smith model for best-fit match to transmission loss data from TL Tests 4 and 5, May 1989

Frequency (kHz)	Parameter					
	b	sin ϕ_c	A_b(dB/bounce)	A_n(dB)	E_{rms}(dB)	Fig. No.
A. TL Test 4						
0.05	0.45	0.2	0.15	-4	2.8	46A
0.1	0.65	0.2	0.22	-3	3.8	46B
0.2	0.90	0.2	0.17	-1	2.4	46C
0.5	1.35	0.8	0.20	-4	1.7	46D
1	0.85	0.8	0.17	-6	5.3	46E
2	0.25	0.8	0.30	-7	5.1	46F
5	1.74	0.8	0.30	-6	3.7	46G
B. TL Test 5						
0.05	0.40	0.2	0.03	-1	3.9	47A
0.1	0.88	0.8	0.05	-1	2.8	47B
0.2	0.95	0.8	0.05	-5	1.9	47C
0.5	1.20	0.8	0.07	1	1.9	47D
1	0.67	0.8	0.17	-1	0.7	47E
2	1.22	0.8	0.11	-2	1.7	47F
5	1.29	0.8	0.40	-2	6.4	47G

The E_{rms} column in Table 14 shows the average difference between the data and the values expected based on the best-fit Weston/Smith curves. The smallest errors occurred in the mid-frequency range. Those data apparently were less influenced by station-specific variations in local bottom and ice conditions than were the low and high frequency results.

Figure 46A-G shows the curves obtained using the Weston/Smith models with the parameters shown in Table 14A for TL Test 4. As indicated by the E_{rms} values in the table, the largest differences between the fitted curves and the data occur at 1 and 2 kHz (Fig. 46E,F). For both of these frequencies, TL values based on the 2 or 3 different signal types frequently were closely grouped but offset some distance from the fitted curve. This is probably partly a result of the fact that the Weston/Smith model predictions are for depth-averaged TL, whereas the data were all measured at one hydrophone depth (18 m). Also, for narrow band data (e.g. the pure tones) and even for bandwidths as broad as 1/3-octave (e.g. the *Karluk* and HFM signals), multipath interference effects cause local deviations from the overall transmission loss trend. These deviations are particularly common at short distances from the source. These effects can be minimized by using frequency or spatial averaging in obtaining the transmission loss data. The TL data from the *Karluk* signals and HFM sweeps already incorporate some frequency averaging, since their bandwidths were 1/3-octave. Another approach is to use a model that does not incorporate depth averaging.

A. 50 Hz



B. 100 Hz

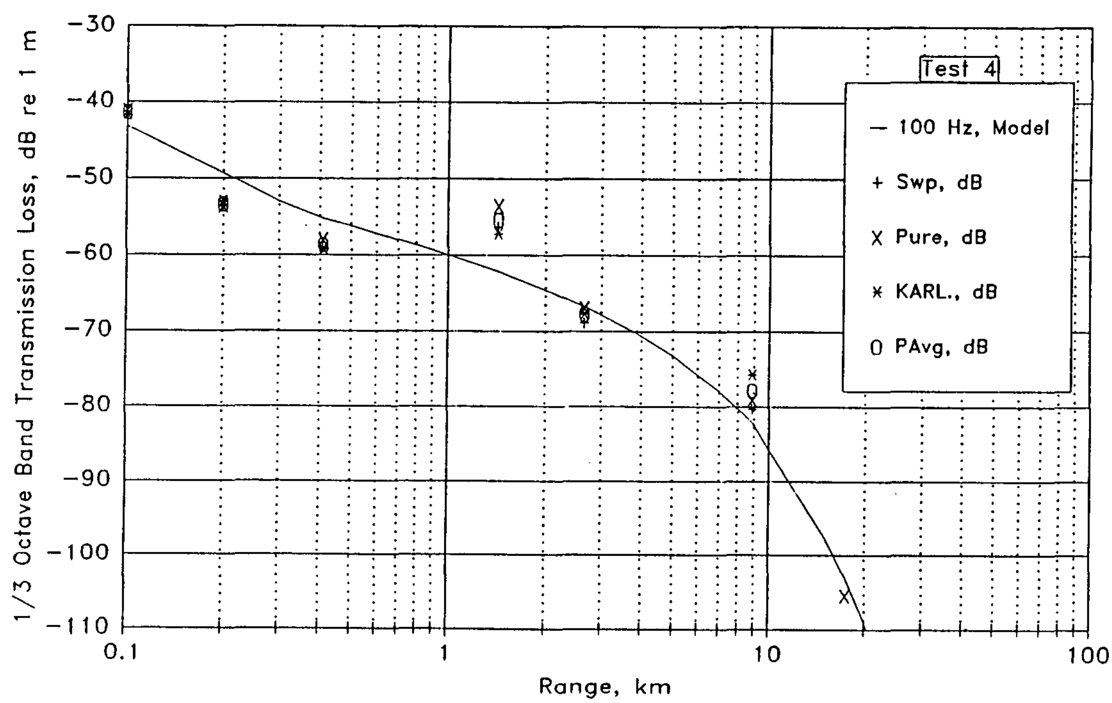
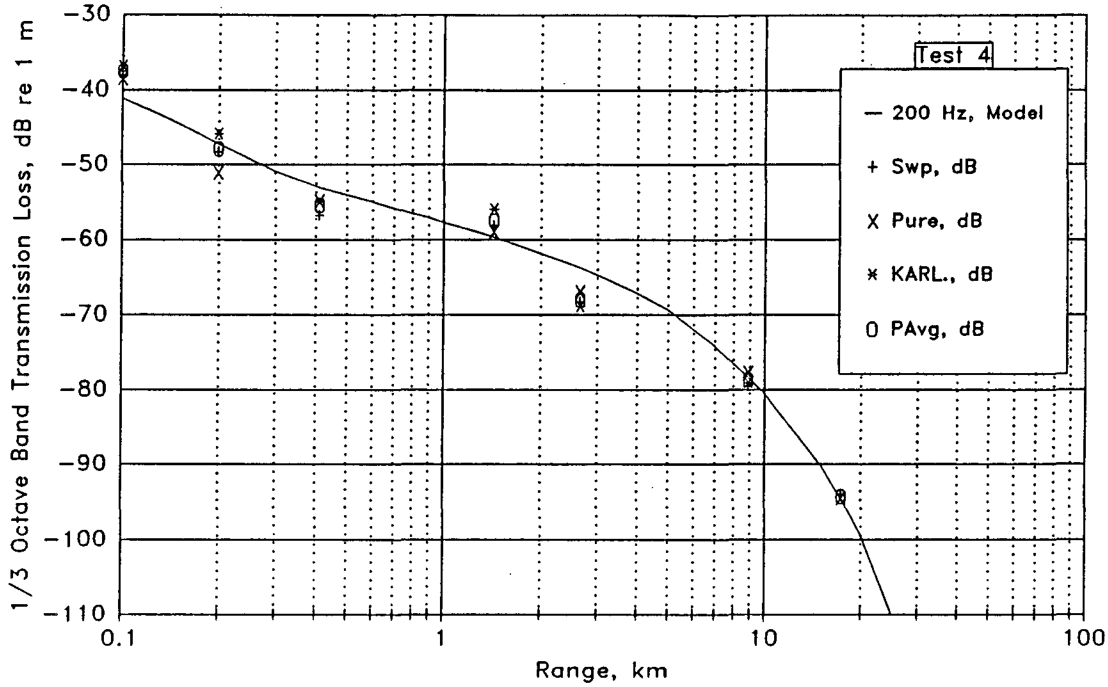


Fig. 46. Measured transmission loss data from TL test #4, 9 May 1989, compared with best-fit Weston/Smith model with ice scattering term. (**A**) 50 Hz, (**B**) 100 Hz, (**C**) 200 Hz, (**D**) 500 Hz, (**E**) 1 kHz, (**F**) 2 kHz, (**G**) 5 kHz.

C. 200 Hz



D. 500 Hz

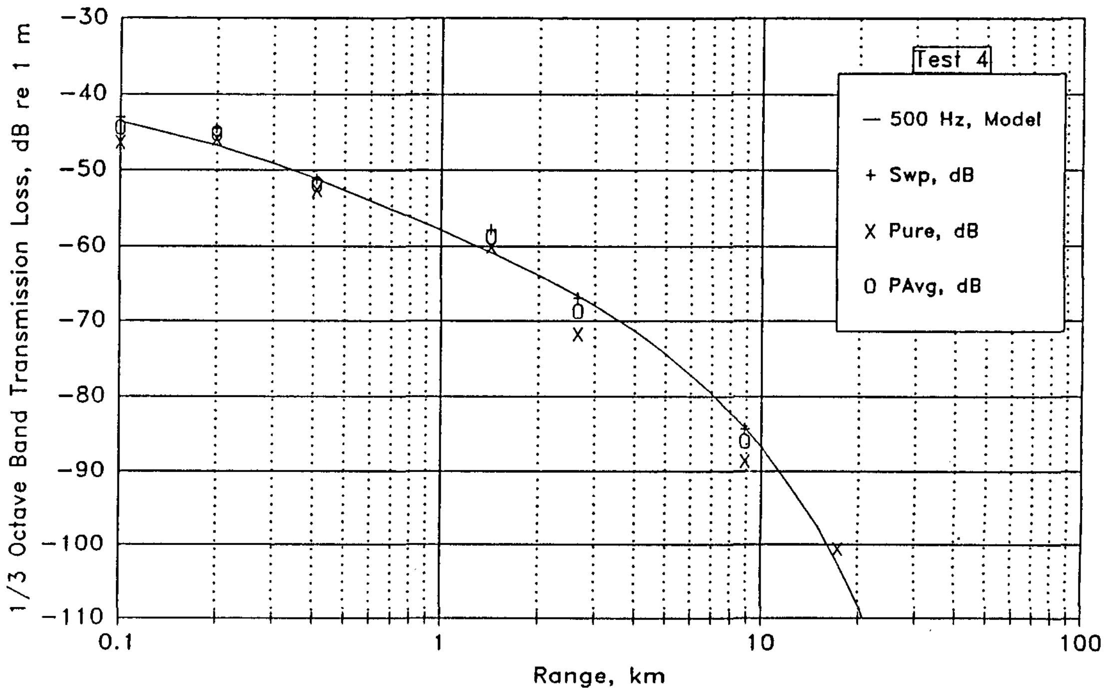
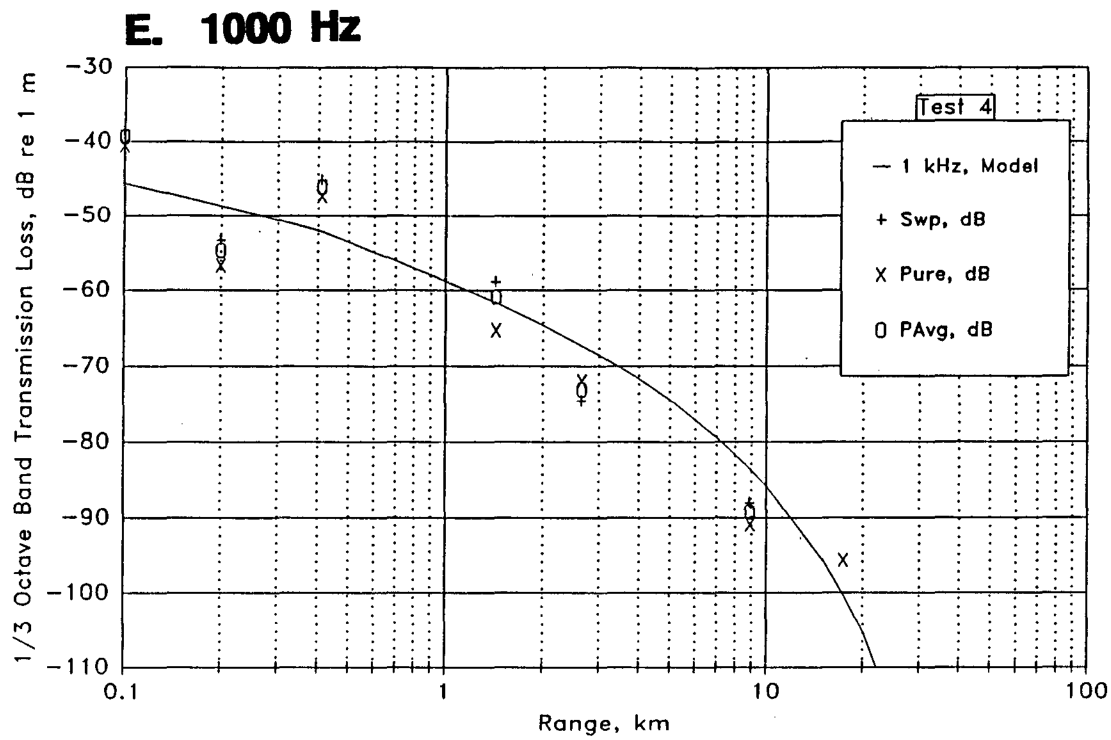


Fig. 46. Continued.



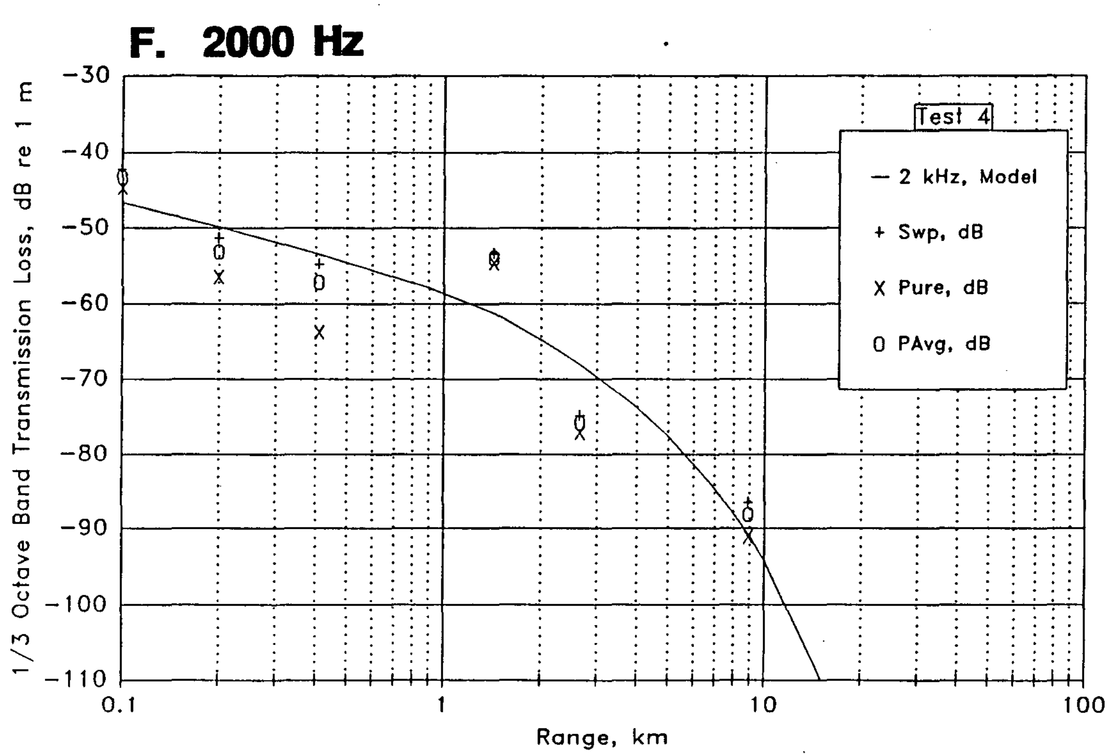


Fig. 46. Continued.

G. 5000 Hz

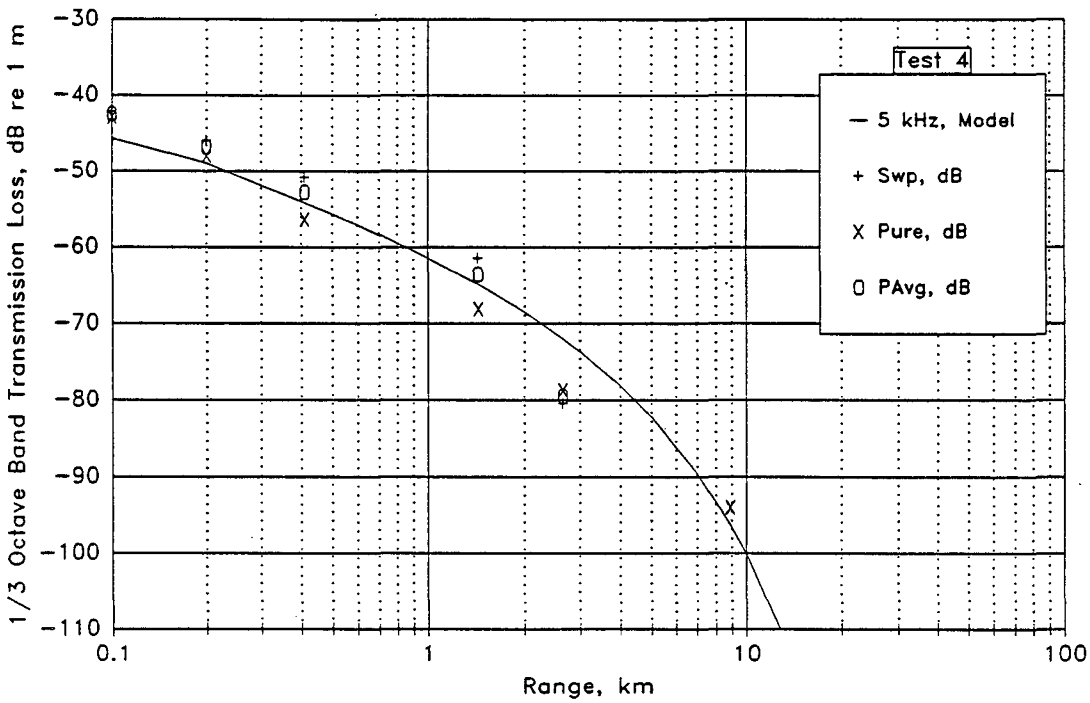


Fig. 46. Concluded.

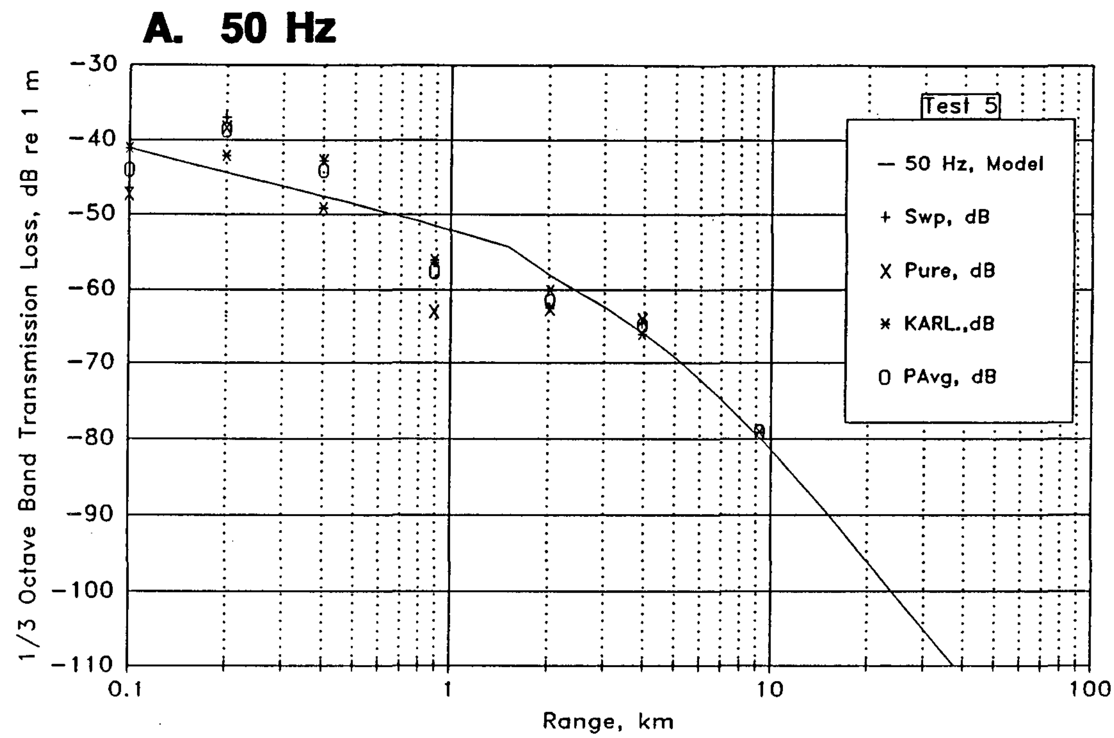
Figure 47A-G show the comparisons for TL Test 5. Here the agreement between the fitted curves and the data is fair at 50 and 100 Hz, and generally good for the mid-frequencies. However, at 5 kHz the data showed considerable scatter (Fig. 47G). The outlying data point for the pure tone measurement at range 4 km was not used in the analysis. The BBN matched-filter HFM data point (Fig. 47G) suggests that the model may overestimate transmission loss (i.e. underestimate received levels) at ranges beyond 4 km. As noted earlier, the matched-filter HFM data points were not included in the Weston/Smith analyses but are shown in Fig. 47 for comparison with the model predictions.

Caution is necessary in any application of these Weston/Smith models to other source locations and transmission paths within the study area. The models are specific to the ice conditions and bottom slope geometries that were involved in TL Tests 4 and 5, among other restrictions. However, some generalizations to other Beaufort regions with similar water depths and ice cover can be made. These models may be useful in predicting sound transmission ranges under similar field conditions during future spring seasons.

Figure 48A summarizes the Weston/Smith predictions of transmission loss as a function of frequency for a series of ranges extending southwest from a source in the Test 4 area. The effects of moderate bottom losses and moderate ice scattering losses produce a generally frequency-independent transmission loss below 1 kHz in this region. Ice conditions in this test area were nearly 100% cover, largely by relatively smooth pack ice. The apparent increase in transmission loss around 100 Hz at the longer ranges was the result of the slightly higher estimated ice scattering loss at this frequency (see Table 14A). Above 1 kHz, the effects of molecular absorption as well as higher rates of ice scattering loss become significant at longer ranges.

Similar curves are shown in Figure 48B for westward propagation from the Test 5 area. There the low frequency transmission loss was independent of frequency up 500 Hz. The transmission losses were lower in this area than in the Test 4 area in part because of lower ice scattering losses at low frequency (see Table 14). The propagation path during Test 5 was near a pack ice edge bordering an open lead. The relatively low ice scattering losses at 2 kHz (possibly anomalous) as compared with those at 1 kHz caused greater attenuation at 1 kHz than at 2 kHz, unlike the situation in the Test 4 area. Another reason for the predicted slower attenuation of sounds in the Test 5 than in the Test 4 area was the increasing water depth along the Test 5 propagation path, as opposed to the diminishing water depth along the Test 4 path (Fig. 49).

Comparison with Theoretical PE Models.--Prior to the 1989 field season, some preliminary transmission loss modeling was performed for the present study area (Malme et al. 1989; included as Appendix A of this report). The objective was to estimate, for the sounds that were to be projected during this study, received levels vs. range and maximum anticipated ranges of audibility. These models assumed that the sounds would be projected from sites 60 km ENE or NE of Pt. Barrow (see Fig. 1A in Appendix A). The models attempted to predict sound



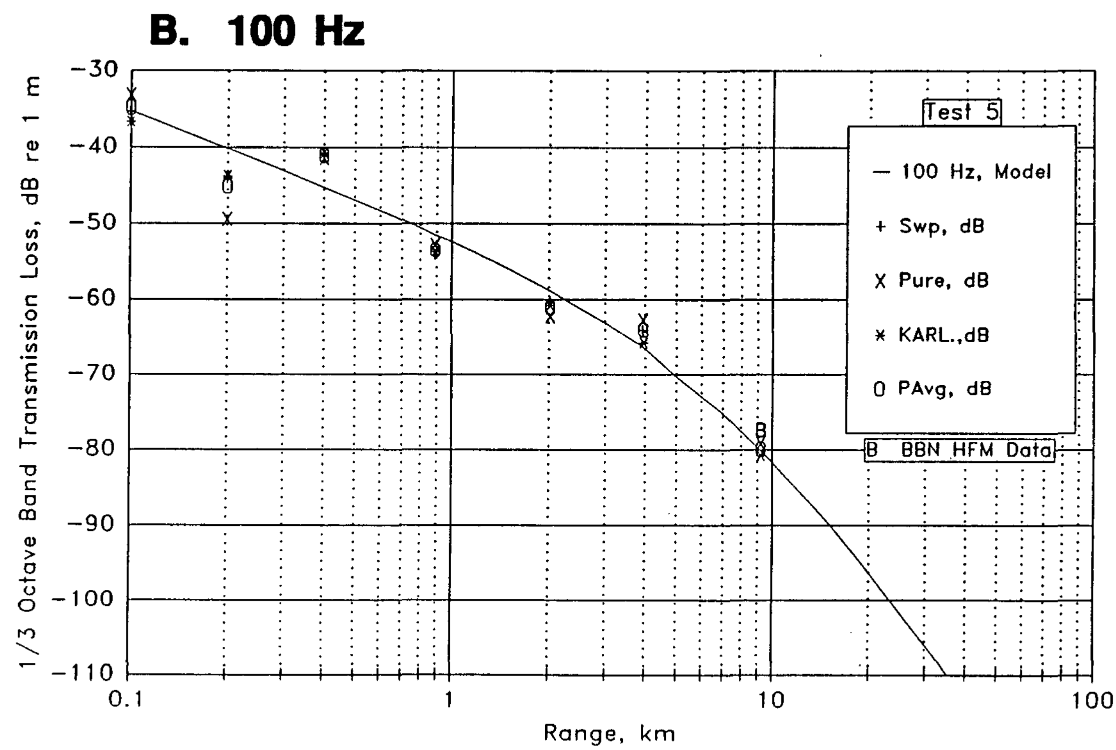
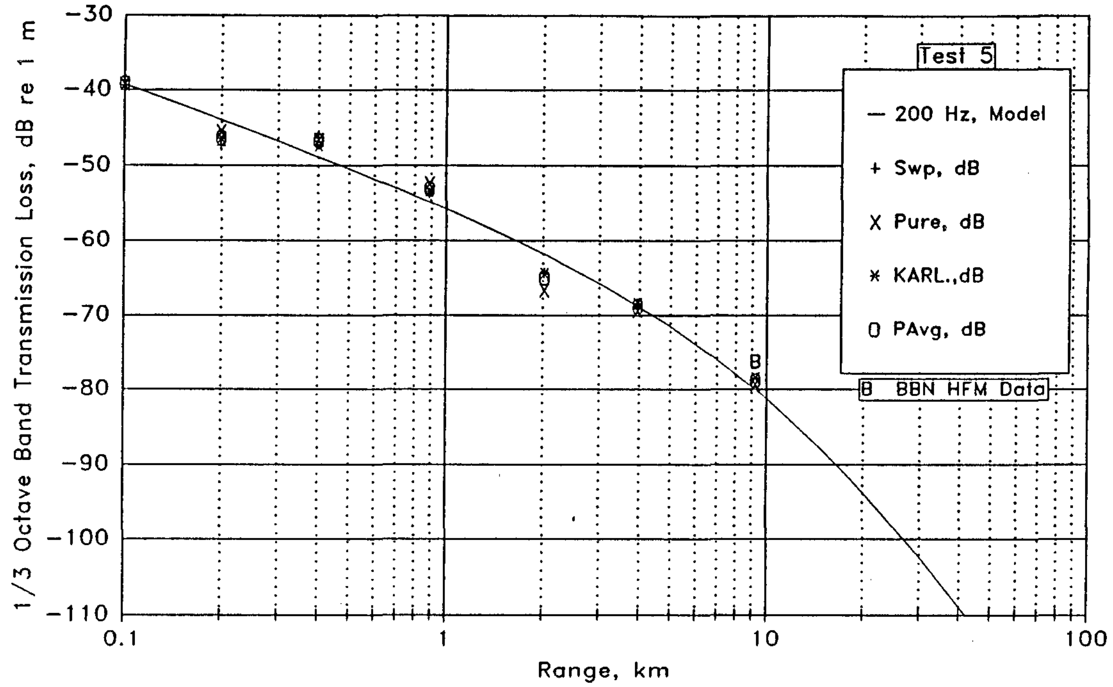


Fig. 47. Measured transmission loss data from TL test #5, 25-26 May 1989, compared with best-fit Weston/Smith model with ice scattering term. (**A**) 50 Hz, (**B**) 100 Hz, (**C**) 200 Hz, (**D**) 500 Hz, (**E**) 1 kHz, (**F**) 2 kHz, (**G**) 5 kHz.

C. 200 Hz



D. 500 Hz

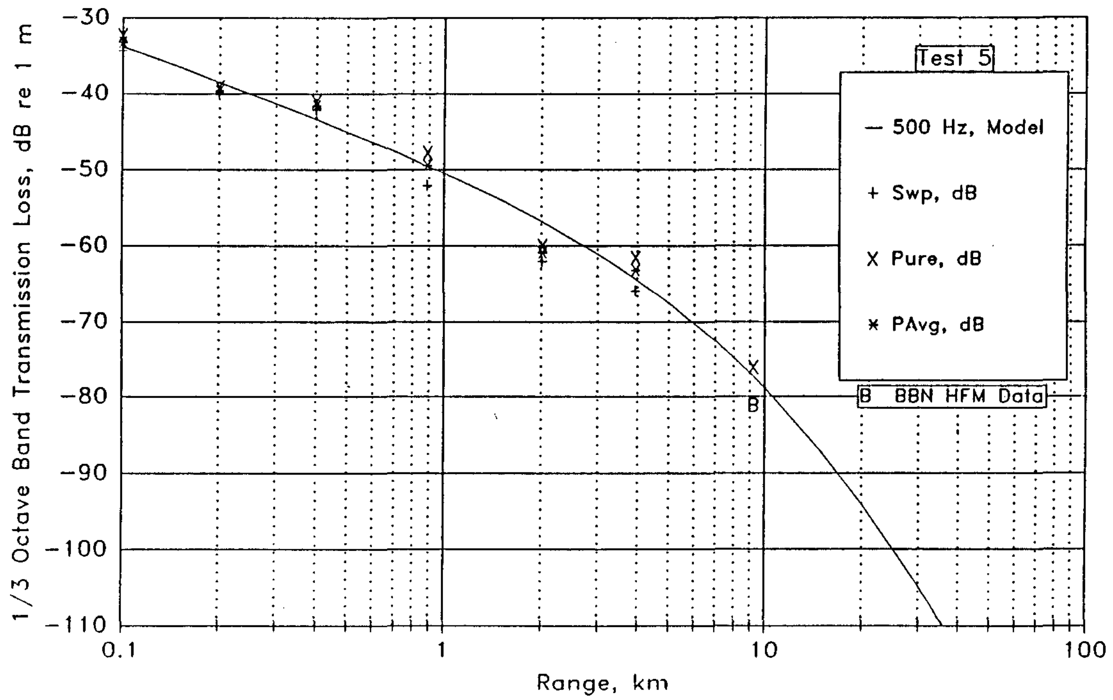
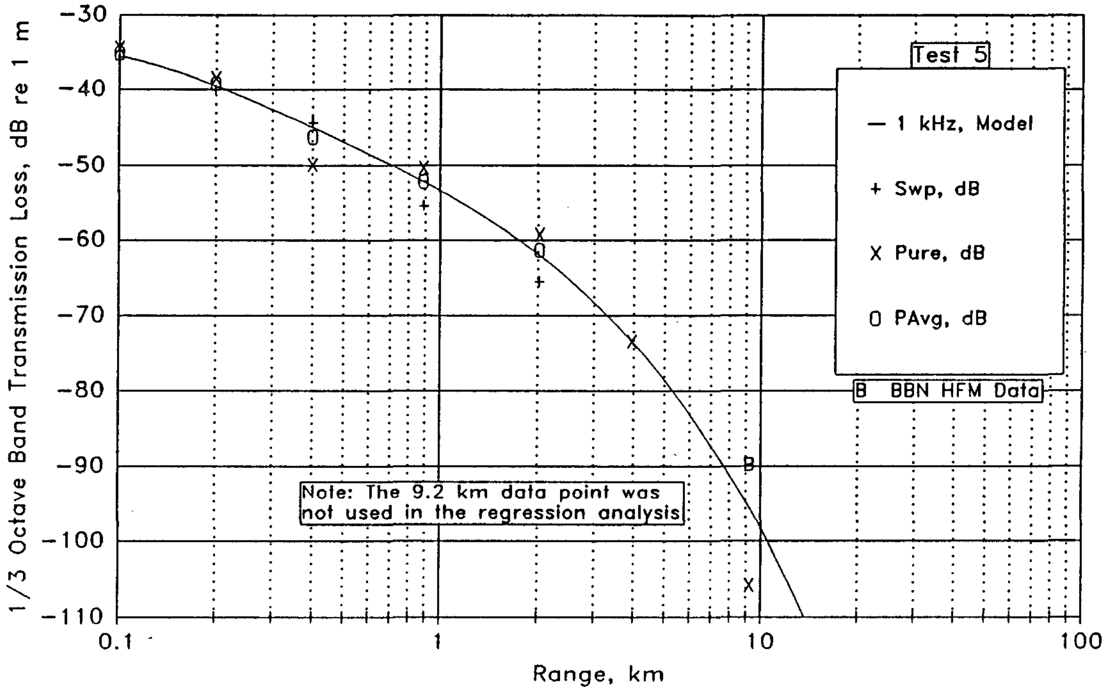


Fig. 47. Continued.

E. 1000 Hz



F. 2000 Hz

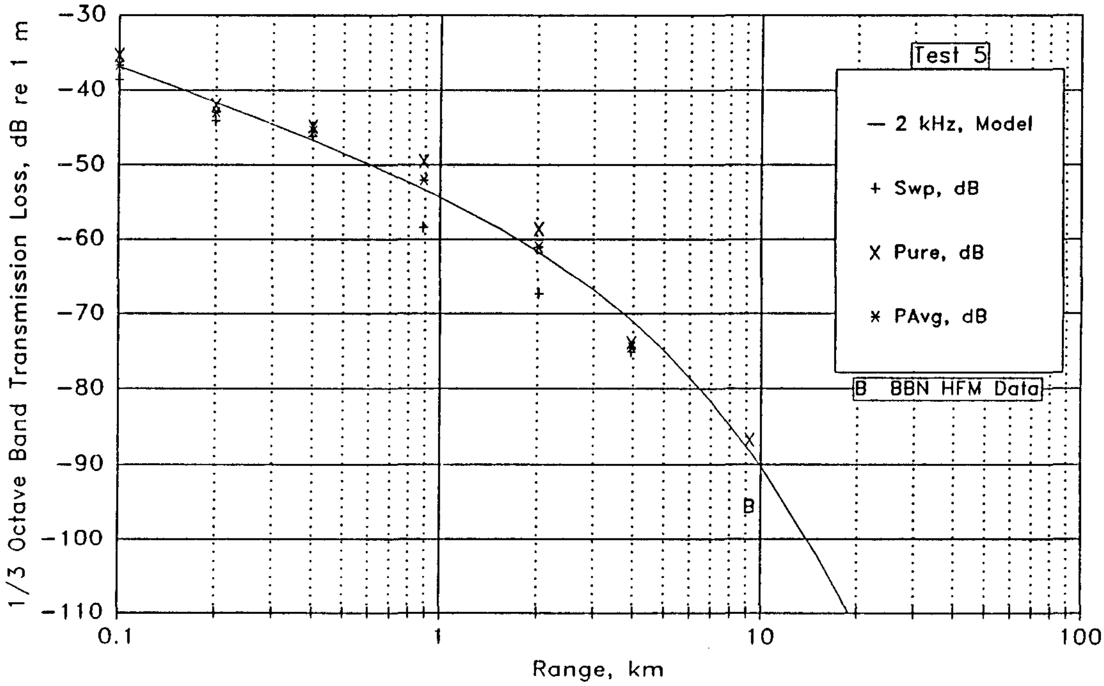


Fig. 47. Continued.

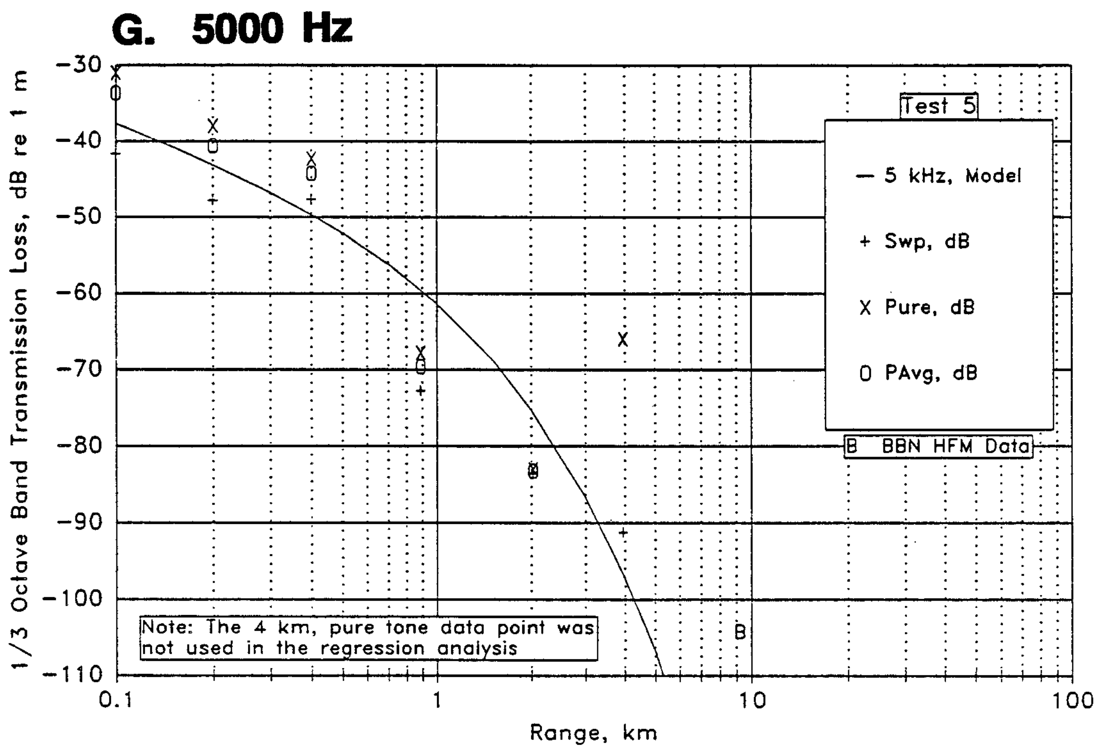
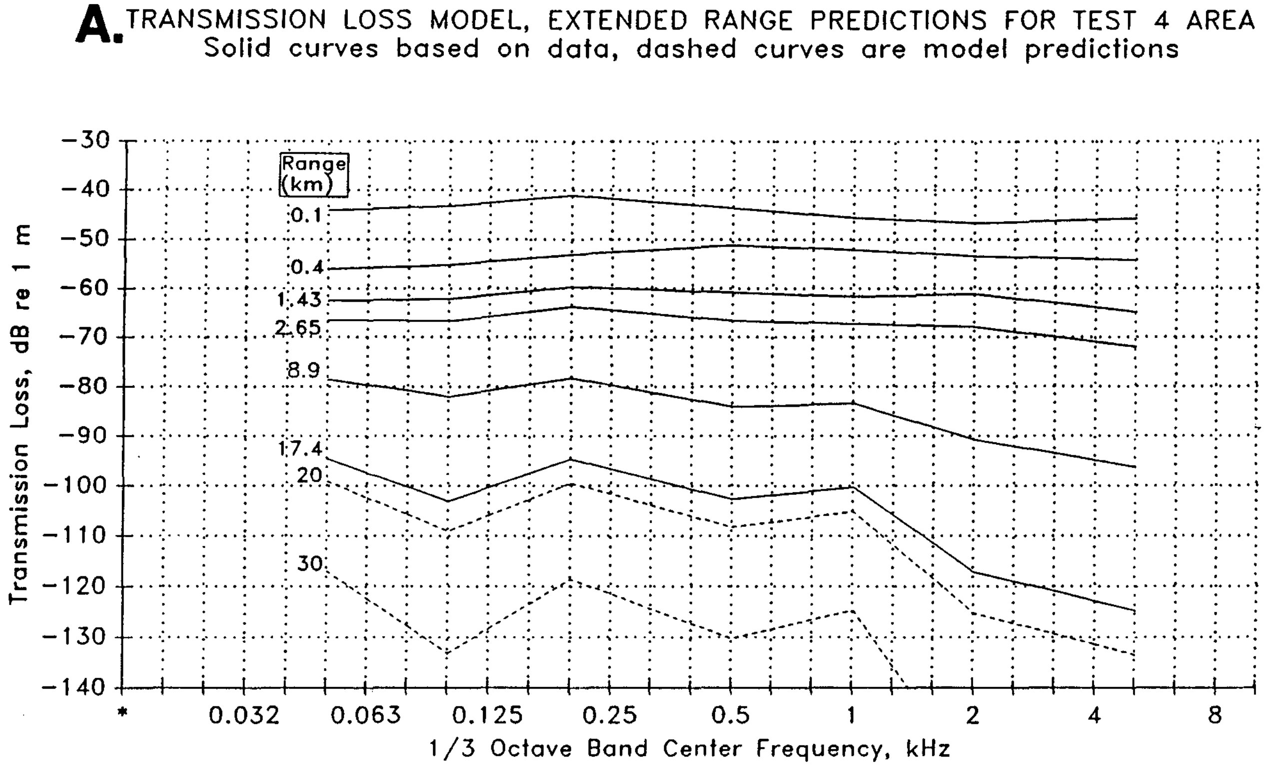


Fig. 47. Continued.



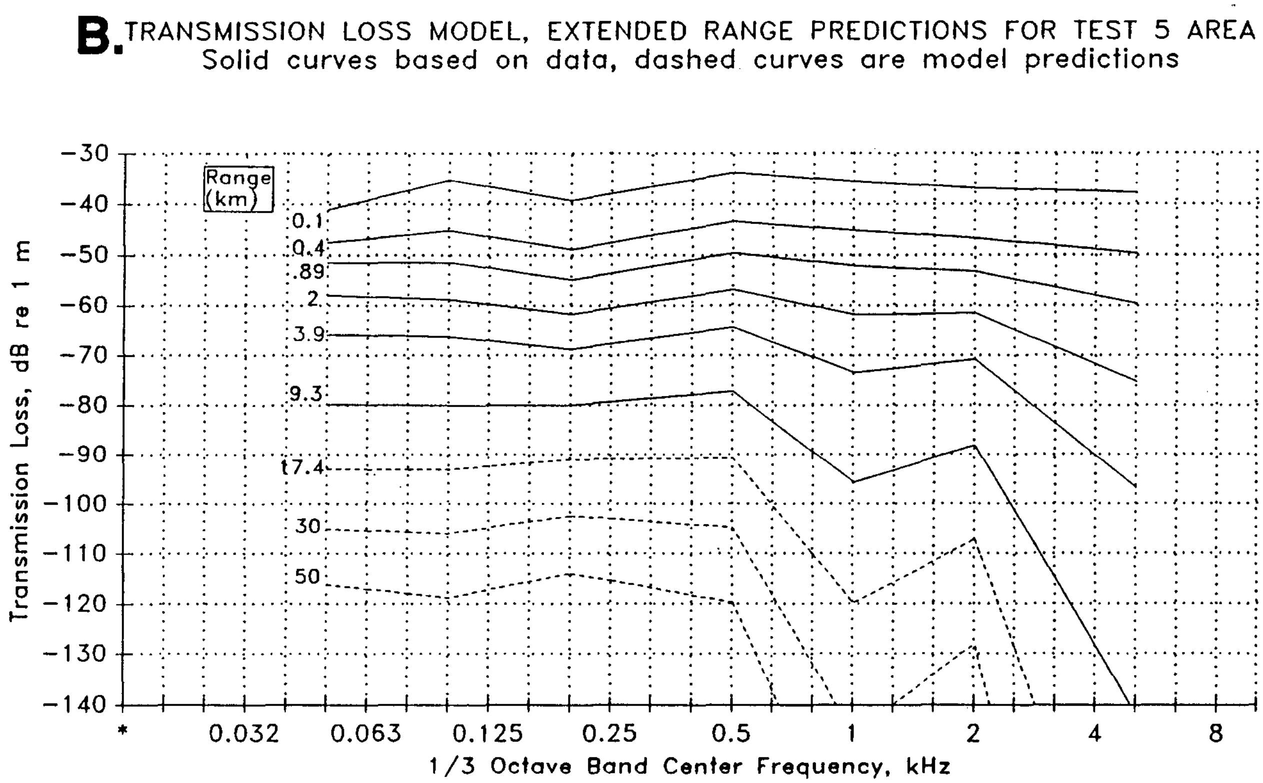


Fig. 48. Predicted transmission loss vs. frequency at selected ranges, based on the Weston/Smith models for (**A**) southwest propagation from the TL test #4 area, and (**B**) westward propagation from the TL test #5 area. Solid curves based on data; dashed curves are model predictions beyond the range of data.

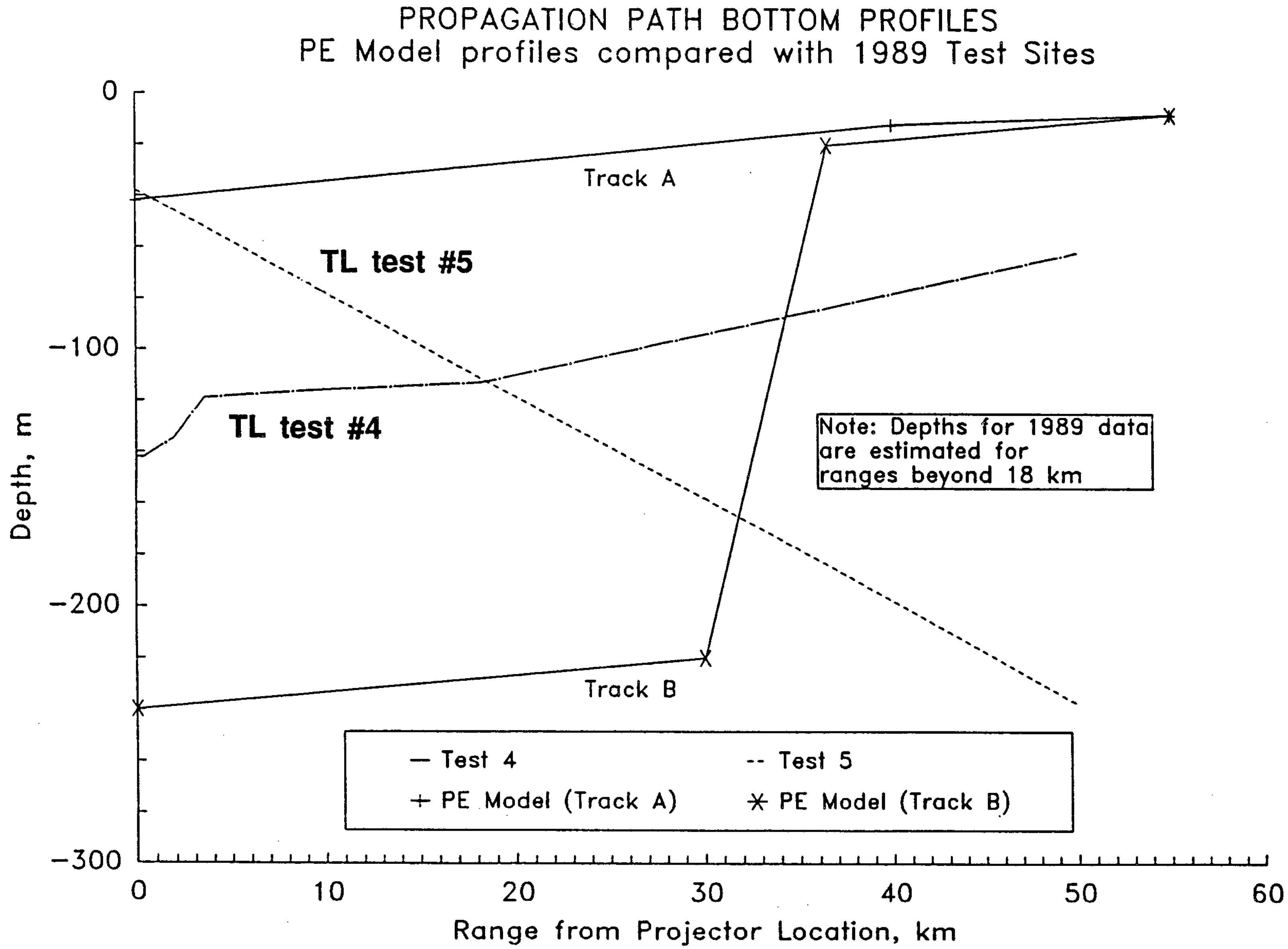


Fig. 49. Propagation path bottom profiles for two paths to which the PE model was applied before the 1989 field season (Tracks A and B) and for 1989 TL test #4 and 1989 TL test #5.

attenuation rates along propagation paths oriented to the WSW or SW, toward the Pt. Barrow area. This modeling was done using the Parabolic Equation or PE model (U.S. Naval Oceanographic Office 1988a,b,c), which is capable of modeling sound transmission under ice cover based on information about bottom composition, bottom slope, sound speed profile, and ice layer roughness. Bottom profiles for the two transmission paths modeled are shown in Figure 49 (Tracks A and B).

A comparison of these depth profiles with the profiles for the test areas actually studied in 1989 shows considerable differences. However, in order to compare the PE model results and the measured data, we decided to compare the predictions for Track B, commencing in deep water NE of Pt. Barrow, with the Weston/Smith model and empirical data from TL Test 4. In both cases, sounds propagated southwest from deeper water into shallower water. The bottom slopes were generally similar for the first 30 km, but the bottom depth was 120 m deeper for Track B than for the actual TL Test 4. A 1-m rms ice roughness was assumed in the PE model. Test 4 was conducted in an area of relatively smooth pack ice where the under-ice roughness probably was not inconsistent with the 1-m average used in the PE model. As a result, the ice scattering losses in the Test 4 area would be expected to be comparable to those predicted by the PE model for Track B. However, the shallower water in the Test 4 area would be expected to cause higher transmission losses than predicted by PE model for Track B, except near the end of Track B where the water shoals rapidly (Fig. 49).

The measured results shown in Figure 50A-C generally agree with the shape of the transmission loss curves predicted by the PE model for Track B. However, as expected, the measured data had somewhat higher transmission losses. It is not possible to resolve whether this was attributable to the depth difference alone, or whether it was also affected by differences in ice conditions. Perhaps the actual ice conditions during Test 4 averaged somewhat rougher than the ice assumed in the PE model. More detailed field measurements of ice conditions and bottom topography, beyond the scope of the present project, would be needed to resolve this. (The prominent "valley" and "peak" near 1 km in the results from the PE model were caused by interference of the modeled sound components transmitted via direct and bottom-reflected paths. These effects are strongly dependent on the precise frequency and receiver depth being modeled. They are usually not as pronounced in broadband or depth-averaged data.) This comparison shows that the PE model is useful for predicting transmission loss in ice-covered regions, but that it is important to use accurate input parameter values, and to be cautious in interpreting the predictions--especially for longer ranges.

PE model predictions for Track A, oriented toward Pt. Barrow from a point 60 km to the ENE, were inappropriate for comparison with the Weston/Smith models and data from Test 5, even though the assumed (Track A) and actual (Test 4) sources were in the same general area. The bottom slopes for these two tracks are quite different--downslope into deeper water for westward propagation during Test 5 vs. upslope into shallower water for WSW propagation along Track A.

Transmission Loss in Various Shallow-Water Areas

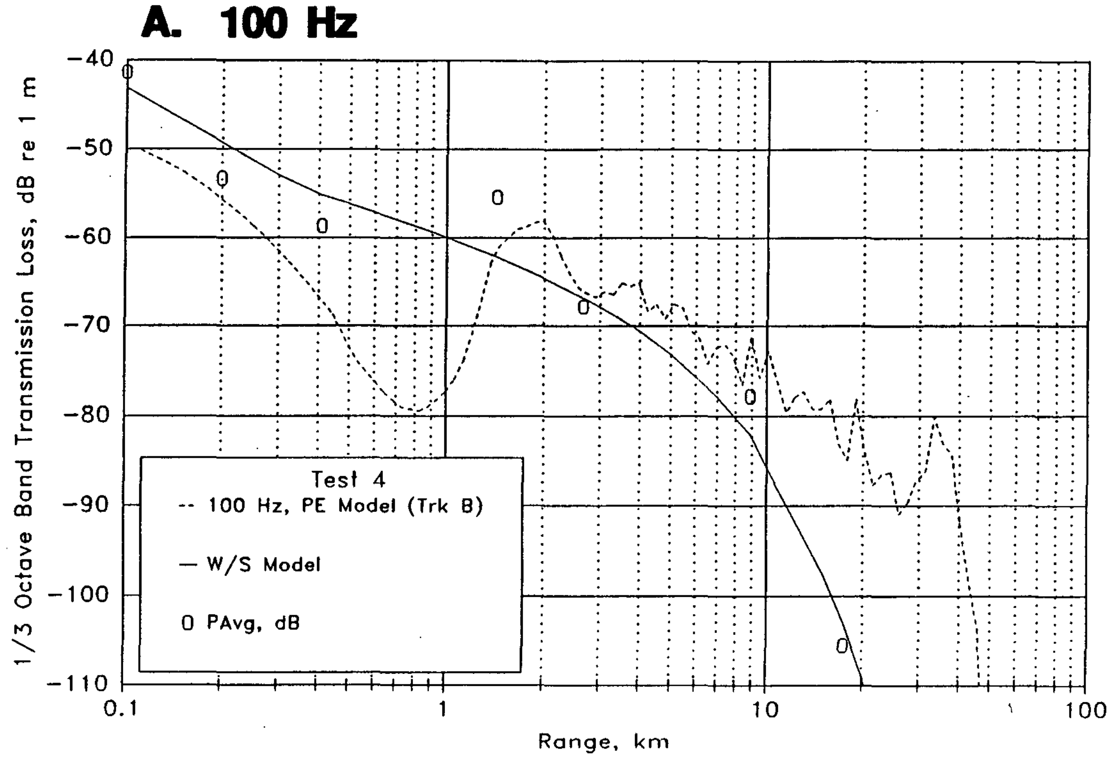
Sound transmission data have been reported in a more-or-less standardized way based on several studies of TL in the Beaufort and Chukchi Seas and off the California coast. It is of interest to compare sound attenuation rates in these various regions with those during spring in our study area northeast of Pt. Barrow (specifically at Test Sites 4 and 5).

