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CONTINUATION OF THE ARCTIC NEARSHORE IMPACT MONITORING IN THE DEVELOPMENT AREA (cANIMIDA): SYNTHESIS, 1999 - 2007

Contract No. M03PC00014

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Submitted to:
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Alaska OCS Region
Anchorage, Alaska

Submitted by:
Neff & Associates LLC
Duxbury, MA

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EXECUTIVE SUMMARY

The cANIMIDA Project extended the ANIMIDA field program to the summers of 2004, 2005, 2006, and 2007. An explicit goal of the cANIMIDA Project is to examine temporal and spatial changes in chemical and biological characteristics of the oil and gas exploration and development area of the Alaskan Beaufort Sea and to determine if any observed changes are related to the Northstar development and production operations. This review summarizes and integrates the results of the ANIMIDA Project (1999 - 2003) and the cANIMIDA Project (2004 - 2007).

The ANIMIDA and cANIMIDA Projects are divided into several interrelated monitoring tasks:

- Sources of sediments and partitioning of metals and hydrocarbons in the Beaufort Sea;
- Spatial distribution and concentrations of metals and hydrocarbons in sediments on the Beaufort Sea continental shelf, with emphasis on the Northstar and Liberty prospect areas;
- Spatial distribution and concentrations of metals and hydrocarbons in tissues of marine invertebrates and fish in the Beaufort Sea, with emphasis on the Northstar and Liberty prospect areas;
- Ecology of the Boulder Patch ecosystem adjacent to the Liberty prospect; and
- Assessment of fall subsistence Bowhead whaling near Cross Island in the development area.

Sources and Partitioning of Sediments, Metals, and Hydrocarbons in the Beaufort Sea

About 90% of the annual transport of total suspended solids (TSS) from the Sagavanirktok, Kuparuk and Colville River occurs during the spring floods. More than 85% of the data points for Ba, Cu, Cr, Ni, and Pb in suspended sediments from the three rivers during 2004 and 2006 were within predicted ratios to Al for Beaufort Sea sediments. This overall continuity shows strong support for river particles as a key source for metals in coastal sediments as well as showing that anthropogenic inputs or diagenetic processes are not important in controlling concentrations of these metals in Beaufort Sea.

A trend of maximum concentrations of dissolved trace metals in rivers during peak flow in spring, first observed during the ANIMIDA Project, was again observed in some cases in the 2004 and 2006 data. This trend is natural and is influenced by the discharge of soil interstitial water and shallow surface water that is diluted by snow melt and flushed from surrounding soils into the rivers. In contrast concentrations of dissolved major elements such as Ca, or even Ba, varied by <10% over the May-June period in the rivers.

A simple distribution coefficient (K_d) was used to describe metal partitioning between particulate and dissolved phases. For example, the K_d values calculated for Ba in the Sagavanirktok, Kuparuk and Colville Rivers were statistically equal, despite differences in absolute values, suggesting that partitioning of Ba between dissolved and particulate phases is a quasi-equilibrium controlled process between free Ba^{2+} and suspended particles. Reasonably good agreement in K_d values among rivers and seasons also was found for Cd, Cu, Cr, Pb and other

metals. The K_d relationship can be used to help explain and predict concentrations of dissolved metals in area rivers.

During the spring floods, water from the Sagavanirktok River (SR) was traced beneath the ice, relatively undiluted, to a distance of ~6 to 8 km offshore and ~8 to 10 km alongshore in ~3 days. The SR plume was ~1.0 to 1.5 m thick with the majority of the river water ($\geq$60%) in the top 1 m over an area of ~315 km^2. This information can be used to help predict potential spill trajectories under ice as well as transport pathways for freshwater, suspended sediments and dissolved chemicals in the coastal Beaufort Sea.

No significant differences in concentrations of TSS were found due to oil and gas operations near Northstar Island relative the overall cANIMIDA study area. Concentrations of dissolved trace metals were lower than reported values for surface seawater worldwide and well below the EPA water quality criteria for chronic impacts in marine waters. No significant difference in concentrations of dissolved trace metals were observed near Northstar Island relative to the overall cANIMIDA study area during the 2004, 2005 and 2006 study period.

Concentrations of particulate metals during the open-water season varied as a function of the dissolved and particulate organic matter concentrations and the clay concentration and composition of suspended sediments, as shown by variations in concentrations of Al and Fe and associated shifts in concentrations of trace metals. Concentrations of some metals were influenced by uptake by biota (e.g., Cd) and possibly by anthropogenic inputs (e.g., Pb) to metal distributions. Only concentrations of particulate Cd during 2004 (plankton) and particulate Pb during 2006 (possibly anthropogenic) were higher in the Northstar area than in the overall cANIMIDA study area.

River sediments and peat from river banks and coastal soils contained significant concentrations of saturated and polycyclic aromatic hydrocarbons (SHC and PAH). The compositions of the SHC and PAH assemblages in the sediments, soils, and peat were consistent with mixed petrogenic, pyrogenic, and biogenic sources. The PAH compositions in river sediments and the offshore water column and sediments throughout the development area were similar, indicating that much of the hydrocarbons in offshore sediments came from terrestrial sources, probably eroding peat and organic rich shales and kerogens.

With respect to potential contaminants, the overall conclusion is that concentrations in suspended sediments, as well as dissolved and particulate metals and hydrocarbons in the development area, are primarily from terrestrial sources and are nearly always at background levels.

Metals and Hydrocarbons in Beaufort Sea Sediments

Monitoring in ANIMIDA and cANIMIDA has shown that there were no detectable associations between Northstar development activities and metals and hydrocarbons in sediments and marine animals. That is, any observed changes in the monitored environmental conditions were well within the natural spatial and temporal variability of the study area.

Sediment grain size distributions were highly variable on small spatial scales throughout the development area, and from year to year. Most areas were erosional rather than depositional; highest sediment deposition rates were in the range of 0.04 to 0.3 cm/year. In most of the area,

sediments were continually deposited from spring river flows and then eroded and transported and redistributed by storms in the open-water season.

Concentrations of 11 metals were similar in surface sediments in the Northstar, Liberty, and BSMP areas in 2000 through 2006. None of the metals was consistently present at a higher range of concentrations in sediments from the Northstar production facility than in sediments from the Liberty prospect or the historic BSMP stations.

Total polycyclic aromatic hydrocarbon (TPAH), total saturated hydrocarbon (TSHC), and total steranes and triterpanes (StTr) concentrations in surface sediments collected throughout the development area between 1999 and 2006 indicated that hydrocarbon concentrations increased significantly in post-1999 sediments in the Northstar area. However, the composition of the different hydrocarbon fractions was similar from year to year, indicating that the higher levels in sediments in 2000, after construction of the Northstar facility, were natural and not from construction activities. Sediments near Northstar were coarser in 1999 than in 2000, indicating that fine grained sediments, containing much of the hydrocarbons, were eroded from sediments in the area by storm currents in 1999.

Metals and Hydrocarbons in Tissues of Marine Animals from the Development Area

The ANIMIDA/cANIMIDA Project has shown that oil development activities in the Alaskan Beaufort Sea are not contributing ecologically important amounts of petroleum hydrocarbons and metals to the near-shore marine food web of the of the area. Mean total PAH concentrations in fish, deployed mussels, amphipods, isopods, mysids, and clams collected from all stations in 2004, 2005, and 2006, as well as in fish collected in 2001 and amphipods, clams, and deployed mussels collected in 2000 and 2002 in the ANIMIDA Project, were similar to or lower than concentrations in the same or similar species from clean coastal waters elsewhere in the world.

The PAH profiles in tissues of fish and invertebrates from the Beaufort Sea is consistent with a mixed petrogenic/pyrogenic source; petrogenic PAH probably are derived from aerial deposition, oil and gas operations in the vicinity, erosion of coastal and riverine peat deposits, and runoff from land. TPAH concentrations were not higher in tissues of marine animals from the vicinity of the Northstar development than in the same species from other locations. The concentrations of individual and total PAH in tissues of Beaufort Sea marine animals are well below concentrations that would represent a health risk to marine animals and the animals, including man, that might consume them.

Concentrations of 18 metals in tissues of several species of fish, amphipods, isopods, clams, and deployed mussels collected in the Northstar development and the Liberty prospect areas and in other reference areas were similar in 2004, 2005, and 2006. A few metals concentrations were slightly higher in marine animals from Northstar than in the same species from the other sampling sites; however, there were no consistent metal, year, or species patterns. Metals concentrations were in the range reported for the same or similar species from other locations throughout the world, and are below concentrations that would pose a health risk to the marine animals or their consumers, including man. There is no evidence that metals from the development and production activities at Northstar are entering the Beaufort Sea food web.

Regression analysis of concentrations of several metals, TPAH, and TSHC in sediments and tissues of benthic amphipods and clams residing in the same sediments, collected between 1999 and 2006, revealed that there was no relationship between concentrations of metals and hydrocarbons in sediments and tissues of amphipods and clams. In most cases, concentrations were higher in the sediments than in tissues of the benthic invertebrates. These results indicate that the metals and hydrocarbons in sediments of the development area have a very low bioavailability.

Monitoring the Boulder Patch Ecosystem

The Arctic Kelp, *Laminaria solidungula,* effectively integrates dynamic ecosystem characteristics, such as water transparency in the Stefansson Sound Boulder Patch. These ecosystem characteristics may vary due to changing arctic climate and oil and gas development along the coast of Northern Alaska. These plants represent excellent indicators of interannual changes in nearshore ecosystems and provide an effective way of monitoring such changes.

Data collected during ANIMIDA/cANIMIDA strongly suggest that both the spatial and interannual variations in water transparency are correlated with TSS. In general, the majority of the Boulder Patch, including areas with dense kelp populations (> 25% rock cover), was found predominantly in clear offshore waters where light attenuation measurements were consistently less than 1.0 m^{-1}. Our data show that years characterized by frequent storm activity are likely to have significant impacts on annual kelp growth and production. Local climatic change that results in more frequent storm events are thus likely to have a significant and detrimental impact on nearshore kelp bed community production, and could lead to large scale losses of these plants and their associated diverse epilithic and epiphytic fauna.

Offshore oil and gas operations also could affect the Boulder Patch community if they cause increases in TSS concentrations in the water column during the summer open water season. There is no indication that this has happened during development of the Northstar facility. Concentrations of metals and hydrocarbons are similar in benthic invertebrates collected in the Boulder Patch and elsewhere in the development area.

Monitoring of Subsistence Bowhead Whaling off Cross Island

The objective of this long-term ongoing study was to determine if offshore oil and gas development was affecting the annual (fall) Cross Island subsistence bowhead whale hunt. During ANIMIDA/cANIMIDA, Northstar went from construction/development to production. Cross Island whalers noted few if any direct effects of Northstar on their whaling activities, other than that the whalers themselves avoided scouting for whales near Northstar. The lack of effects was attributed primarily to Northstar being west of Cross Island, while the whales were coming from the east and so did not encounter any potential disturbance from Northstar until they had passed Cross Island and the Nuiqsut whalers.

The most important factors affecting the success of the whale hunt included stormy weather, ice drift into nearshore waters, and unexplained differences from year to year in the time of arrival, numbers, and distance from shore of bowhead whales.

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1 INTRODUCTION

1.1 Project Background

1.1.1 Monitoring Environmental Impacts of Offshore Oil and Gas Exploration and Development in the Alaskan Beaufort Sea

The Outer Continental Shelf Lands Act (OCSLA) of 1953 is administered by the US Department of the Interior, Minerals Management Service (MMS) (renamed the Bureau of Ocean Energy Management, Regulation and Enforcement [BOEMRE]), and covers the territorial seas from the outer boundary of state waters to the edge of the exclusive economic zone (200 nautical miles [370 km]). The Submerged Lands Act, also enacted in 1953, gave the Federal Government title to submerged lands located on a majority of the continental margin. States were given jurisdiction over any natural resources within 3 nautical miles (5.55 km) off the coastline (except Texas and the west coast of Florida, where jurisdiction extends to 9 nautical miles (16.66 km). The OSCLA subsequently defined the outer continental shelf (OCS) as any submerged US land outside State jurisdiction. In 1983, the government declared Federal jurisdiction over the US Exclusive Economic Zone (EEZ), defined as all waters up to 200 nautical miles (370 km) from the U.S. coastline.

The OCSLA guides and regulates many offshore oil and gas activities from initial leasing of Federal offshore lands on the US outer continental shelf to emplacement of offshore development and production platforms, pipelines, and floating production, storage, and offloading facilities (FPSO), to final decommissioning and removal of platforms (MMS, 1987). It includes requirements for monitoring environmental impacts of exploration, development, and production activities.

Amendments of 1978 (92 Stat. 629) established a policy for the management of oil and gas development on the Outer Continental Shelf (OCS) and for protection of the marine and coastal environments. The amendments authorize the Secretary of the Interior to conduct studies in areas of offshore leasing activities to assess potential impacts on the marine and coastal environments resulting from oil exploration, development, and production activities.

BOEMRE Alaska OCS Region is responsible for managing oil and gas development in Federal waters of Alaska, including the Beaufort and Chukchi Seas. Shallow State and Federal waters of the Beaufort Sea continental shelf were made available for exploratory drilling through a series of joint Federal/State lease sales, beginning in 1979. BOEMRE has sponsored three major environmental effects monitoring projects in the Beaufort Sea: the Beaufort Sea Monitoring Program (BSMP), the Arctic Nearshore Impact Monitoring in the Development Area (ANIMIDA) Project, and the Continuation of the Arctic Nearshore Impact Monitoring in the Development Area (cANIMIDA) Project. The objective of this report is to summarize and integrate the results of the ANIMIDA and cANIMIDA Projects.

1.1.2 The Beaufort Sea Monitoring Program (BSMP), 1984-1989

Shallow State and Federal waters of the Beaufort Sea continental shelf were made available for exploratory drilling through a series of lease sales, beginning in 1979 with the joint Federal/State Beaufort Sea Oil and Gas Lease Sale (Sale BF), followed by Sale 71 in 1982, Sale 87 in 1984,

and several additional sales. The oil industry showed great interest in lease tracts in the eastern and western Alaskan Beaufort Sea.

In 1983, MMS and the National Oceanic and Atmospheric Administration (NOAA) co-sponsored a workshop to develop approaches to assess the potential for environmental disturbance from exploratory drilling in the Beaufort Sea. The proceedings of the workshop (Dames and Moore, 1984) established a framework for environmental monitoring and for implementing the initial phase of the BSMP.

The BSMP was performed in two phases. The initial three-year project was performed between 1984 and 1986 and focused mainly on areas offered in Beaufort Sea Lease Sales BN, 71, and 87. The objective of Phase 1 of the BSMP was to evaluate the impact of offshore oil and gas exploration and production on environmental quality of the Beaufort Sea through examination of changes in the concentrations of metals and hydrocarbons in sediments and tissues of marine animals. The specific objectives of the initial three-year project were:

- To detect and quantify changes in the concentrations of trace metals and hydrocarbons in Beaufort Sea sediments and sentinel marine animals that might:
  - result from discharges from OCS oil and gas exploration activities;
  - adversely affect or induce adverse effects on humans or those parts of their environment by which they judge quality; and
  - influence Federal OCS management decisions.
- To identify the potential causes of these changes.

The results of Phase 1 of the BSMP were summarized in a final report (Boehm et al., 1987) and publications (Crecelius et al., 1990; Steinhauer and Boehm, 1992).

Phase 2 of the BSMP was performed in 1989. The sampling and analytical projects were modified slightly from those in Phase 1 to address additional needs of MMS. The most important changes were:

- To extend the regional survey to include three stations east of Barter Island; and
- To add six additional stations around the Endicott development area to help identify gradients of chemical parameters in sediments with distance from the facility.

The results of Phase 2 of the BSMP were summarized in a final report (Boehm et al., 1990).

1.1.3 ANIMIDA Phase 1 (1999, 2000), ANIMIDA Phase 2 (2000 - 2002)

In 1998, MMS decided to perform additional monitoring studies in the Beaufort Sea to characterize the pre-construction and pre-development marine environment in the Northstar and Liberty prospects and to continue to monitor selected environmental parameters over time to assess possible long-term effects of these oil development and production activities, the first to occur on Federal OCS lease tracts in the Beaufort Sea. MMS intended to use information generated in these studies in post-leasing decisions aimed at minimizing and mitigating any environmental effects of development activities in the Beaufort Sea.

The primary objectives of the ANIMIDA Project were to monitor and characterize the marine environment of the Northstar and Liberty development areas to evaluate potential and actual effects of these major offshore oil developments. The ANIMIDA Project initially was designed to carefully monitor environmental disturbance directly related to construction, drilling, and production activities at Northstar and Liberty. Priorities were placed on characterizing the pre-construction marine environmental baseline to aid in establishing a scientific basis for post-construction and production monitoring (Phase 1) and repeated monitoring after initiation of production at Northstar at site-specific and regional stations to detect long-term and area-wide disturbance of the marine environment in the development area (Phase 2).

Phase 1 of ANIMIDA was designed and implemented with a focus on the 1999 late-summer, open-water period and the 2000 winter, ice covered period. The late summer 1999 sampling represented pre-construction baselines at both the Northstar and Liberty areas. The winter 2000 sampling represented the first construction monitoring period at Northstar and another pre-construction data acquisition opportunity for Liberty. The results of Phase 1 of the ANIMIDA Project were summarized in a final report (Boehm et al., 2001).

Phase 2 of ANIMIDA focused on monitoring during the summers of 2000 and 2002 at the same regional BSMP and site-specific Northstar and Liberty stations as were sampled in Phase 1. Phase 2 also included support for ongoing studies of the ecology of the Boulder Patch, near the Liberty prospect and subsistence bowhead whaling at Cross Island, off Prudhoe Bay. Phase 2 of ANIMIDA included seven technical tasks in addition to a project management task (Task 1). The seven technical tasks were the following.

Task 2: Hydrocarbon and Metal Characterization of Sediments, Bivalves, and Amphipods in the ANIMIDA Study Area. Task 2 was designed to characterize potential chemical contaminants in sediments and marine animal tissues (bivalve mollusks and amphipod crustaceans) near ongoing and proposed offshore oil developments and to serve as a continuation of the Phase 1 organic and inorganic chemistry project.

Task 3: Baseline Acoustic Monitoring: Bowhead Whale Migration Corridor. The primary objective of Task 3 was to augment the design of BP Exploration Alaska (BPXA), the lease-holder for the Northstar prospect, for acoustic monitoring of bowhead whale migration offshore of Northstar by adding one or two seafloor recorder systems further offshore than the BP recorders. This task was deferred indefinitely; results of the Phase 1 component of this project were summarized by Shepard et al. (2001).

Task 4: Annual Assessment of Subsistence Bowhead Whaling Near Cross Island. The objective of this task was to provide an annual narrative report describing subsistence bowhead whaling activities, resources, and harvests on and near Cross Island offshore of Prudhoe Bay.

Task 5: Sources, Concentrations and Dispersion Pathways for Suspended Sediment in Areas of Oil and Gas Development along the Coastal Beaufort Sea. The objectives of this task were to determine the amounts of suspended sediments introduced each year to the near-shore Beaufort Sea from rivers, concentrations of suspended sediments at different distances from construction- related gravel deposits during open-water and ice-covered seasons, and sources of suspended sediments near the Northstar and Liberty development areas.

Task 6: Monitoring the Boulder Patch. The objective of Task 6 was to monitor the potential effects of future Liberty Island and pipeline construction activities on the unique biological communities in the Boulder Patch. The focus of the work was to establish the relationship between total suspended solids (TSS) concentrations and the amount of light available for primary production by the macroalgal community of Stefansson Sound.

Task 7: Partitioning of Potential Contaminants between Dissolved and Particulate Phases in Waters of the Coastal Beaufort Sea. The objectives of this task were to determine the concentrations of selected metals and hydrocarbons in dissolved and particulate forms in nearshore waters of the Beaufort Sea and partition coefficients and equilibrium kinetics of these chemicals in the Beaufort Sea, particularly after sediment resuspension events.

Task 8: Baseline Characterization of Anthropogenic Contaminants in Biota Associated with the Liberty and Northstar Production Facilities in the Nearshore Beaufort Sea. The objectives of Task 8 were to detect exposure and effects of anthropogenic chemicals, including those that might be released to the environment during development of offshore oil resources, in fish, including some of importance in the subsistence fishery, in the nearshore Beaufort Sea. Baseline levels of organochlorines and hydrocarbons and exposure biomarkers, cytochrome P450 (CYP1A) and bile fluorescent compounds were measured in several species of fish collected throughout the development area.

1.1.4 cANIMIDA (2004-2006)

The cANIMIDA Project extended the ANIMIDA field project to the summers of 2004, 2005, and 2006. cANIMIDA included six technical tasks and a project management task (Task 1). An explicit goal of the cANIMIDA Project was to examine temporal and spatial changes and to determine if any observed changes in chemical and biological characteristics of the development area of the Beaufort Sea are related to the current Northstar development and production operations. The objectives of the six technical tasks are as follows.

Task 2: Hydrocarbon and Metal Characterization of Sediments in the ANIMIDA Study Area.

This task is a continuation of parts of ANIMIDA Task 2. The key questions, which drive Task 2 of cANIMIDA, are as follows:

- What are the background concentrations of chemicals of concern (i.e., metals and hydrocarbons) that are known to be associated with oil exploration, development, and production activities, and are the concentrations of these chemicals increasing in area sediments as a result of development and production?
- If concentrations of metals and/or hydrocarbons do increase in the environment as a result of development and production activities, do the increased concentrations exceed environmental quality guidelines (Effects Range-Lows [ERLs]: Long et al., 1995)?
- What trends in the background levels of metal and hydrocarbon concentrations in sediments that are known to be associated with oil exploration, development, and production activities are seen in the historic sediment record, and do the concentrations of these chemicals increase as a result of these activities?

Task 3: Sources, Characteristics and Dispersion Pathways for Suspended Sediment in the cANIMIDA Study Area
and
Task 4: Partitioning of Potential Contaminants between Dissolved and Particulate Phases in the cANIMIDA Study Area.

These two tasks were closely coordinated and are a continuation of ANIMIDA Tasks 5 and 7. The objectives of Tasks 3 and 4 are to:

- Determine the major element, trace metal, and organic carbon content of water and suspended sediments carried to the coastal Beaufort Sea by the Sagavanirktok, Kuparuk and Colville Rivers.
- Determine concentrations of dissolved and particulate metals across the freshwater-seawater mixing zone into the Beaufort Sea.
- Determine pathways for transport of water, chemicals and suspended sediments from rivers under ice to the coastal Beaufort Sea during the spring floods.
- Determine concentrations of suspended sediments, dissolved metals, particulate metals and supporting parameters in the coastal Beaufort Sea, including areas near offshore oil- and gas-related activities such as Northstar.
- Determine distribution coefficients (K_d) for metals in the Beaufort Sea and adjacent rivers.

Task 5: Integrated Biomonitoring and Bioaccumulation of Contaminants in Biota of the cANIMIDA Study Area.

Task 5 is a continuation of certain aspects of ANIMIDA Tasks 2 and 8. The objectives of Task 5 are to:

- Improve and validate the Contractor's proposed conceptual model of bioaccumulation and trophic interaction in cANIMIDA biota.
- Measure bioaccumulation of metals and hydrocarbons in selected species, including indigenous bivalves, benthic amphipods, and fish, and in caged bivalves and SPMDs.
- Compare bioaccumulation data from the Beaufort Sea to published data for the same or similar species outside the cANIMIDA area.
- Develop a strategy for longer-term upper trophic level contaminant monitoring.
- Develop a strategy and rationale for future Boulder Patch contaminant monitoring in conjunction with cANIMIDA Task 6.

Task 6: Monitoring the Boulder Patch as Part of the cANIMIDA Project.

cANIMIDA Task 6 is a continuation of ANIMIDA Task 6. The overarching objective of Task 6 field studies in the cANIMIDA project is:

- To use synoptic and long-term measurements of photosynthetically active radiation (PAR), light attenuation coefficients, total suspended solids (TSS; mg/L), and indices of benthic diversity and kelp biomass to determine the impact of sediment resuspension on kelp productivity and biodiversity in the Stefansson Sound Boulder Patch.

Task 7: Continuation of Annual Assessment of Subsistence Bowhead Whaling Near Cross Island as part of the cANIMIDA Project.

cANIMIDA Task 7 is a continuation of ANIMIDA Task 7. This study has gathered long-term monitoring data to help the MMS assess whether OCS oil development activities at Northstar and/or Liberty result in changes to bowhead whale subsistence hunting practices, or to hunting success at Cross Island. Two research questions addressed in this study are:

- Does Cross Island subsistence whaling display significant variation over time?
- Can such variation be attributed to offshore oil and gas industrial activities?

1.1.5 Other Studies Associated with ANIMIDA/cANIMIDA

MMS Alaska OCS Region also sponsored a physical oceanographic project in the ANIMIDA area. These oceanographic studies of water currents and water properties were performed from 1999 and 2007 and were coordinated with but not part of ANIMIDA/cANIMIDA. The results of these and related studies of the physical oceanography of the Beaufort Sea have been summarized by Potter and Weingartner (2009), Weingartner (2006), Weingartner and Okkonen (2001), and Weingartner et al. (2005, 2009).

1.2 The Alaskan Beaufort Sea

1.2.1 Geographic Setting

The physical characteristics of the Beaufort Sea, including the development area monitored in ANIMIDA/cANIMIDA, have been described in detail in the Environmental Impact Statements for the Oil and Gas Lease Sales for Beaufort Sea Planning areas 87, 97, 124, 144, 202, 209 (MMS, 1984, 1987, 1990, 1996, 2006, and 2008, respectively).

The Beaufort Sea is the southern part of the Arctic Ocean off the coasts of Alaska and the Yukon and Northwest Territories of Canada. The Alaskan Beaufort Sea extends from the Barrow Sea Valley off Point Barrow eastward approximately 600 km to the Alaska-Canadian border and northward for a distance of 322 km (200 miles) to water depths greater than 100 m at 73°N latitude (Figure 1-1). The continental shelf of the Alaskan Beaufort Sea, measured from the shoreline to the 200-m isobath, is about 60 to 120 km wide, among the narrowest in the circumpolar Arctic (NRC, 2003), with an average water depth of about 37 m (USAEDA, 1999). The continental slope in the northern Beaufort Sea extends to a depth of more than 1000 m. The major bathymetric features on the inner continental shelf, 1.6 to 32 km from the coast, are barrier islands and shoals, the boundaries of which migrate from year to year, due mainly to spring freshets from rivers and winter ice scour (Weingartner et al., 2005).

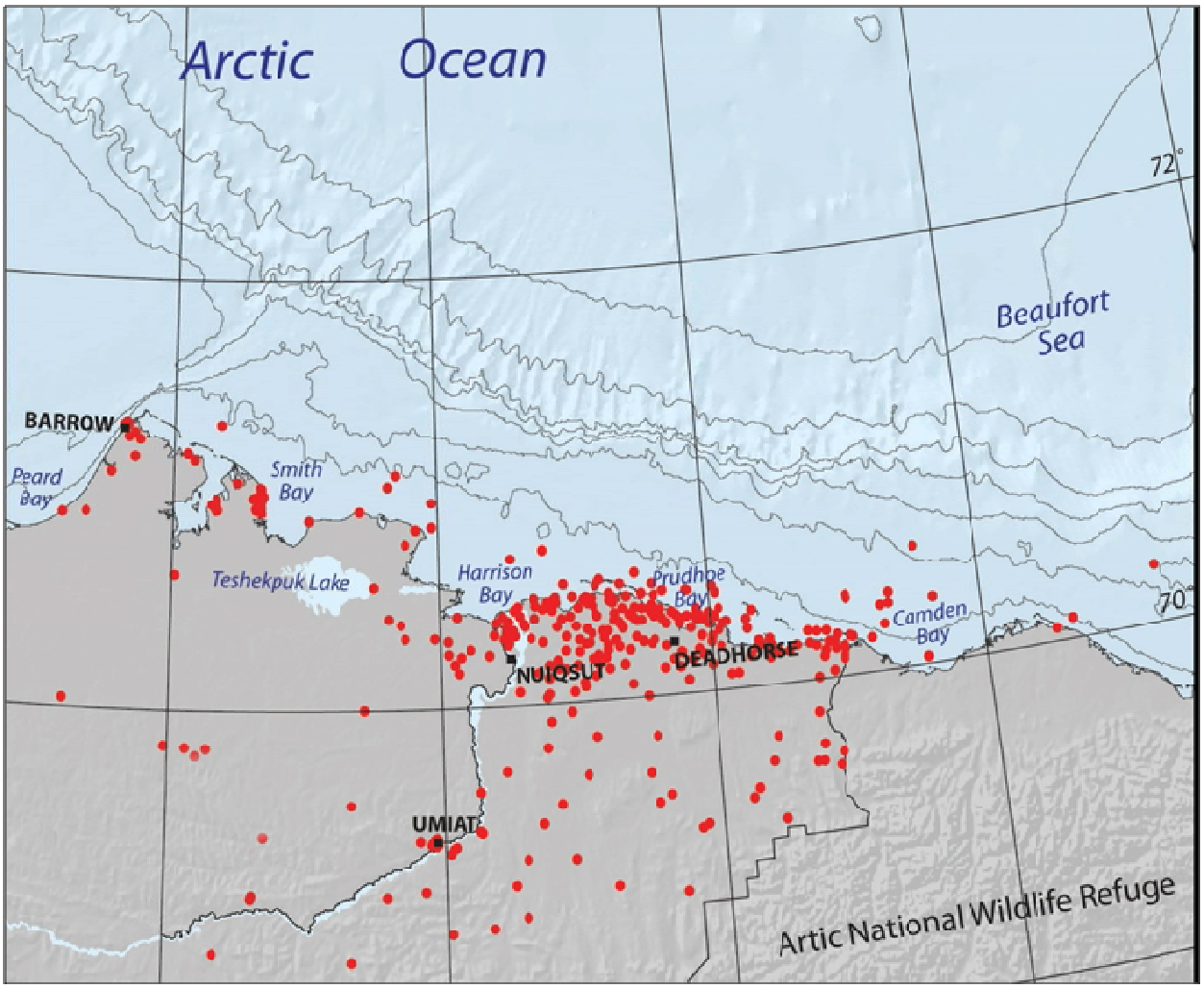

Figure 1-1. Map of the Alaskan North Slope and the Beaufort Sea showing locations of wells drilled. Offshore wells are on State and joint State/Federal lease tracts. Modified from National Research Council (2003).

1.2.2 Physical Oceanography

Three distinct oceanic regimes bound the Alaskan Beaufort Sea and influence water masses and current regimes in the Beaufort Sea (Weingartner et al., 2009; Potter and Weingartner, 2009). To the west, waters from Pacific Ocean and Bering Sea flow northward through the Bering Strait and across the Chukchi shelf. Part of the Barrow Canyon outflow continues eastward as a subsurface current (or slope undercurrent) along the Beaufort shelf-break and slope, where it forms the upper waters of the Canada Basin. Part of the water rounds Point Barrow and continues onto the inner portion of the western Beaufort Shelf.

The outer shelf and continental slope provide the offshore boundary for the Alaskan Beaufort Sea. In the upper ~50 m, the flow is westward and part of the southern limb of the wind-driven Beaufort Gyre. This flow can occasionally be reversed by strong winds from the east and/or by occasional shelf-break upwelling that advects eastward momentum from the slope undercurrent onto the shelf as far inshore as the 50 m isobath (Potter and Weingartner, 2009).

The Mackenzie shelf joins the Alaskan Beaufort shelf to the east and water currents on the eastern Beaufort Sea shelf (Canada) are influenced by year-round discharges from the Mackenzie River, the largest river flowing into the Arctic Ocean off North America (Potter and Weingartner, 2009). Mackenzie shelf water has been detected throughout much of the Canada basin, including the continental slope of the western (Alaskan) Beaufort Sea and Chukchi Sea as far west as 160°N latitude. Wind-driven currents also transport Mackenzie shelf waters westward onto the inner shelf of the Alaskan Beaufort Sea. The Mackenzie River and several smaller rivers introduce large volumes of fresh water, containing suspended sediments, metals, and hydrocarbons, into near-shore waters of the Canadian and Alaskan Beaufort Seas affecting nearshore water currents.

There are two distinct water circulation patterns in the Alaskan Beaufort Sea. Water currents on the inner shelf in water depths of less than 40 meters are strongly wind driven and undergo dramatic seasonal changes due mainly to buildup of land-fast ice. Because the principal wind direction is from the northeast in all seasons, particularly during the spring and fall, including ice-free season, nearshore flow usually is westward, (Weingartner et al., 2009; Potter and Weingartner, 2009).

Residual water currents on the outer continental shelf (water depths greater than 40 meters) are dominated by the Beaufort Gyre, flowing toward the west, and the Beaufort Undercurrent, which transports Pacific/Bering water eastward to the Canadian Beaufort Sea (NRC, 2003; Weingartner et al., 2005).

Sea ice can cover the Beaufort Sea shelf year-round; however, the inner shelf (and the entire shelf in recent years) is ice-free during summer months from late June to the beginning of October (Weingartner et al., 2009). Land-fast ice begins to form in October and extends 20 to 40 km offshore until mid-June. The OCS may remain ice-free longer, although ice usually covers the entire shelf by late November. Ice ridges form as the ice extends offshore. Ice keels extend beneath the ridges and can gouge the seafloor if the offshore ice moves inshore during spring breakup.

1.3 History of Oil Exploration and Development in the Alaskan Beaufort Sea

1.3.1 Exploratory Drilling, 1981 - 2002

Shallow State and Federal waters of the Beaufort Sea continental shelf were made available for exploratory drilling through a series of lease sales, beginning with Federal/State Beaufort Sea Oil and Gas Lease Sale (Sale BF) in 1979. Thirty-one exploratory wells were drilled over a period of 23 years (1981 to 2002) in State/Federal lease tracts administered by MMS between Barrow and Kaktovik in the Alaskan Beaufort Sea (Wainwright, 2002; NRC, 2003) (Table 1-1, Figure 1-2). The Alaska Dept. of Natural Resources (ADNR, 2007) lists 19 oil and gas fields in State and Federal waters of Alaska. Some of the wells in these fields are in State lease tracts in coastal waters (< 5.55 km from shore) in the Beaufort Sea.

Table 1-1. Chronological order of exploratory wells drilled to date or planned on State/Federal lease tracts in the U.S. Beaufort Sea. Several wells drilled on State leases are not included. Data from MMS, Alaska OCS Region, Anchorage, AK. Spud dates for the new wells are tentative because of ongoing litigation. (From Neff, 2010).

Prospect	Spud Date[a]	Water Depth (m)	Drilling Unit
Beechey Point	11/1/81	5.5	Gravel Island
Beechey Point	12/27/81	5.5	Gravel Island
Tern	5/28/82	6.4	Gravel Island
Tern	10/16/82	6.4	Gravel Island
Mukluk	11/1/83	15	Gravel Island
Cross Island	11/2/83	0.15 - 2.4	Gravel Island
Seal	2/4/84	12	Gravel Island
Antares	11/1/84	15	CIDS[c]
Antares	1/19/85	15	CIDS[c]
Seal	2/22/85	12	Gravel Island
Hammerhead	8/10/85	31	Explorer II Drillship
Harvard	9/2/85	15	Gravel Island
Orion	11/10/85	15	CIDS[c]
Sandpiper/Harvard	2/8/86	15	Gravel Island
Mars	3/12/86	7.6	Ice Island
Corona	7/28/86	35	Explorer II Drillship
Phoenix	9/23/86	18	SSDC/MAT[d]
Hammerhead	9/27/86	33	Explorer II Drillship
Tern	2/10/87	6.7	Gravel Island
Aurora	11/2/87	20	SDC/MAT[b]
Belcher	9/5/88	51	Kulluk[e]
Fireweed	10/19/90	15	SCD/MAT[b]
Galahad	9/15/91	51	Explorer II Drillship
Cabot	11/1/91	17	SDC[b]
Kuvlum	8/22/92	34	Kulluk[e]
Kuvlum	7/28/93	29	Kulluk[e]
Kuvlum	9/7/93	33	Kulluk[e]
Wild Weasel	10/13/93	27	Kulluk[e]
Liberty	2/7/97	6.4	Gravel/Ice Island
Warthog	11/1/97	11	CIDS[c]
McCovey	12/6/02	11	SDC/MAT[b]
Proposed Exploratory Wells			
Sivulliq	2011	31	Frontier Discoverer Drillship

[a] Spud date is the date drilling was started; [b] SDC/MAT, steel drilling caisson or steel drilling caisson/drilling mat unit; [c] CIDS, concrete island drilling system; [d] SSDC/MAT, single steel drilling caisson/drilling mat; [e] Kulluk, an ice-reinforced conical drilling unit (CDU).

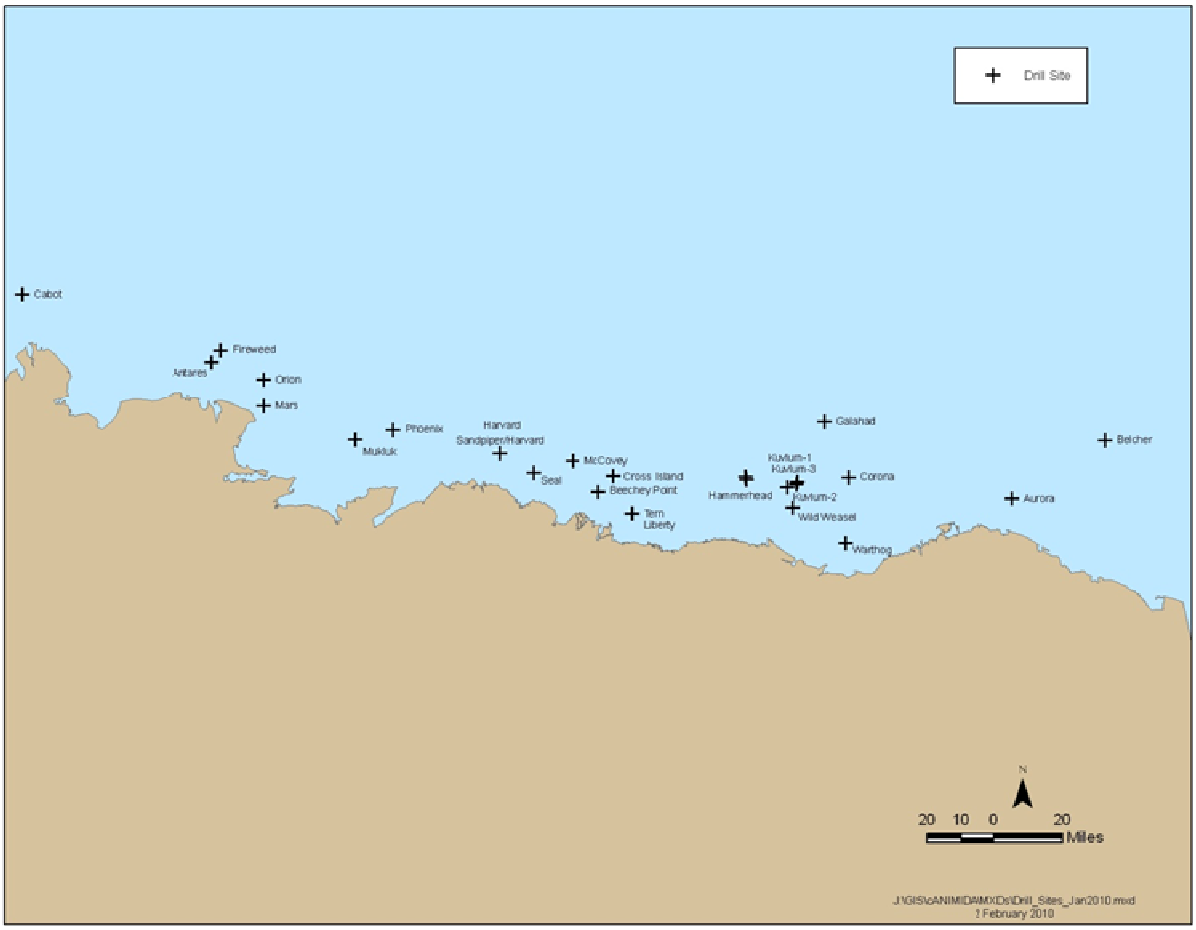

Figure 1-2. Map of the Alaskan Beaufort Sea showing locations of exploratory wells drilled between 1982 and 2002 on State/Federal lease tracts. The location of Cross Island, the site of the annual Nuiqsut bowhead whale hunt also is shown.

Records are incomplete on drilling in State lease tracts in waters of river deltas and coastal lagoons and within 5.5 km of the shore or barrier islands. At least 33 exploration, delineation, and development wells were drilled in State waters before 1986 (2 wells at Northstar, 6 wells at Niakuk, and 25 wells at Endicott) (Boehm et al., 1987). Several exploratory wells were drilled from gravel pads on or adjacent to barrier islands in state waters (e.g., Endeavor Island, Resolution Island, Challenge Island, Goose Island, and Alaska Island). Three exploratory wells were drilled in 2003 from a gravel island at the Oooguruk prospect located about 8 km off Harrison Bay in about 1.5 m of water.

Shell Offshore, Inc. (SOI, 2009) plans to drill an exploratory well in the Beaufort Sea on the Sevulliq prospect near the Hammerhead prospect, discovered by Union Oil Co. in 1985-1986 (Table 1-1). Drilling has been delayed several times, and currently is expected to occur during the summer of 2011. The exploratory drill sites are in approximately 30 m of water 24 miles north of Flaxman Island off Camden Bay. An ice-reinforced drillship, the *Frontier Discoverer*, will be used for exploratory drilling.

Exploratory wells located in shallow water (6 to 15 m) close to shore in the Beaufort Sea were drilled from man-made islands constructed from gravel and/or ice or from concrete island drilling system (CIDS) or steel drilling caisson/drilling mats (SDC/MAT) (Table 1-1). Gravel islands constructed for exploratory drilling usually are much smaller than those constructed for development/production facilities. Mukluk Island was just over half an acre, compared to five acres for the Northstar production facility and six acres for the Oooguruk drilling island. Most of these wells were drilled during the winter when ice was present and they were accessible from shore via ice roads. Further offshore in deeper (15 to 21 m) water, exploratory wells were drilled from specialized bottom-founded drilling units such as concrete island drilling units (CIDS), single steel caisson systems (SSDC or SDC/MAT), or the single steel drilling caisson (SSDC), a converted tanker that sat on a reinforced steel platform and could be moved, allowing year-round drilling (McCracken et al., 2007). McCovey, the most recent exploratory well drilled in the Alaskan Beaufort Sea (2002), as well as the Paktoa C-60 exploratory well drilled off the Mackenzie River delta in the Canadian Beaufort Sea in 2004 were drilled from the SDC/MAT. Wells located in deeper water further offshore were drilled during the open-water season using ice-reinforced floating drill rigs such as the 24-sided conical drilling unit, the *Kulluk,* and the drillship *Frontier Explorer*.