Data Sources.--For the Canadian Beaufort Sea, measurements of radiated noise from dredging and drilling activities during summer open-water conditions (Greene 1985) were analyzed by Miles et al. (1987) to obtain transmission loss information. For the Alaskan Beaufort Sea, transmission loss was measured directly by Miles et al. (1987) during late summer. Greene (1981) reported TL data from the Chukchi Sea during winter and summer conditions. Malme et al. (1984) obtained data on TL off the California coast. Malme et al. measured received levels of pulses from an airgun source; the dominant frequencies were in the 1/3-octave band centered at 100 Hz. Considering all of these studies, most data were obtained in water depths <100 m. Consequently, data from the Test 5 area, with depths 42 to 112 m, were considered to be the most appropriate for comparison.

All of the above datasets were analyzed to obtain best-fit coefficients for the Weston/Smith model such that comparisons could be made on a numerical basis as well as graphically. (The Chukchi Sea "dataset" used in this analysis was actually generated using the regression formulae reported by Greene (1981), which were based on his analysis of measured data.) The Weston/Smith models are most accurate when vertical gradients of sound speed are small. Because of this, we attempted to select datasets with little or no vertical variation in sound speed. Unfortunately, this was not always possible because sound speed profiles sometimes were not reported. Also, in some areas the measurements were made during seasons when sharp speed gradients exist.

Weston/Smith Parameters.--In most arctic regions that become ice-free in summer, a layer of slightly warmer water develops near the surface in late summer. Since sound speed is faster in this layer, sound rays tend to be bent (refracted) downward from a shallow underwater source. Hence, these sound rays undergo many reflections from the bottom and surface as they travel away from the source. Because of these reflections, the transmission loss is higher than would occur in water with a more uniform temperature distribution.

In late autumn, the surface layer becomes colder than the deeper, more saline water, and sound speed near the surface becomes slower than that at depth. In this case sound rays are bent upward as they travel away from a shallow source, and the number of bottom reflections is reduced. If the surface is calm or covered with smooth ice, the transmission loss is reduced relative to that in the neutral gradient case. However, when the surface is covered with rough broken ice, reflection and scattering losses are high and transmission loss is increased.



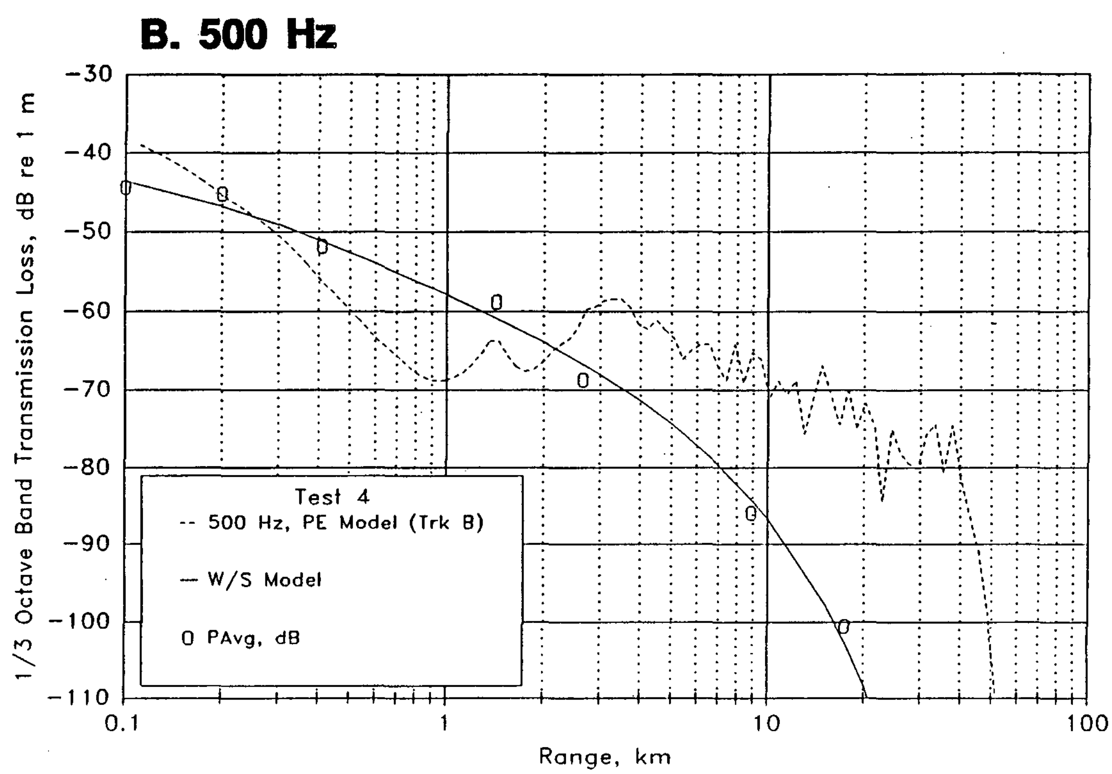


Fig. 50. Transmission loss data from TL test #4 (0) compared with the Weston/Smith model fitted to those data (———) and with the PE model for Track B (- - -). (A) 100 Hz, (B) 500 Hz, and (C) 1 kHz.

C. 1000 Hz

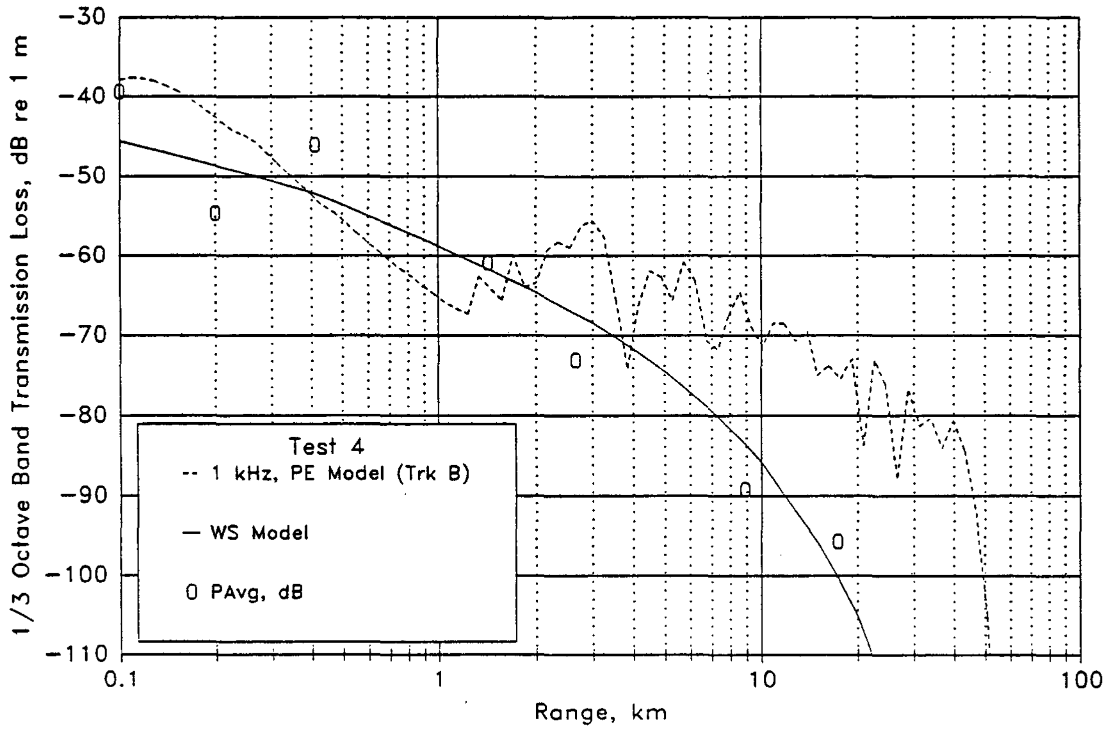


Fig. 50. Concluded.

The regional and seasonal comparisons are shown in Table 15 for 1/3-octave frequency bands centered at 100, 500, and 2000 Hz. The bottom loss parameter (b) estimates for our Test 5 site were higher than the values derived for other sites in the Beaufort Sea, with the exception of the Nerlerk site in the Canadian Beaufort. The b values tend to increase with frequency, i.e. more bottom loss at higher frequencies. The low values of bottom loss reported for many nearshore sites in the Beaufort Sea have been hypothesized to result from the presence of sub-bottom permafrost layers (Miles et al. 1987). The seaward extent of these layers has not been reported for most regions of the Beaufort. The Test 5 site may not have a sub-bottom permafrost layer. However, the higher values of b estimated for Test 5 may also be artifactual; the modeling process cannot totally isolate the effects of bottom loss parameter b from those of the scattering loss parameter, A_b. The analysis optimizes the parameter estimates to obtain the lowest possible E_{rms} error value. However, several pairs of b and A_b values could be found that would produce similar near-minimum error values.

The estimated ice scattering loss parameter A_b at 100 Hz was lower for our Test 5 area in spring than for the Chukchi Sea in winter. This was to be expected; measurements in the Test 5 area were along a pack ice edge bordering an open lead whereas the Chukchi winter measurements were under 100% ice cover. The analysis did not show any measurable scattering loss for the Chukchi summer condition. However, this may have been an artifact, given that our application of the Weston/Smith procedure to the Chukchi Sea was indirect. At 500 Hz, scattering loss during Test 5 in spring was comparable to that in the Chukchi Sea in winter. Again, however, the indirect analysis process for the Chukchi may have obscured any differences.

TL vs. Area and Frequency.--The transmission loss curves corresponding to the parameter estimates in Table 15 are shown in Figure 51A-C for 100 Hz, 500 Hz, and 2 kHz.

At ***100 Hz*** (Fig. 51A), the lowest values of transmission loss were found at the Belcher and Erik sites in the eastern Alaskan Beaufort Sea, where TL was measured during predominantly open water conditions. Sound speed gradients were slightly downward refracting (Belcher) or neutral (Erik). Transmission loss during our Test 5 in spring was significantly greater, and similar to that evident in the Chukchi Sea during winter with 100% ice cover. Transmission loss curves obtained for two California sites were intermediate between those for the eastern Alaskan Beaufort in late summer versus the Chukchi and Test 5 areas in winter or spring. TL in the Chukchi Sea during summer (50% ice cover) was also intermediate and similar to that off California (Fig. 51A).

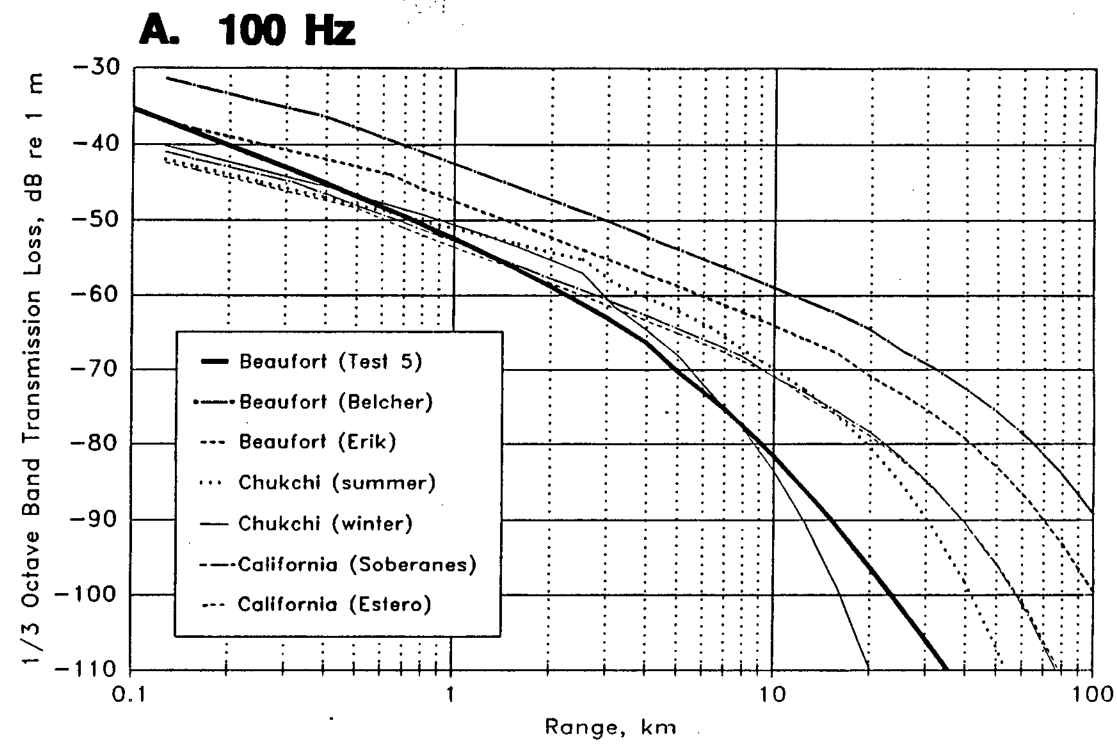
The two California curves were nearly identical to one another (Fig. 51A) although their depths and bottom loss parameters were quite different (Table 15). This demonstrates an interaction between bottom loss and water depth in influencing transmission loss. In this case, the shallow area has low bottom loss and the deeper area relatively high bottom loss.

Table 15. Summary of Weston/Smith parameters for shallow water propagation in several regions.

Area/Site	Depth (m)	Ice cover	Sin ϕ_c	A_b	b	A_n	E_{rms}	Refs.
A. 100 Hz								
AK Beaufort, spring/Test 5	42	50%	0.2	0.03	0.40	-1	3.9	
AK Beaufort, summer/Belcher(east)	55	0%	0.8	-	0.30	5	1.5	(a)
AK Beaufort, summer/Erik	40	10%	0.8	-	0.15	-2	2.7	(a)
Can. Beaufort, summer/Nerlerk(1)	46	0%	0.3	-	1.15	-	1.8	(b)(a)
Can. Beaufort, summer/Amerk(2)	28	0%	0.3	-	0.20	-	2.1	(b)(a)
Chukchi, summer	48	50%	0.2	0	0.76	-1	1.4	(c)
Chukchi, winter	48	100%	0.2	0.08	0.78	2	1.3	(c)
Calif. Coast/Soberanes	80	0%	0.4	-	2	0	4.7	(d)
Calif. Coast/Estero Bay	35	0%	0.8	-	0.16	-8	8.4	(e)
B. 500 Hz								
AK Beaufort, spring/Test 5	42	50%	0.8	0.07	1.20	1	1.9	
AK Beaufort, summer/Belcher(east)	55	0%	0.2	-	0.25	3	1.2	(a)
AK Beaufort, summer/Erik	40	10%	0.3	-	0.40	-1	2.8	(a)
Chukchi, summer	48	50%	0.8	0.04	1.18	-6	2.6	(c)
Chukchi, winter	48	100%	0.8	0.07	0.89	-3	1.6	(c)
C. 2 kHz								
AK Beaufort, spring/Test 5	42	50%	0.8	0.11	1.22	-2	1.7	
AK Beaufort, summer/Belcher(east)	55	0%	0.4	-	0.40	0	1.4	(a)
AK Beaufort, summer/Erik	40	10%	0.3	-	0.55	-1	3.9	(a)

Notes: (1) 250 Hz band data, radiated noise from dredge AQUARIUS.
(2) 315 Hz band data, radiated noise from caisson drill rig.

Refs: (a) Miles et al. (1987)
(b) Greene (1985)
(c) Greene (1981)
(d) Malme et al. (1984)
(e) Malme et al. (1986)



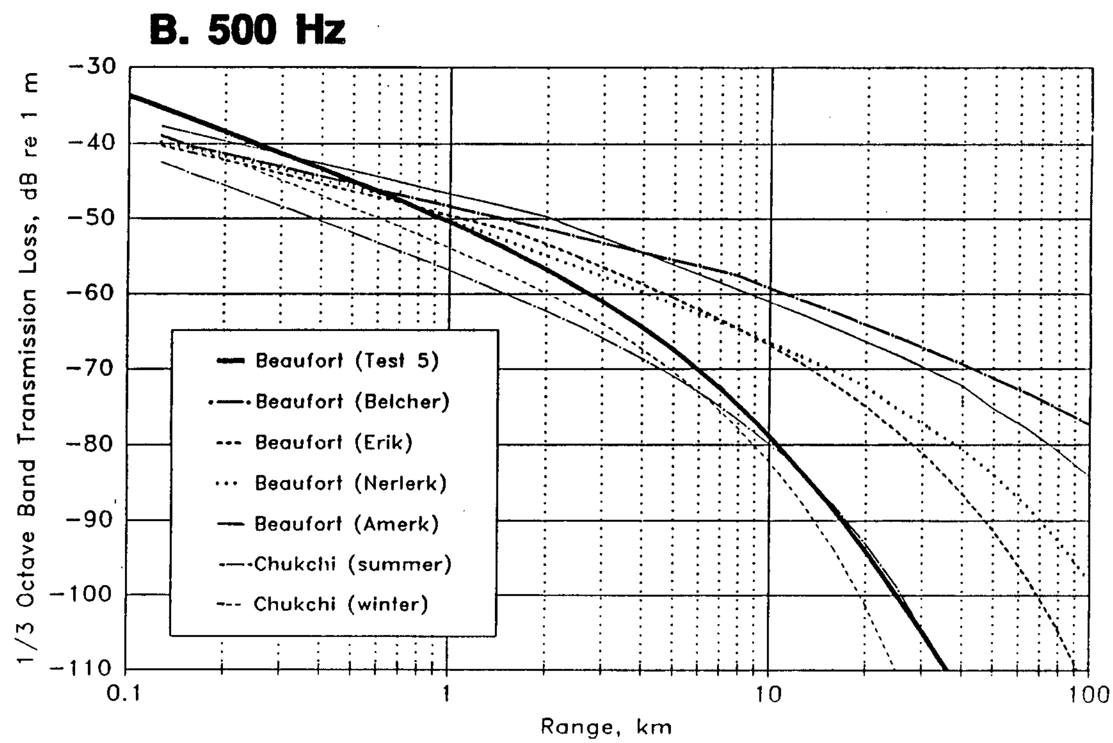


Fig. 51. Comparison of transmission loss in various shallow-water regions based on Weston/Smith models fitted to measure data for (A) 100 Hz band, (B) 500 Hz band, and (C) 2 kHz band. See text for sources of data.

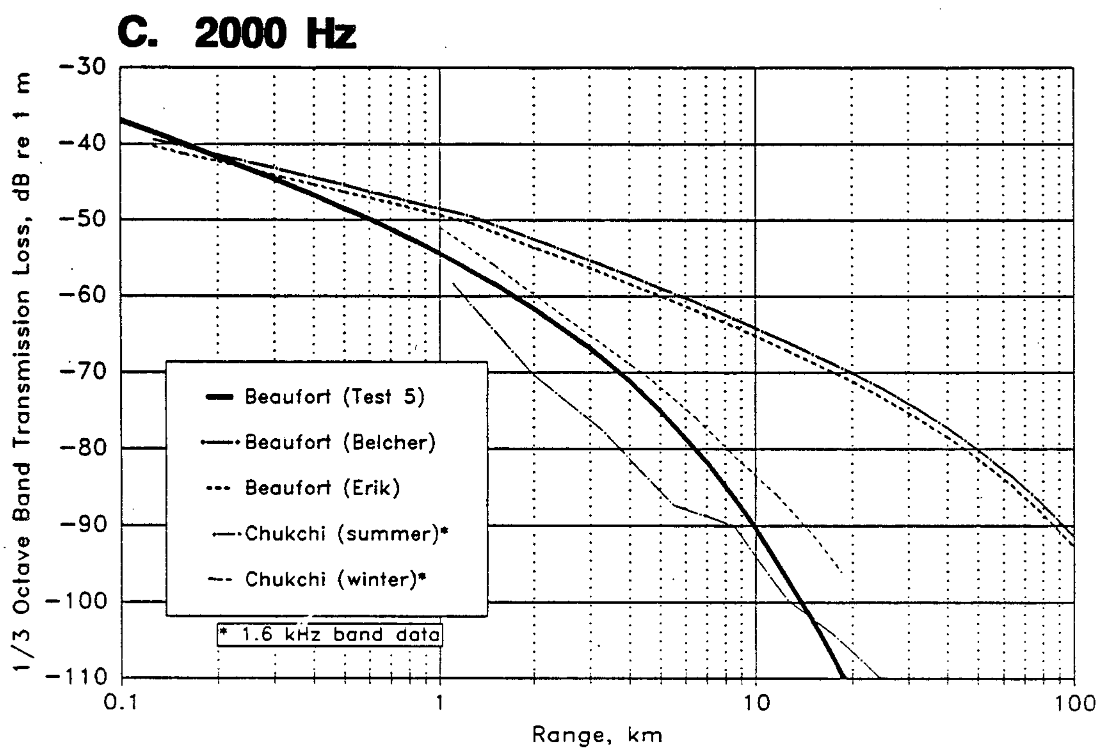


Fig. 51 Concluded.

At ***500 Hz***, the lowest transmission losses again were found under open water conditions in the Beaufort Sea (Fig. 51B). The curves for two sites in the Canadian Beaufort (Nerlerk and Amerk) were between those obtained at the Alaskan Beaufort sites (Belcher and Erik). As at 100 Hz, there was more transmission loss in the Test 5 and Chukchi Sea areas. TL in the Test 5 area was comparable to that obtained in the Chukchi Sea. At 500 Hz, there was little apparent difference between TL in the Chukchi during summer and winter, contrary to the results for 100 Hz. Unfortunately, no 500 Hz data are available for the California coast.

At ***2 kHz***, the two sites in the eastern Alaskan Beaufort had very similar and quite efficient transmission characteristics during the open water season (Fig. 51C). Transmission losses were again considerably higher in the Test 5 area in spring and in the Chukchi Sea during both winter and summer. The Test 5 and Chukchi curves were similar to one another. At this frequency, TL in the Chukchi Sea under summer 50% ice cover was apparently greater than that under winter 100% ice cover (Fig. 51C). More data are needed to determine whether this is a general or site-specific phenomenon in the Chukchi.

These transmission loss comparisons confirm that ice cover has a significant influence on shallow water transmission loss. TL in our study area was considerably higher than that observed previously in the Beaufort Sea during late summer, when there was little or no ice. It is not known whether all or only part of this increased loss was attributable to the ice layer present in spring. Some of the increase may have been caused by increased bottom loss in our study area relative to that in the central and eastern Beaufort Sea. Measurements at the same site under varying ice conditions would be useful to help answer this question. Such data would also be useful for refining sound propagation models for ice cover conditions.

The general similarity between transmission loss in our study area in the western Beaufort Sea during spring and in the Chukchi Sea during late winter-early spring (Greene 1981) is also noteworthy. It suggests that reactions of whales to man-made noise may occur at similar distances from noise sources in these two areas, assuming that reaction thresholds are the same (see point 1b in "Assumptions and Limitations" section, p. 22).

BOWHEAD WHALE RESULTS

This section begins with a general description of the spring bowhead migration east of Pt. Barrow in 1989, including results from aerial surveys and sightings from the ice, photogrammetry/photoidentification work, and behavioral observations in the absence of disturbance. These data address part of specific objective 6, "To document ... the movements, behavior, basic biology ... of bowheads ...". These "normal behavior" data are also needed as background (control) information for the analysis of reactions to disturbance (specific objectives 4 and 5), covered later in this section.

Distribution and Movements of Bowheads

Bowheads in General

Forty-five bowhead whales were recorded during late April and the early part of May (Fig. 52). Two of these were recorded on 29 April and four on 30 April when the ice-based crew was conducting preliminary sound propagation tests, before the main field program started. Because ice cover was extensive during this period, whales tended to be concentrated in the few open-water areas amidst the pack ice, and directions of movement of whales were influenced by the orientation of open areas. The predominant orientation of whales was northeast, but a few bowheads were moving NNW along leads oriented NNW-SSE. The bowheads observed were primarily migrating or socializing; a few whales were resting.

More bowheads (70) were sighted during the 11-20 May period than during the previous and following periods (Fig. 53). The main E-W lead along the fast ice edge within our study area did not start to form until the end of the period (20 May). Narrow leads oriented NE-SW developed amidst the pack ice at the start of this period and whale sightings were scattered throughout these leads. Sightings were more dispersed and farther offshore during mid-May than during early or late May. Bowheads tended to be found farther north as they moved eastward. Almost all bowheads that were moving were oriented in a northeast direction. Most whales observed during this period were migrating and few were socializing or resting.

A well-defined E-W "nearshore" lead was present along the landfast ice edge during the 21-30 May period. Most of our bowhead sightings in late May were along the north side of this lead or amidst the pack ice just north of the lead (Fig. 54). Only 54 bowheads were recorded, although survey effort by the Twin Otter crew increased to 23.7 h during this period from 15.5 h during the previous period (Table 3). Poor weather limited survey coverage during the first half of the late May period. Hence most of the effort and sightings were on 26-29 May. A high proportion of the bowheads passing on those dates were cows with calves (Fig. 54). Their movements are discussed in greater detail below. Whales sighted during this period were migrating, engaged in local movements, or resting. Most of those that were migrating were traveling generally eastward along the northern (offshore) side of the nearshore lead or through the pack ice

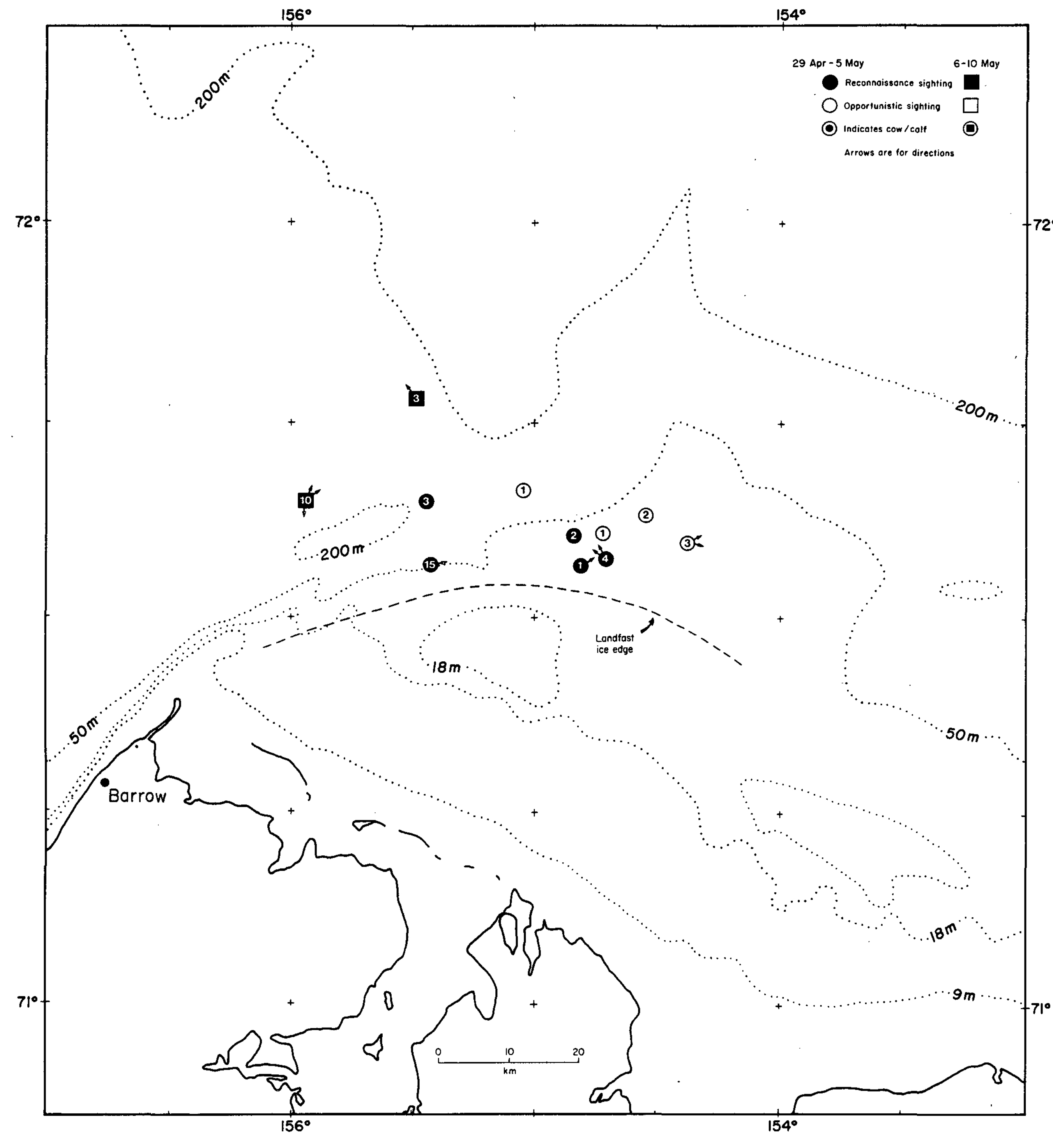


Fig. 52. Sightings of bowhead whales, 29 April-10 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

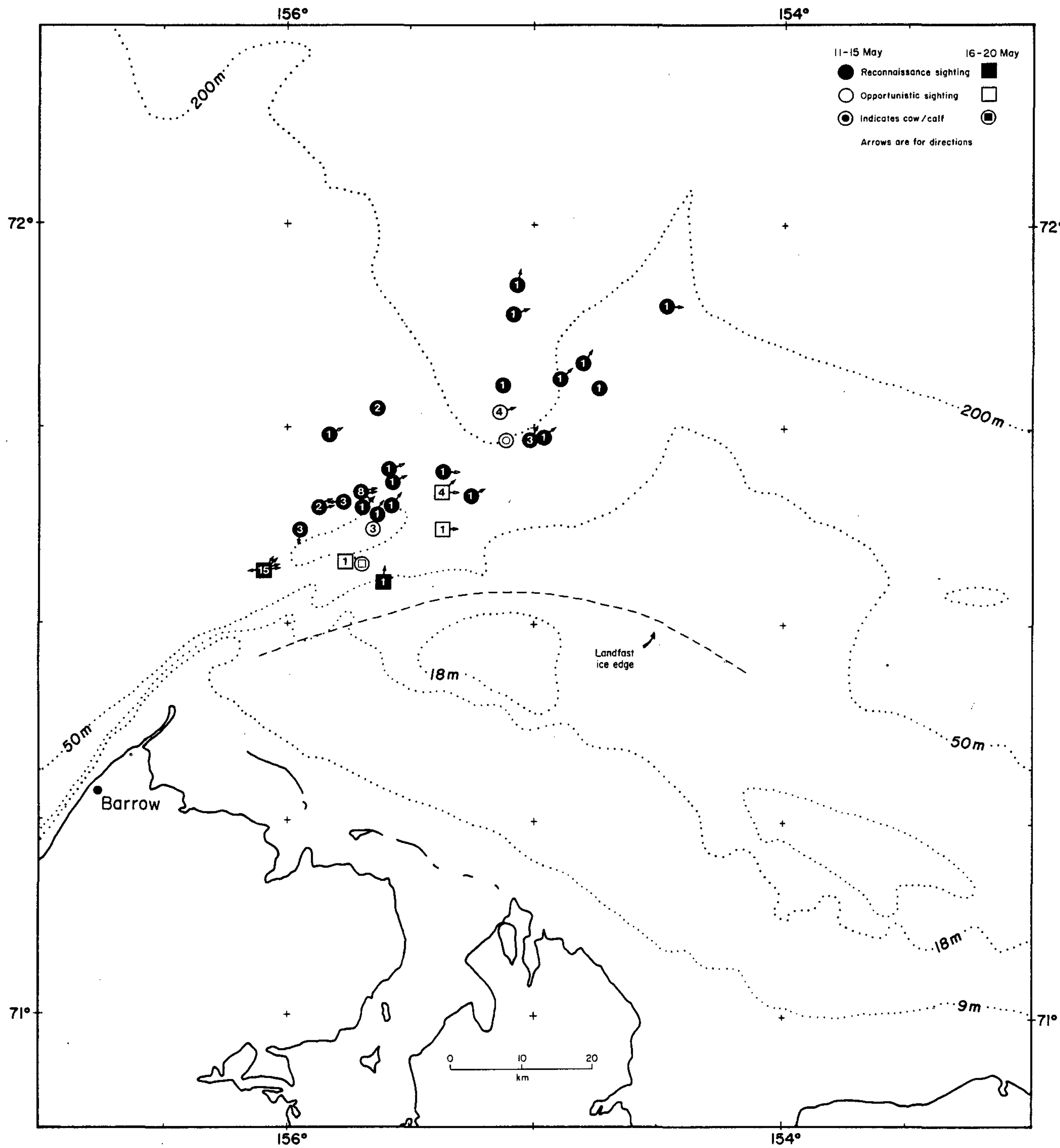


Fig. 53. Sightings of bowhead whales, 11-20 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

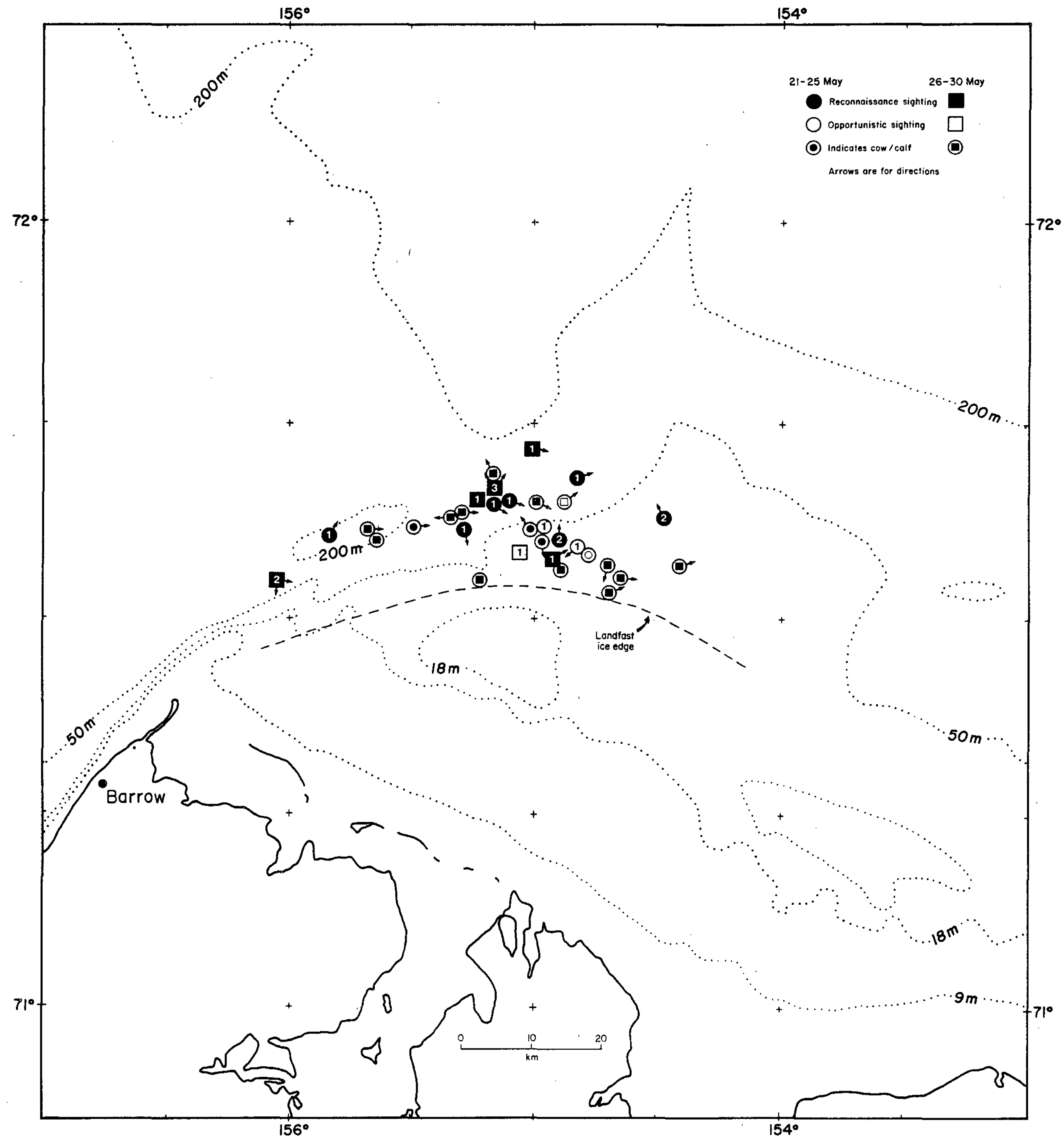


Fig. 54. Sightings of bowhead whales, 21-30 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

north of that lead. However, many of the cow/calf pairs that were sighted were oriented in other or random directions (see below).

Figure 55 shows the locations where the NMFS photogrammetry crew photographed bowheads from mid April to early June 1989--a longer period than our study. They also found that bowheads were widely scattered in 1989. Their results show that bowheads were less concentrated along the southern edge of their migration corridor (the fast ice edge) than they had been during 1985 and 1987 (*cf.* Fig. 4A,C, p. 8-10). Because of the absence of a well-defined lead along the fast ice or in the offshore shear zone within our study area, the bowhead migration corridor appears to have been wider in 1989 than in most years. As a result, numbers of bowheads passing any one location were smaller in 1989 than in some other years. This reduced the numbers that we could expect to observe passing a fixed study site, and made it necessary to relocate the experimental site from day to day.

Mothers and Calves

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 fast ice edge during the last third of May (Fig. 54). 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 pack ice north of the lead and in the open water of the lead.

Bowhead Photogrammetry and Photoidentification

Bowhead Sizes

Usable length measurements (grades 1-6) were obtained from 30 bowheads during this 1989 spring study. An additional four approximate measurements were obtained for whales that were deeply submerged or from photographs that were taken when the altitude of the aircraft was changing rapidly. The locations where these photographs were taken are shown in Figure 20 (p. 73).

Few length measurements were obtained during the first half of May because of poor weather, little open water, and technical problems during some of the few opportunities for photogrammetry. Of the seven whales measured from 3 to 15 May, one was an immature (10.6 m) and the others were adults ranging in size from <14.0 to 15.7 m (Fig. 56). On 18 May, seven additional adult whales, ranging in size from 14.5 to 16.7 m, were photographed (Fig. 56).

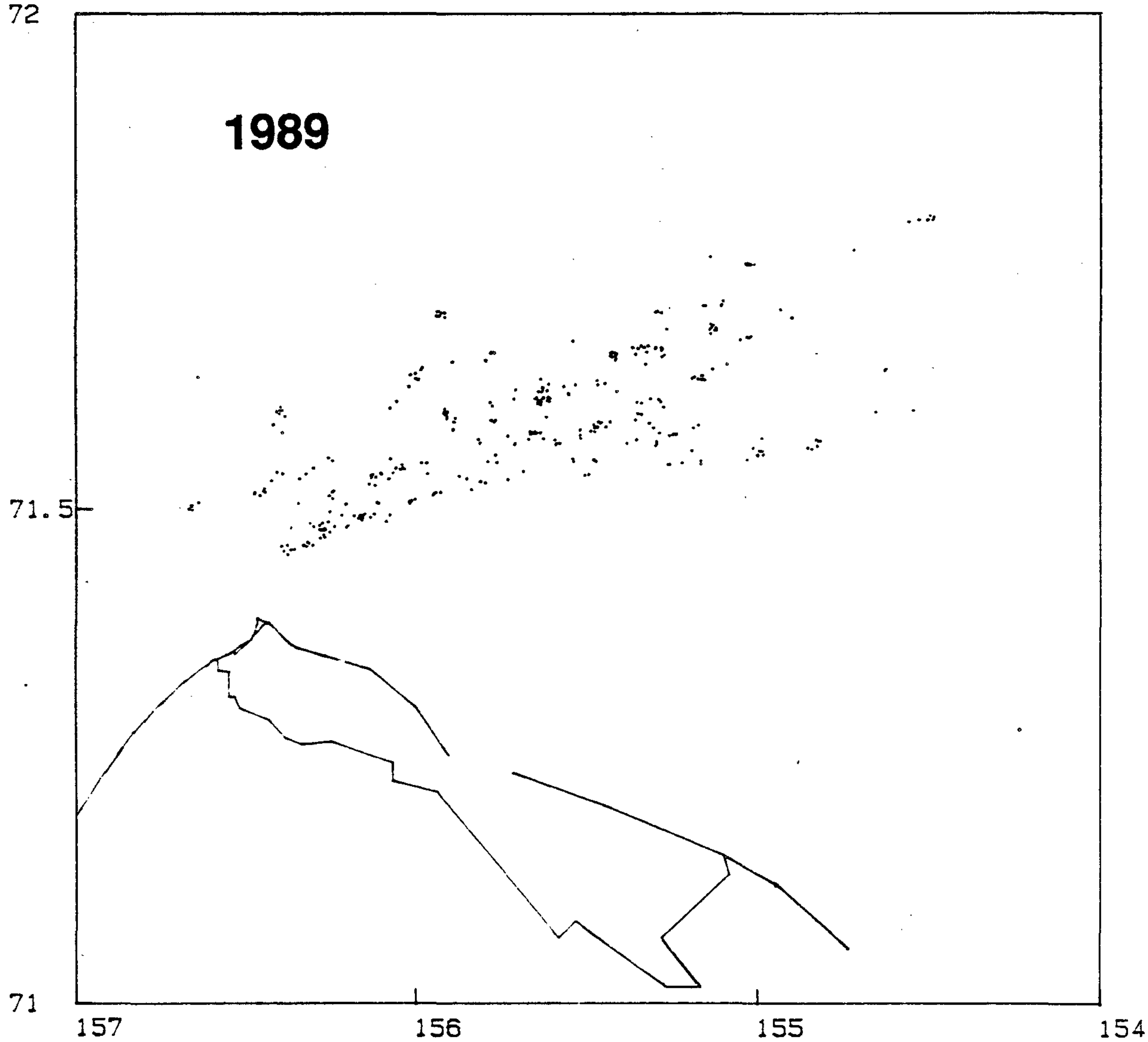


Fig. 55. Locations where bowheads were photographed during spring photogrammetric surveys conducted by the U.S. National Marine Fisheries Service in 1989 (NMFS unpubl. data).

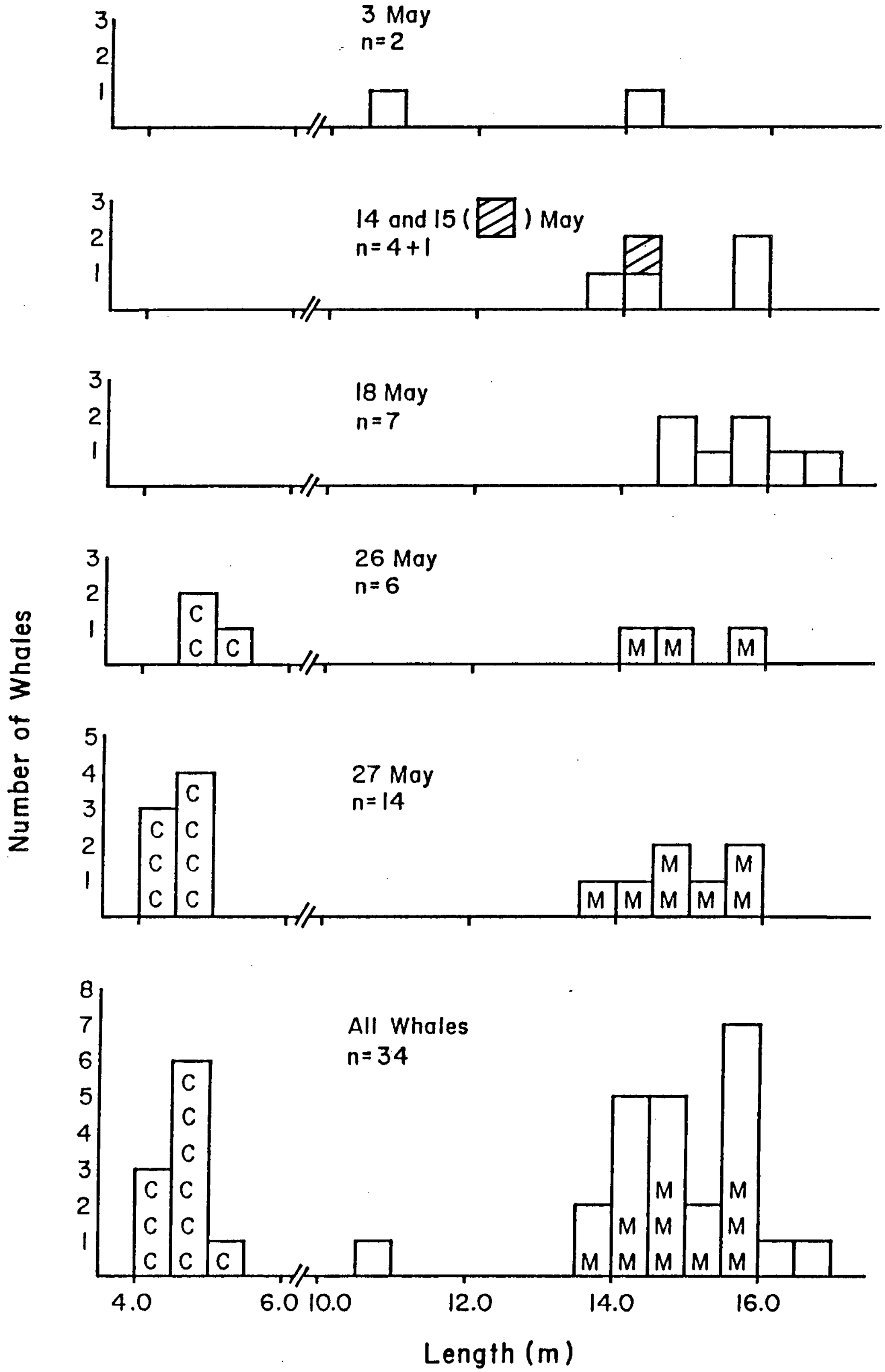


Fig. 56. Length-frequency distribution for bowhead whales photographed during this study, 3-27 May 1989. Repeat measurements are excluded within each day and a cow/calf pair photographed initially on 27 May and subsequently on 28 and 29 May are not shown for the latter two dates. Mothers and calves are indicated by M and C, respectively.

All 20 whales measured on 26-27 May were cow/calf pairs (Fig. 56). One of these pairs was initially photographed on 27 May and re-photographed on 28 and 29 May, when the whales were 10 and 13 km, respectively, from their initial (27 May) position. The mean length of all mothers photographed was 14.96 m (± 0.77 s.d.; n = 9 excluding one approximate length). The calves averaged 4.62 m (± 0.32 s.d.; n = 8 excluding two approximate lengths). The smallest and largest calves were 4.0 and 5.0 m long, and the smallest and largest mothers were 13.9 and 15.9 m.

Although we obtained few length measurements during this study, our data confirm the age segregation noted by Nerini et al. (1987). In fact, the data suggest that segregation may have been more pronounced in 1989. Nerini et al. (1987) found that subadult whales (<13.0 m long) were most common during the early part of the migration, and that adult whales were most common during the latter part. In addition, Nerini et al. found that mothers with calves tended to be among the last of the migrants. We found that virtually all bowheads passing Barrow after 13 May were either adults or calves. After 24 May 1989, most of the bowheads encountered were mothers with calves (28 of 37, or 76%).

<u>Within Season Resightings</u>

Besides providing data on the sizes of bowheads whose behavior was studied, aerial photography documented the movements of bowheads that were photographed during more than one photo session. Within-season resightings were recognized by comparing each of our recognizable photographic images with (1) each other, and (2) the spring 1989 photographic images obtained by the National Marine Mammal Laboratory (NMML).

In May 1989, we acquired a total of 45 potentially re-identifiable (grade A and B) images of bowheads. These images were of 20 different adult bowheads photographed on 14-29 May. 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 the adults we photographed were accompanied by calves, including the one photographed on 27-29 May.

We also compared our photos with images of 47 adult bowheads photographed by NMML on 12-31 May 1989. Five of our 20 different recognizable adults (25%) were also photographed by NMML in 1989. In addition we recognized a sixth bowhead, not photographed by us, that was photographed by NMML on two different days. Of these six whales photographed during more than one photo-session, two were resighted on the same day that they were originally photographed, and four were photographed on two or three different days (Table 16).

The movements of the re-identified bowheads are shown in Figure 57. Two bowheads photographed in the same general location and at approximately the same time on 17 May had traveled in opposite directions when they were resighted on the following day. The resighting locations on 18 May were 19 km apart. One of these bowheads traveled 6 km ENE over a 23 h period (net rate of movement

Table 16. Inter-session resightings of bowheads, May 1989.

Source of Photos[a]	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 Rate of Movement (km/hr)	Heading (°T)	Whale Length (m)	Accompanied By Calf?
NMML-NMML	17 May	16:22:08	71°35.5'N	155°53'W	18 May	15:13:51	71°36.7'N	155°43'W	22.86	6.25	0.3	69	15.0[b]	no
NMML-LGL	17 May	16:35:32	71°35.8'N	155°55'W	18 May	11:39:30	71°34.3'N	156°16;W	19.07	12.58	0.7	257	16.0	yes
LGL-NMML	18 May	12:00:30	71°34.6'N	156°08'W	18 May	15:09:08	71°36.3'N	155°47'W	3.14	12.67	4.0	75	14.5	no
LGL-NMML	18 May	12:00:30	71°34.6'N	156°08'W	18 May	15:09:08	71°36.3'N	155°47'W	3.14	12.67	4.0	75	15.1	no
LGL-NMML	26 May	00:04:15	71°37.7'N	155°30'W	27 May	11:23:10	71°39.9'N	155°21'W	35.32	6.64	0.2	52	14.2	yes
LGL-NMML	27 May	20:28:50	71°37.2'N	155°19'W	28 May	11:14:34	71°40.5'N	155°01'W	14.76	12.13	0.8	60	14.9	yes
LGL					28 May	12:50:30	71°38.9'N	155°05'W	1.60	3.77	2.4	218		
NMML					29 May	11:26:57	71°41.1'N	155°08'W	22.61	4.43	0.2	337		
LGL					29 May	15:32:50	71°42.3'N	155°08'W	4.10	2.22	0.5	357		

[a] NMML - 1989 spring photographic studies by National Marine Mammal Laboratory. LGL - This study by LGL for MMS.
[b] NMML preliminary length measurement, subject to revision.

Table 17. Between-year bowhead resightings, various origins and years, to MMS study area, May 1989.

Source of Photos[a]	Year	First Photographed Date	First Photographed Loc'n[b]	First Photographed Latitude	First Photographed Longitude	Resighting(s) Date	Resighting(s) Loc'n	Resighting(s) Latitude	Resighting(s) Longitude	Whale Length in Year of Resighting (m)
LGL-NMML	1982-89	16 Aug	HI	69°48.5'N	138°49'W	27 May	BR	71°37.0'N	155°33'W	15.8[c]
LGL-(NMML-LGL)	1982-89	18 Aug	HI	70°05.0'N	138°26'W	17, 18 May	BR	71°34.3'N[d]	156°16'W[d]	16.0
NMML-LGL	1985-89	2 June	BR	71°24.1'N	156°37'W	15 May	BR	71°54.0'N	154°28'W	14.0
NMML-LGL	1985-89	2 June	BR	71°24.2'N	156°37'W	18 May	BR	71°35.3'N	156°05'W	14.7

[a] LGL - 1982 photographic study by LGL for National Marine Fisheries Service (Davis et al. 1983), or this study by LGL for MMS (1989).
NMML - Spring photographic studies by National Marine Mammal Laboratory.
[b] HI = Herschel Island, BR = Barrow Region.
[c] NMML preliminary length measurement, subject to revision.
[d] 18 May position.

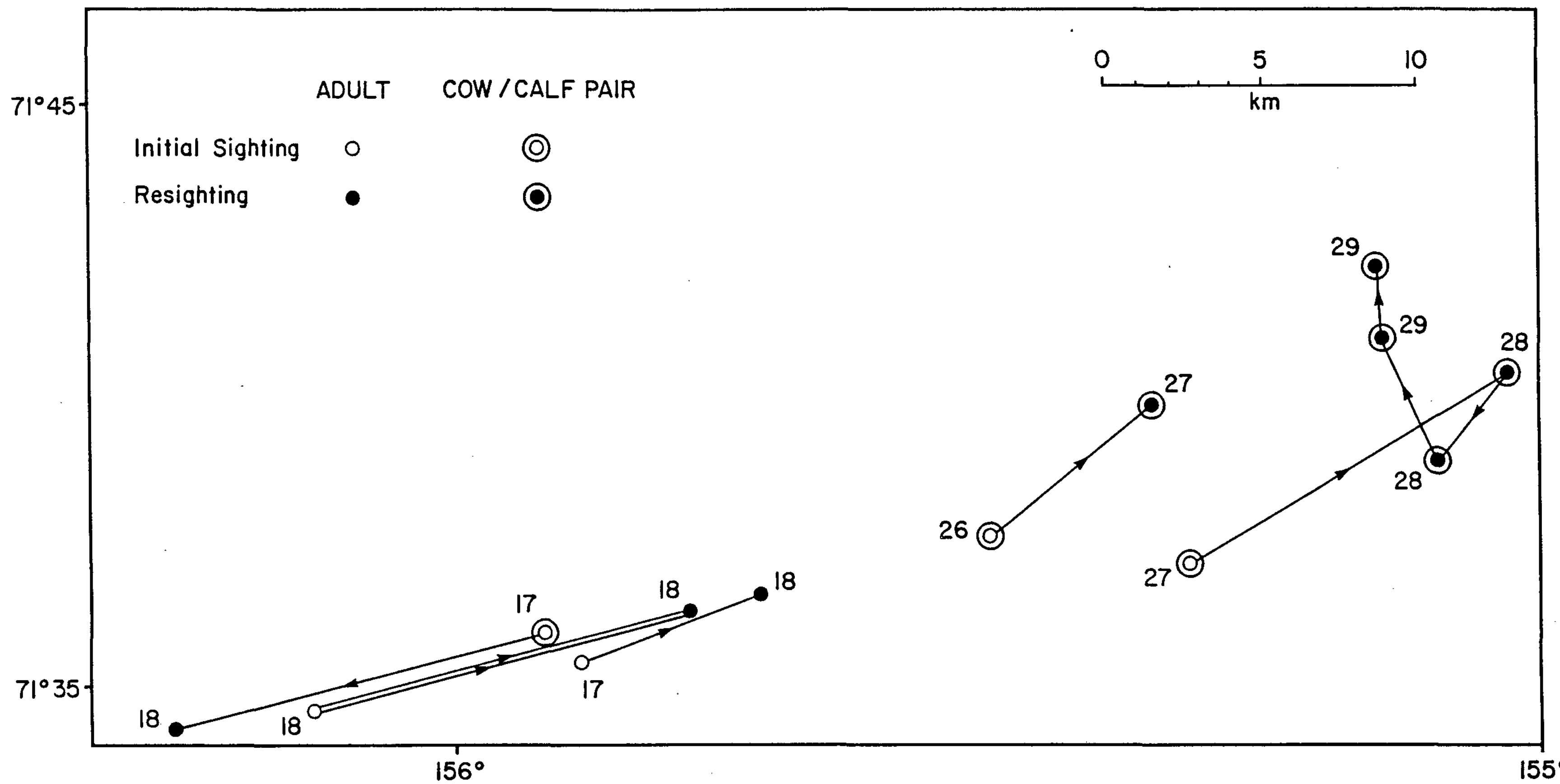


Fig. 57. Inter-day resightings and within-day sightings >1 h apart of bowhead whales photographed in the study area during May 1989. Photographs were obtained during this study and the NMFS photogrammetry project (NMFS, unpubl. data).

0.3 km/h). The other bowhead traveled 13 km WSW over a 19 h period (0.7 km/h). The latter bowhead was observed with a calf on 17 May, but the calf was neither observed nor photographed on 18 May.

Two bowheads photographed together on 18 May were still together when they were resighted 3.1 h later. These bowheads had migrated 13 km ENE at an apparent rate of 4.0 km/h, the fastest rate documented photographically in this study.

A cow/calf pair photographed early on 26 May had traveled 7 km NE when they were resighted 35 h later on 27 May. This pair had traveled at an apparent rate of only 0.2 km/h.

Another cow-calf pair was photographed on 27, 28 and 29 May. This pair moved in a variety of directions between sightings, including NNE, SW, WNW and N. The net distances traveled between successive sightings ranged from 2 to 12 km, and apparent speeds ranged from 0.2 to 2.4 km/h. The net distance between the original and final sighting locations was only 12 km. The net rate of movement indicated by this distance over 44 h was 0.3 km/h. The movements of this cow-calf pair are mapped and discussed in more detail in a later section (see Fig. 57 and Fig. 58 on p. 168).

Between-Year Resightings

We documented several between-year resightings by comparing our 1989 grade A photos with all grade A photos obtained in previous summer and autumn photographic studies conducted in the Alaskan and Canadian Beaufort Sea (*cf.* Koski et al. 1988). In addition, some of our most highly marked 1989 whale photos were compared to a subset of the NMML spring photos from 1985-87. We have not yet assigned re-identification grades or file numbers to these spring NMML photographs; the comparisons with these photos were not systematic.

At least three of the 15 (20%) grade A whales photographed by us in the spring of 1989 were also photographed in an earlier year. We also recognized a bowhead in the spring 1989 NMML collection that had been photographed in an earlier year (Table 17). All four of these resighted bowheads were adults, 14 to 16 m long.

Two bowheads photographed on 17-18 and 27 May 1989 were originally photographed by LGL in mid-August 1982 near Herschel Island. These resightings span nearly seven years, the longest resighting period to date. One of these whales, photographed on 17-18 May (see Table 16 for details), was photographed with a calf in 1982. It was observed with a calf on 17 May 1989 (David Withrow, NMML, pers. comm.) but the calf was neither observed nor photographed on 18 May. This is the same bowhead that traveled 13 km WSW between 17 and 18 May.

Two other bowheads photographed on 15 and 18 May 1989 had been photographed by NMML on 2 June 1985 near Barrow. These bowheads were photographed 18 and 15 days earlier, respectively, in 1989 than they were in 1985. Rugh (in press) found that six bowheads photographed in the springs of both 1985 and 1986 were photographed on dates (corrected to a common longitude) differing by 3 to 20 days (mean = 10.0). Five of these six whales were photographed earlier in 1986 than in 1985.

Behavior of Undisturbed Bowheads

We observed the behavior of bowhead whales during 17 behavioral observation sessions on 10 different days from 3 to 29 May 1989 (Table 4). Total observation time was 25.60 h. The estimated number of whales within the area being circled (typically about 2-3 km in diameter) ranged from one to five. On one day (3 May) there were as many as 15 whales within 5 km of the center of the observation circle. Water depths at observation sites ranged from 40 to 280 m, based on the bathymetric chart for the area. Ice cover within the observation circle ranged from 0 to 99%, but was usually 80-95%. Largely because of the dampening effect of ice on wave action, sea states were invariably low (0-2).

Most behavioral observations were amidst pack ice well north of the landfast ice edge (Fig. 20, p. 73). The large amount of ice often made it very difficult or impossible to resight traveling bowheads when they surfaced after a long dive. Hence, we often were unable to determine dive durations of traveling whales, or to follow them for prolonged periods.

The present section is based on observations when bowheads were not exposed to any known source of human disturbance. Observation periods counted as presumably undisturbed were those when the observation aircraft was at an altitude of at least 457 m (≥1500 ft), no other aircraft were nearby, the underwater sound projector was not operating, and there had been no potential disturbance within the preceding 30 min period. Of the 25.6 h of behavioral observations, 12.27 h were under "presumably undisturbed" conditions. These 12.27 h of presumably undisturbed observations came from 12 observation sessions on 8 days. Some observations on 29 May were obtained about 10 km from the operating sound projector. These observations have been treated as potentially disturbed, i.e. excluded from this section, even though there was no evidence that projected drilling noise was detectable at that distance.

General activities of the bowheads varied. The majority were migrating actively toward the northeast or east, but some were actively socializing or resting more or less motionless. Some of the mothers and calves seen during the last week of May were migrating actively in the expected directions, but others were resting or traveling slowly in other directions.

Surfacing, Respiration and Diving Behavior

We determined the durations of surfacings and dives, the number of visible blows per surfacing, and the intervals between successive visible blows within a surfacing. Definitions and criteria were the same as in our previous related studies (e.g. Dorsey et al. 1989). Table 18 summarizes these data for various combinations of whale activity (resting, traveling, socializing) and whale status (mother, calf, other), considering only the presumably undisturbed bowheads.

Table 18. Surfacing, respiration and dive behavior of undisturbed bowheads observed from a Twin Otter aircraft, May 1989.

	Individual Blow Intervals (s)			Mean Blow Interval (s)			# of Blows/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
Calves															
Rest			0			0			0			0			0
Travel	15.62	11.48	190	15.36	6.79	40	6.44	4.28	23	1.57	1.09	31	3.66	2.27	30
Social			0			0			0			0			0
All[a]	17.52	14.00	284	16.46	7.61	62	5.37	4.60	43	1.58	1.70	53	2.91	1.99	52
Mothers															
Rest			0			0			0			0			0
Travel	19.95	15.56	110	22.97	17.94	28	5.37	2.50	19	1.77	1.06	24	6.80	2.89	21
Social			0			0			0			0			0
All	20.77	14.88	139	23.36	15.90	38	4.24	2.64	34	1.44	1.08	39	6.12	3.15	34
Others															
Rest	95.64	141.34	85	70.28	76.71	10	7.60	3.65	5	4.64	2.79	5	13.70	13.19	6
Travel	16.71	8.39	115	17.87	6.50	29	5.00	3.51	7	1.81	1.07	9			0
Social	21.59	15.40	124	23.06	14.03	37	1.50	0.71	2	0.24	0.30	2	1.02	0.00	1
All	34.13	71.07	422	26.31	31.45	86	6.94	5.02	18	2.69	2.08	21	11.89	12.96	7
Mothers & Others															
Rest	95.64	141.34	85	70.28	76.71	10	7.60	3.65	5	4.64	2.79	5	13.70	13.19	6
Travel	18.29	12.50	225	20.38	13.53	57	5.27	2.74	26	1.78	1.05	33	6.80	2.89	21
Social	21.59	15.40	124	23.06	14.03	37	1.50	0.71	2	0.24	0.30	2	1.02	0.00	1
All	30.82	62.33	561	25.40	27.59	124	5.17	3.82	52	1.88	1.61	60	7.10	6.18	41
Calves vs. Mothers															
Travel				t' = 2.14, df = 33, *			t' = 1.01, df = 38, ns			t = 0.68, df = 53, ns			t = 4.34, df = 49, ***		
All				t' = 2.51, df = 48, *			t' = 1.35, df = 70, ns			t' = 0.48, df = 90, ns			t = 5.80, df = 84, ***		
Mothers vs. Others															
Travel				t' = 1.42, df = 34, ns			t = 0.30, df = 24, ns			t = 0.10, df = 31, ns			-		
All				t' = 0.69, df = 122, ns			t' = 2.13, df = 23, *			t' = 2.57, df = 27, *			t' = 1.17, df = 6, ns		

t' is the test statistic calculated without assuming equality of population variances.
ns means $P>0.1$; (*) means $0.1 \geq P > 0.05$; * means $0.05 \geq P > 0.01$; *** means $P<0.001$.

[a] The 'All' activity category includes whales engaged in unclassified activities, so its sample size usually exceeds the sum of the sample sizes for resting, traveling and socializing whales.

The blow interval data are presented in two ways: (1) considering each individual blow interval as a unit, and (2) considering the mean 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 and the standard deviations are both smaller for mean blow intervals (method 2) than for individual blow intervals (method 1). The durations of successive individual blow intervals within a surfacing are presumably not independent. Hence, statistical comparisons of blow intervals are based on the mean 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. $0.1 > P > 0.01$).

Traveling bowheads (calves excluded) surfaced for an average of 1.78 min, dove for 6.80 min, and blew 5.27 times per surfacing (Table 18). Intervals between successive visible blows within a surfacing averaged 18.3 s. These means include results for bowhead mothers with accompanying calves as well "other non-calves". Values for traveling mothers were similar to those for "others". The differences between mothers and others were non-significant, although most sample sizes were small (Table 18).

The average dive duration reported here (6.80 min) may be realistic for bowheads traveling along short leads through pack ice. However, it no doubt underestimates the overall average dive duration during spring migration. We were unable to resight identifiable bowheads when they resurfaced after long dives under areas of extensive ice, so these long dives are absent from our sample. On 27 May, the one day when we observed whales actively migrating through largely open waters near the north side of the nearshore lead, dive durations of two mothers averaged 7.08 ± s.d. 2.42 min (n=14); their surfacings averaged 1.93 ± 1.08 min (n=18).

Resting bowheads (calves excluded) surfaced for an average of 4.64 min, dove for 13.7 min, and were observed to blow 7.60 times per surfacing (Table 18). Sample sizes were small, but each of these means was higher than that for traveling animals. Intervals between successive visible blows averaged 95.6 s, much longer than those for traveling bowheads. For resting whales, the mean number of blows per surfacing may be underestimated and the mean blow interval overestimated, since some blows by resting bowheads are invisible (Carroll and Smithhisler 1980; LGL unpubl. data).

Socializing bowheads (calves excluded) blew, on the average, once every 21.6 s while at the surface. This value is similar to the mean for traveling animals but much less than that for resting bowheads (Table 18). The other variables were rarely recorded for socializing whales.

Other Behavioral Variables

Several other behavioral variables were recorded consistently during aerial observation sessions. This section summarizes the results for five of these variables in the absence of disturbance (Tables 19, 20). Mothers and "others" are considered together. Data of these types can be useful in recognizing alterations in behavior in the presence of disturbance.

The **pre-dive flex** is a concave bending of the back that often occurs 10-20 s before bowheads dive. Although sample sizes for most categories of whales were small, pre-dive flexes were quite uncommon during the spring of 1989 (Table 19; *cf.* Würsig et al. 1985).

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 of 1989, only about 5% of the dives by mothers and "others" were **fluke-out dives** (Table 19). In contrast, during autumn migration in the Alaskan Beaufort Sea, bowheads raise their flukes ~27% of the time (Richardson and Finley 1989:43).

Aerial behaviors include behaviors in which a part of the body is raised above the surface of the water. These behaviors include breaches, flipper and tail slaps, rolls, and various combinations (Würsig et al. 1985, 1989). During a roll along the longitudinal axis of the body, at least one flipper is raised above the surface. Amongst undisturbed mother and "other" whales during the spring of 1989, rolls were seen commonly (8% of 140 surfacings). All of these rolls involved whales that were engaged in social interactions. However, other aerial behaviors were rare or unseen (Table 19).

The frequency of **turns** during surfacings depended on whale activity. Traveling whales usually (33 of 36 surfacings) maintained their original heading throughout the surfacing. Resting whales often turned slowly (5 of 10 surfacings), and socializing whales usually turned (12 of 14).

Swimming speeds during a particular surfacing cannot be determined quantitatively during aerial observations. However, as in previous related studies, we recorded relative speed on an ordinal "none, slow, moderate, fast" scale. Not surprisingly, resting whales were usually classified as having no forward speed, traveling whales were usually moving at slow or moderate speed, and socializing whales had the most variable speeds (Table 20).

Sexual Activity

Several generally low-intensity but distinct bouts of actual or presumed sexual activity were seen in the study area on 3 and 6 May. On 3 May, a group

Table 19. Frequency of pre-dive flexes, fluke-out dives, and aerial behaviors during surfacings by undisturbed bowheads observed from a Twin Otter aircraft, May 1989. The units of observation are surfacings by an individual whale.

Whale Status and Group Activity	Pre-dive Flex			Flukes Out as Diving			Aerial Behaviors						
	No	Yes	Total	No	Yes	Total	None	Roll	Flip-Slap	Tail Slap	Breach	2 or 3 Types	Total
Calves													
Rest			0			0							0
Travel	42	0	42	41	1	42	42	0	0	1	0	0	43
Social			0			0							0
Other/Unk.	29	0	29	29	0	29	29	0	0	0	0	0	29
All	71	0	71	70	1	71	71	0	0	1	0	0	72
Mothers													
Rest			0			0							0
Travel	30	1	31	30	1	31	32	0	0	0	0	0	32
Social			0			0							0
Other/Unk.	16	0	16	16	0	16	16	0	0	0	0	0	16
All	46	1	47	46	1	47	48	0	0	0	0	0	48
Others													
Rest	9	1	10	10	0	10	12	0	0	0	0	0	12
Travel	23	1	24	23	1	24	30	0	0	0	0	0	30
Social	14	1	15	14	0	14	27	11	0	0	0	0	38
Other/Unk.	10	1	11	8	3	11	11	0	0	1	0	0	12
All	56	4	60	55	4	59	80	11	0	1	0	0	92
Mothers + Others													
Rest	9	1	10	10	0	10	12	0	0	0	0	0	12
Travel	53	2	55	53	2	55	62	0	0	0	0	0	62
Social	14	1	15	14	0	14	27	11	0	0	0	0	38
Other/Unk.	26	1	27	24	3	27	27	0	0	1	0	0	28
All	102	5	107	101	5	106	128	11	0	1	0	0	140

Table 20. Frequency of turns and various swimming speeds during surfacings by undisturbed bowheads observed from a Twin Otter aircraft, May 1989. The units of observation are surfacings by an individual whale.

Whale Status and Group Activity	Turns					Estimated Speed at Surface							
	None	Right	Left	Mult-iple	Total	None	Slow	Mod-erate	Fast	Moving; speed?*	Mill	Change Speed	Total
Calves													
Rest					0								0
Travel	22	1	3	7	33	0	14	12	0	5	0	7	38
Social					0								0
Other/Unk.	17	1	2	3	23	1	11	1	0	5	0	3	21
All	39	2	5	10	56	1	25	13	0	10	0	10	59
Mothers													
Rest					0								0
Travel	23	0	2	0	25	1	9	9	0	4	0	4	27
Social					0								0
Other/Unk.	10	1	5	0	16	1	4	0	0	2	0	2	9
All	33	1	7	0	41	2	13	9	0	6	0	6	36
Others													
Rest	5	0	3	2	10	7	1	0	0	0	0	3	11
Travel	10	1	0	0	11	0	12	11	0	0	0	3	26
Social	2	4	4	4	14	6	5	5	1	1	0	3	21
Other/Unk.	7	3	0	0	10	6	2	3	0	0	0	1	12
All	24	8	7	6	45	19	20	19	1	1	0	10	70
Mothers + Others													
Rest	5	0	3	2	10	7	1	0	0	0	0	3	11
Travel	33	1	2	0	36	1	21	20	0	4	0	7	53
Social	2	4	4	4	14	6	5	5	1	1	0	3	21
Other/Unk.	17	4	5	0	26	7	6	3	0	2	0	3	21
All	57	9	14	6	86	21	33	28	1	7	0	16	106

* Moving forward but speed was not estimated.

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 action 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 17:04:30, 17:09:35, 17:11:20 and 17:20:30, we saw pairs of whales with ventrums touching for 5 to 67 s. In the first three observations, 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 final observation, the two whales traveled forward slowly while ventrum to ventrum.

On 6 May, we watched for 6 min (17:12:12 to 17:18:14) 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 socially-active pair, and was not seen to interact with the pair.

Our brief but clear views of social-sexual activity in early May reinforce the general impression that mating occurs mainly in spring, and wanes in frequency thereafter (Nerini et al. 1984).

<u>Mother and Calf Behavior</u>

Bowheads probably calve from about March to July (Nerini et al. 1984). Thus, calves encountered during May may vary in age from newborn to about three months. These calves are much smaller and younger than those whose behavior has been documented during previous late summer and early autumn studies. Thus, calf behavior is expected to differ in spring 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.

<u>Consistency of Eastward Movement</u>.--The movements of mother/calf pairs were less consistently eastward or northeastward than were those of other bowheads. Other whales observed during this study either remained in one location (while resting, feeding or socializing) or traveled generally eastward or northeastward. Traveling whales followed lead systems when leads were available, and deviations in their courses appeared to be related to changes in the orientations of leads or open water. Mother/calf pairs sometimes behaved in a similar manner. However, on other occasions they lingered in one area for a prolonged period, or even moved westward. We obtained two types of evidence bearing on this point: prolonged observations of specific mother/calf pairs during behavioral observation sessions, and re-identifications from day to day based on photoidentification.

We observed the behavior of three mother/calf pairs during periods when no known source of potential disturbance was present. 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 (see Fig. 67, p. 193). The lengths of whales (1)-(4) in meters 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 at this time of year (see "Bowhead Photogrammetry"). Both pairs moved steadily at moderate to slow speed and followed along or just inside the southern edge of the pack ice. The average rates of movement of whales 1 & 2 and 3 & 4 were 5.1 and 4.8 km/h, respectively. These rates are 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).

The third mother/calf pair was observed on 27, 28 and 29 May. Their identity was confirmed on each day by vertical photographs taken after that day's behavioral observations were completed. The lengths of this mother and calf were 14.9 and 4.0 m. This calf was one of the smallest calves that has been measured photogrammetrically. It was probably a recently-born calf. From their initial position at 19:30 h on 27 May, this mother/calf pair moved 12 km NE over a 44.2 h period (Fig. 58). Their net rate of movement was 0.3 km/h. This is slower than average net rates of movement for whales sighted >10 h apart (1.2 km/h) during a photographic study in the same area during the springs of 1985-86 (Rugh 1987).[4] During the observations on 28 May this pair meandered generally southwestward. On 29 May they were several kilometers NNW of the location where they last seen on 28 May (Fig. 58).

We observed only one other instance of bowheads, also a mother/calf pair, moving generally westward during behavior observation sessions. That observation was during a drilling noise playback, and in that case the westward movement may have been attributable to disturbance (see Fig. 64, p. 187). However, photogrammetry data obtained by ourselves and NMFS reveal a third record of westward movement by a mother/calf pair (Fig. 57). Those whales moved 12 km WSW from 17 to 18 May. The sizes of these two calves could not be measured.

The back and forth movements of the mother and calf on 28 and 29 May (Fig. 58) 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

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[4] Rugh (1987) noted that whales that travel slowly or deviate from their migratory course are more likely to be re-photographed on a subsequent date than are whales that migrate steadily through the survey area. In fact, steadily migrating whales would pass through our study area in about ½ day, and thereafter would not be present to be rephotographed.

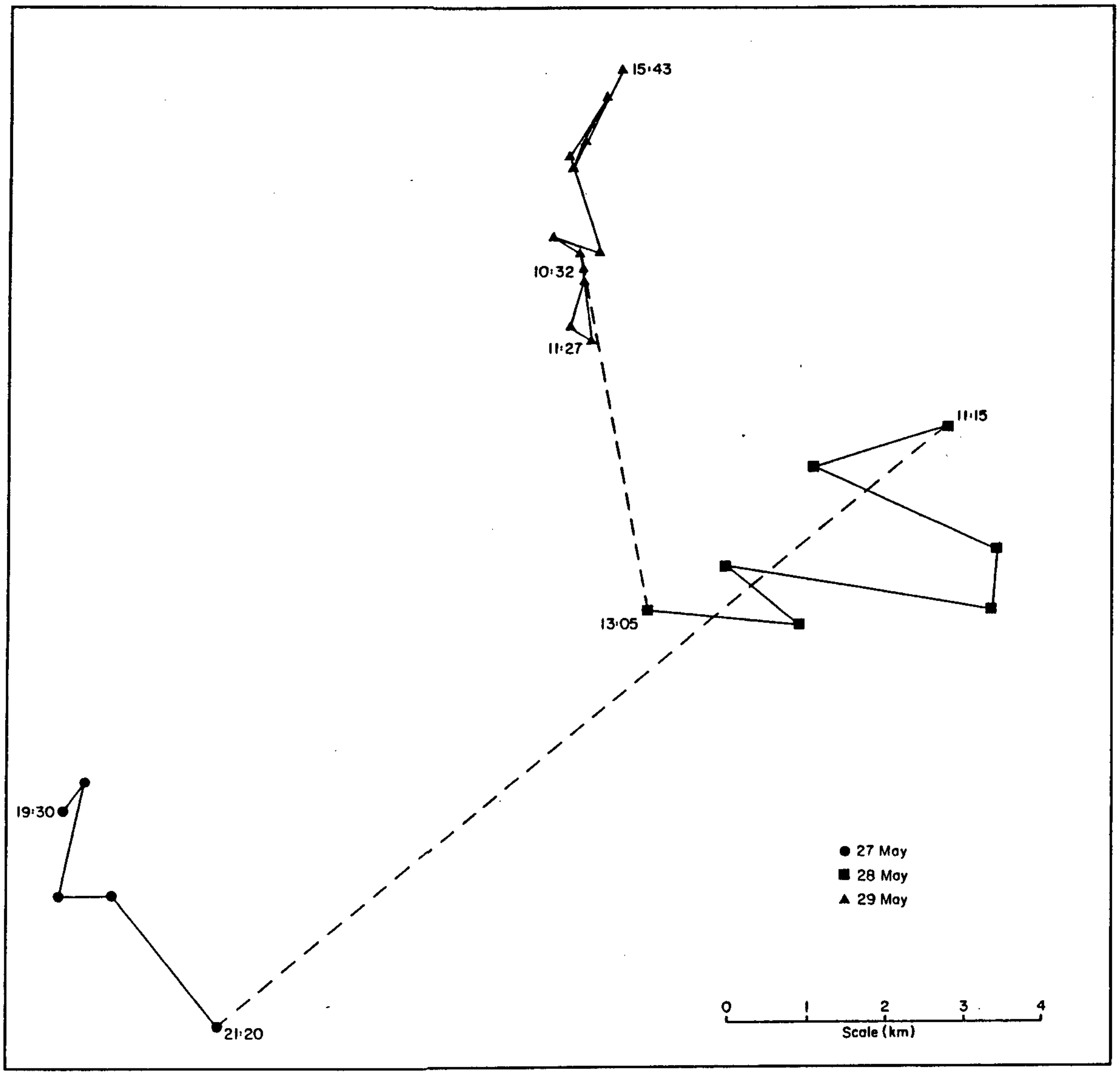

Fig. 58. Track of a mother and calf bowhead whale on 27-29 May 1989, as determined from positions obtained during behavior observation sessions and aerial photogrammetry during this study and during aerial photogrammetry conducted by NMFS on 28 and 29 May (NMFS, unpublished data).

brash ice. Similar open water areas were absent east and northeast of their locations.

In summary, our limited data from 1989 suggest that, during spring migration, bowhead mothers with newly-born calves may be less inclined to travel through heavy ice conditions. The few data available to date suggest that mothers with small calves may linger in areas of open water when ice conditions to the east are severe.

"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. This last form of locomotion has 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.

Riding consists of the calf appearing to lie on the back of the mother, pointed in the same direction as mother, with rostrum slightly behind the mid-back of mother and in an area where 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 simply 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 totally 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.

In bowhead whales, the calf is on the top of the mother rather than beside her during riding. Hence, in bowheads the term "echelon-swimming" is not appropriate. However, riding by bowhead calves appears to function at least as efficiently as echelon-swimming by dolphins. Bowhead calves beat their tails very little (and perhaps at times not at all) while in riding position.

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. Indeed, several times during May 1989 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 vague and 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 vantagepoints 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, although it is likely that the calf still gains a hydrodynamic advantage while close beside or underneath the traveling adult.

Mothers and calves were seen from the air each day from 23 to 29 May. On 23 May, a mother and calf were observed traveling under potentially disturbed conditions (drilling playback) for 33 min, with the calf generally close beside the mother. No riding was seen. On 24 May, a mother and calf were observed for 1.2 hr, traveling at slow to medium speed under potentially disturbed conditions (low aircraft altitude). The calf rode on the back of mother for 50% of that time. On 25 and 26 May, we saw several mothers and calves, but due to low clouds we were not able to make detailed behavioral observations. On 27 May, we observed four mother-calf pairs during three behavioral observation sessions. Pairs were observed for 1.2, 1.0, 2.1, and 0.9 hr. Calves of the first three pairs rode on their mothers only about 10 to 20% of the time while the whales were visible. The fourth calf seen on 27 May rode ~30% of the time as the pair traveled just below the surface. This calf alternated riding with several other activities:

- swimming along the side of the mother;
- apparent nursing as it oriented below the mother; and
- changes in direction (on two occasions). When the calf changed direction, the mother also changed direction and turned sharply in front of the wayward calf, physically forcing it back to the original orientation.

On 28 May, a mother-calf pair was observed as they moved at generally slow speeds for 0.7 hr (11:46-12:30, Fig. 58). The calf rode somewhat less than half of the visible time. On 29 May, the same mother-calf pair was observed for a total of 2.0 hr during three behavioral observation sessions (Fig. 58). The calf again rode somewhat less than one-half of the visible time as the pair slowly meandered back and forth in an open area amidst the pack ice.

Riding is likely important to the calf only during the first few months of life. Riding has not been seen in the Canadian Beaufort Sea in late summer or the Alaskan Beaufort in autumn. By late summer, the combination of the calf's increased size, its muscular development, and the end of spring migration make riding unnecessary.

It is not clear whether "riding" by bowhead calves is a form of assisted locomotion, or whether the mother actually carries the young. Dolphins assist the locomotion of their young by echelon swimming (Kelly 1959). Only a few non-marsupial placental mammals actually carry their young--mainly primates and possibly porpoises (the finless porpoise, *Neophocaena phocaenoides*, Pilleri and Chen 1979). Most female primates carry their infants on their bodies for most of the day (Nicolson 1987). Whitten (1982) has calculated that the energetic cost of infant transport in primates is significant. Some prosimians carry their young for short distances by mouth (Klopfer and Boskoff 1979), but the energy cost of this is thought to be small. In baleen whales, riding likely gives pronounced hydrodynamic and energetic advantages to migrating newborn. We suspect that it will be described in several other baleen whales, such as right and gray whales, in future.

Surfacing, Respiration and Diving Behavior of Calves.--Table 18 summarizes the standard surfacing, respiration and diving variables for all calves observed under presumably undisturbed conditions. Intervals between successive visible respirations tended to be shorter in calves than in mothers (P<0.05). Durations of surfacings and number of visible blows per surfacing did not differ appreciably between calves and mothers, but dive durations tended to be shorter for calves (means 2.91 vs. 6.12 min; P<0.001). Also, dives by "others" averaged considerably longer than those by mothers (means 11.89 vs. 6.12 min). This difference probably would have been more pronounced if we had been able to document the long underice dives by "others". The most notable characteristic of the surfacing, respiration and diving behavior of calves was their short dives.

Surfacing, respiration and dive variables for two large calves migrating with their mothers on the morning of 27 May are compared in Table 21 with values for the single small calf and its mother lingering in the study area on 27, 28 and 29 May. The traveling calves were 4.8 and 4.9 m long; the lingering calf was 4.0 m long. Mean blow intervals and duration of surfacing were similar for the traveling vs. lingering calves. However, the number of blows per surfacing was marginally lower for the small lingering calf, and its average dive duration was markedly shorter (Table 21). It is uncertain whether the difference in dive durations was attributable to the different sizes (and ages) of the calves, or to their different activities.

Table 21. Surfacing, respiration and dive behavior of undisturbed bowhead calves and mothers observed from a Twin Otter aircraft while the whales were traveling (morning of 27 May, two pairs) and lingering (27-29 May, one pair observed repeatedly). The lingering calf was smaller. Because each line of data came from repeated observations of only one or two individuals, the statistical comparisons should be interpreted with caution.

	Mean Blow Intervals (s)				# of Blows/ Surfacing				Duration of Surfacing (min)				Duration of Dive (min)			
	Mean	s.d.	n	P	Mean	s.d.	n	P	Mean	s.d.	n	P	Mean	s.d.	n	P
Calves																
Travel	14.9	6.18	28	t	7.5	2.95	11	t'	1.78	0.75	19	t'	5.20	1.83	17	t'
Linger	17.7	8.48	34	ns	4.7	4.88	32	*	1.47	2.05	34	ns	1.80	0.70	35	***
Mothers																
Travel	23.6	20.27	22	t'	5.9	2.14	13	t	1.93	1.08	18	t	7.08	2.42	14	t
Linger	23.1	6.95	16	ns	3.2	2.40	21	**	1.02	0.90	21	**	5.44	3.47	20	ns

"P" columns show the type of t-test used to compare traveling vs. lingering (t=standard; t'= unequal variances), and the nominal significance of the difference:
ns P>0.1 (*) 0.1>P>0.05 * 0.05>P>0.01 ** 0.01>P>0.001 *** P<0.001

Riding confers a hydrodynamic advantage to the young calf, and may allow migration at times and places when the calf would be unable to travel unassisted. It may, for example, allow the calf to hold its breath longer while mother and calf migrate under ice between leads. Blow rate (number of blows per minute, averaged over surfacing and dive periods) may be a good measure of energy utilization. Because most of the present observations were in relatively short sequences, we could not calculate blow rates with adequate accuracy. We could, however, compare blow intervals of calves that were riding with those immediately before or after riding, while the same calf was swimming beside the adult at a speed of travel similar to that during riding. Intervals between successive visible blows by calves were longer when the calves were riding than while they were swimming on their own (Table 22). Both presumably undisturbed and potentially disturbed calves are considered in this Table. Likewise, killer whale (*Orcinus orca*) calves breathe about twice as often when swimming unassisted than when echelon swimming beside an adult (von Kugelgen 1988). These results are suggestive, but do not necessarily prove that blow rates would be lower for calves that are riding.

Table 22. Individual blow intervals (in seconds) for calves that were riding vs. those during adjacent non-riding periods.

	Riding			Not Riding		
Date	Mean	s.d.	n	Mean	s.d.	n
24 May	20.7	18.76	39	16.5	9.40	13
27 May	32.3	19.34	14	10.1	5.09	9
29 May	33.9	20.48	10	18.0	13.42	26
29 May	41.8	11.84	4	21.3	14.48	8

If riding confers an energetic advantage to the young, it should be of some energetic disadvantage to the assisting adult. Such a disadvantage has been demonstrated for echelon-swimming killer whale adults. They breathe 90 ± s.d. 18.0 times/hr (n = 41) when moving with a calf compared to 74 ± 16.0 times/hr (n = 9) when alone (Waite 1988). We do not have comparable data for bowhead whale adults due to the scarcity of prolonged observations in 1989.

Other Behavioral Variables.--Pre-dive flexes were not seen in calves, and only 1 of 71 surfacings ended with a fluke-out dive (Table 19). The only aerial behavior noticed was a single surfacing with a tail slap. Calves often turned while at the surface; their speeds were typically classified as slow or moderate (Table 20).

Mother and Yearling.--On one occasion, we observed a large bowhead accompanied by a small whale that we assumed to be a one-year-old (yearling). These whales were seen at 18:58 on 24 May in a small crack in the pack ice. The ceiling was low (160-200 m), so we were unable to observe them without potentially disturbing them with the observation aircraft. Therefore, we observed for only 5 min. Unfortunately, photogrammetry was impractical on this occasion.

The assumed yearling was a uniform dark color and noticeably larger than a small light-colored calf sighted only 9 min later. The yearling was strongly associated with the larger animal. It swam close to the tail of its presumed mother. The position and behavior of the yearling were similar to those of calves that we have observed during summer and autumn.

Adults that are closely accompanied by yearlings have not been reported previously during spring or summer. This information is important in relation to the unknown age of weaning in bowheads. Photographs obtained by NMFS at Barrow during the spring have not been examined systematically for the presence of mothers accompanied by yearlings. Two adults accompanied by probable yearlings have been identified among their photographs, but at most only a few more exist (D. Withrow, NMFS, pers. comm.). All vertical photographs taken in the Beaufort Sea from late July to mid October have been examined for adult/yearling pairs but none have been identified (Koski et al. 1988). Assuming that calves are born from March through July, the scarcity of mother-yearling pairs in May suggests that most calves are weaned before they reach an age of 10-15 months. A few individuals, presumably some of those born in summer rather than spring, may not be weaned by the following May.

High priority should be given to photographing mothers accompanied by yearlings if they are encountered. Photogrammetric data on these animals would provide much-needed information on lengths of yearlings.

<u>Timing of Migration by Mothers with Calves</u>.--The tendency for mothers with calves to pass Barrow late in the spring migration season (Nerini et al. 1987; this study) may be related, in part, to avoidance of severe ice conditions. During late May of 1989, we saw bowhead mothers and calves meandering back and forth in large openings, apparently unwilling to travel eastward under large ice pans, even though adults without calves were migrating through those areas. However, there probably are other reasons for the late migration of mothers with calves, since the same phenomenon is seen in other baleen whales that do not have to contend with ice. Similar segregation, with females and their newly-born young migrating to higher latitudes after the rest of animals, has been observed in the closely related southern right whale, *Eubalaena australis* (Payne in press), the humpback whale, *Megaptera novaeangliae* (Dawbin 1966; Forestell 1986), and the gray whale, *Eschrichtius robustus* (Rice and Wolman 1971).

Most baleen whales undergo extensive migrations that take them to relatively warm waters in winter and to more productive and colder waters in summer (review by Evans 1987). It has been assumed that it is of advantage for the young to be born into warm waters, although this hypothesis has not been investigated adequately on physiological grounds. However, bowheads remain near ice most of the year, and they are in near-freezing water at most times. The only exception is when they feed in shallow nearshore waters warmed by the summer sun and river outflows, such as that of the Mackenzie River (Bradstreet et al. 1987). In that case, the whales experience warmer temperatures in summer, not winter. Water temperatures are not appreciably warmer near Barrow (or elsewhere along the spring migration route) during late May and early June than they are earlier in the spring.

Why, then, are bowhead mothers and calves the last to pass Pt. Barrow in spring? We believe that the segregation of mothers and calves may, at least in part, be due to the tendency for ice conditions to improve as the spring progresses. At any time during spring, ice leads may close in response to shifting winds or refreeze in cold weather. However, these deteriorating conditions tend to be less common, less severe, and less prolonged later in the spring season. These conditions may be most dangerous for calves, which do not dive for nearly as long as adults.

Bowhead Reactions to Playbacks of Drilling Platform Sound

Specific objective 4 was to measure the short-term behavioral responses of whales visible in open water areas along their spring migration corridor in the western Beaufort Sea to underwater playbacks of continuous drilling sound (p. 18). In this section we first describe each individual observation of bowheads exposed to projected drilling sounds. We then summarize and integrate all of these results. The daily accounts include considerable information about ice conditions, since the movements of the whales (as well as our ability to monitor them) were strongly influenced by ice.

30 April 1989

The ice-based crew conducted a transmission loss (TL) test on this date amidst heavy pack ice several kilometers north of the landfast ice edge. The test sounds consisted of HFM warble tones, pure tones, and samples of drilling platform noise (see "Methods: Sound Propagation", p. 45). These sounds were projected into a partially refrozen hole amidst the pack ice intermittently from 13:28 to 15:20 and for 5.5 of every 7.5 minutes from 15:37 to 17:39 (Table 23). The open-water area initially was ~50 x 180 m and was oriented east-west, but by 18:00 the lead had closed to ~50 x 120 m (Fig. 59). This test was not designed to study the reactions of whales to the projected sounds, so no systematic observation protocol had been established. However, the crew tending the projector watched for whales when possible.

Three single bowheads surfaced in the lead and swam east along it, passing 60-75 m from the projector (distances estimated by eye by the ice-based crew; believed accurate within ± 10 m). One of these (whale 2 in Table 23) surfaced just previous to a transmission of the test sounds that started at 15:37:30. During the 1.4 min period while it was at the surface and under observation, the projected sounds were two tonal sweeps centered at each of 50, 100, 200 and 500 Hz. If it was swimming at 5 km/h, whale 2 would have been 1.4 km from the projector during the previous sound transmission period, which ended 17 min before whale 2 was seen (Table 23).

The other two whales surfaced during quiet periods at 15:34 and 18:06, 14 and 27 min, respectively, after the end of the most recent sound transmission. At the times of these transmissions, the whales would have been 1.1 km (whale 1) and 2.2 km (whale 3) from the projector if they swam at 5 km/h (Table 23).

None of the whales showed visible signs of disturbance. Whale 2 blew one or more times immediately before and five times during the period while the test tones were being broadcast. There was no change in its orientation or speed of movement, as estimated by visual observations from the ice, at the time the tones

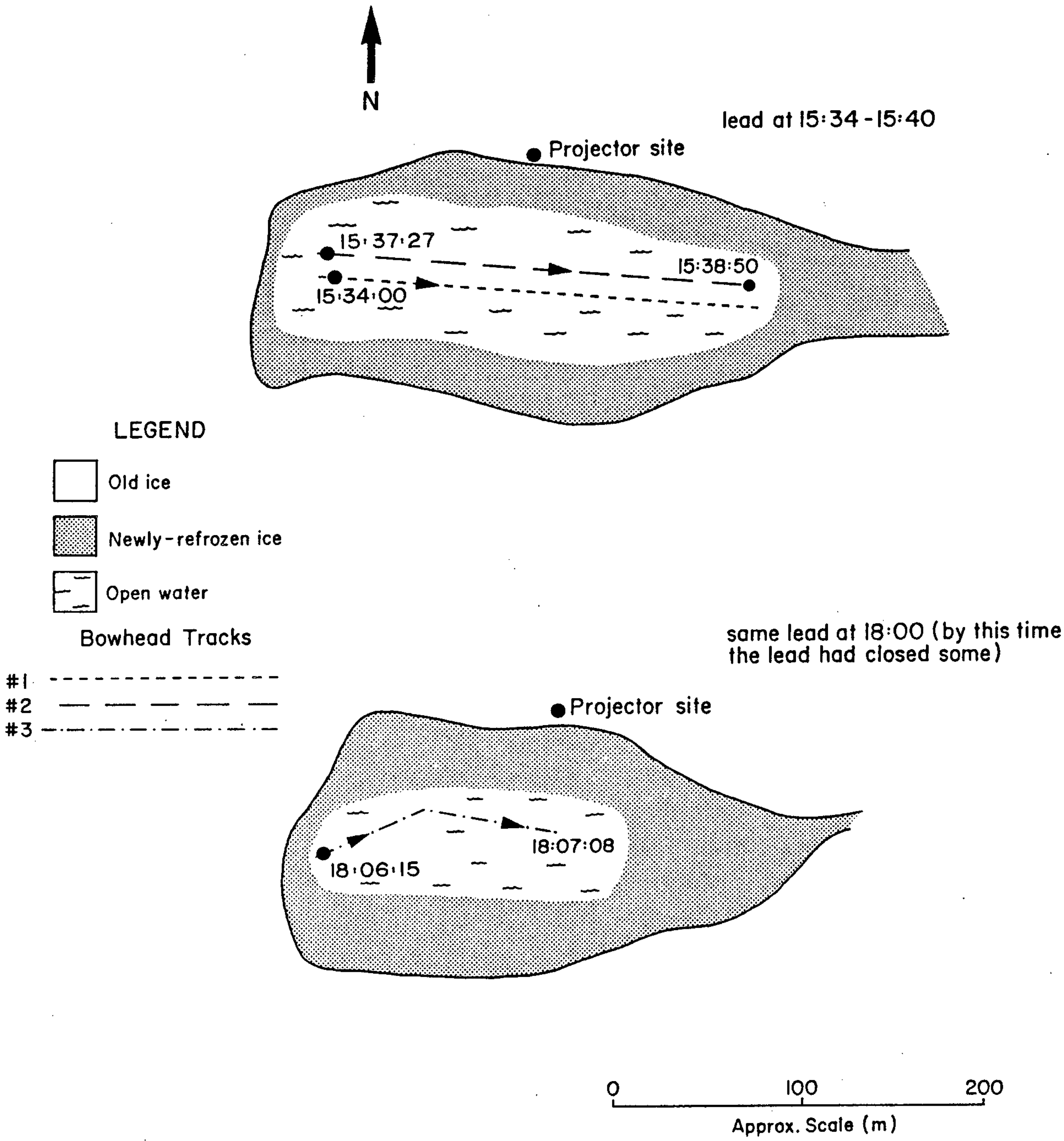

Fig. 59. Ice conditions and whale tracks near the projector during a transmission loss test, 30 April 1989. The projector was operating for most of the time while whale #2 was under observation.

Table 23. Estimated distances of three bowhead whales (1, 2, 3) from the sound projector during underwater transmission of test sounds and during surfacing sequences near the projector, 30 April 1989.

Time of TL Projection	Time When Whale at Surface	Estimated Distance of Whale from Projector (km)
14:39:30-14:53:30		* #1 @ ~3.4 #2 @ ~3.7
15:14:50-15:20:15		* #1 @ ~1.1 #2 @ ~1.4
	#1 @ 15:34:00	** #1 @ 0.075 #2 @ 0.070
15:37:30-15:43:00	#2 @ 15:37:27-15:38:50	** #2 @ 0.060-0.070
⋮		
17:30:00-17:36:00		* #3 @ ~2.5
17:38:00-17:39:20		* #3 @ ~2.2
	#3 @ 18:06:15-18:07:08	** #3 @ 0.060-0.075

* This estimate assumes a migration speed of 5.0 km/h (see Koski and Davis 1980; Rugh 1987; George and Carroll 1987).
** These are visual estimates and are probably accurate to ± 10 m.

started or at any other time during its surfacing. It followed the same course as the whale that surfaced 2.5 minutes earlier (previous to the 15:37 playback).

Source and received levels of the test tones and the samples of *Karluk* drilling sounds were measured on 30 April at the site where the whales were observed. The source levels of the various test tones 1 m from the projector were 158-171 dB re 1 μPa, depending on frequency (Table 5, p. 112). Received levels of the tones depended on frequency as well as range. The levels of the strongest tones measured are shown in Table 24, along with the received broadband sound levels of the samples of *Karluk* drilling sounds.

Based on the measurements in Table 24, we estimate that whale 2 was exposed to tones with received levels as high as ~130 dB when it swam within about 60 m of the sound projector; the strongest tone at that range was probably at 500 Hz. The ambient noise level was ~80 dB in the 1/3-octave band centered at 500 Hz and 95 dB on a broadband basis. Thus, the strongest tone received by the whale was ~50 dB above the background noise level within the relevant 1/3-octave band[5] and 35 dB above the broadband ambient level. It should be noted that all of these estimated received levels and S:N ratios apply to a receiver at least a few meters deep. The whale probably would not have received levels this strong, at least for frequencies below 500 Hz, when it was at the surface. The effective depth of the hearing apparatus of a bowhead swimming at the surface is unknown. In theory, the received level of a 50 Hz signal received 60 m from the source

[5] Assuming that masking bands for bowhead hearing are roughly 1/3-octave in width.

Table 24. Selected acoustical data vs. range during the transmission loss test and bowhead observations on 30 April 1989 (see Table 5 for details).

	Strongest Tone			Ambient Levels**	
Range	Frequency	Level	*Karluk* Level*	Broadband	1/3-Oct.
1 m	200 Hz***	169 dB	164 dB	95 dB	81 dB
	10 kHz	171			
100	500 Hz	126	125	95	80
200	100	125	122	98	87
930	100	119	113	91	82
1850	100	100	104	94	87
4070	100	86			

* Broadband level, frequencies up to 350 Hz.
** Ambient levels are given for (a) the same broad band as used for the *Karluk* drilling sounds, and (b) the 1/3-octave band containing the strongest tone.
*** Source levels at 50, 100 and 500 Hz were 158, 168 and 165 dB re 1 μPa.

would be ~18 dB less at depth 1 m than at depths ≥15 m (Lloyd mirror effect--Urick 1983). The corresponding attenuation values would be ~12 dB at 100 Hz, 6 dB at 200 Hz, and nil at 500 Hz.

Assuming that the three whales swam at 5 km/h, they were 1.1-2.2 km from the projector during their "penultimate" surfacings. At those distances, they would have been exposed to a series of tones with levels up to 95-115 dB, based on the measurements in Table 24. During the same "penultimate" surfacing, each whale was exposed to a brief sample of drilling sounds. At these ranges, the 1/3-octave band with the strongest drilling sound was the band centered at 160 Hz, for which the received levels at 1.1-2.2 km were about 95-100 dB (measured as 98 dB at 1.85 km). The ambient noise level in that 1/3-octave band was 86 dB, so the drilling:ambient noise ratio in that band was about 9-14 dB. The broadband level of drilling sounds at these ranges was about 100-110 dB, or about 9-19 dB above the background ambient level in the corresponding band.

If the whales were swimming slower than 5 km/hr, they would have been closer to the projector during their "penultimate" surfacing, and exposed to stronger sounds than those estimated above. It is unlikely that they swam much faster than 5 km/hr. Even if they did travel as much as 7.5 km/hr, and thus were farther away than estimated above during the penultimate surfacing, received levels and drilling:ambient ratios would have been no more than 3.5 dB lower than estimated above--still well above the background noise level.

Despite exposure to these sounds during the "penultimate" surfacing 14-27 min before they surfaced in the lead with the projector, the whales apparently continued eastward toward the projector.

<u>14 May 1989</u>

The ice-based crew set up the sound projector along the east side of a long lead oriented SSW to NNE; the projector was toward the NNE end of the lead (Fig. 60). This was the largest area of open water within many kilometers. Both the east and west sides of the lead consisted of large consolidated pans >5 km across. The SW end of the lead consisted of numerous large pans 0.5-2.0 km in diameter with crushed ice (brash) and open-water areas 50-200 m in diameter between the pans. These open-water areas provided an apparent migration corridor for whales to enter the lead where the projector was set up. To the NNE of the projector site the lead was blocked by converging pans, but small elongated open water areas and small leads filled with brash provided the most obvious migration corridor for whales to leave the lead. There was a series of small narrow leads several km to the NE of the projector site, but whales would have to pass under several km of apparently solid ice to reach this area.

During an initial reconnaissance flight around the lead, while the projector was being set up, bowheads were sighted swimming NE both at the north end of the main lead N of the projector site and along the narrow leads to the NE (Fig. 60). Also, about eight bowheads were distributed amidst the pack ice 27 km to the WSW of the open area at 10:34-11:08.

The ice-based crew began projecting the drilling platform sound at 11:58 and projected it continuously until 18:35. The projected sounds were monitored intermittently at a sonobuoy located along the ice edge 1.0 km SSE of the projector. After 18:35, the tape containing tonal sweeps, tones, and a brief sample of the drilling noise was projected, and these test sounds were monitored by the sonobuoy 1.0 km SSE of the projector. All sound projection ended at 18:44.

At 11:30, before the playback began, the aircraft crew began observing a single bowhead that was tail slapping 4.6 km SSW of the projector site. It dove at 11:31 and was not recognized again.

At 12:18, after the start of the playback, the aircraft crew sighted two bowheads moving NE about 4.7 km SSW of the projector. These two whales (#8 and #9 in Fig. 61) were monitored until 13:52 as they followed the eastern side of the lead northward to positions 0.9 and 0.5 km SE of the projector site. These final distances were determined by visual estimates from the aircraft, and are believed to be accurate within ±20%. Both of these bowheads were last seen heading NNE under the ice. In addition to the three bowheads mentioned above, several single bowheads were observed for short periods of time and one active bowhead was observed from 14:25 to 14:46 as it performed aerial activities 2.5 to 2.8 km south of the projector (C in Fig. 61).[6] The observation aircraft then

[6] The designation of some whales by letter and others by number has no special significance.

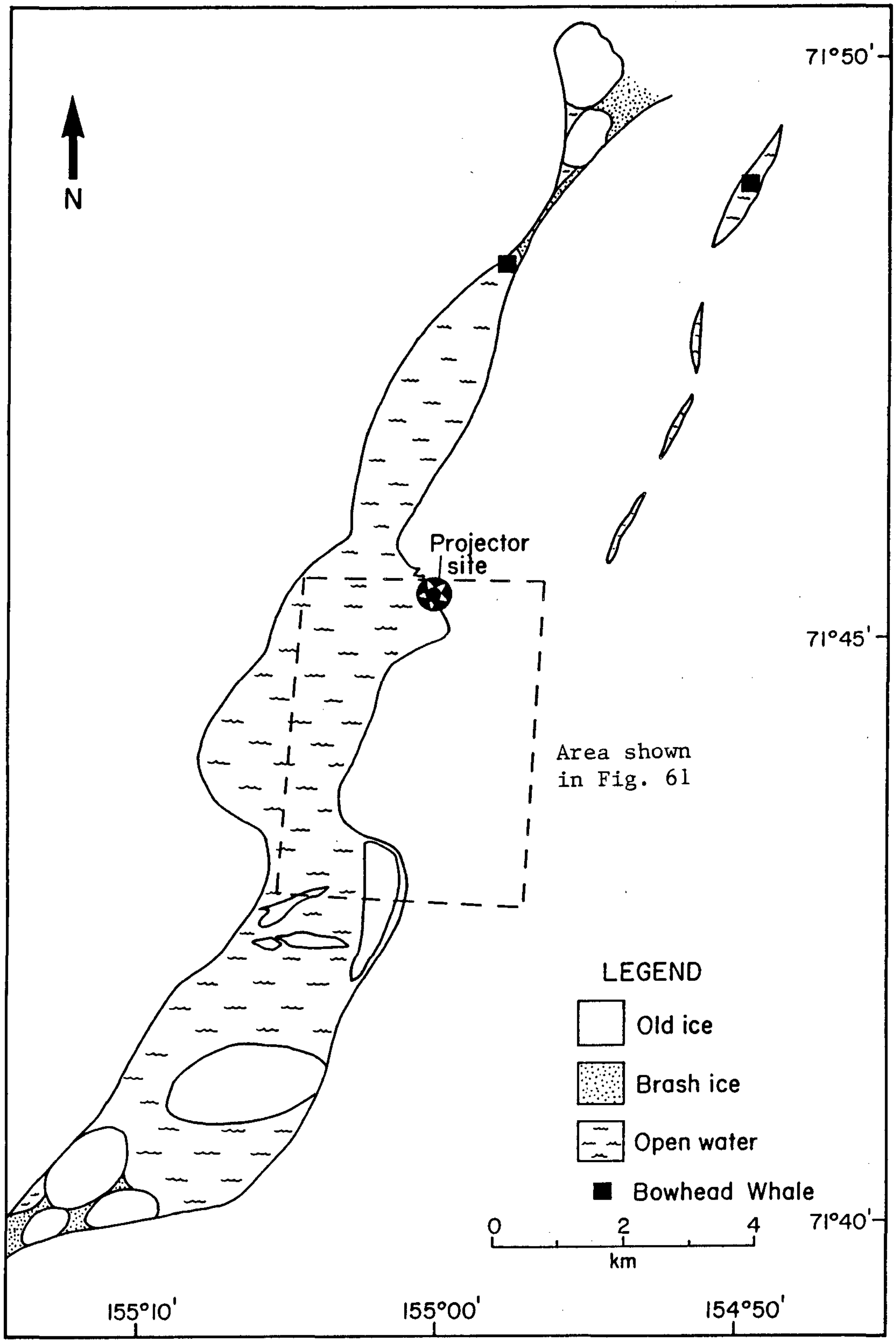

Fig. 60. Ice and lead conditions during a playback of drilling platform sounds conducted amidst the pack ice NE of Barrow, Alaska, 14 May 1989. See next Figure for a more detailed view of the area near the projector.

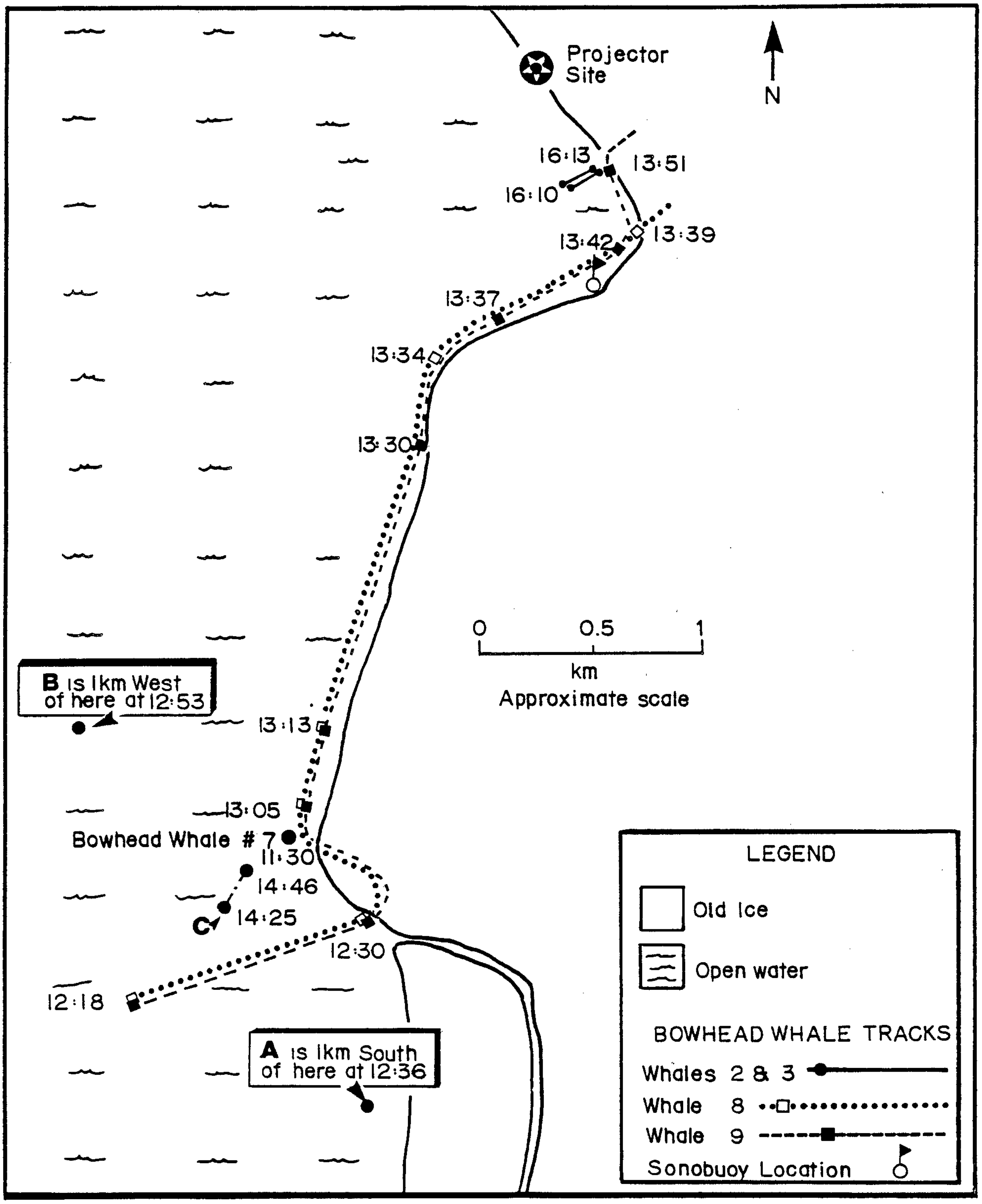

Fig. 61. Locations and tracks of bowhead whales observed by the ice-based crew (whales #2 and 3) and aerial crew (other whales) during a playback of drilling platform sounds conducted amidst pack ice NE of Barrow, Alaska, 14 May 1989. All positions are plotted relative to the projector. See preceding Figure for view of the broader area around this location.

left to refuel. Upon its return about 1.8 h later, the cloud ceiling had decreased to ~275 m, preventing further aerial observations.