1.3.2 Development of Beaufort Sea Oil Resources

Eleven of the exploratory wells in the Beaufort Sea were discoveries with a potential for development (NRC, 2003). Five of these were significant discoveries: Kuvlum, Hammerhead, Sandpiper, Tern Island/Liberty, and Seal Island/Northstar (ADNR, 2009). Seven producing fields include offshore production (Badami, Endicott, Milne Point, Niakuk, Northstar, Point McIntyre, and Oooguruk). However, all but Endicott, Northstar, Point McIntyre, and Oooguruk are being produced through directional wells drilled from onshore facilities. The Endicott, Northstar, Point McIntyre, and Oooguruk facilities were constructed on gravel islands. Both Endicott and Point McIntyre use causeways to support offshore drilling and production facilities. Northstar, the only facility that gathers oil from Federal waters, pumps oil to shore by buried, ice-resistant pipelines and uses winter ice roads for re-supply of materials.

The Liberty prospect will be developed by ultra-extended-reach drilling from and expansion of the existing Endicott satellite drilling island (BPXA, 2007).

1.3.2.1 Endicott

Endicott was the first continuously-producing offshore oil field in the Arctic, including the Alaskan Beaufort Sea (BPXA, 2004). Endicott is near the Tern Island prospect discovered and delineated in 1982-1987 (Table 1-1). The original discovery well was drilled in the Duck Island/Sag Delta prospect leased by Exxon in the 1969 State Lease Sale 23 and Sohio in the 1979 State/Federal Lease Sale BF. The field was developed by BPXA with deviated wells drilled from two man-made gravel islands located in 4 m of water. Production facilities and producing wells are located on the 45-acre Main Production Island. Producing wells also are located closer to shore on the Satellite Drilling Island (SDI). The production islands are connected to the mainland by a 2.5-km long gravel causeway. The causeway has breaches that are crossed by steel bridges to allow passage of migratory anadromous fish and to minimize disruption of nearshore currents. Oil production began at Endicott in October 1987 and oil is transported to shore by pipeline on the causeway. Production began at Sag Delta North in 1989 and at Eider in 1998 through long-

reach deviate wells from Endicott's main production island. In 2004, there were 70 oil producing wells, five gas injection wells, and 28 water injection wells at the Endicott production facility, as well as one oil producing well and one water injection well for the Eider satellite production, and two oil producing wells and two water injection wells for the Sag Delta North satellite production (BPXA, 2004).

1.3.2.2 Northstar

Northstar, the only Arctic production facility producing Federal oil, is in State waters, but with bottomhole locations partly in Federal waters. Northstar was developed from a five-acre man-made gravel island constructed partly on the remains of the old Seal Island and from additional gravel hauled to the island from a gravel mine site near the mouth of the Kuparuk River. The island is surrounded by a linked concrete mat armor island slope protection system and the working surface of the island is surrounded by sheet piling. Shell Oil Company discovered oil at Seal Island in 1983 and drilled four additional appraisal wells there between 1983 and 1986 (Siok, 1999). BPXA acquired Seal Island in 1995. The Northstar production island is outside the barrier islands about 19 km northwest of Prudhoe Bay and 9.7 km offshore in about 12 m of water. Island construction began in the winter of 1999-2000. In 2004, Northstar had 15 producing wells and five gas-injection wells (BPXA, 2004). Northstar is connected to onshore oil processing facilities by a double pipeline that was buried 2.1 to 3.4 m below the seafloor to avoid damage from ice scour. Continuous oil production began in November 2001.

Although the Northstar Island is in Alaska State waters, several slant wells were drilled into Federal waters. State and Federal leases were allocated 82.16 percent and 17.84 percent, respectively, of total unitized production. Total oil production rose from 201,259 m^3 in 2001 to 3,987,245 m^3 in 2004 and then declined to an estimated 446,964 m^3 in 2010. Thus, total unitized annual production has declined by 88.8% between 2004 and 2010 (MMS Production Stats, July 2010).

1.3.2.3 Oooguruk

The Oooguruk facility was constructed on an artificial gravel island in State waters. Oil production began in June 2008 and is expected to reach 2400 to 3200 m^3/day in 2010. The facility consists of three main components – an offshore drill site, an onshore interconnect and production support facility, and a system of flowlines, power cables, and communications cables connecting the onshore and offshore facilities. The offshore drill site is a six-acre artificial gravel island about 9 km from shore with facilities for development drilling and field operations. Forty horizontal development wells will be drilled from the island, half of them for production and half for water injection.

1.3.2.4 Liberty

The Liberty Prospect is inside the barrier islands about 10 km offshore in Foggy Island Bay, at a water depth of about 7 m. The Liberty Prospect is a short distance south of the Boulder Patch, a unique and sensitive marine ecosystem. It is approximately 50 km southeast of the Northstar development and about 10 km from the Endicott Causeway, near Tern Island, where Shell Oil Co. drilled in 1982 (MMS. 2007). BP Exploration (Alaska), Inc. (BPXA) drilled the discovery well in the Liberty Prospect in 1997. The original development plan for Liberty called for development drilling from an artificial island, similar to that at Northstar. In August 2005, BPXA

announced that it will develop the Liberty Prospect by ultra-extended-reach drilling (uERD) from an expansion of the existing Endicott SDI, mitigating potential offshore environmental impacts to the Boulder Patch, marine mammals, and concerns of the North Slope Inupiat communities related to the bowhead whale and subsistence whaling. Six wells are planned, four producing wells and two waste injection wells, in the initial phase of development. The wells will extend 10.3 to 13.0 km from the drill site and to a vertical depth below the sea floor of about 3.4 km (BPXA, 2007). The Final Development and Production Plan for Liberty was submitted to MMS in April 2007 (BPXA, 2007).

1.4 Environmental Disturbances Associated With Oil Exploration and Development in the Arctic

1.4.1 Seismic Exploration

Many operations performed during evaluation, exploration, and development/production of offshore oil and gas resources may cause physical disturbance or chemical contamination of the marine environment (Table 1-2). Seismic surveys during geophysical evaluation produce loud noises that may harm or alter behavior of marine animals, particularly marine mammals (pinnipeds and cetaceans) that naturally rely on acoustic navigation and communication. There is no evidence that the low-frequency, high-energy sound pulses produced by modern, towed acoustic arrays consisting of air guns cause physical harm to marine animals, though they may cause avoidance reactions in some marine mammals (OGP, 2004).

1.4.2 Offshore Infrastructure Construction

Platform, gravel island, and subsea pipeline construction and emplacement during exploration, development, and production may cause physical disturbance at the sea floor and may interfere with other uses of the local marine environment. Construction sounds associated with winter and summer construction, development drilling, and production activities at Northstar were moderate in the winter, below levels likely to cause significant disturbance to marine animals and birds. The sounds reached background levels within 7.5 km under water, 3 km in the air, and 10 km for in-ice vibrations. Background sound levels were reached closer to the island in the summer. However, some airborne sounds from the island were heard up to 37 km away (Blackwell and Greene, 2006; Greene et al., 2008).

As discussed above, most exploratory drilling and all development operations in the Beaufort Sea were performed from artificial gravel Islands or grounded drilling structures, such as the concrete island drilling system (CIDS) and the single steel drilling caisson/drilling mat (SDC/MAT) (Table 1-1). These structures cause considerable long-lasting physical disturbance to the sea floor, effectively smothering all benthic fauna in the area of the facility footprint.

Table 1-2. Major activities and associated potential environmental disturbance during exploration and development/production of an offshore oil and gas field in the Arctic. From Neff et al. (1987).

Activity	Potential Disturbance
Geophysical Evaluation	
Seismic surveys	Low-frequency noise effects on marine animals, particularly marine mammals
Exploration	
Drilling structure emplacement	Seabed disturbance from gravel island construction or grounded drilling structure emplacement, and anchor scour and mud line cellar emplacement from floating rigs
Drilling	Discharge of drilling muds and cuttings, and risk of blowout
Routine drilling structure operations	Discharge of deck drainage, cooling water, and sanitary wastewater
Drilling structure support operations	Discharges from support vessels and coastal port development
Development and Production	
Platform installation	Disturbance to navigation, and marine animal migration, reef effects (fish attraction and biofouling), seabed disturbance from platform structure, template, anchor scour, and bottom scour
Drilling	Large volumes of drilling mud and cuttings from multiple wells, accumulation of solids on the sea floor, creating a cuttings pile that may contain elevated concentrations of metals and hydrocarbons, and risk of a blowout or oil spill.
Pipeline construction	Disturbance to the sea floor
Produced water disposal	Treatment and discharge to ocean, transport to shore, or reinjection
Platform support operations	Support vessel traffic, exhaust and wastewater discharges from vessels, and coastal port development
Routine platform operations	Discharge of deck drainage, cooling and firefighting water, and treated domestic wastewater

Since 1975, more than 20 gravel islands have been constructed in waters less than 15 m deep on State and State/Federal lease tracts in the Alaskan Beaufort Sea for exploratory drilling and production. Most of these islands remain in some form, but most have been abandoned by removal of all equipment and erosion protection. Natural barrier islands also have been used for exploratory drilling activities and for staging areas (USAEDA, 1999). Gravel drilling pads were constructed on many of these barrier islands. Some of the gravel islands erode away after completion of exploratory drilling, spreading coarse sediments over a large area. Others, such as Seal Island, may be reused for development drilling. The gravel islands also may leach chemicals, particularly metals, from the gravel material used to construct the island, as happened at the Netserk F-40 Island exploratory drilling site in the Canadian Beaufort Sea (Crippen et al., 1980).

Floating platforms, such as drill ships, ice resistant platforms, such as the Kulluk, and occasionally semisubmersible rigs, are used for most exploration in deeper waters in the Arctic.

These drilling structures are anchored to the sea floor and may cause serious sea floor scour. Similar physical disturbance may be caused by pipeline emplacement.

1.4.3 Drilling Waste Discharges

Large volumes of wastes are generated during drilling of exploratory, production, and workover wells; some of these wastes may be permitted for discharged into the marine environment where they may cause ecological damage. The wastes produced in largest volumes during drilling are drilling muds and drill cuttings (Neff, 2010). Water based drilling muds (WBM) are the only types that have been used and discharged offshore in the Alaskan Beaufort Sea. Oil based drilling muds (OBM) and synthetic based drilling muds (SBM) have been used extensively in the Canadian Beaufort Sea and the associated drill cuttings have been discharged to the ocean. Some of these drilling wastes may have been carried into Alaskan Beaufort Sea waters by the prevailing westerly along-shore water currents.

Modern WBM are composed of a weighting agent, usually barium sulfate (barite), clay or organic polymers, and small amounts of additives suspended in freshwater, seawater, or a saline brine. The WBM ingredients of major environmental concern are metals and petroleum hydrocarbons. The drill cuttings generated when drilling with WBM also may contain metals and hydrocarbons, derived mainly from the geologic strata being penetrated by the drill, and usually at concentrations similar to those in local marine sediments. The total estimated volume of WBM and cuttings discharged from each exploratory well drilled in the Beaufort Sea between 1981 and 1997 ranged from about 940 to 2530 m^3/well (Table 1-3).

The oil industry monitored environmental impacts of some of the exploratory drilling and development in the Alaskan Beaufort Sea. The results of these studies as well as studies of effects of offshore oil and gas development in other cold-water environments were reviewed recently by Neff (2010). If only water based drilling muds (WBM) and associated cuttings were discharged to these cold-water environments, environmental effects usually were minor and short-lived, consisting mainly of physical disturbance of benthic communities and accumulation of small amounts of several metals in sediments and benthic animals near exploratory platforms.

1.4.4 Production Waste Discharges

Formation water usually is produced with fossil fuels during production; produced water may be treated to remove hydrocarbons and discharged to the ocean if local environmental regulations permit, adding chemical contaminants to the water column. Historically, produced water from onshore and offshore production wells has not been discharged to the Alaskan Beaufort Sea. Most is treated and reinjected, primarily for water-flood to enhance production of oil.

1.4.5 Blowouts and Oil Spills

Though rare, there is a risk of blowouts or oil/gas spills from offshore platforms during drilling and production. There was a total of 149 oil spills (>380 liters), releasing an estimated 556 metric tons of crude oil, from offshore platforms to the US outer continental shelf between 1990 and 1999 (National Research Council, 2003). The largest crude oil spills from offshore platforms were the 1979 Ixtoc I blowout in the Sonda Campeche, in the Mexican Gulf of Mexico and the 2010 New Horizon oil spill in 1525 m of water in the US Gulf of Mexico off the Mississippi River. The Ixtoc 1 blowout began in June 1979 and lasted 295 days, resulting in the release of

Table 1-3. Estimated volumes of water based drilling mud and cuttings discharged to the Alaskan Beaufort Sea from exploratory wells for which information is available from Exploration Plans. Volumes are m^3 = 1000 liters or 264 gallons. From Neff (2010).

Prospect	Date	Water Depth (m)	Drilling Unit	Discharge Method	Estimated Volume (m^3)
Alaskan Beaufort Sea					
Beachy Pt.	1981	5.5	Gravel island	Cuttings hauled to shore, injected[d]	1590
Tern	1982/1987	6.4	Gravel island	To water per NPDES permit	2380
Fireweed	1990	15	SDC/MAT[a]	To water per GP AKG284100	1590
Antares	1984/1985	15	CIDS[b]	To water per GP	1110
Mars	1986	7.6	Spray ice island	To sea ice per GP	1420
Mukluk	1983	15	Gravel island	To water under ice per NPDES permit	1110
Harvard	1985	15	Gravel island	To water or on ice per NPDES permit	1420
Sandpiper	1986	15	Gravel island	To water or on ice per NPDES permit	1420
Belcher	1988	51	Kulluk[c]	Per GP; method not specified	2530
McCovey	2002	11	SDC/MAT[a]	To sea ice surface per GP AKG2842005	939
Liberty	1997	6.4	Gravel/ice island	To sea ice surface per GP	1730
Warthog	1997	11	CIDS[b]	To sea ice surface per GP	1520
Mean Volume					1445

[a] SDC/MATT = Steel drilling caisson or steel drilling caisson/Mat drilling unit; [b] CIDS = Concrete island drilling unit; [c] These are ice-reinforced drilling rigs; [d] This exploratory well was drilled in winter when the gravel island was attached to shore by an ice road. Cuttings were transported to Prudhoe Bay for reinjection. Drilling muds were stored on the gravel island and reinjected into the well at the end of drilling.

approximately 500,000 metric tons of crude oil to the southern (Mexican) Gulf of Mexico (Boehm et al., 1983). The New Horizon blowout occurred on April 20, 2010 and was capped on July 5. During that time, approximately 700,000 metric tons of a light crude oil were released just above the sea floor (Crone and Tolstoy, 2010). Offshore oil spills, especially large ones, can cause serious environmental damage if the oil sinks to the sea floor or reaches the shore. The potential impacts of oil spills in Arctic marine environments, such as the Alaskan Beaufort and Chukchi Seas are largely unknown, but may be more serious than spills in temperate and tropical environments, because of the difficulty in managing oil spill response and cleanup/remediation in a seasonally ice-covered environment and the slower rate of microbial degradation of the oil in cold-water environments (Nuka Research and Planning Group LLC, 2007).

1.4.6 Air Emissions

Fugitive and intentional (venting and flaring) emissions to the air may also occur during development drilling and production (OGP, 2000) and may result in release to the air of greenhouse gases (CO_2, CH_4, and N_2O), non-greenhouse gases (SO_x, H_2S, NO_x, and VOC), and petrogenic and pyrogenic hydrocarbons. Polycyclic aromatic hydrocarbons (PAH) are among the hydrocarbons emitted to the atmosphere by venting and flaring waste gases at production facilities. Approximately 500,000 million standard cubic feet (mscf) of natural gas was vented/flared at Northstar in 2001(AOGCC, 2004). This total rose to more than 1,100,000 mscf in 2002, the highest amount vented/flared in a single year between 2000 and 2004 at any oil and gas facility on the North Slope. Gas venting/flaring at Northstar declined to 162,321 mscf in 2004, representing 3% of the total gas vented/flared on the North Slope in 2004 (5,459,844 mscf). The PAH concentration in the flare exhaust is not known. Hydrocarbons, including PAH, also may be emitted in diesel exhaust and fugitive emissions from petroleum production, treatment, storage, and transportation facilities. Some of these flared or vented PAH may settle on the sea surface and eventually settle in sediments down-wind from the platform.

1.4.7 Waste Disposal Near Northstar Production Facility

Drilling muds and cuttings were not discharged to the Beaufort Sea during development of the Northstar facility. Some non-aqueous phase drilling muds (i.e., SBM and OBM) were used for development drilling at Endicott and Northstar and all drilling wastes were disposed of in waste disposal wells at the drill site or transported to shore for onshore disposal (Krieger et al., 2002). At Northstar Island, all drilling muds and cuttings, as well as other platform wastes, initially were trucked to shore over an ice road for on-land treatment and disposal. Subsequently, a reinjection well was drilled on the gravel island for disposal of development wastes.

WBM and cuttings from the exploration and delineation wells drilled on and near Seal Island before construction of Northstar Island were discharged to the ocean. If it is assumed, based on the data in Table1-3 that approximately 1.5 million liters of WBM and cuttings were discharged from each of the five exploratory and delineation wells drilled at Seal Island between 1983 and 1986, the total volume of mud and cuttings discharged was approximately 7.5 million gallons.

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2 METHODS

Detailed descriptions of field study designs and field methods and laboratory analytical methods are included in the ANIMIDA and cANIMIDA final reports cited below. The sections that follow include brief summaries of field and analytical methods for each of the cANIMIDA tasks.

2.1 Study Designs and Field Methods

2.1.1 Sources and Partitioning of Metals and Hydrocarbons in the Beaufort Sea

Field activities for cANIMIDA Tasks 3 and 4 included sampling rivers during spring breakup in May-June 2004 and 2006 (Figure 2-1), through ice sampling of the Beaufort Sea during spring floods in May-June 2004 and 2006, and sampling rivers and offshore waters during the open-water periods of July-August 2004, 2005 and 2006 (Figure 2-2) (Trefry et al., 2009). These tasks were a continuation of ANIMIDA Task 5 (Trefry et al., 2004a) and Task 7 (Trefry et al., 2004b)

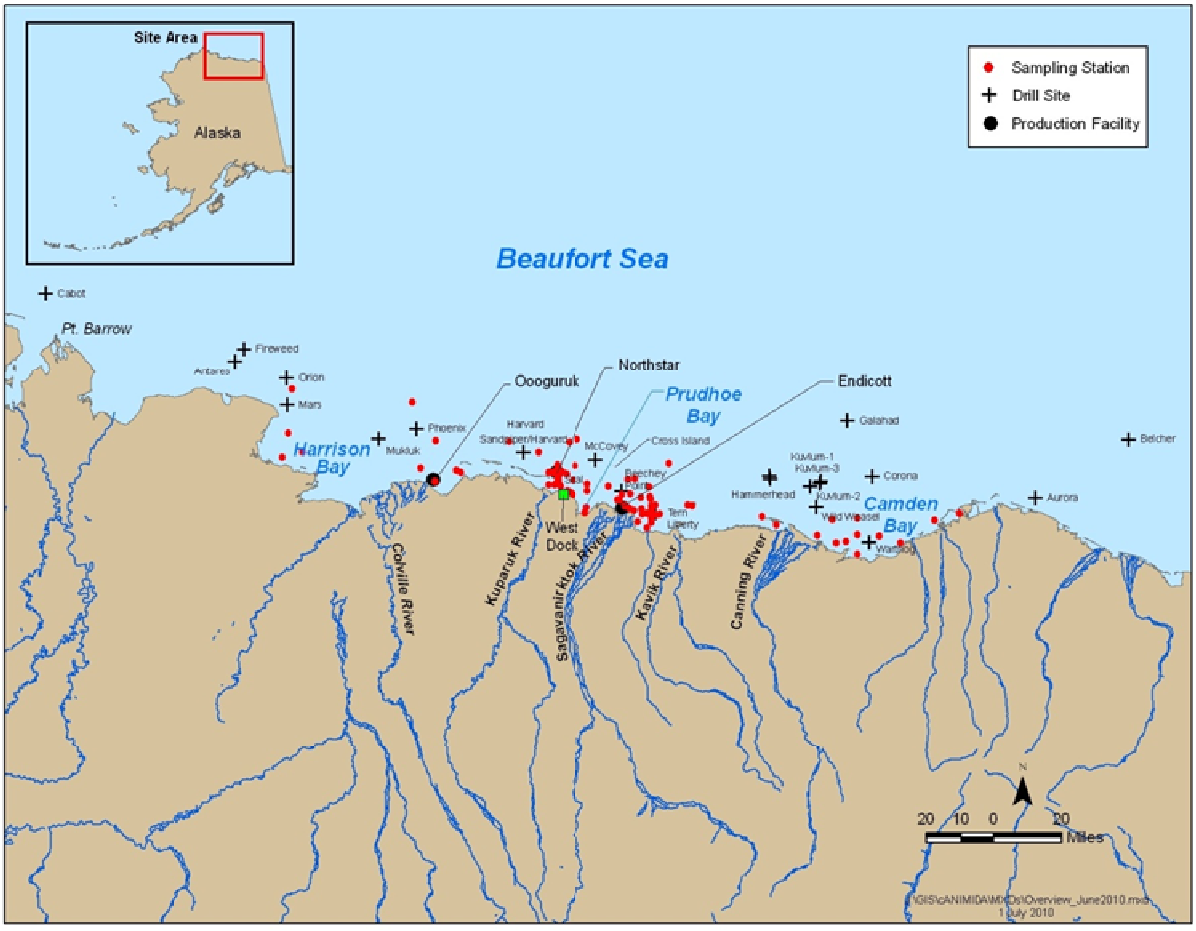


Figure 2-1. Map showing locations of sampling stations for the cANIMIDA Program in relation to locations of exploratory well sites and production facilities. The location of Cross Island where the subsistence whaling study was performed (cANIMIDA Task 7) also is shown.

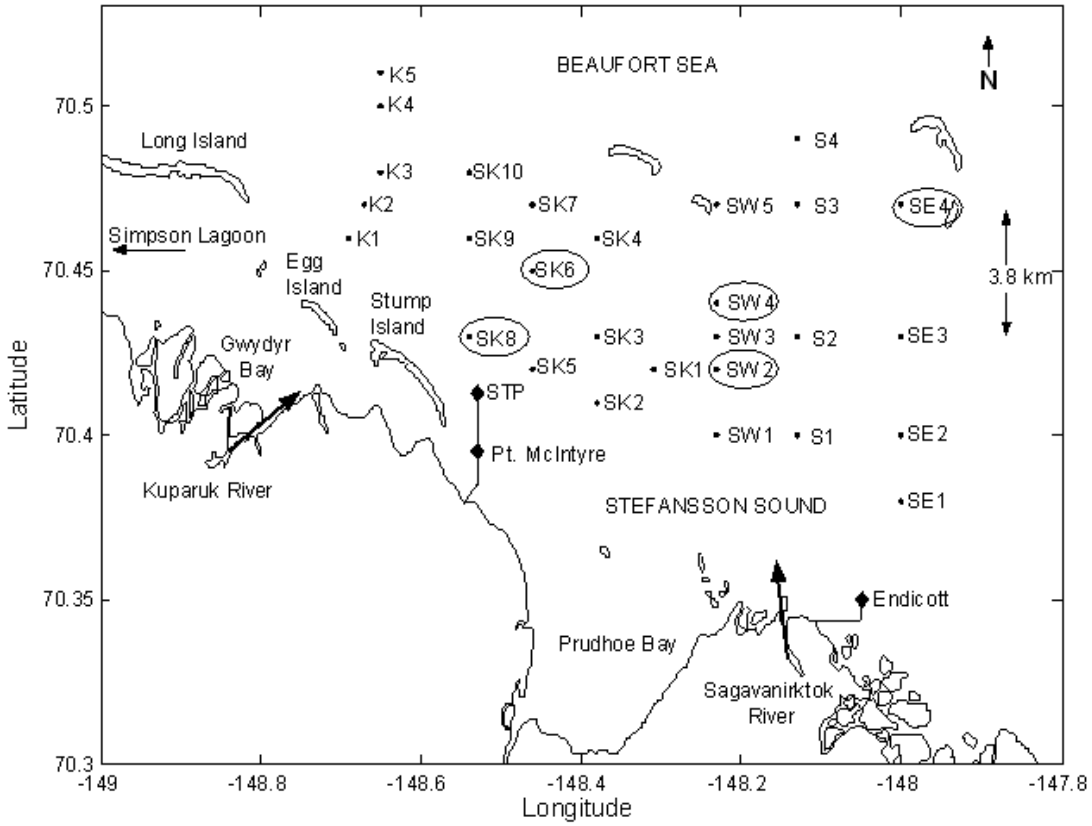


Figure 2-2. Sampling sites in Stefannsson Sound with inset map of Alaska showing study area during May-June 2004. Causeways connecting the Seawater Treatment Plant (STP), Pt. McIntyre, and Endicott Island to shore are shown by the solid lines. Station numbers in ovals identify locations where ice cores also were collected. Arrows show approximate direction of primary river outflow. From Trefry et al. (2009).

that included sampling of rivers during spring breakup in May-June 2001 and 2002, through-ice sampling of the Beaufort Sea during spring floods of 2001 and 2002, and rivers and offshore waters during open-water periods of June-August 2000, 2001, and 2002.

The Sagavanirktok and Kuparuk Rivers were sampled daily during late May and June in 2004 and 2006. Laboratory analyses included total suspended solids (TSS) and the following particulate metals: aluminum (Al), arsenic (As), barium (Ba), calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), zinc (Zn) and organic carbon. Concentrations of the following dissolved metals also were determined: As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb and Zn.

Water and suspended sediments also were collected under the ice, seaward of the rivers during the early days of spring runoff in 2004 and 2006 when the coastal Beaufort Sea was still ice

covered. Vertical profiles of conductivity, temperature and turbidity were collected at each site along with samples for TSS, particulate metals, particulate organic carbon and dissolved metals.

During the open-water period in 2004, 2005 and 2006, numerous vertical casts in the water column were made throughout the coastal Beaufort Sea to measure salinity, temperature and turbidity. Turbidity also was measured by in situ turbidimeter, by laboratory turbidimeter using discrete samples, and by filtration/gravimetry using discrete samples. Samples were analyzed for the same particulate and dissolved trace metals as listed above for rivers.

2.1.2 Hydrocarbon and Metal Characterization of Sediments in the ANIMIDA Study Area

Field studies for cANIMIDA Task 2 included sampling sediments at stations in the Northstar, Liberty, and BSMP areas during the summers of 2004, 2005, and 2006 (Table 2-1; Figure 2-3) for chemical analysis (Brown et al., 2010). cANIMIDA Task 2 is a continuation of parts of ANIMIDA Task 2 (Brown et al., 2004) and the Phase 1 ANIMIDA Project (Boehm et al., 2001).

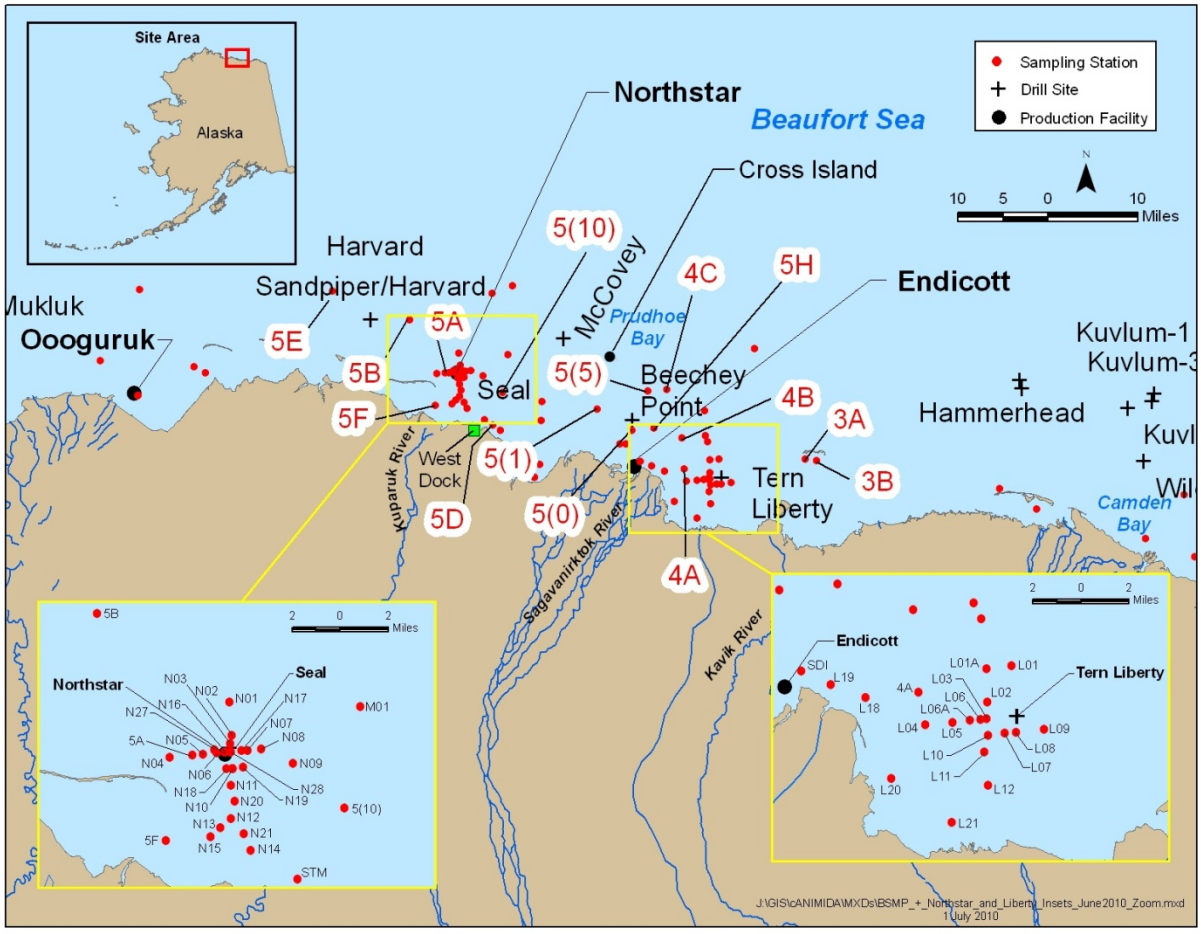


Figure 2-3. Locations of the BSMP, Northstar, and Liberty stations sampled in the cANIMIDA Program in relation to exploratory drilling sites and production facilities.

Table 2-1. Station numbers, sorted by area, where sediment and invertebrate tissue samples were collected for chemical analysis in ANIMIDA (1999-2002) and cANIMIDA (2004-2006).

Area	Station	1999		2000		2002		2004		2005		2006	
		Sed.	Tiss.[1]	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.
BSMP	1A									1	C,I		
BSMP	1B									1			
BSMP	1C									2[2]	A		
BSMP	1D									1	I		
BSMP	1E									1	C		
BSMP	2A									2			
BSMP	2B									1			
BSMP	2C									1			
BSMP	2D									1			
BSMP	2E									1			
BSMP	2F									1	A,C,I		
BSMP	2G									1	M		
BSMP	2H									1			
BSMP	3A	1	C	1	C	1	C	1	C,M	1	C		
BSMP	3B	1		1		1		1		1			
BSMP	4A	1		1	A	1	A	1	A	1	A	1	A
BSMP	4B	1		1		1		1		1	A,I		
BSMP	4C	1		1		1		1					
BSMP	5(0)	1		1	A	1	A	1	A				
BSMP	5(1)	1		1		1		1		1	A,C,M	1	
BSMP	5(10)	1		1		1		1					
BSMP	5(5)	1		1		1		1		1		1	
BSMP	5(5A)							1					
BSMP	5A	1		1		1		1				1	M
BSMP	5B	1	A	1		1		1	A				
BSMP	5D	1		1		1		1					
BSMP	5E	1		1		1		1					
BSMP	5F	1	C	1	C	1	C	1	C				
BSMP	5H	1	C	1	C	1	C	1	C,M		C		
BSMP	6A											1	A
BSMP	6B											1	A.I
BSMP	6D											1	
BSMP	6F											1	A
BSMP	6G												
BSMP	6H												
BSMP	7A											2	
BSMP	7C											1*	
BSMP	7E											2	A
BSMP	7G											1	A

Table 2–1. Continued.

Area	Station	1999		2000		2002		2004		2005		2006	
		Sed.	Tiss.[1]	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.
Liberty	BP01									2	A,M	1	A,M
Liberty	E01									2	A,M	1	M
Liberty	E02											1	
Liberty	L01	1		1		1		1					
Liberty	L01A							1					
Liberty	L02	1		1									
Liberty	L03	1		1								1	C
Liberty	L04	1	A	1		1		1	A				
Liberty	L05	1		1									
Liberty	L06	1		1		1		1	M				
Liberty	L06A	1		1									
Liberty	L07	1		1		1		1		1	I		
Liberty	L08	1	C	1	C	1	C	1	C	1	C,I,M		A.C,I, M
Liberty	L09	1	C	1	C	1	C	1					
Liberty	L10	1		1									
Liberty	L11	1		1									
Liberty	L12	1		1									
Liberty	L17							1					
Liberty	L18							1	A				
Liberty	L17B									2			
Liberty	L19											1	A
Liberty	L20											1	
Liberty	L21											1	
Liberty	L22											2	
Northstar	M01											1	
Northstar	N01	1		1		1		1					
Northstar	N02	1		1		1		1					
Northstar	N03	1		1	A	1	A	1	A	1	A,M	1	A,M
Northstar	N04	1		1		1	A	1	A,M	1			
Northstar	N05	1		1		1		1	M	1			
Northstar	N05N11												I,My
Northstar	N06	1		1		1		1	M	1		1	A
Northstar	N07	1		1		1		1					
Northstar	N08	1		1		1		1		1			
Northstar	N09	1		1		1		1					
Northstar	N10	1		1		1		1					
Northstar	N11	1	A	1		1		1	A	1	A	1	A,M
Northstar	N11N08												A,I,My
Northstar	N11S												I,My

Table 2–1. Continued.

Area	Station	1999		2000		2002		2004		2005		2006	
		Sed.	Tiss.[1]	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.	Sed.	Tiss.
Northstar	N12	1	A	1	A	1	A	1					
Northstar	N13	1		1	A	1	A	1					
Northstar	N14	1		1		1		1		1		1	A
Northstar	N15	1		1		1		1					
Northstar	N16			1		1		1					
Northstar	N17			1		1		1				1*	
Northstar	N18			1	A	1	A	1		1	A		
Northstar	N19			1		1		1					
Northstar	N20			1		1		1					
Northstar	N21			1		1		1					
Northstar	N22			1									
Northstar	N23			1		1		1					
Northstar	N25								M				
Northstar	N26									2			A
Northstar	N27												A
Northstar	N28											1	A
Other	WD01											1	A,I,M
Other	SDI01											1	

1Tissue types: A= Amphipod, C=Clam, I=Isopod, M=Mussels, My=Mysids
2Sediment samples: 1 = Grab, 2 = 1 Grab and 1 Core; 1*=Core only

In ANIMIDA Task 2, sediments were sampled for chemical analysis at Northstar, Liberty, and BSMP stations during the summers of 2000 and 2002; sampling in ANIMIDA Phase 1 was performed in 1999 and represents the pre-development conditions at Northstar. ANIMIDA and cANIMIDA sampling stations are summarized in Tables 2-1 and 2-2.

Table 2-2. Stations, sorted by area, where fish samples were collected for chemical analysis and biomarker assays in ANIMIDA (1999-2002) and cANIMIDA (2004-2006). Total number of fish samples (8 species sampled) collected at each station and year is included. From Spies et al. (2003) and Neff et al. (2009).

Area	Station	2001	2004	2005	2006
Reference	Bullen Point	25			
Reference	Tigvariak Island		30		
Liberty	L14	18	5		
Liberty	L15				
Liberty	PBS	27	26	18	20
Northstar	N25	7	5		
Northstar	SIS	48	31	17	19

The focus of this monitoring was to identify and characterize the distribution and concentrations of chemical contaminants (metals and hydrocarbons) from the Northstar and Liberty developments in Beaufort Sea sediments. ANIMIDA Phase 1 sampling was intended to characterize the distribution of metals and hydrocarbons in sediments before construction of Northstar Island. ANIMIDA Task 2 was intended to characterize changes in sediment chemistry during and shortly after island construction and start-up of production. cANIMIDA Task 2 was intended to characterize long-term changes in sediment chemistry in Northstar, Liberty, and BSMP areas. All sediment samples were analyzed for saturated hydrocarbons (SHC), polycyclic aromatic hydrocarbons (PAH), and sterane/triterpane (StTr) hydrocarbon source biomarkers.

Surficial sediment samples were collected using a modified Van-Veen grab sampler. During the collection and handling of sediment samples from the grab sampler, extreme care was taken to avoid contact with metal and hydrocarbon sources. Samples were taken away from the sides of the grab and metal spatulas were not used for the collection of trace metal samples. The grab sampler was protected from stack smoke, grease drips from winches and wire, and other potential airborne contamination during the sampling process. Sediment samples were collected from the top 1 cm of the grab to represent recent accumulation. Unconsolidated sediment 1 cm deep was removed from the grab with a stainless-steel scoop coated with Kynar® or a Teflon® spatula.

The sediment core sampling procedure included deployment of a dual-barrel gravity corer weighted with lead to allow "freefall" into the bottom to collect "side-by-side" cores for geochronology and chemistry. Polybutyrate core liners were placed within the metal barrels of the corer. After the cores were collected, the core liners were removed from the metal sleeves, sealed with plastic end caps and stored until returned to shore.

2.1.3 Integrated Biomonitoring and Bioaccumulation of Contaminants in Biota of the cANIMIDA Study Area

Field studies for cANIMIDA Task 5 focused on sampling marine animals from the Northstar, Liberty, and BSMP areas during the summers of 2004, 2005, and 2006 (Tables 2-1 and 2-2; Figure 2-3) for chemical analysis (Neff et al., 2009). Biological samples were collected during field surveys performed during the summers of 2004, 2005, and 2006 at a subset of the stations sampled for sediment chemistry in cANIMIDA Task 2. cANIMIDA Task 5 is a continuation of parts of ANIMIDA Phase 1 (Boehm et al., 2001), ANIMIDA Task 2 (Brown et al., 2004) and ANIMIDA Task 8 (Spies et al., 2003). Sampling station stations for marine invertebrates during ANIMIDA and cANIMIDA are summarized in Table 2-1. Sampling sites for fish are summarized in Table 2-2.

Task 5 of cANIMIDA focused on an assessment of concentrations of petroleum hydrocarbons, including PAH, SHC, StTr petroleum biomarkers, and 13 to 19 metals in soft tissues of representative species of marine bivalve mollusks, crustaceans, and fish from the offshore areas in the Alaskan Beaufort Sea near ongoing or planned oil and gas development activities.

Biological samples were collected at several sampling stations near the Northstar production facility, the Liberty prospect, and at reference locations, mostly east (up-current) of development activities (the BSMP stations). Five different types of biological samples were collected during cANIMIDA; semi-permeable membrane devices (SPMDs) were deployed only in 2004 to

estimate concentrations of dissolved PAH in the water column. Indigenous clams (*Astarte montagui* and *Cyrtodaria kurriana*), amphipods (usually *Anonyx nugax*), and fish were collected locally. Caged blue mussels (*Mytilus trossulus*) were collected from Port Chatham in southern Cook Inlet and deployed for approximately two weeks at stations near Northstar and in the Liberty and BSMP areas. During all three years, isopods (*Saduria sabini*) were collected whenever available; mysids (*Mysis* sp) were collected opportunistically in 2006. Amphipods and clams also were collected in 1999, 2000, and 2002 as part of the ANIMIDA Project. Station locations where each invertebrate species was collected in 1999 through 2006 are summarized in Table 2-1.

Eight species of fish were collected one or more times in 2004, 2005, and 2006 at different locations in the study area in the Beaufort Sea (Table 2-2) for analysis of hydrocarbons and metals in whole tissues and for measurement of the biomarkers of PAH exposure, cytochrome P450A mixed function oxygenase (CYP1A) activity in selected tissues and fluorescent aromatic compounds (FACs) in bile. CYP1A and bile FAC analyses were preformed on fish tissue samples collected in 2004 and 2005, but not 2006. The following species were analyzed for PAH, 13 metals, and PAH exposure biomarkers:

- Arctic char (Salvelinus alpinus)
- Arctic cisco (Coregonus autumnalis)
- Least cisco (C. sardinella)
- Broad whitefish (C. nasus)
- Humpback broad whitefish (C. pidschian)
- Arctic cod (Boreogadus saida)
- Arctic flounder (Liopsetta glacialis)
- Four horn sculpin (Myoxocephalus quadricornis)

2.1.4 Long-Term Monitoring of the Kelp Community in the Stefansson Sound Boulder Patch: Detection of Change Related to Oil and Gas Development

Field studies for cANIMIDA Task 6 focused on monitoring water quality, light intensity, kelp growth, and biodiversity in the associated invertebrate community in Stefansson Sound Boulder Patch (Dunton et al, 2009). Stefansson Sound is about 20 km northeast of Prudhoe Bay and immediately east of the Endicott production facility (Figure 2-4). The Liberty prospect is in southwestern Stefansson Sound. The sound extends from the Midway Islands in the west to Tigvariak Island in the east and is enclosed by a barrier island chain to the North, including Cross Island, the site of the fall Nuiqsut subsistence bowhead whale harvest. Boulders and cobbles cover large areas of the silt-clay sediments in the sound; these boulder fields are called the Stefansson Sound Boulder Patch. The field surveys were performed during the summers of 2004, 2005, and 2006. cANIMIDA Task 6 is a continuation of ANIMIDA Task 6 that monitored the Boulder Patch in the summers of 2001, 2003, and 2003 (Dunton et al., 2004).