The ice-based crew recorded five bowheads between 14:27 and 18:38. The first of these was the aerially active bowhead that was also observed by the aircraft crew (whale C in Fig. 61). Also, three bowheads were sighted between 16:10 and 16:13. Two were swimming ENE 520-530 m south of the projector (#2 and #3 in Fig. 61; distance measured by theodolite). They were last seen heading under the ice near the CPA position of whale #9, observed from the aircraft over 2 h earlier. No changes in speed of movement or direction of travel were noted during the brief period while they were at the surface. The other whale was far behind the first two and was also heading ENE, but it was not resighted. The fifth whale was sighted at 18:38, traveling NE at the horizon SSW of the projector as it dove. It was not resighted, but systematic observations terminated before 18:44 when the projector was turned off and the ice-based crew began to disassemble gear.

Figure 62 shows respiration, surfacing and dive variables of bowheads observed on 14 May 1989 in relation to the distance from the operating sound projector. There were no statistically significant correlations between any of these variables and the distance from the projector. However, whale #9's dives seemed to become shorter as it approached the projector (Fig. 62). Given the known variability of these variables among undisturbed bowheads, the sample sizes from this single experiment were too small to allow a meaningful interpretation of the data from this experiment alone.

The path followed by whales #8 and #9 from 12:18 to 13:52 suggests that they were not deflected by the projector, at least at distances exceeding 1.5 km. Extensive open water was present to the west of the ice camp, and whales could have detoured around the west side of the projector. However, they swam parallel to the ice edge and toward the projector until they were 1.5 km from it. At that point the ice edge turned northeastward, slightly away from the projector (Fig. 61). The whales turned NE, continuing to travel parallel to the ice edge, and were no longer oriented toward the projector. The ice edge turned sharply to the NW ~0.9 km SSE of the projector site. Both whales maintained their previous NE headings as they approached this corner and appeared to dive under the ice at 13:40 and 13:46. Whale #8 dove 0.9 km from the projector and was not seen again. However, whale #9 surfaced once more at 13:51, 400 m NNW of its 13:46 position. It was oriented NNE, although the adjacent ice edge was oriented NW and the whale had moved NNW from its previous position. It dove and was not seen again, although we circled the area until 14:24.

Whales #8 and #9 apparently passed to the east of the projector by moving under an area of extensive ice toward the long narrow leads NE of the projector (Fig. 60). It is uncertain whether the presence of the operating projector altered the paths of these two whales. Their turn from NNE to NE 1.5 km south of the projector at 13:36 might have been attributable to the projector, but it is also consistent with the general orientation of spring migration and the change in the orientation of the ice edge at that position. In any case, both

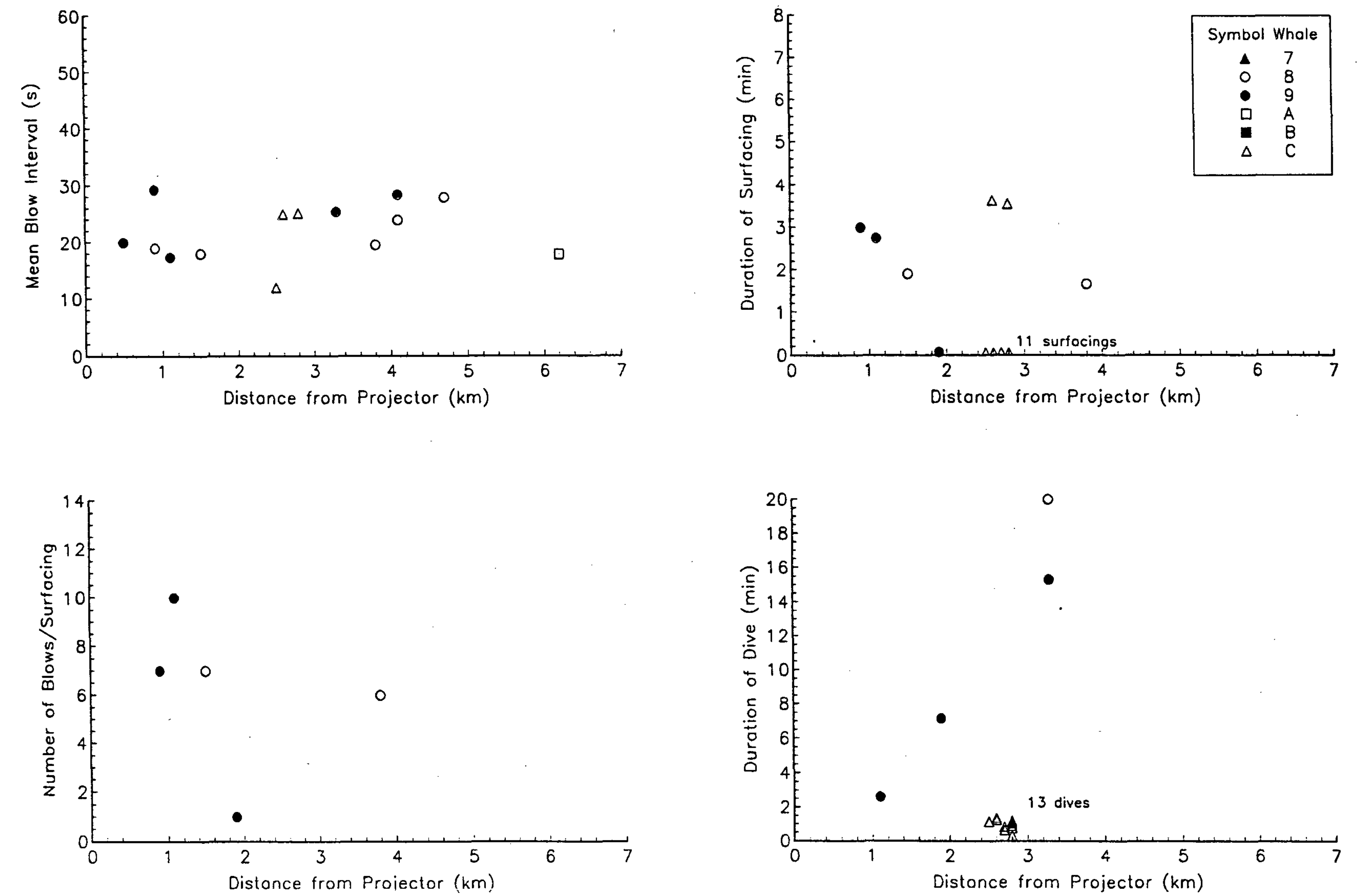

Fig. 62. Respiration, surfacing and dive variables for bowhead whales observed on 14 May 1989 in relation to distance from a projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska. All data shown were collected by aerial observers. Different symbols represent different individual whales. Positions of these whales are shown on the preceding Figure. Whale C (open triangles) was engaged in breaching and other aerial behaviors.

whales approached to 0.9 km, and #9 approached to 0.5 km. Two whales seen by the ice-based crew over two hours later at 16:10 apparently dove under the ice at the same location as whale #9--about 0.5 km SE of the projector site. Thus, at least three bowheads approached to ~0.5 km from the projector during the playback on this date.

During this playback experiment, a monitor sonobuoy was placed 1015 m SSE of the projector, along the ice edge (Fig. 61; distance determined by theodolite). The CPA locations where bowheads disappeared under the ice at 13:40 and 13:52 were very close to the line from the projector to the sonobuoy. The broadband source level of drilling platform sounds was 165 dB re 1 μPa-m, and the broadband (20-1000 Hz) received level at the buoy 1.0 km away was 101 dB (Fig. 36, p. 105). The broadband levels at distances of 0.5 and 0.9 km, the CPA distances of at least 4 bowheads, are estimated to have been ~107 and ~102 dB. The natural ambient noise level in the same band was 94 dB (Fig. 35, p. 104), so the broadband signal to noise ratios at ranges 0.5 and 0.9 km were about 13 and 8 dB. Within various 1/3-octave bands, the S:N ratio at 1.0 km was as high as 18 dB (for the band centered at 80 Hz). Hence, S:N for this band at the CPA distances (0.5 and 0.9 km) was about 24 and 19 dB:

	Distance	Type	20-1000 Hz			Peak 1/3-Octave*			
		of	Drill.	Amb.	S:N	Freq.	Drill.	Amb.	S:N
	(km)	Data	(dB)	(dB)	(dB)	(Hz)	(dB)	(dB)	(Hz)
Buoy	1.0	Meas.	101	94	7	80	96	78	18
CPA Bhd #9 @ 13:51	0.5 to								
& 2 Bhd @ 16:10	0.52	Est.	107	"	13	80	102	"	24
" Bhd #8 @ 13:40	0.9	"	102	"	8	80	97	"	19

* 1/3-octave with maximum received level was same as that with maximum S:N.

The strongest tones in the spectrum of the drilling noise as received 1 km away were at 66, 78, 101 and 225 Hz.

Thus, on 14 May at least four bowheads migrated toward and past the projector, passing as close as 0.5 km (n=3) and 0.9 km (n=1). These whales were exposed to levels of drilling noise that were well above the natural background level. The routes of the several other bowheads that were observed briefly during this playback are unknown. Hence, we do not know how close they came to the projector, or whether their movements were affected by the noise.

<u>19 May 1989</u>

The ice-based crew set up the sound projector on the west corner of an ice pan ~1 km square. The pan was situated at the vertex of an L-shaped open lead whose arms extended NW and SW from the ice pan (Fig. 63). The projector was ~1.14 km to the NW of the SE edge of the lead (Fig. 63). The SW arm of the lead was ~1 km wide as viewed from the projector site and the NW arm was 1.5 km wide. Two additional narrow leads continued to the NE on either side of the pan (Fig. 63). Of these, the southern lead narrowed from ~500 m wide until it was no longer visible as the "ice camp pan" and the southern edge of the lead came together. Another narrow lead continued around the north end of the pan; this narrow lead contained brash ice where the two pans were converging, but appeared to be a potential migration corridor for whales continuing to the NE.

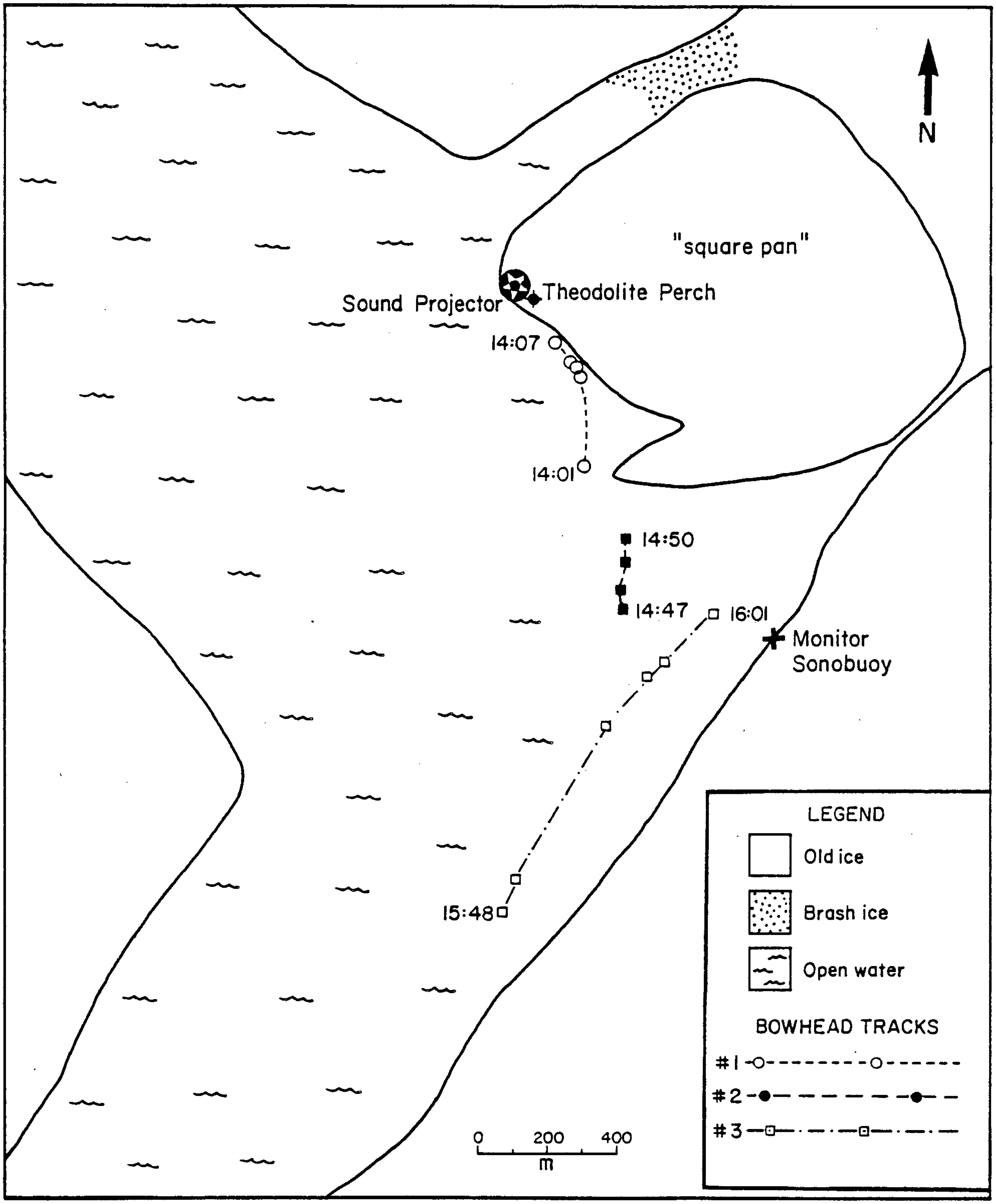

Fig. 63. Bowhead tracks observed by ice-based observers during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 19 May 1989. Whale positions are plotted from theodolite readings relative to the projector.

The Twin Otter aircraft did not fly on this day because of low ceilings (<150 m ASL). No bowheads were seen during arrival of the helicopter at the camp at 10:37, or during set up of the equipment, which required until ~13:30. The observers started full-time observations for whales at 13:30. Other members of the ice-based crew projected the transmission loss tape from 13:43 to 13:50. They began projecting the drilling platform sound at 13:51 and projected continuously until 18:10. They then projected the transmission loss tape again from 18:11 to 18:18.

At 14:01, 10 min after the start of the playback of continuous drilling noise, a single bowhead whale was sighted traveling NNE at medium speed toward the pan with the sound projector. This whale was 500 m SSE of the projector as measured by theodolite. The whale was north of the mouth of the narrow lead to the SE of the ice camp. The bowhead surfaced again at 14:04, north of its original position and at the edge of the pan supporting the projector. The whale's forward speed had decreased to slow-none. The whale appeared to drift NW at the surface, closely following the edge of the pan toward the projector. The whale disappeared behind ice rubble at the pan edge at 14:05, but was still moving slowly NW toward the projector. Observers were able to follow the whale by hearing and seeing its blows rise above the rubble until it submerged at the edge of the pan at ~14:07. It was still moving toward the projector.

The closest observed point of approach of this bowhead--the 14:07 location when it last blew--was 120 m from the projector. This distance was measured along the ice edge using a Rolotape model 400 measuring wheel. This measurement is believed to be accurate within 2-3 m (accuracy ±¼% claimed by manufacturer). The whale may have approached closer to the projector before diving, but it would have emerged from behind the rubble ice if it had approached within 100 m of the projector. Thus, CPA while at the surface was 100-120 m. This whale did not seem to be deflected by the projector sounds but it reduced its speed of travel as it closely approached the projector. This might have been related to the noise, but might also have been related to the arrival of the whale at the eastern end of the lead. The whale followed the ice edge north along the most extensive available channel of open water even though it might instead have avoided close approach to the projector if it had moved NE along the south side of the pan (Fig. 63). It is possible that the bowhead was headed toward the small lead along the north side of the pan on which the projector was located. However, the whale was not sighted after 14:07. Its true CPA may have been less than 100-120 m if it continued to approach the projector after diving.

A second bowhead was first sighted at 14:46. It was initially traveling N at medium speed 910 m SSE of the projector (theodolite measurement). The whale subsequently appeared to change course slightly, and oriented NNW toward the projector until 14:49. It then slapped a flipper, blew three more times, and dove when 720 m SSE of the projector. It was not sighted again. With the possible exception of the flipperslap, the animal showed no overt signs of disturbance. Similar to the first bowhead, the second bowhead appeared to reorient generally northward along the open lead and toward the projector when it approached the closing lead to the south of the projector. It was also traveling NNW when last seen.

A third and final group of two large bowheads was first sighted at 15:47 traveling NE at medium speed 1.8 km SSW of the projector (1.9 km when the earth curvature is considered; perch height = 5.68 m). The whales followed the lead in a relatively straight-line NEward course. They were tracked for 13 min, during which time 13 positions were determined by theodolite. The group was last sighted traveling NE up the narrowing section of the lead SE of the projector site. The whales were lost from view 1.0 km SE of the projector (measured by the theodolite) at 16:00 when they were obscured behind ice rubble. There was no evidence that they were affected by the sound from the projector, as they did not deviate from course, nor did they closely follow the southernmost edge of the lead as might have been expected if they were attempting to minimize exposure to the projector. On the other hand, they did not curve to the north close to the projector, as had the previous two whales. Their failure to do so might have represented avoidance of the projector, but this cannot be proven given the fact that continued NEward migration southeast of the pan would be expected in the absence of disturbance.

Projected sounds (source level 162 dB re 1 μPa) were monitored by a sonobuoy placed 1.14 km SE of the projector, just beyond the location where the last two bowheads were seen. The broadband (20-1000 Hz) received level of the drilling sounds at the sonobuoy was 106 dB re 1 μPa, or about 22 dB above the broadband ambient noise level of 84 dB in the same band (Fig. 37, p. 107). Received levels 120 m, 720 m, and 1.0 km from the projector, where the various whales were last seen, were estimated to be 125, 110 and 107 dB, or 41, 26 and 23 dB above the broadband ambient noise level. Within single 1/3-octave bands, signal to noise ratios were as high as 30 dB at range 1.14 km (for the band centered at 200 Hz), and thus about 49, 34 and 31 dB at the CPA distances of the whales:

	Distance	Data	20-1000 Hz			Peak 1/3-Octave*			
	(km)	Type	Drill.	Amb.	S:N	Freq.	Drill.	Amb.	S:N
Buoy	1.14	Meas.	106	84	22	200	102	72	30
CPA Bhd #1	0.12	Est.	125	"	41	200	121	"	49
" Bhd #2	0.72	"	110	"	26	200	106	"	34
" Bhd #3+4	1.0	~Meas.	107	"	23	200	103	"	31

* 1/3-octave with maximum received level was same as that with maximum S:N.

<u>23 May 1989</u>

The ice-based crew set up the sound projector on a large pan that jutted out from the east side of an irregular hole amidst the pack ice. This location gave them a view across open water extending ~3 km to the SW, 1 km to the west and 2 km to the NW. The overall lead system ran from WNW to ESE. The lead contained some large pans and much recently consolidated small pans and brash (Fig. 64). Although there was little open water along the lead system, whales apparently could surface amidst the recently consolidated brash; all whales observed in this region on 23 May entered and left the open-water areas along the brash-filled leads.

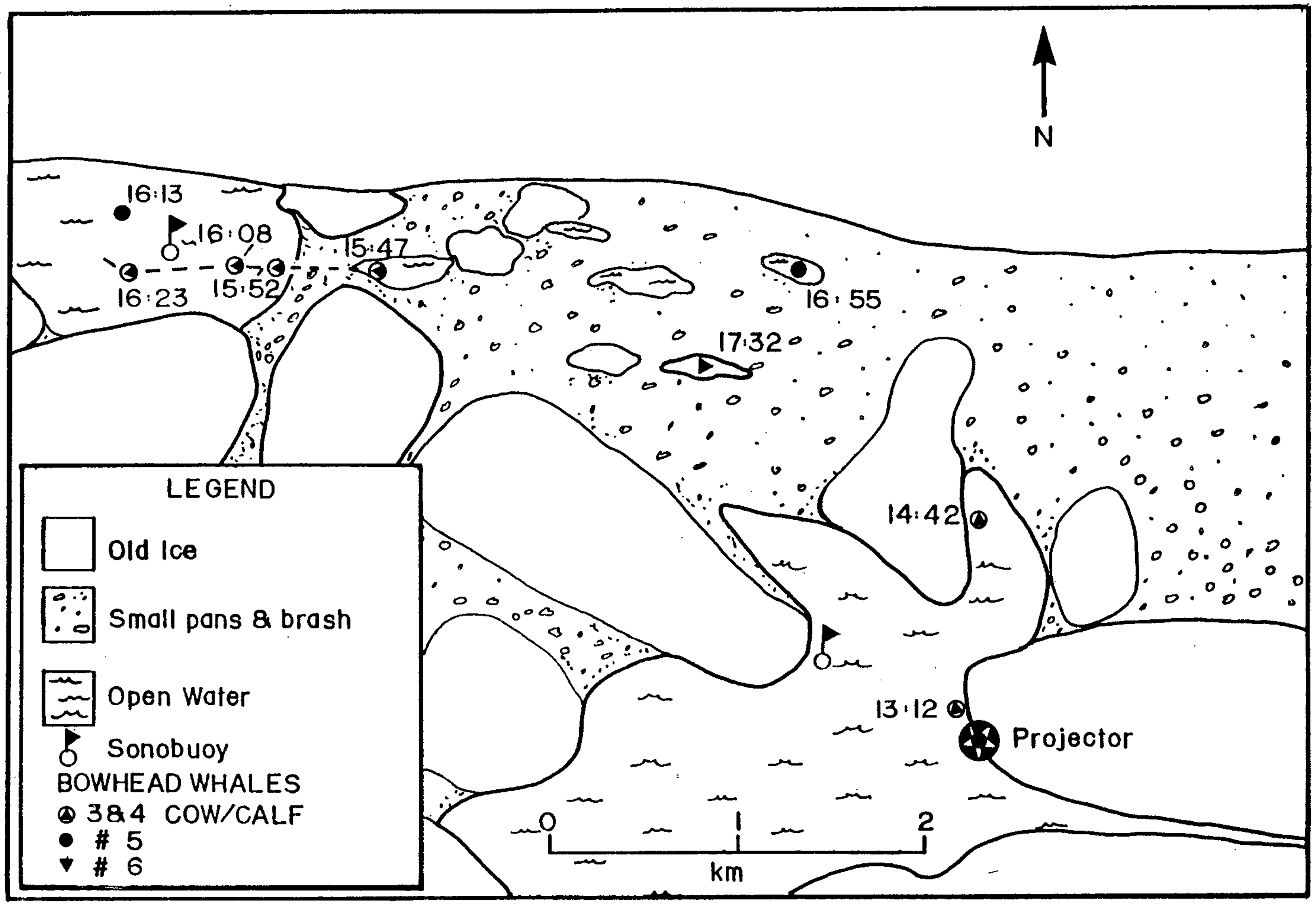

Fig. 64. Ice conditions and bowhead whale tracks and sightings relative to the sound projector during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 23 May 1989. The 13:12 sighting of the cow/calf pair was made before the projector was operating.

Before sound playbacks began, aerial observers saw two bowheads well away from the ice camp. At 11:10 a single bowhead was sighted traveling NE 34 km west of the projector; it was circled briefly. From 12:32 to 13:49, a second whale was followed as it moved east ~10 km NE of the ice camp.

At 13:12 the ice-based observers sighted a mother and calf bowhead moving SE past the sound projector, which was not yet operating. When last sighted by the ice-based crew at 13:14, the whales were estimated to be 40-50 m from the quiet projector. At 14:42, the aerial crew sighted a mother-calf pair moving north ~1 km north of the projector (distance estimated, believed accurate within ±0.3 km). The whales were moving parallel to the edge of a large pan. The aircraft did not fly over or circle these whales because the cloud ceiling was too low (350 m) to allow observations from ≥457 m altitude. During the interval between the two sightings the transmission loss test tape was projected (13:59 to 14:05) and the continuous playback of drilling platform sound was started (at 14:09); the latter continued until 19:06.

The aircraft crew also sighted a mother-calf pair 4.2 km NW of the projector at 15:41 in a small open-water area among consolidated small and medium sized pans and brash. The ceiling had lifted to 460 m so the mother-calf pair was observed until 16:23. During this period they moved slowly westward, i.e more or less away from the operating projector. At 15:52 they entered a 1x2 km area of open water that was oriented E-W, and they continued to move slowly west until 16:18. When they were next sighted, at 16:23, they were moving slowly but steadily NW through the open water 5 km WNW of the projector. We left them at that time to follow another whale heading generally toward the projector. Weak drilling sounds were audible to the human ear in the signal received from a sonobuoy dropped near the mother/calf at 16:03, about 5 km from the projector. Spectral analysis of those signals confirmed the presence of the low frequency tones characteristic of the *Karluk* drilling sounds (Fig. 65, lower dotted spectrum).

We suspect that the mother/calf pairs observed by the aerial crew at 14:42 and 15:41-16:23 represent sightings of the same two whales. The headings and positions as a function of time were consistent with gradual NW and W movement by one mother-calf pair. Between 14:42 and 15:41, we repeatedly surveyed all open water areas 2-30 km NW, W and SW of the projector site and no other bowheads were sighted. It is unknown whether this pair of whales traveling W was the same pair as was observed moving SE near the projector at 13:12, before the start of the playback.

At 16:13 a single bowhead whale was first sighted migrating ESE at medium speed about 5.2 km WNW of the sound projector (whale #5 in Fig. 64). This sighting was near the sonobuoy dropped a few minutes earlier, where the drilling sounds (97 dB re 1 μPa, 20-1000 Hz) were barely audible (Fig. 65). At 16:55, 42 min later, it was seen 3.0 km east of its original position and 2.4 km NNW of the projector, heading east. These distances were calculated from the aircraft's VLF navigation system, and are believed to be accurate, relative to one another, within ~0.3 km. Whale #5 had an average "ground speed" of 4.3 km/h

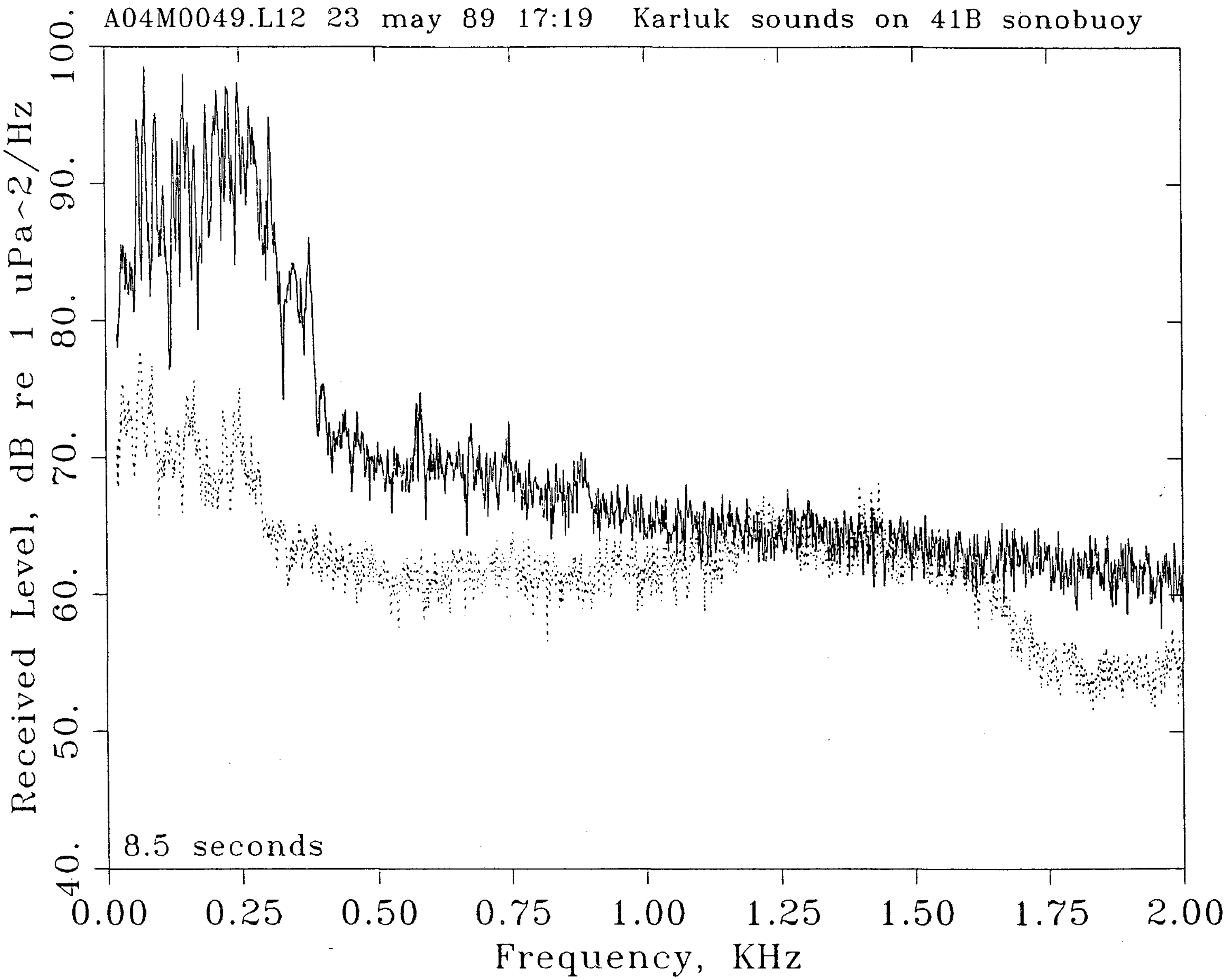

Fig. 65. Spectrum of drilling sounds received on 23 May 1989 at sonobuoys located 1 km (upper spectrum) and 5 km (lower spectrum) west of the sound projector. Drilling sounds, concentrated below 300 Hz, were weakly detectable above the background noise level at 5 km and strong at 1 km. Broadband (20-1000 Hz) received levels were ≈97 dB and 116 dB re 1 μPa, respectively.

into the westward-moving current, including a 36 min dive. Relative to the westward-moving ice, it averaged 5.1 km/h. A whale suspected to be the same individual was seen at 18:04 about 6 km ESE of its 16:55 location and 5.5 km east of the sound projector. The average speed of movement from 16:55 to 18:04, if this was the same whale, was 5.2 km/h ("ground speed"). The straight line path between the 16:55 and 18:04 positions passed as close as 2 km from the operating projector. The movements of whale #5 appear to have been unaffected by the projection of the drilling platform sounds. Neither the direction nor speed of movement appear to have changed markedly as the whale approached and passed the projector; however, the closest point of approach was ~2 km away, and the whale was below ice and invisible at that time.

One additional bowhead (#6 in Fig. 64) was sighted moving ESE 2.3 km NW of the projector from 17:26 to 17:31, but was not seen again. It appeared to be migrating along a route similar to that of whale #5.

Most of the respiration, surfacing and dive data from the 23 May experiment were obtained from the mother/calf pair while they were 4.2-5.0 km from the projector and traveling away from it (Fig. 66). Sample sizes (n = 4-7, excluding calves) were too small for meaningful interpretation of these data by themselves.

The broadband source level of the drilling sounds on this date was ~162 dB re 1 μPa-m. A monitor sonobuoy was deployed manually 1.3 km WNW from the projector at 13:00. By 18:00, they had drifted closer together--to 0.96 km, determined by theodolite. In addition, a sonobuoy was airdropped 5 km WNW of the projector at 16:03. Received levels of drilling sounds at these two locations are summarized below, in relation to ambient noise recorded at the monitor buoy before the playback began. The drilling sounds were weakly audible to the human ear at 5 km range, and evident by power spectrum analysis (Fig. 65, lower spectrum). The sounds were strong at the manually-deployed sonobuoy ~1 km from the projector (Fig. 65, upper spectrum):

	Distance	Data	20-1000 Hz			Peak 1/3-Octave**			
	(km)	Type	Drill.	Amb.	S:N	Freq.	Drill.	Amb.	S:N
Buoy #12 @ 14:10	1.2	Meas.	111	102	9	200	105	89	16
" " @ 16:04	1.1	"	108	"	6	200	100	≤86	≥14
" #25 @ 16:05	5	"	~97	<97	low*	160,250	88*	-	-
Cow/calf @ 14:42	1	~Meas.	110	102	8	200	104	89	15
" @ 15:41	4.2	"	100	<97	low*	160,250	89	-	-
" @ 16:23	5	"	98	<97	low*	160,250	88*	-	-
Bhd #5,6, est. CPA	2	Est.	107	<97	~10	200	101	≤86	≥15

* Drilling noise was faintly detectable 5 km from projector, but broadband and all 1/3-octave levels there were slightly less than the ambient noise at 13:12, before the playback started.

** 1/3-octave with maximum received level was same as that with maximum S:N.

We estimate that the broadband (20-1000 Hz) received level was ~110 dB at the 1 km distance where the mother/calf pair was seen heading away from the projector at 14:42. The level in the strongest 1/3-octave band was ~104 dB, or ~15 dB above the ambient level in that band. This mother/calf pair presumably was exposed to higher levels earlier in the playback period when they apparently were closer to the projector. At range 2 km, the approximate CPA position for

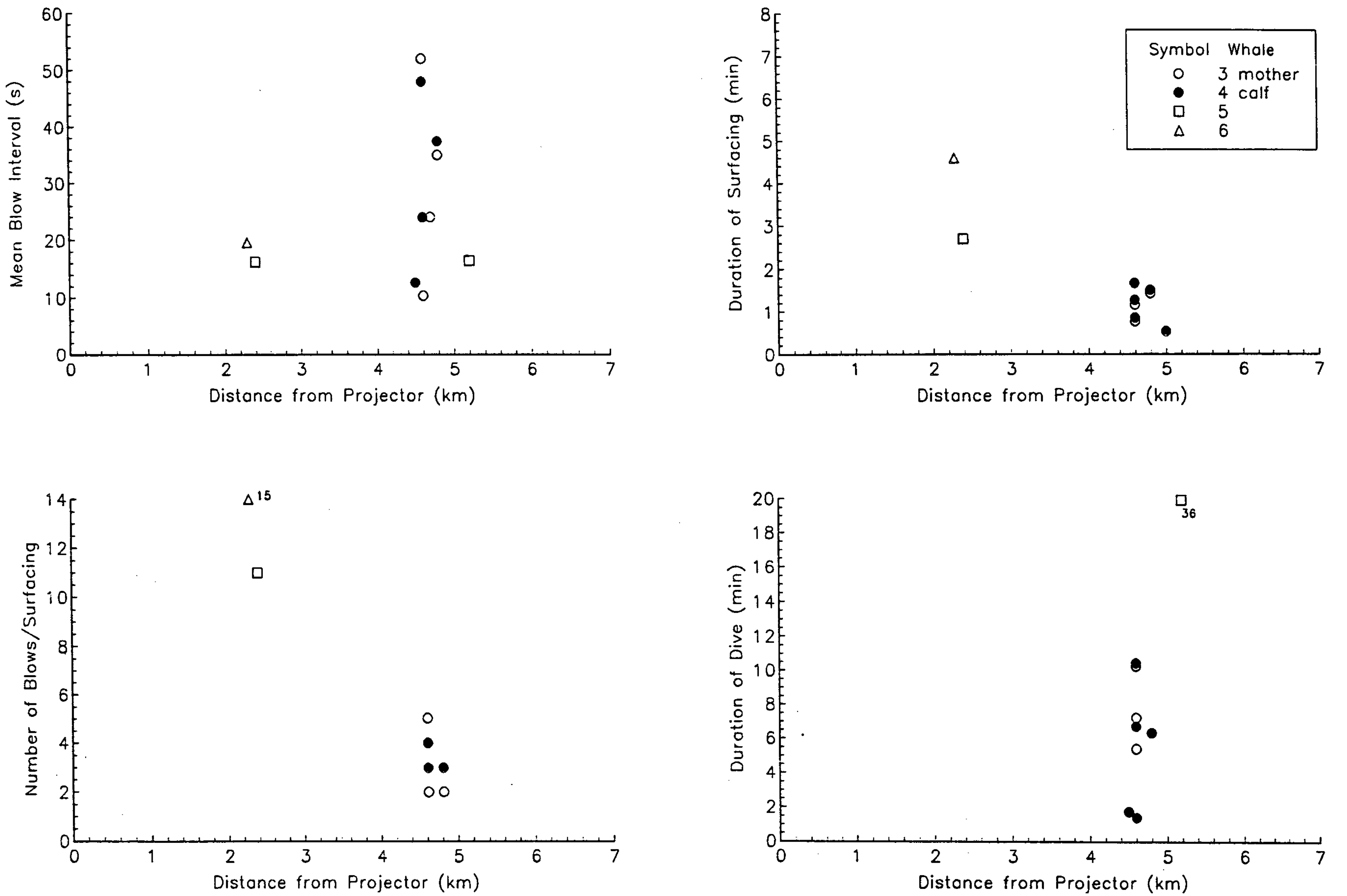

Fig. 66. Respiration, surfacing and dive variables for bowhead whales observed on 23 May 1989 in relation to distance from a projector broadcasting drilling platform sounds amidst pack ice NE of Barrow, Alaska. All data shown were collected by aerial observers. Different symbols represent different individual whales. Positions of these whales are shown on Figure 64.

two whales that migrated ESE past the projector, the broadband level was ~107 dB (S:N ~10 dB), and the peak 1/3-octave band level was ~101 dB, ≥15 dB above ambient in that band (200 Hz)

<u>27 May 1989</u>

Whale observations and playback experiments were conducted along the southern edge of the pack ice that formed the north side of the open lead along the fast-ice edge. Two projector sites were used. The first site was ~4 km north of the open lead amidst the pack ice. It was along a secondary lead oriented SSW to NNE. Although it seemed to be a likely migration corridor for whales arriving from the west, no bowheads migrated into the secondary lead during the observation period. However, several whales were seen migrating east along the south edge of the pack ice, i.e. along the north edge of the main lead. Hence, in late afternoon the projector was moved to a second site on a large pan facing SW into the open lead (Fig. 67).

Two mother-calf pairs were observed by the aircraft crew from 09:36 to 11:45 as they moved along the south edge of the pack ice from 3.8 km SSW of the projector site to 6.7 km ESE of the projector site. The whales sometimes traveled inside the irregular pack ice edge among loose pans, and at other times traveled along the open water side of the pack-ice edge (Fig. 67). No sounds were projected during this period; the playback equipment was being set up.

The transmission loss test tape containing warble tones, pure tones, and a sample of drilling noise was projected at the first site intermittently from 12:28 to 12:58. Drilling noise was then projected from 12:59 to 15:42. A mother-calf pair was observed from 12:46 to 14:47 as they moved from 3.7 km WSW of the projector to 4.0 km south. Unexpectedly, these whales were severely disturbed by a sonobuoy dropped about 750 m ahead of the whales at 13:30, and they did not resume their eastward migration until about 14:00 (see later section on reactions to sonobuoys).

The sensitivity of these bowheads to the sonobuoy drop complicated interpretation of the data. However, it appears that the mother-calf pair observed during the playback followed a route similar to the routes followed by the two mother-calf pairs observed before the playback began. The closest point of approach to the projector was about 3.7 km, about when the projector was first turned on (Fig. 67).

The transmission loss test tape was already being broadcast when this mother/calf pair was first seen, so these whales were exposed to various warble tones, pure tones, and samples of drilling sounds when they were passing their CPA position. Received levels of the pure tones near the whales (range 3.7 km) were estimated to be as high as 104 dB, depending on frequency, with the strongest tone at 200 Hz. These estimates are based on the measured levels of the tones at a sonobuoy 1.1 km from the projector, adjusted based on the measured rate of attenuation of *Karluk* sounds between 1.1 and 4.6 km. The estimated

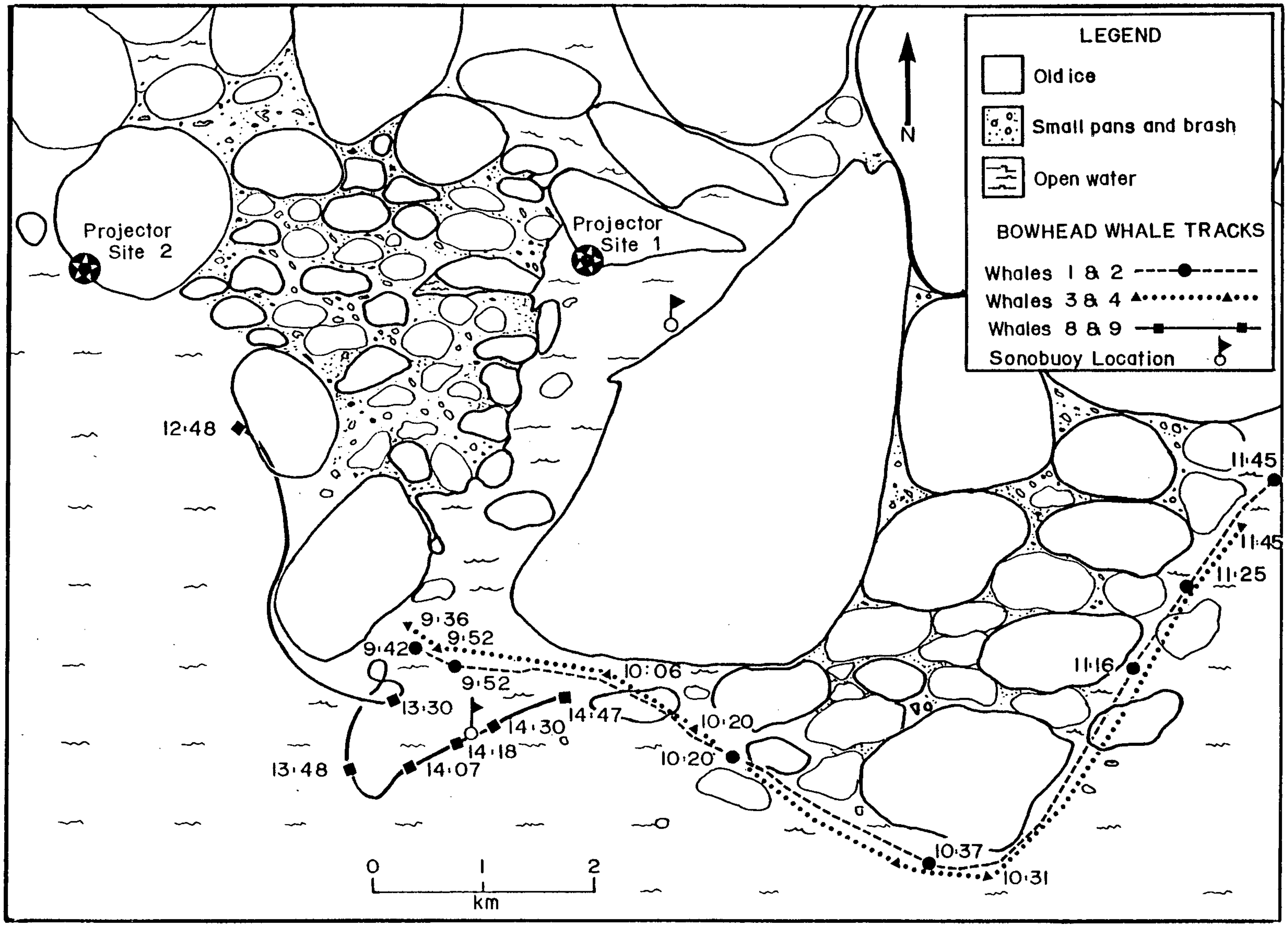

Fig. 67. Ice conditions and bowhead whale tracks relative to the sound projector during a playback of test tones and drilling platform sounds amidst pack ice NE of Barrow, Alaska, 27 May 1989.

received levels of the tones were as much as 31 dB (at 200 Hz) and 27 dB (at 500 Hz) above the ambient noise level in the corresponding 1/3-octave bands:

Tone Frequency	Measured Source Level	Measured Level @ 1.1 km	Estimated Level @ 3.7 km	1/3-OB Ambient Noise	S:N
50	153	99	84	72	12
100	162	102	87	68	19
200	165	119	104	73	31
500	159	109	94	67	27
1000	156	107	92	80	12
2000	152	102	87	-	-
5000	152	87	72	-	-
10000	155	95	80	-	-

The received broadband level of drilling sounds was 113 dB at the monitor sonobuoy located 1.1 km SE of the projector, and 94 dB at the location 4.6 km from the projector where a buoy was airdropped. Thus, the broadband level at the CPA position would have been about 97 dB, or about 11 dB above the background ambient level on this occasion. The received level within the strongest 1/3-octave band would have been about 92 dB, or 22 dB above the ambient level in that band:

	Distance	Data	20-1000 Hz			Peak 1/3-Octave**			
	(km)	Type	Drill.	Amb.	S:N	Freq.	Drill.	Amb.	S:N
Buoy #28 @ 12:49	1.1	Meas..	113	86	27	200	110	70	40
" #15 @ 14:52	4.6	"	94	"	8*	200	89	"	19
Cow/calf @ CPA	3.7	Est.	97	"	11	200	92	"	22

* Drilling noise faintly audible to the human ear 4.6 km from the projector.
** 1/3-octave with maximum received level was same as that with maximum S:N.

When the data from the period of sonobuoy disturbance are excluded, there was no significant relationship between any of the respiration, surfacing and dive variables and distance from the sound projector (Fig. 68). However, sample sizes were small, and the range of distances from the projector (3.7-4.7 km) was too narrow for meaningful interpretation. Likewise, there were no dramatic differences between values for the mother and calf observed during the playback versus those for two mothers and two calves observed migrating along similar paths earlier in the day (Fig. 68; P>0.1 in each case).

Because the whales seen during the morning and early afternoon were moving along the north side of the main W-E lead, ~4 km from the projector, we decided to relocate the projector closer to the lead. Oil production sounds were broadcast from the second projector site (Fig. 67) from 18:15 to 21:13. However, no more bowheads were observed near that site by either the ice-based or the aircraft crew.

<u>29 May 1989</u>

The ice camp was set up along the SE side of a 2x6 km open lead in the pack ice about 8 km north of the main lead. The 2x6 km lead was oriented WSW to ENE and was the largest area of open water north of the main lead. A series of

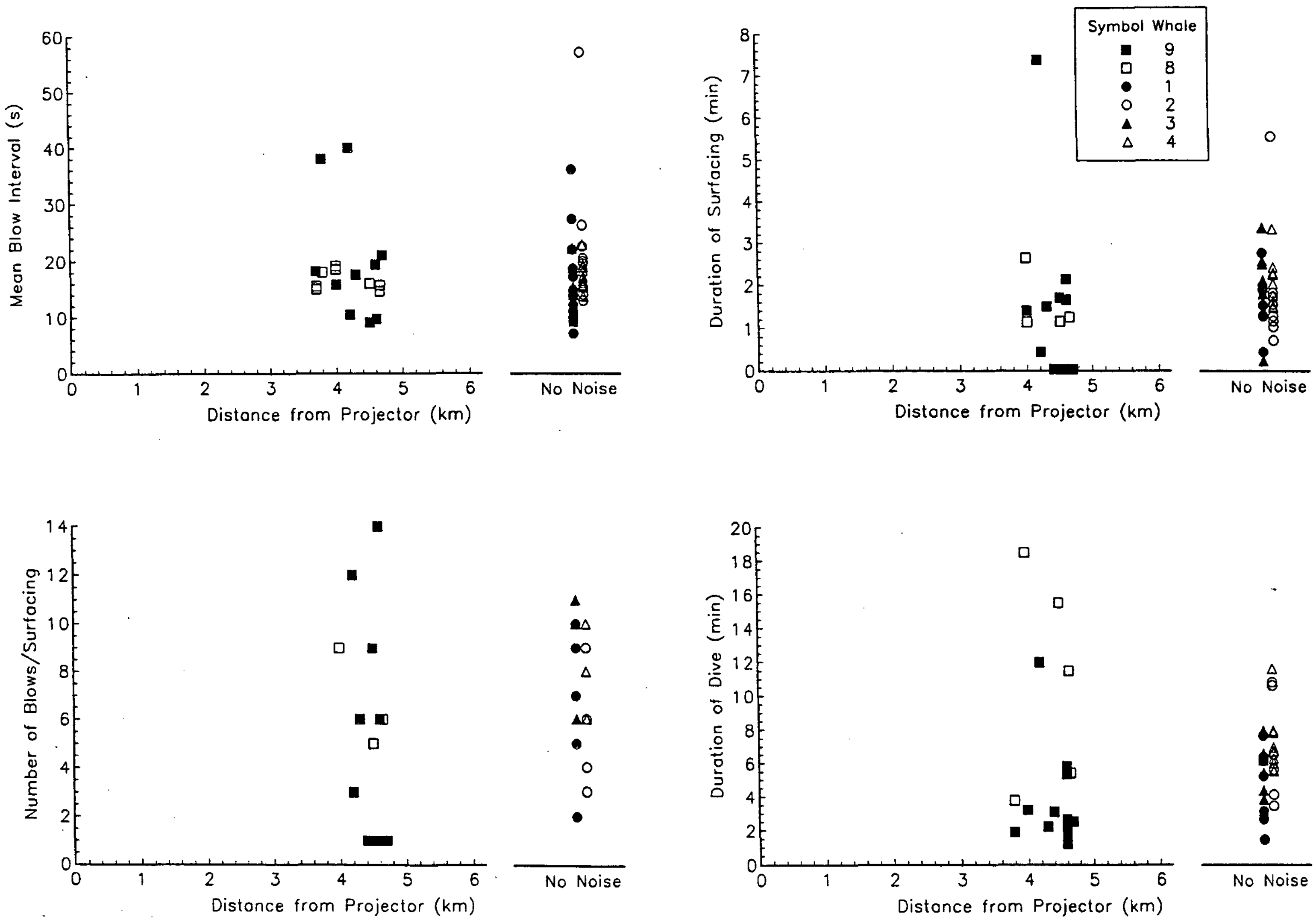

Fig. 68. Respiration, surfacing and dive variables for bowhead whales observed on 27 May 1989, plotted in relation to distance from a projector broadcasting test tones and drilling platform sounds amidst pack ice NE of Barrow, Alaska. The column of data points at the right side of each graph represents the two mother/calf pairs observed before the playback began, i.e. not exposed to drilling sounds or any other known disturbances. All data shown were collected by aerial observers. The open and closed symbols on the scatter plots represent data for mothers and calves, respectively. Positions of these whales are shown on the preceding Figure.

widely spaced open areas and very narrow cracks west of the 2x6 km lead provided a possible whale migration corridor from the main lead toward the 2x6 km lead. Drilling sounds were broadcast from 13:03 to 19:47. No bowheads entered the lead where the projector was operating, but a mother-calf pair was observed 9-11 km from the projector at various times throughout the day. This cow and small (4.0 m) calf had also been observed and photographed on 27 and 28 May (Fig. 57, p. 158). On 29 May, these whales were in a secondary lead about 1x2 km in size, which was connected to the lead with the projector (Fig. 69). The activity of these whales was a combination of resting, local travel, nursing and probable feeding by the mother, but no net movement occurred during the 10:31 to 15:57 period (Fig. 58, p. 168).

No change in behavior was evident when the drilling sounds began to be projected at 13:03. At 10:31, when we first encountered these whales, the mother was swimming slowly and the calf was riding on her back. The calf nursed briefly, the mother dove (probably to feed), and the calf remained on or near the surface. They remained at the same location for 14 min. We then left to search for whales that were either closer to or traveling toward the projector. This search was unsuccessful. When we returned at 12:26, the mother/calf pair had moved only 100-200 m to the NW. Their behavior was unchanged, and at 13:02 they were only 250-300 m NW of their initial (10:31) position. They continued to feed, rest and slowly travel along the west side of the open water area. The calf traveled on its mother's back and occasionally nursed. We left this area at 13:55 and returned at 14:52. The whales were then 1 km north of their last position. They swam slowly northward until the open water narrowed to a small crack; then they turned and swam slowly southward. The calf continued to ride on its mother's back.

These whales probably could not hear the projected drilling sounds. The sounds were not evident to the human ear in the signals detected by a sonobuoy dropped near the whales at 13:22 (10 km from projector). Spectral analysis of those signals also failed to reveal any evidence of the tones that are characteristic of the *Karluk* drilling sounds. Given this, plus the fact that these whales had been lingering in the area for at least two days before the playback began (Fig. 57, 58), their failure to travel east toward the projector was probably not related to the playback of drilling noise.

All Bowhead Observations Combined

Distribution and Movements.--We observed bowheads within the areas ensonified by the sound projector on five dates: 30 April and 14, 19, 23 and 27 May. Whales were exposed to sounds from the transmission loss test tape on 30 April and on 27 May. That tape included various sounds at frequencies from 50 to 10,000 Hz, including warble tones, pure tones, and a sample of drilling platform sound. On 27 May, a mother/calf pair was exposed first to the test tape (at range 3.7 km) and then to continuous drilling noise. On 14, 19 and 23 May, bowheads were exposed to continuous drilling sounds but not to tones.

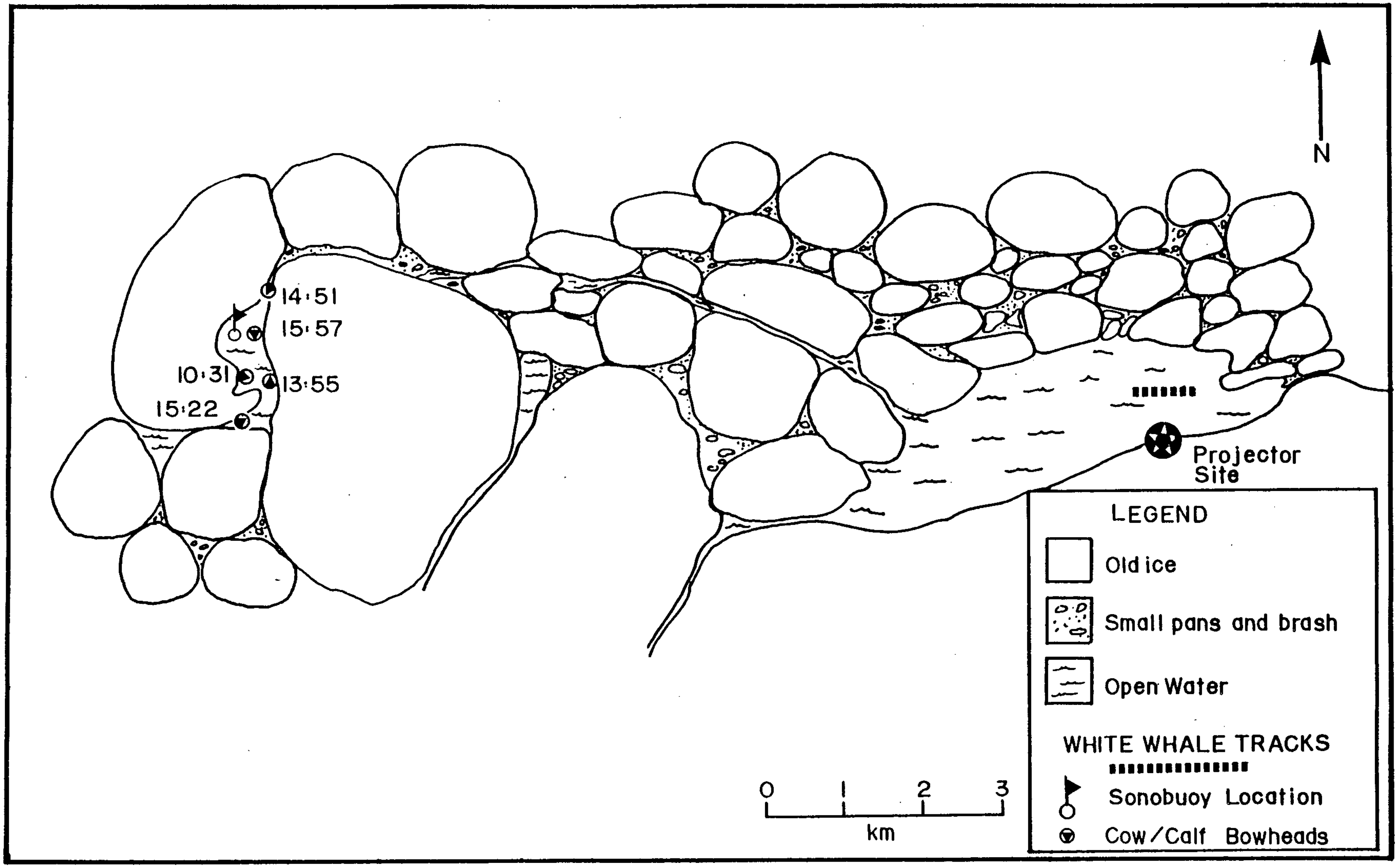

Fig. 69. Ice conditions, bowhead whale positions, and white whale tracks in relation to distance from a projector broadcasting drilling platform sounds amidst pack ice NE of Barrow, Alaska, 29 May 1989.

The number of bowheads seen near the sound projector in 1989 was too small to allow any statistical analysis of distribution or movements. However, a collation of the observations provides some information about the movements of bowheads toward and past the operating projector (Table 25). All whales listed in that table are known to have been in waters where the projected sounds were detectable above the natural ambient noise. The "Noise" column in Table 25 summarizes the maximum noise levels received by the whales. More detailed data about noise exposure are given in the preceding section describing each individual day of observations.

Table 25. Summary of sightings of bowheads passing near the operating sound projector during 1989.

Date	Whale	Distance	CPA	Noise*	Nature of Track
30 Apr	#1-#3	~1.1 - 2.2 km	60-75 m	≤115/≤20**	Continued toward projector after exposure to test tones at range ~ 1.1-2.2 km.
	#2	-	60 m	130 / 35**	Tones started while whale passing tangentially; no obvious change in behavior.
14 May	#8	4.7 → 0.9 km	0.9 km	102 / 8	Along ice edge almost directly toward projector and then tangentially past it.
	#9	4.7 → 0.5 km	0.5 km	107 / 13	Same.
	C	2.8 → 2.5 km	?		Aerial activity; subsequent movements unknown.
	#2,#3	0.5 km	0.5 km	104 / 10	Moving tangentially past during brief observation period.
19 May	#1	500 → ≤120 m	≤120 m	125 / 41	Curved from partially toward to almost directly toward projector; dove 100-120 m before reaching projector.
	#2	910 → 720 m	≤720 m	110 / 26	Heading partly toward projector; dove before reaching CPA position.
	#3,#4	1.8 → 1.0 km	1.0 km	107 / 23	Moved tangentially past projector on straight course.
23 May	Cow/Calf	1 → 5 km	<1 km	110 / 8	Headed NW and W away from projector.
	#5	5.2 → 2.4 km	~2 km	107 / 10	Headed partially toward projector and apparently passed tangentially with CPA ≈ 2 km.
	#6	2.3 km	~2 km?	107 / 10	Apparently on similar path as #5.
27 May	Cow/Calf	3.7 → 4.0 km	3.7 km	104/ 15**	Projector started broadcasting test tones while whales were moving tangentially at CPA (3.7 km). Continued SE on or near original course while exposed to drilling sounds.

* Received broadband level (dB re 1 μPa) and S:N ratio (dB) of drilling noise or tones at the closest distance where the whale was seen.
** Received levels for 30 April and 27 May refer to the strongest tone. Received levels of drilling noise were lower: 100-110 dB at 1.1-2.2 km on 30 April (S:N = 6-19 dB), and 97 dB at 3.7 km on 27 May (S:N = 11 dB).

Continuous drilling sounds: Several whales were observed migrating northeast, east or southeast past the projector while it was broadcasting drilling sounds. On 19 May, one bowhead swam almost directly toward the projector until it was only **100-120 m** away. It then dove, and its subsequent movements are unknown. On 14 May, at least three migrating bowheads passed **0.5 km** to the side of the projector while it was broadcasting drilling sounds.

Another bowhead seen on 19 May was heading almost directly toward the projector when it dove **720 m** away; its subsequent movements are unknown. Bowhead #8 seen on 14 May passed tangentially at a CPA distance of **~0.9 km**, and two additional bowheads seen on 19 May passed tangentially at CPA=**1.0 km**. On 23 May, at least one and probably two bowheads migrated eastward past the projector with CPA distances near **2 km**.

Tonal sounds: On two dates, we observed whales migrating toward or past the projector while it was broadcasting a sequence of tonal sounds and a brief sample of the drilling noise. ▸ On 30 April, one whale continued migrating east when the projector started to broadcast swept tones at 50-500 Hz while the whale was at the surface less than 100 m away. This whale and two others had been exposed to weaker tones several minutes earlier when the whales were approaching the projector. This previous exposure did not deter them from continuing on toward the projector. ▸ On 27 May, a mother/calf pair was exposed to tones and the other sounds on the transmission loss test tape when they were 3.7 km from the projector and passing tangential to it. Then these whales were exposed to the continuous drilling sounds. They continued migrating along a path similar to that taken by two other mother/calf pairs earlier on that day in the absence of man-made noise.

Even though some bowheads were seen migrating on seemingly straight courses past the operating sound projector, other bowheads may have been diverted when they came that close. As noted in the next subsection, one mother/calf pair *may have* reversed course in response to drilling noise in 1989 even though other bowheads were seen migrating northeast closer to the projector. It is well established from previous studies that sensitivity to noise disturbance varies over time and among whales. Thus, the fact that some bowheads migrated past the projector at CPA distances of 0.5 km or less does not necessarily mean that all bowheads would do so. A larger sample of experiments and observations will be needed to determine what proportion of the bowheads change course when approaching within various distances of the projector.

If some whales diverted around the projector site at distances exceeding a few kilometers, they probably would not have been detected. Ice-based observers, in particular, are more likely to see whales that approach close to the projector than to detect those that veer away. Even for airborne observers, the large amount of ice present near most 1989 observation sites made it difficult to sight whales, or to follow them for long distances. Because observations were concentrated in the often-small open water areas near the projector sites, the probability of detecting whales was no doubt inversely related to their distances of closest approach to the projector. If any whales began to avoid the projector at distances exceeding the dimensions of the open water areas around the projector (usually a few kilometers), those whales probably would not have been detected. It will be important, in future work, to observe bowheads that are 10 km or more west of the projector when they are first sighted. However, it will only be practical to follow bowheads for distances of 10+ km if they are migrating along an open lead. In 1989, there were no opportunities of this nature, given the heavy ice conditions.

Avoidance Reactions? We obtained one observation suggestive of an avoidance reaction. On 23 May, a mother/calf pair was noticed swimming north ~1 km north of the projector (i.e. directly away). Continuous drilling noise had been projected for the 33 min preceding this sighting. The location of the whales when the playback period started is not known. The received broadband noise level 1 km from the projector was 110 dB (~8 dB above the natural ambient level). These whales initially could not be followed by the aerial observers because the cloud ceiling was below 457 m[7]. However, a mother and calf--probably the same animals--were seen 1 hour later 4.2 km NW of the projector, traveling slowly but consistently west. The drilling sounds were faintly detectable in the water as much as 5 km west of the projector. The westward direction of travel was inconsistent with the normal NE, E or SE movements of migrating whales in spring, and suggestive of a disturbance reaction.

When interpreting the above observation, it is important to take into account the behavior of other mother/calf pairs observed in the absence of drilling sounds. The available data on mother/calf pairs observed in late May 1989 suggest that they were not as consistently engaged in eastward migration as were other bowheads (see "Mother and Calf Behavior", above). It is possible that calves (and thus mother/calf pairs) are unable to travel through ice conditions as heavy as those negotiated by other whales. If so, this may induce mother/calf pairs to linger awaiting improved ice conditions, or even to retreat westward temporarily. On 23 May, there was little open water east of the projector. Perhaps the mother, because of her young calf, was reluctant to enter the ice-filled lead that other large whales followed on this date.

It is impossible to determine whether the one mother/calf pair seen moving west away from the operating projector did so because of the drilling noise or for some natural reason. Additional fieldwork is needed. In particular, it will be important to determine whether any bowheads that are initially heading generally toward the projector turn and veer away. It will also be important to determine whether such changes in course are more common for whales approaching the projector than for whales observed in other situations. This last comparison will require a larger sample of observations of whales approaching the projector than it was possible to obtain under the difficult weather and ice conditions encountered in 1989.

Surfacing, Respiration and Diving Behavior.--The small sample of observations from 1989 precludes any extensive analysis of relationships between distance from the noise projector and subtle aspects of the behavior of individual whales. We have, however, examined the relationships between distance from the projector and four standard measures of surfacing, respiration and diving behavior. For this analysis, we recognized three distinct groups of

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[7] Previous studies have shown that bowheads are sometimes disturbed by an observation aircraft if it circles at an altitude <457 m (Richardson et al. 1985a,b).

whales: calves (neonates), mothers accompanying calves, and other whales. We excluded whales whose predominant activity was socializing or aerial activity. Studies in other seasons have shown that these special activities have pronounced confounding effects on surfacing, respiration and diving behavior.

The durations of surfacings by whales and the number of blows per surfacing were not significantly related to distance from the sound projector. This was true for mothers, calves, and other whales (Fig. 70-72). In this analysis, we included not only the observations at varying distances from the operating sound projector, but also data on presumably undisturbed whales. The latter data are shown at the right side of each scatter diagram. By assuming that these data were collected at an arbitrary long distance from the projector, it was legitimate to include them in Spearman rank correlation analyses of behavioral variables vs. distance from projector[8]:

	Mothers			Calves			Others		
	r_s	n	P	r_s	n	P	r_s	n	P
Surface Time	-0.107	51	ns	0.005	76	ns	0.042	26	ns
Blows/Surfacing	-0.171	45	ns	-0.064	63	ns	-0.090	23	ns
Mean Blow Interval	0.086	55	ns	-0.195	89	(*)	-0.226	60	(*)
Dive Duration	-0.295	46	*	-0.140	77	ns	-0.035	11	ns

* $0.05 \geq P > 0.01$ (*) $0.1 \geq P > 0.05$ ns $P > 0.1$

Mean blow intervals were not significantly (α=0.05) related to distance from the projector. However, for "calves" and "others" there was an indication of a negative relationship ($0.1 > P > 0.05$), i.e. blow intervals showed a weak tendency to increase with diminishing distance from the projector[9]. The biological significance of this possible but unproven relationship is unclear. However, bowheads disturbed by some types of industrial activity during late summer or autumn also tend to exhibit increased blow intervals (Richardson et al. 1985b, 1986, 1990; Ljungblad et al. 1988). Additional data will be needed to assess whether the weak trend noted for "calves" and "others" in May 1989 was indicative of an actual disturbance effect or merely coincidental.

Durations of dives were unrelated to distance from projector in the cases of "calves" and "others", but negatively related for "mothers" ($P \approx 0.05$). Dive durations tended to be slightly longer for "mothers" near the operating projector. Again, this correlation was weak and of marginal statistical significance. Additional data are needed to determine whether the effect is

[8] Ranks of distances rather than distances *per se* are used in this nonparametric analysis. Hence, it does not matter what arbitrary distance is assumed for the "undisturbed" whales, provided that the assigned distance exceeds the distances of all whales observed near the operating projector.

[9] In this analysis, each surfacing during which one or more blow intervals were determined contributed one datum. The datum for a surfacing was the mean duration of whatever blow intervals were recorded during that surfacing.

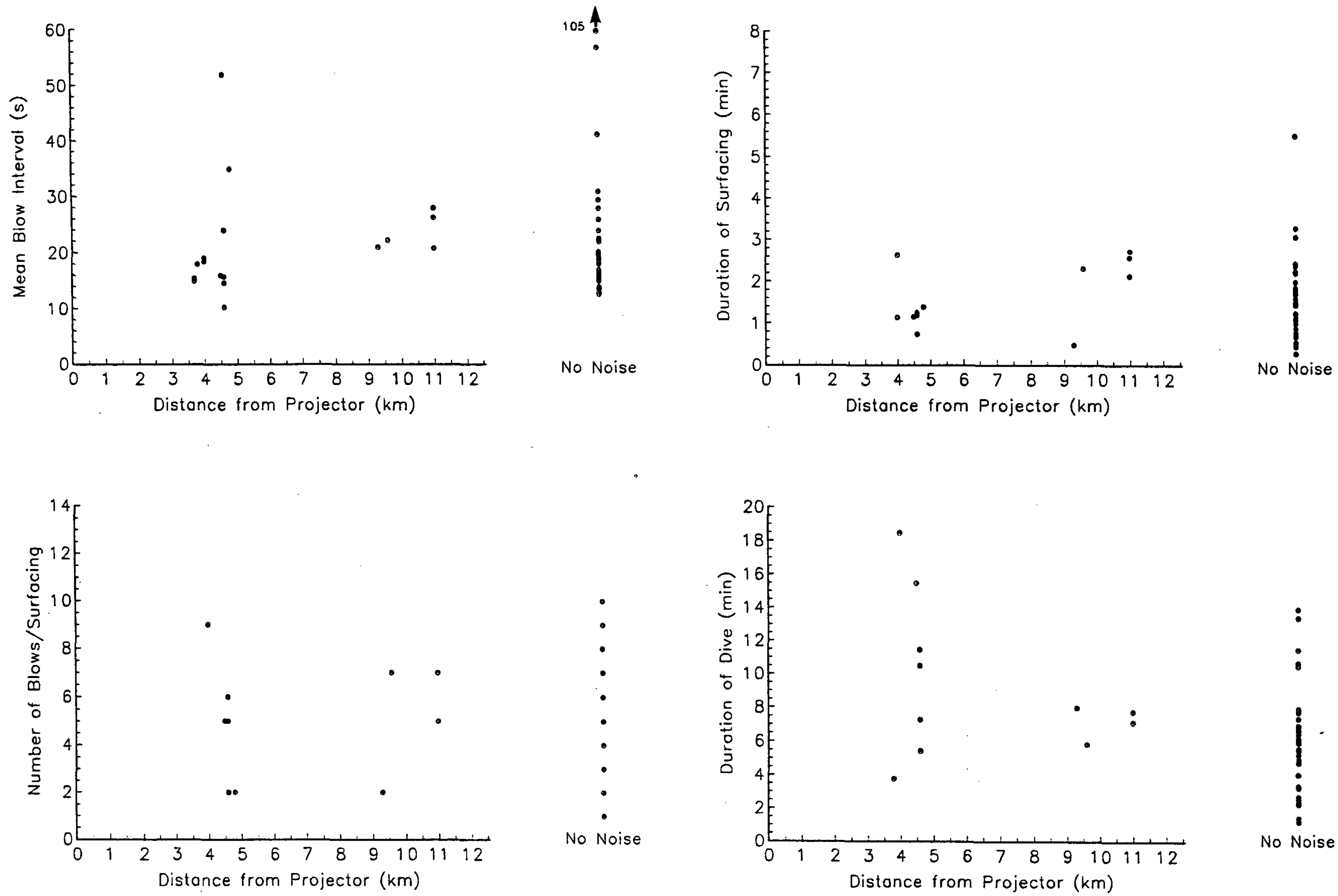

Fig. 70. Respiration, surfacing and dive variables for bowhead mothers observed in May 1989, plotted in relation to distance from a projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska. The column of data points at the right side of each graph represents whales not exposed to drilling sounds or any other known disturbances. All data are from aerial observations with aircraft altitude ≥457 m.

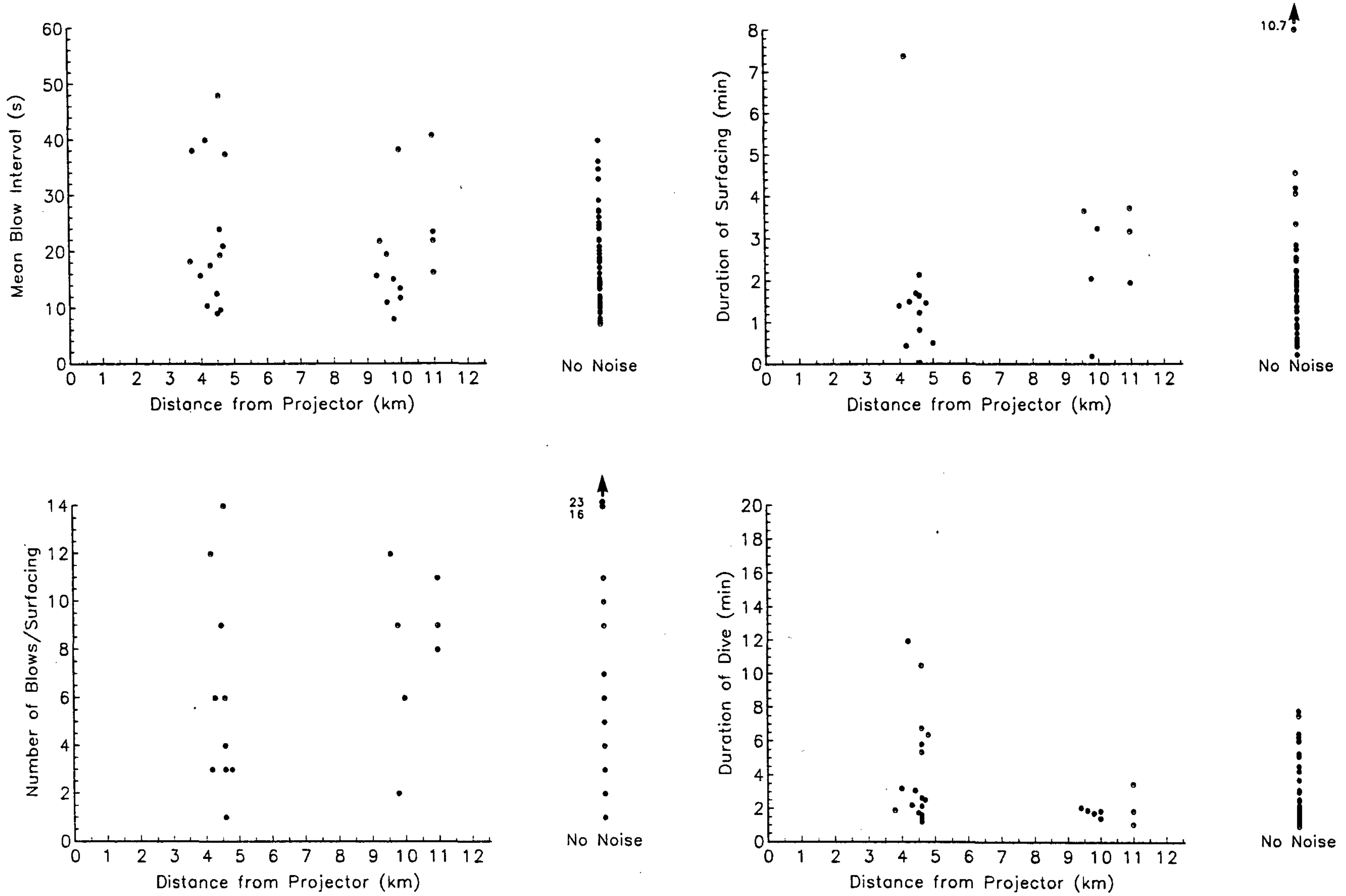

Fig. 71. Respiration, surfacing and dive variables for bowhead calves observed in May 1989, plotted in relation to distance from a projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska. Otherwise plotted as in preceding Figure.

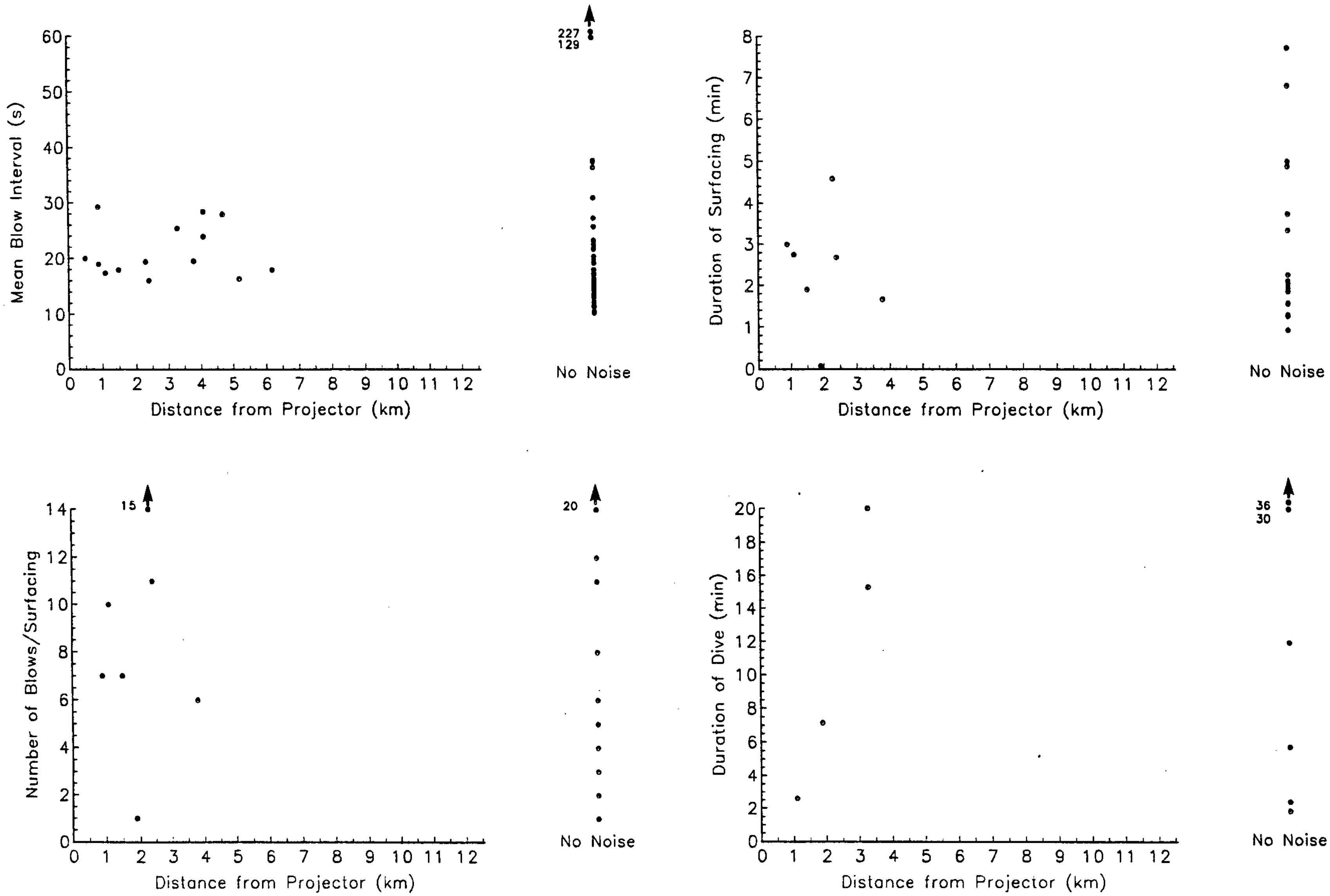

Fig. 72. Respiration, surfacing and dive variables for "other bowheads" (not mothers or calves) observed in May 1989, plotted in relation to distance from a projector broadcasting drilling platform sounds amidst the pack ice NE of Barrow, Alaska. Breaching whales are excluded. Otherwise plotted as in preceding two Figures.

repeatable. In most situations in which dive durations of bowheads have been found to be affected by disturbance, dives have been shorter in the presence of disturbance (Richardson et al. 1985b, 1986; Ljungblad et al. 1988). That is the opposite tendency to the one suggested here.

Other Behavioral Variables.--In addition to these statistical relationships, certain incidental behavioral events noted in the field during playback experiments *might* have been attributable to drilling noise, although this is unproven in each case.

In previous studies of bowheads and other baleen whales, it has sometimes been suspected that certain **aerial behaviors** (breaches, tailslaps, flipperslaps) are triggered by disturbance. On 14 May, whale C engaged in repeated aerial activities about 2½ km from the operating projector. On 19 May, whale #2 flipperslapped once before diving and disappearing 720 m from the projector. It is unknown whether these aerial activities by two whales were in response to the noise. Bowheads often engage in similar aerial behaviors in the absence of disturbance (e.g. Würsig et al. 1989), although little aerial activity was seen amongst undisturbed bowheads during May 1989 (Table 19, p. 164). To assess whether certain aerial behaviors occur in response to noise disturbance, it would be necessary to compare the frequency of these events in the presence and absence of industrial noise. A considerably larger number of observations during spring migration will be needed before such a comparison would be meaningful.

Swimming speeds of bowheads near the operating projector were not noticeably different from those of undisturbed whales. The bowheads seen within 5 km of the projector were traveling, so the appropriate comparison is with traveling whales under undisturbed conditions (*cf.* Table 20, p. 165). Each surfacing of a whale contributes one value to the tabulation:

	Calves				Mothers				Others			
	None	Slow	Mod	Fast	None	Slow	Mod	Fast	None	Slow	Mod	Fast
≤5 km from proj.	1	8	4	0	1	8	2	0	0	2	14	0
Undist. traveling	0	14	12	0	1	9	9	0	0	12	11	0

Estimated speeds of "others" within 5 km of the projector tended to be slightly higher than those of undisturbed whales, but this trend was reversed for mothers and calves. Given this, plus the small number of animals involved, it is uncertain whether speeds of bowheads close to the projector differed from those of undisturbed bowheads.

On 19 May, whale #1 reduced its swimming speed as it approached within ~120 m of the operating projector. It is not known whether this was in response to the projector or for some other reason. Besides being near the projector, this whale was nearing the ice at the east end of the lead. Even in the absence of the projector, bowheads often slow down, apparently to respire, before diving under the ice. With a considerably larger sample size, one might compare the frequency of "slowing" by whales nearing the operating projector vs. that by whales in other circumstances.

Frequencies of **turns during surfacings** were similar for bowheads within 5 km of the operating projector versus undisturbed traveling bowheads (*cf*. Table 20, p. 165):

	Calves				Mothers				Others			
	None	Right	Left	Mult.	None	Right	Left	Mult.	None	Right	Left	Mult.
≤5 km from proj.	12	1	1	4	7	2	0	0	7	1	1	2
Undist. traveling	22	1	3	7	23	0	2	0	10	1	0	0

However, because of the small sample sizes and the small number of individual whales involved, it would be premature to draw firm conclusions from these data on turns.

Both **pre-dive flexes** and **fluke-out dives** were rare or absent for all categories of whales within 5 km of the operating sound projector as well as in undisturbed conditions (*cf*. Table 19, p. 164):

	Pre-dive Flex						Flukes-out On Diving					
	Calves		Mothers		Others		Calves		Mothers		Others	
	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
≤5 km from proj.	21	0	11	0	29	1	21	0	12	0	27	3
Undist. traveling	42	0	30	1	23	1	41	1	30	1	23	1

In **summary**, the 1989 data do not provide firm evidence of changes in the behavior of individual whales nearing the source of drilling noise, but there are some hints of possible effects. Some of the possible effects are consistent with the types or directions of behavioral change demonstrated in previous studies of disturbance to bowheads during summer or autumn. On the other hand, a few bowheads came quite close to the projector during this study. In contrast, during previous playback experiments with bowhead whales, avoidance reactions often have been seen at greater distances even though projection equipment and source levels of man-made noise were comparable (Richardson et al. 1990). It is not yet known whether the few bowheads seen close to the operating projector in 1989 were representative of the population during spring migration.

In general, the sample sizes from 1989 are too small to allow meaningful quantitative interpretation of these observations. However, the 1989 results provide useful guidance concerning types of behaviors that should be recorded systematically in the presence and absence of industrial noise during future fieldwork. The 1989 data will also, when combined with additional data, provide a useful contribution to the overall dataset needed to test the null hypothesis concerning noise effects on subtle aspects of individual bowhead behavior.

<u>Sound Levels Tolerated</u>.--Broadband (20-1000 Hz) levels of drilling noise received by bowheads migrating past the projector ranged from 97 dB re 1 μPa for the mother/calf pair passing 3.7 km to the side of the projector on 27 May[10] to 125 dB for the whale 100-120 m away on 19 May. These levels were 8 to 41 dB above the ambient noise levels in the 20-1000 Hz band on those days (Table 25).

[10] The whales whose CPA was 3.7 km were also exposed to tones with received levels as high as 104 dB before the drilling noise was projected.

On a 1/3-octave basis, the strongest drilling noise received by the bowheads was usually in the band centered at 200 Hz. Received levels in the 1/3-octave band of strongest noise were necessarily slightly lower than broadband levels, e.g. 92 dB at 3.7 km on 27 May, and 121 dB at 100-120 m on 19 May. However, corresponding drilling noise to ambient noise ratios were 22 and 49 dB. These data are examples of a general principle: signal to noise ratios in some 1/3-octave bands are usually considerably higher than broadband S:N ratios.

The intensity of sound that is barely audible in the absence of significant ambient noise is the absolute hearing threshold, which varies with frequency. From anatomical evidence, Fleischer (1976) suggested that baleen whales are adapted to hear low frequencies. Norris and Leatherwood (1981) examined the hearing apparatus of bowheads and concluded that they likely hear sounds ranging from "high infrasonic [or] low sonic to high sonic or low ultrasonic frequencies". Watkins (1986) reports that other baleen whales often react to sounds with frequencies from 15 Hz to 28 kHz, but not to pingers and sonars at 36 kHz and above. Many authors have suggested that marine mammals probably hear best in the frequency range of their calls. Although some bowhead calls include components up to 4-5 kHz, most are at 50-400 Hz (Ljungblad et al. 1982; Clark and Johnson 1984; Cummings and Holliday 1987). Thus, bowheads probably are well adapted to receive frequencies below 1 kHz plus those in the low kilohertz range.

The effective filter bandwidth of the bowhead auditory system is unknown. However, for mammals in general, it is typically 1/3-octave or less within the range of best hearing (Fay 1988; Richardson et al. 1989). Thus, the bowhead's effective filter bandwidth for low frequency sounds is probably 1/3-octave or less. Given this assumption, signal to noise ratios in 1/3-octave bands are probably useful as rough measures of the prominence of a sound to a bowhead. As a first approximation, a sound signal like drilling noise is expected to be detectable by a bowhead if its received level exceeds that of the background noise within at least one 1/3-octave band, i.e. if S:N > 0 dB in at least one such band.

It is apparent that some bowheads continued migrating NE, E or SE past the operating sound projector when the received level of drilling noise was well above the natural background noise level not only in the strongest 1/3-octave band, but also on a broadband basis. This result for spring-migrating bowheads is consistent with previous observations of reactions of summering bowheads to drilling and construction sounds. In summer, some bowheads have been observed to tolerate sounds of these types whose received levels were 115 dB or more on a broadband basis (S:N ≥ 20 dB), and 110 dB or more on a 1/3-octave basis (S:N ≥ 30 dB). On the other hand, during summer some individual bowheads reacted to considerably fainter sounds, e.g. with broadband S:N = 10 dB, or 1/3-octave S:N = 20 dB (Miles et al. 1987; Richardson et al. 1990). This type of individual variability in sensitivity is likely in spring as well.

The mother/calf pair traveling north and west away from the projector on 23 May was receiving drilling noise with broadband level ~110 dB (S:N ≈ 8 db) when they were first seen at range 1 km. At that range, the received level of drilling noise in the strongest 1/3-octave was about 104 dB (S:N ≈ 15 dB). These levels and S:N ratios are less than those tolerated by some other bowheads (Table 25). However, we do not know how close to the projector these whales were when the projector was first turned on. They may have been exposed to considerably stronger sounds at that time. This mother/calf pair was still traveling westward 5 km from the projector, where the drilling sound was barely detectable above the ambient noise. As discussed above, it is not certain that these whales were reacting to the drilling noise. However, if they were, it is clear that the reversed(?) westward movement continued even after the animals had traveled far enough from the projector such that the received drilling noise was quite weak.

All of the noise data quoted above were measured 9-18 m deep in the water column. Close to the surface of open water, the pressure release or "Lloyd mirror" effect can result in somewhat lower received levels (Urick 1983). This phenomenon becomes evident within ½-¼ wavelength of the surface. At 200 Hz and 80 Hz, two of the dominant frequencies in the drilling platform sound, the wavelengths are 7 and 18 m, respectively. Any bowhead that has dived deep enough to be invisible to aerial observers is likely deep enough for the pressure release effect to be negligible for sounds at ≥ 200 Hz. However, this effect will cause reduced received levels in the cases of whales that are visible at the surface. This may be important in interpreting reactions to sounds that start while the whales are at the surface. On 30 April, for example, the whale exposed to the onset of tonal sounds when it was within 100 m of the projector probably did not receive intense low-frequency sounds until it dove out of sight.

Further interpretation of the behavior of the bowheads observed in 1989 in relation to received sound levels would be premature, given the low sample sizes and the brief durations of the majority of the whale observations. However, some bowheads migrating NE, E and SE through the pack ice east of Pt. Barrow in spring did tolerate received levels of low-frequency drilling noise well above the assumed detection threshold. Although some of these whales continued migrating past the projector, the available data are insufficient to determine whether or not there were subtle changes in their individual behaviors. Other individuals, e.g. the mother/calf pair traveling north and west on 23 May, *may* have reacted strongly to noise levels no higher than those tolerated by some bowheads.

Because of the heavy ice conditions in 1989, we could not follow migrating bowheads as far as we wished. Thus, we could not determine whether some bowheads reacted to the operating sound projector when they were still a few kilometers away from it. Furthermore, it should not be assumed that migrating bowheads would react the same way to other types of industrial sounds with different levels, spectral characteristics, or temporal patterns. Also, under some circumstances bowheads may react to sight, odor, infrasound, vibration or other stimuli from an industrial site. This project has not been designed to test the reactions of whales to these other attributes of industrial sites.

Potential Importance of Infrasounds.--The playbacks of *Karluk* drilling sounds did not include much energy below 50 Hz because of the limitations of practical underwater sound projectors (p. 99-101). The original drilling sounds included considerable energy at frequencies as low as 20 Hz, and probably lower. Thus, the playbacks did not simulate the full frequency range of the sounds emitted from the *Karluk* site.

There are no specific data on the lower limit of hearing sensitivity of any baleen whale. Given the anatomical evidence mentioned above, plus the fact that bowhead calls include energy as low as 50 Hz, bowheads likely have good sensitivity at frequencies as low as 50 Hz. We are not aware of any published data on the possibility that bowhead calls include infrasonic components. Thus, it is not certain that 50 Hz is the lower limit of frequencies in bowhead calls.

In other mammals, the low frequency portion of the audiogram slopes upward gradually as frequency decreases. Inspection of the mammalian audiograms in Fay (1988) indicates that, at low frequencies, sensitivity typically deteriorates by 20-40 dB with a 10-fold reduction in frequency. If this applies to bowheads, and if their sensitivity is good at frequencies as low as 50 Hz, then they may be able hear strong sounds at 5 Hz or below. At least in the case of the CIDS caisson, drilling produced a strong tone near 1.5 Hz (Hall and Francine 1990).

Several unknowns prevent an assessment of the importance of the very low frequency components of the *Karluk* sound:

- it is unproven whether bowheads can sense sounds below 50 Hz, although this is likely;
- the acoustic output of the *Karluk* drilling operation below 20 Hz is unknown;
- the attenuation rate of infrasonic components in continental shelf waters of the western Beaufort Sea is unknown but probably high;
- the ambient noise levels in the study area at infrasonic frequencies are unknown.

The first of these points will be difficult to resolve in the absence of an underwater projector that can reproduce very low frequency sounds. However, it would be helpful to determine whether bowhead calls include any infrasonic components; if they do, then it is likely that bowheads can hear those frequencies. The remaining three points are amenable to study, but data are lacking at this time.

In summer, bowhead whales seemed to be at least as sensitive to playbacks of drilling and dredge noise as to actual drillships and dredges (Richardson et al. 1990). Those playback experiments were done with the same types of playback equipment as used in the present study. Likewise, the reaction thresholds of gray whales to playbacks of continuous industrial noises are generally similar to those of bowheads (Malme et al. 1984). These results suggest that playbacks are a useful method for evaluating the probable reactions of baleen whales to noise from stationary industrial sources. The playback technique provides the only way to address this issue in the absence of actual industrial operations in the area and season of interest.

Bowhead Reactions to Aircraft

A secondary objective of this study is to determine the reactions of bowhead whales to helicopter overflights during the spring migration season (see specific objective 5, p. 18). In addition, reactions of bowheads to the fixed-wing observation aircraft are of interest. During 1989, there were no opportunities for systematic tests of the responses of bowheads to aircraft overflights. However, a few incidental observations of apparent reactions were noted.

Reactions to Twin Otter

On two occasions, observers in the Twin Otter survey aircraft noticed behaviors that they attributed to aircraft disturbance. ***(1)*** On 26 May, a mother and calf exhibited unusually brief surfacings when the Twin Otter circled to pass over them at an altitude of 145 m during a photography session. During the late summer and autumn, bowheads often exhibit brief surfacings in the presence of various types of disturbance (Richardson et al. 1985a,b, 1986, 1989; Ljungblad et al. 1988). ***(2)*** On 14 May, a bowhead dove hastily as the aircraft flew almost directly overhead, but slightly behind the whale, at 457 m altitude. No other observations of apparent reactions to the aircraft were noticed while it was flying at ≥457 m ASL.

On a few occasions when low cloud ceilings prevented behavioral observations from ≥457 m altitude, we observed at least briefly from lower altitudes. During these periods, the aircraft flew in circles with the usual radius of about 1 km, centered on the whale(s). Almost all bowheads observed while the aircraft circled at <457 m altitude were classified as traveling. No obvious behavioral reactions were noticed. Too few quantitative data on surfacing, respiration and diving behavior were obtained during this low-altitude circling to merit interpretation. Likewise, there were few observations concerning the occurrence of discrete behaviors like turns, pre-dive flexes, fluke-out dives, and aerial activities. However, cross-tabulations of these variables vs. whale status (calf, mother, other) revealed no evidence that any of these discrete behaviors was noticeably different during circling at <457 m than at ≥457 m altitude.

During previous studies in late summer and autumn, we have found that reactions of bowheads to a circling observation aircraft are common when it is at ≤305 m altitude, rare when it is at 457 m, and virtually absent when it is above 457 m (e.g. Richardson et al. 1985a,b). Few data have been reported concerning reactions of bowheads to aircraft in spring (reviewed by Richardson et al. 1989). We will need additional spring data before drawing firm conclusions about relative sensitivity to aircraft in spring vs. late summer. However, preliminary indications from the 1989 phase of the present study are that bowheads seem no more sensitive to a fixed-wing observation aircraft during spring migration through pack ice conditions than they are in late summer in largely open waters.

Reactions to Bell 212 Helicopter

Whenever bowheads were accessible during May 1989, helicopter-supported work was devoted to noise playback experiments. Hence, no systematic helicopter disturbance experiments were done in 1989. However, on 16 May a bowhead mother and calf were present near the planned projector site when the ice-based crew arrived from Barrow by helicopter. The movements and behaviors of this mother and calf were observed from the ice while the helicopter made four short flights past the whales to deploy a monitor sonobuoy on the opposite side of the lead. This lead was ~500 m wide and was covered by thin newly-refrozen ice. All behavioral observations were made prior to the onset of a noise playback, mostly before the theodolite could be set up.

When the helicopter arrived, a bowhead mother and calf were resting at the surface in a small hole in the SSE corner of the thinly-refrozen lead. They subsequently moved west a few hundred meters to other small holes in the middle of the lead, where they were exposed to four helicopter passes: ***(1)*** About 45 min after the helicopter had arrived, it took off and flew across the lead. At this time the calf was quiescent at the surface and the mother was invisible below the surface. The helicopter passed within a horizontal distance of 100 m at an altitude of 15-30 m (pilot's estimates) of the calf. The calf remained stationary at the surface throughout this overflight. ***(2)*** About 20 min later, the helicopter flew back across the lead to the ice camp while both mother and calf were at the surface, separated by ~150 m. The helicopter purposefully remained >150 m from the calf, but inadvertently passed close to the mother (<50 m to the side at 15-30 m ASL) when she surfaced as the helicopter was approaching. During this pass, the calf remained at the surface but the mother dove. ***(3)*** The helicopter made a third pass over the lead ~7 min later, while the calf was still at the surface. The calf remained at the surface when the helicopter passed 100-150 m to the side at 15-30 m ASL. ***(4)*** Some 12 min after pass (3), both mother and calf were at the surface. Both bowheads dove when the helicopter flew past at a distance of about 500 m. They surfaced at the same location <2 min later. However, several minutes thereafter they moved underwater to a new location a few hundred meters to the northwest, farther to the side of the route that the helicopter had been following. They remained at that location for ~40 min, and then departed westward.

In summary, the mother was at the surface during two of the helicopter passes, and on each occasion dove as the helicopter approached or flew over. The calf was at the surface during all four passes, and dove only once. In each case, the path of the low-flying helicopter was within 200 m of the whales, and once was only <50 m from the mother. Despite the repeated close passes, the bowheads did not show any obvious signs of disturbance other than the dives, which may or may not have been attributable to the overflights. The calf, in particular, showed no overt responses during three overflights at 15-30 m ASL and 100-200 m lateral distance. It remained resting at the surface before, during and after 3 of 4 overflights. The mother and calf remained near the path of the helicopter for ~25 min after the mother was overflown at close range during pass (2). If the helicopter had disturbed them severely, we would have expected the whales to have moved away sooner than they did.

No generalizations should be drawn based on this single observation, but in at least this one case a mother and calf bowhead did not flee in response to intense helicopter disturbance. We obtained some information about the surfacing, respiration and dive behavior of this mother/calf pair. However, given the small sample size and the absence of pre-disturbance control data from the same animals, these data are not interpretable.

Bowhead Reactions to Sonobuoy Drops

We dropped sonobuoys near bowhead whales on four occasions in May 1989 in order to measure received industrial noise levels near whales during playback tests. Air-dropped sonobuoys have been used during many previous studies by ourselves and others in order to monitor bowhead calls and man-made sounds being received by bowheads. Bowheads generally have not reacted overtly to these sonobuoy drops. In this and previous studies, we typically dropped sonobuoys ½-1 km from bowheads, generally along the observation aircraft's circular path around the whales. When bowheads are actively traveling, we usually drop the sonobuoy ½-1 km ahead of the whales, so they will pass close to the sonobuoy if they maintain their original course. On many occasions in previous studies we have dropped sonobuoys less than ½ km from bowheads. In most such cases, no reaction has been evident. When a reaction has been noticed during previous studies, it has been a momentary startle response. However, during this study one migrating mother/calf pair reacted dramatically to a sonobuoy dropped 700-800 m in front of the whales, and another mother/calf pair may have reacted mildly to sonobuoys dropped 400-500 m from them on two occasions.

At 16:03 on 23 May, we dropped a sonobuoy ~500 m WNW of a submerged mother/calf pair that were slowly moving west during a drilling noise playback test. We were unable to see the whales when the sonobuoy hit the water but we observed three surfacings of each whale during the 20 min period following the sonobuoy drop. The whales changed neither their heading nor their speed of movement after the sonobuoy drop (Fig. 64, p. 187). Thus they did not appear disturbed in any way by the sonobuoy drop on 23 May.

The reaction of a mother/calf pair to a sonobuoy dropped at 13:30 on 27 May was the most severe reaction to a sonobuoy drop that we have seen. The sonobuoy was dropped 700-800 m[11] ahead of the slowly migrating whales during a drilling noise playback experiment. Immediately after the sonobuoy hit the water, the whales turned left by 90°. They reoriented several times in the following 30 min (Fig. 67, p. 193) and their speed of movement was reduced from medium to slow or no forward movement. They moved farther south into the open water area of the lead than their initial path would have taken them. After 30 min, they finally moved eastward toward the sonobuoy and their initial track, but they were

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[11] Distance estimated visually; believed accurate to within 200 m.

still moving slowly. Some 45 min after the sonobuoy drop they approached the sonobuoy and resumed their initial migratory behavior. Mean blow intervals and durations of dives did not appear to change following the sonobuoy drop, but number of blows/surfacing and durations of surfacings by the calf tended to increase during the 45 min period following the sonobuoy drop (Fig. 73). These latter two variables appeared to remain higher than pre-disturbance values even after the whales had resumed their eastward migration.

At 20:11 on 27 May we dropped a sonobuoy 400-500 m NE of a third mother/calf pair that was moving slowly eastward in the middle of the main nearshore lead under undisturbed conditions (Fig. 58, p. 168). The calf was small (4.0 m) and probably was recently-born. Before the sonobuoy drop, these whales had reoriented several times and they were traveling slowly. Immediately after the sonobuoy drop, they turned SSW, directly away from the sonobuoy, and slowly moved away from it. Formal behavioral observations ceased at 20:22, but their reaction appears to have been brief. From 20:29 to 21:20, while the aircraft was flying low over these whales to obtain photographs, the whales moved to the east and then SE, and rates of movement were moderate (2.4-3.8 km/h).

A sonobuoy was dropped ~500 m north of this same lingering cow/calf pair at 13:21 on 29 September (identity confirmed by photography later on 29 May). Their reaction was subtle and would not have been perceptible if we had not observed these whales for 1.3 h before the buoy was dropped. Before the drop, the whales were oriented south, which was directly away from the sonobuoy location. Their movements were slow and included numerous reorientations. During the previous 1.3 h they had moved only 250-300 m (visual estimate) to the NW of their initial position (Fig. 58). After the sonobuoy was dropped, they slowly turned right and made a small circle until they were headed S again. By 13:55 they were 1000 m from the sonobuoy. There was no obvious startle response, and the slow southward movement would not have been attributable to the sonobuoy drop if the whales had not made a small circle following the sonobuoy impact and if their limited movements during the previous 1.3 h had not been documented. No changes in surfacing, respiration and dive variables were apparent following the sonobuoy drop (Fig. 74).

When a sonobuoy is dropped from an aircraft, it is slowed somewhat by a small drogue, but it nonetheless hits the water at a considerable speed. On 29 May 1989, we dropped a sonobuoy from 457 m altitude at a position ½ km from the ice-based observers (measured by theodolite). They were projecting drilling sounds at the time. Despite this, the slap sound of the sonobuoy impacting the water was detected by a hydrophone at 3 m depth only 6.5 m (slant distance) from the operating projector. Because of the background noise from the projector, detailed acoustical analysis of this slap was unsuccessful. However, the fact that it was audible ½ km from the impact location despite strong background noise indicates that a sonobuoy drop causes a strong but momentary noise pulse.

The reasons for bowhead reactions to sonobuoy drops during this study when few reactions have been seen during previous studies are not clear. The most dramatic response was seen when a sonobuoy was dropped 700-800 m from a mother/

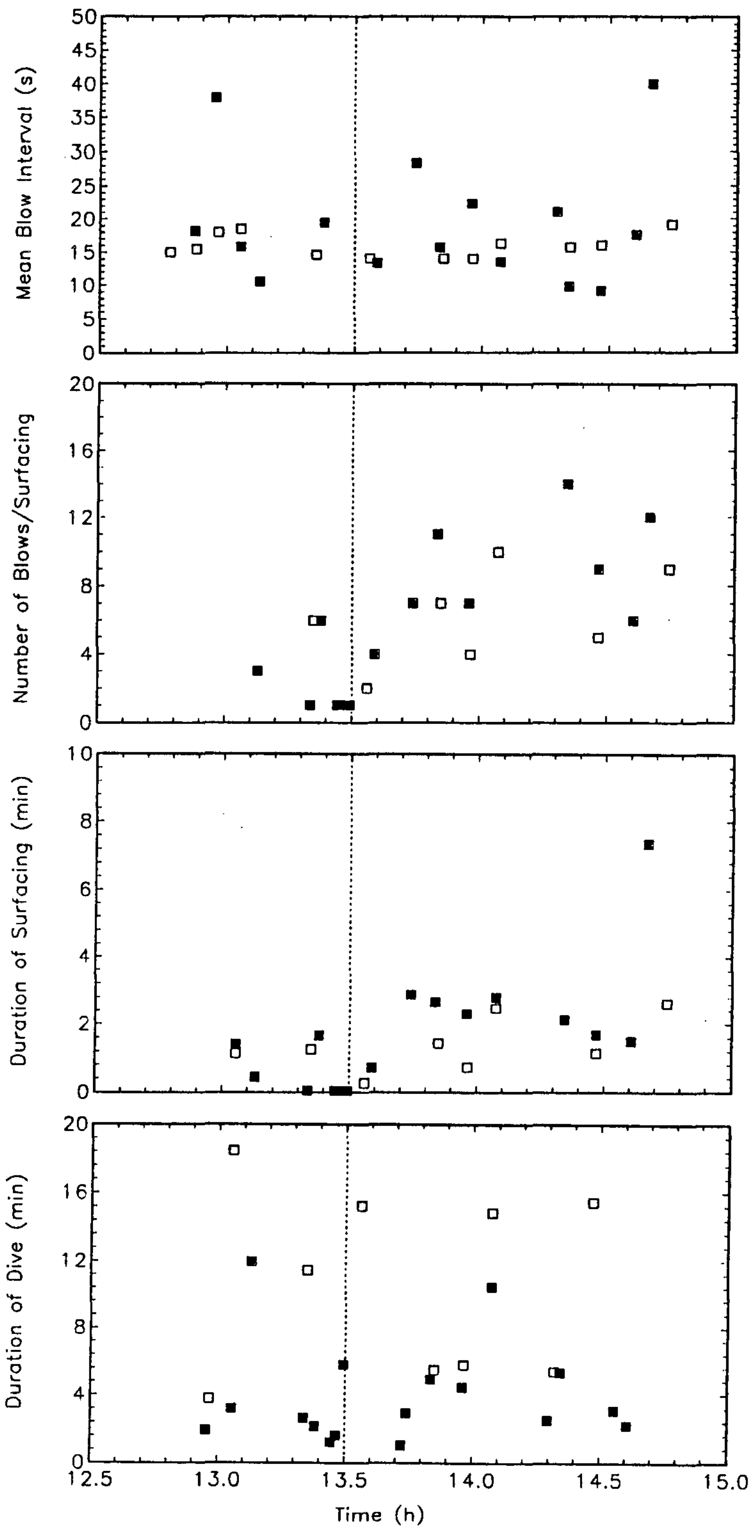


Fig. 73. Respiration, surfacing and dive variables for bowhead whales observed on 27 May 1989 in relation to time. A sonobuoy was dropped 700-800 m in front of a slowly migrating mother and calf at 13:30 (indicated by the vertical dashed line on the scatterplots). Open symbols represent the mother and closed symbols represent the calf.