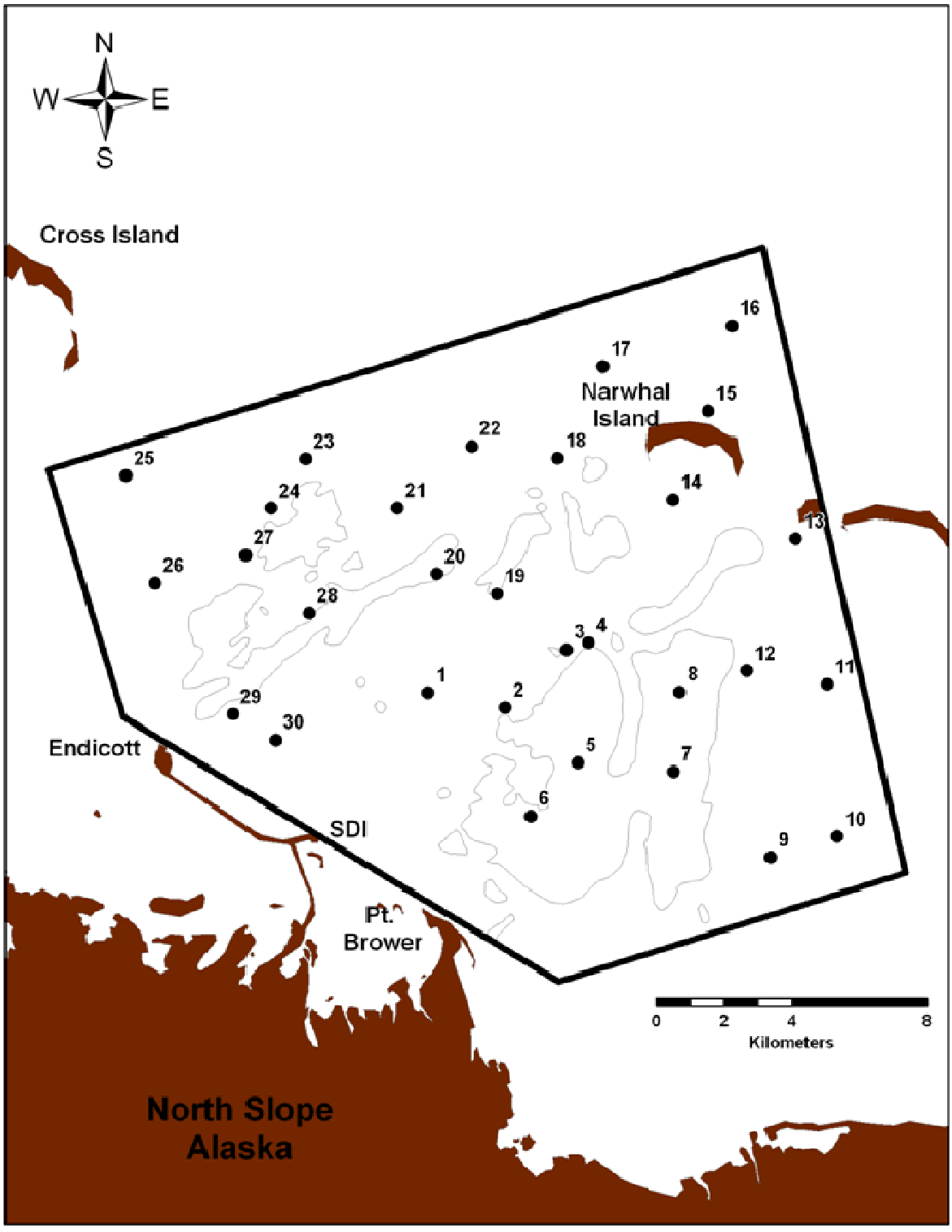


Figure 2-4. Map of the cANIMIDA 2004 - 2006 project study area showing the location of the 30 synoptic collection sites used in summers 2004, 2005 and 2006. The thin lines outline the areas containing boulders. SDI: Satellite Drilling Island.

Three sampling strategies were used in summers 2004, 2005 and 2006:

- semi-synoptic maps of total suspended solids (TSS) and light attenuation parameters were generated through sampling at 30 randomly-selected points in a 300 km^2 area that included the Boulder Patch and the region south of Narwhal Island to the Sagavanirktok Delta;
- long-term variations in underwater photosynthetically active radiation (PAR) were monitored at three fixed sites and incident PAR at one coastal site during the summer open-water period;
- benthic faunal diversity was measured at seven monitoring stations established during the 1984-1991 Boulder Patch Monitoring Project (LGL Ecological Research Associates and Dunton, 1992).

In addition to simultaneous measurements of PAR and TSS, other parameters measured included water column chlorophyll, ammonium, phosphate, silicate, nitrate + nitrite, temperature, salinity, dissolved inorganic nitrogen, and pH.

2.1.5 Continuation of Annual Assessment of Subsistence Bowhead Whaling Near Cross Island as part of the cANIMIDA Project

cANIMIDA Task 7 is a continuation of ANIMIDA Task 4. Field work for ANIMIDA Task 4 was performed during the fall (September) subsistence bowhead whale hunt at Cross Island in 2001, 2002, and 2003 (Galginaitis and Funk, 2004). Field work for cANIMIDA Task 7 was performed at Cross Island in the fall of 2001 through 2007 (Galginaitis, 2009).

These tasks focused on monitoring potential effects of offshore development on subsistence whaling near Cross Island by the residents of the village of Nuiqsut. Three primary methods of information collection were employed – systematic observations, collection of daily vessel location information during each hunt from handheld GPS units, and whalers' self-reports and perceptions. All whaling boats were given handheld GPS units that recorded their tracks during searches for whales and significant point locations. Debriefing of whalers by talking with them while examining these tracks on a computer screen after they came back from their hunt was also an important source of information.

2.2 Analytical Methods

2.2.1 Water Chemistry

Salinity of water samples was measured in the field with a conductivity probe; in the laboratory salinity was calculated from chlorinity measured by Mohr titration. River water chlorinity (Cl^-), sulfate (SO_4^{2-}) and fluoride (F^-) concentrations were determined by ion chromatography with a Dionex DX-600 ion chromatograph (IC). Alkalinity was determined by titration using the method of Strickland and Parsons (1972).

Concentrations of dissolved silica, phosphate, and nitrate were determined by standard methods within 48 hours of collection. Concentrations of $\delta^{18}O$ were determined in 62 water samples from key under-ice stations in spring 2004 that were selected based on salinity and dissolved silica values. Analyses for $\delta^{18}O$ were performed with a VG Micromass gas source stable isotope ratio mass spectrometer.

Samples for particulate organic carbon (POC) and dissolved organic carbon (DOC) were prepared by filtration of seawater and river water through pre-combusted Gelman Type A/E glass fiber filters mounted on acid-washed filtration glassware within a Class-100 laminar-flow hood. The filters containing POC were treated with H_3PO_4 to remove inorganic carbon phases, rinsed with distilled water, dried and their particulate mass determined. The filters were combusted at 900°C to measure POC. The DOC concentrations in the seawater and river water samples were calculated by difference, total carbon (TC) minus inorganic carbon (IC) as determined by combustion.

2.2.2 Analysis of Metals in Water, Sediments, and Tissues

Detailed descriptions of analytical methods for metals in water, sediment, and tissues of marine animals, as well as a complete discussion of laboratory quality control, are in three cANIMIDA final reports (Brown et al., 2010; Neff et al., 2009; and Trefry et al., 2009). All metals analyses were performed in the laboratory of John Trefry at Florida Institute of Technology, Melbourne, FL. A brief summary of the analytical methods is given here.

Concentrations of dissolved As, Cd, Cr, Cu, Pb and Zn in seawater and riverwater were determined on extracts obtained using a reductive precipitation procedure. Ultra-high purity Pd, Fe and $NaBH_4$ were used to precipitate the metals that were then collected by filtration and redissolved in ultra-high purity HNO_3 and HCl. Concentrations of dissolved Ba were determined directly on diluted aliquots of the seawater samples. River water samples were analyzed directly for Ba, Ca, Cu, Fe, K, Mg, Mn, Na and Ni as described below. Concentrations of Pb and Zn in river water were determined by reductive precipitation of the water sample and a certified reference material (CRM).

Total dissolved Hg concentrations in seawater and river water were determined on separate aliquots of water that had been treated with bromine monochloride solution to oxidize organic ligands and preserve the samples until analysis. Mercury in water samples was preconcentrated by gold amalgamation followed by analysis with CVAFS in a Brooks-Rand Model III Mercury System.

The metal concentrations of the river water, river water extracts, seawater extracts, CRMs, and blanks were determined by FAAS, GFAAS, ICP-MS or cold-vapor atomic fluorescence spectrometry (CVAFS) (Table 2-3). Analytical methods for some metals were slightly different for river water and seawater extracts.

Filters bearing field samples of suspended sediments, as well as separate milligram quantities of a standard reference material (SRM), were digested in stoppered, 15-mL Teflon test tubes with Ultrex II HNO_3, HF and HCl. Refluxing of the acids at 80°C completely dissolved the particles on the filters. Metal concentrations for the digested particulate samples, SRMs and blanks were determined by flame atomic absorption spectrometry (FAAS), graphite furnace atomic absorption spectrometry (GFAAS) or inductively coupled plasma mass spectrometry (ICP-MS) (Table 2-3).

Selected sediment core samples also were analyzed for excess ^{210}Pb and total ^{137}Cs in an effort to determine whether sediment at a particular location was recently deposited. Sediment core samples were sub-sectioned in 0.5-cm intervals in an effort to age-date the cores. Sediment samples were freeze-dried and ground to a fine powder. The samples were then set aside for at

Table 2-3. Summary of instrumental methods and method detection limits (MDL) for analysis of metals in water, suspended sediments, sediments, and soft tissues of marine animals. Concentrations are µg metal/g dry sediment or mg/L (parts per million). From Brown et al. (2009), Neff et al. (2009), and Trefry et al. (2009).

Metal	Method	Method Detection Limit (MDL)			
		Water	Suspended Sediment	Sediment	Tissue
Silver (Ag)	ICP-MS			0.007	
	ZGFAAS				0.004
Aluminum (Al)	FAAS		1500	10	2.3
Arsenic (As)	GFAAS	0.0000081	1.8		
	ZGFAAS				0.012
	ICP-MS			0.02	
Barium (Ba)	1CP-MS	0.0001	9	0.01	0.01
Beryllium (Be)	ICP-MS			0.009	0.001
Calcium (Ca)	FAAS	0.01	230		
Cadmium (Cd)	ICP-MS	0.0000001	0.03	0.001	0.001
Cobalt (Co)	ZGFAAS			0.001	
	ICP-MS				0.001
Chromium (Cr)	FAAS		0.33	1.0	0.01
	GFAAS	0.000005			
Copper (Cu)	FAAS		0.4	2	0.7
	GFAAS	0.000003			
Iron (Fe)	FAAS		250	10	2.5
	GFAAS	0.00001			
Potassium (K)	FAAS	0.02	250		
Mercury (Hg)	CVAAS	0.00003		0.001	0.001
Magnesium (Mg)	FAAS	0.01	40		
Manganese (Mn)	FAAS		170	2	1.1
	GFAAS	0.0001			
Sodium (Na)	FAAS	0.008	0.7		
Nickel (Ni)	ICP-MS	0.00002	0.2	0.004	0.004
Lead (Pb)	ICP-MS	0.000002	82	0.002	0.001
Antimony (Sb)	ICP-MS			0.001	0.001
Selenium (Se)	ZGFAAS				0.03
Thallium (Tl)	ICP-MS			0.001	0.001
Vanadium (V)	FAAS			10	0.002
Zinc (Zn)	FAAS		2.0	0.5	0.4
	ICP-MS	0.00001			

Analytical methods:
CVAAS = Cold Vapor Atomic Absorption Spectrometry
FAAS = Flame Atomic Absorption Spectrometry
GFAAS = Graphite Furnace Atomic Absorption Spectrometry
ICP-MS = Inductively Coupled Plasma-Mass Spectrometry
ZGFAAS = Zeeman Graphite Furnace Atomic Absorbtion Spectrometry

least 20 days to establish secular equilibrium and the activities of the various radionuclides were then determined by counting. Sediment geochronology was determined using excess ^{210}Pb and ^{137}Cs following methods described by Kang et al. (2000). Vials containing about 10 g of freeze-dried sediments were counted for 2 to 3 days until peak areas were sufficient to provide <10% counting error for total ^{210}Pb. The activities of ^{210}Pb, ^{214}Pb, ^{214}Bi and ^{137}Cs were determined with a well-type, intrinsic germanium detector.

Freeze-dried samples of marine animal tissues were digested by a sequential addition of concentrated, high-purity nitric acid (HNO_3), hydrogen peroxide (H_2O_2), and hydrochloric acid (HCl). Tissue subsamples for mercury analysis were digested with concentrated, high-purity nitric acid (HNO_3) and sulfuric acid (H_2SO_4) and refluxed in the sealed extraction tubes.

Metal concentrations in the digested tissue samples and associated quality control samples were determined by FAAS, GFAAS (Zeeman or Continuum background correction), CVAAS, or ICP-MS (Table 2-3).

2.2.3 Sediment Grain Size and Total Organic Carbon (TOC)

Grain size analyses of sediments were performed by the classic method of Folk (1974) that includes a combination of wet sieving and pipette techniques. Total organic carbon (TOC) analyses of sediments were performed by a combustion method described by Froelich (1980) for the analysis of organic carbon in marine sediments.

2.2.4 Analysis of Saturated Hydrocarbons (SHC), Polycyclic Aromatic Hydrocarbons (PAH), and Sterane/Triterpane Petroleum Biomarkers (StTr)

Detailed descriptions of analytical methods for PAH, SHC, and StTr in sediments and tissues of marine animals, as well as a complete discussion of laboratory quality control, are in two cANIMIDA final reports (Brown et al., 2010; Neff et al., 2009). All hydrocarbon analyses in the cANIMIDA Project were performed at the Battelle environmental chemistry laboratory in Duxbury, MA. Hydrocarbon analysis of some samples in the ANIMIDA Project were performed at Arthur D. Little, Inc., in Cambridge, MA. A brief summary of the analytical methods is given here.

Dry sediment and tissue samples were extracted by serial solvent extraction method designed to more accurately measure trace-levels of PAH and other petroleum hydrocarbons in the samples. All samples were spiked with representative surrogate compounds (Tables 2-4, 2-5, and 2-6) and serially extracted three times with dichloromethane (DCM). Between extractions the samples were centrifuged to facilitate solvent removal and the extract was decanted into an Erlenmeyer flask. The extracts are then treated with sodium sulfate to remove water and concentrated on a water bath.

Sediment and tissue samples were analyzed for PAH, SHC, and StTr and, therefore, were fractionated to remove potential interference and improve the quality of the low-level analysis. The sample extracts were loaded on an alumina clean up column and eluted with dichloromethane. The eluate was concentrated and an aliquot was removed for lipid weight determination. The remaining extract was fractionated on a silica gel column to isolate the PAH, SHC and StTr fractions. The column was eluted first with hexane (F1 fraction), followed by a mixture of hexane and methylene chloride (F2 fraction). The F1 fraction was spiked with

recovery internal standards for SHC and StTr analysis (Tables 2-5 and 2-6), divided into two aliquots and analyzed for SHC by gas chromatography with flame ionization detection (GC/FID) and for StTr by gas chromatography-mass spectroscopy (GC/MS). The F2 fraction was spiked with PAH recovery internal standards (Table 2-4) and analyzed by GC/MS.

Table 2-4. Target polycyclic aromatic hydrocarbons (PAH) analyzed in sediments and soft tissues of marine animals collected in the ANIMIDA and cANIMIDA program from the Beaufort Sea. The C prefix for alkyl PAH indicates the number of alkyl carbons. Each alkyl-PAH isomer group is the total of all quantified isomers. Reporting codes are used in graphic presentation of PAH data. The MDL for individual PAH or alkyl-PAH isomer groups ranged from 1.2 to 4.7 ng/g dry wt.

Compound	Reporting Code	Compound	Reporting Code
Naphthalene	N	C2-Fluoranthenes/Pyrenes	C2FLU/PYR
C1-Naphthalenes	C1N	C3-Fluoranthenes/Pyrenes	C3FLU/PYR
C2-Naphthalenes	C2N	Benzo[a]anthracene	BaA
C3-Naphthalenes	C3N	Chrysene	C
C4-Naphthalenes	C4N	C1-Chrysenes	C1C
Biphenyl	BIP	C2-Chrysenes	C2C
Acenaphthene	ACE	C3-Chrysenes	C3C
Acenaphthylene	ACY	C4-Chrysenes	C4C
Fluorene	F	Benzo[b]fluoranthene	BbFLU
C1-Fluorenes	C1F	Benzo[k]fluoranthene	BkFLU
C2-Fluorenes	C2F	Benzo[e]pyrene	BeP
C3-Fluorenes	C3F	Benzo[a]pyrene	BaP
Anthracene	A	Perylene	PER
Phenanthrene	P	Indeno[1,2,3-c,d]pyrene	IcdPYR
C1-Phenanthrenes/Anthracenes	C1P	Dibenzo[a,h]anthracene	DBahA
C2-Phenanthrenes/Anthracenes	C2P	Benzo[g,h,i]perylene	BghiP
C3-Phenanthrenes/Anthracenes	C3P	Total PAH	TPAH
C4-Phenanthrenes/Anthracenes	C4P	Surrogate Compounds	
Dibenzothiophene	DBT	Naphthalene-d8	
C1-Dibenzothiophenes	C1DBT	Acenaphthene-d10	
C2-Dibenzothiophenes	C2DBT	Phenanthrene-d10	
C3-Dibenzothiophenes	C3DBT	Benzo(a)pyrene-d12	
Fluoranthene	FLU	Internal Standard	
Pyrene	PYR	Fluorene-d10	
C1-Fluoranthenes/Pyrenes	C1FLU/PYR	Chrysene-d12	

The GC/MS analysis of the F1 and F2 fractions for StTr and PAH was performed by a modification of USEPA Method 8270 that included additional target compounds (e.g., alkyl PAH and hydrocarbon biomarkers), and obtained lower detection limits and better specificity by operating the detector in the selected ion monitoring (SIM) mode. Analytical instruments were

calibrated before sample analysis with a 5-point calibration (minimum) and varying level check standards were analyzed every 10 samples bracketing field and quality control sample analysis. A North Slope crude reference oil, North Star control oil, and a series of other quality control (QC) samples were analyzed with the samples. A PAH independent check QC sample also was analyzed.

Table 2-5. Target saturated hydrocarbons (SHC), including the n-C_9 through n-C_{40} normal alkanes, pristane, phytane and selected isoprenoids, analyzed in sediments and soft tissues of marine animals in the ANIMIDA and cANIMIDA Programs. The MDL for individual saturated hydrocarbons ranged from 40 to 190 ng/g dry wt.

nC_8 (optional)	1650	nC_{23}	nC_{33}
nC_9	nC_{16}	nC_{24}	nC_{34}
nC_{10}	nC_{17}	nC_{25}	nC_{35}
nC_{11}	Pristane	nC_{26}	nC_{36}
nC_{12}	nC_{18}	nC_{27}	nC_{37}
nC_{13}	Phytane	nC_{28}	nC_{38}
1380	nC_{19}	nC_{29}	nC_{39}
nC_{14}	nC_{20}	nC_{30}	nC_{40}
1470	nC_{21}	nC_{31}	Total SHC
nC_{15}	nC_{22}	nC_{32}	

Table 2-6. Target sterane and triterpane (StTr) petroleum biomarkers analyzed in sediments and soft tissues of marine animals collected in the ANIMIDA and cANIMIDA program from the Beaufort Sea. Reporting codes are used in graphic presentation of PAH data. The MDL for individual StTr ranged from 0.01 to 4.7 ng/g dry wt.

Compound	Reporting Code	Compound	Reporting Code
C_{23}-Diterpane	T4	13β,17α-Diacholestane-20S	S4
C_{29}-Tricyclictriterpane	T9	13β,17α-Diacholestane-20R	S5
C_{29}-Tricyclictriterpane	T10	5α,14α,17α,24-Methylcholestane-20R	S24
18α(H)-22,29,30-Trisnorhopane-TS	T11	5α,14α,17α,24-Ethylcholestane-20S	S25
17α(H)-22,29,30-Trisnorhopane-TM	T12	5α,14α,17α,24-Ethylcholestane-20R	S28
17α(H),21β(H)-30-Norhopane	T15	Unidentified Ethylcholestane	S28a
18α(H)-Oleanane	T18	Surogate Compound	
17α(H),21β(H)-Hopane	T19	5b(H)-Cholane	
22S-17α(H),21β(H)-30-Homohopane	T21		
22R-17α(H),21β(H)-30-Homohopane	T22		

The concentrations of the individual PAH target compounds were calculated versus the internal standards that were spiked into the sample prior to analysis**.** The target compound concentrations were corrected for surrogate recoveries to best represent the original sample concentration. The PAH concentrations were quantified using average relative response factors (RRF) generated

from the five point calibration. The RRF of the alkyl homologues were based on the RRF of the parent compound for each alkyl homologue series.

The concentrations of all identified StTr were calculated versus the internal standard chrysene-d12. All target triterpane concentrations were quantified using the average relative response factor of 17b(H), 21b(H)-hopane (T23) generated from the initial calibration. All target sterane concentrations were quantified using the average relative response factor of cholestane (S17) in the initial calibration. The target compound concentrations were corrected for surrogate recovery. Surrogate recovery of 5 β (H)-cholane was calculated relative to the internal standard.

F1 fractions were analyzed by GC/FID to determine concentrations of SHC. Instrumental methods, maintenance, and QC procedures for the GC/FID analysis of samples were performed by a modification of USEPA Method 8015. Analytical instruments were calibrated before sample analysis with a 5-point calibration (minimum) and check standards bracketed the analytical run of field and quality control samples.

The n-C9 through n-C40 normal alkanes, pristane, phytane and selected isoprenoids were determined in the extract (Table 2-5). The total (resolved and unresolved) saturated hydrocarbons (TSHC) also were determined. A reference sample of North Slope crude oil was analyzed with the samples. Quantification of the compounds was based on the internal standard compound (d62-triacontane) that was spiked into the sample just prior to analysis. The target compound concentrations were corrected for surrogate recovery.

2.2.5 Analysis of CYP1A Activity and Bile Fluorescent Aromatic Compounds (FAC) in Fish

Bile samples were collected from several species of fish collected in 2004 and 2005, but not 2006 and analyzed for fluorescing aromatic compounds (FACs). FAC concentrations were quantified by HPLC- fluorescence spectroscopy, with the detector excitation and emission wavelengths optimized for separate analysis of naphthalene-equivalent, phenanthrene-equivalent, and benzo(a)pyrene-equivalent metabolites.

Fish tissues or whole fish (small specimens) collected in 2004 and 2005 at Beaufort Sea stations were fixed in formalin in the field for analysis by immunohistochemistry for CYP1A activity. The immunohistochemical method for CYP1A staining was described by (Smolowitz et al., 1991).

3 RESULTS

3.1 Sources of Suspended Sediments, Metals, and Hydrocarbons in the Coastal Beaufort Sea

On the Alaskan North Slope, the frozen tundra and snow pack upstream begin to melt during spring and meltwater slowly flows downstream (northward), melting the river water en route. The meltwater carries particulate and dissolved components frozen in the ice and snow from the previous year along with weathered rock and soil layers from the surrounding river banks. This thawing and weathering contribute to the specific chemical compositions of the particulate and aqueous phases carried by each river. During high discharge, that lasts only 1 to 2 weeks, Alaskan Arctic rivers typically transport 40 to 80% of their total annual discharge of water and >80% of their load of suspended sediments (Rember and Trefry, 2004).

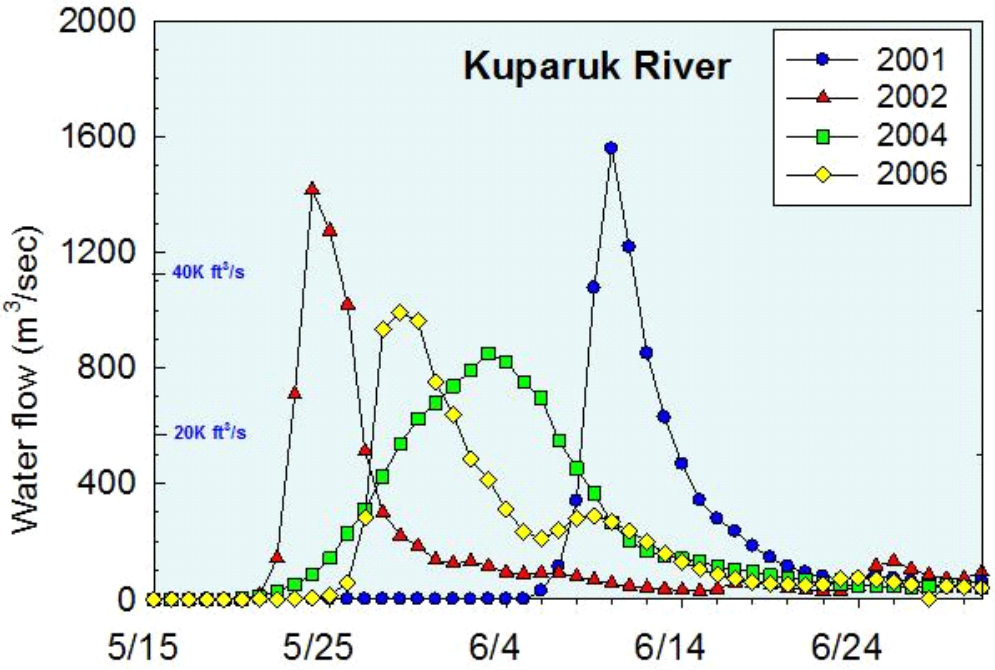
Spring floods under-ice were tracked during 2004 and 2006 in Stefansson Sound, a small and shallow area (average water depth <15 m) located offshore of the North Slope of Alaska and partially protected by barrier islands that separate it from the Beaufort Sea. Seasonal landfast ice (~2 m thick) that covers the area from October through April begins to melt in late May and eventually breaks up and blows offshore in July (Weingartner and Okkonen, 2001). During the spring melt, Alaskan Arctic rivers, including the Sagavanirktok River, flow at maximum discharge above and below the landfast ice. The ambient shelf water has a salinity that ranges from 28 ‰ (July-September) to 34 ‰ (mixing with brine drainage during ice formation in winter) with spring salinity of 31 to 32 ‰ and temperatures of -1.6 to -1.8°C that increase to as high as 4°C during the summer open water period (Weingartner and Okkonen, 2001). This shelf water is referred to here as the Polar Mixed Layer (PML), a term adopted from MacDonald et al. (1989). Circulation in the study area varies with the season as the presence of the ice determines the influence of winds on water movement. The area has a tidal range of ~0.2 m with currents that range from <1 to 24 cm s^{-1} and average 2 cm s^{-1}, with <10% of the current magnitudes >10 cm s^{-1} during the landfast ice period (Matthews, 1981; Weingartner and Okkonen, 2001).

3.1.1 Transport of Water, Sediments, and Chemicals from North Slope Rivers during the Spring Melt

3.1.1.1 Water and Sediment Transport from Rivers During the Spring Melt

During the 2 to 3 weeks of the spring floods in May-June, about 60% of the annual water flow from the Kuparuk River and about one third of the annual flow of the Sagavanirktok River are carried to the Beaufort Sea (Rember and Trefry, 2004). Although the overall trends in annual flow are similar, inter-annual variations and differences between rivers are observed in hydrographs during the spring melt (Figure 3-1).

The Kuparuk River can be categorized as a tundra stream with most of the water derived from the tundra and foothills, not the mountains. Water and sediment discharge from the Kuparuk River usually occurs as a brief event (3-5 days) when upstream ice jams break up and allow a large pulse of water to pass down the river. The date of peak flow can vary by up to a month (Figure 3-1).



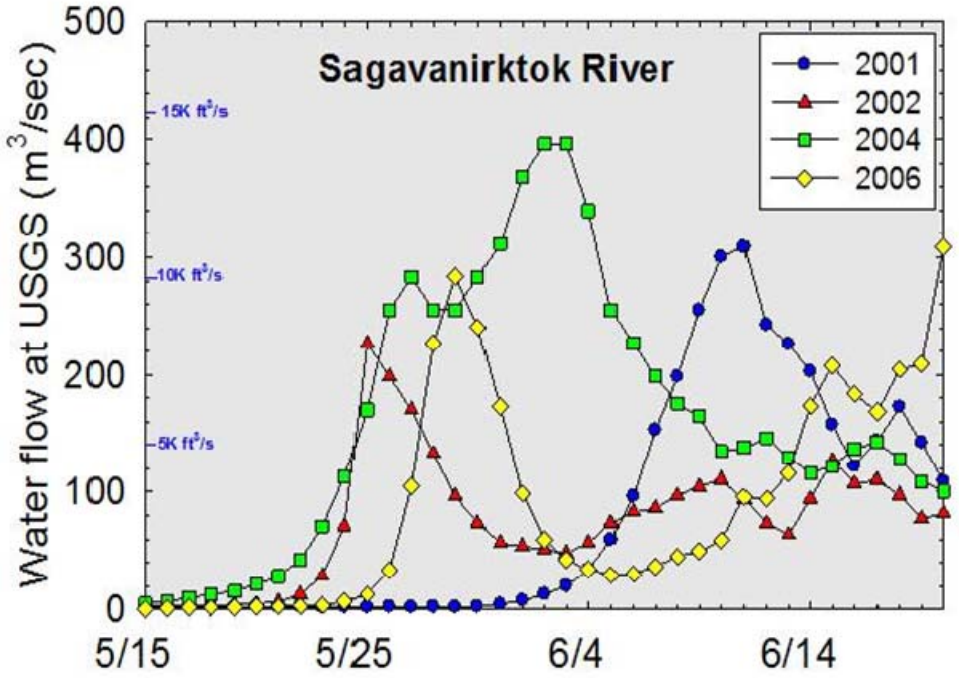


Figure 3-1. Hydrographs during the spring floods in 2001, 2002, 2004 and 2006 for the Kuparuk and Sagavanirktok rivers. Data from U.S.G.S. can be accessed at http://waterdata.usgs.gov/ak/nwis.

The Sagavanirktok and Colville rivers can be classified as mountain streams that drain snowfields and glaciers in the Brooks Range. Peak flow, though quite pronounced, tends to extend over a longer time period than observed in the Kuparuk River (Figure 3-1). The dates of peak flow in the Kuparuk and Sagavanirktok Rivers coincided within just a few days (Figure 3-1). However, the annual discharge of the Sagavanirktok River has increased by about 50% over the past 3 decades, probably caused by increased precipitation in the headwaters in the Brooks Range. There has been no discernable change in water flow of the Kuparuk River, which drains the tundra, over a similar time period. Concentrations of total suspended solids (TSS) in the spring flow water from the Sagavanirktok and Kuparuk Rivers in 2001, 2002, 2004, and 2006 and from the Colville River in 2001 and 2006 were highly variable both among years and within each annual spring flood (Table 3-1). TSS concentrations were highest in the Colville River and lowest in the Kuparuk River. Concentrations varied on a daily basis. Thus, the suspended matter load in the river water that was moving offshore under the ice varied on a daily basis. All TSS concentrations in rivers during summer were 10 to >300 times lower than during the spring melt. About 90% of the annual transport of TSS from the rivers occurs during the spring floods.

Table 3-1. Mean, maximum and minimum concentrations of total suspended solids (TSS) in the Kuparuk, Sagavanirktok and Colville Rivers during May-June of the years listed. From Trefry et al. (2009).

River and Year		n	TSS – Mean (mg/L)	TSS – Max. (mg/L)	TSS- Min. (mg/L)
Kuparuk	2006	10	25	60	4.6
	2004	8	60	106	32
	2002	14	19	120	0.5
	2001	10	27	67	1.8
Sagavanirktok	2006	13	130	353	9.5
	2004	11	127	285	43
	2002	26	92	244	3.5
	2001	27	158	609	14
Colville	2006	3	722	785	637
	2001	13	343	545	42

3.1.1.2 Particulate Metals and Organic Carbon in River Water

The composition of suspended matter in rivers can provide a geochemical signature that may allow differentiation between incoming natural suspended sediments and anthropogenic contributions from industrial activity in the coastal Beaufort Sea. Furthermore, changes in the composition of the river-borne particles may help identify future shifts in mechanical and chemical weathering in the Brooks Range and across the North Slope that may be related to changing climate and other processes.

Concentrations of Al in suspended sediments were highest in the Colville and lowest in the Kuparuk River. However, Ca concentrations were about 8 to 10 times higher in Sagavanirktok River suspended sediments than in those from the Kuparuk or Colville Rivers (Figure 3-2).

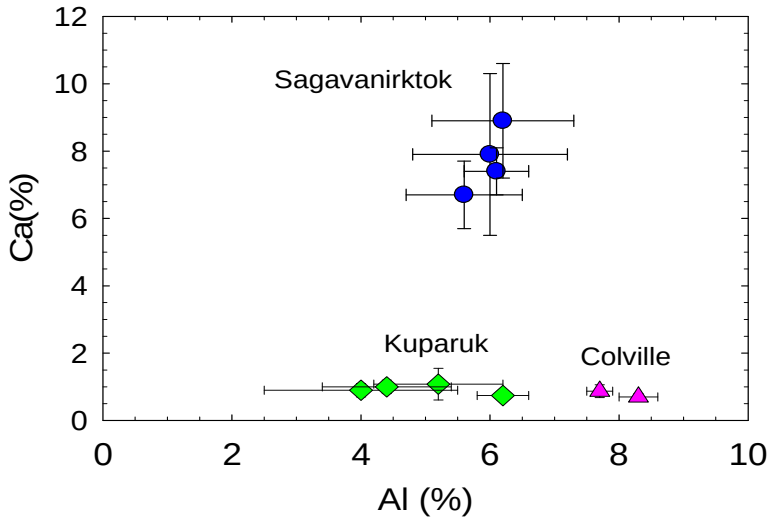


Figure 3-2. Concentrations of calcium (Ca) versus aluminum (Al) for suspended sediments from the Sagavanirktok (circles), Kuparuk (diamonds), and Colville (triangles) Rivers during 2001, 2002, 2004 and 2006. Markers show means and lines show standard deviations. From Trefry et al. (2009).

These differences are directly related to the greater abundance of aluminum-bearing phases (clay minerals) in the Colville River relative to the Sagavanirktok and Kuparuk Rivers, as well as the much greater abundance of particulate calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$ in the Sagavanirktok River. Unfortunately, the differences in the Ca/Al ratios among suspended sediments from the three rivers were not readily observed in coastal sediments, because of the presence of particulate calcite from marine invertebrate shells in coastal sediments.

There also were differences in K and Mg concentrations in river suspended sediments. Concentrations were slightly higher in suspended sediments from the Colville River than in those from the other two rivers. However, there was a good correlation between both K and Mg and Al for all river suspended sediments. This trend suggests that the source minerals bearing K (most likely illite clays with some micas and potassium feldspars) are similar enough for each river that the linear variations are due to differences in the relative amounts of K phases in the suspended sediments. A similar relationship between Mg and Al supports common source minerals, such as chlorite, $Mg(ClO_2)_2$, for Mg.

Concentrations of trace metals in river suspended matter provide another possible point of reference for differentiating among river sources of sediment and for comparison with bottom sediment in the cANIMIDA study area. Such comparisons may enable us to determine whether incoming suspended particles have been modified by chemical processes in marine sediments or if metal concentrations in marine sediments have been enhanced by anthropogenic inputs.

Mean concentrations of particulate Ba, Cu, Fe, Ni and Pb in the Colville River averaged ~20 to ~50% higher than concentrations in suspended particles from the Sagavanirktok and Kuparuk rivers (Table 3-2). However, suspended sediments from the Colville River also contained higher concentrations of Al, suggesting that suspended sediments in the Colville River, originating

farther to the west in the Brooks Range, have been more thoroughly sorted during transport, resulting in enrichment of metal-rich fine-grained aluminosilicates relative to coarser non-aluminosilicate minerals than suspended sediments in the other two rivers.

When concentrations of particulate Fe were plotted versus Al (Figure 3-3), the results for the Sagavanirktok River fit the same Fe/Al trend reported for sediments in the coastal Beaufort Sea (Trefry et al., 2003). Concentrations of Fe were as much as ~10% higher than predicted from the Beaufort Sea sediment data in most of the suspended sediment samples from the Kuparuk and Colville rivers. Higher concentrations of dissolved Fe in the Kuparuk and Colville Rivers may enhance the formation of insoluble Fe hydrous oxides, increasing concentrations of particulate Fe as described by Rember and Trefry (2004).

More than 85% of the data points for Ba, Cu, Cr, Ni and Pb in suspended sediments from the three rivers during 2004 and 2006 plotted below the upper prediction intervals on the metal versus Al graphs, as shown for the plot of Ba versus Al concentrations in river suspended sediments (Figure 3-4). The higher metal concentrations, that plotted at <25% above the upper prediction interval, were from the Kuparuk River that usually contained lower concentrations of TSS with more variable metal concentrations than the other rivers (Table 3-2). Some of the observed anomalies in metal/Al ratios for Ba, Cu, Cr, Ni, Pb, and Zn may be due to anthropogenic inputs of metals from industrial activities on the North Slope. With the large data base from 2001 to 2006, river particles may provide a useful long-term tool for monitoring inputs of metals from land to the cANIMIDA study area.

Table 3-2. Mean and range of concentrations of metals and total particulate organic carbon (POC) in suspended sediments collected in the Kuparuk and Sagavanirktok Rivers in the spring (May-June) of 2001-2, 2004, and 2006 and in the Colville River in the spring of 2001 and 2006. Concentrations are % or µg/g (parts per million) on a dry-weight basis. From Trefry et al. (2009).

Metal	Kuparuk R. (2001-2, 2004, 2006)	Colville R. (2001, 2006)	Sagavanirktok R. (2001-2, 2004, 2006)
Aluminum (Al) (%)	5.0 (2.6 - 7.5)	8.0 (7.5 - 8.9)	6.0 (4.0 - 8.8)
Arsenic (As) (µg/g)	11.6 (3.9 - 29.7)	12.2 (10.2 - 15.3)	11.1 (4.7 - 24.5)
Barium (Ba) (µg/g)	591 (358 - 1219)	964 (887 - 1190)	652 (433 - 1110)
Calcium (Ca) (%)	0.9 (0.6 - 2.2)	0.8 (0.58 - 1.05)	7.7 (3.6 - 10.9)
Copper (Cu) (µg/g)	30.1 (17.6 - 45.1)	38.8 (35.3 - 42.6)	31.7 (23 - 45)
Iron (Fe) (%)	4.0 (2.7 - 5.4)	4.9 (4.5 - 5.3)	3.4 (2,6 - 4,7)
Potassium (K) (%)	1.3 (0.6 - 1.1)	2.0 (1.3 - 2.2)	1.6 (1.3 - 2.5)
Magnesium (Mg) (%)	0.6 (0.5 - 1.1)	1.2 (0.8 - 1.4)	1.0 (0.7 - 13)
Nickel (Ni) (µg/g)	44.0 (28.6 - 63.8)	63.3 (52 - 81)	52.0 (27 - 76)
Lead (Pb) (µg/g)	14.2 (5.0 - 24.6)	21.8 (18 - 36)	14.3 (4.0 - 27)
Zinc (Zn) (µg/g)	133 (81 - 264)	129 (116 - 147)	136 (109 - 214)
Particulate organic carbon (POC) (%)	4.5 (1.6 - 7.8)	2.2 (1.7 - 3.3)	1.6 (0.7 - 3.0

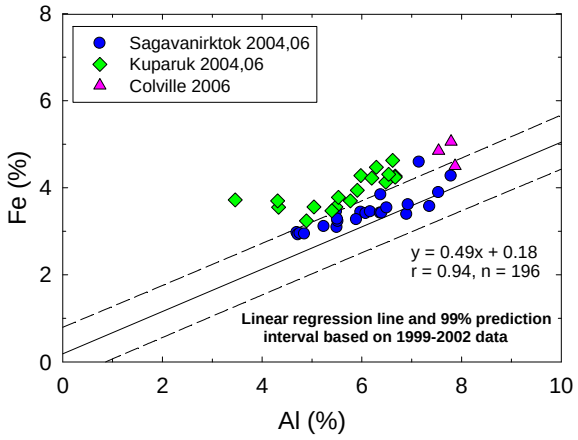


Figure 3-3. Concentrations of iron (Fe) versus aluminum (Al) for suspended sediments from the Sagavanirktok (circles), Kuparuk (diamonds) and Colville (triangles) Rivers during May-June 2004 and 2006. Solid line is from a linear regression for sediment data from the ANIMIDA study area and dashed lines show 99% prediction interval for sediment data. From Trefry et al. (2009).

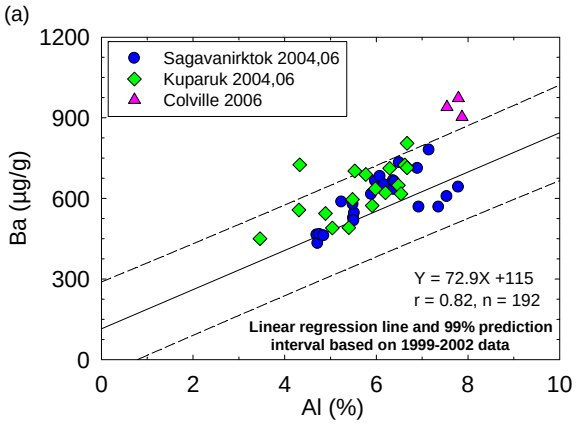


Figure 3-4. Concentration of barium (Ba) versus aluminum (Al) for suspended sediments from the Sagavanirktok (circles), Kuparuk (diamonds), and Colville (triangles) Rivers during May-June 2004 and 2006. Solid lines are from linear regressions for sediment data from the ANIMIDA study area and dashed lines show 99% prediction intervals for sediment data. From Trefry et al. (2009).

Concentrations of POC (as a % of TSS) varied by factors of 2 to 5 in each of the rivers between 2001 and 2006, with the highest POC concentrations in Kuparuk River suspended sediments (Table 3-2).

3.1.1.3 Dissolved Metals and Organic Carbon in River Water

Concentrations of dissolved trace metals, defined as metals that pass a 0.4-µm polycarbonate membrane filter, in North Slope rivers can be quite variable during the spring floods and often reach maximum concentrations during peak flow (Rember and Trefry, 2004; Trefry et al., 2004b). This trend for maximum concentrations of dissolved trace metals during peak flow in spring is influenced by the discharge of soil interstitial water and shallow surface water that is diluted by snow melt and flushed from surrounding soils into the rivers. During the short summers, the arctic coastal plain is covered with pools of standing water and lakes, into which trace metals are leached from soils. The permafrost and a relatively flat topography on the coastal plain inhibit lateral water flow during the summer months, extending the residence time of the surface water in the system. After the long frozen winter (8 to 9 months), increased surface runoff in the spring provides a direct pathway for the release of accumulated and freshly leached metals into the rivers from the thawing ponds and soils.

Mean and range of concentrations of dissolved metals in the Kuparuk, Sagavanirktok and Colville Rivers during May-June 2001, 2002, 2004 and 2006, are summarized in Table 3-3. The mean dissolved Fe concentrations were 3.5 and 4.4 times higher in water collected in May-June from the Kuparuk and Colville Rivers, respectively, than in water collected at the same times from the Sagavanirktok River. The maximum concentrations of dissolved Fe and other metals occurred in all three rivers near the time of peak flow. The higher concentrations of dissolved Fe in Kuparuk and Colville River water may be related to higher concentrations of dissolved organic carbon (DOC) and lower pH in these waters than in Sagavanirktok River water. The high DOC concentration and lower pH tend to enhance leaching and transport of dissolved Fe and other metals.

Concentrations of most other dissolved metals also were highly variable and were highest near the times of peak flow. However, concentrations of dissolved Ba and Ca did not vary much during spring in Sagavanirktok and Colville River water, but were highly variable in Kuparuk River water (Table 3-3). The concentration of dissolved Ca was higher in Sagavanirktok River water than in water from the other two rivers, reflecting the high concentration of calcite in suspended sediments (Table 3-2). Concentrations of dissolved As, Cu, Mn, and Zn also were highly variable in Kuparuk River water, possibly reflecting changes in redox potential in the waterlogged tundra sediments draining into this river.

Concentrations of DOC were measured in water from the Sagavanirktok, Kuparuk, and Colville Rivers during peak and off-peak flow in June 2001 (Rember and Trefry, 2004; Trefry et al., 2004b). Mean DOC concentrations during peak flow ranged from 5.0 mg/L in the Sagavanirktok River to 14.0 mg/L in the Kuparuk River (Table 3-3). These DOC concentrations were higher than those in river water during off-peak flow. DOC tends to complex with dissolved metals and hydrocarbons, increasing their apparent solubility.

Table 3-3. Mean and range of concentrations of dissolved (passing a 0.45 µm filter) metals in water collected in the Kuparuk and Sagavanirktok Rivers in the spring (May-June) of 2001-2, 2004, and 2006 and in the Colville River in the spring of 2001 and 2006. Concentrations of dissolved organic carbon (DOC) in river water samples collected in June 2001 are included (ANIMIDA task 7: Trefry et al., 2004). Concentrations are µg/L (parts per billion) or mg/L (parts per million). From Trefry et al. (2009).

Metal	Kuparuk R. (2001-2, 2004, 2006)	Colville R. (2001, 2006)	Sagavanirktok R. (2001-2, 2004, 2006)
Arsenic (As) (µg/L)	0.065 (0.041 - 0.153)	0.14 (0.12 - 0.16)	0.068 (0..05 - 0.11)
Barium (Ba) (µg/L)	20.1 (3.5 - 79.3)	50 (46 - 54)	26.4 (16.1 - 35.1)
Calcium (Ca) (mg/L)	11.2 (3.4 - 41.6)	9.3 (5.7 - 11.9)	27.8 (20.3 - 37.0)
Cadmium (Cd) (µg/L)	0.011 (0.003 - 0.038)	0.008 (0.007 - 0.010)	0.015 (0.006 - 0.062)
Chromium (Cr) (µg/L)	0.10 (0.08 - 0.15)	0.12 (0.11 - 0.12)	0.122 (0.08 - 0.206)
Copper (Cu) (µg/L)	0.46 (0.05 - 0.99)	2.1 (1.5 - 2.7)	0.55 (0.06 - 1.6)
Iron (Fe) (µg/L)	120 (17 - 259)	148 (60 - 282)	34 (1.0 - 7.2)
Magnesium (Mg) (mg/L)	1.3 (0.5 - 3.9)	2.6 (1.8 - 3.6)	3.6 (1.0 - 7.2)
Manganese (Mn) (µg/L)	18 (0.5 - 94)	22 (8 - 53)	10 (1.3 - 20.2)
Nickel (Ni) (µg/L)	0.7 (0.1 - 1.2)	1.6 (1.2 - 2.3)	0.72 (0.33 - 1.27)
Lead (Pb) (µg/L)	0.032 (0.003 - 0.066)	0.060 (0.039)	0.020 (0.006 - 0.040)
Zinc (Zn) (µg/L)	0.45 (0.11 - 2.37)	0.29 (0.12 - 0.47)	0.42 (0.03 - 3.6)
Dissolved organic carbon (DOC) (mg/L)	14 (12.6 - 15.8)	10.0 (8.0 - 13.2)	5.0 (2.0 - 8.9)

3.1.2 Partitioning of Metals between Dissolved and Particulate Phases in River Water and Beaufort Sea Water

An understanding of the chemical forms of metals in river water and coastal seawater is essential for understanding chemical reactions and bioaccumulation of the metals. Dissolved metals are more reactive and bioavailable than solid metals. Therefore, the kinetics of dissolution and precipitation of metals in waters of different hardness and salinity has a strong influence on the bioaccumulation and toxicity of the metals to aquatic plants and animals (Neff, 2002a).

A simple distribution coefficient (K_d) has been used to provide one perspective on metal partitioning between dissolved and particulate phases, and resulting bioavailability to marine organisms (Neff, 2008). Therefore, a K_d can be used to model the behavior of dissolved and particulate Ba during the spring flood of river water. Distribution coefficients were calculated in this study as:

$$K_d = \frac{\text{(concentration of particulate metal in µg metal/g particles)}}{\text{(concentration of dissolved metal in µg metal/g water)}}$$

Despite significant differences in concentrations of dissolved and particulate Ba (Tables 3-2 and 3-3) among the three North Slope rivers, the K_d values calculated for Ba were statistically equal

(t-test, $\alpha = 0.05$). These results suggest that partitioning of Ba between dissolved and particulate phases is a quasi-equilibrium controlled process between free Ba^{2+} and suspended particles. Considering the large variations in water discharge, TSS, and concentrations of organic carbon, the apparent uniformity of the distribution coefficients for Ba indicates that discharge of TSS and organic carbon have little impact on the partitioning of Ba between dissolved and particulate phases. Each of the other metals has similar K_d values in spring flood waters from the three rivers (Table 3-4).

Table 3-4. Mean and standard deviation distribution coefficients (K_d) for metals in spring flood water from the Sagavanirktok, Kuparuk, and Colville Rivers. K_d is the ratio of the concentration of particulate metal in water (µg metal/g particles) to the concentration of the dissolved metal in water (µg metal/g water). From Trefry et al. (2009).

Metal	Sagavanirktok River		Kuparuk River		Colville River
	2004	2006	2004	2006	2006
Arsenic (As)	5.20 ± 0.20	5.11 ± 0.11	4.99	4.91 ± 0.21	4.89 ± 0.10
Barium (Ba)	4.55 ± 0.04	4.36 ± 0.08	5.01 ± 0.10	4.44 ± 0.19	4.29 ± 0.01
Calcium (Ca)	3.53 ± 0.05	3.33 ± 0.33	3.25 ± 0.09	2.96 ± 0.11	2.95 ± 0.03
Cadmium (Cd)	4.58 ± 0.12	4.68 ± 0.15	4.48 ± 0.15	4.85 ± 0.24	4.70 ± 0.11
Chromium (Cr)	5.89 ± 0.11	5.78 ± 0.13	5.90	5.80 ± 0.15	5.88 ± 0.04
Copper (Cu)	4.82 ± 0.18	4.62 ± 0.20	5.32 ±0.35	4.70 ± 0.13	4.25 ± 0.06
Iron (Fe)	5.99 ± 0.24	5.61 ± 1.15	5.50 ± 0.10	5.45 ± 0.18	5.47 ± 0.06
Potassium (K)	4.64 ± 0.11	4.32 ± 0.35	4.43 ± 0.08	4.16 ± 0.12	4.24
Magnesium (Mg)	3.52 ± 0.08	3.37 ± 0.34	4.04 ± 0.10	3.75 ± 0.21	3.75 ± 0.02
Manganese (Mn)	4.78 ± 0.11	4.75 ± 0.17	4.54 ± 0.08	4.63 ± 0.41	5.05 ± 0.04
Nickel (Ni)	5.04 ± 0.08	4.98 ± 0.10	5.37 ± 0.22	4.94 ± 0.07	4.68 ± 0.03
Lead (Pb)	5.99 ± 0.22	5.71 ± 0.17	5.81 ± 0.34	5.68 ± 0.19	5.70 ± 0.04
Zinc (Zn)	5.71 ± 0.10	5/32 ± 0.29	5.61 ± 0.23	5.33 ± 0.24	5.55 ± 0.15

Metal K_d values provide a useful tool for predicting the bioavailability of metals in suspended sediments and surficial bottom sediments. Metals with high K_d values will be present almost exclusively in the low-bioavailability solid phase, whereas, a potentially significant fraction of metals with low K_d values may be in bioavailable, potentially toxic forms. By this metric, only the alkaline earths, Ca and Mg, both essential micronutrients, are likely to be highly bioavailable to freshwater and marine animals (Table 3-4).

The use of a K_d is more complicated in rivers and seawater when concentrations of DOC change. For example, increased concentrations of dissolved Cu, Pb, and Zn in rivers during peak discharge occur despite relatively constant concentrations of particulate metals. These results suggest that a K_d is less likely to explain dissolved concentrations of these metals. During peak discharge, K_d values (x 10^4) for Cu (4.4), Pb (116) and Zn (67) were 40 to 50% lower than during off-peak discharge in the Sagavanirktok River. In contrast, concentrations of DOC were ~40% greater during peak discharge. Strong correlations between dissolved metals and DOC suggest that elevated concentrations of organic ligands during peak discharge alter partitioning of

Cu, Pb and Zn between dissolved and particulate phases. Thus, K_d values, are potentially more useful in low or more uniform DOC riverine environments. Results from previous studies in rivers have shown that distribution coefficients for Cu, Pb and Zn often have order-of-magnitude differences where a large fraction of the variance can be explained by concentrations of DOC (Shafer et al., 1999).

3.1.3 Dispersion of River Water, Suspended Sediments, and Chemicals Under the Ice in the Beaufort Sea

The high water flow from rivers during the spring floods is carried to a Beaufort Sea that is covered with ~2-m thick, land-fast ice. Thus, the river water flows out above and below the ice. The fresh and relatively warm (slightly >0° C) discharge from the rivers flows out onto and then under the land-fast ice where it mixes with the colder marine waters (-1.8° C) forming a 1-2 m thick under-ice lens of brackish waters that can extend >15 km offshore. This under-ice mixing takes place in the absence of wind and wave effects and sets the stage for the estuarine conditions and stratification that dominate nearshore regions during the early to mid open-water time period. Furthermore, river water that is not advected off the shelf can retain its distinct geochemical signature and move with the local circulation (Granskog et al., 2005).

The main objectives of components of cANIMIDA Task 3 & 4 were to track the under-ice river water during the spring melt and to identify general flow patterns and behavior of freshwater, dissolved and particulate chemicals, and potential contaminants from the Sagavanirktok and Kuparuk Rivers. This information can be used to help predict dispersion patterns for freshwater, suspended sediments, dissolved chemicals and potential contaminants originating from activities on the North Slope of Alaska. The under-ice movement of freshwater plumes is an important component of potential spill trajectories as well as biogeochemical models during the period of maximum river discharge when these plumes provide a means for offshore transport of potential contaminants.

During the breakup of the Kuparuk and Sagavanirktok Rivers in 2004, river water initially flowed out over the bottom-fast ice before encountering ice cracks, seal holes, and other breaks in the ice surface that allowed most of the river water to make its way through and under the ice canopy. Typically, over-ice flow extended 5 to 10 km from the river mouths and would sometimes recede after finding passages down through the ice, whereas the under-ice plume of mixed river water was transported up to 15 to 20 km offshore before encountering offshore barrier islands or the shear zone. At least 50% of the total flow of the Sagavanirktok River during the study period could be accounted for as being under ice within the somewhat limited area that was sampled.

3.1.3.1 Dispersion of River Water under Ice in the Beaufort Sea During Spring 2004

River water flow began in both rivers on May 20, 2004. River water, seawater, and ice cores were collected from May 23 to June 2, 2004 during the landfast ice period while rivers were at high flow. River water was sampled daily and seawater was collected over a nine-day period through holes drilled in the ice at 28 stations (Figure 2-2). Vertical profiles of salinity, temperature and turbidity also were obtained at each location. Sampling through the ice was limited to nine days by the time of onset of the floods, weather conditions, and accessibility when nearshore areas flooded above the ice.

Objectives of the under-ice study were to trace the dispersion of freshwater to track the mixing and movement of suspended sediments and dissolved chemicals. Representative salinity and temperature profiles for the Kuparuk River transect stations K1, K3 and K4 (see map in Figure 2-2) show the sharp vertical pycnocline due to the flow of river water under the ice and above seawater (Figure 3-5). The profiles also show increasing salinity in the surface water with distance offshore. No detectable fraction of river water was detected at station K4, the station farthest offshore, even near the end of the sampling period on May 29.

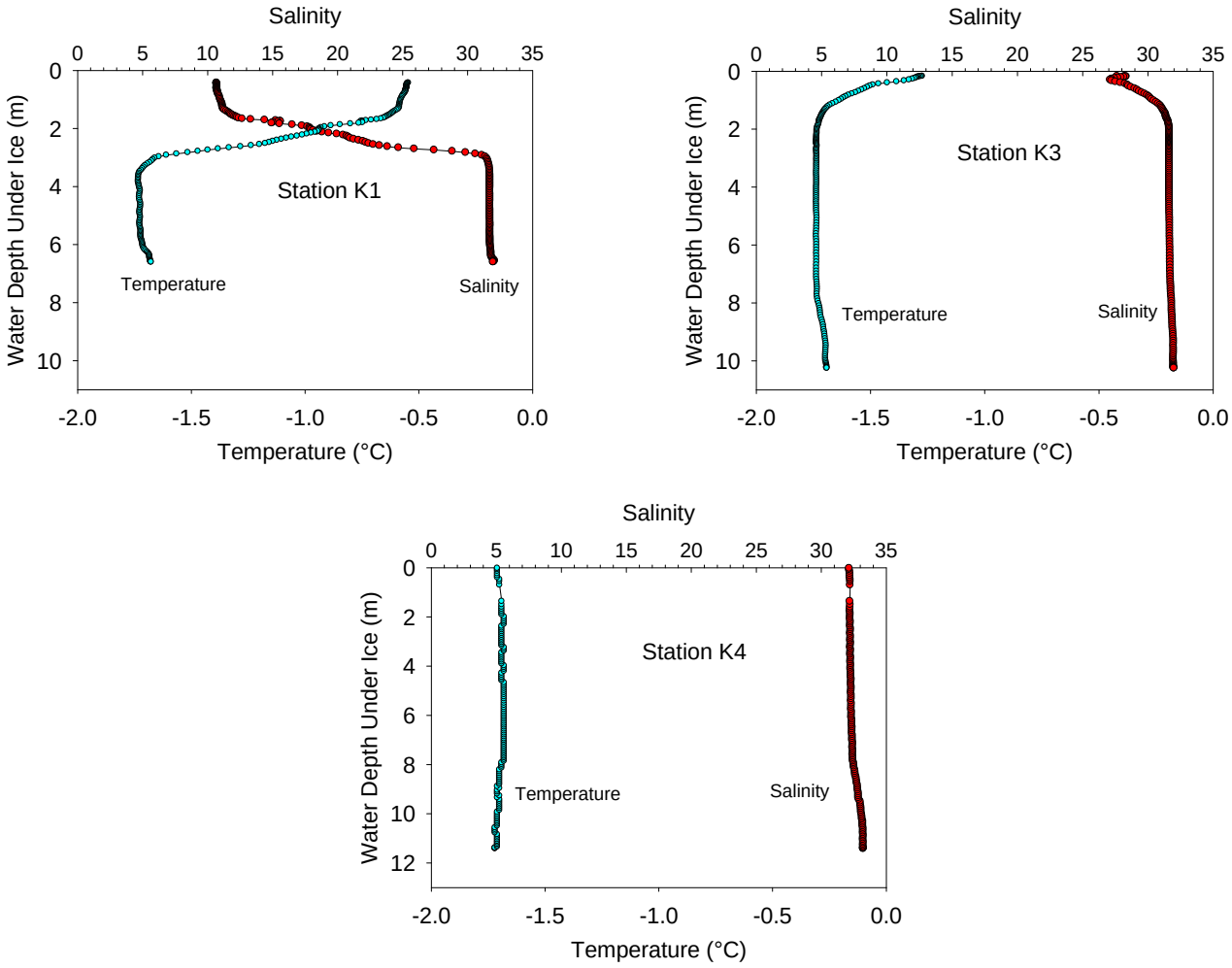


Figure 3-5. Vertical profiles for salinity and temperature for stations K1, K3 on May 23, 2004 and station K4 on May 29, 2004, all located offshore of the mouth of the Kuparuk River (See Figure 2-2 for station locations. From Trefry et al. (2009).

There was a similar rapid shift in salinity off the Sagavanirktok River. Over just six days, the salinity in the surface water decreased from ~18 to 5‰ and the thickness of the pycnocline increased by ~2 m. In 2004, strong haloclines and thermoclines were observed near the mouth of the Sagavanirktok River at Stations SE0 and SE1 (Figure 3-6). River water mixed along a frontal zone as the under-ice plume extended offshore to stations SE2 and SE3. Turbidity in the under-ice river plume decreased with distance from the river mouth as shown in Figure 3-6 for the

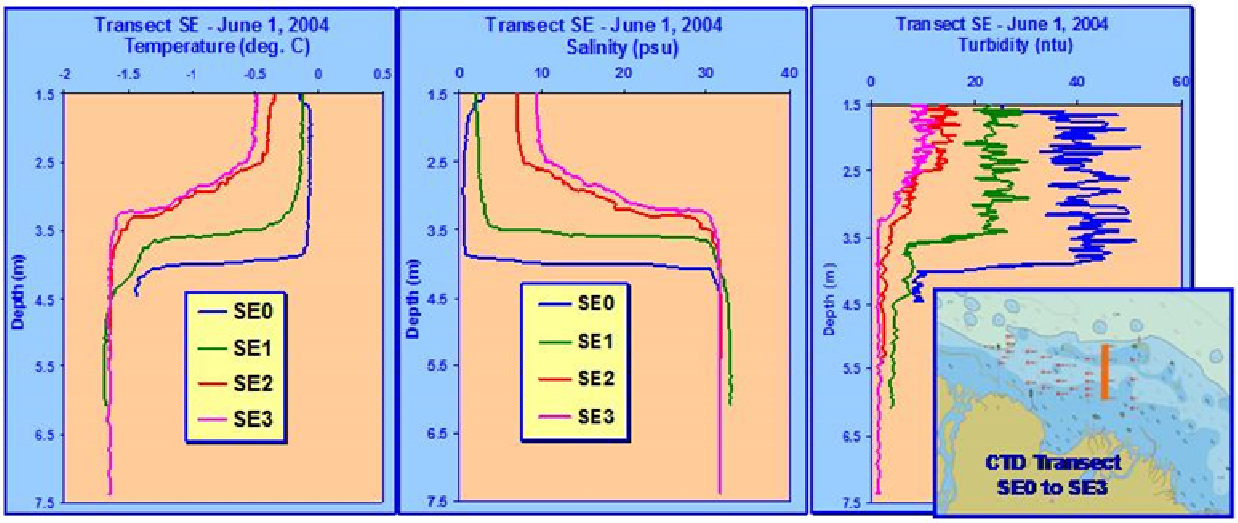


Figure 3-6. Under-ice vertical profiles of temperature, salinity, and turbidity taken along the SE transect off the Sagavanirktok River, starting near the bottom-fast ice zone and extending offshore beyond the barrier islands just south of the offshore shear zone, 1 June 2004. From Trefry et al. (2009).

transect from nearshore station SE0 to offshore station SE3. This trend probably is caused by settling of suspended sediments from the water column. The influence of runoff from both the Kuparuk and Sagavanirktok Rivers extended >15 km from their respective mouths where the under-ice plume encountered the barrier islands and the shear zone offshore of Northstar and Cross Islands (see map in Figure 2-2). Horizontal contour maps of temperature, salinity and turbidity at a depth of 2 m (~0.5 m below the ice canopy) show the under-ice plume extending well offshore. In contrast, turbidity decreased from nearshore to offshore as suspended sediments settled from the water column. The under-ice plume associated with the Sagavanirktok River had much higher concentrations of suspended sediments than the Kuparuk River.

Distinct differences in turbidity patterns at the mouths of the two rivers were observed due to the higher suspended sediment load of the Sagavanirktok River; however, the behavior of the TSS during mixing was non-conservative; therefore, turbidity was not useful for following the seaward progression of freshwater from the two rivers. Two additional variables, $\delta^{18}O$ and dissolved silica, did prove to be useful tracers for the two rivers and were used to determine the relative amounts of river water, seawater and sea ice melt at each station.

Three tracers, salinity, $\delta^{18}O$, and dissolved silica, provided distinct geochemical fingerprints that were used to calculate the relative contributions of four water masses, Sagavanirktok River (SR), Kuparuk River (KR), sea ice melt (SIM) and polar mixed layer (PML), to individual water samples and to trace the under-ice dispersion of freshwater. Some background perspective on use of $\delta^{18}O$ and silica as tracers is provided below.

The $\delta^{18}O$ of water (e.g., $^{1}H^{1}H^{18}O$ versus $^{1}H^{1}H^{16}O$) is zero for standard mean ocean water (SMOW) where

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \times 1000$$

and SMOW is the standard. The $\delta^{18}O$ of freshwater in rivers becomes more negative (richer in ^{16}O relative to the standard) at higher latitudes due to a process called Rayleigh distillation whereby cycles of evaporation and rainfall north of the equator favor the transport of the lighter isotope (^{16}O) away from the equator. Thus, the SR and the KR had $\delta^{18}O$ values of -21.7 and –23.0, respectively, relative to -3.4 in Beaufort Sea water (PML) and -0.8 in SIM. These differences allow $\delta^{18}O$ to be used as a second tracer, one that is independent of salinity.

The strong linear relationship between salinity and $\delta^{18}O$, coupled with marked differences in end-member values for each parameter, yielded two variables that facilitated discrimination between river water and seawater. However, the data for salinity and $\delta^{18}O$ could not be used to effectively differentiate SR from KR water. Despite daily variations in the concentrations of dissolved silica for the SR, silica could be used to distinguish between water from the SR and KR because the endmember values for each river were significantly different. Concentrations of dissolved silica in the SIM also were distinct and helped to better define the contribution from sea-ice melt. Water at some SK stations contained a mixture of SR and KR water. Data points for some of the SW stations plotted below the SR-PML mixing line due to variations in the silica endmember for the SR. Dissolved silica was essentially conservative in the study area because the seasonal landfast ice cover restricted growth of phytoplankton, thereby greatly reducing the amount of biological uptake in the surface water (Granskog et al., 2005; Weingartner and Okkonen, 2001).

The fraction of SR water under ice in Stefansson Sound increased during the late May 2004 flood period. On May 25, the top 1 m of the water column at stations SW1 to SW3 contained 61 to 84% SR water. Three days later, there was an increase in the percent and depth of penetration of SR water along the SW transect. For example, the fraction of SR water increased from 10 to 63% at 1.5 m for station SW2 and from 2 to 29% at 1 m for station SW4. The increased fractions of SR water along the SW transect showed both the seaward and vertical progression of the SR plume.

The largest fractions of SR water ($\geq$90%) were found at depths of 0.5 to 1.5 m along the S1-S4 transect on May 31. Samples in the top 1 m at station S4 contained >60% SR water, even though station S4 was 16.7 km offshore and was the most seaward station sampled (Figure 2-2). The higher fractions of SR water observed along the S transect were partly due to the May 31 sample date. However, station SW4 was re-sampled on May 31 when it had a SR water fraction of 62% at 1 m depth. This fraction was similar to values of 73% and 62% (on May 31) at stations S3 and S4 that were located ~2.7 and 5.6 km farther north, respectively. Therefore, regardless of time, the SR plume progressed predominately along the S transect, as discussed in more detail below.

East of the S transect, the SR plume extended ~6.3 km seaward with $\geq$70% SR water in the top 1 m of the water column at stations SE1 and SE2. However, no detectable SR water was found at stations SE3 and SE4. Collectively, the OMP results supported movement of the SR plume seaward primarily along the S transect and secondarily along the SW transect with some eastward movement along the SE transect closer to shore.

A layer of water with a salinity of 25 to 30‰ was observed beneath the SR plume at ~2.5 m for all stations due to entrainment of denser waters below the pycnocline. As the plume shoaled and the water depth increased (moving offshore), this water layer widened below the plume and surfaced ahead of the front. The observed trend suggested mixing of SR water with another layer

of lower salinity water that was deeper (>1.5 m) in the water column at stations seaward of the SR plume. This additional source of lower salinity water was attributed to inputs of sea-ice melt (SIM) that was pulled downward beneath the seaward-moving plume front via convergence due to a shoreward flow at depth. The percent of SIM was generally <20% throughout the study area, with larger fractions present at stations farther offshore due to greater melting in the vicinity of offshore barrier islands. However, at some nearshore stations (SW1, S1, SE1, and SE2), >10% of SIM was calculated for some water samples. These larger fractions of SIM nearshore may have formed by heat advected directly by the river water or indirectly via the increased absorption of solar radiation from turbid river water flowing above the ice canopy.

The SR plume probably was a single, large structure that moved predominately northward along the S and SW transects and spread >15 km to the west and ~5 km to the east of the S transect (Figure 3-7). Turbulent mixing near the mouth of the SR created a well-mixed, fresher water column that advected seaward with increasing discharge to form a well-stratified flow beneath the ice farther offshore. The spread of the SR plume was limited by entrainment, lateral mixing, and buoyancy forcing.

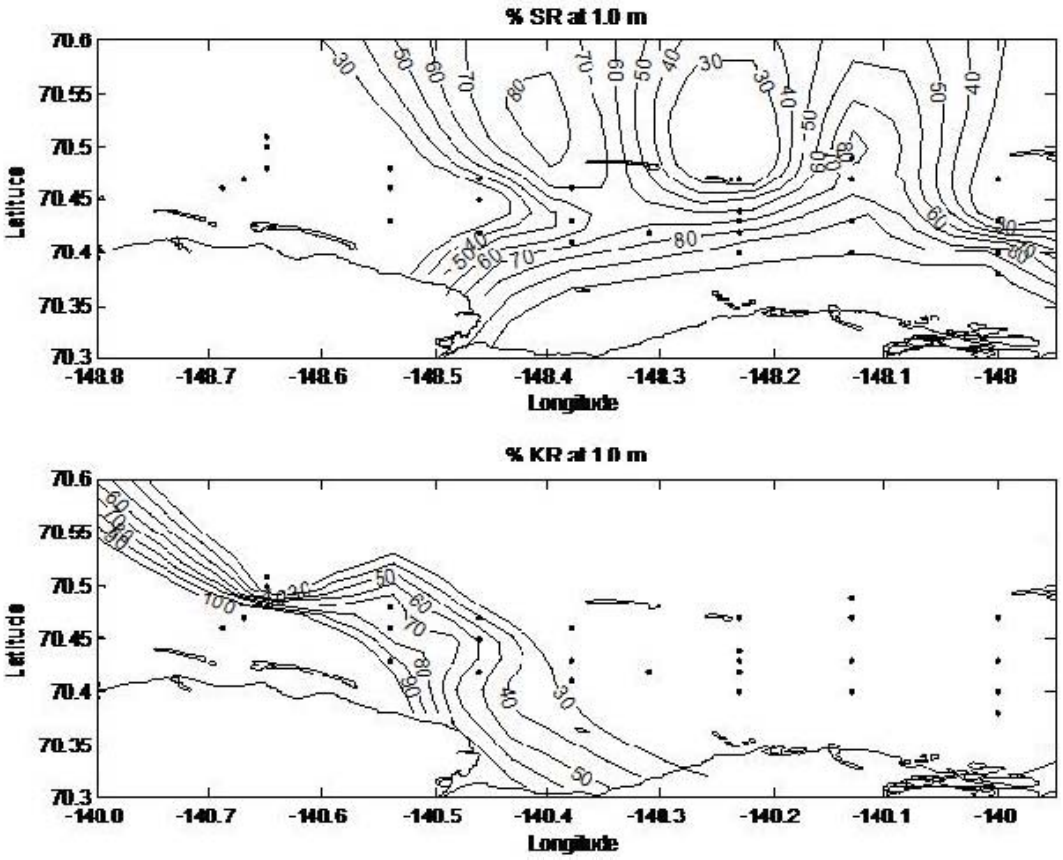


Figure 3-7. Quasi-synoptic view of the percent Sagavanirktok River (SR) water (top) and Kuparuk River (KR) water (bottom) at 1.0 m for May 27-31. Water mass fractions were rounded to the nearest 10%. From Trefry et al. (2009).

Results from the SK stations (SK2-SK10), sampled on May 29 and 30, show the movement of SR water westward as well as the interaction between SR and KR plumes as they converged beneath the ice. Flow from the KR that moved eastward toward the SK stations was channeled by barrier islands and man-made causeways just north of the river mouth that effectively re-directed the plume alongshore.

Approximately equal fractions of ~40-50% SR and KR water were found in the top 1 to 1.5 m of the water column at stations SK5 and SK7, where the two plumes met. The distribution of the water mass fractions suggest a northward flow of plume water as a result of convergence at or shoreward of station SK5 between the SR plume moving west and the KR plume moving east. For example, the eastward flow of the KR plume, with maximum fractions of KR at stations SK8 and SK10, was driven upward to ~1 m depth by increased mixing with SR water that was moving westward and downward from SK2 and SK4. As the two plumes converged, a northward flow may have been generated and guided by the shallower bottom topography to the east. As a result, the KR plume appears to have forced the westward flowing SR water to the north and increased the offshore movement of freshwater.

No SR water was identified at station SK8 and <20% SR water was found at station SK10. Thus, the SR plume did not flow farther west than station SK5, but was advected north to stations SK6 and SK7. In contrast, KR water was abundant to >2 m depth at stations SK8 to SK10 as a result of further re-direction northward by the causeway connecting Point McIntyre and the STP to shore (Figure 2-2) as well as the westward moving SR plume. As a result of mixing between the two plumes along the SK5, SK6, and SK7 transect (meridional), more SR water was advected along the 1.5 m isobath as the SR and KR plumes merged and mixed in the top 1 m of the water column. Furthermore, the decrease in the fraction of KR water east of stations SK8, SK9, and SK10 showed the seaward deflection of the plume due to interaction with the SR water. The KR plume was mixed more easily by turbulence with the oppositely-flowing local circulation. However, the presence of the KR plume was sufficient to force westward-spreading SR water north, increasing the possibility of advection to the outer continental shelf. Such interaction among the many rivers along the northern coast of Alaska may aid in the transport of freshwater off the shelf between barrier islands via convergence of alongshore flows (Weingartner et al., 1999; 2009) and steering by bottom topography (Carmack et al., 1997; Weingartner et al., 2009).

Currents under the ice averaged 7.2 ± 3.2 cm/sec at 309 ± 76° compass direction (n = 40). The current data were categorized as surface (1 and 1.5 m) and sub-surface ($\geq$2.5 m) based on the observed 1-1.5 m thickness of the SR plume. Surface currents, with an average magnitude of 6 ± 3 cm/sec at 313 ± 115° (n = 17) were not significantly different from sub-surface currents that averaged 8 ± 3 cm/sec at 303 ± 34° (n = 23). These results suggest that a landward flow present in the top layer of the water column under ice prior to the spring floods reversed during high river discharge. Water flow in Stefansson Sound was northwestward and parallel to the shoreline for the entire study period. Exceptions to this trend occurred only where there were mixing fronts, changes in bathymetry, or barrier islands. Maximum current velocities of $\geq$10 cm/sec in this study usually were found in regions of plume fronts.

Weak relationships ($r^2 \leq 0.33$) were observed among alongshore and cross-shore current magnitudes, changes in sea level height, and stage height. Thus, local circulation was most likely forced by the baroclinic pressure/density gradient set up by the initial high discharge of river

water over the saline shelf water. We also observed that the northwestward flow of the local circulation contradicts the usual eastward deflection of northward moving waters due to the Coriolis force. This resultant flow was most likely due to the influence of the high intensity of the river runoff as well as possible forcing from the larger scale anti-cyclonic Beaufort Gyre offshore (Weingartner and Okkonen, 2001).

Mixing gradients were calculated using the fractions of SR water along isobaths between stations. These gradients helped to quantitatively support qualitative inferences of SR water movement based on the distributions of water mass fractions. Calculations were carried out for the top 1.5 m of the water column where differences in the SR water mass fractions between stations were >10 %. Gradients were calculated in % km^{-1} as follows:

$$\text{Gradient}\ (z) = ([\%\ \text{River}]_2 - [\%\ \text{River}]_1) / L$$

where flow was assumed to be from station 1 to station 2 (subscripts 1 and 2) along a given sampling depth (z = 0.5, 1, or 1.5 m) and L = distance (in kilometers) between stations. The calculation yielded negative gradients along an assumed flow pathway and positive gradients when opposite the proposed flow. The following simplifying assumptions were applied to the gradient calculations: (1) a single source was selected for the SR water at what was believed to be the primary outflow and (2) gradient calculations assumed all river water entering the study area did so via only this outflow.

Flow pathways were determined by comparing horizontal gradients and assumed that smaller gradients (<-5% km^{-1}) represented primary flow pathways and larger gradients ($\geq$-10% km^{-1}) represented a resistance to flow or shear that was identified where physical barriers or water mass fronts were present. For example, on May 25, two possible flow pathways of SR water to station SK1 along the 1 m isobath were chosen, one from the SR mouth (ΔSR/L = -69%/10.5 km = -7% km^{-1}) and the other from station SW2 (ΔSR/L = -44%/3.3 km = -16% km^{-1}). The two gradients suggested that SR water more likely flowed directly from the mouth of the SR because it would have been less mixed by approximately a factor of two along that route.

The flow pathways determined by comparing horizontal gradients in this manner are shown schematically in Figure 3-8. Generally, mixing (larger gradients) was comparatively lower in a cross-shore (N-S) versus alongshore (E-W) direction, indicating a preferential seaward advection of SR water. The presence of relatively unmixed SR water ($\geq$90% SR) from the mouth of the SR to stations closest to the shore (e.g., SK1, SW1, S1, and SE1) indicated a large and increasing pool of SR water located shoreward of these stations. Mixing fronts were consistently observed between stations located farther offshore (e.g., SW4 and SW5) with magnitudes >20% km^{-1}, marking the limits of the spread of SR water. Small mixing gradients ($\leq$4% km^{-1}) observed between the SR mouth and the SK stations confirmed a large westward spread of SR water.

A freshwater budget was calculated for the SR discharge based on water mass fractions. The total amount of SR water was calculated as water depth equivalents (in meters) for each station by summing the distribution of water mass fractions over the water column to a depth of 2.5 m (no river water was observed below this depth during the study). Water mass fractions were assumed to be evenly distributed between sampling depths. The top 0.5 m of the water column under ice was assumed to be homogeneous.

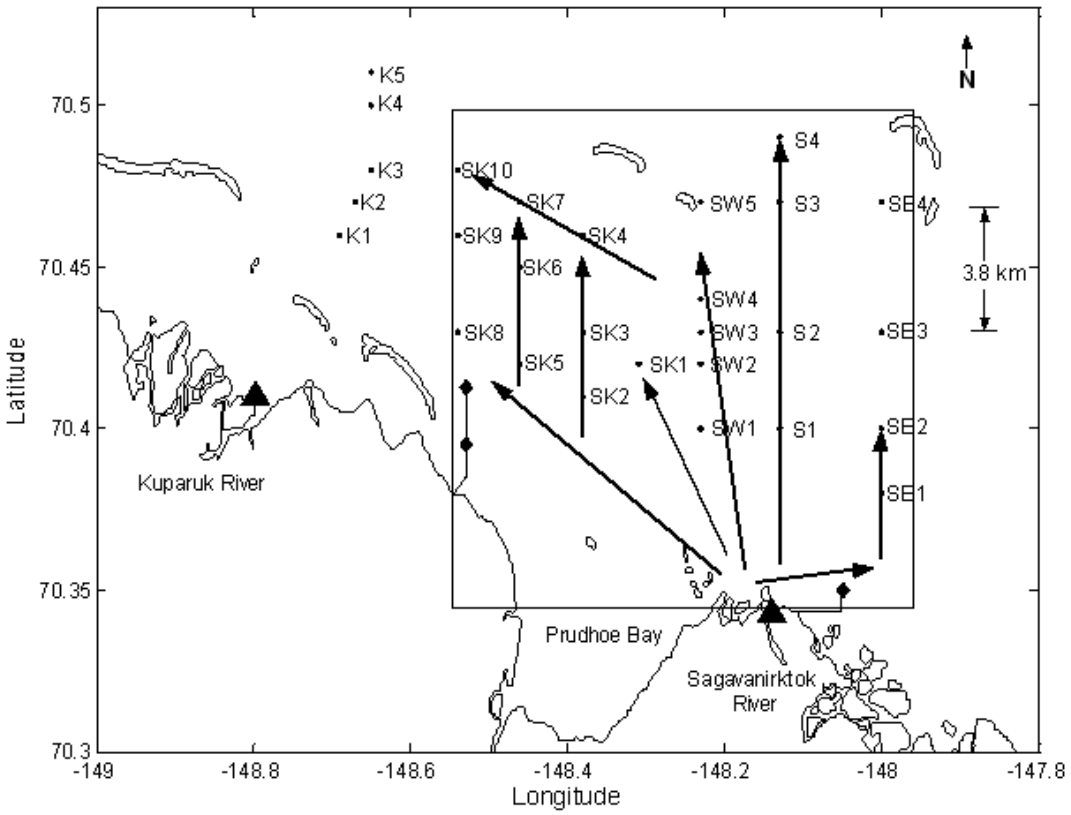


Figure 3-8. Qualitative flow pathways for Sagavanirktok River (SR) water according to lowest negative gradients and the calculated area of influence of the SR plume (rectangle). Solid triangles show the locations of the SR and Kuparuk River (KR) outflows in gradient calculations. The lengths of arrows show the distance over which the SR plume was observed. From Trefry et al. (2009).

Data from stations that were re-occupied during the study were used to estimate the rate of change in SR water for the entire sampling area. These rates were then utilized to estimate the total SR water at each station at the end of the study (June 2), and thereby obtain the discharged water depth equivalent for the study area (Figure 3-7). Some values were adjusted so that the depth equivalent of SR water was $\leq$2.5 m, and data for stations SK1 and SK2 were adjusted so that values did not exceed their total bottom depths of 1.5 and 1.0 m, respectively.

The comprehensive sum of SR water in the study area was 34.7 m, ~14 % of which flowed east to stations SE1 and SE2, ~35% flowed west to the SK stations, and ~50% flowed north to the SW (28%) and S (22%) stations. Overall, ~65% of the SR discharge identified during this study was found east of Prudhoe Bay. These observations supported the primary movement of SR water northward along the S transect with an influence from both the local circulation and KR plume (Figure 3-8).

The depth equivalent of SR water at individual stations was averaged to obtain a value of 1.6 ± 0.7 m. This average value was multiplied by the relative area of SR plume influence (~315 km^2), to yield a total volume in the study area on June 2, 2004 of 0.5 ± 0.2 km^3. Based on the USGS data, the measured total SR flow during our study period was ~1 km^3 (includes 5X multiplier from Rember and Trefry (2004) that was based on a determination that the U.S.G.S. gauge accounts for only ~20% of the total SR flow). Therefore, on June 2, 2004, the calculated 0.5 km^3 of SR water that was under the ice at the mouth of the SR in the coastal Beaufort Sea accounted for only ~50% of the total discharge. The discrepancy between the two values for flow was most likely due to several factors including the following: movement of water away from our sampling area in the Beaufort Sea, open water closer to shore that was not included in the calculation, possible errors in gauge measurements at flood stages, use of the 5X multiplier, and water that was above ice during our sampling period. Any above-ice water will eventually re-enter the water column via strudel holes or during the sea ice melt and consequent break-up in July.

3.1.3.2 Dispersion of Sediments and Metals Under Ice in the Beaufort Sea during Spring 2004

Sediments. Concentrations of TSS did not follow a simple mixing trend versus salinity and some of the particles settled out of the surface layer of the incoming fresh water (Figure 3-9). All data points, excluding one data point from the mixing zone, plotted below a simple mixing line between the seawater end-member of ~1 mg/L and the lowest value for TSS in the river of 43 mg/L. Thus, concentrations of TSS in offshore samples are 15 to 90% lower than predicted from the smallest simple mixing gradient for particles along the pathway of the Sagavanirktok River plume. A similar trend was observed for the Kuparuk River. Concentrations of TSS along the mixing zone in the Kuparuk River decreased sharply and showed settling of >50% of the suspended sediments. Concentrations of TSS in samples off both rivers with salinities >30 averaged 1 mg/L and ranged from 0.1 to 4 mg/L.

Vertical profiles also are available for *in situ* turbidity. At station SW4, the first vertical profile for turbidity (May 25) shows a thin layer of suspended sediments at the surface with a gradual decrease across the pycnocline (Figure 3-10). After three days (from May 25 to May 28), the layer of suspended sediment thickened as the layer of fresh water thickened. No significant changes in turbidity occurred after an additional three days (May 31). However, when turbidity was viewed as a function of salinity for station SW4, the turbidity on May 31 was about half of the turbidity on May 28 for the same salinity. This trend is most likely related to a combination of mixing and thickening of the plume and continued settling of particles from the under-ice plume, as well as increased flocculation of clay particles with decreasing salinity.

Some links between river inputs of suspended sediments and local offshore sedimentation rates can be made with available data from the cANIMIDA Project. Our previous results showed that sedimentation rates ranged from ~0.04 cm/yr to ~0.10 cm/yr with several sites having little or no net accumulation of sediment during at least the past 50 years (Trefry et al., 2003). At two sites, we identified 3 to 5 cm thick layers of sediment that were deposited since development on the North Slope began during the 1960s. Our overall results are consistent with those of Naidu et al.

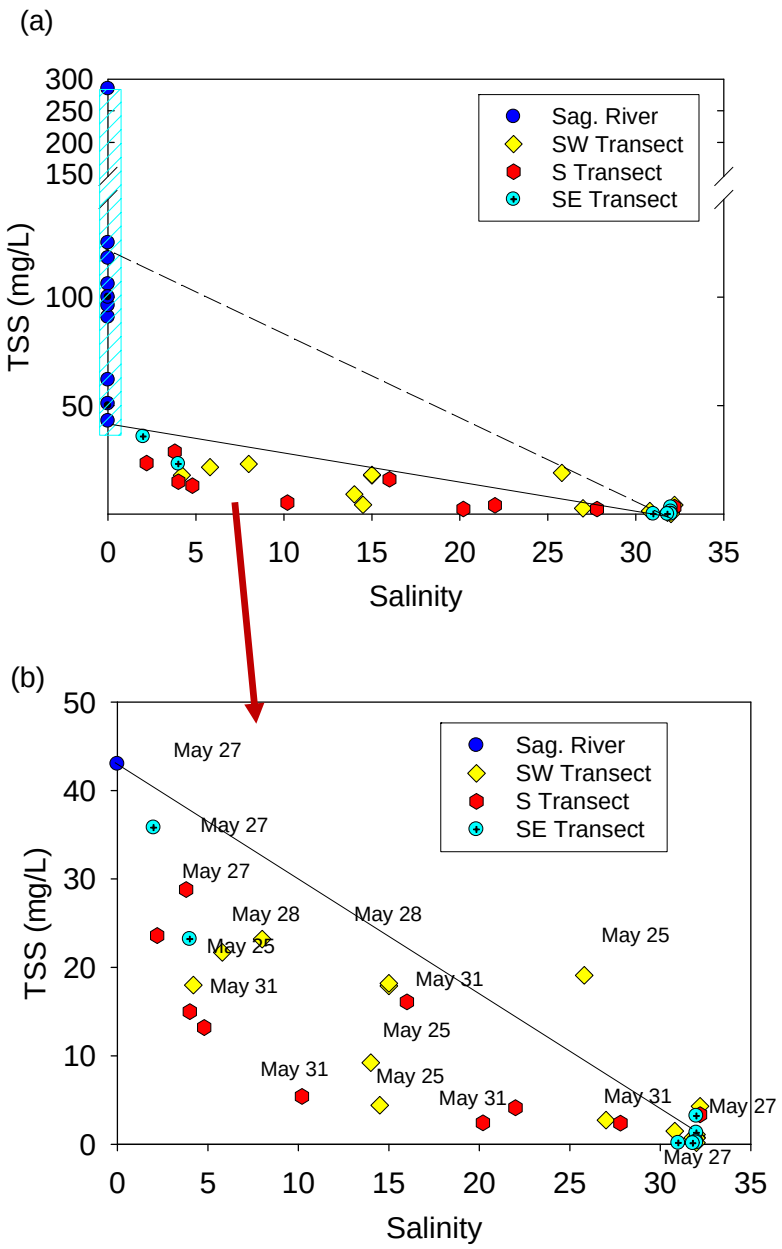


Figure 3-9. Total suspended solids (TSS) versus salinity (a) full-scale for TSS and (b) TSS at 0 to 50 mg/L for the Sagavanirktok River and offshore in Stefansson Sound during May-June 2004. Dashed line on (a) shows simple mixing line between TSS of average river water (127 mg/L) and seawater (1 mg/L). Solid line on (a) and (b) shows simple mixing line between lowest value for TSS in river water during peak flow (43 mg/L) and a value of 1 mg/L for seawater. From Trefry et al. (2009).