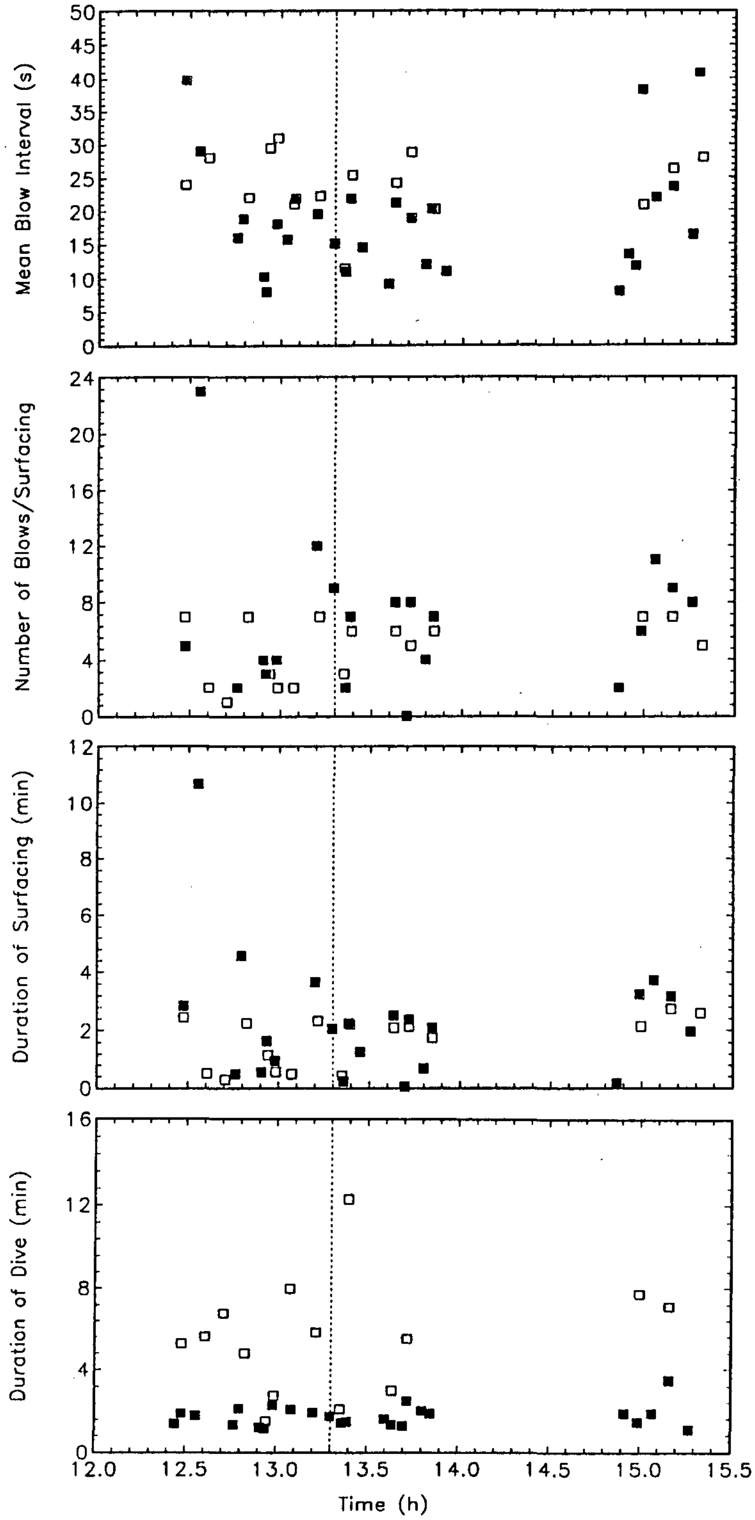


Fig. 74. Respiration, surfacing and dive variables for bowhead whales observed on 29 May 1989 in relation to time. A sonobuoy was dropped 500 m from a resting mother and calf at 13:21 (indicated by the vertical dashed line on the scatterplots). Open symbols represent the mother and closed symbols represent the calf.

calf pair. We have dropped sonobuoys at similar and lesser distances on many previous occasions in summer and autumn without eliciting similar responses. Two possible explanations are as follows: (1) Mothers with young calves may be more sensitive than other whales to potential sources of disturbance. (2) In spring, all whales may be more sensitive to abrupt sounds, such as the slap of a sonobuoy hitting the water, because bowheads are hunted from unpowered boats at this time of year.

In any case, sonobuoy drops have the potential to confound behavioral observations of bowheads, at least during spring. Caution should be exercised when selecting times and locations for sonobuoy drops near bowheads whose behavior is being observed. Caution should also be exercised when interpreting behavioral data collected shortly after a sonobuoy is dropped nearby.

WHITE WHALE RESULTS

Distribution and Movements of White Whales

Specific objective 6 (p. 18) required us to document, as opportunities allowed, the movements, behavior and basic biology of white whales along their spring migration route. Although priority was given to observations of bowheads, sightings of white whales were more numerous than those of bowheads (Fig. 75-78 vs. 52-54). We saw about 1327 presumably-different white whales in comparison to only ~169 presumably-different bowheads.

About 355 white whales were sighted during the 1-10 May period. White whale sightings tended to be more widely scattered and slightly farther offshore than bowhead sightings (Fig. 75 vs. 52 on p. 150). Most white whales were either migrating in a generally NE direction or resting on the surface. Migrating white whales tended to follow leads or cracks, changing heading as necessary to remain within the crack. They seemed to travel around some large pans and areas of consolidated ice that bowheads dove under. Before and after long dives, white whales were often seen resting motionless on the surface.

Two other interesting behaviors were observed in early May. ***(1)*** On 2 May we saw a group of 18 widely scattered white whales resting motionless (sleeping?) underneath thin "black" ice. Similarly, on 9 May we found at least 50 white whales distributed in smaller groups, mostly quiescent, within an area ~3 km in diameter. There was ~95% cover by heavy pack ice, >4% thinner ice, and <1% thin "black" ice within narrow cracks. Many whales were motionless just below the thinnest ice, with their flukes lower than their heads. ***(2)*** In the group of 50 white whales seen on 9 May, one subgroup of ~25 whales vigorously swam back and forth between two holes ~15 m apart. They apparently were trying to keep the holes from freezing over.

White whales were more numerous during the 11-20 May period than during early May; 594 whales were recorded on 11-20 May. In contrast to bowheads, there was no major change in the distribution of white whales between the early and mid May periods (Fig. 75 vs. 76). White whales moved through the offshore pack ice well north of the landfast ice during both periods. However, the movements of white whales were less strongly oriented to the NE during mid-May than during early May. Although the overall trend in direction of movement was eastward, movements in virtually all directions were recorded.

Only 378 white whales were recorded during the 21-30 May period, although the number of hours of survey coverage was higher in late than in mid May. Most of our flights did not extend as far north during late May as during early-mid May, so the distribution of sightings in late May may not be representative of overall white whale distribution in the study area in late May. During the 21-25 May period, just after the E-W "nearshore" lead developed along the fast ice edge, white whales were seen moving eastward along both the north and south sides of the lead and amidst the pack ice just north of the lead (Fig. 77). During

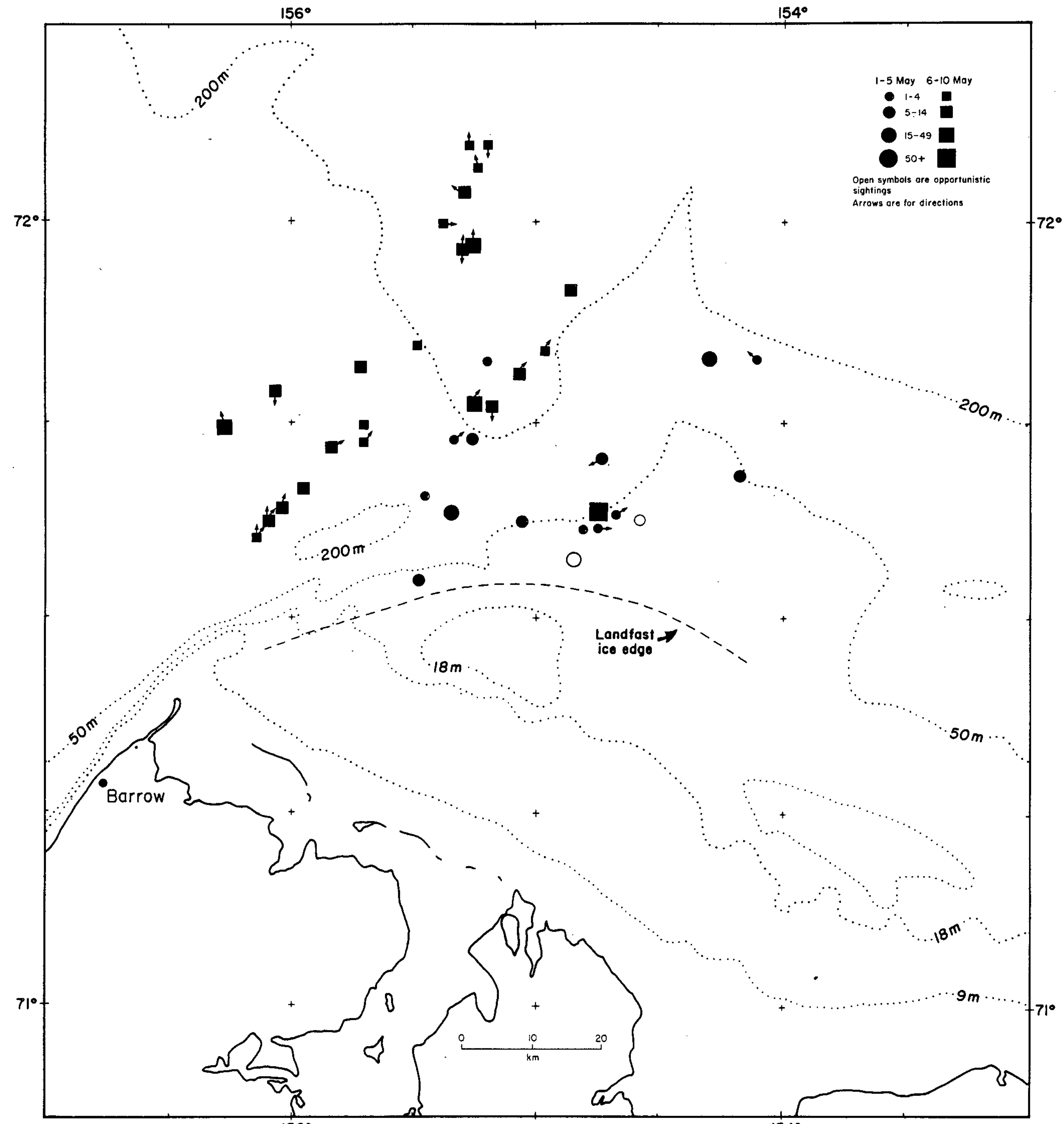


Fig. 75. Sightings of white whales, 1-10 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

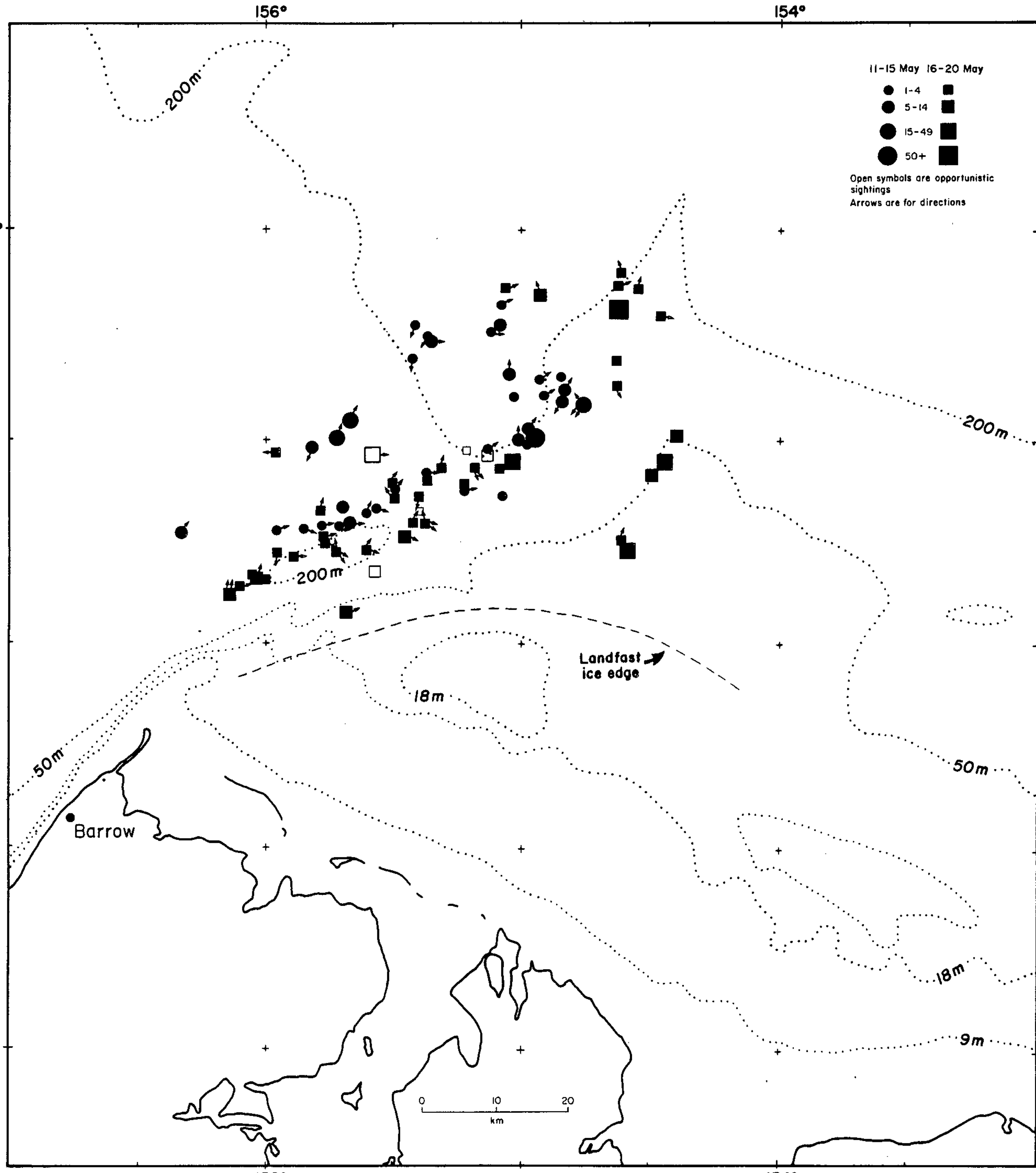


Fig. 76. Sightings of white whales, 11-20 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

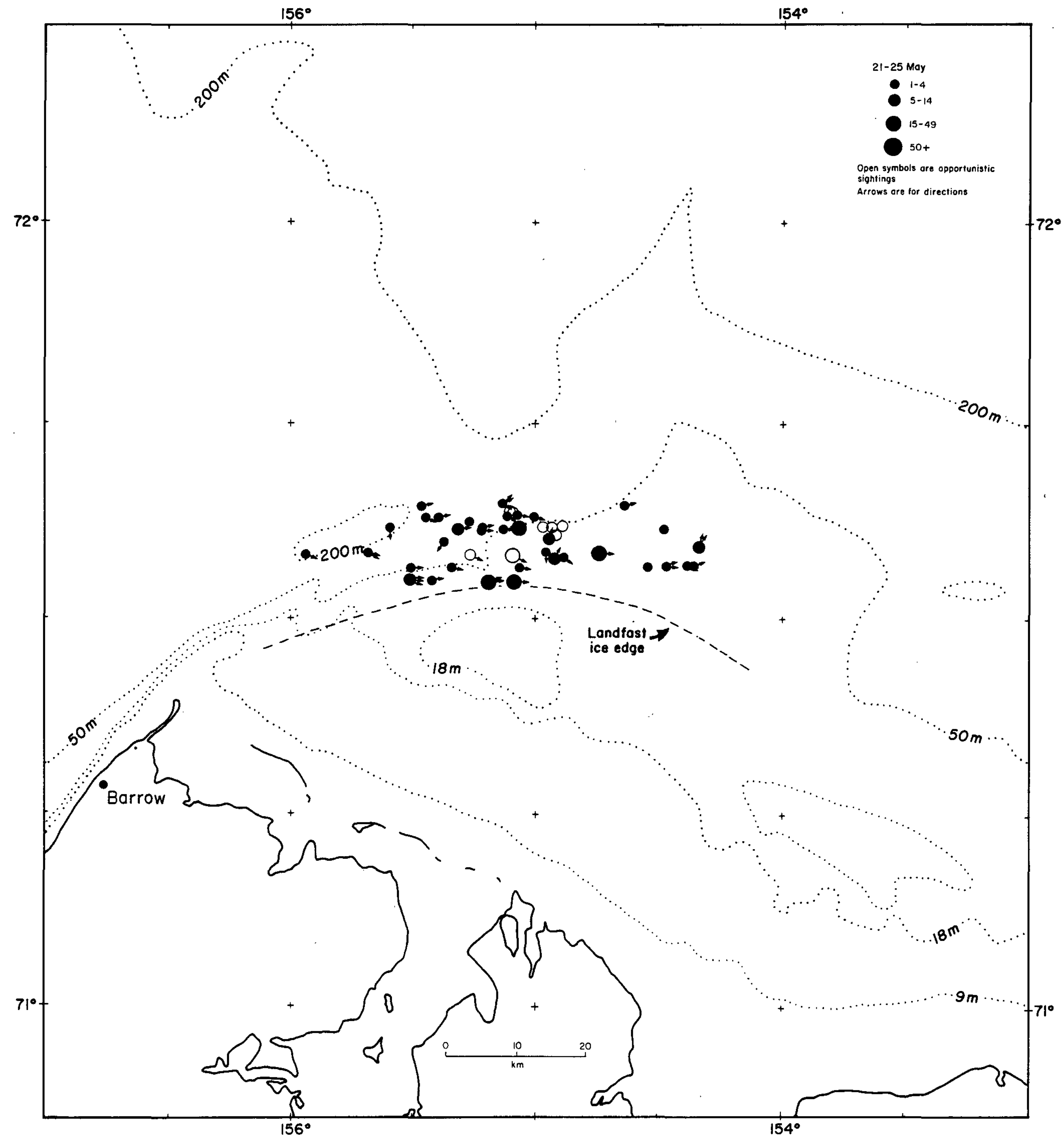


Fig. 77. Sightings of white whales, 21-25 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

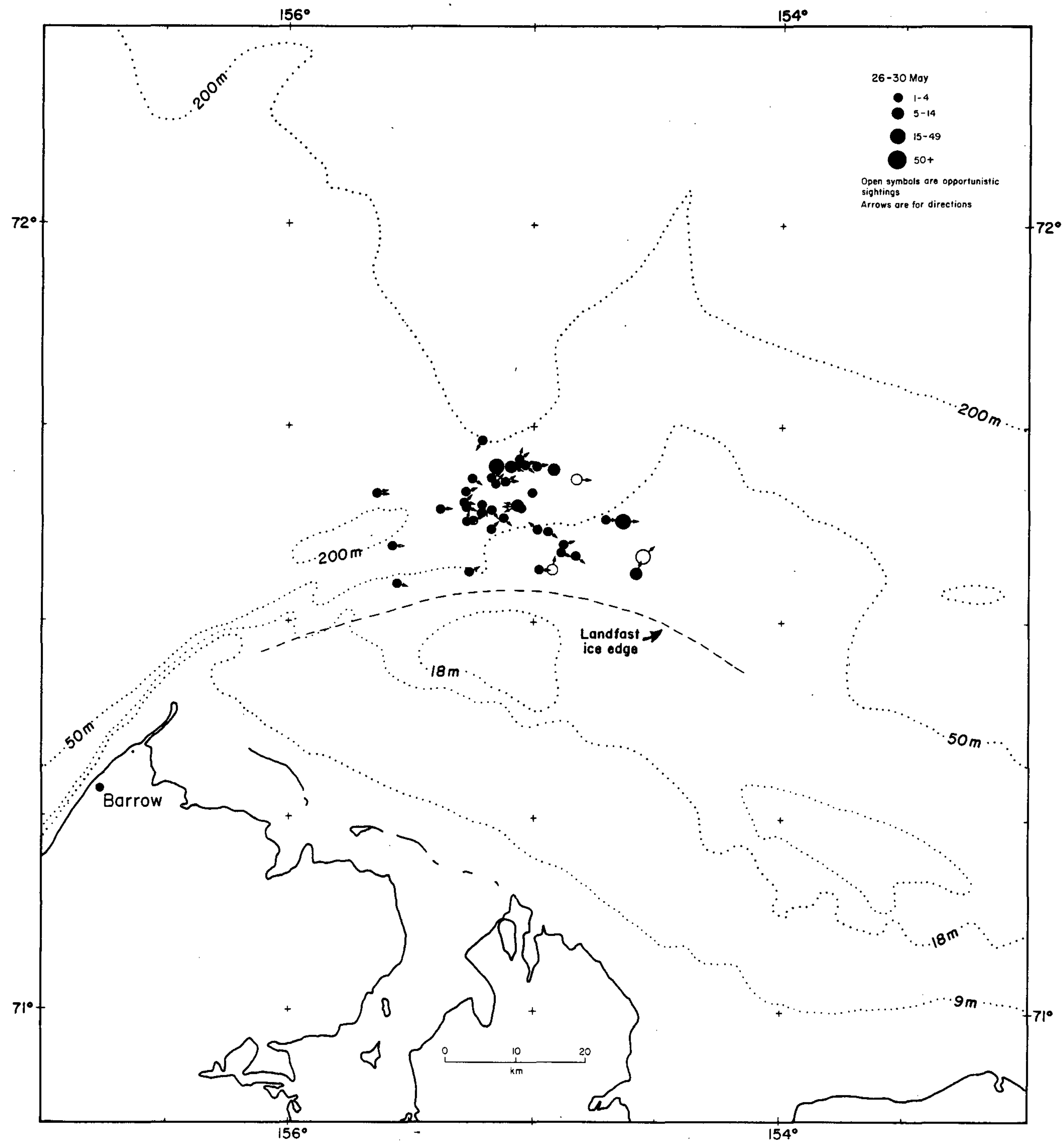


Fig. 78. Sightings of white whales, 26-30 May 1989. Reconnaissance sightings were made by the Twin Otter crew during surveys or behavioral observation sessions; opportunistic sightings were made by the ice-based crew from the ice camp and during helicopter ferry flights.

the 26-30 May period most of the white whales seen were along the north side of the lead or amidst the pack ice north of it; few white whales were seen along the south side of the lead (Fig. 78). Again most of the whales sighted were traveling in a generally eastward direction.

In summary, white whales were more numerous than bowheads during May 1989. Although there was broad overlap in their 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 the study, when a broad nearshore lead developed along the edge of the landfast ice, both species migrated both along the lead and amidst the pack just north of the lead. White whales seen in May 1989 were most often traveling or resting; there was seldom any indication of feeding and never any active socializing.

White Whale Reactions to Playbacks of Drilling Platform Sound

Specific objective 4 required us to study, when possible, the short-term behavioral responses of white whales visible in open water areas along their spring migration route to underwater playbacks of continuous drilling noise. Work on white whales was secondary to that on bowheads, but a significant number of data were collected.

14 May 1989

On this date, the ice-based crew set up the sound projector along the east side of a long lead oriented SSW to NNE (Fig. 60, p. 179). The aerial observation crew searched for whales approaching this lead from the southwest or west while the ice-based crew was setting up the projector. During an initial aerial reconnaissance of the lead from 10:07 to 10:27, the aircraft crew sighted 18 white whales in the lead with the projector. Seven of these were seen moving past the sound projector, which was not yet broadcasting. Five white whales swam north 200 m from the projector at 10:15 and two swam east 400 m from the projector at 10:25. Drilling sound was projected from 11:58 to 18:35.

A large group of ~100 white whales entered the main lead between 11:00 and 12:00 through the heavy pack ice SW of the main lead. The aerial crew observed many of these whales, at least briefly, from 11:35 to 14:00. During this period, these whales followed the eastern side of the lead northward toward and past the sound projector. Of this group of ~100, eight individuals (in 5 subgroups) were observed by the ice-based crew.

Aerial Observations: The white whales sighted by the aircraft crew at distances ranging from several kilometers to several hundred meters south of the projector were generally moving parallel to the ice edge at medium speed, in most cases 5-15 m out from the east edge of the lead. Some turns of 30-90° were seen and a few whales appeared to stop and feed under the ice edge. However, the northward movement of most whales was steady. At these distances, the whales did not stop to rest or divert from their travel route parallel to the ice edge.

In contrast, when the whales approached within a few hundred meters of the operating projector, their motions became notably less consistent:

- At 13:55, a group of nine white whales was observed moving north 400 m south of the operating projector. These whales were 200 m south of the projector and slowly swimming *southward* near the ice edge at 14:09. They swam 50 m southward and then turned and slowly swam northward. At 14:10 they were again 200 m south of the projector and near the ice. By 14:17 they were 100 m south of the projector and oriented north, parallel to and near the ice edge. They dove under the ice and surfaced 100 m north of the projector. Their speed of movement increased to moderately fast and they continued to follow the ice edge northward away from the projector. Their closest point of approach to the projector while under the ice is uncertain, but probably within 50 m.
- At 14:05 a different group of three white whales was observed slowly swimming northward 200 m south of the projector and 15 m from the ice. One minute later this group had turned southward and was moving slowly; they then increased their speed to fast and maintained their southerly heading. At 14:16 a group of three white whales (probably the same group) was observed swimming northward 120 m south of the projector and near the ice.
- Two mother/yearling pairs and several single white whales were observed as they closely approached the sound projector. They swam parallel to and 7-15 m from the ice edge. Some were seen "milling" (remaining in one spot, but changing orientation or circling), some were seen moving southward, and some were seen moving northward. A few of these whales may have been involved in all three activities. However, the observations were not continuous, so we were unable to identify many of the white whales individually. Interestingly, one of the mother/yearling pairs "milled" 50-75 m NW of the projector and close to the ice edge for more than 4 min. These whales had apparently already passed the projector, but remained near it for at least 4 min rather than continuing on to the north.

It should be noted that the aerial observers were unable to watch these white whales continuously because bowheads were under observation at some of the same times. Hence, the above observations do not constitute a complete record of white whale activities near the projector.

Ice-based Observations: At 13:46 the ice-based crew first sighted a single white whale 800 m SSE of the projector (distance measured by theodolite); it was swimming NNW at medium speed parallel to and 30 m from the ice edge. When next sighted, at 13:48, it had moved 360 m NNW to a position 440 m SSE of the projector; it had moved at an average speed of 8.1 km/h. The subsequent erratic path of this whale is shown in Figure 79.

This whale was apparently disturbed when it came within 185-400 m of the operating projector. From 13:48 to 13:55 the white whale moved slowly toward the projector, but reoriented several times. Its average speed of movement along its irregular track during this interval was 1.6 km/h. At 13:55, when

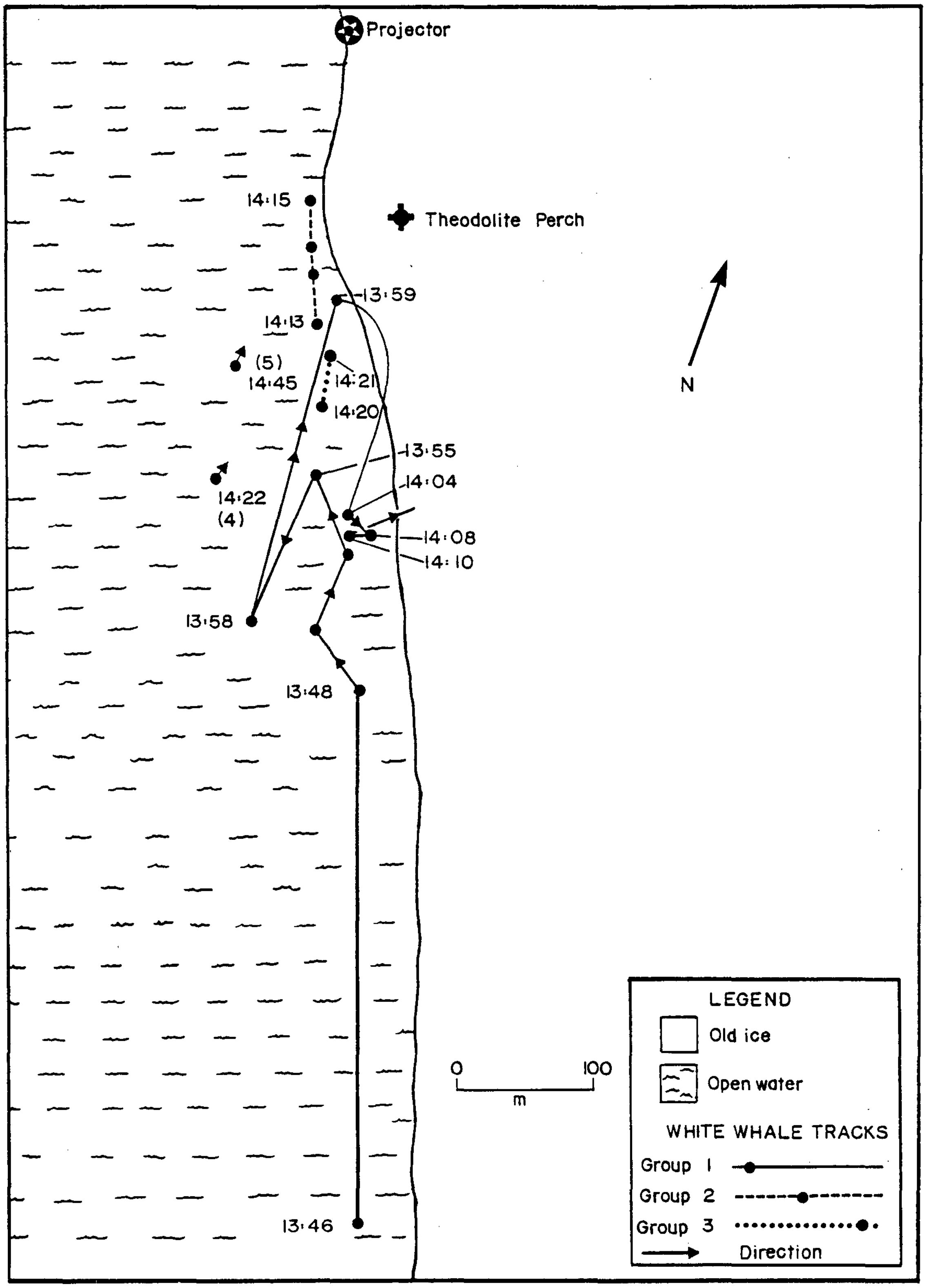


Fig. 79. Locations and tracks of white whales as determined by theodolite in relation to the sound projector during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 14 May 1989. See Figure 60 for a view of the broader area around this location.

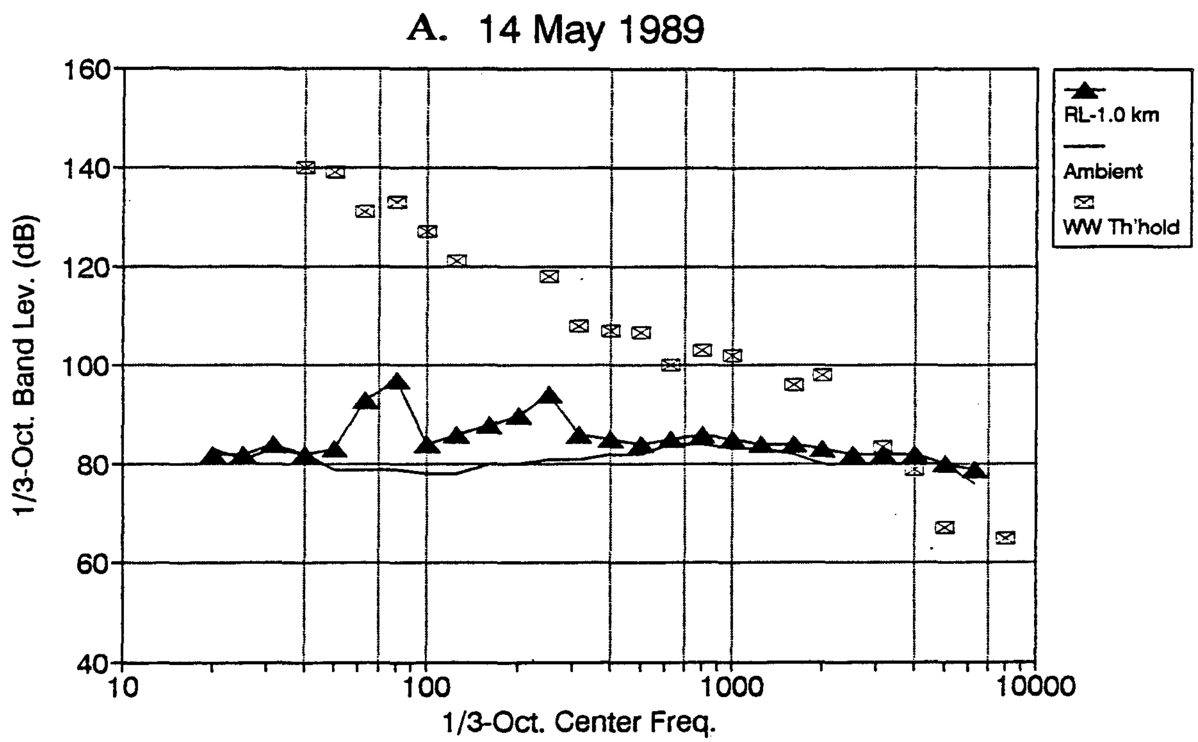
275 m from the projector, it turned 150° to the left and swam slowly (2.1 km/h) south, moving away from the projector and slightly farther from the ice edge. At 13:58 it was 100 m from the ice edge and 400 m south of the projector. It then turned and swam north at medium speed (8.0 km/h) until 13:59 when it was 185 m SSE of the projector and 10 m from the ice edge. The white whale dove under the ice and was next sighted at 14:04, 325 m SSE of the projector, oriented SE, and almost motionless on the surface. At 14:08 it reoriented to the WSW and at 14:10 it reoriented to the NE while 340 m south of the projector. It then dove under the ice and was not seen again (Fig. 79). From 14:04 to 14:10 the speed of movement of the white whale along its irregular track as measured by theodolite was 0.4 km/h.

Four additional groups of white whales were seen by the ice-based observers (Fig. 79). These whales were all moving N to NNW, toward the projector, 5-125 m from the ice edge and 115-315 m SSE of the projector (all distances measured by theodolite). Group 2, observed from 14:13 to 14:15, was moving slowly (2.6 km/h) northward 115 m south of the projector and 5 m from the ice edge when last seen.

Summary: On 14 May, white whales were migrating northward following the ice edge at medium speed. They initially approached to within 200-400 m of the projector at which time at least some of them they slowed to slow speed. Some whales proceeded at slow speed past the projector, but others turned southward for a short distance and then turned north again and continued past the projector. A few groups were seen diving under the ice, possibly circumnavigating the projector at close range (50-200 m). Only one of several groups that reversed course was seen to head rapidly away from the projector. Most groups that were observed apparently passed the projector at close distances (<200 m) and within ~15 minutes of their initial approach. They approached within 100-200 m even though the lead alongside the projector was several km wide and the whales could have diverted westward to move past the projector along the west side of the lead (Fig. 60, p. 179).

Received Noise: On this date, the drilling noise was monitored by a sonobuoy 1.0 m SSE of the projector along the ice edge. The received level of drilling noise there was 101 dB re 1 μPa in the 20-1000 Hz band. At that 1.0 km range, the 1/3-octave band with the strongest received level was centered at 80 Hz, where the received level was 96 dB (Fig. 80A). Received levels of drilling sounds in all 1/3-octave bands containing significant drilling noise were well below the absolute auditory thresholds of the white whale at corresponding frequencies (Fig. 80A).[12] At the low frequencies where the drilling sounds are concentrated, white whale hearing is not very sensitive (Awbrey et al. 1988; Johnson et al. 1989). Thus, it is unlikely that white whales could hear the drilling sounds until they were considerably less than 1 km from the projector.

[12] Above about 3 kHz, third-octave received levels during the playback exceeded the hearing threshold. However, this was due to ambient noise, not drilling noise, since received levels above 500 Hz were almost identical with the projector operating and silent (Fig. 80A).



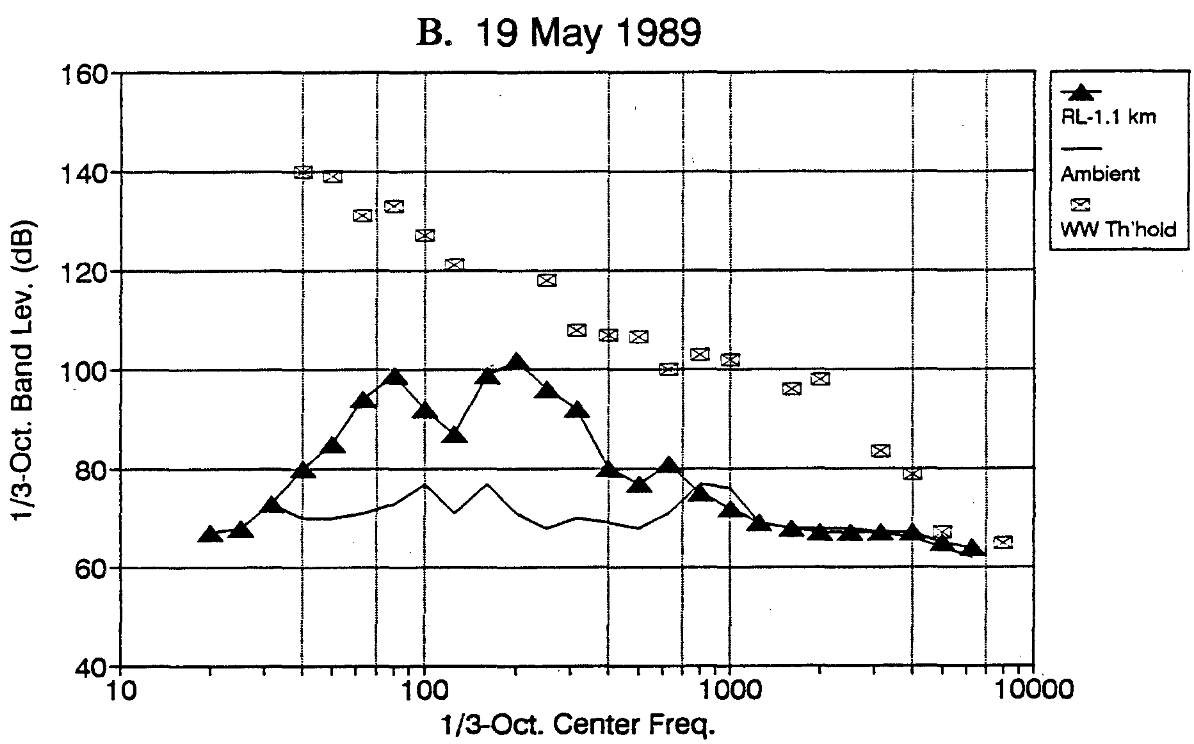


Fig. 80. Third-octave received levels of drilling sound at sonobuoys 1 km from the projector (triangles) during playbacks on 14 and 19 May 1989. Data are in dB re 1 µPa and are plotted in relation to the background ambient noise level and the hearing threshold of the white whale (squares, from White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989).

Noise levels were not monitored at ranges between 1 m and 1 km on 14 May. However, during propagation loss tests on other days, the peak 1/3-octave levels at range 200 m, where some white whales did react to the drilling sounds, were typically around 110 dB near 200 Hz (Fig. 81). The hearing threshold near 200 Hz is probably about 115 dB (Fig. 6, 81). Thus, on 14 May it appears that some white whales began to react at about the range where they would have first heard the low-frequency drilling sounds. However, it is not known whether white whales reacted to the low frequency drilling sounds *per se*, to higher frequency components of the projected noise, or to visual cues. During playbacks of *Karluk* sound, high frequency noise levels close to the projector appeared to exceed the natural ambient noise levels at corresponding frequencies (Fig. 81A-C). This high frequency noise was electronic system noise, not industrial sound (p. 99). This noise probably originated prior to projection of *Karluk* sounds, in which case it was projected with them into the water. If so, white whales close to the projector may have heard and reacted to this high frequency noise instead of (or in addition to) the low frequency drilling sounds. High frequency noise levels during playbacks were very low relative to those at the low frequencies where *Karluk* sounds were concentrated (Fig. 81). However, the white whale auditory system becomes much more sensitive with increasing frequency. Thus, it is uncertain whether the reactions seen at distances of a few hundred meters were to the low-frequency drilling sounds or to high-frequency system noise. Reactions to visual cues were also a possibility at such short distances.

<u>19 May 1989</u>

On this date, drilling sounds were projected into a lead from 13:51 to 18:10. All observations were from the ice because the ceiling was too low for aerial observations.

At 15:15 a group of two white whales was sighted traveling SE at medium speed 360 m (measured by theodolite) south of the projector (Fig. 82). The whales did not deviate from their course over a period of 7 min and a distance of 800 m; 13 positions were determined with the theodolite during this period. The white whales were last sighted at 15:22 heading SE at medium speed 1.1 km SE of the projector, near the monitor sonobuoy (Fig. 82). The heading of the white whales from there was not observed, but ice conditions favored movement to the NE from that point (Fig. 82).

The whales were not sighted until they had apparently passed their closest point of approach to the projector. The CPA position was probably about 225 m southwest of the projector (Fig. 82). It is not possible to determine whether, to avoid the projector, they had deviated southeastward from some other initial course. As the lead was ~1.5 km wide at the location where the whales were initially sighted, they could have given the projector a wider berth to either the north or the south while remaining within the area of open water. Figure 80B shows the 1/3-octave levels of the drilling noise as received 1.1 km from the projector. For the strongest 1/3-octave bands, levels at the estimated CPA distance of 225 m would have been higher, about 110 dB based on propagation experiments on other dates and perhaps as much as 115 dB based on the rate of attenuation between the projector and the monitor sonobuoy on this date.

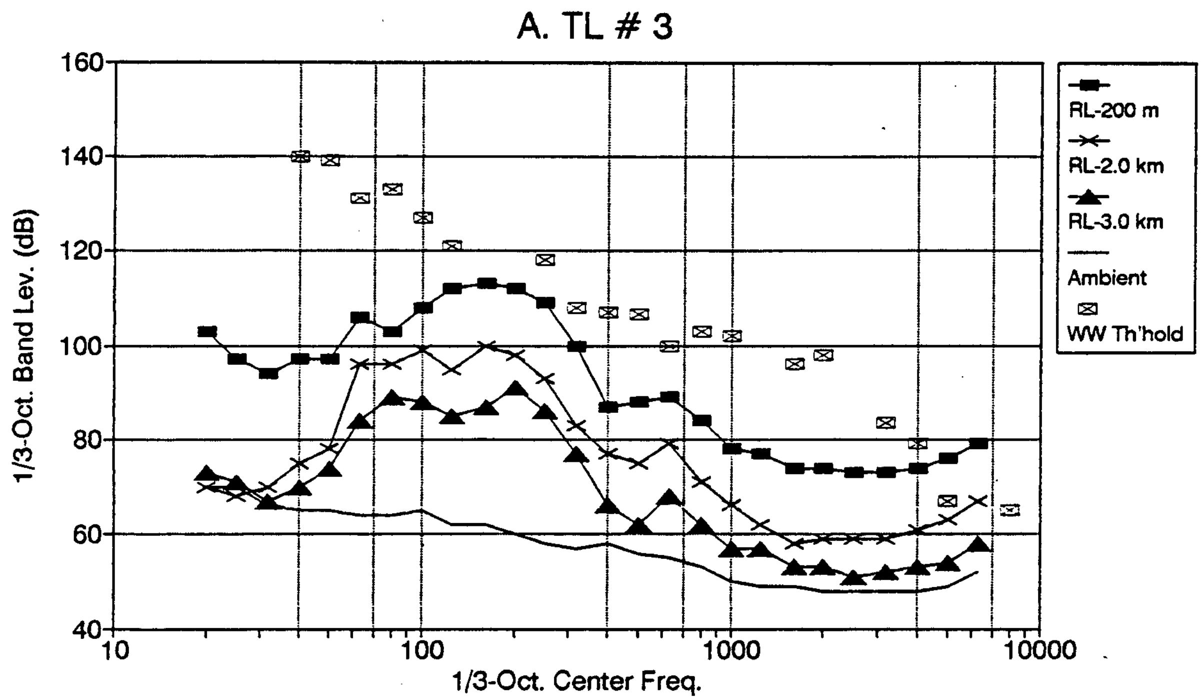
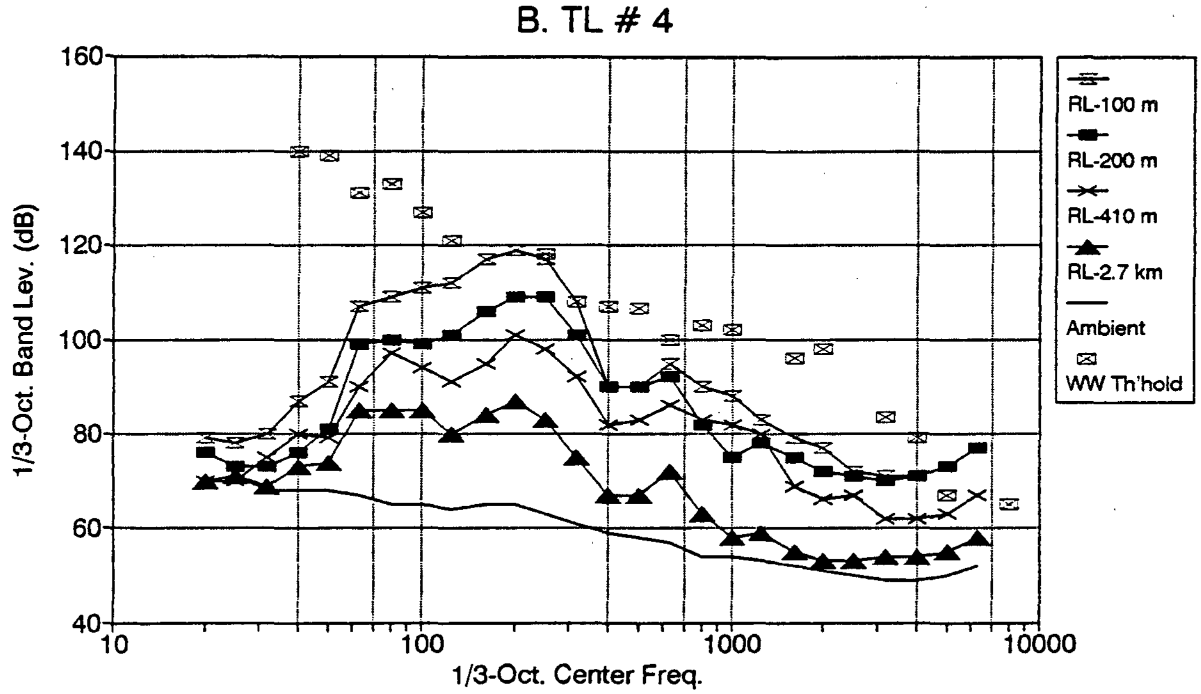


Fig. 81. Third-octave received levels of drilling sound at various ranges during three sound transmission loss (TL) experiments. Lowest curve shows average ambient noise levels during that TL test. Squares show hearing threshold of the white whale (White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989). [Some plotted received levels differ slightly from corresponding data in Tables 8, 10, 13 (p. 117, 121, 125). In re-doing the analyses to include frequencies 2-8 kHz, slightly different periods were considered.]



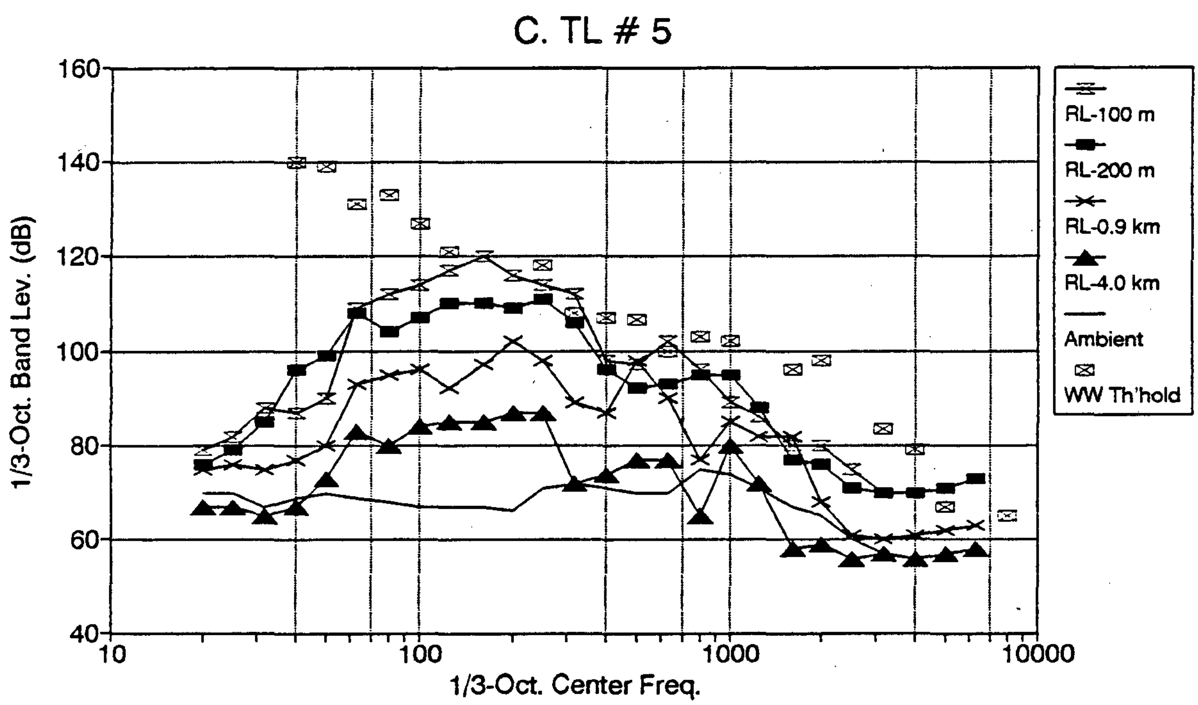


Fig. 81. Concluded.

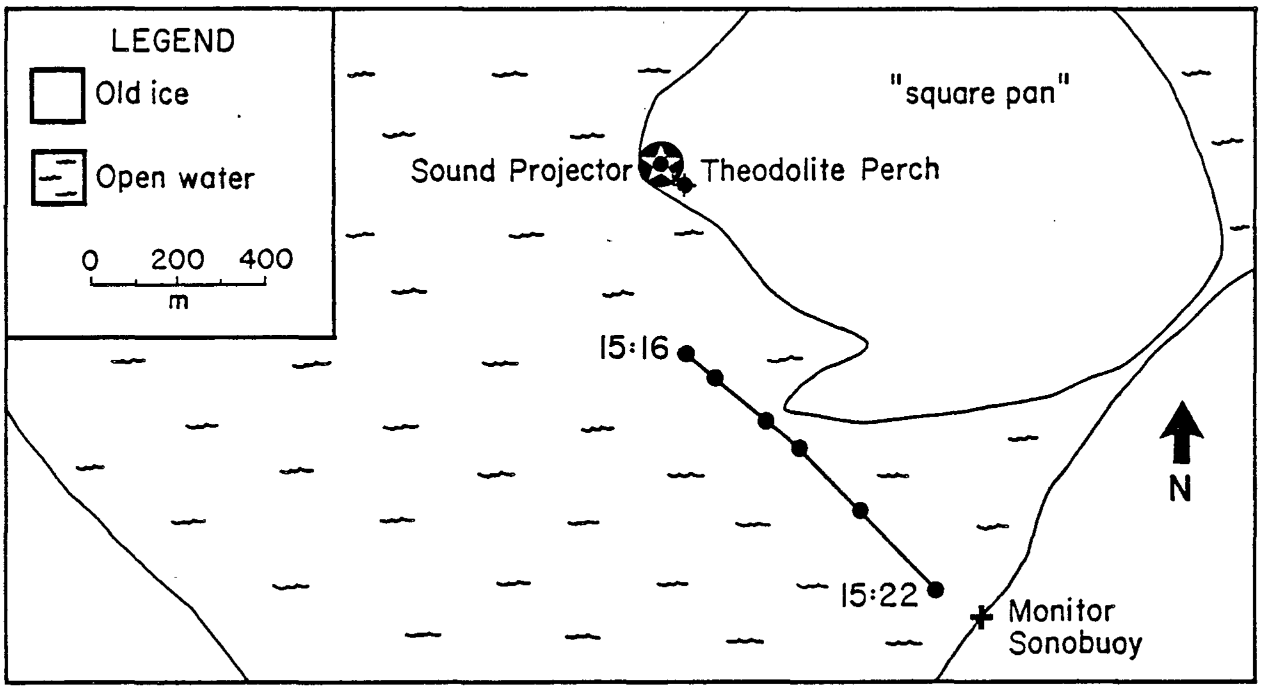


Fig. 82. Track of a white whale observed by ice-based observers during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 19 May 1989. Whale positions are plotted from theodolite readings relative to the projector.

23 May 1989

Drilling sounds were projected into a lead from 14:09 to 19:06. Small numbers of white whales moved through the general area of the sound projector throughout the day, but only four groups containing 7 whales passed within view of the ice-based observers. The aerial crew observed many additional white whales during intervals between surfacings of bowhead whales, but white whales were observed only when it was believed that the bowheads under observation were unlikely to surface.

Aerial Observations: A total of 6-8 white whales in groups of 1-2 were sighted from 15:45 to 15:52 swimming east at a location 4.8 km WNW of the operating sound projector (position "A" on Fig. 83). By 15:57-16:00, ~20 white whales were in this general area. The whales were in close-knit groups of 1-8, oriented primarily east to ESE and moving at slow to medium speeds. A few whales stopped and milled briefly but after 1-2 min they continued their eastward movements toward the open water areas marked "B" and "C" on Figure 83. They moved through these and other smaller open water areas among the brash, and around 16:45 they started to arrive at area "D", about 1.3 km north of the operating projector (Fig. 83). A few white whales (at least 3-5) moved along a more southerly corridor and arrived at "F" on Figure 83; we did not circle near these whales.

Between 17:00 and 18:30, ~50 white whales in a long strung-out group passed position "D" and approached the projector from the north (Fig. 83). This group included the white whales described above plus others that arrived later. After passing "D", they headed S to SSE through the open lead at medium speed until they were ~600 m N to NNE of the projector. They slowed and then stopped as they approached the north edge of the pan supporting the projector. The whales were ~500 m from the projector at this point, but not visible to the ice-based observers because of the intervening ice. A few whales milled (swam in circles) as they approached the pan, but none turned north. After resting for ~12-20 min, the whales disappeared southward under the ice. It is uncertain whether the hesitation north of the pan supporting the projector was related to the presence of the drilling sounds, or whether the behavior was a normal antecedent to a dive beneath several hundred meters of ice.

The whales resurfaced in a long, narrow E-W crack SE of the projector ("G" on Fig. 83). Some whales surfaced as close as 300 m SSE of the projector. Their CPA position would have been ~175 m to the east of the projector if they traveled under the ice in a straight line. However, most whales surfaced about 200-300 m farther east along the crack, making their assumed closest point of approach to the projector ~200-300 m.