(2001) for the same area, namely that sedimentation rates and isotope activities are very low. We also know from our previous work that the presence of fine-grained sediment at a given location can vary from year to year and that the sediment movement along much of the shallow, coastal Beaufort Sea is quite dynamic.

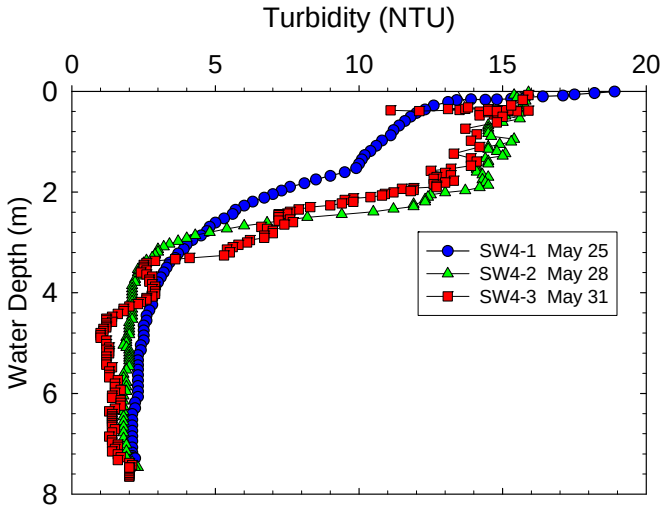


Figure 3-10. Vertical profiles of turbidity at station SW4 on May 25, May 28 and May 31, 2004. From Trefry et al. (2009).

The low sedimentation rates at stations in Prudhoe Bay and near the Endicott development can be supported by comparison with data for river inputs of suspended sediments. For example, the Sagavanirktok River, the major river source of sediments to this area, is estimated to have an annual sediment load of about 6 x 10^5 metric tons (Rember and Trefry, 2004). The depositional area for this sediment in the coastal Beaufort Sea is about 1000 km^2, yielding an estimated deposition rate of ~0.04 cm/y, based on a sediment bulk density of 1.6 g/cm^3 ([0.6 x 10^{12} g dry sediment/10 x 10^{12} cm^2] x [(1.6 g wet sediment/$cm^{3)}$/(2.6 g dry sediment/cm^3)]). This calculated value is consistent with results from direct determinations of sedimentation rate.

Metals. Concentrations of dissolved and particulate metals were traced under ice across the freshwater-seawater mixing zones in a manner similar to that described previously for salinity, dissolved silica, $\delta^{18}O$ and suspended sediments. The data are used here as follows: (1) to describe how the mixing process influences concentrations of dissolved and particulate metals and (2) to obtain a better perspective about concentrations of metals in suspended sediments relative to bottom sediments. Concentrations of dissolved and particulate metals may provide a useful and more sensitive short-term (days to months) integrator of any future metal contamination than bottom sediments (Trefry et al., 2003). Concentrations of dissolved and particulate metals also provide an important link with biological uptake of potentially toxic metals. However, the complexities of natural trends for dissolved and particulate metals must be well understood in order to use them as tracers of contamination and bioaccumulation in the ecosystem. The metals chosen for study in this project represent a combination of metals selected by MMS and us because of their usefulness as tracers of potential contamination in the study area and their presence in drilling/production wastes.

Concentrations of dissolved As followed a strong positive trend versus salinity across the freshwater-seawater mixing zone, even when data for both the Sagavanirktok and Kuparuk Rivers were combined on the same graph (Figure 3-11). Concentrations of dissolved As in both the Sagavanirktok (0.068 ± 0.015 µg/L) and Kuparuk (0.041 µg/L) rivers were low relative to

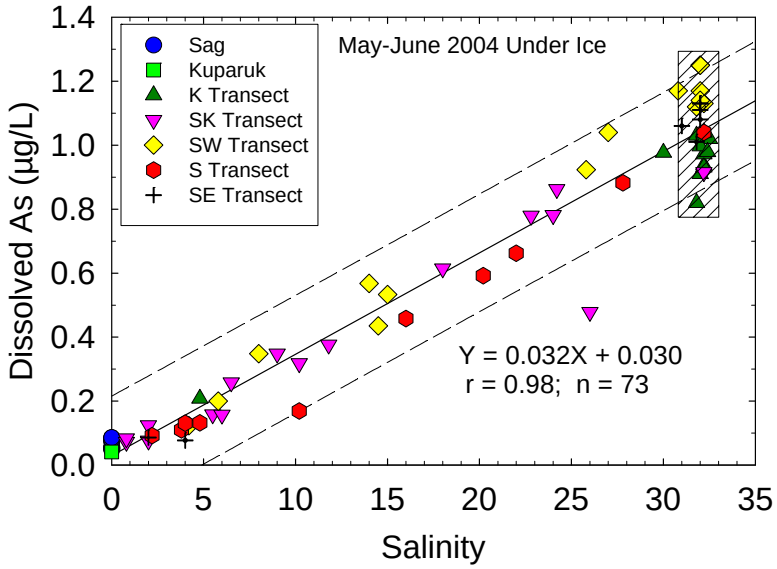


Figure 3-11. Concentrations of dissolved As versus salinity for water samples collected under ice across the mixing zones from the Sagavanirktok and Kuparuk Rivers to the coastal Beaufort Sea. Shaded area was drawn to emphasize the range of dissolved As concentrations in the polar mixed layer. Line and equation are from a linear regression. Dashed lines show 95% prediction interval. From Trefry et al. (2009).

seawater values of 1.0 ± 0.1 µg/L. The observed trend supports simple mixing of dissolved As under the ice with no easily detectable biological or physical removal or addition of dissolved As over the one to two week study period. The large range of dissolved As concentrations at a salinity of 32 (the polar mixed layer) was most likely the effect of long-term (many months) biological and chemical processes. The data in Figure 3-11 also support the hypothesis that the primary source of dissolved As to the coastal water of the cANIMIDA study area was from upwelling of deeper, offshore water with advection into Stefansson Sound, not from river runoff.

When the data for As in suspended matter collected under ice were plotted versus particulate Al, >80% of the data points plotted within the 99% prediction interval developed using sediment data from the coastal Beaufort Sea (Trefry et al., 2003). However, 10 data points for samples from the K Transect and two from the SW Transect plotted above the upper confidence interval. Each of these samples of suspended matter contained a lower Al content (at 1-5% Al) relative to river particles, suggesting that they contained more As-rich organic matter (Trefry et al., 2004a,b).

Based on the absolute amount of As per liter of sample, river water contained >90% particulate As whereas seawater (the polar mixed layer at a salinity of 32) contained <5% particulate As. Along the freshwater-seawater mixing gradient (with linearly increasing concentrations of dissolved As), the decrease in concentrations of particulate As (in µg/L) was much sharper than the increase in concentrations of dissolved As. This trend of higher concentrations of dissolved As at higher salinity also supports upwelling of offshore waters, rather than desorption of As from river particles, as the primary source of dissolved As in Stefansson Sound.

The relationship of particulate Cu versus particulate Al concentrations is very similar to that observed for particulate As versus particulate Al with some higher concentrations of Cu at lower concentrations of Al. The observed Cu enrichment is for the same samples of suspended matter that were enriched with As. In addition to the Cu-rich samples, samples from the SW and S transects are Cu-poor relative to Al (plot below the lower prediction interval based on typical regional sediments). Such a decrease in particulate Cu concentrations and the Cu/Al ratio could be due to desorption of Cu across the freshwater-seawater mixing zone as described for other rivers for Ba and Cd (Hanor and Chan, 1977) or addition of some more Al-rich (or Cu-poor) suspended matter in the area of transects SW and S.

In contrast with As, concentrations of dissolved Cu in the Sagavanirktok River (0.5 ± 0.2 μg/L) are similar to those in offshore water samples (0.5 ± 0.2 μg/L) and both are slightly higher than concentrations of 0.2 ± 0.1 μg/L in the Kuparuk River. Thus, it is difficult to see any significant deviations from a conclusion of no change or simple dilution across the freshwater-seawater mixing zone for dissolved Cu. Any other trends for dissolved Cu concentration versus salinity seem to be masked by expected temporal variations in concentrations of Cu in the rivers during high flow.

However when dissolved Cu concentrations for just the S and SE transects are regressed versus salinity, a relatively strong negative relationship is observed (river water data are excluded from linear regression). This trend suggests that Cu was not very reactive during mixing. Some high particulate Cu/Al ratios at a salinity of ~32, as well as at dissolved Cu concentrations of 0.3-0.4 μg/L, support the possibility of biological Cu enrichment.

Concentrations of particulate Fe were skewed to the high side of the Fe/Al ratio obtained for bottom sediments in the cANIMIDA area (Figure 3-12a). Data points that exceeded the upper prediction interval for Fe/Al in sediments were predominantly for suspended sediments from the Kuparuk River and adjacent K and SK Transects (Figure 3-12a). A trend of slightly higher particulate Fe concentrations, relative to Al, in the Kuparuk River was observed consistently during the ANIMIDA Project (Rember and Trefry, 2004; Trefry et al., 2004a,b). The Kuparuk River drains mainly arctic tundra and the river water contains higher concentrations of DOC and dissolved Fe (Rember and Trefry, 2004). The higher Fe/Al ratio in suspended sediments under the ice is consistent with previous observations. However, the impact of such particles on bottom sediments in the study area seems limited based on the narrow 99% prediction interval for Fe/Al in Figure 3-12a. This observation is consistent with a lower sediment load for the Kuparuk River and trapping of incoming particles by the Kuparuk delta and adjacent barrier islands.

Very few deviations were observed for particulate Ba/Al in suspended sediments relative to trends predicted from bottom sediments (Figure 3-12b). This observation is consistent with previous data sets, as was the occasionally higher Ba/Al ratio for suspended sediments from the Kuparuk River.

The regression of particulate Cr versus particulate Al concentration in water is similar to that for particulate Fe versus Al concentration in that some data points from the K and SK transects plot above the upper confidence interval based on the sediment data. However, the regression for particulate Cr versus particulate Al concentration from the Kuparuk River plotted on the lower half within the prediction interval rather than above the upper prediction interval as observed for Fe. When particulate Cr values were plotted versus concentrations of particulate Fe, most of the

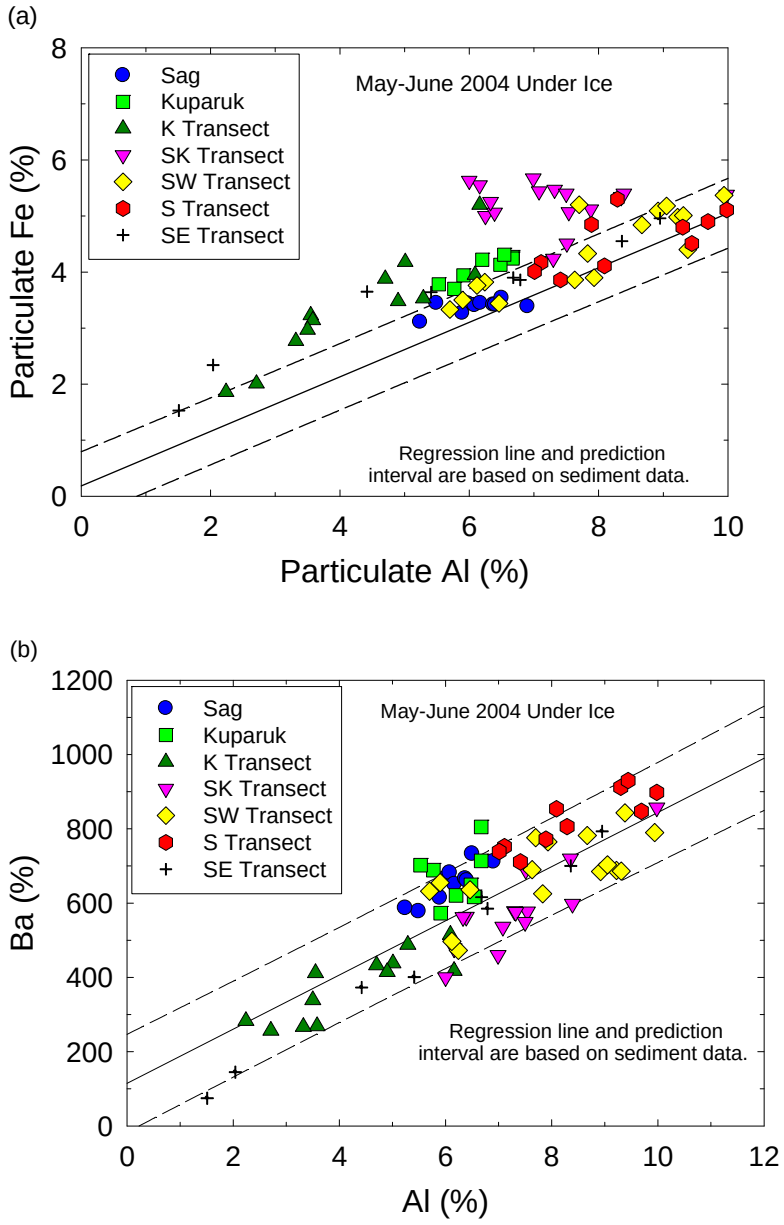


Figure 3-12. Concentrations of particulate Fe (a) and Ba (b) versus particulate Al for samples from the Sagavanirktok and Kuparuk Rivers and the coastal Beaufort Sea. Solid lines are from a linear regression and dashed lines show 95% prediction intervals based on sediment data for the coastal Beaufort Sea. From Trefry et al. (2003, 2004).

data for the K and SK transects plotted within the prediction interval for Cr/Fe in bottom sediments. however, the Kuparuk River samples and selected other samples plotted below the lower prediction interval.

No discernible shifts in concentrations of dissolved Cr were observed across the freshwater-seawater mixing zone under ice. This indicates that Cr was not very reactive during mixing under

the ice. The low values for dissolved Cr in some low salinity samples from the SK transect may be related to lower concentrations of dissolved Cr in the Kuparuk River than shown by the single data point available for the river.

Concentrations of particulate Cd follow the same trend previously described for As and Cu with high concentrations in samples with a lower Al content that were collected at higher salinity. In the case of Cd, the anomalously high concentrations of particulate Cd were 4 to 12 times greater than in typical Al-rich suspended or bottom sediments (Figure 3-13). Enrichment of Cd in sediments due to diagenetic processes (Gobeil et al., 1997) is not likely to have played a role in the observed Cd enrichment of suspended particles because the highest sediment Cd value that has been observed and linked to such processes in the cANIMIDA study area was 0.4 µg/g (Trefry et al., 2003). Data for plankton show that Cd concentrations were typically in the range of 1 to 10 µg/g, dry wt. Suspended matter from our study with 50% of the typical values for Al (i.e., 4% instead of 8%) contained Cd at about 2 µg/g (dry wt.) that would extrapolate to a reasonable value of 4µg/g at 0% Al (all plankton or organic matter).

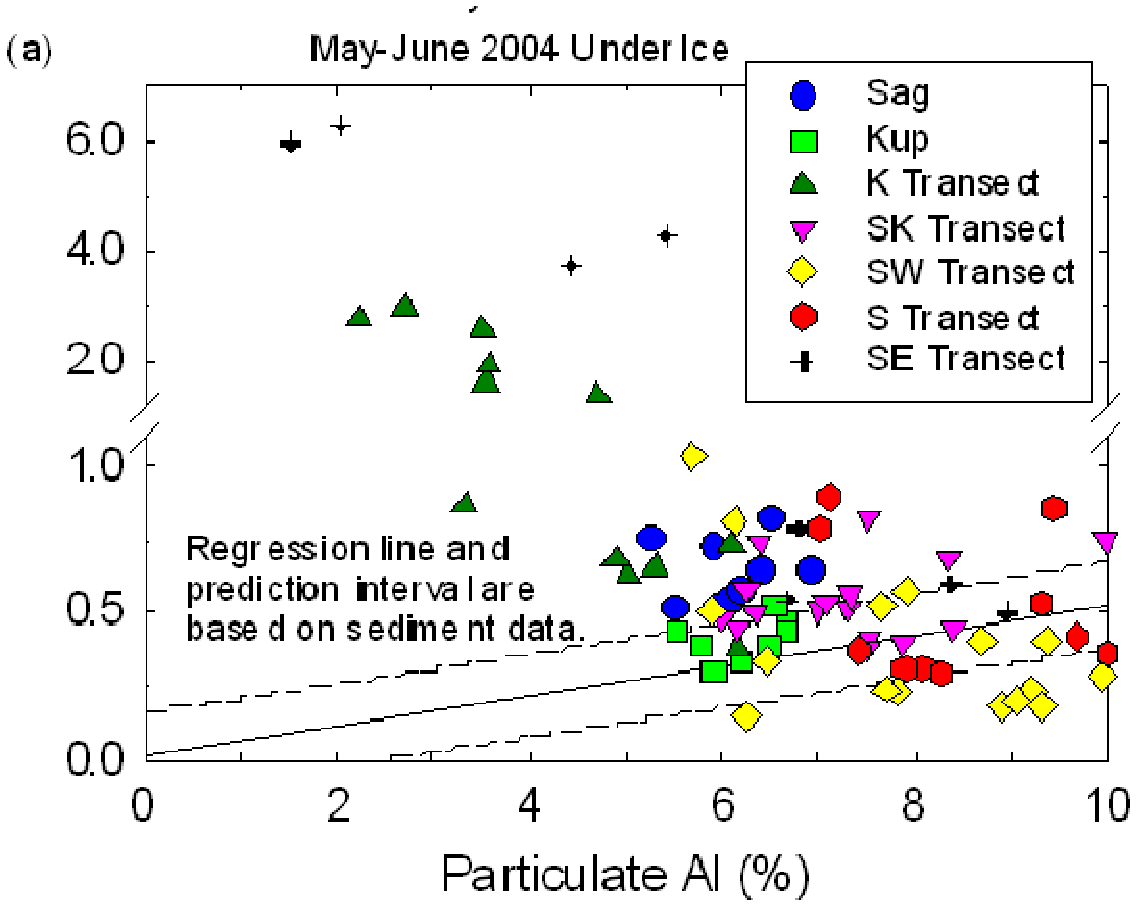


Figure 3-13. Concentrations of particulate Cd versus particulate Al for water samples from the Sagavanirktok and Kuparuk rivers and the coastal Beaufort Sea. Solid line is from a linear regression and dashed lines show 95% prediction intervals based on sediment data for the coastal Beaufort Sea from Trefry et al. (2003). From Trefry et al. (2009).

Concentrations of dissolved Cd increased from 0.016 ± 0.005 µg/L in the rivers to 0.067 ± 0.013 µg/L in seawater samples with salinities of 32‰ (Figure 3-14). However, considerable scatter was observed in the regression of dissolved Cd concentration versus salinity, and the correlation coefficient was 0.73. River water contained 50-90% particulate Cd and seawater (at a salinity of 32‰) contained<5% particulate Cd (Figure 3-15). Unlike the situation for As, concentrations of dissolved Cd along the freshwater-seawater mixing gradient may be influenced by desorption of Cd. However, as shown for As, the relationship between particulate and dissolved Cd seems to suggest that the main source of dissolved Cd in the study area is from upwelling from deeper, offshore water.

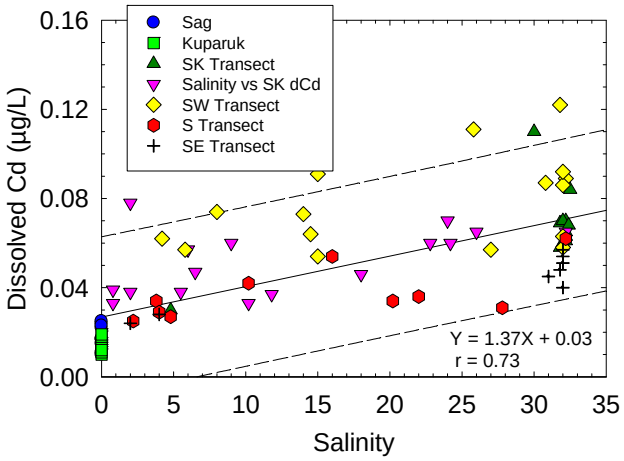


Figure 3-14. Concentrations of dissolved Cd versus salinity for water samples collected under ice across the mixing zones from the Sagavanirktok and Kuparuk Rivers to the coastal Beaufort Sea. The solid line and equation are from a linear regression calculation, r is the correlation coefficient, and the dashed lines show the 95% prediction interval. From Trefry et al. (2009).

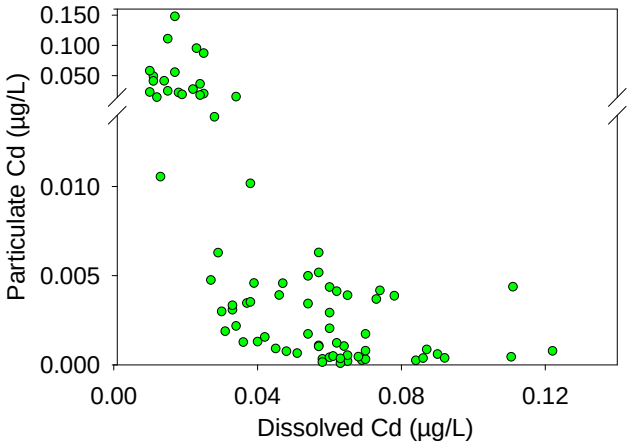


Figure 3-15. Concentrations of particulate Cd versus dissolved Cd in water samples collected in the Sagavanirktok and Kuparuk Rivers and under ice in the coastal Beaufort Sea. From Trefry et al. (2009).

Concentrations of particulate Zn did not vary greatly from the predicted trend with Al because the concentrations of Zn in the suspended aluminosilicates were generally as high as or higher than found in plankton. In contrast, concentrations of As, Cu and Cd in plankton were much greater than found for aluminosilicates and thus the anomalies at low concentrations of Al reflected the higher levels of these three metals in plankton.

The data for particulate Pb show a mix of trends previously discussed for Cr. Some high concentrations of particulate Pb were found at a variety of locations and some low concentrations were found in the Kuparuk River (Figure 3-16).

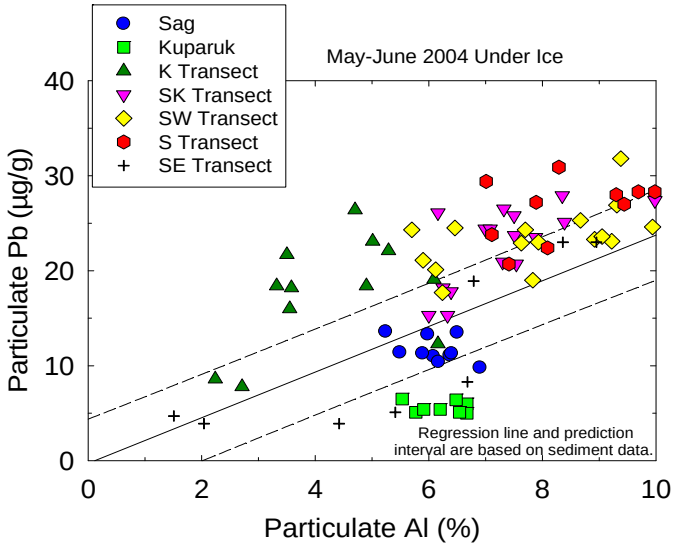


Figure 3-16. Concentrations of particulate Pb versus particulate Al in water samples from the Sagavanirktok and Kuparuk Rivers and the coastal Beaufort Sea. From Trefry et al. (2009).

3.1.3.3 Dispersion of Water under Ice in the Beaufort Sea during Spring 2006

Offshore sampling was carried out at 15 stations plus 5 moorings from May 22 through June 2, 2006 (Figure 3-17). Sampling was focused along three transects, two from the Kuparuk River and one from the Sagavanirktok River, all of which were along the main flow path of the respective rivers as determined during the 2004 study.

Vertical profiles of salinity, temperature, and turbidity in 2006 were similar to those seen during prior years (Figure 3-18). The first survey was conducted on May 22 prior to the breakup of the Sagavanirktok River, with subsequent surveys taking place during under-ice transport of river runoff. Vertical profiles of temperature and salinity from Station S2 show a sharp pycnocline during the May 24 and 26 surveys, with some vertical mixing taking place and a gradual thickening of the plume during the May 30 to June 3 surveys. The plume was about 2 m thick at the inshore locations and gradually mixed and thinned to less than 1 m further from shore (Figures 3-18 and 3-19). In the spring of 2006, the under-ice plume extended beyond the barrier islands (Reindeer and Cross Islands), but did not extend as far as the beginning of the shear zone which was located approximately 1 km beyond the barrier islands at the time of the survey. In

2004, the plume extended to the edge of the shear zone which appeared to provide an underwater ice barrier to increased spreading of the plume in the offshore direction.

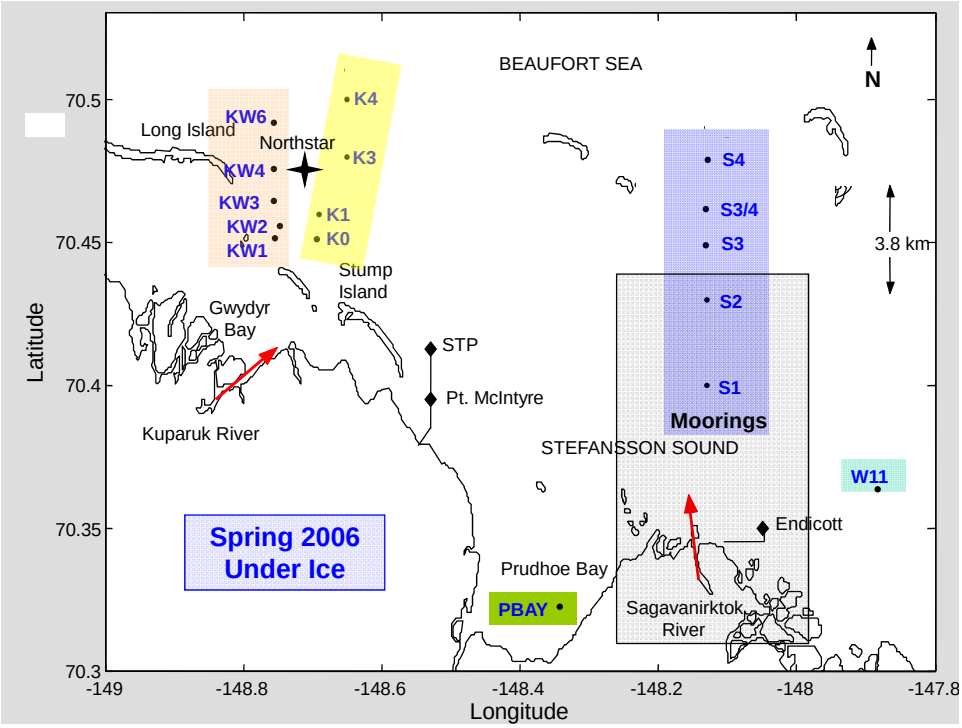


Figure 3-17. Map showing sampling stations for the May-June 2006 under-ice study in the coastal Beaufort Sea. From Trefry et al. (2009).

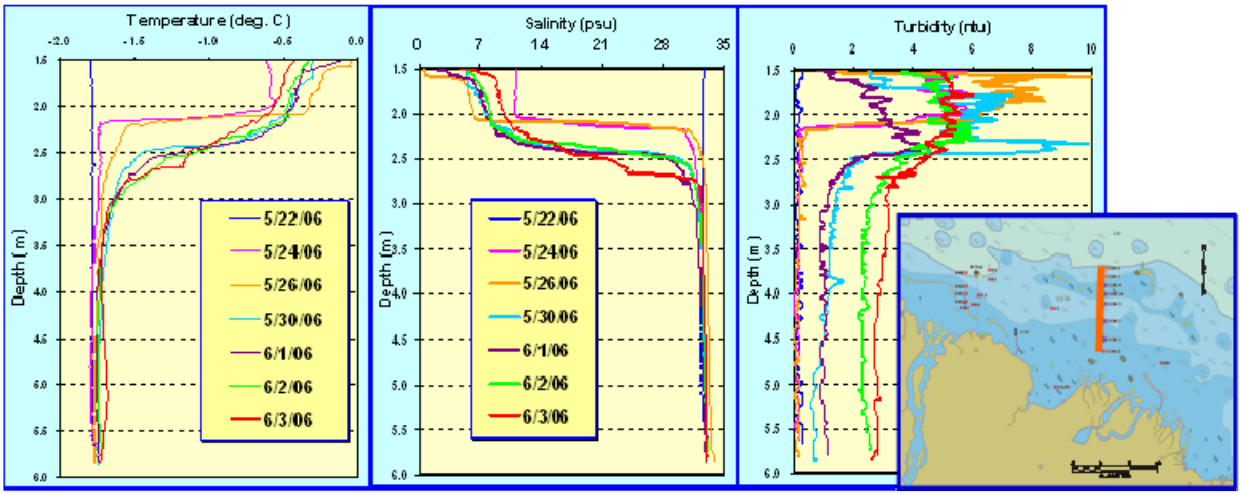


Figure 3-18: Vertical profiles of temperature, salinity, and turbidity taken at station S2 over a 10-day period during May-June 2006. The accompanying map depicts the station location along with the location of the onshore-offshore transect for salinity. From Trefry et al. (2009).

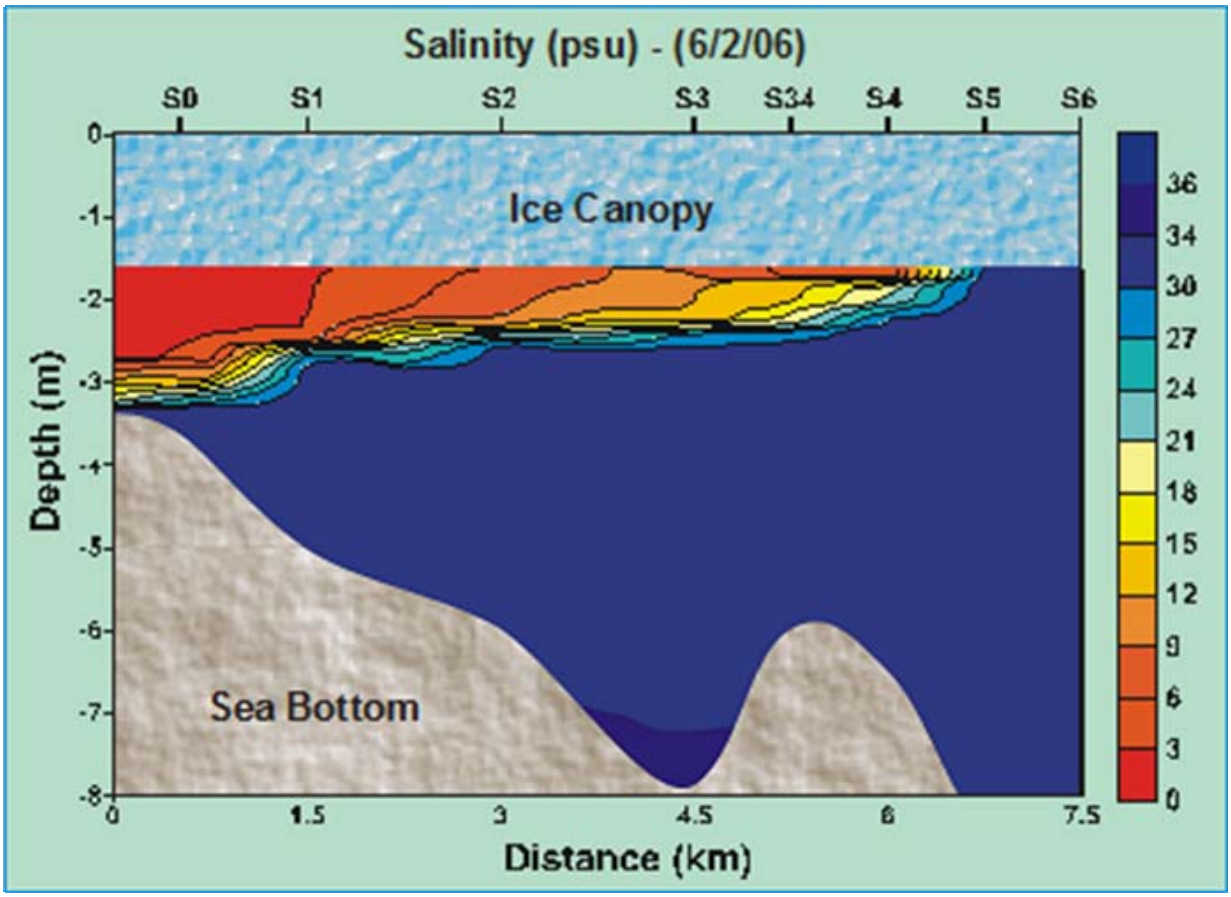


Figure 3-19. Vertical contour map of salinity along an onshore-offshore transect extending from Station S0 near shore to Station S6 beyond the barrier islands, June 2, 2006 (refer to above map in Figure 3-16 for transect location). From Trefry et al. (2009).

Turbidity and TSS concentrations did not follow the same mixing trends found for salinity as sediment particles settled out of the water column. This pattern can be seen clearly in the turbidity profile where concentrations increase in the lower water column over time even though these bottom waters are marine and unmixed in terms of salinity and temperature characteristics (Figure 3-18).

Five moorings were deployed during 2006 from the ice surface with sensors located at a depth of 2 m (~0.5 m below the ice canopy). The time series plots from these moorings show trends from Station SON-1 near shore to Station SON-4 located 4.5 km offshore . At the time of deployment on May 22, the Sagavanirktok River plume had already reached SON-1; salinity decreased and temperature increased over the next few days. The under-ice plume first reached SON-3, located 3 km from SON-1, about 6 days later; another 3 days passed before the plume reached SON-4 located 1.5 km from SON-3. Based on these two traverse times for the plume, the under-ice plume and associated currents were traveling at approximately 5 to 6 cm/s (0.5 km/day). These under-ice current estimates agree with the ADCP under-ice current measurements made by Weingartner (2006) during the breakup of the Sagavanirktok River in 2002 and with our data for

2004 that showed an average under-ice current of 7 ± 3 cm/sec. The time series plots for turbidity indicated that turbidity initially increased but later decreased as particles settled out. In contrast, salinity and temperature showed consistent trends of increasing temperature and decreasing salinity in the plume as a function of time.

3.1.3.4 Dispersion of Chemicals Under Ice in the Beaufort Sea During Spring 2006

Concentrations of dissolved As increased linearly across the freshwater-seawater mixing zone for the Sagavanirktok River under-ice plume into the Beaufort Sea (Figure 3-20a). The trend was similar to that observed during May-June 2004 with a similar slope and range in concentrations of dissolved As at the seawater endmember. The trend for dissolved Cd was similar to that observed for As because concentrations increased with increasing salinity (Figure 3-20b). For both As and Cd, the trends once again reinforce the observation that the key sources of As and Cd were from upwelling of deeper water on to the shelf. The trend for Ba was opposite of that observed for As and Cd with a linear decrease offshore and data that support a minor degree of desorption of Ba from particles at low salinities (Figure 3-20c). Trends for Cr, Cu and Zn show relatively uniform values from salinities of 2 to 32; however, in each case, the higher concentrations observed in the rivers were not observed in the coastal Beaufort Sea (Figure 3-20d).

Concentrations of TSS were very low along the freshwater-seawater mixing zone from the Sagavanirktok River with all TSS concentrations at salinities >2‰ of <10 mg/L, except for one value of 20 mg/L. In 2004, most of the TSS concentrations at salinities of 2 to 20‰ were >10 mg/L with at least half >20 mg/L. This trend is most likely due to the much higher flow and longer duration of high flow in the Sagavanirktok River in 2004 compared to 2006 (Figure 3-1).

There was a six-fold difference in peak concentrations of TSS in the Kuparuk River versus the Sagavanirktok River during May-June 2006. On a relative basis, concentrations of TSS in the Kuparuk River decreased less along the salinity gradient than observed for the Sagavanirktok River; however, the absolute TSS values were similar along the two different freshwater-seawater mixing zones.

Concentrations of Fe in suspended sediments from the Sagavanirktok River and its seaward plume plotted within, or very close, to the 99% prediction interval developed for Fe versus Al using sediments from the coastal Beaufort Sea (Figure 3-21a). In contrast, most of the data points for the Kuparuk River and under-ice plume plotted above the upper prediction interval (Figure 3-21b). This has been a recurrent trend that emphasizes differences in the composition and drainage basins of the two rivers as well as supporting a much larger role for the Sagavanirktok River as a source of sediments to the cANIMIDA study area than the Kuparuk River.

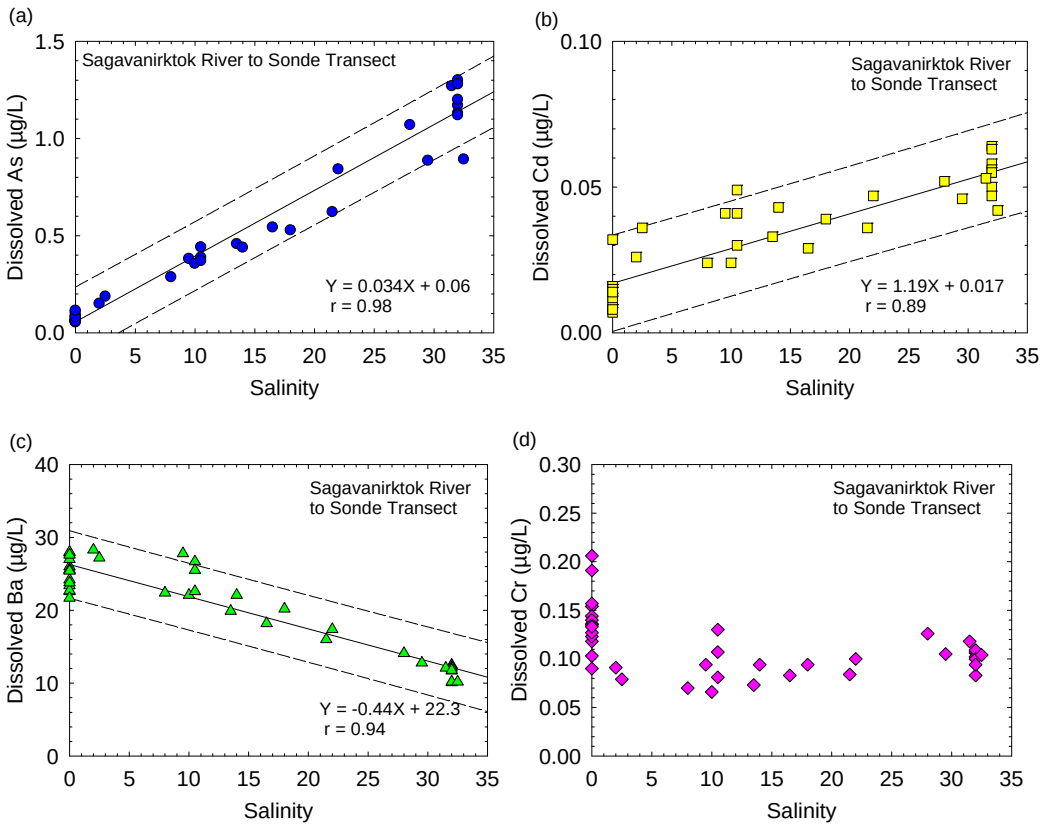


Figure 3-20. Concentrations of dissolved As (a), Cd (b), Ba (c), and Cr (d) versus salinity across the freshwater-seawater mixing zone from the Sagavanirktok River to the coastal Beaufort Sea. Solid lines and equations are from linear regression calculations. Dashed lines show 95% prediction intervals and r is the correlation coefficient. From Trefry et al. (2009).

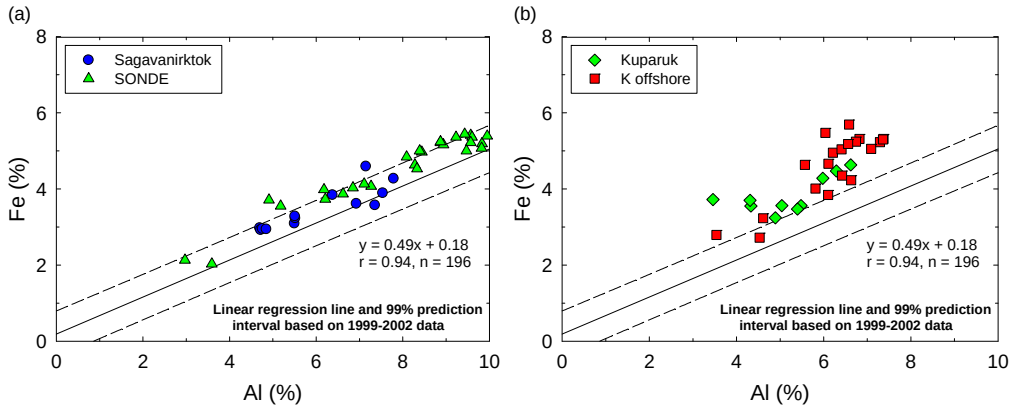


Figure 3-21. Concentrations of Fe versus Al for suspended sediments from the Sagavanirktok River (a) and Kuparuk River (b) and respective offshore, under-ice plumes in the coastal Beaufort Sea. Solid lines and equations are from linear regression analysis for the 1999-2002 data for bottom sediments from the coastal Beaufort Sea; dashed lines show 99% prediction intervals and r is the correlation coefficient. From Trefry et al. (2009).

Concentrations of Ba in essentially all suspended sediment samples from each river and plume plotted within the 99% prediction interval established for bottom sediments in the coastal Beaufort Sea. This trend supports and absence of any anthropogenic Ba inputs or reactions with particles from either river as they are carried seaward under the ice.

Most concentrations of Pb, Cr, Cu and Zn in samples of suspended sediments collected in 2006 from the Sagavanirktok River and plume plot within the 99% prediction intervals for bottom sediments from the coastal Beaufort Sea (Figure 3-22). In contrast, a few data points for Cr and Cu, and many data points for Pb and Zn, from the Kuparuk River and under-ice plume plot above the upper prediction interval on the metal versus Al template in bottom sediments. Some of the Pb and Zn concentrations may have an anthropogenic origin; however, the elevated concentrations of Fe in the Kuparuk River and plume samples may indicate natural scavenging of Fe oxides that also contain Pb and Zn.