Ice-based Observations: All white whales seen by the ice-based crew were south to west of the projector and headed southeast toward a lead along the south side of the pan with the projector (Fig. 83). Before the projector started operating, a single whale and a mother/yearling pair were seen 100 m and 50 m

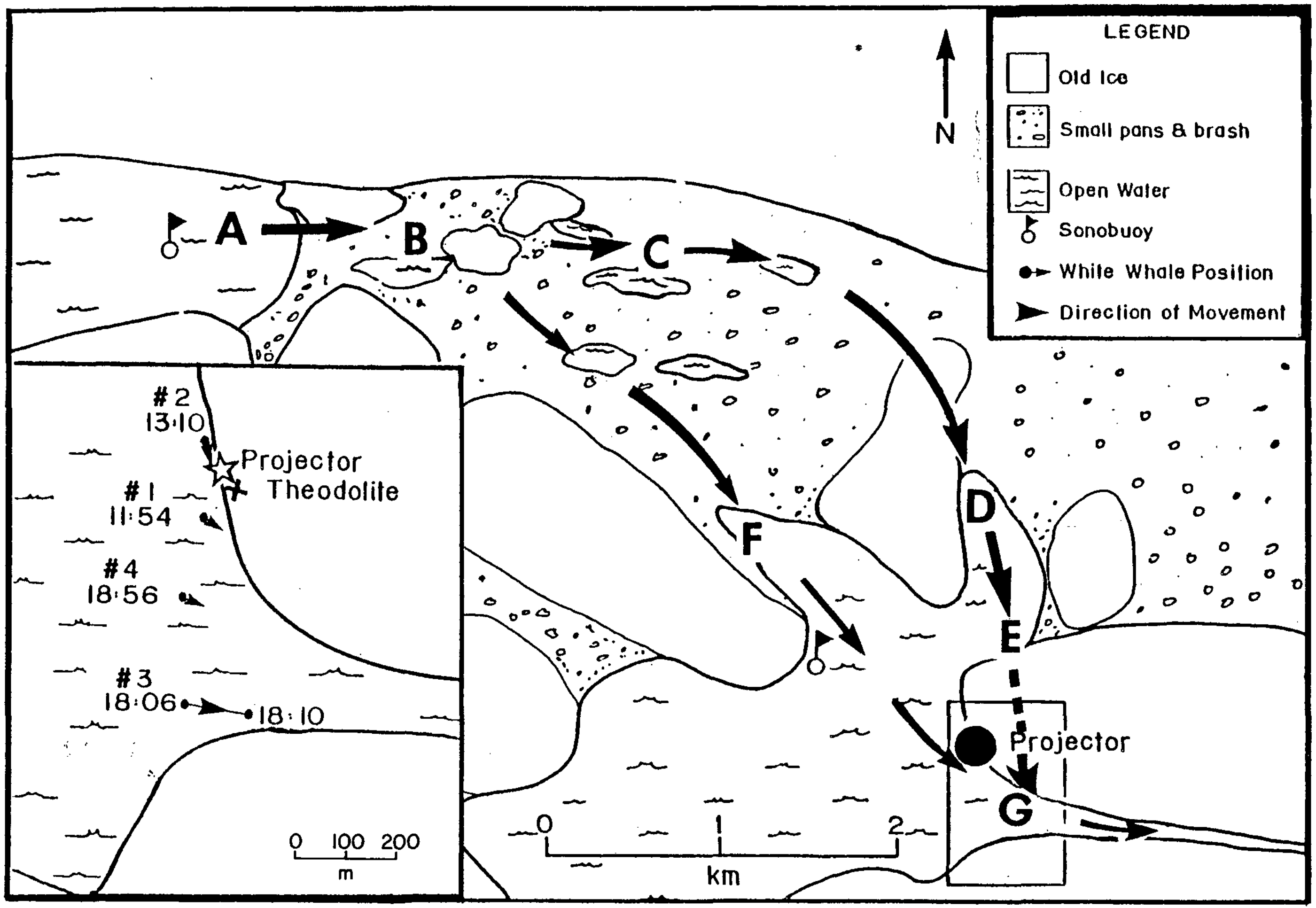


Fig. 83. Ice conditions, white whale sightings, and white whale travel corridors relative to the sound projector during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 23 May 1989. Positions shown in the inset map are based on visual estimates by the ice-based observers. Whale #1 (11:54) and #2 (13:10) were sighted before the projector was operating.

from the projector (group #1 and #2 on inset to Fig. 83). The two groups seen while the projector was operating were seen at 18:06 (2 whales) and 18:56 (adult/yearling pair). They were, respectively, about 450 and 250 m from the projector (visual estimates). The paths of groups 3 and 4 toward the projector are unknown. However, based on their headings when first seen, groups 3 and 4 were apparently near their CPA positions when first seen.

Summary: On 23 May numerous migrating white whales were observed as they swam toward the sound projector from a distance of 4.8 km WNW of it to a point 500 m north of it. The majority of these whales would have passed well to the north of the projector if they had maintained their original eastward course, but instead they curved south toward the projector when they were ~2.5 km northwest of it. This change in course was probably related to ice conditions rather than to the sounds. Many of the whales hesitated for several minutes about 500 m north of the projector, but then continued past it at CPA distances of ~175-300 m.

Received Noise: The broadband level of drilling sounds was 111 dB at a monitoring site 1.2 km from the projector. The level in the strongest 1/3-octave band, centered at 200 Hz, was 106 dB (Fig. 84A). Levels at closer distances were not monitored, but would have been at least 110-115 dB for the strongest 1/3-octave bands at locations 200 m from the projector. As noted above, this would have been close to the hearing threshold of white whales at this frequency. Also, white whales within a few hundred meters of the projector may have detected high frequency system noise (Fig. 81).

<u>27 May 1989</u>

The projector was set up at the north end of a lead ~1.1 km wide. This lead was oriented SSW/NNE, and was located amidst pack ice a few kilometers north of the main E-W lead along the landfast ice edge (Fig. 67 on p. 193; Fig. 85). Drilling sounds were projected from 12:58 to 15:42. No white whales were observed from the aircraft during behavior observation sessions on this date, but 14 white whales in 3 groups were seen by the ice-based observers.

From 14:46 to 15:02, a single white whale was observed as it travelled NE up the lead at medium speed. No other data on its position were obtained.

The second group, including 3 adults and 2 yearlings, was first sighted at 15:05 traveling NE at medium speed along the ice edge on the opposite side of the lead. They were 1080 m south of the projector (theodolite measurement). At 15:10 they had passed their closest point of approach and were headed NE, 1100 m ESE of the projector. They were last sighted at 15:16, still heading NE and following the ice edge 1.4 km from the projector.

The third group consisted of 8 white whales, including 3 yearlings, and was sighted behind the preceding group. They were traveling NE up the lead ~1 km from the projector (visual estimate). This group was last seen at 15:18 continuing NE (Fig. 85).

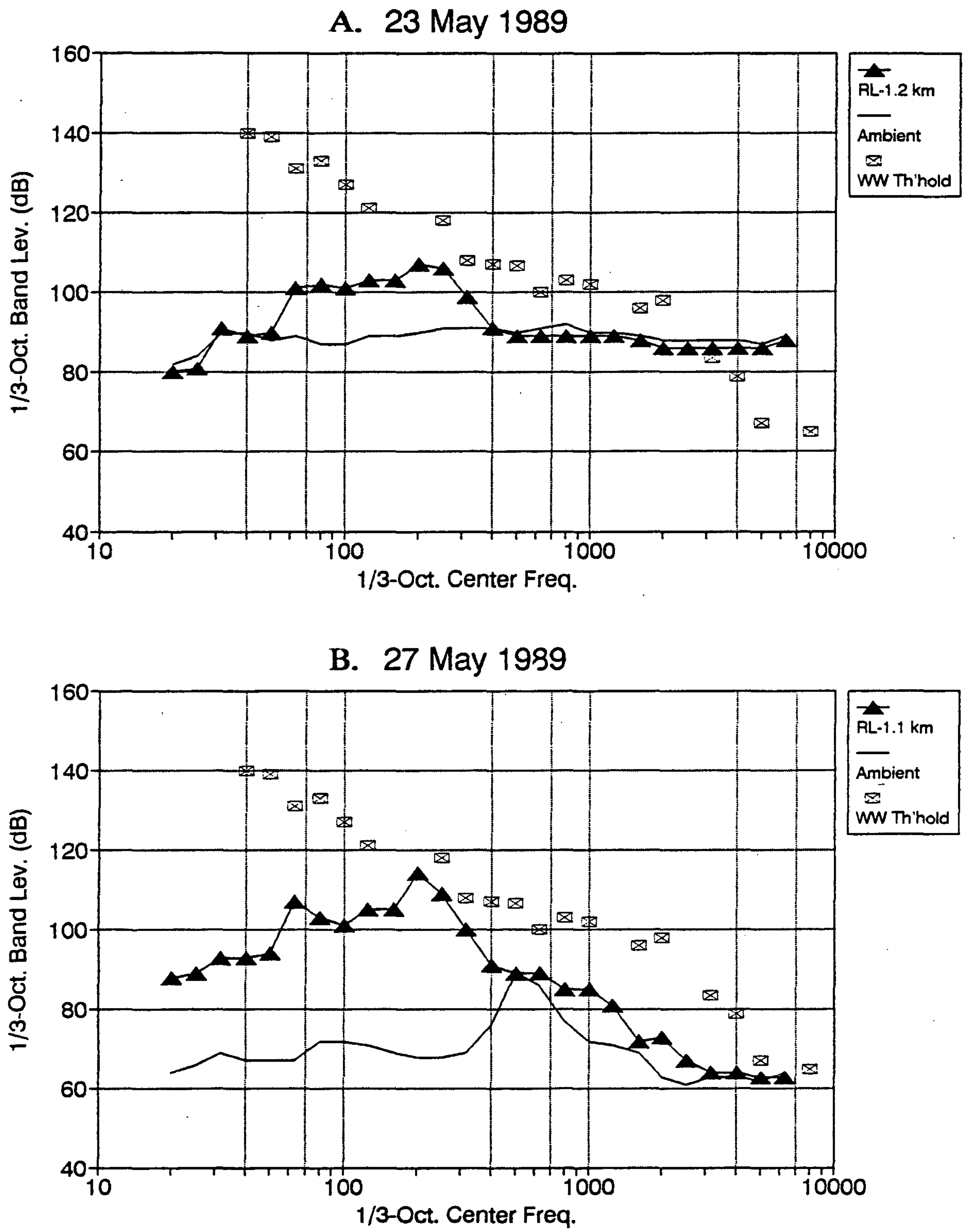


Fig. 84. Third-octave received levels of drilling sound at sonobuoys 1 km from the projector (triangles) during playbacks on 23 and 27 May 1989. Data are in dB re 1 μPa and are plotted in relation to the background ambient noise level and the hearing threshold of the white whale (squares, from White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989).

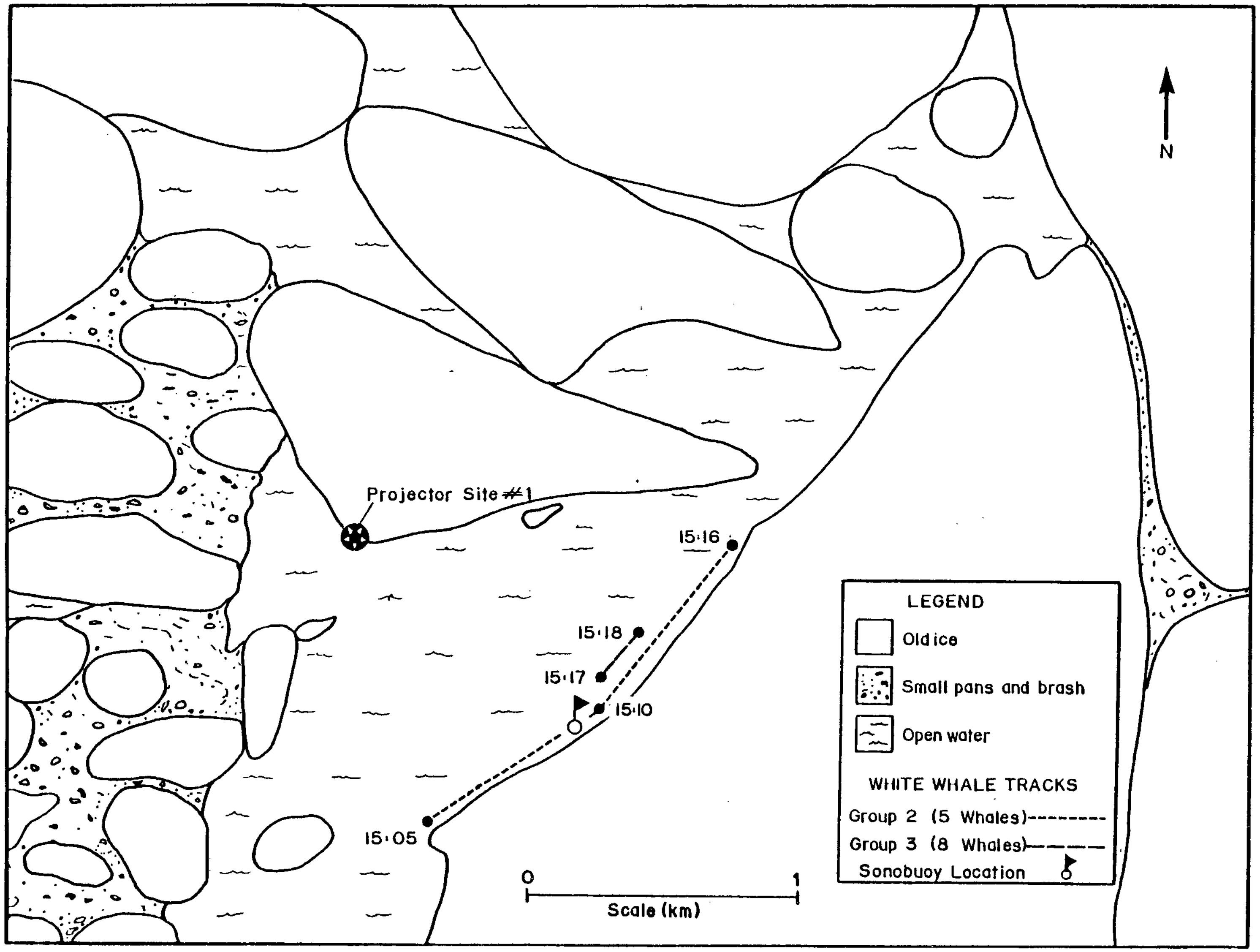


Fig. 85. Tracks of white whales recorded by ice-based observers relative to a sound projector broadcasting drilling platform sounds amidst pack ice NE of Barrow, Alaska, 27 May 1989. Positions of group 2 were measured by theodolite. Positions of group 3 were estimated by observers. See Figure 67 for an expanded view of the area.

In summary, the few white whales observed migrating NE on 27 May closely followed the ice edge on the east side of the lead, i.e. the side farthest from the projector. Their closest points of approach were ~1 km away. It is not known whether they would have passed closer to the projector site in the absence of drilling sounds, but no specific evidence of diversion or hesitation was noticed. Given the behavior observed on other days, white whales migrating through today's observation area in the absence of drilling sounds also would have been expected to move NE along the east side of the lead.

The broadband level of drilling sounds 1.1 km from the projector was 113 dB, or 24 dB above the ambient level. On a 1/3-octave basis, the strongest sounds were near 200 Hz (Fig. 84B). On this date, unlike 14, 19 or 23 May, white whales may have been able to hear the low-frequency drilling sounds at distances as great as about 1 km. The drilling sounds apparently did not attenuate quite as rapidly on this date as on 14, 19 or 23 May, when the level in the 200 Hz band diminished to 110 dB within roughly 200 m (*cf.* Fig. 80, 84A). It may have been a coincidence, but white whales were not seen as close to the projector on 27 May as on the three earlier dates.

29 May 1989

On this date, aerial observations were concentrated in an open area amidst the pack ice about 10 km west of the projector (Fig. 69, p. 197). The projected drilling sounds were not detected by a sonobuoy dropped into that open area. A total of 55 white whales were observed during behavioral observation sessions conducted from the aircraft. The first group (13) was sighted at 13:46 moving north ~9.5 km west of the operating sound projector. By 14:50, after a gap in observations, an additional 40 white whales were swimming north at medium speed in the same area of open water. These whales moved into a narrow lead that meandered eastward to the larger lead where the projector was operating (Fig. 69). At 15:52 we resighted some of these whales in a narrow lead ~5 km WNW of the projector. They were slowly swimming east, generally toward the projector. At some time thereafter these whales apparently slowed, stopped, or diverted. They were not seen by the ice-based crew, who continued to watch for them until 19:47. No white whales were seen by the ice-based crew on this date while the projector was operating.

All White Whale Observations Combined

We observed migrating white whales close to the source of drilling noise on four dates: 14, 19, 23 and 27 May. On three of these dates, at least a few whales came within 175-225 m of the projector. On one of these three days (14 May), a few white whales came even closer--within 50-75 m of the projector. On the fourth day, several white whales migrated past the projector at CPA distances near 1 km. In general, white whales that were migrating toward the projector appeared to travel unhesitatingly toward it until they came within a few hundred meters. Some of those whose paths came within a few hundred meters continued past the projector without apparent hesitation or turning. However, others definitely did react temporarily at distances on the order of 200-400 m.

There was clear evidence of short-term behavioral reactions on one day--14 May. On that occasion, an unknown but substantial proportion of the white whales that came within 200-400 m of the operating projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was brief in the few cases that we could observe in detail. (We were observing bowheads at the same time.) After several minutes of interrupted migration, the whales continued past the projector, in some cases passing within 50-100 m of it. On all three of the days when white whales were seen passing within ~225 m of the projector, there was enough open water such that they could have given the projector a wider berth while remaining within the same lead.

We suspect that the apparent lack of reactions of white whales to the drilling sounds at distances greater than 200-400 m was related to the poor hearing sensitivity of this species at the low frequencies where the drilling sounds were concentrated. On most days in May 1989, the received 1/3-octave levels of the low-frequency drilling sounds were less than the measured hearing sensitivity of white whales at all distances beyond about 200 m (Fig. 81). Interestingly, on one day when the drilling sounds attenuated less rapidly (27 May, Fig. 84B), no white whales were seen within 1 km of the projector.

Some higher frequency sound apparently was emitted by the projector during playbacks. This was system noise, not recorded industrial sound *per se* (p. 99). This noise was not strong enough to raise the third-octave levels as received about 1 km from the projector above the corresponding ambient levels (Fig. 80, 84). However, it apparently did exceed the ambient level at closer distances, and probably was detectable by white whales within a few hundred meters of the projector (Fig. 81). Thus, we do not know whether the white whales that reacted when within a few hundred meters of the projector were reacting to low-frequency drilling noise, to the much weaker high-frequency noise that was probably projected into the water, or to visual cues. In any case, they apparently did not react until they were quite close to the projector.

These results provide evidence about the seemingly low sensitivity of white whales to the one type of drilling sound used in the 1989 experiments. However, the sample sizes were low. Also, many of the observations of white whales were less systematic than desirable. On the two occasions when many white whales approached the projector (14 and 23 May), most of our effort had to be devoted to the bowhead whales that were present simultaneously. Hence, additional replications of the types of experiments conducted in 1989 are desirable. This work should be done before the hypotheses listed early in this report are evaluated and before firm conclusions are drawn.

The 1989 results refer to the reactions of migrating white whales to one particular *experimental* situation. It is of interest to assess how white whales might have reacted to an actual drillsite emitting noise like the *Karluk* noise. Considering the 20-1000 Hz band, sounds received near the projector were apparently weaker than those near the actual *Karluk* drillsite at distances within ~200 m, similar at 200-500 m, and stronger than those near the actual drillsite at distances beyond ~500 m (Fig. 34, p. 103). The projector did not adequately reproduce the low frequency components of the actual *Karluk* sounds (see p. 99). However, this was probably not a significant limitation given the poor sensitivity of white whales to low frequency sounds (Fig. 6, p. 14). Some white whales reacted temporarily to the projected sounds at distances on the order of a few hundred meters. Received levels (20-1000 Hz band) at those distances from the projector were similar to those at corresponding distances from the actual drillsite (Fig. 34). The higher levels of very low frequency noise (<50 Hz) near the actual drillsite than near the projector were probably unimportant to white whales, given their poor sensitivity at low frequencies.

Hence, for white whales, acoustic reaction distances near a shallow-water drillsite like *Karluk* are predicted to be similar to those observed in our tests. Reaction distances near the actual drillsite might, in fact, be less than those near the projector if the observed reactions were to the high-frequency system noise rather than the drilling noise *per se*. This high-frequency noise would not be present near the actual drillsite.

The above results and discussion concern reactions of white whales to one particular type of drilling noise that was continuous and concentrated at low frequencies. Sensitivity to other types of sounds associated with oil exploration or production may differ. Some sources, e.g. a bottom-founded caisson, may emit considerably less noise than the *Karluk* drillsite or our projector, at least at the frequencies important to white whales (Hall and Francine 1990). The acoustic zone of influence around such a "quiet" source would be expected to be smaller than that around a drillsite like *Karluk*.

Noise from other sources, e.g. icebreakers working on ice, may be stronger and more variable, with more energy at moderately high frequencies (Fig. 24, p. 85). There are many reports that cetaceans react more strongly to variable than to continuous noises (Richardson et al. 1989). Also, the hearing sensitivity of white whales improves greatly with increasing frequency (Awbrey et al. 1988; Johnson et al. 1989; Fig. 6). Thus, reaction distances are likely to be greater in the cases of industry noises containing higher frequency components. In the Canadian high arctic during spring, migrating white whales react strongly to noise from ships and icebreakers tens of kilometers away (LGL and Greeneridge 1986; Cosens and Dueck 1988). To understand the effects of industrial noise on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989.

A further reason for caution in interpreting these results is that we tested the reactions of whales to drilling platform noise, but not to any other stimuli associated with it. An actual industrial site would differ greatly in visual characteristics. Non-acoustic stimuli are unlikely to be important if whales react to noise at long distances from the source, but may be important in the absence of long-distance acoustic effects. If white whales within some distance of an industrial site are sensitive to visual stimuli or perhaps odor, they might react differently to the actual site than to a playback (however realistic) of its noise. Also, white whales--unlike bowheads--have good high-frequency echolocation abilities. This ability probably would not be masked by the low frequency sounds projected during our playbacks (Johnson et al. 1989). The echo characteristics of an actual industrial source would be very different than those of our projector. For all of these reasons, white whales close to an actual industrial site might react differently than they do to its noise alone. However, we doubt that echolocation or non-acoustic effects would be important at distances exceeding a few hundred meters.

White Whale Reactions to Aircraft

Specific objective 5 requires us to determine the reactions of white whales to helicopter overflights. Specific objective 6 includes a requirement to determine reactions to other sources of disturbance. During May 1989, we noticed several occasions when white whales may have been reacting to the Twin Otter observation aircraft or to the Bell 212 helicopter. The following subsections describe occasions when overt reactions were noted or when aircraft altitude was low and reactions might have been expected. We do not describe the many occasions when we flew over white whales at altitudes ≥457 m ASL and saw no reactions.

Reactions to Twin Otter

We observed responses of white whales to overflights of the Twin Otter on three occasions in May 1989. *(1)* On 14 May, an adult white whale accompanied by a subadult rolled slightly and looked up at the aircraft as it flew over at 260 m (860 ft) ASL. *(2)* On 24 May, a group of seven white whales dove abruptly and steeply when the aircraft flew almost directly over them at 200 m (650 ft) while circling bowheads. *(3)* On 29 May, one white whale among a group of 13 adults looked up at the aircraft as it passed over at 457 m ASL; again, the aircraft was circling bowheads at the time.

Reactions to Bell 212 Helicopter

The behavior of white whales exposed to close approaches by the helicopter were observed on three occasions.

On 16 May, the ice-based observers were watching a group of three white whales as the helicopter passed within 500 m laterally at 15-30 m ASL. The whales remained at the surface and continued on their original NNE heading. No overt reaction was noticed.

On 17 May, the ice-based crew observed six groups of white whales between 16:58 and 17:40. Two of these groups were overflown by the Bell 212 while it was flying back and forth over a pair of hydrophones. The helicopter was at 152 m and 457 m ASL when it flew over these groups; both dove immediately. These groups dove 20-50 m before reaching the end of the lead in which they were swimming, whereas other groups that were not disturbed did not dive until they were within a few meters of the ice. Thus, the two groups overflown by the Bell 212 very likely dove in response to the helicopter.

On 26 May, a single white whale dove rapidly and steeply when the Bell 212 flew 50 m to the side at 120 m ASL and at cruise speed while en route to Barrow.

These few anecdotal observations are generally consistent with previous observations of white whales exposed to aircraft overflights (Richardson et al. 1989). Reactions are variable. Some individuals show no overt response. Others look upward at the passing aircraft. Some dive abruptly as the aircraft passes overhead. It is not known whether these reactions are to the noise from the aircraft or to visible cues.

REACTIONS OF SEALS TO PLAYBACKS

When they were not busy observing bowhead and white whales, the ice-based observers also recorded the distribution and behavior of ringed and bearded seals near the sound projector. A total of 69 seals were observed; 60 were seen while the projector was broadcasting drilling platform sounds or test tones, and 9 were recorded when the projector was not operating (Table 26). The majority (59) of these seals were alone; five groups, each consisting of two seals, were seen.

Table 26. Closest point of approach of seals to **(A)** a sound projector broadcasting drilling platform sounds and **(B)** a quiet projector. Sightings were made by the ice-based crew and include distances estimated visually and distances determined using a theodolite.

	A. Projector Operating			B. Projector Off		
Closest Point of Approach (m)	Ringed Seal	Bearded Seal	Unid. Seal	Ringed Seal	Bearded Seal	Unid. Seal
<50	14	4	2	3	1	1
50-99	3	3	0	2	1	0
100-149	3	7	1	1	0	0
150-199	2	2	0	0	0	0
>200	7	7	2	0	0	0
Unknown	1	1	1	0	0	0
Total	30	24	6	6	2	1

Few seals (9) were noticed when the projector was not operating, probably because the observers were usually busy setting up or dismantling equipment at those times. During quiet periods, seals were seen to approach as close as 10 m (ringed seal) from the projector.

While the projector was operating, five ringed seals (3 singles and a pair) approached to ~25 m (visual estimates) from the projector; 33% of the seals sighted (20 of 60) approached within 50 m of the projector (Table 26). Reactions of ringed and bearded seals may have differed. Of the seals seen while the projector was operating, ringed seals tended to be closer to the projector ($chi^2 = 5.40$; $df = 1$; $P<0.05$). This difference is difficult to interpret. It could have been at least partly artifactual, given that bearded seals are more visible at long distances. However, it is possible that ringed seals were attracted to the operating projector, or perhaps to the appearance of the ice camp. Almost half of the ringed seals (14 of 30) seen while the projector was operating approached within 50 m. Some of these were initially recorded farther from the projector, and approached while being observed.

The most extensive track of a ringed seal was obtained on 19 May between 17:11 and 17:18 (Fig. 86). Locations were measured by theodolite on nine occasions when the seal surfaced. Durations of dives between surfacings ranged

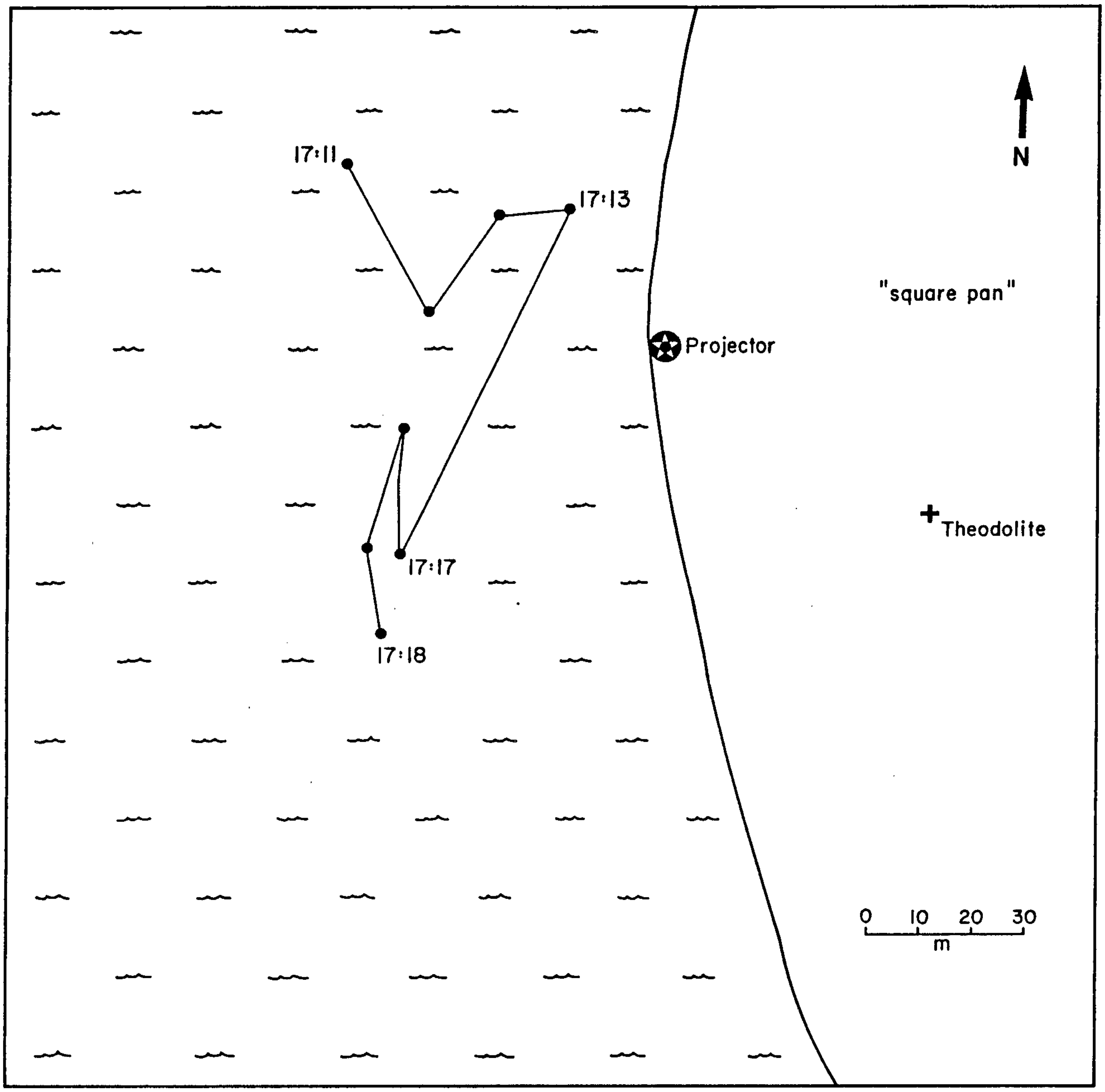


Fig. 86. Track of a ringed seal observed by ice-based observers during a playback of drilling platform sounds amidst pack ice NE of Barrow, Alaska, 19 May 1989. Seal positions are plotted from theodolite readings relative to the projector.

from 10 to 220 s. The ringed seal was first sighted at 17:11, 68 m WNW of the operating projector (Fig. 86). When next sighted, 30 s later, the seal had moved SE and had approached to within 44 m of the projector. The seal then moved to the NNE and ENE and gradually approached to within 31 m of the projector at 17:13 via a semi-circular path (Fig. 86). This was the closest observed point of approach of this seal to the projector. At 17:17 the seal surfaced 64 m SW of the projector after a dive of 220 s. It presumably passed closer to the projector between 17:13 and 17:17. It then surfaced north of this position twice, following short dives, before it turned SSW and S. It was last sighted at 17:18 traveling southward 78 m SW of the projector. This seal apparently altered its initial course to more closely approach the projector, or the ice camp in general, before it continued on its course.

A possible disturbance reaction of a bearded seal was recorded on 23 May. This observation is difficult to interpret because one of the ice crew was walking along the ice edge during the observation. The bearded seal initially approached the projector (and observer) from 250 to 100 m. The seal remained on the surface and intermittently splashed violently.

Although all observations were necessarily of seals at the surface of the water, the seals also dived out of sight. During their dives they were exposed to high levels of drilling sounds. If seals dove down to depths of ~15 m or more, they would have been exposed to broadband received levels of about 138 dB re 1 μPa at a distance of 20 m from the projector, and 130 dB at 50 m. These estimates are based on the known source level of ~164 dB re 1 μPa-m and an assumption of spherical spreading over the short distances relevant here. The hearing sensitivity of the ringed seal has been measured at 1 kHz and above (Terhune and Ronald 1975), but there are no data on the hearing sensitivity of any species of hair seal at frequencies below 760 Hz (reviewed in Richardson et al. 1989). The absolute threshold of the ringed seal at 1 kHz is ~75 dB re 1 μPa. The received level of the projected sounds in the 1/3-octave band centered at 1 kHz was above 75 dB out to distances of a few hundred meters (Fig. 81). Sound components near 1 kHz would have been strong at all depths greater than about a meter. Hence, regardless of their hearing sensitivity at low frequencies, ringed seals within a few hundred meters of the operating projector probably could hear the projected sounds.

In summary, ringed and bearded seals often were seen within 50 m of the operating sound projector. When they dove, they were exposed to strong drilling sounds. We surmise that ringed seals would have been able to hear these sounds at distances as great as a few hundred meters. Despite this, seals approached the ice camp and operating projector to much closer distances. Ringed seals, in particular, may have been attracted out of curiosity. It is uncertain whether they were attracted by the projected sounds or by other stimuli, visible or acoustic. Seals may have avoided very close approach to the projector, but if so the zone of exclusion appeared to be very small (radius ≤25 m).

SUMMARY AND CONCLUSIONS

The helicopter-supported crew worked from the ice on 18 days between 29 April and 30 May 1989. They conducted sound transmission loss experiments on five days, aircraft noise measurements on two days, and projected drilling noise into the water for several hours on each of 11 days. On five of these days, bowhead whales were observed within the area ensonified by the projector. On four days, white whales were also observed near the operating projector. Whales near the operating projector were observed from the ice on two dates, and from both the ice and the air on three dates. Overall, the aircraft crew conducted reconnaissance surveys on 24 days from 1 to 30 May, behavioral observations on 10 days, and photogrammetry on 8 days.

Physical Acoustics

Underwater noise from the *Karluk* drillsite, on a grounded ice pad, was concentrated below 300 Hz. Infrasonic components of the *Karluk* sounds--those below 10 Hz--were not studied, and may have been significant. Most components of the noise above 10 Hz had diminished below background levels after propagating only 2 km through the shallow (6-7 m), ice-covered waters. However, tones at 25 Hz and 294 Hz were still evident at that range.

As expected, helicopter noise contained more tonal components than did Twin Otter noise. Helicopter noise was usually stronger at 3 m depth than at 18 m, but this was not evident for the Twin Otter. Underwater noise increased and decreased more gradually when the aircraft was high than when it was low. The peak level, recorded when the aircraft was overhead, was higher when the aircraft was low than when it was high. All of these trends are consistent with theory and previous measurements. However, there was evidence that the presence of ice had a modifying influence on some of these trends.

Ambient noise was recorded in small to large open areas amidst the pack ice, and occasionally through thin ice covering recently-refrozen leads. No measurements were obtained during periods of strong wind. The ambient noise was usually dominated by ice noises, wave slap, and marine mammal calls. Bearded seal calls were ubiquitous and often strong; white whale calls were also heard commonly. Bowhead calls were less common. Most measurements of ambient noise were averaged over 8.5 s. Much of the variability in ambient noise, especially above about 500 Hz, was attributable to the variable occurrence and levels of marine mammal calls in these 8.5 s samples.

When no sounds were being projected, tonal sounds from the generator used to power the underwater projector were detectable underwater (18 m deep) at distances as great as 400 m, but not at 1 km. These tones consisted of a harmonic family with fundamental frequency 60 Hz. However, when the projector was in operation, the generator sounds were much less intense than the projected sounds at corresponding frequencies. Hence, the generator would not have been audible to whales during playbacks.

During playback experiments, *Karluk* drilling platform noise was projected into the water at a source level of about 164 dB re 1 μPa. Received levels of the projected drilling noise were strong at distances within ~1 km of the projector. The drilling sound was usually weakly detectable out to distances of about 4-5 km, and occasionally to 9-10 km but not farther than that.

During noise propagation tests, pure tones often were detectable about twice as far away as were the *Karluk* sounds (typically 9-18 km for tones vs. 4-10 km for *Karluk* sounds). This occurred because all of the projected power was concentrated at a single frequency when tones were projected, but not when broadband drilling sounds were projected. A special matched-filter signal processing technique was effective in measuring received levels of oscillating tones at distances greater than those where they could be measured by conventional methods.

Semi-empirical Weston/Smith sound propagation models were fitted to the transmission loss data acquired during two propagation experiments. Bottom loss and ice scattering loss coefficients tended to increase with increasing frequency. At frequencies in the kilohertz range, volumetric absorption was also a factor. Underwater sound attenuated more rapidly under pack ice conditions northeast of Pt. Barrow in spring than had been found previously in largely open water conditions in the central and eastern Beaufort Sea during late summer. It is not known whether all of this difference can be attributed to the difference in ice conditions. It may also have been partly attributable to increased bottom loss in our study area. The propagation results from this study were generally consistent with those found during a previous late winter and summer study in the Chukchi Sea.

Bowhead Whales

Movements and General Behavior

Bowheads migrated northeast and east through the study area throughout late April and May 1989, often through heavy pack ice conditions. Even in late May, when a nearshore lead extended east along the landfast ice edge through the study area, the migration corridor 40-80 km ENE of Pt. Barrow was mainly along the offshore side of the lead or through the pack ice north of the lead.

Bowhead calves and their mothers were seen only in the latter half of May in 1989, and constituted the majority of the bowheads present in the last week of May. They did not migrate as strongly or consistently eastward as did other bowheads. A few mother/calf pairs traveled *west* for at least a few kilometers, based on direct observations or photoidentification. One mother/calf pair traveled only 12 km in 44 h. 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. The calves apparently were pulled along by hydrodynamic forces created by the motion of the mothers. It is not known whether the animals touched one another during this "riding" behavior. Riding has not been seen in late summer or autumn, when the calves are older and larger.

One adult seen on 24 May 1989 was closely accompanied by a presumed yearling.

Photogrammetric data showed that the bowheads without calves present in mid and late May 1989 were mainly adults (>13 m long). The mothers that were measured were 13.9-15.9 m long (n=9); calves were 4.0-5.0 m long (n=8). Four individually-recognizable adults were photographed on two or three different days in May 1989 either by ourselves or by National Marine Fisheries Service personnel. At least four adults photographed by ourselves or NMML in May 1989 had also been photographed in earlier years, including two photographed as early as 1982. One of the latter had a calf in both 1982 and 1989.

Bowheads visible under undisturbed conditions in May 1989, mainly amidst the pack ice, were engaged in traveling (migration), socializing, and resting. Several behaviors that have been observed commonly in late summer and autumn were seen only infrequently in May 1989: pre-dive flexes, fluke-out dives, and aerial activities. A few bouts of sexual activity were observed. Many bowheads apparently migrated through the study area unseen during periods of heavy ice cover and poor weather. It is not known whether the observed frequencies of behaviors in visible whales were representative of frequencies in the population as a whole.

Drilling Noise Playbacks

Because of the difficult field conditions in 1989, there were only five days when we were able to observe bowheads that were exposed to projected drilling noise. All data had to be collected from holes and leads amidst the pack ice rather than along the landfast ice edge. The number of bowheads seen near the sound projector in 1989 was too small to allow detailed statistical analysis of acoustic effects on distribution or movements. However, some noteworthy data were obtained.

Several bowheads were observed migrating east past the projector while it was broadcasting continuous drilling sounds. The closest observation was on 19 May, when one bowhead swam almost directly toward the operating projector until it was only 100-120 m away. This whale then dove. The drilling noise : ambient noise ratios 100-120 m from the projector were estimated to be S:N = 41 dB in the 20-1000 Hz band and S:N = 49 dB in one third-octave band centered at 200 Hz. On the same day, another bowhead swam almost directly toward the projector until it was 720 m away, whereupon it dove and disappeared. Two more bowheads swam past with a closest point of approach 1 km away. All of these positions were determined by theodolite. During this period the sounds received 1.1 km from the projector were monitored via a sonobuoy. The drilling sounds were quite prominent there, well above the natural background noise. Hence, it seems inevitable that all of these whales were able to hear the drilling sounds.

Similarly, on 14 May, at least three migrating bowheads passed as close as 500 m to the side of the projector while it projected continuous drilling sounds, and a fourth passed 900 m to the side. Two of these whales were observed from the circling aircraft for ~1½ hours as they swam NE and N, generally toward the projector. Again, the drilling sounds were monitored 1 km from the projector, and confirmed to be well above background noise levels there. S:N 500 m from the projector was estimated to be 13 dB in the 20-1000 Hz band and 24 dB in one third-octave band centered at 80 Hz.

The bowheads mentioned above were migrating NE past the operating sound projector, with no evidence of hesitation or diversion. However, other bowheads may have been diverted when they came that close. On 23 May, we saw a mother and calf swimming north and then west, directly away from the projector, while it emitted drilling noise. They were 1 km away when first seen, and were still heading away when last seen 5 km west of the projector. Below 350 Hz, the drilling noise was quite prominent 1 km from the projector. S:N 1 km from the projector was estimated to be 8 dB in the 20-1000 Hz band and 15 dB in one third-octave band centered at 200 Hz. However, the noise was barely detectable 5 km away, where the whales were still heading west away from the projector.

The westward travel by this pair of bowheads was inconsistent with the normal NE, E or SE movements of bowheads migrating in the study area in spring, and was suggestive of a disturbance reaction. However, we cannot be certain that these whales reacted to the sound projector. Other bowheads, particularly mothers and calves, occasionally traveled west in the absence of drilling noise. It is well known from previous studies that the sensitivity of bowheads to man-made noise varies. It is possible that there is additional variation in sensitivity in spring because some bowheads are subjected to pursuit by whaling crews before reaching our study area. Thus, it would not be surprising if some individual whales migrated past the projector at relatively close distances while other bowheads showed avoidance reactions even to quite weak industrial sounds.

In summary, only limited data have been acquired to date on reactions of bowheads to noise playbacks in spring lead systems. However, some bowheads that were visible migrating through the pack ice east of Pt. Barrow in spring tolerated low-frequency drilling noise without interrupting or diverting their migration. Some bowheads tolerated levels of industrial noise as high as or higher than the levels that elicited avoidance reactions during playbacks near summering bowheads. Other individuals *may* have reacted strongly to drilling noise no stronger than that tolerated by certain bowheads. It would be premature to generalize these few observations. In particular, it should not be assumed that all bowheads migrating in spring would tolerate sounds as strong as those a few hundred meters from the projector. The ice present near all 1989 observation sites made it impossible to determine whether some whales were reacting at greater distances. Also, it should not be assumed that bowheads would behave in the same way when exposed to other types of industrial sounds differing in spectral characteristics or source level.

Aircraft Disturbance

Only a few opportunistic observations of reactions of bowheads to aircraft were obtained in 1989. Our preliminary impression is that bowheads are no more sensitive to fixed wing aircraft like the Twin Otter during spring migration through pack ice than they are in late summer in largely open waters. In the one observed case of repeated exposure to low-altitude helicopter passes, a mother and calf bowhead did not flee, but may have dived in response to some passes. No generalizations should be drawn from these preliminary data on reactions to helicopters.

White Whales

Movements and General Behavior

Sightings of white whales were much more numerous than those of bowheads in May 1989. As previous workers have reported, white whales tended to be more widely scattered and slightly farther offshore than bowheads, but their migration corridors overlapped broadly. Most of the white whales seen were amidst the pack ice, although in late May a few were traveling east on the offshore side of the lead bordering the landfast ice edge.

Most white whales were either migrating in a generally NE direction or resting on the surface. Migrating white whales tended to follow leads or cracks, changing heading as necessary to remain within the crack. 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.

Drilling Noise Playbacks

We observed migrating white whales close to the operating projector on four dates in May 1989. On three of these dates, at least a few white whales came within ~200 m of the operating projector, including a few within 50-75 m of the projector. White whales that were 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 to the projector continued past it without apparent hesitation or turning. However, others did react temporarily to the noise (or perhaps visual cues) at distances on the order of 200-400 m.

On 14 May, a substantial proportion of the white whales that came within 200-400 m of the projector slowed down, milled, and in some cases reversed course temporarily. This interruption of migration was very obvious, but lasted only several minutes. Then the whales 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. We suspect that this was related to their poor hearing sensitivity at the low frequencies where the *Karluk* drilling sounds were concentrated. On most days during the study, received levels of the low-frequency drilling sounds (on a 1/3-octave basis) were less than the measured hearing sensitivity of white whales at all distances beyond ~200 m. This suggests that white whales may have been unable to hear the low-frequency drilling sounds at distances much beyond 200-400 m, even though the sounds were detectable by hydrophones (and audible to humans) up to several kilometers away.

These results provide preliminary evidence about the seemingly low sensitivity of white whales to the one type of continuous drilling sound used in the 1989 experiments. However, the sample sizes were small. Also, the results refer to a particular experimental situation. Some oil industry activities have higher source levels than we could simulate with a J-11 sound projector. Reaction distances are expected to be greater in such cases. Some other activities have lower source levels than did the J-11 projector.

Also, sensitivity of white whales to other types of oil industry sounds probably differs. The hearing sensitivity of white whales improves greatly with increasing frequency. Thus, reaction distances are likely to be greater in the cases of industry noises containing higher frequency components. In the Canadian high arctic, spring-migrating white whales react strongly to noise from vessels tens of kilometers away. To understand the effects of industrial noises related to oil production on spring-migrating white whales in the Beaufort Sea, we need to test their reactions to additional types of noise whose characteristics differ from those studied in 1989.

Aircraft Disturbance

Only a few opportunistic observations of the reactions of white whales to aircraft overflights were obtained in 1989. *Twin Otter*: Two white whales rolled slightly and looked up at the Twin Otter as it flew over at altitudes of 260 and 457 m ASL. A group of seven white whales dove abruptly and steeply when it flew almost directly over them at 200 m. *Bell 212*: Two groups of white whales dove immediately when the helicopter flew over at altitudes of 152 and 457 m ASL. A single white whale dove rapidly and steeply when the helicopter flew 50 m to the side at 120 m ASL. Additional data are needed before conclusions can be drawn about reactions of white whales to aircraft overflights during spring migration through the study area.

Prior to the 1989 field season, doubts had been expressed about the feasibility of a study of this type, given the logistical problems and potential for interference with whaling or other research programs. The initial 1989 phase of the study demonstrated that it is possible to conduct an experimental study of noise effects on whales migrating through leads in spring, and to do so without interfering with spring whaling.

Formal tests of the overall null versus alternate hypotheses concerning disturbance effects on migrating whales were required by specific objective 8 (p. 18). Although the 1989 data have been analyzed in this report, formal tests of the hypotheses have been deferred because of the generally low sample sizes from the 1989 experimental work. Sample sizes were small because of the difficult ice and weather conditions encountered in 1989. In a year with different weather and ice conditions, considerably larger sample sizes might be obtained.

After additional data are collected, the results of this study should be useful in assessing the acoustic effects of oil exploration and development near spring lead systems on migrating bowhead and white whales. These results should help resolve questions about possible jeopardy to bowheads if oil development proceeds near spring leads.

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APPENDIX A:

PREDICTION OF SPRING ACOUSTIC ENVIRONMENTAL CONDITIONS NEAR POINT BARROW

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This Appendix is a copy of BBN Technical Memorandum 1026, prepared for LGL and MMS prior to the 1989 field season. The purpose was to provide the background material on physical acoustics necessary to predict the radius of audibility of the sounds that were to be projected during the 1989 field season. The accuracy of some of the predictions in this memorandum was subsequently evaluated based on the results of the 1989 field measurements (see "Physical Acoustics Results" section, earlier).

1.0 Introduction

A study of the response of migrating bowhead whales to the noise from petroleum industry production activities is being planned to be conducted this spring at a site about 60 km northeast of Point Barrow. This study will use underwater acoustic playback techniques to simulate the noise produced by representative industry sources such as production platforms and icebreakers. The estimated overall source level of the playback signals will be about 165 dB re 1 uPa at 1 m. During the initial calibration period of the study, short modulated tone signals will be used to measure sound transmission conditions in the test area. These signals will also be transmitted at source levels up to 165 dB, but will be a series of short frequency-modulated tone bursts totalling about 60 seconds for each test sequence.

In planning for the field program, it is desirable to predict the sound transmission characteristics for the test signals and to estimate the expected level of underwater noise produced by ice movement and by biological sources in the area. This information would be useful to predict the effective range at which bowheads may react to the playback signal. It would also be important in predicting the level of transmission test signals propagating toward the bowhead census site and whaling sites near Point Barrow. The work described in this memorandum was performed to collect and synthesize presently available information on the expected sound transmission and ambient noise conditions at two candidate site locations.

Transmission loss (TL) information is available from studies in nearby regions. Greene (1981) reported TL measurement results for the Chukchi Sea for the conditions of 100% ice-cover in winter and 50% ice-cover in summer. Miles et al. (1987) presented the results of TL measurements in the Beaufort Sea for several near-shore locations west and east of Prudhoe Bay. These measurements were made in late summer for conditions ranging from open-water to 20% ice-cover. Clark et al. (1986) made TL measurements in the spring lead near Barrow where they were conducting acoustic research on migrating bowhead whales. No TL data relevant to the expected largely ice-covered conditions in the candidate test locations northeast of Point Barrow were found in the literature. To obtain the specific information required, mathematical propagation models were used to predict the expected sound transmission characteristics for the water depth and ice-cover conditions at the test sites and along potential transmission paths to the Barrow region. The predicted results were then compared with results obtained using the available TL data from the nearby regions in the Beaufort and Chukchi Seas.

Ambient noise data were available from the literature and from recent measurements by Holliday et al. (1980) and by Clark et al. (1986)* in open leads near Point Barrow. The ambient noise levels expected during the test period were compared with estimated signal levels at various ranges to determine the degree of potential audibility of the transmission test signals near the test locations and near the whale census location. Based on these calculations, we also comment on the expected detection distances for the broadband industrial sounds to be used in the behavioral response experiments.

The environmental conditions considered in the analysis are summarized in Section 2 of this memorandum. The results of the propagation model calculations are presented in Section 3. A comparison of the model predictions with predictions using available TL data and general conclusions are given in Section 4.

2.0 Environmental Conditions

Two potential projector sites were selected to study the influence of environmental conditions representative of (1) a region near the land-fast ice edge in relatively shallow water and (2) a region offshore in deeper water where a large stable ice floe could be used as a base for the test operations. These sites were required to be sufficiently far from the census and whaling activities near Barrow to provide high sound attenuation for the test signals but also within reasonable flying time from an operations base and staging area in Barrow. A range of 32 nm (60 km) from Point Barrow was selected after reviewing TL data obtained from measurements near Prudhoe Bay (Miles et al. 1987). This distance was estimated to provide a sufficiently high TL to prevent audibility of the test signals in the Barrow area. Figure 1A shows the

*Additional data were provided to this study by Dr. C.W. Clark including ambient noise information not analyzed for the cited reference.

two site candidates considered in the analysis. Site A is on a bearing of ENE (true) from Point Barrow with Site B on a bearing of NE (true); both are at a range of about 55 km from an assumed census site location (R) several kilometers NE of Point Barrow, the northeasternmost location where census work has been done in previous years.

2.1 Sound Transmission Conditions

The bottom profiles along Track A and Track B are shown in Fig. 1B (the vertical scale is greatly exaggerated). The bottom profiles were simplified to a series of constant slope segments for use in the propagation models. The slopes along the track seqments used in the models are as follows:

Track A, 0 - 40 km, -0.00075
40 - 55 km, -0.00027

Track B, 0 - 30 km, -0.00067
30 - 36.5 km, -0.031
36.5 - 55 km, -0.00065

In shallow water sound transmission conditions are influenced strongly not only by the sound speed gradients in the water column but also by sound transmission properties of the bottom material. For ice-covered conditions in the arctic the water near the surface is colder than the water near the bottom. This causes horizontally transmitted sound waves to be refracted upward since sound travels faster in the warmer water near the bottom. As a result ice roughness becomes an important factor influencing sound transmission since sound waves tend to reflect more often from the ice layer than from the bottom under these conditions. A representative sound speed profile for the test site locations is shown in Fig. 1C. This profile, which was used for the propagation model, shows the influence of the cold ice layer at the surface.

In spite of the upward refracting conditions existing in the water column, the acoustic properties of the bottom material retain an important influence on sound transmission, particularly at low frequencies below 500 Hz. At low frequencies sound transmitted through the bottom material contributes significantly to the total sound level received at a distant point in the water. This is particularly true in the coastal region of the Beaufort Sea where a sub-bottom layer of permafrost exists which is believed to be the cause of the low values of TL that have been measured in several areas (Miles et al. 1987). The high sound speed and low internal losses of the permafrost layer cause this layer to act as an efficient sound reflector.

It is necessary to provide information on the bottom material properties to enable the sound propagation model to compute the sound fields produced in the bottom by the propagating field in the water column. While this information was not available specifically for the two site locations, data from several surveys of nearby areas are available, e.g. Neave and Sellman (1984) and Rogers and Morack (1980). By using seismic profile information from these studies, a set of estimated bottom material profiles were obtained for use with the sound propagation model. The profile interface depths are shown in Table 1 for the two propagation tracks. In this table the layers are assumed to be relatively homogeneous between interfaces; i.e. for Track A, at the 40 km range from the sound projector, the ice layer extends from the surface to a depth of 2 m, the water layer extends from depths of 2 to 12 m, a silt-clay (mud) layer extends from depths of 12 to 17 m, and a permafrost gravel layer extends from depths of 17 to beyond 150 m (the limit of the model computations). When layer depths are changed from one profile range to the next, the model assumes that a uniform interface slope is intended and it automatically makes the changes as the computations are stepped out in range.

Table 1. Bottom Layer Profiles Used for PE Model

Track A Interface depths, m

Range(km)	ice-water	water-mud	mud-perm. froz.grav.	model end
0	2	44	55	150
40	2	12	17	150
55	3	8	11	150

Track B Interface depths, m

Range(km)	ice-water	water-mud	mud-fine sand	fine sand-sand-gravel	grav.-perm. froz.grav.*	model end
0	3	240	300	320	500	500
30	3	220	260	280	500	500
34.5	3	90	117	117	480	500
37	3	20	40	40	100	300
55	3	8	11	11	11	200

* The offshore extent of the permafrost layer is estimated to be at the 34.5 km range where the water depth is 90 m. The 500 m interface values are used for model continuity.

The ice layer interface data shown in Table 1 indicate that the ice layer was modeled as a uniform layer. While this is true for the average ice thickness, another parameter, the rms ice roughness, was also included in the model calculations. This is a measure of the roughness of the underside of the ice layer and has an important influence on sound attenuation, particularly at high frequencies. This parameter ranges from about 0.25 m for new ice to 2 m or higher for multi-year ice fields. A value of 1 m was used for most of the model calculations of this study, based on polar sea ice roughness data from LeSchack and Chang (1977) for the Beaufort Sea near Point Barrow.