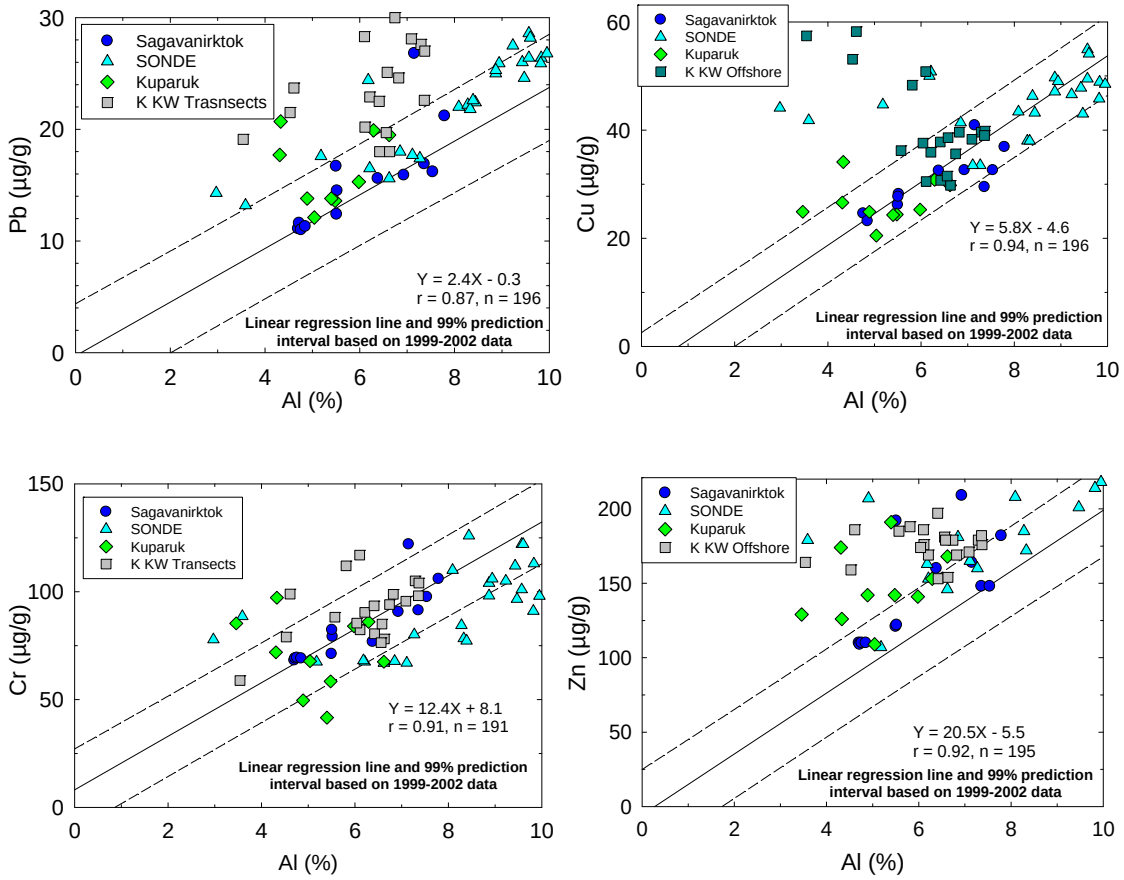


Figure 3-22. Concentrations of Al versus (a) Pb, (b) Cu, (c) Cr and (d) Zn in suspended sediments from the Sagavanirktok and Kuparuk Rivers and their respective offshore, under-ice plumes in the coastal Beaufort Sea. Solid lines and equations are from linear regression analysis for the 1999-2002 data for bottom sediments from the coastal Beaufort Sea; dashed lines show 99% prediction intervals and r is the correlation coefficient. From Trefry et al. (2009).

3.1.4 The Distribution of Suspended Sediments and Chemicals during the Open-Water Period

Vertical profiles of salinity, temperature, and turbidity, as well as water samples for suspended sediments and dissolved and particulate metals were collected during the summers of 2004, 2005 and 2006 from the coastal Beaufort Sea. Data from a small sampling project in rivers also were collected during the summer period during the cANIMIDA Project.

3.1.4.1 Suspended Sediments and Metals in Rivers: Summer 2004, 2005 and 2006

Sampling of rivers during summer was performed to maintain a long-term data base for concentrations of TSS, particulate, and dissolved metals (Tables 3-5, 3-6, 3-7, and 3-8). Concentrations of TSS in the Kuparuk River during summers of 2004, 2005 and 2006 averaged 1.0 mg/L, about 25 to 60 times lower than during the spring floods (Table 3-6). Only one elevated concentration of TSS (1.4 mg/L) was obtained in the Kuparuk River during the summer of 2004 (Table 3-6). This concentration of TSS was higher than typical values of 0.2-0.6 mg/L in previous years and in two out of three samples in 2005 and 2006. The slightly higher concentrations observed probably were due to increased construction activity in the area west of the bridge where we sampled. Concentrations of TSS in the Sagavanirktok River were more variable during summer with a range of 0.5 to 53.4 mg/L (Table 3-5). An increase in TSS concentrations >1-2 mg/L was typically linked to a rain event that raised flow and TSS (Table 3-5). During 2004, a rain storm raised the water flow rate and concentrations of TSS to 53 mg/L in the Sagavanirktok River on August 3. All TSS concentrations during summer were 10 to >300 times lower than during the spring melt.

Table 3-5. Concentrations of particulate metals, total suspended solids, and particulate organic carbon in Sagavanirktok River water in the spring and summer of 2004, 2005, and 2006. From Trefry et al. (2009).

Metal	Summer 2004 (n=2)	Spring 2004 (n=9)	Summer 2005 (n=2)	Summer 2006 (n=1)	Spring 2006 (n=12)
Aluminum (Al) (%)	4.12 - 6.66	5.2 - 6.9	4.18 - 4.53	6.91	4.7 - 7.8
Arsenic (As) (µg/g)	9.9 - 10.3	5.4 - 17.0	11.6 - 12.0	7.6	4.7 - 7.8
Barium (Ba) (µg/g)	561 - 743	578 - 733	644 - 668	625	433 - 780
Cadmium (Cd) (µg/g)	0.71 - 1.12	0.52 - 0.83	1.0 - 1.39	0.67	0.44 - 0.70
Chromium (Cr) (µg/g)	102 - 105	41.1 - 88.8	96 - 102	113	68.2 - 122
Copper (Cu) (µg/g)	32.0 - 38.0	23.6 - 38.6	28.8 - 35.1	31.8	23.2 - 40.9
Iron (Fe) (%)	3.35 - 3.87	3.1 - 3.5	3.46 - 3.48	3.65	2.0 - 4.6
Lead (Pb) (µg/g)	10.7 - 19.4	9.8 - 13.6	11.7 - 12.0	19.3	11.0 - 26.8
Zinc (Zn) (µg/g)	87.9 - 144	115 - 161	106 - 117	167	109 - 208
Total Suspended Solids (TSS) (mg/L)	1.45 - 53.4	43 - 285	0.50 - 1.36	8.9	9.5 = 353
Particulate Organic Carbon (POC) (%)	0.6 - 1.0	0.8 - 1.5	---	1.3	1.2 - 3.0

Table 3-6. Concentrations of particulate metals, total suspended solids, and particulate organic carbon in Kuparuk River water in the spring and summer of 2004, 2005, and 2006. From Trefry et al. (2009).

Metal	Summer 2004 (n=1)	Spring 2004 (n=8)	Summer 2005 (n=2)	Summer 2006 (n=1)	Spring 2006 (n=11)
Aluminum (Al) (%)	3.44	5.5 - 6.7	2.44 - 3.47	4.01	3.5 - 6.6
Arsenic (As) (µg/g)	7.6	3.9 - 13.1	6.3 - 20.6	12.4	4.7 - 11.6
Barium (Ba) (µg/g)	551	573 - 805	495 - 667	448	450 - 725
Cadmium (Cd) (µg/g)	0.20	0.30 - 0.52	0.70 - 2.56	6.6	0.35 - 0.71
Chromium (Cr) (µg/g)	43.7	57.1 - 82.4	85.8 - 97.6	76.6	41.6 - 97.2
Copper (Cu) (µg/g)	29.4	28.7 - 45.1	18.6 - 25.2	31.9	20.5 - 34.1
Iron (Fe) (%)	3.06	3.7 - 4.3	2.39 - 3.28	4.59	3.2 - 4.6
Lead (Pb) (µg/g)	15.7	5.0 - 6.5	5.9 - 17.0	38.0	12.1 - 23.7
Zinc (Zn) (µg/g)	131	112 - 130	59.3 - 96.5	155	109 - 191
Total Suspended Solids (TSS) (mg/L)	1.35	32 - 130	0.19 - 2.0	0.39	4.6 - 59.7
Particulate Organic Carbon (POC) (%)	3.9	1.6 - 4.9	1.1	8.6	2.6 - 7.8

At typical concentrations of TSS in summer (~2 mg/L), concentrations of particulate metals and organic carbon in the Sagavanirktok River were lower than in spring (Table 3-5) but close to results obtained during summer for previous years (Trefry et al., 2004a,b). After the 2004 rainstorm, the concentrations of particulate metals increased to levels that were closer to those for particulate metals in spring 2004, except for Pb (Table 3-5). The rain seems to have carried in particles that were slightly more Pb-rich than typically observed (duplicate samples with Pb at 19.0 and 19.9 µg/g), perhaps representing a contribution from road runoff or deposition with rain.

Concentrations of dissolved metals in the Sagavanirktok River following the summer rain in 2004 were higher than in the pre-rain river water with concentrations of Cu and Pb ~3 times higher following the rain (Tables 3-7).

Concentrations of dissolved metals in the Kuparuk River during summer showed variations that were similar to those observed for the Sagavanirktok River with overall higher values for As and Cu and lower concentrations of Cd, and Pb in the Kuparuk River relative to the Sagavanirktok River (Tables 3-7 and 3-8).

The percent of total metal in the rivers that was dissolved increased greatly during summer due to much lower values for TSS during summer. For example, the % dissolved Ba in the Sagavanirktok River increased from an average of ~30% in May-June to >97% in summer 2005. Even the % dissolved Pb increased from <5% in May-June to >20% in summer for the Sagavanirktok River. Similar trends were found for each year when spring and summer data were compared.

Table 3-7. Concentrations of dissolved metals in the Sagavanirktok River in the spring and summer of 2004, 2005, and 2006. From Trefry et al. (2009).

River		As (µg/L)	Ba (µg/L)	Cd (µg/L)	Cr (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
Sagavanirktok Summer 2004 (n=2)	-	0.126 0.174	38.0 31.8	0.009 0.003	0.166 0.160	0.233 0.661	0.004 0.010	0.18 0.21
Sagavanirktok Spring 2004 (n=9)	Mean Std. Dev. Min. Max.	0.068 ±0.015 0.048 0.086	19.0 ±1.8 16.1 22.6	0.018 ±0.006 0.010 0.025	0.096 ±0.17 0.080 0.110	0.50 ± 0.17 0.34 0.88	0.013 ±0.006 0.007 0.023	0.28 ±0.08 0.19 0.40
Sagavanirktok Summer 2005 (n=2)	-	0.096 0.102	41.6 44.8	0.003 0.004	0.108 0.137	0.264 0.196	0.004 0.004	0.14 0.13
Sagavanirktok Summer 2006 (n=1)	-	0.076	35.8	0.033	0.126	0.547	0.007	0.17
Sagavanirktok Spring 2006 (n=12)	Mean Std. Dev. Min. Max.	0.069 ±0.016 0.054 0.108	25.2 ±1.9 22.6 28.0	0.012 ±0.004 0.007 0.016	0.147 ±0.027 0.118 0.206	0.79 ± 0.38 0.46 1.6	0.031 ±0.006 ± 0.039	1.0 ±1.0 0.3 3.6

Table 3-8. Concentrations of dissolved metals (µg/L) in the Kuparuk River in the spring and summer of 2004, 2005, and 2006. From Trefry et al. (2009).

River	Value	As	Ba	Cd	Cr	Cu	Pb	Zn
Kuparuk Spring 2004 (n=8)	Mean ±SD Min - Max	0.041 (n=1)	7.0±1.5 3.5-8.6	0.014 ±0.003 0.01-0.019	0.085 (n=1)	0.21±0.14 0.05-0.49	0.011 ±0.008 0.003- 0.023	0.35±0.19 0.16-0.69
Kuparuk Summer 2004 (n=1)	---	0.161	35.8	0.002	0.147	0.858	0.014	0.28
Kuparuk Summer 2005 (n=2)	---	0.080- 0.084	41.8-52.2	0.002- 0.002	0.083- 0.088	0.630- 0.630	0.013- 0.013	0.18-0.18
Kuparuk Spring 2006 (n=10)	Mean± SD Min - Max	0.089 ±0.028 0.061- 0.153	25.2±19.1 16.8-79.3	0.008 ±0.004 0.003- 0.013	0.115 ±0.022 0.078- 0.152	0.57 ±0.019 0.35-0.99	0.038 ±0.013 0.020- 0.062	0.82±0.57 0.37-2.37
Kuparuk Summer 2006 (n=1)	---	0.081	40.6	0.012	0.081	0.626	0.019	0.11
Colville Summer 2006 (n=1)	---	0.141	59.0	0.012	0.107	1.06	0.026	0.13

Values for log K_d in the summer samples were within the range of values found for spring for As, Cr and Zn in the Sagavanirktok River, but lower in summer than spring for Ba, and higher in summer than spring for Cd, Cu, and Pb. For the Kuparuk River, the log K_d values for summer were within the range of values for spring for As, Cu, Pb and Zn, lower for Ba and Cu and higher for Cd. To some degree, the distribution coefficients are conditional constants that respond to variations in mineralogy and surface area of the particles. Overall, the K_d values provide a first order approximation of the dissolved concentrations of metals as a function of metal concentrations of the suspended sediments.

3.1.4.2 Suspended Sediments and Metals Offshore – Summer 2004, 2005, 2006

In 2004, 2005, and 2006 salinity, concentrations of suspended sediments and turbidity, and particulate and dissolved metals in the water column were monitored at several of the nearshore stations off the Sagavanirktok and Kuparuk Rivers, and at selected stations near Northstar, in the Liberty prospect, and historic BSMP stations (Figures 2-2 and 2-3).

Typically, salinities in the upper layer of the water column increased between early June and late July as break-up of the ice cover was followed by mixing due to wind. Bottom water salinity was essentially unchanged. The water column remained stratified.

Turbidity was high throughout the water column at most sites in late-July and August, 2004. Both salinity and turbidity were uniform to a depth of ~5 m at most stations in August, due to active mixing during relatively strong winds. However, in shallow water (<5 m), the salinity and turbidity profiles were uniform from top to bottom. The overall absolute values for TSS and turbidity during the open-water period were directly related to wind conditions (Trefry et al., 2004a). Thus, during a given summer, the mean and range of measured TSS concentrations typically reflected the winds and weather.

There were higher mean concentrations of TSS in 1999, 2000 and 2004 relative to 2001, 2002, 2005 and 2006 in the cANIMIDA area collectively as well as in the area of Northstar Island (Table 3-9). The very high TSS concentrations in 1999 are anomalous relative to the complete data set. Northstar Island was not constructed until winter 2000. However, much of the 1999 data were collected following a 5-day storm with >20 knot winds. In contrast, 2002, 2005 and 2006 data were collected during relatively calm conditions with considerable sea ice throughout the study area. During the 2000, 2001, and 2004 sampling periods, conditions were moderate with 5 to 15 knot winds during most of the sampling period. Furthermore, more samples from deeper water, seaward of the barrier islands are included in the mean values for 2005 and 2006. During 2004, relative calm was encountered during most of the study period as reflected in the low mean value for TSS in the Northstar area and in much of the rest of the study area (Table 3-9). The strong winds late in the 2004 study period yielded the high maximum value of 64 mg/L TSS east of Endicott. Relatively little sediment resuspension is required to increase the TSS concentration in shallow offshore waters. For example, a layer of fine sediment only 0.02 cm thick would need to be resuspended and mixed through 8 m of water column to yield TSS concentrations of 40 mg/L.

The data presented here and from many vertical profiles and horizontal tows presented in previous reports (Trefry et al., 2004a) show no significant differences in turbidity or concentrations of TSS in proximity (within 100 to 500 m) to Northstar Island relative to other

Table 3-9. Summary data for total suspended solids (TSS) for all stations in the ANIMIDA and cANIMIDA study area during the open-water period and for a subset of stations in the area of Northstar Island. From Trefry et al. (2009).

All Stations Year	n	TSS Mean ± SD (mg/L)	TSS Maximum (mg/L)	TSS Minimum (mg/L)
1999	31	30 ± 27	119	2.9
2000	51	8.2 ± 4.8	26	1.7
2001	34	5.1 ± 2.1	8.7	0.9
2002	32	2.1 ± 1.3	4.4	0.2
2004	45	13 ± 16	64	0.5
2005	65	1.7 ± 1.4	6.7	0.3
2006	26	1.3 ± 0.7	4.0	0.4
Northstar Area	**n**	**TSS**	**TSS**	**TSS**
1999	17	38 ± 33	119	2.9
2000	35	7.3 ± 4.0	16	1.7
2001	15	4.1 ± 1.8	6.3	0.9
2002	11	2.5 ± 1.5	4.4	0.2
2004	15	6.2 ± 4.8	16	0.5
2005	9	1.4 ± 0.8	3.6	0.8
2006	12	1.1 ± 0.4	2.1	0.6

locations in the ANIMIDA study area. This result is consistent with the coarse-grained composition of the original sand and gravel used to construct the island and the armoring that covers the slope of the island to the seafloor.

Concentrations of particulate metals in the open-waters of the Beaufort Sea varied with the organic matter and clay concentrations in the particles. The grand averages for 2000, 2001, 2002, 2004, 2005, and 2006 in Table 3-10 show some interannual variability; however, most of the variations are due to differences in the composition of the suspended sediments as shown by variations in concentrations of Al and Fe and generally comparable shifts in concentrations of trace metals. Average concentrations of Al, Fe and trace metals in bottom sediments (Table 3-10) are lower than found in suspended sediments because the bottom sediments contain more quartz sand and carbonate shell material, both of which contain low metals concentrations, diluting concentrations of trace metals in whole sediments. Thus, any comparisons of metal concentrations between suspended sediments and bottom sediments are made based on metal/Al ratios.

Concentrations of particulate metals in the water column in the Northstar area were not significantly different from values obtained throughout the cANIMIDA area during 2004, 2005 and 2006 with the exception of Cd in 2004 and Pb in 2006. The Cd anomaly probably is due to high concentrations of particulate organic matter (plankton), as shown by the lower Al content in the 2004 samples of suspended sediment from the Northstar area. The slightly elevated particulate Pb concentration may be related to trace amounts of input from flaring or other island operations.

Table 3-10. Mean concentrations of particulate metals in water samples collected from the coastal Beaufort Sea and near Northstar Island (NS) during the open-water season. From Trefry et al. (2009).

Year	Al (%)	As (µg/g)	Ba (µg/g)	Cd (µg/g)	Cr (µg/g)	Cu (µg/g)	Fe (%)	Pb (µg/g)	Zn (µg/g)
2000 (n=51)	7.4	21	738	0.66	104	40	4.3	30	154
2001 (n=34)	8.0	21	775	0.49	111	48	4.8	27	132
2002 (n=32)	5.9	28	564	0.72	82	39	4.1	21	103
2004 Area-wide (n=42)	6.9	22	680	0.54	105	31	4.0	19	137
2004 NS (n=7)	6.3	18	674	0.91	90	38	3.8	21	144
2005 Area-wide (n=65)	4.9	22	507	1.4	99	31	3.6	19	124
2005 NS (n=9)	5.0	27	581	1.0	106	27	3.7	18	108
2006 Area-wide (n=26)	5.7	25	574	1.1	88	36	3.9	22	161
2006 NS (n=12	5.7	26	598	1.0	84	39	4.1	30	163
Beaufort Sea Sediment	3.9	11	394	0.22	57	19	2.3	10	70

Some concentrations of Cd in suspended sediments show a good fit to the sediment prediction intervals, whereas others show a negative trend versus Al for data that plotted above the upper prediction interval on the Cd versus Al plot (Figure 3-23). The higher concentrations of Cd at lower Al concentrations may be related to high Cd concentrations in plankton, up to several µg/g. In contrast, the higher As concentrations in suspended sediments at lower concentrations of Al (Figure 3-23) cannot be related to plankton because all plankton had As concentrations <8 µg/g. The excess As probably is bound to fine-grained Fe oxides.

Concentrations of dissolved trace metals were determined in seawater samples from the coastal Beaufort Sea during both the ANIMIDA and cANIMIDA Projects (Table 3-11). Concentrations of dissolved As, Cr, and Pb were lower than reported values for surface seawater worldwide. Lower As concentrations were found because dissolved As concentrations increase with increasing salinity. In contrast, concentrations of dissolved Cd, Cu, and Zn were higher than in typical surface seawater. Concentrations of dissolved Cd in summer were about 50% lower than values obtained in winter. Concentrations of dissolved Cd, at 14 to 18 ng/L, in rivers were lower than in seawater at any time of year. Concentrations of dissolved Ba were similar to those in typical surface seawater, except during 2000 and 2001, when a more nearshore samples were collected. Dissolved Ba concentration usually were lower in seawater (10 to 32 µg/L), than in river water. Concentrations of dissolved Ba averaged 20, 26, and 50 µg/L for the Kuparuk, Sagavanirktok and Colville rivers, respectively (Table 3-3).

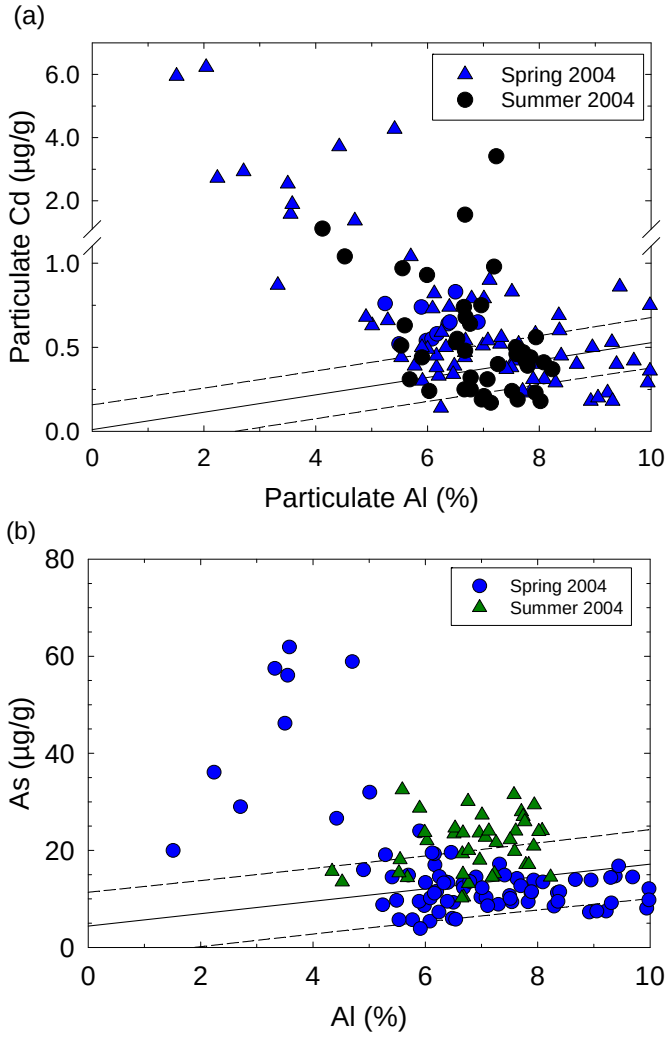


Figure 3-23. Concentrations of particulate (a) Cd and (b) As versus particulate Al in suspended sediment samples collected during May-June (Spring) and July-August (Summer) 2004. Solid and dashed lines show the linear regression fit and prediction interval based on data for bottom sediments. From Trefry et al. (2003, 2009).

All dissolved metals concentrations were in the range of background values and these values are well below the EPA water quality criteria for chronic effects in marine organisms (Table 3-11). Furthermore, concentrations of dissolved metals were not significantly different in the Northstar area than in the overall cANIMIDA study area.

The observed enrichment of dissolved Cd in the coastal Beaufort Sea during summer is consistent with the global Cd/P relationship for seawater; however, such high concentrations of dissolved Cd are unusual for surface seawater. The cANIMIDA study area probably has low concentrations of dissolved nitrate such that the N:P ratio of the seawater inside the barrier

Table 3-11. Mean concentrations of dissolved metals and salinity in seawater water collected from the coastal Beaufort Sea and near Northstar Island during the open-water season in 2000 through 2006. All dissolved metal concentrations are µg/L (parts per billion). From Trefry et al. (2009).

Year	Salinity	As	Ba	Cd	Cr	Cu	Hg	Pb	Zn
2000 (n = 49)	22	0.49	26.8	0.02	0.06	0.54	0.0005	0.005	0.20
2001 (n = 34)	17	0.38	31.9	0.02	0.09	0.64	0.001	0.01	0.16
2002 (n = 31)	20	0.51	14.2	0.03	0.07	0.47	0.0009	0.07	0.11
2004 Area wide (n = 42)	23	0.72	13	0.04	0.11	0.36	-	0.01	0.16
2004 NS (n =7)	25	0.81	12	0.04	0.10	0.40	-	0.01	0.14
2005 Area wide (n = 65)	27	0.93	10.6	0.05	0.09	0.31	0.0007	0.01	0.32
2005 NS (n = 9)	25	0.88	11.5	0.04	0.09	0.30	0.0008	0.02	0.28
2006 Area wide (n = 26)	23	0.60	13	0.04	0.09	0.31	-	0.008	0.17
2006 NS (n =12)	21	0.56	14	0.03	0.08	0.31		0.007	0.20
Average Surface Seawater[a]	35	1.2	13	0.01	0.16	0.10	0.0002	0.02	0.1
EPA Marine Water Quality Criteria[b]	Chronic	36	-	8.8	50[c]	3.1	0.94[d]	8.1	81

[a] Donat and Bruland (1995).

[b] USEPA (2009).

[c] Criterion for trivalent chromium.

[d] Criterion for inorganic mercury.

islands during summer is typically <1 (rather than 16:1) as is typical for seawater. Dissolved Cd, phosphate, and nitrate move onto the inner shelf during upwelling of deeper, offshore water. Carmack and MacDonald (2002) showed that seawater (salinity 34‰) at a water depth of several hundred meters in the Canadian Beaufort Sea has an N/P ratio of ~8:1. As this water is moved

up onto the outer shelf, the N/P ratio is <5:1 (salinity of 30-32‰). Increased depletion of nitrate, relative to phosphate continues into the nearshore area (such as Stefansson Sound) such that the N/P ratio becomes <1 in summer and the Cd/P ratio is consistent with global seawater values. However, in winter, concentrations of dissolved Cd are high (~0.50 ng/L) when concentrations of dissolved phosphate are low (<0.1 μM).

As discussed previously, concentrations of dissolved Cd in the Arctic rivers are lower than in offshore water; thus, upwelling is an important source of dissolved Cd to the study area. Suspended matter with lower concentrations of Al contains high concentrations of Cd in both spring (under ice) and summer. Such enrichment is typical of plankton and was also observed for Cu.

3.1.5 Hydrocarbons in River Sediments, Peat, Northstar Oil and Nearshore Seawater

Concentrations of hydrocarbons were measured in river sediments, coastal peat, and Northstar crude oil in one or more of the BSMP Program (Boehm et al., 1987)), Task 2 of the ANIMIDA Project (Brown et al., 2004), and Task 2 of the cANIMIDA Project (Brown et al., 2010). PAH were measured in the dissolved and particulate fractions of seawater from the Northstar, Liberty, and BSMP areas in ANIMIDA Task 7 (Trefry et al., 2004b). The objective of this work was to help identify sources of hydrocarbons in sediments and marine animal tissues in the vicinity of the Northstar production facility and the Liberty prospect.

3.1.5.1 Hydrocarbons in River Sediments

Sediment samples were collected for hydrocarbon analysis from the mouth of the Sagavanirktok, Kuparuk, Colville, and Canning Rivers between 1985 and 2002. Concentrations of total PAH, SHC, and StTr were quite variable in these North Slope river sediments, both among the rivers and among years (Table 3-12). Highest TPAH concentrations were in some Colville River sediment samples collected in all years. These river sediment samples also contained relatively high concentrations of TSHC and TStTr. The high hydrocarbon concentrations did not seem to be related closely with TOC concentration or % silt + clay (mud) in the sediments.

The PAH, SHC, and StTr profiles of typical river sediment samples indicate a mixed petrogenic, pyrogenic, and biogenic source (Figure 3-24). The SHC fraction is characterized by abundant longer chain-length alkanes (C25 - C29) and a relatively high carbon preference index (CPI: ratio of odd-numbered to even-numbered alkanes), both characteristic of terrestrial plant material (Boehm, 1984). The greater abundance of the triterpane, T22, over T21 in Kuparuk and Sagavanirktok River sediments and the abundance of T15 in Colville River sediments also indicates the presence of recent diagenic plant material (Douglas et al., 2007). The greater abundance of alkyl naphthalenes, phenanthrenes, and fluoranthenes/pyrenes than the un-alkylated parent PAH and higher molecular weight PAH is characteristic of a petroleum source, whereas, the higher molecular weight 4- through 6-ring PAH are primarily from pyrogenic (combustion) sources (Douglas et al, 2007). The exception is perylene, which is a primarily recent biogenic PAH, derived from transformation of natural plant material in oxygen-free sediments (Venkatesan, 1988; Silliman et al., 1998).

Table 3-12. Concentrations of TPAH, TSHC, TSrTr, TOC, and silt + clay (mud) in river sediments collected in 1985/86 (Boehm et al., 1987) and 1999-2002. From Brown et al. (2005).

River	Year	Total PAH (ng/g)	Total SHC (ng/g)	Total StTr (ng/g)	TOC (%)	Mud (%)
Sagavanirktok River	1985/86	210 - 460	8700 - 14,000	---	4.2 - 18.5	16
	1999	317	3500	25.4	---	---
	2000-02	33.3 - 670	1680 - 18,000	30 - 65	2.8	---
Kuparuk River	1986	50	4100	---	4.2	56
	1999	102	3500	72.4	4.72	---
	2000/02	8.6 - 161	550 - 22,000	2.2 - 140	7.4	---
Colville River	1985/6	660 - 700	8300 - 11,000	---	6.6 - 93	69
	1999	2222 - 2634	1630 - 1660	345	1.61 - 2.44	---
	2000	140 - 2024	320 - 25,000	2.19 - 282	0.42 - 7.39	2.4 - 39
	2002	695	5200	73	---	---
Canning River	1986	190	1200	---	41	66
	2002	195 - 490	9100 - 19,000	18 - 23	---	---

3.1.5.2 Hydrocarbons in Coastal Peat

Peat is formed by the deposition and slow biodegradation and abiotic rearrangement (diagenesis) of plant material in suboxic soils and sediments. It is an early diagenic stage in the formation of petroleum, coal, and gas (Neff, 2002a). Extensive peat bogs formed in the Alaskan tundra with the warming climate that followed each period of glaciation (Jones and Yu, 2010). Upon burial, peat is converted to kerogens (humates and lignites), hard coal, petroleum, and natural gas by millions of years of exposure to high temperatures and pressures. These peat, kerogen, and coal deposits are continually being eroded by the North Slope rivers and crumbling of the coastal shoreline. Chemical rearrangements during diagenesis convert plant debris into the complex mixture of saturated, naphthenic, and aromatic hydrocarbons, and complex polar organic compounds, characteristic of peat, coal, and petroleum. Surface or shallow sub-surface Holocene (deposited during the last ~12,000 years) deposits of peat and kerogen, such as those frequently found in permafrost tundra soils and in shallow layers of offshore sediments, may contain high concentrations of SHC, PAH, and StTr with both biogenic/diagenic and petrogenic properties. Peats have a strong sorptive capacity for PAH. A large fraction of the PAH in North Slope peat probably is pyrogenic (Venkatesan and Kaplan, 1982), derived from aerial deposition of combustion carbon from the Arctic aerosol.

Several samples of peat from near the mouths of Arctic rivers, and from eroding deposits along the coasts were analyzed for SHC, PAH, and StTr as part of the BSMP, ANIMIDA, and cANIMIDA Projects (Boehm et al., 1987; Brown et al., 2004, 2010) (Table 3-13). Total PAH concentrations ranged from 13 to 740 ng/g dry wt (parts per billion). As expected total SHC concentrations in the peat were much higher, ranging from 8700 to 260,000 ng/g. Most peat samples contained comparatively low concentrations of total StTr; highest concentrations were in Kuparuk River sediments, probably because the Kuparuk River drains primarily Arctic tundra soils. There were no clear relationships among concentrations of PAH, SHC, StTr, and TOC in the Arctic peat.

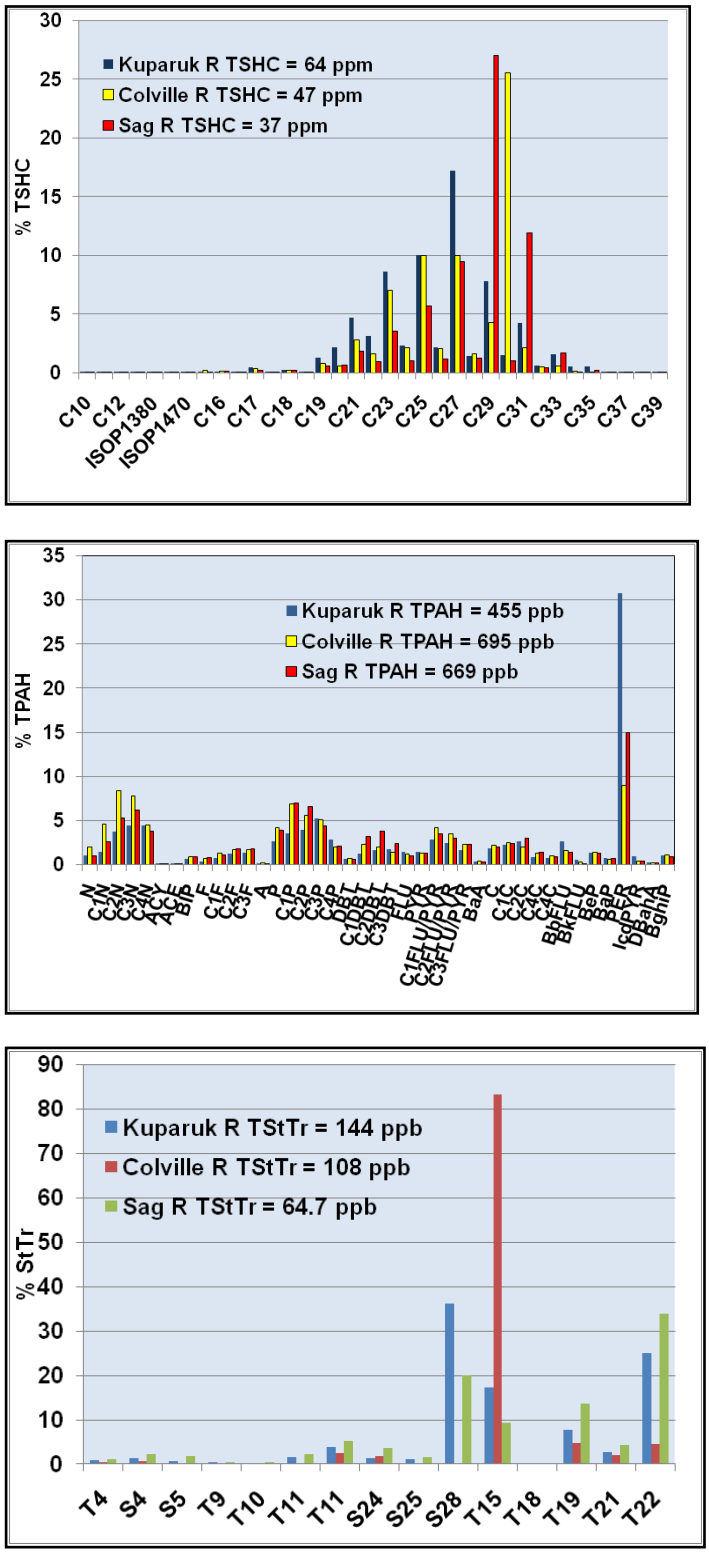


Figure 3-24. SHC, PAH, and StTr profiles in river sediments collected in 2002. SHC. PAH, and StTr acronyms are defined in Table, 2-4 - 2-6. Data from Brown et al. (2005).

Table 3-13. Concentrations of TPAH, TSHC, TSrTr, TOC, and silt + clay (mud) in river or coastal peat collected in 1985/86 (Boehm et al., 1987), 2000/02 (Brown et al., 2005), and 2006 (Brown et al., 2010).

River	Year	Total PAH (ng/g)	Total SHC (ng/g)	Total StTr (ng/g)	TOC (%)
Sagavanirktok River	2002	160	41,000	38	---
	2006	290	25,000	41	---
Kuparuk River	2000	100	18,000	51	2.4
	2002	140 - 450	71,000 - 72,000	92 - 390	---
	2006	110	57,000	35	---
Colville River	2002	360	50,000	110	---
	2006	740	47,000	83	---
Canning River	1985	410	84,000	---	1.7
Arey Lagoon	1985	620	260,000	---	0.95
Flaxman Island	1985	170	39,000	---	0.42
Tigvariak Island	1985	180	230,000	---	2.3
Heald Point	1985	50	83,000	---	0.93
Milne Point	1985	200	240,000	---	2.6
Cape Halkett	1985	710	41,000	---	0.23
Kogru Island	1885	50	600,000	---	3.0
Eskimo Island	2006	120	230,000	87	---
Pingok Island	2006	13	8700	3.0	---

Profiles of SHC, PAH, and StTr in representative river peat samples (Figure 3-25) were somewhat different from those for river sediments (Figure 3-24). The SHC profiles contained a broader range of abundant alkanes, extending from C21 to C33 or C34, compared to C23 to C31 in river sediments. However, the CPI was high in both river sediments and peat, indicating a predominantly terrestrial plant origin for the hydrocarbon assemblages.

The river sediment and river peat samples had similar PAH profiles (Figures 3-24 and 3-25). The greater abundance of alkyl naphthalenes and alkyl phenanthrenes compared to parent naphthalene and phenanthrene was even more prominent in the peat than in the sediments, primarily because of the lower relative concentration of perylene in the peat than in the river sediments. The PAH assemblage in the peat samples is indicative of a mixture of petrogenic and biogenic PAH, with a smaller contribution of pyrogenic PAH.

The StTr profiles are characteristic of a relatively recent (Holocene) plant origin. Thus, the peat shows a transitional phase between biogenic to petrogenic characteristics, with some pyrogenic PAH, possibly from aerial deposition.

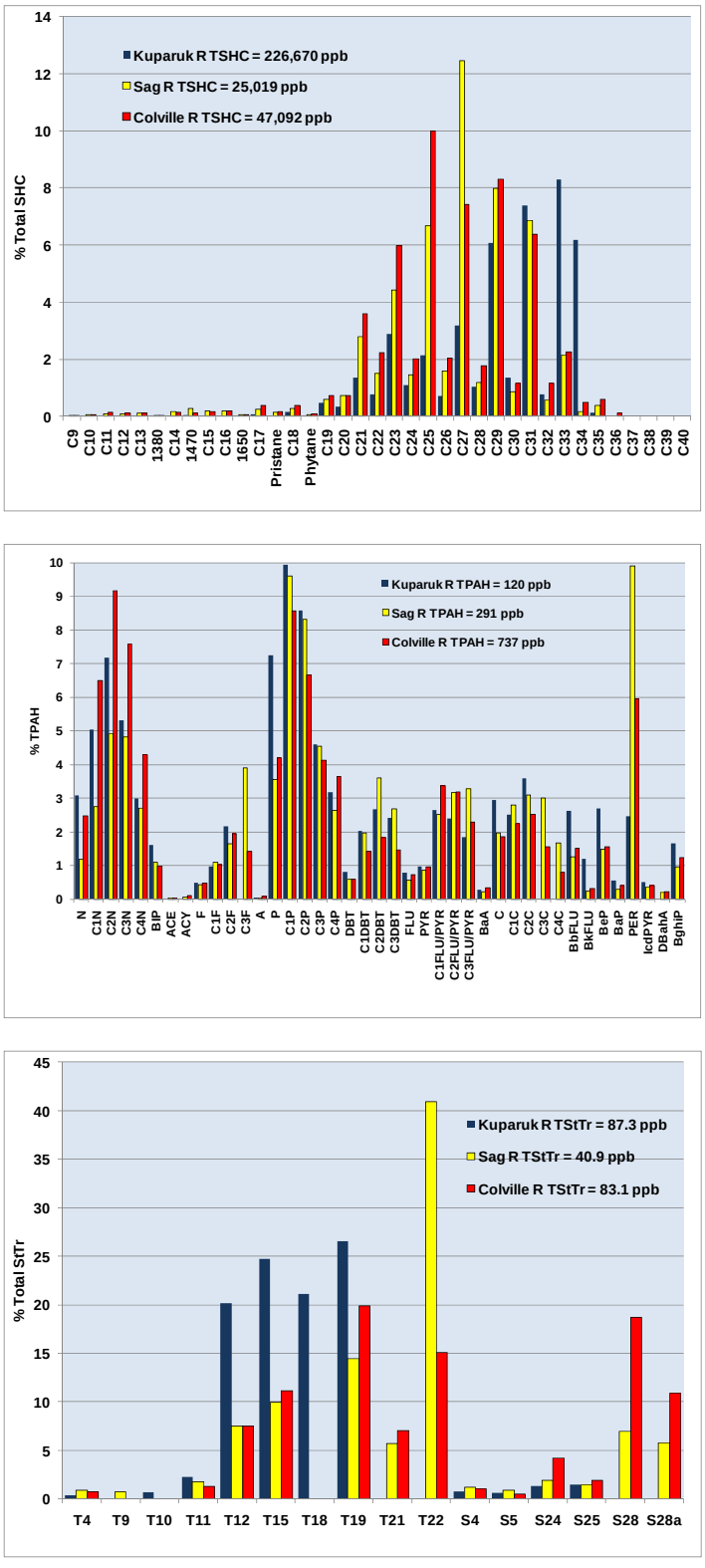


Figure 3-25. SHC, PAH, and StTr profiles in river peat collected in 2006. SHC, PAH, and StTr acronyms are defined in Table, 2-4 - 2-6. Data from Brown et al. (2010).

3.1.5.3 Hydrocarbons in Northstar Crude Oil

Samples of Northstar crude oil were collected several times during the cANIMIDA Project for hydrocarbon analysis. Northstar crude oil is a light crude oil (ºAPI = 40.8 @ 15ºC). Mean concentrations of total SHC, total PAH, and total StTr in the unweathered oil were 642,770. 15,260, and 324 mg/kg oil, respectively. The SHC, PAH, and StTr profiles of the crude oil (Figure 3-26) were quite different from those of river sediments (Figure 3-23) and river peat (Figure 3-24). The relative abundance of alkanes decreased with increasing carbon number. The isoprenoid alkanes, including pristane and phytane, were less abundant than the n-alkanes of similar molecular weight. The CPI index was approximately 1, characteristic of petrogenic hydrocarbon mixtures.