2.2 Ambient Noise Conditions

Underwater ambient noise is highly variable under ice-covered conditions. For conditions of low wind and low thermal stress, ambient noise levels become much lower than under open water Sea State 0 conditions. Conversely, for high wind with broken ice conditions, or for high thermal stress conditions with solid ice cover, ambient noise levels become much higher than would be the case for open water conditions with the same wind speed. Vocalizations of marine mammals are also an important ambient noise factor in many arctic regions, including the Point Barrow area. Bearded seals, in particular, contribute significant sound in the frequency range from 300 - 2kHz during spring.

Urick (1983) provides a summary of ambient noise spectra for ice-covered regions. However the data included are mostly from deep-water arctic regions. Some ambient noise data were presented by Holliday et al. (1980) from measurements in an open lead near Barrow. Also, a tape with samples of ambient noise recorded in the lead near Barrow in 1985 was made available to this study by Dr. C.W. Clark with the approval of the North Slope Borough Department of Wildlife Management. The results of 1/3 octave analysis of sequences from this tape are shown in Fig. 2A. These results are also compared to the range of data given by Urick (1983) and to representative data from Holliday et al. (1980). The ambient noise levels in the data obtained by Clark et al. are strongly influenced by marine mammal vocalizations. In order to obtain analyses which are primarily representative of wind and ice noise, it was necessary to use very short data samples to avoid intervals dominated by marine mammal sounds. A condition with 8 - 10 in. pan ice covering 99% of the lead, with low biologic noise ("Frozen LoBio") will be considered to represent the lowest probable ambient condition that will exist near the census site during the test period. This spectrum can be seen to be comparable to the 10th percentile ambient levels reported by Urick (1983).* The open water, low biological noise condition ("OpenWat LoBio") is similar to the data reported by Holliday et al.(1980), with the exception of higher levels at low frequencies. This condition was considered by Dr. Clark to be more representative of the usual noise level in the lead (personal communication). When a long data sample was used to determine the average ambient noise level for the pan ice condition, the biological noise contributions dominate the results as shown by the "Frozen HiBio" spectrum in Fig. 2A.

A comparison of ice-related ambient noise spectra with open water ambient noise spectra is shown in Fig. 2B. In this figure the "Frozen LowBio" noise spectrum can be seen to be up to 10 dB quieter than an open water Sea State 1/2 spectrum in the mid frequency range (wind speed of 1 to 3 kts). The "OpenWat LoBio" spectrum is seen comparable to the open water Sea State 7 spectrum (wind speed of 34 to 40 kts) at low frequencies; probably because of noise generated near the ice edge.

3.0 Sound Propagation Model Procedures and Results

A preliminary study of acoustic transmission loss for open water conditions in the region of concern was made using the Weston/Smith semi-empirical analytic model (Malme et al. 1986). This was done to obtain received level estimates for the study before an appropriate under-ice propagation model became available. While the Weston/Smith Model is intended for use in areas with a uniformly sloping bottom, it can be used for multi-sloped bottoms if separate solutions are obtained over the range increment for each bottom slope and then combined using range-related scaling factors. The bottom loss parameters needed by this model were obtained from measurements at the Erik Site east of Prudhoe Bay in 1986 when there was about 20% ice cover (Miles et

*The range of an ambient noise spectrum is conveniently expressed statistically as a percentile; the actual sound is below the 10th percentile noise level 10% of the time, and below the 90th percentile 90% of the time.

al. 1987), and are as follows:

Frequency	b	$\sin\phi_c$
100 Hz	0.15	0.8
500 Hz	0.4	0.3
2 kHz	0.55	0.3

The results of this preliminary TL model study were used to compute estimated received level (Lr) characteristics for sound transmission along Tracks A and B for open water conditions using the relationship

$$Lr = Ls - TL \qquad \text{dB re 1 uPa} \qquad (1)$$

where Ls is the source level in dB re 1 uPa at 1 m from the source. The computed open water Lr characteristics using the Weston/Smith (W/S) Model are included in the figures presented in the next section.

3.1 The Parabolic Equation Model

The under-ice sound propagation modeling was done using the The Parabolic Equation Model (PE) developed for U.S. Navy applications by C. Spofford, J. Hanna, L. Dozier, and E. Holmes of Science Applications International Corporation (SAIC) and described in Naval Oceanographic Office Reports OAML-SPS-22, OAML-STD-22, and OAML-SRS-22. This model is based on the parabolic solution of the wave equation and is capable of computing sound field solutions for range-dependent conditions such as sloping or irregular bottoms and range-dependent sound velocity gradients*. It has a provision for incorporating boundary condition subroutines such as the Buck/Wilson Model for ice layers. The output of the computer model is a detailed listing of transmission loss versus range from the source for a given input frequency and source depth. Predicted TL values at several selected receiver depths can be output concurrently. The upper frequency limit of the PE Model is 1 kHz.

*The Implicit Finite Difference (IFD) Model developed by Lee and Botseas (1982), also a method of solving the parabolic equation, has been used by BBN in previous shallow water sound propagation studies. Unfortunately this model does not, at present, have any operational ice boundary condition subroutines.

The PE Model was implemented on a VAX minicomputer and tested by running a model of the Beaufort Sea area representative of some of the sites where transmission loss data were measured by Miles et al. (1987). This model incorporated bottom layer structure similar to that shown in Table 1 for Track A. Good agreement was obtained between predicted values of TL and the measured data for the two sites with water depths comparable to those for Track A (Erik and Hammerhead).

Several model runs were then made using the sound speed profile and bottom parameters appropriate for the Track A and Track B propagation paths in the planned test area. A source depth of 10 m and a receiver depth of 5 m were used for all of the model results presented here. A TL averaging program was used to smooth the output. The resulting TL information was used with Eqn. 1 to calculate the estimated received level versus range for the maximum test source level of 165 dB. This source level is the highest output available from the planned projector. It was used in the model analysis because of the anticipated need for high signal levels for the TL calibration tests to overcome expected interference from seal calls. If ambient noise conditions permit, lower signal levels may be used to obtain the needed TL data.

The received level predictions shown in Figures 3 - 6 all are based on an assumed 165 dB test tone as a source signal. These predictions are directly relevant to the late April and May periods in 1989. Special tones with source levels up to 165 dB will be projected for brief periods during these tests. These predictions are <u>not</u> directly relevant to the behavioral response experiments, in which the playback signal will be a broadband industrial sound with an overall source level of up to 165 dB. During playback the source level will be at least a few decibels lower in each 1/3 octave band, and in each critical bandwidth of a listening whale. Thus detection distances for broadband industrial sounds projected for prolonged periods during playback experiments will be less than those during the brief propagation tests modeled in Figures 3 - 6. For this and other reasons (see Section 4.0 below), the predictions in Figures 3 -6 represent "worst case" scenarios.

Initial runs using the PE Model were made for open water conditions and for two different ice roughness conditions. Figures 3A and 3B show the effect of relatively smooth ice (0.25 m rms roughness) compared with that of ice with the expected roughness in the test area (1 m rms). The figures show the estimated received level for a source level of 165 dB at Test Site A. The effect of an increase in ice roughness can be seen to be greater at 1 kHz than at 100 Hz (Fig. 3B vs. 3A). In all cases the received level is lower than the expected ambient noise level at a range of 50 km.

Figure 4A shows the results of a PE model calculation at 100 Hz for an open water condition along Track A compared with the preliminary results obtained using the semi-empirical Weston/Smith Model. In this plot the PE results have not been averaged with the output smoothing routine. The trends of the two predictions are comparable, with the PE results showing higher Lr values beyond a range of 20 km. Figure 4B, also for 100 Hz along Track A, shows the PE predictions for ice-covered conditions (1 m rms roughness) compared with the open water W/S results. Ice-cover can be seen to produce about a 10 dB predicted reduction in Lr at a range of 40 km when the PE results in Figs. 4A and 4B are compared. In both cases the Lr values are below the lowest expected ambient levels at a range of about 40 km (based on Clark et al. data).

Figures 4C and 4D show predicted received levels along Track A for 500 Hz and 1 kHz respectively. The results obtained from the PE Model for ice cover with 1 m roughness are compared with the W/S results for the open water condition.* The additional TL produced by the ice cover is more evident at these frequencies than at 100 Hz. The predicted Lr values for the 500 Hz and the 1 kHz curves for the ice-covered condition drop below the expected lowest ambient noise level at a ranges of about 38 km and 40 km respectively.

Predicted received levels along Track B for 100 Hz are shown in Figs. 5A and 5B. As shown previously in Fig. 1B, the water depths along this track are, near the projector, considerably greater than those along Track A (220 m versus 44 m). The predicted Lr results from the PE model show a large dip near the source which reaches a minimum at a range of 800 m. This results from destructive interference between the direct sound path and the bottom reflected

*The preliminary W/S Model analysis was performed using source frequencies of 100 Hz, 500 Hz, and 2 kHz. The PE Model is limited to an upper frequency of 1 kHz. The W/S Model was not rerun at 1 kHz to obtain a direct comparison with the PE output since the results are expected to be similar to those for 2 kHz.

path for a tone at 100 Hz. This effect would not be as pronounced for a broadband source with a wide frequency range. At ranges beyond 1.3 km the bottom reflected sound energy becomes dominant and the Lr curve becomes smoother with increase in range. The path interference effect is not predicted by the W/S Model which, as a result, shows higher predicted Lr values for the open water condition. The predicted steeply rising values of Lr at ranges beyond 30 km are produced by the concentrating effects of the steeply rising bottom as sound energy moves into shallow water (Fig. 1B). This increase in level is predicted by both the PE and W/S model. Note that as the shallow water region with a gradual slope is reached at a range of about 35 km, the predicted Lr values decrease rapidly. The Lr values predicted by the PE Model for the ice-covered condition can be seen to be near or below the expected lowest ambient noise level at ranges beyond about 47 km (Fig. 5B).

Figures 5C and 5D show the predicted Lr values for 500 Hz and 1 kHz along Track B based on the PE Model with 1 m ice roughness conditions. These results are again compared to the open water W/S Model predictions for 500 Hz and 2 kHz. The PE Model continues to predict a dip in Lr at a range of about 1 km due to the interaction between the direct and bottom reflected sound paths. This dip is not as deep at these frequencies as it was for the results at 100 Hz; moreover, there is also closer agreement between the PE and the W/S Model predictions in the mid-range region. The PE results do not show the rise in Lr at a range of about 30 km that is predicted by the W/S Model. The predicted Lr values for the ice-cover condition can be seen to drop below the expected lowest ambient noise level at a range of about 51 km for both the 500 Hz tone and the 1 kHz tone.

The predicted received signal levels along Track B are higher than those predicted along Track A, at least at 500 Hz and above (compare Fig. 4B,C,D with Fig. 5B,C,D). As a result, Site A is recommended as the best choice from the standpoint of obtaining the highest signal level reduction along the transmission path from the test area toward Barrow. Site A also has the smoothest transmission characteristic at short ranges since there is no irregularity due to direct and bottom path interaction. The smooth TL characteristic at Site A, particularly at 100 and 500 Hz, also would facilitate estimation of exposure levels for the playback stimulus.

4.0 Comparison of Received Level Predictions and Conclusions

Transmission loss data reported by Greene (1981) for the Chukchi Sea under winter 100% ice-cover conditions and by Miles et al. (1987) for the Beaufort Sea under late-summer 20% ice-cover conditions were used to obtain Lr estimates using Eqn. 1 with a source level of 165 dB. The resulting curves are plotted together with the spring Lr predictions using the PE Model in Figs. 6A and 6B. This was done only for Track A since the water depth near Site A (44 m) was similar to the water depths of the Greene and Miles data sets (49 m and 40 m, respectively).

The Chukchi Sea data can be seen to provide an Lr prediction that falls off more rapidly with range than the PE prediction. The higher TL in the Chukchi Sea may be the result of very rough ice cover and/or higher bottom absorption losses than in the areas studied in the Beaufort Sea. The Chukchi Sea is warmer than the Beaufort and does not have the extensive offshore sub-bottom layer of permafrost that has been found in the coastal regions of the Beaufort Sea (Selmann and Hopkins 1984). The TL data from the Erik Site in the Beaufort provide predicted Lr results which are consistent with the results predicted by the PE model considering that the PE model results are for 100% ice cover with a 1 m rms roughness where the Erik data were obtained with 20% ice cover.

The results of the model calculations presented in the preceding figures have been obtained considering a uniform depth ice layer and a constant roughness dimension. Observations of the ice conditions in the census area near Barrow have shown that large ice blocks or ridges often are grounded along the probable transmission tracks considered in this analysis. The effect of this type of ice geometry would be a reduction of the effective water column depth and an introduction of additional scattering losses. This would result in additional transmission losses, particularly at frequencies above 300 Hz. At lower frequencies a significant amount of sound energy is transmitted though water-saturated bottom sediments and, as a result, sound transmission would occur beneath grounded ice. However, if the extent of the grounded ice region covers a large number of acoustic wavelengths, as is likely along Track A, significant additional transmission loss would occur above that predicted in the model results presented in the previous figures, even for low frequencies. It is believed, therefore, that the sound transmission predictions presented in this analysis represent a minimum loss condition along the tracks considered, and especially so for Track A. It is likely that actual transmission losses will be higher because of the highly variable ice conditions that will probably exist.

Another factor which must be considered is the probable significant contribution of marine mammal vocalizations to the ambient noise level in the vicinity of the census area. The ambient noise levels used in the figures for comparison to the estimated signal levels are primarily representative of periods where wind and ice noise dominated the ambient noise spectra. As shown previously in Fig. 2, the presence of frequent bearded seal and/or bowhead vocalizations often will completely dominate the ambient spectra over wind and ice noise. Under these conditions, the test tones will become inaudible at much reduced ranges than those mentioned above. For this reason a special set of signals (hyperbolic FM slides) will be used to facilitate transmission loss measurements at the test site in the anticipated presence of numerous similar sounding marine mammal vocalizations. These signals will allow the test tones to be distinguished from biological sounds by using matched filter processing.

Another important consideration is that the sounds to be projected into the water during behavioural experiments will be broadband industrial noises, not pure tones. The preceding model results discussion pertains to test tones in which up to a 165 dB source level may be concentrated at one frequency. During behavioral experiments the 165 dB output capability of the projector will be distributed among the 1/3 octave bands in the industrial noise signal spectrum. This will mean that the output in any given 1/3 octave band will be at least several dB less than the maximum overall output level of 165 dB. Hence, the broadband industrial sounds to be projected during behavioral experiments will not be detectable as far away as the tones discussed in this memorandum.

The likely reduction in the detection range of broadband sounds relative to the 165 dB tones can be evaluated from the graphs in this memorandum by assuming a 5 - 10 dB lower source level for any one 1/3 octave band, or alternatively by raising the horizontal ambient noise lines in the graphs by 5 - 10 dB. When this is done, it can be seen that the received levels of broadband industrial noise will drop below typical ambient noise levels (excluding biological noise) at distances considerably less than those discussed above for 165 dB tones. Table 2 shows the results of this analysis.

Again, even the reduced detection distances for broadband sounds listed in the 160 dB and 155 dB columns of Table 2 are undoubtedly overestimated for most periods. Background noise levels will normally be higher than those assumed here because of the biological noise (bearded seals, bowheads). Transmission loss will often be higher than assumed here, especially along Track A, because of the presence of grounded ice and ice rougher than that assumed in the models.

Table 2. Range For 0 dB Signal/Noise Ratio for Beaufort Test Tracks Versus Source Level and Lead Condition (km)*

Test	1/3 Oct.	Ls = 165 dB		Ls = 160 dB		Ls = 155 dB		Fig.
Track	Band(Hz)	Frozen	Open	Frozen	Open	Frozen	Open	Ref.
A	100	40	21	37	16	35	12	4B
A	500	38	30	36	27	34	22	4C
A	1000	40	36	38	33	35	30	4D
B	100	47	16	45	11	44	5	5B
B	500	51	43	50	40	48	38	5C
B	1000	51	38	50	35	48	32	5D

* Based on "LoBio" ambient noise spectra from Clark et al. data using PE Model TL predictions for 100% ice cover, 1 m roughness.

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FIG. 1A TEST SITE LOCATIONS AND SOUND TRANSMISSION TRACKS

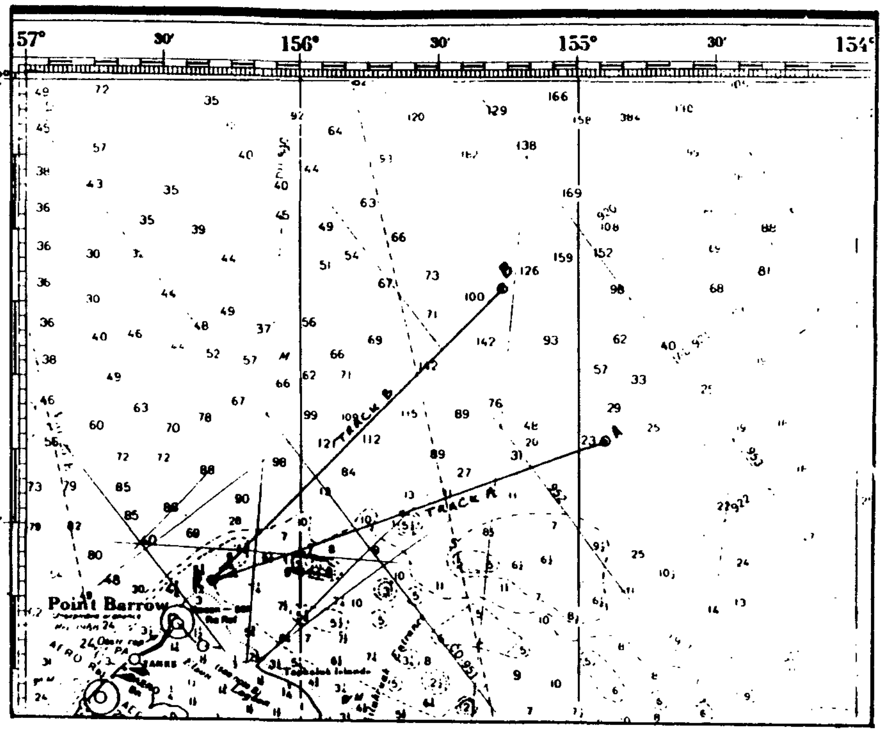

FIG. 1B PROPAGATION PATH, BOTTOM PROFILES

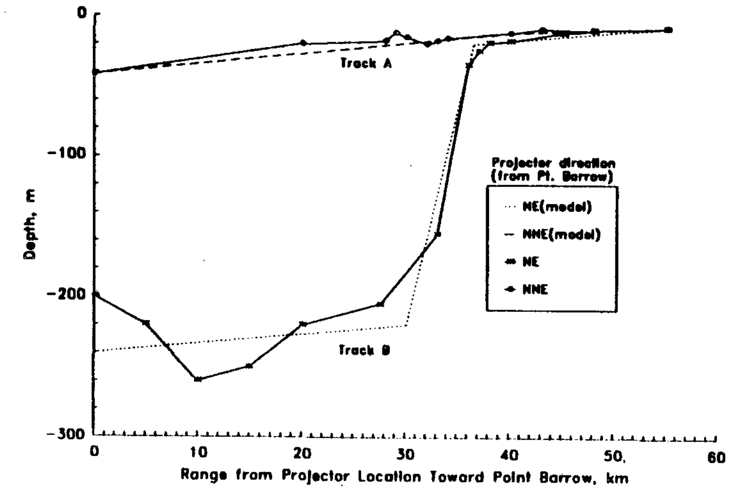

FIG. 1C ESTIMATED SOUND SPEED PROFILE FOR POINT BARROW AREA
Based on Milne 1963 and Garrison et al. 1974

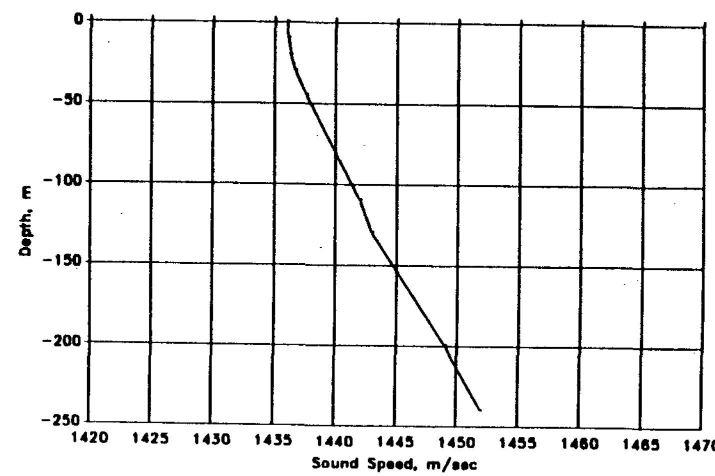

FIG. 2A AMBIENT NOISE LEVEL SPECTRA FOR ICE COVER AND OPEN LEAD CONDITIONS NEAR POINT BARROW

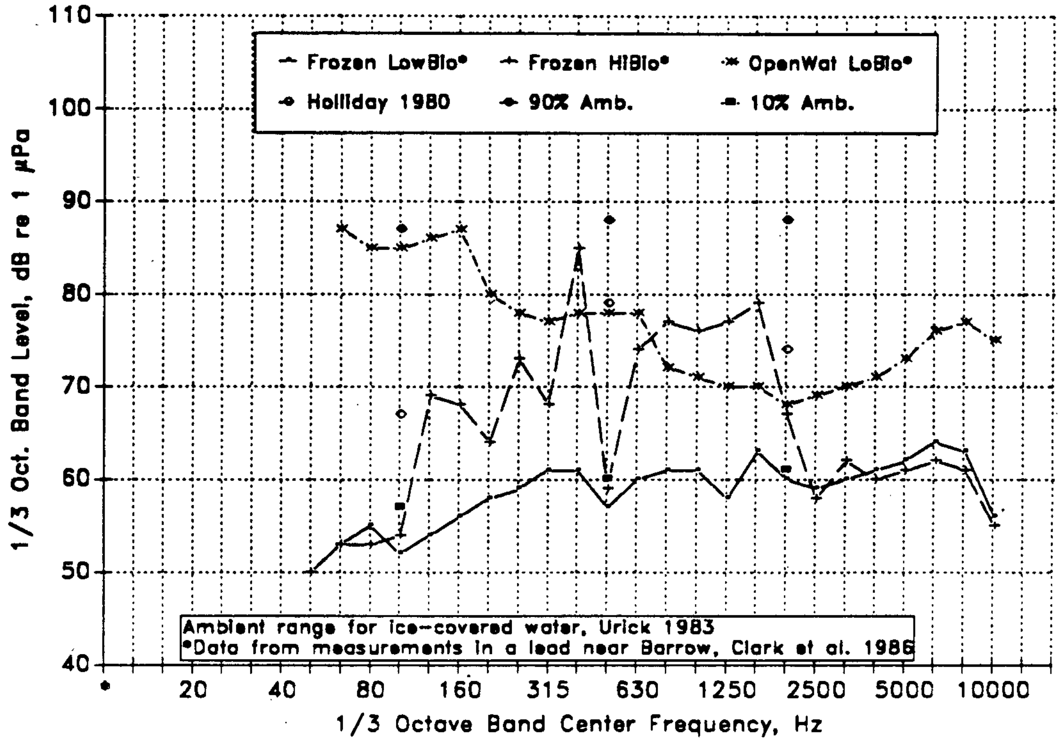

FIG. 2B AMBIENT NOISE SPECTRA MEASURED IN LEAD COMPARED WITH AMBIENT NOISE IN OPEN SHALLOW WATER

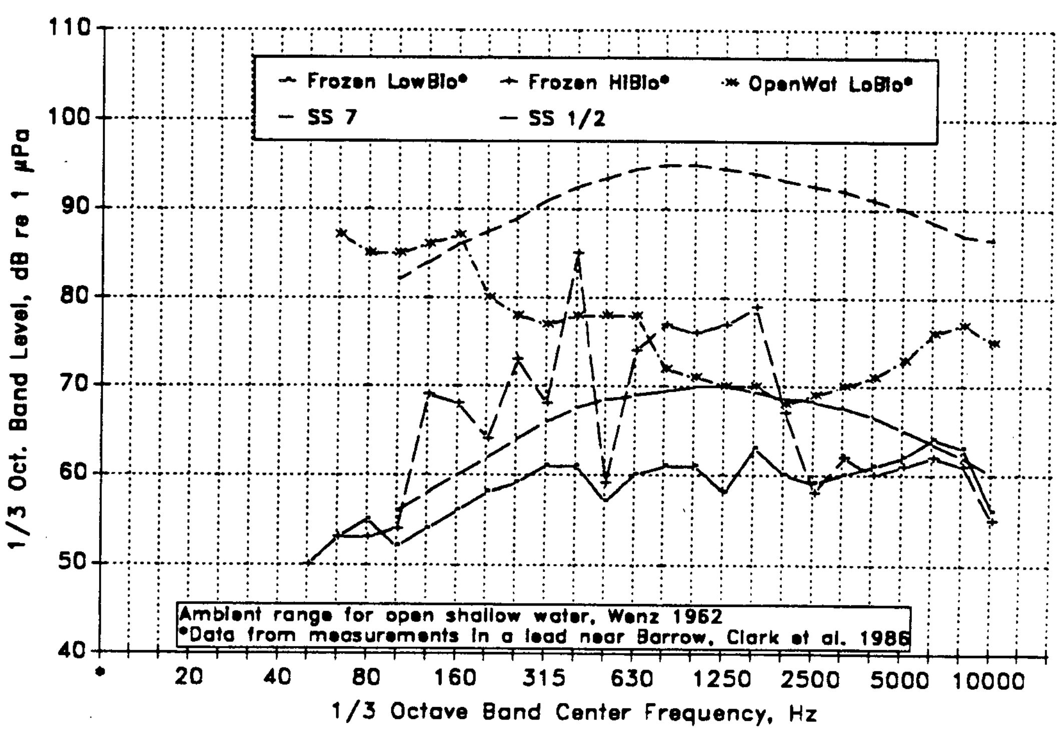

FIG. 3A ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Effect of ice roughness variation
Track A, 100 Hz – PE Model, Ls = 165 dB

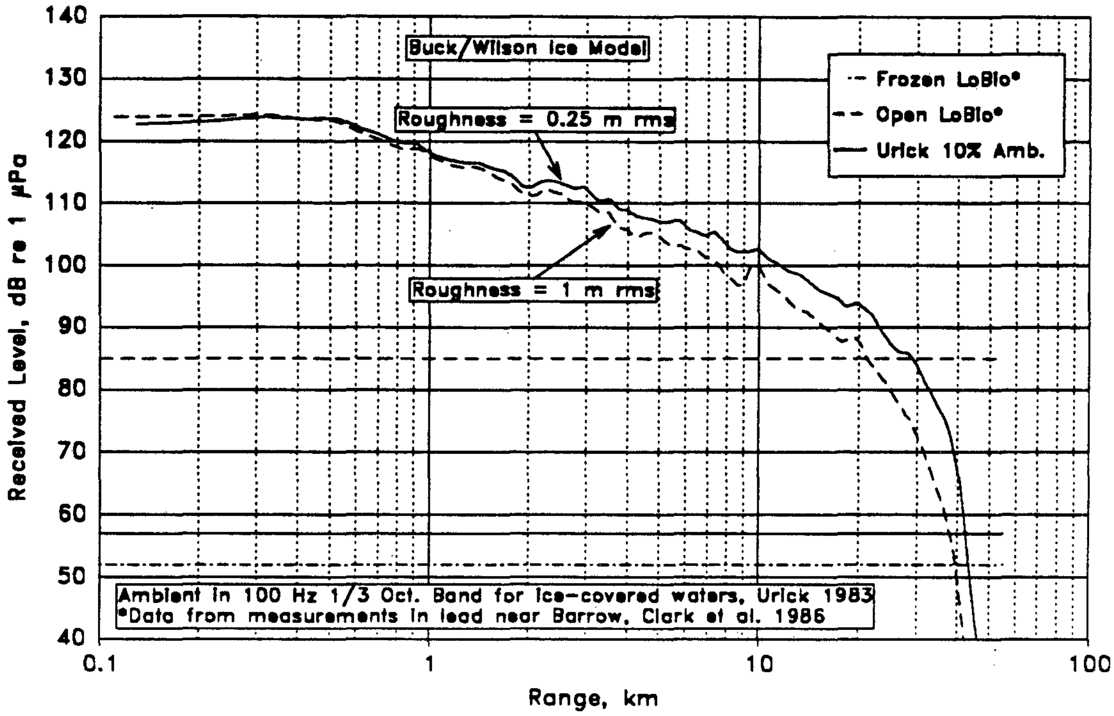

FIG. 3B ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Effect of ice roughness variation
Track A, 1 kHz – PE Model, Ls = 165 dB

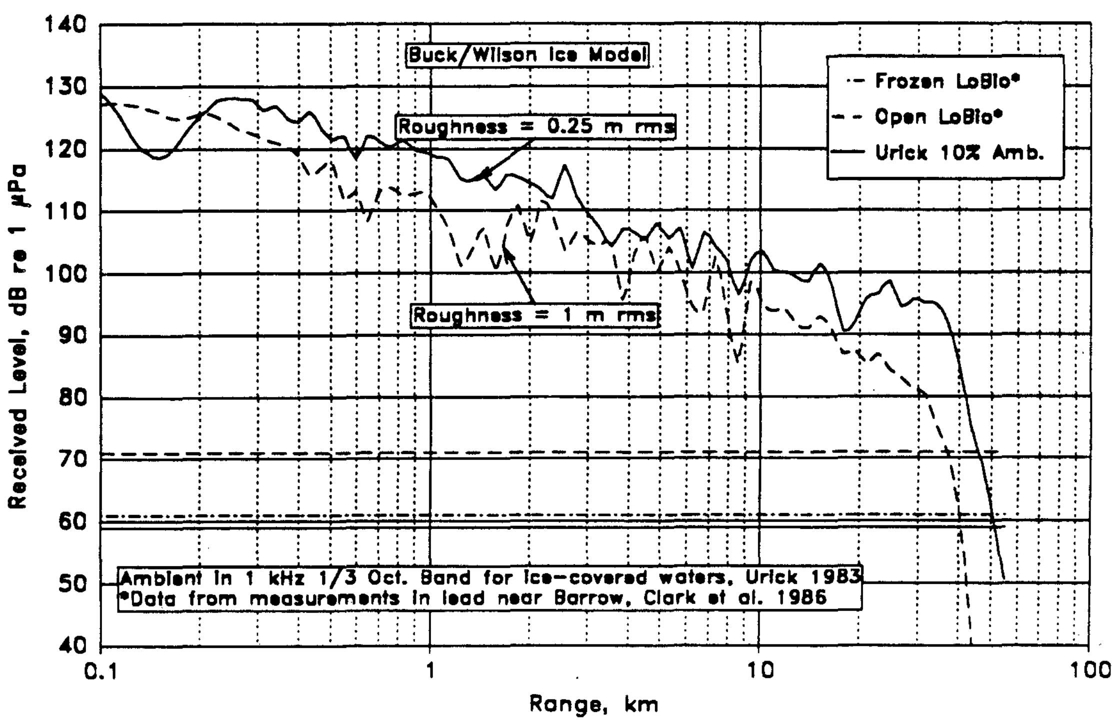

FIG. 4A ESTIMATED SOUND LEVEL FOR TRANSMISSION CALIBRATION TONE
Track A, 100 Hz Band, Ls = 165 dB, Open Water Condition

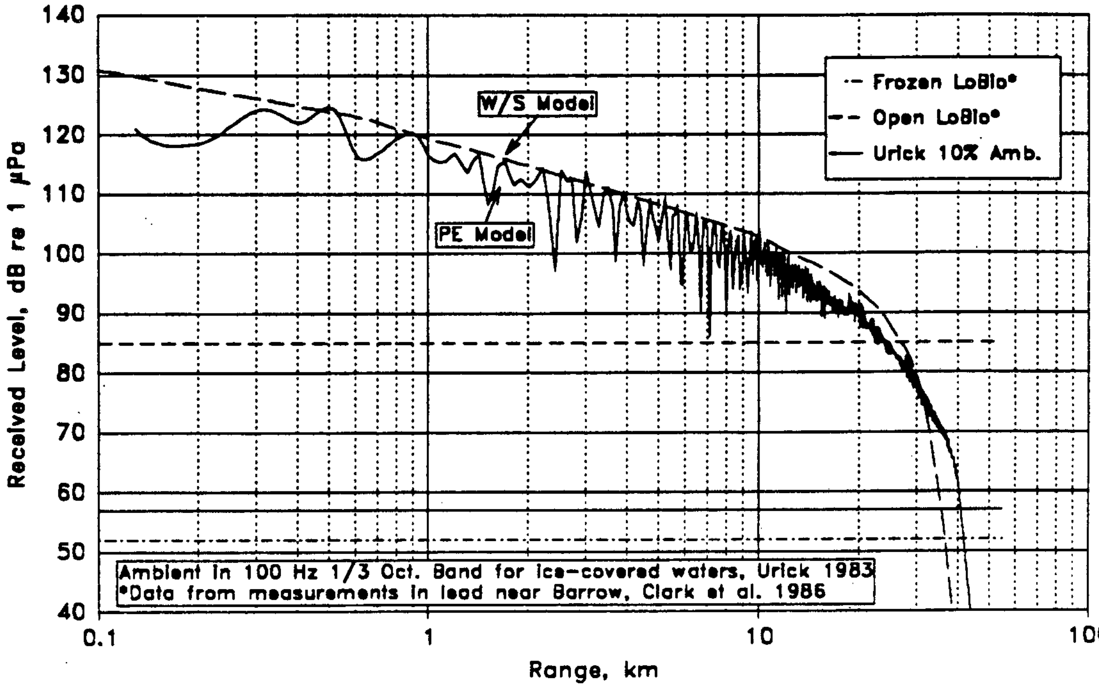

FIG. 4B ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track A, 100 Hz Band, Ls = 165 dB, PE and W/S Models

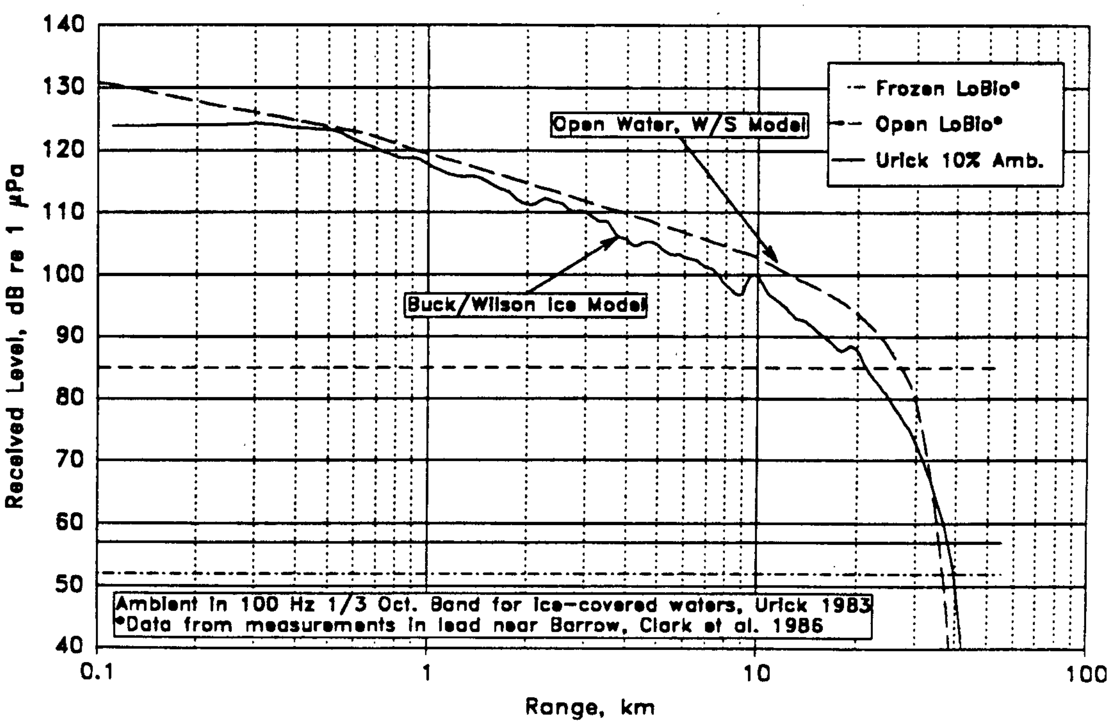

FIG. 4C ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track A, 500 Hz Band, Ls = 165 dB, PE and W/S Models

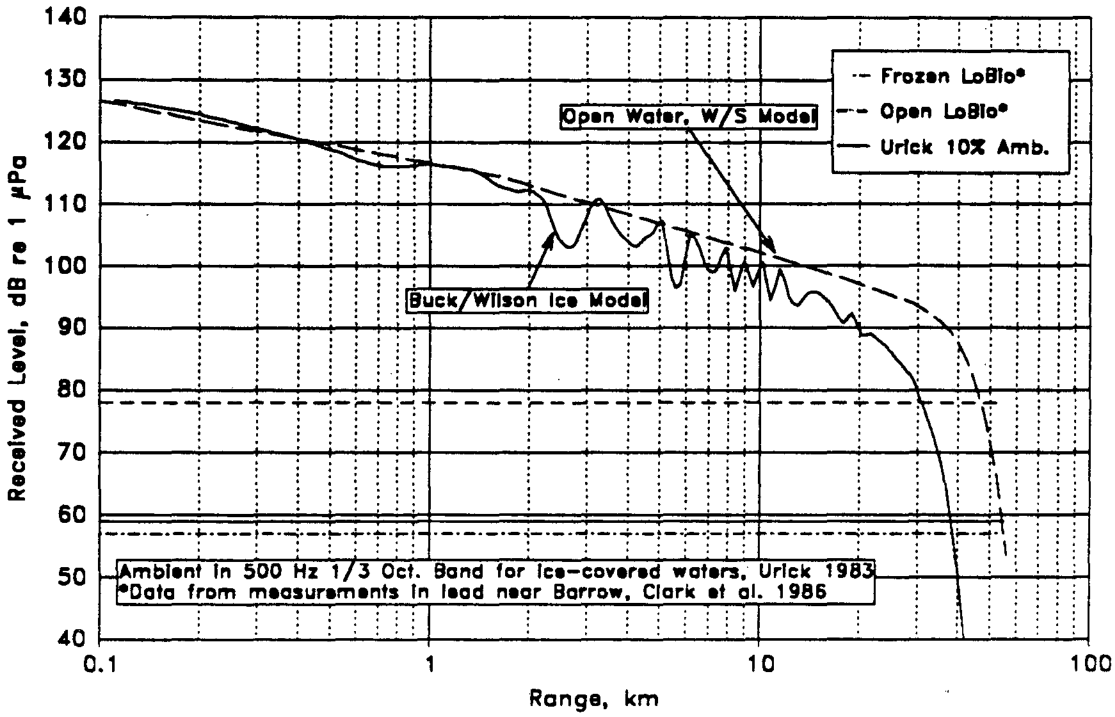

FIG. 4D ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track A, 1 kHz – PE Model, 2 kHz – W/S Model, Ls = 165 dB

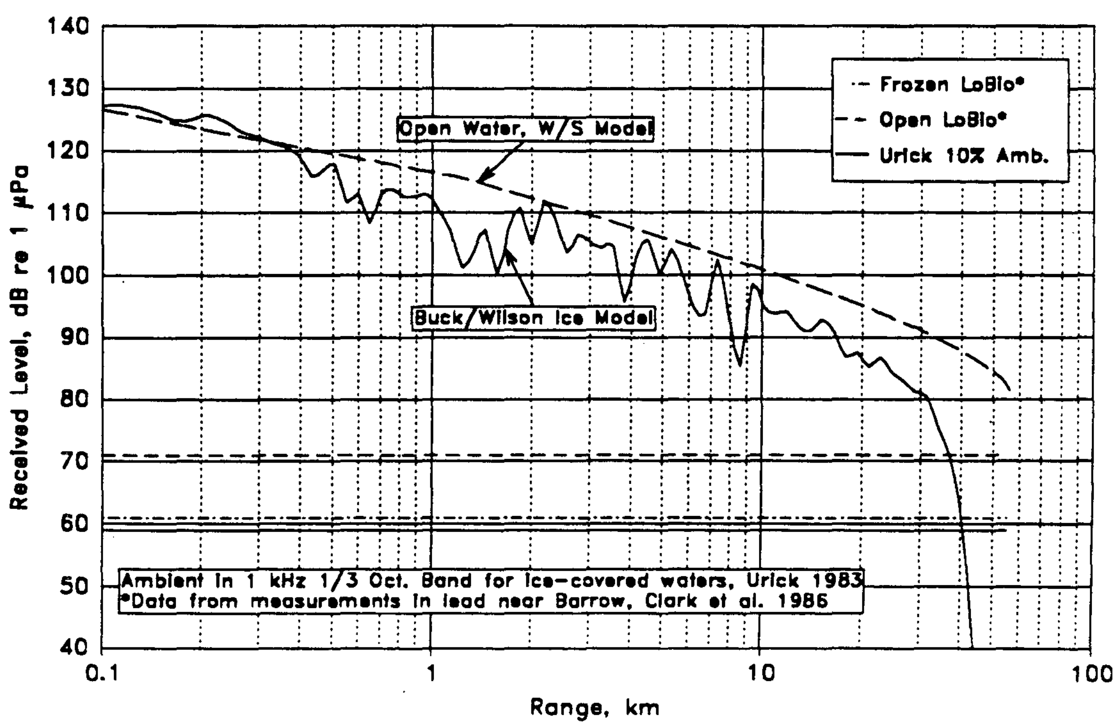

FIG. 5A ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track B, 100 Hz Band, Ls = 165 dB, PE and W/S Models

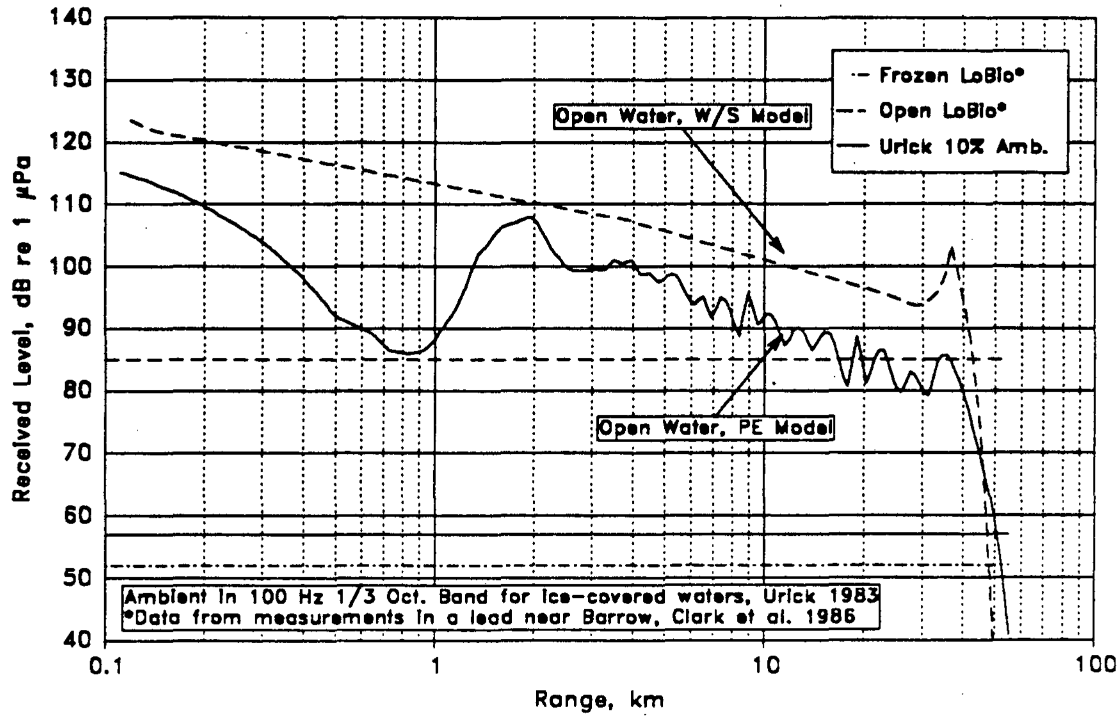

FIG. 5B ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track B, 100 Hz Band, Ls = 165 dB, PE and W/S Models

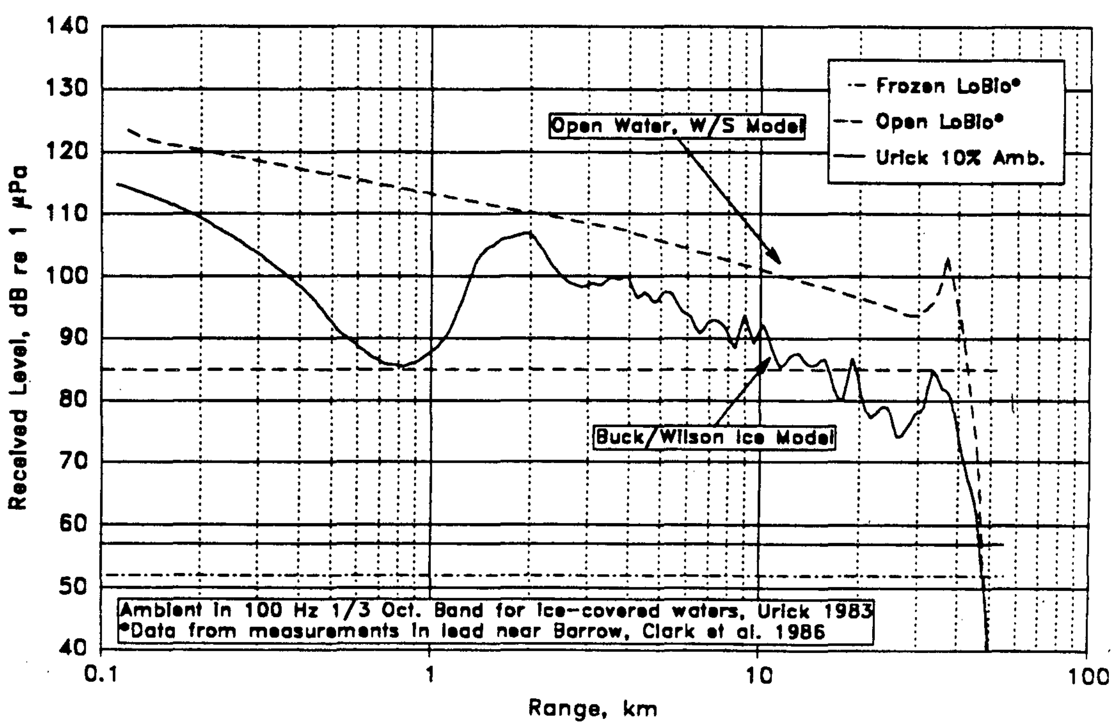

FIG. 5C ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track B, 500 Hz Band, Ls = 165 dB, PE and W/S Models

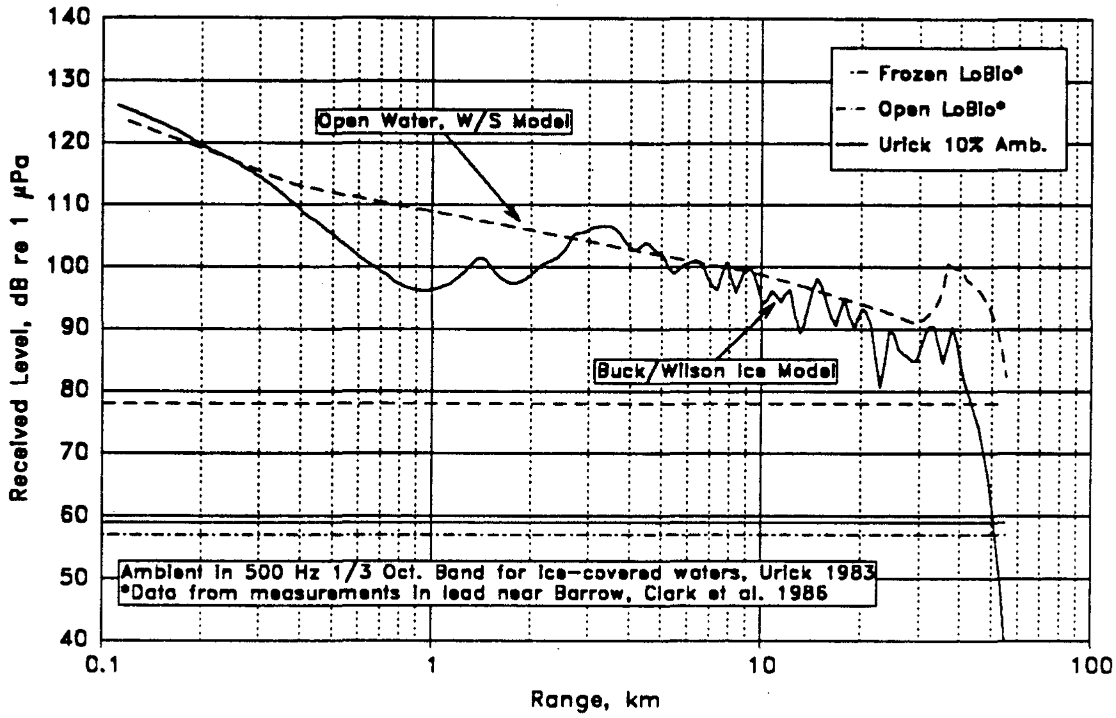

FIG. 5D ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track B, 1 kHz – PE Model, 2 kHz – W/S Model, Ls = 165 dB

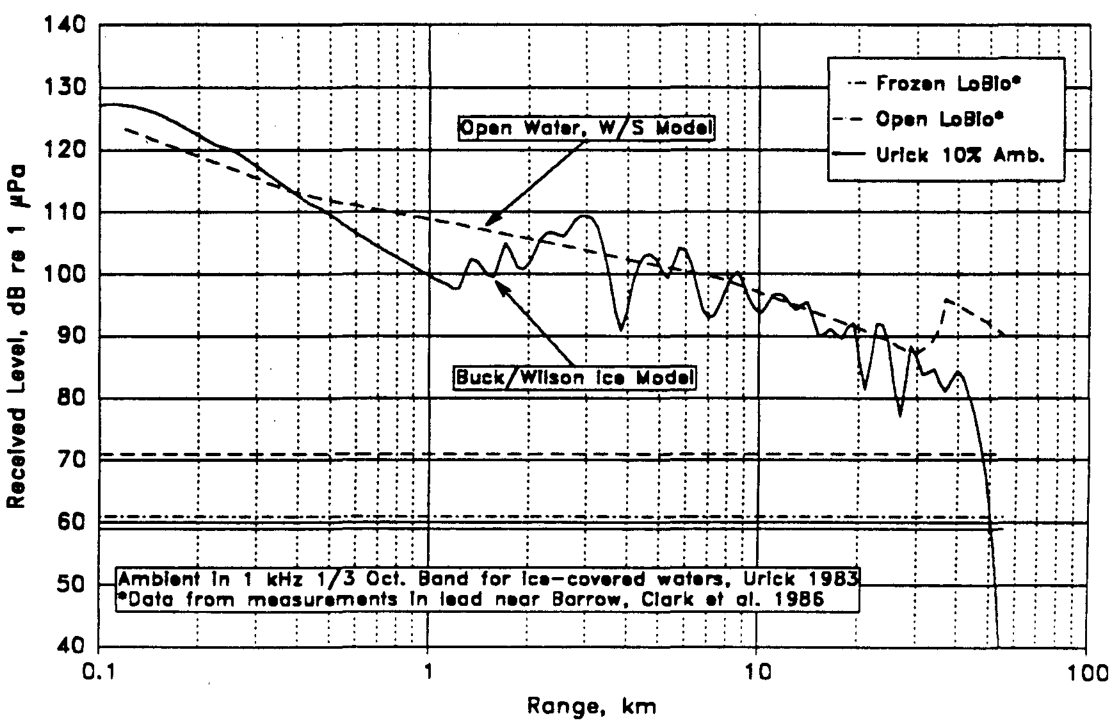

FIG. 6A ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track A, 100 Hz Band, Ls = 165 dB, PE Model results
compared with estimates using TL data from other areas

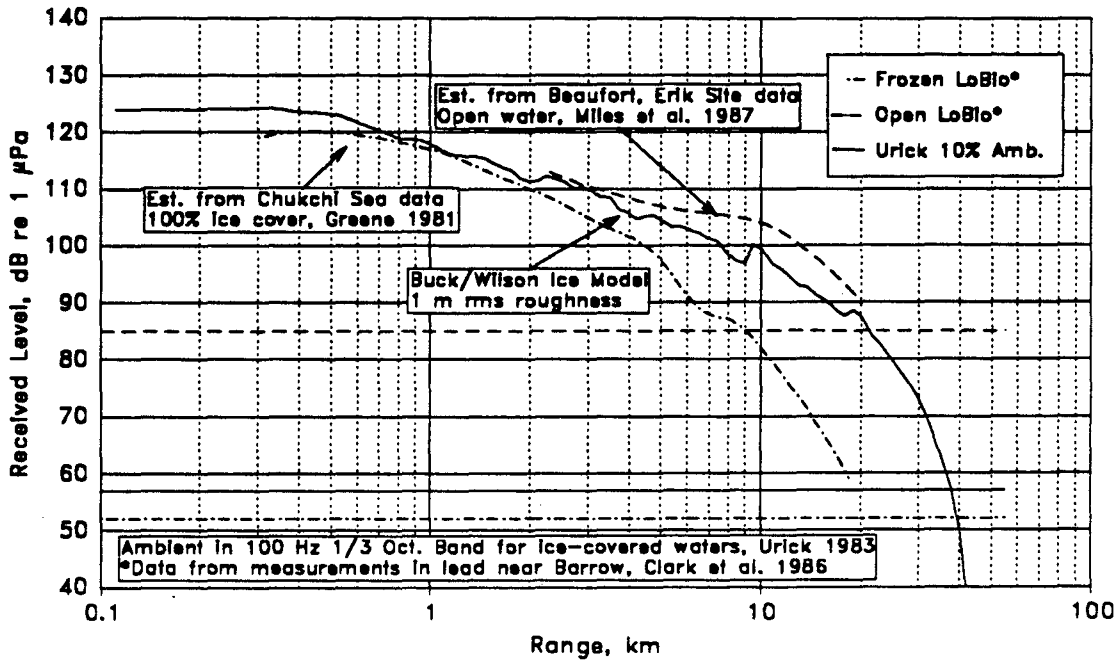

FIG. 6B ESTIMATED SOUND LEVEL FOR CALIBRATION TONE
Track A, 1 kHz Band, Ls = 165 dB, PE Model results
compared with estimates using TL data from other areas