The most abundant PAH were alkyl naphthalenes, with the C2-alkylnaphthalene the most abundant (Figure 3-26). Alkyl phenanthracenes were the next most abundant PAH. As is frequently the case, especially with light crude oils, more than 95% of the total PAH were 2- and 3-ring compounds. The concentrations of the high molecular weight PAH, including biogenic perylene, were very low, usually below the method detection limit. This is a characteristic PAH profile of a light crude oil.

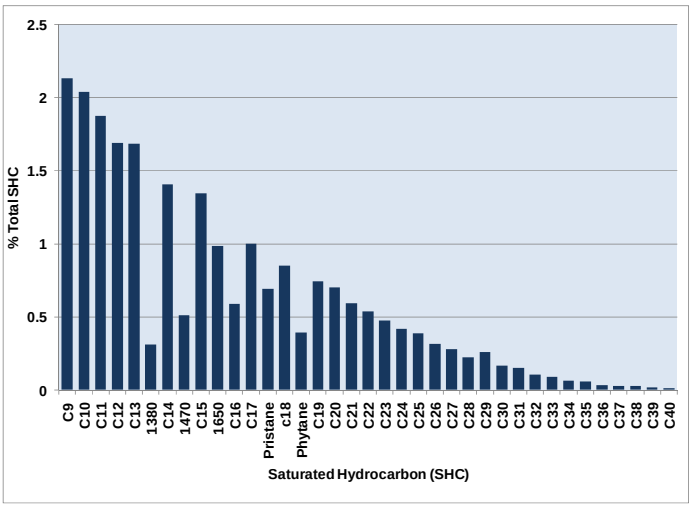
The most abundant StTr in Northstar crude oil were S4 (13β,17α-diacholestane(20S), T19 (17α(H),21β(H)-hopane), and T4 (C_{23} Diterpane) (Figure 3-26). These compounds are characteristic of crude oil (Douglas et al., 2007).

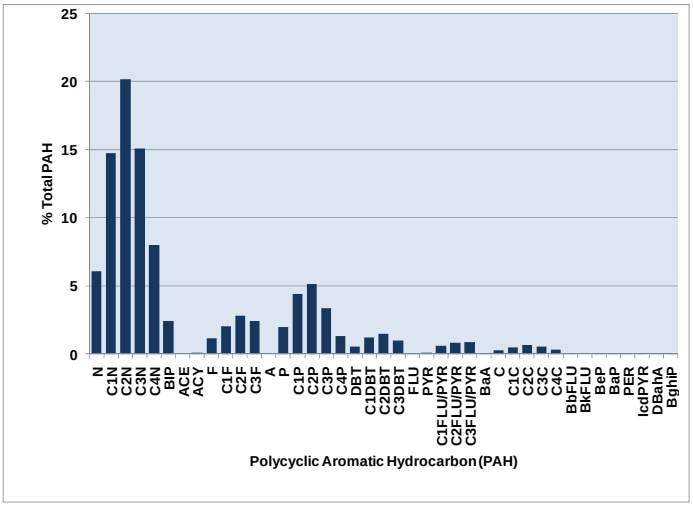
3.1.5.4 Hydrocarbons in Nearshore Beaufort Sea Water

Several surface seawater samples were collected for hydrocarbon analysis near the Northstar development, the Liberty prospect, and at a small number of BSMP stations in 2000 to 2002 as part of ANIMIDA Task 7 (Trefry et al., 2004b). Concentrations of TPAH and individual PAH were measured in whole water, the particulate fraction, and the dissolved (including colloidal) fraction of the seawater samples (Table 3-14).

Whole water samples from the three areas contained 37 to 69 ng/L (parts per trillion) TPAH (Table 3-14). Most of the PAH in whole water were associated with the particulate fraction. Concentrations of dissolved PAH ranged from 13 to 19 ng/L. The low molecular weight 2- and 3-ring PAH were much more abundant than the higher molecular weight 4- through 6-ring PAH in both the particulate and dissolved fractions. Concentrations of PAH were similar in whole water from Northstar, Liberty, and BSMP. However, concentrations of particulate PAH were significantly higher in water from the Liberty prospect than in water from the vicinity of the Northstar development and BSMP stations.

Blank samples, particularly for the dissolved phase, contained relatively high concentrations of TPAH compared to concentrations in the corresponding water samples. Thus, the actual concentrations of dissolved, and to a much lesser extent, particulate TPAH are lower than reported in Table 3-14. If the blank concentrations are considered, the actual TPAH concentrations in whole water and the particulate and dissolved fractions, ~15 - 40 ng/L, ~11 - 45 ng/L, and ~<1 - 6 ng/L, respectively, are in the range frequently reported for uncontaminated nearshore surface seawater (Neff, 2002a).





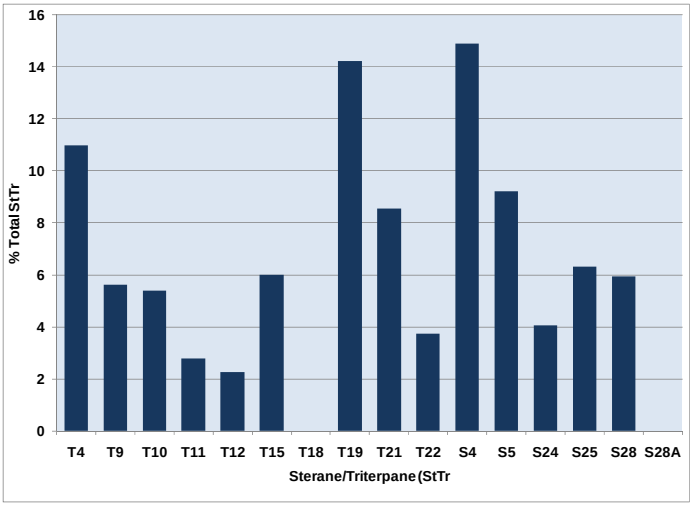


Figure 3-26. Mean SHC, PAH, and StTr profiles in Northstar crude oil collected in 2004. SHC, PAH, and StTr acronyms are defined in Table, 2-4 - 2-6. Data from Brown et al. (2010).

Table 3-14. Ranges of concentrations of TPAH, 2-3-ring PAH, and ≥ 4-ring PAH in the dissolved and particulate fractions of water samples collected as part of ANIMIDA Task 7 (2000 to 2002). Concentrations are ng/L (parts per trillion). From Trefry et al. (2004a).

Region	Fraction	TPAH	2-3-Ring PAH	≥ 4-Ring PAH
Northstar	Whole water	40.1 - 54.0	33.2 - 42.3	6.86 - 11.7
	Particulate	21.1 - 40.7	15.2 - 29.0	5.85 - 11.8
	Dissolved	15.9 - 18.5	15.1 - 17.6	0.73 - 0.87
Liberty	Whole water	59.0 - 68.5	44.4 - 50.5	14.6 - 18.0
	Particulate	48.4 - 54.8	33.8 - 36.9	14.6 - 18.0
	Dissolved	14.4 - 17.7	13.2 - 16.4	1.19 - 1.36
BSMP	Whole water	37.6 - 50.8	31.8 - 56.1	5.85 - 10.3
	Particulate	22.0 - 40.8	16.9 - 31.0	5.17 - 9.72
	Dissolved	13.2 - 16.9	11.9 - 15.9	0.6 - 1.34
Water blank	Whole water	22.6	21.5	1.55
	Particulate	9.86	9.06	0.8
	Dissolved	12.7	11.9	0.75

The most abundant PAH in the particulate fraction of river water and nearshore seawater were phenanthrene and naphthalene, with lower concentrations of their alkyl homologues. The higher molecular weight PAH, fluoranthene, benzo(b)fluoranthene, and perylene were more abundant than the other high molecular weight PAH. The most abundant PAH in the dissolved fractions were naphthalene, alkyl naphthalenes, and phenanthrene, all of which were present in the dissolved sample blanks. Thus, the particulate PAH profile resembled a combined pyrogenic and biogenic source, whereas, the dissolved fraction contained traces of naphthalenes, possibly from light fuels or aerial deposition.

PAH concentrations often are relatively high in the particulate fraction of Arctic river water and nearshore seawater. Yunker et al. (1993) measured several PAH in particulate and colloidal (same as dissolved) fractions of water from the Mackenzie River and estuary, Canada. The largest fraction of PAHs always was associated with the large particulate fraction (>1.2 μm), followed by the fine particulate fraction (1.0 to 0.2 μm), followed by the colloidal fraction (<0.2 μm). A water sample from the mouth of the river contained 107 ng/L, 1.2 ng/L, and 0.31 ng/L total PAHs in the large particle, fine particle, and colloidal phases, respectively. Most of the high molecular weight PAHs were associated with the >1.2-μm fraction. Little or none was associated with the colloidal fraction. Phenanthrene and anthracene were enriched in the colloidal fraction.

The PAH distribution reported by Yunker et al. (1993) for McKenzie River water is similar to that reported in the ANAMIDA Project for Alaskan river and nearshore waters. It may be caused by tight binding of high molecular weight PAH to the particulate (particularly the particulate organic carbon: POC) phases. The high molecular weight PAH are tightly bound to peat, kerogen, coal, and soot (the large particle phase) in the suspended particulate phase. Because of the tight binding of the PAH to these organic-rich particles, the particulate PAH are inert and do not partition into the water phase (Yunker et al., 1991, 1993). For example, pyrogenic PAH

associated with soot in sediments do not partition into the pore water phase and onto pore water colloids and so have a low mobility, bioavailability, and toxicity (Readman et al., 1987; McGroddy and Farrington, 1995; Maruya et al., 1997).

3.1.6 Biogeochemistry of Arsenic and Mercury in the Coastal Beaufort Sea

The cANIMIDA Tasks 3 and 4 summer 2005 project included a more detailed investigation of As and Hg in the coastal Beaufort Sea. The results of this study are based on Semmler (2006), as presented by Trefry et al. (2009).

3.1.6.1 Arsenic

Concentrations of dissolved As were very low (0.03 to 0.17 µg/L) in the Sagavanirktok and Kuparuk rivers during the summer of 2005. Concentrations were similar to or lower than concentrations reported for other uncontaminated rivers (0.13 to 0.54 µg/L). Worldwide, concentrations of dissolved As in rivers vary as a function of drainage basin characteristics including geology and climate (Andreae et al., 1983; Andreae and Froelich, 1984) and contamination from anthropogenic sources such as mining and industrial effluents (van der Sloot et al., 1985).

Concentrations of dissolved As in the coastal Beaufort Sea (salinity ~ 30 to 32‰) ranged from 0.8 to 1.4 µg/L during the summer of 2005. These values agree well with concentrations of 0.9 to 1.3 µg/L previously reported by Trefry et al. (2004b) for the coastal Beaufort Sea, and are within the range of typical seawater concentrations. Dissolved As is found at higher concentrations in the ocean than in uncontaminated freshwater due to its long residence time of 39,000 years in seawater (Broecker and Peng, 1982).

Concentrations of dissolved As typically increase linearly with increasing salinity across a freshwater-seawater mixing zone, although deviations from this behavior have been observed in some estuaries, particularly those with anthropogenic sources of As (Andreae et al., 1983; Sanders, 1985; van der Sloot et al., 1985; Seyler and Martin, 1990; Yao et al., 2006). Concentrations of dissolved As in water samples collected from the mixing zone of the Sagavanirktok River during summer 2005 were 8 to 57% lower than the concentrations predicted by conservative mixing between river water and seawater end members, suggesting removal of As at intermediate salinities (Figure 3-27).

To determine whether this "missing" dissolved As at intermediate salinities was associated with suspended particles, "expected" concentrations of particulate As (As_p) were calculated based on the mass ratio of As to Fe in suspended sediments from the Sagavanirktok (Sag) River using the following equation:

$$\text{Expected } As_p\ (\mu g/g) = \left(\frac{As_p}{Fe_p}\right)_{Sag} \times \text{ Actual } Fe_p(\%)$$

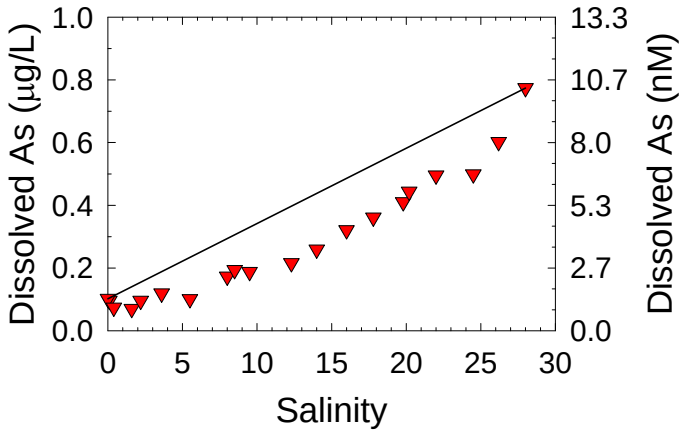


Figure 3-27. Concentrations of dissolved As versus salinity across the freshwater-seawater mixing zone from the Sagavanirktok River to the coastal Beaufort Sea during summer 2005. The solid line is a conservative mixing line between river water and seawater. From Trefry et al. (2009).

This calculation is based on the assumption that the Sagavanirktok River was the predominant source of suspended solids to the mixing zone. The average mass ratio of As_p to particulate Fe (Fe_p) in the Sagavanirktok River during the summers of 2000 to 2002 and 2004 to 2005 $[(\frac{As_p}{Fe_p})_{Sag}]$ was $2.78 \pm 0.46 \times 10^{-4}$ (n = 9). The expected As_p concentrations were then subtracted from the actual As_p concentrations to yield an estimated "excess" As on the particles as follows:

$$\text{Excess } As_p \text{ (µg/L)} = \text{Actual } As_p \text{ (µg/L)} - [\text{Expected } As_p \text{ (µg/g)} \times \text{TSS (g/L)}]$$

When values for excess As_p (converted to µg/L), calculated for each sample, were added to the corresponding concentrations of dissolved As and plotted as a function of salinity, they provided a better fit to the river water and seawater end-members and the conservative mixing line than the uncorrected data. This observation suggests that dissolved As was being removed by suspended particles across the freshwater-seawater mixing zone by means of biological uptake or scavenging of As by suspended sediments. Biological removal of As by phytoplankton seems to be of minor importance because the estimated contribution of organic matter to TSS along the salinity gradient is < 10% based on concentrations of POC (0.8 to 3.3%), indicating that phytoplankton constitute only a small fraction of the suspended matter. Furthermore, concentrations of As in phytoplankton collected during this study were low (4.2 ± 2.6 µg/g, n = 9) compared to concentrations of particulate As in the salinity gradient (18.2 ± 4.3 µg/g, n = 20).

Colloidal Fe in river water flocculates upon entering the freshwater-seawater mixing zone in an estuary, resulting in the precipitation of Fe oxides and oxyhydroxides with coprecipitation of As and adsorption to suspended clay (Howard et al., 1984; van der Sloot et al., 1985). This process provides a possible removal mechanism for dissolved As across the freshwater-seawater mixing zone in this study.

The distribution of dissolved reactive phosphate (DRP) across the freshwater-seawater interface was similar to that observed for dissolved As, and dissolved As correlated strongly with DRP

across the salinity gradient. Concentrations of DRP were 3 to 53% lower than the concentrations predicted by a conservative mixing line between river water and seawater; however, no particulate P data were obtained. One possible conclusion is that DRP may be removed across the freshwater-seawater mixing zone by a mechanism similar to that described for dissolved As. Phosphate is known to adsorb strongly to and coprecipitate with Fe oxides and oxyhydroxides (Feely et al., 1991), suggesting that scavenging or coprecipitation with Fe oxides also was a possible mechanism for removal of DRP across the salinity gradient.

The salinity of surface seawater in Stefansson Sound during July and August 2005 was within the range observed at the seaward end of the Sagavanirktok River salinity gradient. However, concentrations of dissolved As were higher in coastal seawater than in the mixing zone and were highly variable (0.48 to 1.34 µg/L, n = 50), especially at S = 28‰ (0.77 to 1.16 µg L^{-1}, n = 13) and S = 32‰ (0.90 to 1.34 µg/L, n = 8). Concentrations of DRP were higher in coastal seawater than along the very nearshore salinity gradient; DRP values also were variable, especially at S = 32 (0.57 to 1.0 µM, n = 7). The variability in concentrations of dissolved As and DRP in Stefansson Sound appears to be related to a combination of the following: (1) dilution by sea ice meltwater, (2) upwelling of offshore seawater onto the continental shelf, and (3) scavenging by or coprecipitation with Fe oxides. Biological uptake by phytoplankton did not appear to be an important mechanism controlling concentrations of dissolved As and DRP during this study, as discussed later.

Vertical profiles of dissolved As generally followed those of salinity at water depths ranging from about 4 to 12 m, with higher concentrations and greater stratification in the deeper, more saline water. However, this trend was not observed in most vertical profiles for DRP or dissolved NO_3^-. The dissolved As/DRP ratios at some stations were similar to the value previously reported by Feely et al. (1991) for the North Atlantic Ocean (1.5×10^{-2}). The similarity of the dissolved As to DRP ratios at some locations in nearshore waters of the Beaufort Sea with that of the North Atlantic Ocean suggests that offshore seawater that upwells onto the continental shelf of the Beaufort Sea may originate in the North Atlantic Ocean. Seawater from the Pacific Ocean enters the Beaufort Sea via the Alaskan Coastal Current and flows along the continental slope of the Beaufort Sea over deeper water originating from the Atlantic Ocean which contributes to this current by upwelling (Weingartner, 2006). The continental shelf receives some input of offshore seawater by upwelling (MacDonald et al., 1987; Weingartner, 2006). Thus, the variability in concentrations of dissolved As at some locations appears to be controlled, to some extent, by upwelling and mixing of offshore seawater with coastal seawater in Stefansson Sound.

Suspended sediments collected during the summer of 2005 from Stefansson Sound (n = 21) were enriched in As and Fe relative to Al (Figure 3-28). Concentrations of As_p (14.5 to 53.0 µg/ g, n = 21) and Fe_p (2.4 to 5.9%, n = 21) in most suspended sediment samples plot above the 95% prediction intervals established by Trefry et al. (2003) for As versus Al and Fe versus Al in bottom sediments collected from the coastal Beaufort Sea during the summers of 1999 through 2001. These observations support the presence of iron oxides, most likely on clay particles, as the source of Fe enrichment. Scavenging of As by iron oxides is the most likely explanation for observed As enrichment in suspended particles. Concentrations of As in phytoplankton (4.2 ± 2.6 µg/g, n = 9) and zooplankton (2.3 ± 1.1 µg/g, n = 9) collected from Stefansson Sound during the summer of 2005 were too low to account for the high concentrations of As found in suspended sediments. Likewise, resuspension of bottom sediments cannot account for the high

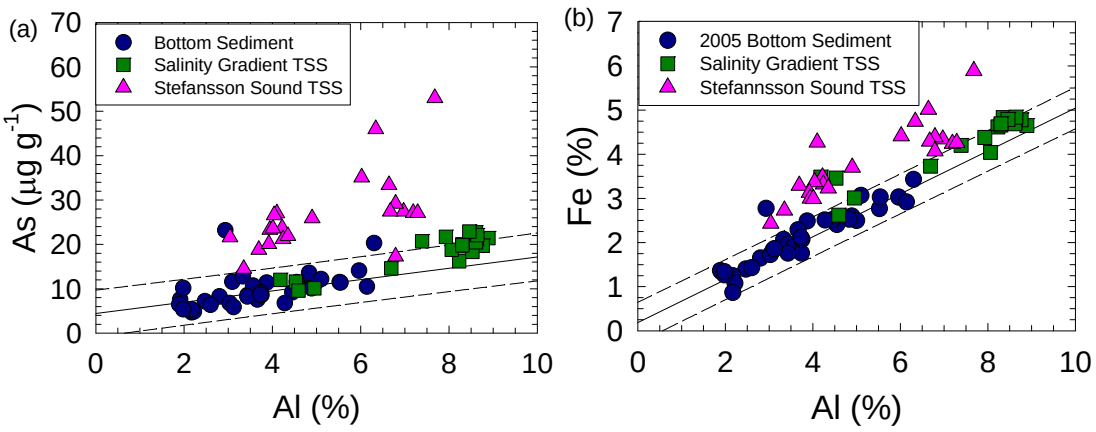


Figure 3-28. Concentrations of (a) As versus Al and (b) Fe versus Al in total suspended solids (TSS) and bottom sediments collected from Stefannsson Sound during the summer of 2005. Solid lines are from a linear regression and dashed lines are 95% prediction intervals for bottom sediments from the coastal Beaufort Sea collected in 1999 through 2001 (Trefry *et al*., 2003; n = 194). From Trefry et al. (2009).

concentrations of As_p because concentrations of As in surficial bottom sediments collected during the summer of 2005 (9.8 ± 3.8 µg g^{-1}, n = 38) fit well within the 95% prediction intervals of Trefry et al. (2003). Thus, scavenging of As by iron oxides seems to be a common occurrence in the study area and a reasonable explanation for the As-rich particles found in the water column.

Concentrations of As in phytoplankton, zooplankton, amphipods, clams, and fish collected during summer 2005 are summarized in Table 3-15. Enrichment factors (EF) were determined as the ratio of the average concentration of As in tissue (in µg/g dry weight) to the average concentration in water (in µg/g of water) or tissue belonging to the next lower tropic level. The EF between surface seawater and phytoplankton was ~5,000, indicating that bioaccumulation of dissolved As by phytoplankton was occurring. However, this process seemed to have little influence on the concentrations of dissolved As in the water column due to the relatively high concentrations (1 to 1.5 µg/L) that occur naturally in seawater. No significant differences were found for concentrations of As between phytoplankton and zooplankton ($t = 1.444$, $p > 0.05$, $df = 16$) or between zooplankton and fish ($t = 0.451$, $p > 0.05$, $df = 27$; Figure 3-29). Concentrations of As were significantly greater in amphipods than in zooplankton ($t = 8.563$, $p < 0.001$, $df = 18$), and also were significantly greater in clams than in phytoplankton ($t = 5.770$, $p < 0.001$, $df = 11$). Enrichment factors between successive trophic levels ranged from 0.55 (between phytoplankton and zooplankton) to 4.9 (between zooplankton and amphipods). As does seem to biomagnify in some steps of marine food webs because inorganic arsenic is converted to arseno-sugars and arsenobetaine, probably by sediment bacteria. These organo-arsenic compounds are much more bioavailable and slower to be released from tissues than inorganic arsenate and arsenite salts, so arsenobetaine, in particular tends to bioaccumulate to high concentrations in marine animals that consume benthic fauna (Neff, 1997). Arsenobetaine is not toxic to the consumers.

Table 3-15. Concentrations of As in surface seawater (dissolved), phytoplankton, zooplankton, amphipods (*Anonyx* sp.), clams (*Astarte* sp.) and fish collected from the coastal Beaufort Sea during the summer of 2005. From Semmler (2006) and Trefry et al. (2009).

Sample Type	As Concentration (µg/g)			
	Mean	SD	Range	N
Surface seawater[a] (S = 14.5 to 29‰)	0.83×10^{-3}	0.19×10^{-3}	(0.48-1.06) $\times 10^{-3}$	14
Phytoplankton[b,c]	4.2 (6.7)	2.6 (4.6)	0.8 – 7.9 (1.4 – 15.3)	9
Zooplankton[b,c]	2.3 (4.7)	1.1 (2.0)	1.2 - 4.1 (2.41 – 8.31)	9
Amphipods (*Anonyx* sp.)	11.2	3.6	5.0 – 17.4	11
Clams (*Astarte* sp.)	13.0	2.2	11.3 – 16.0	4
Fish[d]	2.5	1.5	0.8 – 7.4	20

[a] Dissolved concentrations in seawater are in µg/mL

[b] Concentrations of phytoplankton and zooplankton are sediment-corrected using ratios to Fe (uncorrected concentrations are in parentheses) as described by Semmler (2006).

[c] Details of phytoplankton and zooplankton species composition are in the Appendix to Task 3-4

[d] Average of concentrations found in Arctic char, Arctic cisco, Arctic flounder, four-horn sculpin, and humpback broad whitefish

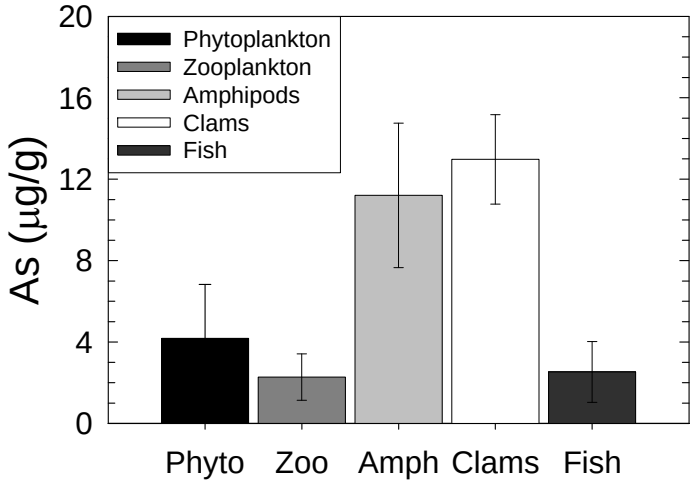


Figure 3-29. Average concentrations of As in phytoplankton, zooplankton, amphipods (*Anonyx* sp.), clams (*Astarte* sp.) and fish collected from Stefannsson Sound during summer 2005. From Trefry et al. (2009).

Concentrations of As in organisms collected during summer 2005 from Stefansson Sound (Table 3-16 and Figure 3-29) compare well with values previously reported by others. For example, Lindsay and Sanders (1990) reported an average concentration of 8.6 µg/g in cultured phytoplankton exposed to ambient water from the Patuxent River (average concentration of dissolved As = 0.71 µg/L). A review by Neff (1997) tabulated average concentrations of As of 2.1 µg/g (0.2 to 24.4 µg/g, n = 4) in zooplankton, 10.4 µg/g (< 0.6 to 214 µg/g, n = 151) in bivalves, and 5.6 (0.05 to 449.5 µg/g, n = 156) in fish.

Table 3-16. Concentrations of total dissolved Hg (TDHg) and dissolved CH_3Hg^+ in selected rivers, estuaries and seawater. Beaufort Sea data are highlighted. From Trefry et al. (2009).

Location	TDHg (ng/L)			Dissolved CH_3Hg^+ (ng/L)			Ref.
	Mean	SD	Range	Mean	SD	Range	
Rivers and Estuaries							
Sagavanirktok River (August, 2005, n = 3)	0.81	0.41	0.5- 1.1	< 0.019	-	-	1
Kuparuk River (August 2005, n = 3)	1.03	0.39	0.8- 1.3	< 0.019	-	-	1
Lena River[a]	1.0	0.1	0.9 – 1.1	-	-	-	2
Ob River[a]	0.6	0.1	-	-	-	-	2
Yenisei River[a]	0.3	0.1	-	-	-	-	2
St. Lawrence River[a]	2.4	0.6	-	-	-	-	3
Garonne River (Gironde Estuary, France)[a]	3.0	-	-	-	-	-	4
Rhône River[a]	1.6	0.7	0.6 – 2.6	-	-	-	5
Loire River[a]	0.82	0.42	0.4 – 2.0				6
Seine River[a]	2.3	1.9	0.5 – 7.9				6
Ochlockonee Estuary[b]	3.2	1.6	0.7 – 6.0	0.08	-	0.06 – 0.09	7
Seawater							
Coastal Beaufort Sea (S = 14.5 to 32) August, 2005 (n = 38)	0.69	0.12	0.5 – 0.9	-	-	< 0.019 – 0.046	1,8
North Atlantic Ocean (surface)[b]	0.23	0.20	0.1 – 0.5	-	-	-	7
South and Equatorial Atlantic Ocean (surface)[a,c,d]	0.56	-	-	<0.01 (MDL)	-	-	9
Laptev Sea (Arctic Ocean; S = 32.6, depth = 35 m)[a]	0.80	-	-	-	-	-	2
Kara Sea (Arctic Ocean; S ~34, depth = 30-45 m)[a]	2.0	1.5	0.4 – 3.4	-	-	-	2
North Sea and English Channel (surface, S ~34-35)[d]	0.29	0.06	0.2 – 0.4	0.03	0.02	0.02 – 0.06	10
Equatorial Pacific Ocean (Mixed layer, 0-100 m)[d]	-	-	-	<0.01 (MDL)	-	-	11
Equatorial Pacific Ocean (>100 m)[d]	-	-	-	-	-	<0.01 (MDL)- 116	11
Arctic Ocean (75°N, 14°W to 16°E)[b]	-	-	-	-	-	<0.005 (MDL) – 0.16	12

Notes: [a] Filtered using 0.8 µm glass fiber filters; [b] Filtered using 0.45 µm filters; [c] Dissolved Hg obtained by subtracting particulate Hg (0.02 ± 0.01 ng/g) from total Hg (unfiltered; 0.58 ± 0.34 ng/L); [d] CH_3Hg^+ reported as total CH_3Hg^+ (unfiltered)

References: (1) Trefry et al., 2009; (2) Coquery *et al*., 1995; (3) Cossa *et al*., 1988; (4) Cossa and Noël, 1987; (5) Cossa and Martin, 1991; (6) Coquery *et al*., 1997; (7) Guentzel *et al*., 1996; (8) Trefry *et al*., 2004b; (9) Mason and Sullivan, 1999; (10) Leermakers *et al*., 2001; (11) Mason and Fitzgerald, 1993; (12) Pongratz and Heumann, 1998.

3.1.6.2 Mercury

Concentrations of total dissolved Hg in the Sagavanirktok and Kuparuk rivers during August 2005 were similar to concentrations reported for other Arctic rivers, including the Lena and Ob rivers in Russia, and were ~ 2 to 3 times lower than average concentrations reported for the St. Lawrence, Garonne, Rhône, and Seine rivers (Table 3-16). Trefry et al. (2004b) previously reported average concentrations of total dissolved Hg of ~ 2 ng/L in the Sagavanirktok, Kuparuk and Colville Rivers. Dissolved mono-methylmercury (CH_3Hg^+) was not detectable (< 0.019 ng/L) in the Sagavanirktok and Kuparuk Rivers during low flow conditions in August 2005.

Concentrations of total dissolved Hg (TDHg) in Stefansson Sound averaged 0.69 ± 0.12 ng/L (0.50 to 0.90 ng/L, n = 38, Table 2-6). Trefry et al. (2004b) previously reported concentrations of 0.70 ± 0.39 ng/L (0.30 to 1.50 ng/L, n = 8) in the coastal Beaufort Sea during August 2000 and 2001. Concentrations of dissolved CH_3Hg^+ were undetectable (< 0.019 ng/L) in 12 of the 17 seawater samples collected during summer 2005. The exceptions included one sample collected at station L18 (0.025 ng/L) and four samples collected at station L01C (0.022 to 0.046 ng/L). In the 15 samples with concentrations of both TDHg and dissolved CH_3Hg^+, CH_3Hg^+ accounted for <3.8 to 7.3% of the TDHg.

Concentrations of TDHg averaged 1.0 ± 0.2 ng/L (n = 9) across the freshwater-seawater mixing zone during the summer of 2005, with no significant trend as a function of salinity (r = 0.14). Similar distributions of TDHg were previously observed by Coquery et al. (1995, 1997) in two Arctic estuaries, the Ob and the Yenisei, and in the Loire and Seine estuaries, with variable concentrations and no clear trend as a function of salinity. The behavior of TDHg in the Loire and Seine estuaries was attributed to a combination of several factors, including anthropogenic inputs from industrial activities, seasonal variations in water flow, association with colloids, and complexation with dissolved organic matter (Coquery et al., 1997).

Concentrations of TDHg in Stefansson Sound (0.69 ± 0.12 ng/L, n = 38) were significantly lower than concentrations of 1.0 ± 0.2 ng/L observed across the freshwater-seawater mixing zone ($t = 6.47$, $p < 0.001$, $df = 45$). Concentrations of TDHg appear to be controlled by a combination of processes including: (1) upwelling of offshore seawater onto the continental shelf, (2) input of dissolved Hg to surface waters from organic matter and/or sediment released from melting sea ice during summer, and (3) biological productivity. Biological productivity was low during summer 2005 and thus it is probably of minor importance in controlling the concentrations of total dissolved Hg in Stefansson Sound. However, productivity may play a role in the distribution of dissolved CH_3Hg^+, as discussed later in this section. The lower concentrations of TDHg in coastal seawater relative to the freshwater-seawater mixing zone could be the result of upwelling of offshore seawater having lower concentrations of TDHg. Concentrations of TDHg in the North Atlantic Ocean (Guentzel et al., 1996) and Northeast Pacific Ocean (Gill and Bruland, 1987) are similar and range from ~ 0.1 to 0.5 ng/L and ~ 0.2 to 0.6 ng/L, respectively. Thus, mixing of river and intermediate-salinity waters (TDHg = 1.0 ± 0.2 ng/L) with offshore seawater originating from the North Atlantic and/or North Pacific Oceans may account for the lower concentrations of TDHg found in Stefansson Sound (0.69 ± 0.12 ng/L).

Vertical profiles of TDHg were relatively uniform with depth at some Beaufort Sea stations and increased slightly with depth at some stations in August. Although this distribution does not clearly show dilution of dissolved Hg at depth by upwelling of offshore seawater or input of

dissolved Hg near the surface from melting sea ice, these processes may occur simultaneously and compete with each other to produce the observed variability.

Concentrations of dissolved CH_3Hg^+ at a station in the Liberty prospect increased from the surface (< 0.019 ng/L) to a mid-depth maximum of 0.046 ng/L at 4 m (Figure 3-30). The observed distribution of dissolved CH_3Hg^+ may be produced by biological activity in Stefansson Sound, although the biomass of plankton was estimated to be low (< 600 µg/L) in Stefansson Sound during this study. Alternatively, this distribution could be the result of upwelling of offshore seawater onto the continental shelf. Pongratz and Heumann (1998) found that concentrations of both CH_3Hg^+ and $(CH_3)_2Hg$ were elevated at the boundary of pack ice in the Arctic and Antarctic Oceans, corresponding to high biological productivity. In addition, CH_3Hg^+ is thought to be the main product of decomposition of $(CH_3)_2Hg$ (Mason and Fitzgerald, 1993; Mason et al., 1995b, Pongratz and Heumann, 1998). $(CH_3)_2Hg$ is produced mainly by anaerobic sulfate-reducing bacteria and accumulates in deep ocean waters (particularly the oxygen minimum layer (200 to 300 m), over long periods of time (> 5 years) (Mason et al., 1995b). Mason et al. (1995) and Mason and Fitzgerald (1993) reported that dimethylmercury,$(CH_3)_2Hg$, and methylmercury, CH_3Hg^+, were not found in surface waters of the North Atlantic or Equatorial Pacific Oceans, respectively but were detectable in deeper waters below the thermocline.

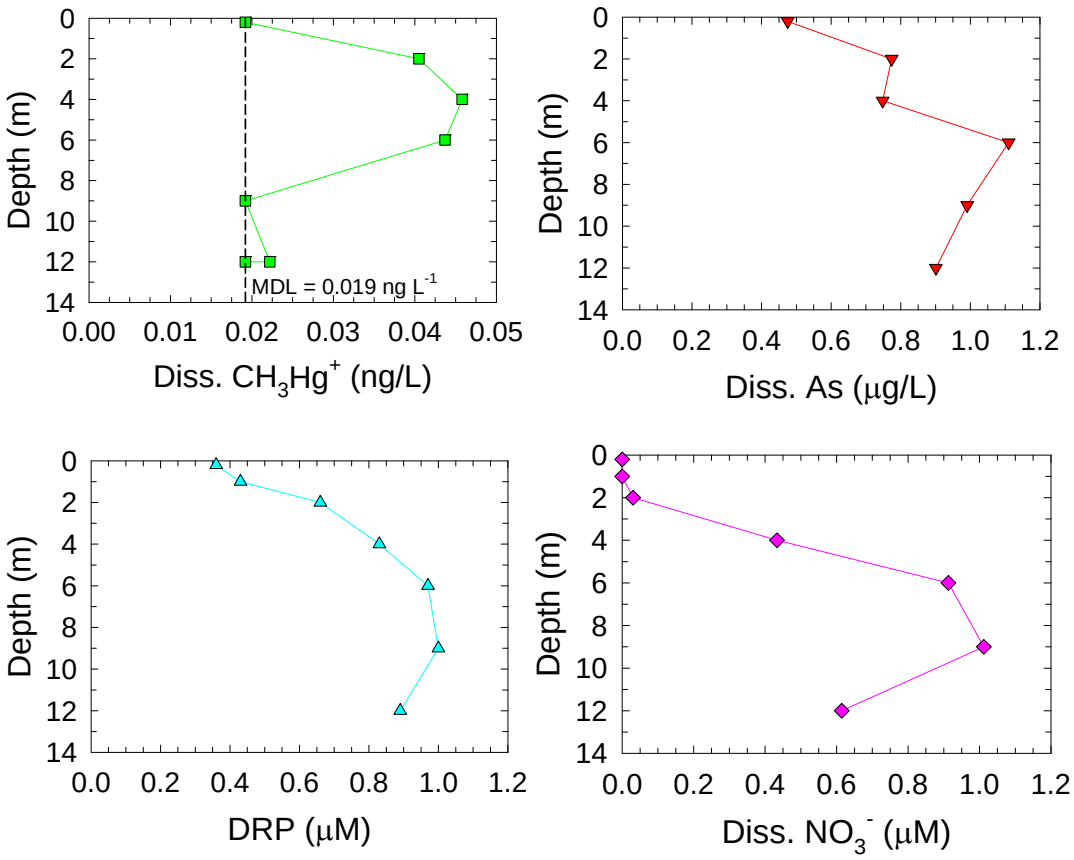


Figure 3-30. Vertical profiles of (upper left) dissolved CH_3Hg^+, (upper right) dissolved As, (lower left) dissolved reactive phosphate (DRP), and (lower right) dissolved NO_3^- in seawater at station L01 (Figure 2-3) on August 3, 2005. From Trefry et al. (2009).

Concentrations in deep waters ranged from < 0.002 (MDL) to 0.07 ng/L for $(CH_3)_2Hg$ and were at or below the MDL (0.01 ng/L) for CH_3Hg^+ in unfiltered samples from the North Atlantic Ocean (Mason et al., 1995). Values ranged from 0.008 to 0.15 ng/L for $(CH_3)_2Hg$ and < 0.01 (MDL) to 125 ng/L for CH_3Hg^+ in unfiltered samples from the Equatorial Pacific Ocean (Mason and Fitzgerald, 1993). Pongratz and Heumann (1998) reported concentrations of dissolved (< 0.45 µm) CH_3Hg^+ and $(CH_3)_2Hg$ of ~ 0.1 to 3 ng/L in surface waters of the North Atlantic (40 to 51° N, 10° W), adjacent to areas of anthropogenic inputs. Thus, upwelling of seawater originating from the deeper waters of the Atlantic or Pacific Oceans and/or influenced by higher concentrations within the region of the pack ice boundary may be a source of CH_3Hg^+ to the coastal waters of Stefansson Sound. This hypothesis is supported by the observation that concentrations of dissolved As, DRP, and dissolved NO_3^- also were highest at intermediate depths and at stations located farthest offshore in Stefansson Sound (Figure 3-30). The methylmercury in Beaufort Sea coastal water probably is from upwelling offshore near the edge of the pack ice (Semmler, 2003) and from runoff from melting permafrost soils containing a large inventory of mercury and methylmercury from aerial deposition and methylation in suboxic layers of frozen soil (MacDonald et al., 2005, 2009).

There is particular concern about mercury in Arctic marine food webs (MacDonald et al., 2005; Jaeger et al., 2007). Mercury concentrations in marine waters in much of the Arctic are higher than concentrations in temperate and tropical waters due in large part to upwelling of Hg at the ice edge and deposition of metallic and inorganic mercury from long-range transport and deposition from the atmosphere (Skov et al., 2004; MacDonald et al., 2005; Outridge et al., 2008; Sommar et al., 2010). Concentrations of TDHg are high in the upper water column and overlying atmosphere of the Alaskan and Canadian Arctic during ice-covered periods (Sommar et al., 2010). The net flux of Hg during this time seems to be from the water to the atmosphere. TDHg concentrations in surface waters usually are much lower in ice-free conditions. There is no evidence that mercury in the Beaufort Sea is coming from onshore or offshore oil and gas operations (Neff, 2010).

Concentrations of total Hg were significantly higher (EF = 2.7) in clams than in phytoplankton ($t = 2.84$, $p < 0.05$, $df = 8$) and also were significantly higher (EF = 1.9) in fish than in zooplankton ($t = 2.13$, $p < 0.05$, $df = 26$; Table 3-17 and Figure 3-31). No significant difference was found for concentrations of total Hg between zooplankton and amphipods ($t = 1.63$, $p > 0.05$, $df = 16$; Table 3-17 and Figure 3-31).

Concentrations of total Hg in zooplankton collected from Stefansson Sound during summer 2005 compare well with concentrations found by Stern and MacDonald (2005) in zooplankton (*Calanus hyperboreus*) from the Canadian Basin of the Beaufort Sea (85 ± 9 ng/g) and from the Chukchi Plateau and Mendeleev Basin of the Arctic Ocean (48 ± 3 ng/g). Stern and MacDonald (2005) also reported concentrations of CH_3Hg^+ in *C. hyperboreus* of ~ 5 to 20 ng/g (~ 10 to 30% of the total Hg), slightly higher than concentrations found during this study. Atwell *et* al. (1998) also determined concentrations of total Hg in zooplankton (*C. hyperboreus*) from Lancaster

Table 3-17. Concentrations of mercury and methylmercury in surface seawater (dissolved), mixed phytoplankton, mixed zooplankton, amphipods (*Anonyx* sp.), clams (*Astarte* sp.), and fish (average for Arctic char, Arctic cisco, Arctic flounder, fourhorn sculpin, and humpback broad whitefish from the coastal Beaufort Sea. From Semmler (2006) as presented by Neff (2010).

Sample Type	Concentration (ng/g dry wt: ppb)[a]			Bioconcentration Factor[b]
	Mean SD	Range	N	
Total Mercury				
Surface seawater[c]	0.69 ± 0.12	0.50 - 0.90	38	-
Phytoplankton	19.6 ± 13.4	11.2 - 39.7	4	28,400
Zooplankton	55.4 ± 30.7	29.6 - 105	8	2.8
Amphipods	78.0 ± 28.2	46.4 - 117	8	1.4
Clams	53.5 ± 18.4	42.6 - 80.9	4	2.7
Fish	106.2± 64.2	30.0 - 266	20	1.9
Methylmercury				
Surface seawater[c]	0.025 ± 0.01[d]	<0.02 - 0.046	15	-
Phytoplankton	0.60 ± 0.56	0.22 - 1.24	3	24,000
Zooplankton	4.25 ± 1.94	2.21 - 6.66	6	7.1

[a] Concentrations of dissolved total mercury and methylmercury in seawater are ng/L (parts per trillion); [b] Bioconcentration factor is the concentration in consumer divided by the concentration in prey (or water for phytoplankton); [c] Salinity varied from 14.5 to 32‰; [d] Average and SD were determined using the method detection limit (MDL) as the concentration for samples in which methylmercury was not detected above the MDL.

Sound, Northwest Territories, Canada, and found a similar average concentration of 60 ± 10 ng/g. Campbell et al. (2005) reported similar concentrations of total mercury in mixed zooplankton from the Northwater Polynya in Baffin Bay, Canada, to those reported by Dehn et al. (2005) for the Alaskan and Canadian Arctic (5 to 50 ng/g). Earlier, Joiris et al. (1997) reported that concentrations of total mercury were lower in zooplankton from the Barents Sea (90 to 120 ng/g) than in those from the North Sea (mean, 320 ng/g). Jaeger et al. (2007) did not detect mercury in copepods and euphausiids (*Meganychtophanes norvegica, Thyasoessa inermis, Thermisto libellula,* and *Calanus hyperboreus*) from the Barents Sea. These zooplankton are the main foods of bowhead whales in the Canadian and Alaskan Arctic.

Concentrations of total Hg in *Astarte* sp. clams collected from Stefansson Sound during this study (53 ± 18 ng/g) were similar to concentrations of total Hg of 70 ± 10 ng/g reported by Atwell *et al*. (1998) in *Mya truncata* (a filter-feeding clam) from Lancaster Sound. Stern and MacDonald (2005) reported concentrations of total Hg in Arctic cod (*Boreogadus saida*) from the Canadian Basin of the Beaufort Sea (270 ± 40 ng/g) and from the Chukchi Plateau and Mendeleev Basin (85 ± 5 ng/g), adjusted for variability in $\delta^{15}N$ and body length. Atwell *et al*. (1998) reported similar concentrations of total Hg in muscle of Arctic cod (190 ± 30 ng/g) from Lancaster Sound. Bloom (1992) reported concentrations of total Hg and CH_3Hg of 200 ng/g (100% of total Hg was CH_3Hg) in Chinook Salmon (*Oncorhynchus tshawytscha*) muscle and 780 and 740 ng/g (95% of total Hg was CH_3Hg) in lingcod (*Ophiodon elongatus*) from southeast Alaska. These concentrations of total Hg and CH_3Hg in various species of fish are similar to or slightly higher than those found in fish collected from Stefansson Sound during summer 2005.

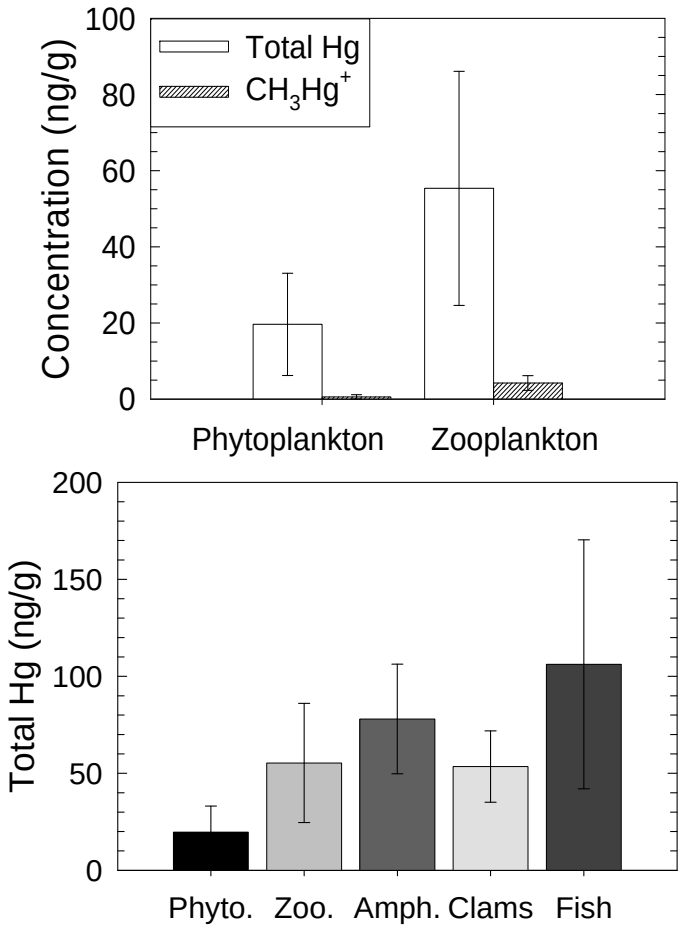


Figure 3-31. Concentrations of total Hg and CH_3Hg^+ in phytoplankton and zooplankton (top) and total Hg in phytoplankton, zooplankton, amphipods, clams, and fish (bottom) collected from Stefansson Sound during summer 2005. From Trefry et al. (2009).

Because CH_3Hg^+ tends to biomagnify in marine food webs, concentrations of total and methylmercury may be high in high trophic level consumers in Arctic seas, such as marine mammals and birds. Concentrations of total and methylmercury are high in liver and muscle tissues of several marine mammals collected off Barrow, AK (Table 3-18). Fish and mammal eating marine carnivores, such as polar bears, beluga whales, and some seals, contain high concentrations of total and methylmercury in liver, with lower concentrations in muscle and other organs. Bowhead whales do not bioaccumulate high concentrations of mercury because they feed at a lower trophic level on large copepods and euphausiids, which contain low concentrations of methylmercury. Most of the mercury in liver is complexed with selenium to form relatively inert concretions. Most of the mercury in muscle is highly toxic methylmercury (Neff, 2010).

Table 3-18. Concentrations of total mercury and methyl mercury in muscle and liver of marine mammals collected off Barrow, Alaska. Concentrations are ng/g dry wt, converted from wet weight by multiplying by 5. From Dehn et al. (2005, 2006a,b).

Species	Tissue	Total Mercury	Methyl Mercury
Polar Bear *Ursa maritimus*	Liver	7500 - 272,000	No data
Ringed Seal *Pussa hispida*	Muscle	50 - 53,000	50 - 1900
	Liver	300 - 82,500	50 - 2500
Beluga Whale *Delphinapterus leucus*	Muscle	650 - 61,500	650 - 12,000
	Liver	1400 - 362,000	950 - 19,400
Bowhead Whale *Balaena mysticetus*	Muscle	<5 - 50	No Data
	Liver	5 - 3000	No Data

3.2 Characterization of Metals and Hydrocarbons in Sediments in the ANIMIDA/cANIMIDA Study Area

A large number of stations in the Northstar, Liberty, and BSMP areas were sampled in 2004, 2005, and 2006 for analysis of metals and hydrocarbons in surficial and core sediments (Table 2-1, Figure 2-3) (Brown et al., 2010). Many of these stations had been sampled one or more times in 1999 through 2002 for analysis of sediment metals and hydrocarbons as part of the Phase 1 and 2 ANIMIDA Project (Boehm et al., 2001; Brown et al., 2004). The objective of this sampling was to better characterize the range of concentrations of several metals and three hydrocarbon classes (SHC, PAH, and StTr) in sediments of the oil and gas development area in the Alaskan Beaufort Sea and to determine if there where changes in physical and chemical properties of the sediments that could be linked to exploration and development activities.

3.2.1 Sediment Grain Size and Concentrations of Total Organic Carbon (TOC), and Metals

3.2.1.1 Total Organic Carbon

TOC concentrations in surficial sediments ranged from 0.02% in sandy sediment in shallow water (1.8 m) at station L21 near the mouth of the Sagavanirktok River to 6.4% in a peat-bearing sample from station N14 (Table 3-19). The overall mean concentration of TOC of 0.77 ± 0.77% for 2004-2006 was not significantly different ($p<0.01$) from the means from 1999-2002 of 0.91 ± 0.86%. There was considerable patchiness in TOC concentrations across the study area, probably related to the patchiness in the occurrence of fine-grained sediment. The mean and range of TOC concentrations was similar in the Northstar, Liberty, and BSMP areas in 2004-2006 (Table 3-19). Overall, the TOC concentrations are typical of values reported by others for the nearshore Beaufort Sea. For example, Carsola (1954) reported a range of TOC values from 0.2-1.2 % for Beaufort Sea sediments.

Table 3-19. Mean and range of concentrations of Al, Fe, TOC, and % silt + clay (mud), in sediments from the Northstar, Liberty, and BSMP areas, 2000 - 2006. Al and Fe concentrations in sediments are useful for normalization of other metals concentrations to the sediment clay fraction. All concentrations are % dry wt. (Data from Brown et al., 2005, 2009).

Metal	Year	Northstar	Liberty	BSMP
Aluminum (Al)	2000	4.23 (0 - 6.76)	3.98 (0 - 6.76)	3.65 (1.26 - 6.98)
	2002	4.49 (1.65 - 5.92)	3.41 (1.56 - 5.42)	2.95 (1.65 - 4.38)
	2004	4.13 (1.64 - 6.32)	4.16 (2.17 - 5.83)	3.24 (1.28 - 5.84)
	2005	3.19 (1.91 - 4.89)	4.36 (2.17 - 6.30)	3.46 (1.89 - 5.52)
	2006	4.43 (1.78 - 5.79)	3.17 (2.04 - 4.01)	4.06 (2.69 - 6.29)
Iron (Fe)	2000	2.38 (0 - 3.66)	2.25 (0 - 3.66)	2.23 (0.92 - 3.91)
	2002	2.52 (0.89 - 3.29)	1.95 (0.99 - 2.82)	1.76 (0.78 - 3.03)
	2004	2.42 (0.94 - 3.70)	2.47 (1.33 - 3.39)	1.96 (0.95 - 3.11)
	2005	2.06 (1.34 - 2.78)	2.34 (1.25 - 3.43)	1.90 (0.97 - 2.77)
	2006	2.74 (1.27 - 3.65)	2.11 (1.12 - 2.76)	2.57 (1.54 - 3.70)
Total Organic Carbon (TOC) (%)	2004	0.56 (0.04 - 1.72)	0.95 (0.25 - 2.38)	0.47 (0.04 - 0.91)
	2005	1.71 (0.11 - 6.42)	0.77 (0.28 - 1.60)	0.66 (0.05 - 1.75)
	2006	1.00 (0.23 - 1.38)	0.85 (0.02 - 2.75)	0.95 (0.08 - 2.17)
Silt + Clay (Mud) (%)	2004	45.6	56.0	44.5
	2005	29.4	58.4	35.6
	2006	66.7	39.6	49.0

3.2.1.2 Sediment Grain Size

The grain size distribution also was variable throughout the study area and from one year to the next. Gravel concentration (>2 mm) ranged from 0% in 68 of 112 surface sediment samples to 61% at station N15, located adjacent to Stump Island and 46% at the pipeline just south of Northstar Island. Likewise, mean silt + clay (mud) concentrations in surface sediments from the three study areas were variable, ranging from 29.4% at Northstar in 2005 to 66.7% at Northstar in 2006 (Table 3-19). The highest clay concentration in sediments sampled in the 1999-2002 ANIMIDA Project was 50% at station 4A in the BSMP area. Sediment resuspension, along with across and along shelf transport, are dynamic components of the inner shelf of the Beaufort Sea that certainly contribute to observed variations in grain size distribution in the top 1 cm of nearshore Beaufort Sea sediments, as discussed above.

The mean % mud in sediments from all stations combined was 47%, 40%, and 50%, in 2004, 2005, and 2006, respectively. Mean sediment mud concentrations were higher at Liberty stations in 2004 and 2005, and at Northstar stations in 2006 (Table 3-19). Thus, although sediment grain size was variable throughout the development area, the mean and range of concentrations of mud were similar in all years, and compared favorably with data from 1999 and 2002.

Inter-annual shifts in the texture of surficial sediments have occurred throughout the cANIMIDA study area. Large changes in grain size distribution were observed first in the ANIMIDA Project between 1999 and 2000. For example, during 1999, surficial sediment at four Northstar stations was essentially all sand and gravel. In 2000, sediment samples from these same stations contained mainly silt and clay. Although the exact mechanism for this shift is not known, the 1999 samples were collected after a 6-day storm with winds in excess of 25 knots that may have eroded away finer-grained material. No such storms preceded collection of the 2000 samples that probably contained finer-grained material carried in by the Kuparuk River during the spring breakup of 2000. The opposite shift occurred at two stations close to the Northstar Island where fine-grained sediments were more abundant in samples collected in 1999 than in 2000. This shift may have resulted from inputs of coarser material at these stations in association with construction of the island. Grain size distribution at the other Northstar stations was similar for 1999 and 2000.

An important observation from the grain size data is that sediments in many locations throughout the cANIMIDA study area are regularly shifting and that the sediment grain sizes found during one year may change prior to sampling during a subsequent year. Furthermore, the grain size distribution in surface sediments is very patchy from site to site. Thus, techniques that normalize sediment chemistry to account for differences in grain size should be used to determine if surface and subsurface sediment collected during any given year is recent and not relict material, and to determine if sediment metals and hydrocarbons are natural or from human activities.

3.2.1.3 Geochronology of Surficial Beaufort Sea Sediments, Based on ^{210}Pb and ^{137}Cs Activity

The cANIMIDA study area has been a net erosional sedimentary environment during the past several thousand years (Reimnitz and Barnes, 1974). At best, sediment deposition in the cANIMIDA area has been patchy during the past century. Trefry et al. (2003) cautioned investigators to be sure that sediments collected for analysis of potential contaminants are representative of the most recent inputs. Surficial sediments from the 2004-2006 surveys were counted for the activities of excess ^{210}Pb and total ^{137}Cs to determine the extent of possible sediment deposition or erosion in the area. The pre-survey assumption was that surface sediments with low activities of excess ^{210}Pb (<0.5 dpm/g) or ^{137}Cs (<0.05 dpm/g) would contain very little silt or clay that had been recently or sufficiently well exposed to the water column or at the sediment-seawater interface to adsorb excess ^{210}Pb or ^{137}Cs. Therefore, such sediments would be less likely to contain recent material that had an anthropogenic contribution of metals or hydrocarbons. However, in some cases, sediments with low excess ^{210}Pb and ^{137}Cs activities might be predominantly sand that had a naturally low affinity for these isotopes. Sediments that have intermediate levels of the two isotopes may be sandy or contain some mixture of old, recent and sandy sediments.

During each of the three years of this study, surface sediments were found with non-detectable amounts of excess ^{210}Pb (<0.05 dpm/g) and ^{137}Cs (<0.015 dpm/g) at some locations. In contrast, maximum values for excess ^{210}Pb of 2.8 dpm/g and ^{137}Cs of 0.20 dpm/g were observed at other locations. Collectively, the activities for ^{226}Ra (parent isotope to ^{210}Pb) correlated well with concentrations of Al. This good relationship is consistent with higher amounts of ^{226}Ra in Al-rich clays. However, there is another ^{226}Ra-bearing phase in many of the sediments, possibly associated with natural barite in fine-grained sediments.

There is considerable scatter in the relationship between Al and excess ^{210}Pb in surface sediments. One explanation for the observed scatter is large differences in the accumulation rates and/or ages among the 112 samples of surface sediment. Samples with low amounts of excess ^{210}Pb (<0.5 dpm/g) and Al concentrations >3% are less likely to contain very much recent sediment relative to samples with excess ^{210}Pb >0.5 dpm/g and Al concentrations >3%. A weak, but observable trend of higher activity for excess ^{210}Pb in sediments with a higher activity of ^{137}Cs than was observed for the surface sediments is consistent with increased adsorption of the two isotopes from water by clay-rich (i.e., Al-rich) sediments.

Weiss and Naidu (1986) used vertical profiles for the activity of total ^{210}Pb to calculate sedimentation rates of 0.6 to 1 cm/year at sites in Simpson Lagoon, near our stations 6A and 6G; however, the total activities for ^{210}Pb averaged <2 dpm/g with variable texture in each core. Naidu et al. (2001) more recently reported no excess ^{210}Pb and no detectable ^{137}Cs in a core from Simpson Lagoon. However, they reported excess ^{210}Pb levels of 0.9 to 1.2 dpm/g and ^{137}Cs activities of 0.2 dpm/g at a site near station 3B. Based on inherent difficulties with area sediments, a primary goal of our geochronology effort was to collect some sediment that was deposited prior to the onset of onshore development during the late 1960s and some sediment that was deposited post-development.

Our results show sedimentation rates that range from ~0.04 cm/year to ~0.10 cm/year, with several sites having little or no net accumulation of sediment during at least the past 50 years. At three sites, we identified 3- to 5-cm thick layers of sediment that were deposited since onshore development began (approximately 1970). Our overall results are consistent with those of Naidu et al. (2001) for the same area. We know from our previous work that the presence of fine-grained sediment at a given location can vary from year to year and that the sediments along much of the shallow, coastal Beaufort Sea are quite dynamic.

Additional support for low sedimentation rates at stations P01 and E01 can be developed from data for river inputs of sediment. The Sagavanirktok River, the major river carrying sediment into this area, is estimated to have an annual sediment load of about 330,000 metric tons (Rember and Trefry, 2004). The depositional area for this sediment in coastal Beaufort Sea is about 1000 km^2 (the approximate area bounded by the mainland to the south, the outer islands such as Cross Island to the north, and between 147.0° N and 148.5° W) to yield an estimated deposition rate of ~0.04 cm/year based on a sediment bulk density of 1.6 g/cm^3 ([0.6 x 10^{12} g dry sediment/10 x 10^{12} cm^2] x [(1.6 g wet sediment/cm$^{3)}$/(2.6 g dry sediment/cm^3)]). As previously noted, however, the coastal Beaufort Sea in this area may be net erosional at this time (Reimnitz and Wolf, 1998).

Despite difficulties in determining sedimentation rates, we now have sediment samples that we know pre-date and post-date development. We also have surface sediments from 1989, 1999, 2000, and 2002 cores that can be used to evaluate any recent trends in deposition of potential contaminants.

3.2.1.4 Aluminum (Al) and Iron (Fe) in Sediments

Concentrations of aluminum (Al) and iron (Fe) usually are high (percent levels) in marine sediments. Most of the Al in marine sediments is in clays (aluminosilicates). The iron in oxidized layers of sediments is present primarily as minute, insoluble iron oxyhydroxide layers on clay

particles. Thus, Al and Fe concentrations can be used to normalize metals concentrations to the fine, clay fraction of sediments. Iron is less reliable for this purpose because solid Fe in sediments varies with sediment redox potential. Mean concentrations of Al in surficial sediments were 3.8% in 2004, 3.6% in 2005 and 3.8% in 2006, relative to 3.6% in 1999, 4.1% in 2000, and 3.8% in 2002 for sediments from all stations combined. Mean concentrations of Al and Fe were similar in sediments from Northstar, Liberty, and BSMP in all years (Table 3-19). Although mean concentrations of TOC, silt + clay, Fe and Al in surficial sediments were similar from year to year, the standard deviations within a given year were large. Therefore, no significant differences in mean concentrations of TOC, silt + clay, or Al have been observed among years from 1999 to 2006.

3.2.1.5 Metals in Surficial Sediments

All surficial sediments, (top 1 cm) were analyzed for concentrations of total Ag, Al, As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Se, Sn, Tl, V and Zn. There was considerable patchiness in the concentrations of all metals in surficial sediments. Sediment metals concentrations vary in response to variations in sediment source, mineralogy, grain size, TOC, and redox potential. As discussed above, Arctic rivers discharge massive amounts of suspended sediments each spring to the nearshore Alaskan and Canadian Beaufort Sea. Clay sediments tend to contain higher concentrations of most metals than quartz or carbonate sediments do. Sediment oxidation/reduction (redox) potential affects speciation and, therefore, solubility of many metals, particularly iron and manganese, which are important adsorptive phases in oxidized sediment layers (Neff, 2002a). The highest concentrations of metals were in Al-rich (>6% Al) sediments from stations N03, N17, L06, L07, and 7C. The lowest metal concentrations were found in sandy sediments. However, concentrations of Fe, Zn, Cu, Cr and Ni were slightly elevated in the gravel-rich, Al-poor sediment from the top of the pipeline (station N23), sampled in 2004. The maximum concentrations were within the normal range for Arctic marine sediments.

Concentrations of eight metals, of the types that are of concern in marine sediments because of their toxicity or association with offshore oil and gas development activities (Neff, 2010), in surface sediments in the Northstar, Liberty, and BSMP areas are summarized in Tables 3-20 and 3-21. Mean concentrations of all eight metals were roughly similar in sediments in the three areas in all years sampled between 2000 and 2006. None of the metals was consistently present at a higher range of concentrations in sediments from the Northstar production facility, than in sediments from the Liberty prospect or the historic BSMP stations. There also were no temporal trends in concentrations of any of the metals in sediments from the three areas.

Concentrations of metals in Beaufort sea sediments have been monitored frequently during the last three decades as part of MMS and oil industry monitoring projects. Tables 3-22 and 3-23 summarize sediment metals data collected between 1984 and 2008 at a large number of locations throughout the Beaufort Sea. Most samples were collected distant, in time and space, from exploratory drilling activities, so the concentrations can be considered to represent the natural background**.**

Grain size distribution and concentrations of TOC and trace metals are variable in sediments in coastal and offshore waters of the western Beaufort Sea. Trefry et al. (2003) reported that nearly all samples of surface sediments and age-dated cores contain natural concentrations of several metals, with metal/Al ratios that have been constant for many decades. Metal concentrations in

river-suspended matter entering the Beaufort Sea in spring runoff compare well with metal concentrations in coastal and offshore sediments. Overall, the constancy of metal/Al ratios in river-suspended sediment, the surface layers of bottom sediments, and deeper, older layers in bottom sediments show that anthropogenic inputs of trace metals have not significantly elevated metals concentrations in sediments in areas of offshore oil exploration and production in the coastal Beaufort Sea.

Concentration ranges of metals in WBM used and discharged offshore in the Beaufort Sea between 1979 and 1982 are also included in Tables 3-22 and 3-23 for comparison. The only metals in historic Beaufort Sea WBM that sometimes are present at higher concentrations than those in Beaufort Sea sediments are barium, chromium, lead, and zinc. There are no area-wide trends in concentrations of these or the other metals that might be associated with ocean discharges of WBM and cuttings from more than 50 Beaufort Sea exploration, delineation, and development wells. Concentrations of barium, chromium, copper, and lead in some samples collected near the historic Hammerhead exploratory drilling site, drilled in 1985/6, were higher than metals concentrations elsewhere in the Camden Bay area. Concentrations of these four metals were slightly elevated over a small area at the drill site. There was no evidence of spread of metals over a larger area of sediments in the 24 years since drilling. Thus, the concentrations of sediment metals summarized in Tables 3-22 and 3-23 can be used as background concentrations for comparison with metals in sediments at Northstar and future exploration and development sites.

Concentrations of trace metals generally correlate well with concentrations of Al because concentrations of both Al and most metals are very low in quartz sand or carbonate shell material and much higher in fine-grained aluminosilicates. Aluminum is rarely introduced by anthropogenic activities and is present at percent levels in most sediments relative to part per million (ppm) levels for trace metals. Thus, for this study, Al provided a valuable normalization tool that incorporated the metal controlling variables of grain size, organic carbon content and mineralogy. In the ideal case, there is a good linear correlation between concentrations of a trace metal and Al in sediment. Significant, positive deviations from this linear trend, can be used to identify possible metal contamination of sediments. Plots of trace metal concentrations versus Al have been used in various forms for many years to identify sediment metal contamination (e.g., Bruland et al., 1974; Trefry et al., 1985; Schropp et al., 1990).

Trefry et al. (2003) used metal data for surface sediments collected in 1999-2002 from the coastal Beaufort Sea to produce a series of metal/Al plots that were used in the ANIMIDA and cANIMIDA Projects as templates for identifying possible metal contamination or deviations from previous observations. A linear regression and a 99% prediction interval were calculated for each of the metal versus Al plots using the 1999-2002 data. Metal/Al concentration ratios for all metals in all sediment samples were compared to values predicted from the regressions. Metal/Al ratios lying above the 99% prediction interval for the model regression were considered to possibly contain excess metal from anthropogenic sources.

Few large anomalies in metal concentrations, based on the metal/Al regressions, or unusually high sediment metal concentrations were observed during this study. However, 44 of 1792 metal concentrations (~2.5% of the data points) in surface sediments plotted slightly above the upper prediction intervals on the respective metal versus Al graphs. Eleven of these anomalies are believed to be due to the presence of a trace amount of natural metal sulfide minerals in anoxic

sediment layers. A total of about 17 minor anomalies on the metal versus Al graphs (0.9% of data points) were identified in the cANIMIDA area.

Metal/Al regressions for the four metals most often associated with offshore exploration and development, Ba, Cr, Pb, and Zn is sediments from the development area of the Beaufort Sea revealed only a small number of sediment metals concentrations above expected values. Figure 3-32 shows the regressions plots for Ba/Al and Cr/Al. Ba concentration was elevated above expected values at Northstar station N06 and at BSMP stations 6H, 7G, and 7A. Chromium concentrations were elevated at Northstar station N03, Liberty station L22, and BSMP stations 6H and 7A, and at the West Dock. All the elevated concentrations for Ba and Cr were in samples collected in 2006, except Ba in N06 sediment that was elevated in 2005. All the BSMP stations were in Harrison Bay or off the Colville River. West Dock is the main supply dock for Prudhoe Bay.

Barium has been used historically as a sensitive indicator for the presence of drilling muds and cuttings in sediment because insoluble barite ($BaSO_4$) usually is the most abundant solid ingredient in drilling muds (Neff, 2010). Concentrations of Ba in surface sediments in the development area ranged from 16 mg/kg to 910 mg/kg between 2000 and 2006, with little difference in sediment Ba concentration in Northstar, Liberty, and BSMP sediments (Table 3-20). This range of Ba concentration is typical for uncontaminated fine-grained marine sediments (Neff, 2010). The graph for Al versus Ba for the 2004-2006 data shows 4 of 112 data points as positive anomalies on the Ba versus Al plot (Figure 3-32a). Barium anomalies were reported previously for stations 7A and 7G by Trefry et al. (2003) for samples collected in 1989 and are consistent with exploratory drilling in sediments in the area (Crecelius et al., 1991). Barium anomalies at stations N06 and 6H also may be due to minor remnants of drilling discharges. The largest observed anomaly of 549 μg/g at 2006 station 5H [anomaly = 863 μg/g – (2.73% Al (72.9) + 115) = 549 μg/g] is equivalent to a residue of 0.1% barite from drilling mud with 53% Ba (Trefry et al., 2007).

A plot of Al versus Cr from the ANIMIDA Project (Figure 3-32b) shows the strong positive relationship observed for the 2004 - 2006 data. The good linear fit for Al versus Cr is consistent with mixing of relatively uniform composition, metal-rich aluminosilicate (clay) phases with metal-poor sand and shell. Chromium concentrations in sediment from the ANIMIDA study ranged from 15 to 116 mg/kg in 2000 to 2006 (Table 3-20). Sediments from five stations

sampled during 2006 had Cr concentrations that plotted above the upper 99% prediction interval (Figure 3-32), with a maximum total Cr concentration among these five stations of 89 μg/g. Concentrations of Cr were previously reported to be elevated at station 7A in Harrison Bay (Boehm et al., 1990; Trefry et al., 2003). Crecelius et al. (1991) reported elevated levels of Cr in eastern Harrison Bay (BSMP stations 7A, 7B and 7G) and western Camden Bay (BSMP station 2E) with a maximum total Cr value in that study also at 89 μg/g. The main source of Cr in sediments near drill sites sometimes is chrome lignosulfonate, used in the past in water based drilling muds. This additive is no longer used in drilling muds (Neff, 2010). Thus, the 2006 Cr anomalies may be from historic drilling discharges or from other sources, such as suspended sediments from Arctic rivers.

Table 3-20. Mean and range of concentrations of As, Ba, Cd, Cr, and Cu, all metals of concern during offshore oil and gas development, in sediments from the Northstar, Liberty, and BSMP areas, 2000 - 2006. Metals concentrations are mg/kg dry wt (parts per million). Data from Brown et al. (2005, 2010).

Metal	Year	Northstar	Liberty	BSMP
Arsenic (As)	2000	9.93 (0 - 15.4)	9.81 (0 - 17.9)	8.73 (5.2 - 15.6)
	2002	10.4 (4.2 - 14.3)	8.71 (4.3 - 13.7)	8.13 (4.5 - 13.0)
	2004	10.7 (17.5 - 22.0)	11.5 (6.7 - 18.6)	9.0 (5.3 - 14.3)
	2005	12.8 (7.6 - 24.9)	11.3 (4.7 - 20.3)	8.9 (4.9 - 13.5)
	2006	11.2 (5.5 - 15.0)	9.0 (5.8 - 13.0)	11.9 (6.9 - 22.8)
Barium (Ba)	2000	428 (0 - 859)	399 (0 - 859)	391 (164 - 912)
	2002	467 (212 - 584)	387 (165 - 538)	348 (203 - 589)
	2004	462 (254 - 654)	441 (221 - 612)	323 (16 - 668)
	2005	469 (299 - 749)	506 (259 - 701)	389 (198 - 620)
	2006	486 (256 - 626)	378 (229 - 575)	515 (307 - 863)
Cadmium (Cd)	2000	0.24 (0 - 0.45)	0.22 (0 - 0.45)	0.21 (0.03 - 0.33)
	2002	0.17 (0.05 - 0.27)	0.16 (0.05 - 0.31)	0.19 (0.06 - 0.59)
	2004	0.17 (0.04 - 0.31)	0.18 (0.05 - 0.36)	0.14 (0.03 - 0.23)
	2005	0.29 (0.09 - 0.77)	0.22 (0.11 - 0.38)	0.15 (0.04 - 0.43)
	2006	0.23 (0.09 - 0.30)	0.21 (0.04 - 0.39)	0.20 (0.10 - 0.46)
Chromium (Cr)	2000	63.1 (0 - 92)	59.1 (0 - 92)	57.8 (16.6 - 116)
	2002	65.1 (22.4 - 83.4)	50.8 (19.7 - 72.8)	46.6 (19.2 - 67.4)
	2004	67.6 (20.2 - 97.1)	66.6 (32.3 - 95.3)	50.0 (14.7 - 81.1)
	2005	56.5 (43.8 - 79.4)	67.8 (37.3 - 96.2)	49.6 (17.2 - 75.2)
	2006	74.9 (33.4 - 95.4)	60.0 (26.9 - 80.6)	71.1 (40.9 - 99.6)
Copper (Cu)	2000	21.1 (0 - 40)	20.0 (0 - 40)	18.7 (3.6 - 37)
	2002	19.2 (5.4 - 26.3)	13.6 (4.2 - 22.1)	14.6 (4.3 -- 34.1)
	2004	19.4 (4.4 - 32.2)	20.9 (7.6 - 38.4)	14.9 (4.9 - 24.1)
	2005	21.5 (8.3 - 46.2)	21.5 (8.8 - 40.6)	14.4 (3.9 - 24.7)
	2006	21.7 (7.5 - 31.9)	15.8 (5.8 - 25.5)	18.0 (9.2 - 30.4)

There were only a few elevated Pb and Zn concentrations in sediments, based on metal/Aluminum concentration plots. In all cases, the concentrations of Pb and Zn were in the range expected for clean Arctic marine sediments (Neff, 2002a). Concentrations of Pb in Northstar, Liberty, and BSMP sediments sampled between 2000 and 2006 ranged between 3 and 20 mg/kg (Table 3-21). Concentrations of Zn in the same sediments ranged from 15 to 136 mg/kg.

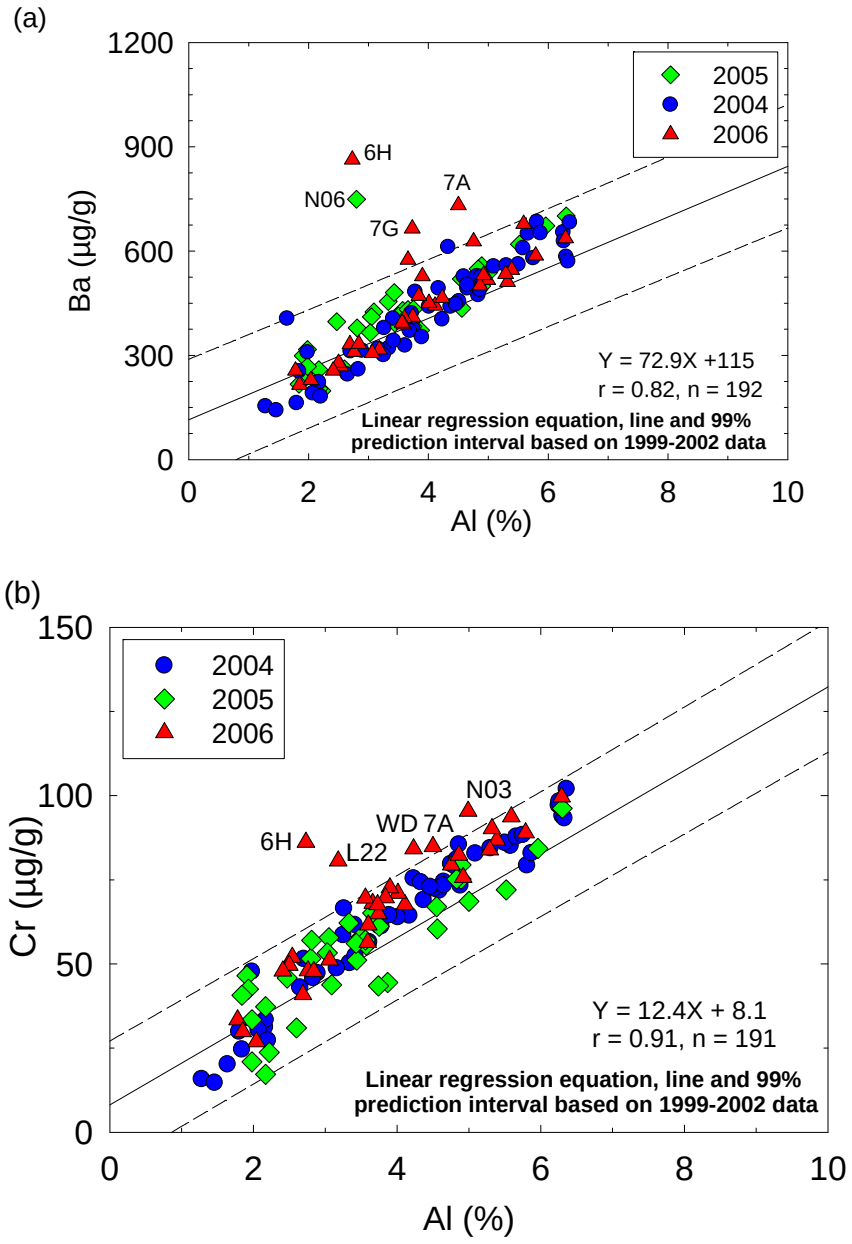


Figure 3-32. Concentrations of barium versus aluminum (a) and chromium versus aluminum (b) in sediments collected in 2004, 2005, and 2006. Metals concentrations plotting above the upper 99% prediction interval may be from anthropogenic sources. From Brown et al. (2009).

Table 3-21. Mean and range of concentrations of Hg, Pb, and Zn, metals of concern during offshore oil and gas development, in sediments from the Northstar, Liberty, and BSMP areas, 2000 - 2006. Metals concentrations are mg/kg dry wt (parts per million). Data from Brown et al., (2005, 2010).

Metal	Year	Northstar	Liberty	BSMP
Mercury (Hg)	2000	0.04 (0 - 0.09)	0.04 (0 - 0.09)	0.03 (0.003 - 0.07)
	2002	0.04 (0.01 - 0.07)	0.03 (0.007 - 0.06)	0.04 (0.006 - 0.08)
	2004	0.04 (0.004 - 0.07)	0.06 (0.023 - 0.097)	0.036 (0.003 - 0.061)
	2005	0.04 (0.016 - 0.113)	0.05 (0.026 - 0.097)	0.03 (0.008 - 0.063)
	2006	0.05 (0.013 - 0.058)	0.03 (0.004 - 0.049)	0.04 (0.013 - 0.066)
Lead (Pb)	2000	10.0 (0 - 20.3)	9.39 (0 - 20.3)	8.40 (3.9 - 17.6)
	2002	10.8 (5.1 - 17.1)	8.59 (4.1 - 14.1)	8.32 (5.1 - 18.4
	2004	9.0 (3.8 - 16.2)	11.1 (4.3 - 18.1)	8.6 (4.2 - 14.6)
	2005	10.6 (5.4 - 16.2)	11.8 (5.2 - 20.1)	9.5 (5.6 - 14.5)
	2006	12.0 (4.3 - 16.7)	9.3 (5.5 - 14.2)	10.7 (5.7 - 16.0)
Zinc (Zn)	2000	76.2 (0 - 123)	72.0 (0 - 123)	72.6 (38.4 - 122)
	2002	77.4 (27.6 - 107)	62.2 (21.5 - 89.1)	62.1 (24.1 - 100)
	2004	80.5 (21.8 - 115)	83.6 (41.4 - 136)	59.2 (15.1 - 89.2)
	2005	67.9 (38.4 - 101)	82.1 (39.7 - 126)	59.1 (22.1 - 97.1)
	2006	85.1 (37.8 - 113)	65.8 (34.3 - 92.1)	72.6 (46.9 - 105)

3.2.1.6 Metals in Sediment Cores

Sampling locations for sediment cores were based on the presence of fine-grained sediments and revisiting some sites, such as several 1989 sampling sites in Harrison Bay. The average percent silt + clay in the 2005-2006 sediment cores was ~70% relative to ~44% for the surface sediments The highest average silt + clay content of 88% was found for the core from station 7C (2006) and the lowest average silt + clay content was 43% from BP01 (2005). Station 7C is located ~55 km from the mouth of the Colville River in western Harrison Bay and station BP01 is located in the general area of the Boulder Patch. The finest-grained layer in all of the cores with 95% silt + clay was at 18-20 cm in the core from station 7C. The coarsest grained sample, with only 28% silt + clay was at 28-30 cm in the core from station N17.

Concentrations of TOC averaged 1.1% for the 2005-2006 sediment cores, compared to 0.9 % for the surface sediment samples. Both these averages show the generally low organic matter content for sediments from the study area. The highest average TOC value was 2.1% for the core from station 7E in western Harrison Bay and the lowest average TOC was 0.46% for the core from station N26 located about 0.2 km northeast of Northstar Island. The most TOC-rich layer was from station 7E at 3.88% (2-4 cm) and the lowest TOC value of 0.34% was for station N26 (2-4 cm).

Concentrations of trace metals were determined for 47 samples from all seven cores collected in 2005 and for 34 samples from 5 cores collected in 2006. Each core was sectioned into 0.5- and

2.0-cm thick layers. The average Al concentration for all sediments from cores was slightly higher than found for the 2005-2006 surface sediments. Slightly higher mean concentrations also were observed for Ba, Co, Cr, Cu, Fe, Hg, Ni, Pb, Sb, Tl, V and Zn in the cores than the surface sediments. These differences are directly related to naturally higher metal concentrations in the clay-rich subsurface sediment layers in the cores.

Some variability was observed in concentrations of metals in most cores, due mainly to shifts in the relative amounts of fine-grained sediment. However, the vertical profiles for metal/Al for most metals in most cores showed a relatively uniform trend because Al concentrations were relatively uniform with increasing depth in each core.

The historical record of metal levels in sediments from the cANIMIDA study area was developed from the 14 cores collected during 2005 and 2006. Collection of sediment cores suitable for age-dating was complicated by bottom-fast ice, ice gouging, low net sediment accumulation rates, low activities of excess ^{210}Pb and ^{137}Cs, and storm-induced resuspension and transport of sediments offshore into deeper water. Even when coring sites were chosen based on bathymetry (i.e., semi-restricted basins) or surface sediment composition (i.e., >90% silt plus clay), only a few cores were useful for establishing a geochronology over the past 50 to 100 years using both ^{137}Cs and excess ^{210}Pb. In many instances, extremely low levels or no detectable amounts of excess ^{210}Pb (<0.2 dpm/g) or ^{137}Cs (<0.02 dpm/g) were found, even in the top 0.5 cm of sediment. Such observations are consistent with previous reports that characterize this coastal area as a net erosional environment (Reimnitz and Wolf, 1998).

Past attempts to reconstruct recent geochronology for coastal sediments from this nearshore Beaufort Sea (Weiss and Naidu, 1986; Naidu and others, 2001) have encountered many of the same difficulties found during the cANIMIDA study. Based on these difficulties with area sediments, a primary goal of the geochronology effort for the cANIMIDA study was to collect some representative sediment that was deposited prior to the onset of on-shore development during the late 1960s and early 1970s and some sediments that were deposited post-development.

Concentrations of trace metals were determined for a total of 81 samples from seven cores collected in 2005 and five cores collected in 2006. Some variability in concentrations of metals was observed in each core, mainly due to variations in amounts of fine-grained sediment. Forty-seven of 1296 metal concentrations (3.6% of the data points) plotted above the upper prediction intervals developed for the ANIMIDA study area. Thirty-five of the 47 data points were for sediments collected in Harrison Bay (the 7 series of stations) and 3 of the 47 data points were for station 2A in Camden Bay. Both Harrison Bay and Camden Bay are not part of the original ANIMIDA study area, but were part of the original BSMP. The remaining 9 data points were from five different cores in different sediment layers: (1) station PB1A at 3-3.5 cm for Ag, Cd, Cu and Ni, (2) station L17B at 3-3.5 cm for As, (3) station N17 at 28-30 cm for As and Hg, (4) station N26 at 16-17 cm for Fe, and (5) station BP01 at 9.5-10 cm for Zn. These 9 data points plot relatively close to the upper prediction interval and do not reveal any striking anomalies that can be clearly tied to anthropogenic sources. The anomalies in the PB1A core from Prudhoe Bay may well be linked with a trace sulfide mineral as described previously for the more discernible anomalies at stations N14 (2005) and 5D (1999).

Twenty of the 38 data points from outside the immediate cANIMIDA study area that plotted above the upper prediction interval were for Ba, 8 from Camden Bay and 12 from Harrison Bay.

The expanded scale graph for Ba (Figure 3-33) shows that the highest Ba anomalies in Camden Bay were at 19-20 cm for both stations 1C and 2A with generally lower anomalies toward the top of each core. Based on the ^{137}Cs data, depths below 17 cm at station 1C and below 9 cm at station 2A were deposited prior to 1950. The data for excess ^{210}Pb are scattered in each core; however, they support a pre-1950 date for the 19-20 cm sections of the cores. At station 2A, but not 1C, the concentration of TOC is >1.5% below 18 cm in the core. In the core from station 1C, the TOC is about 0.5% throughout the core. The source of the Ba anomalies is not clear at this time; however, diagenetic remobilization, diffusion and reprecipitation of Ba in anoxic layers in the sediment column have been observed(McManus et al., 1994; Torres et al., 1995). Dense, fine-grained barite from drilling mud also tends to percolate down through coarser sediment layers, as was observed near exploratory drilling sites on Georges Bank (Neff et al., 1989). These natural processes complicate the identification of drilling mud residues and requires additional support for such determinations as described below for Harrison Bay.

In contrast with the observations in Camden Bay, the Ba anomalies in Harrison Bay (Figure 3-33) are found at a depth in the core that can be best explained by the presence of barite residues from drilling muds. For example, a vertical profile for the Ba/Al ratio for the sediment core from station 7E shows that all 4 samples with significant Ba anomalies are between 2 and 10 cm in the 30-cm vertical section of sediment (Figure 3-34). The maximum anomaly of 396 µg/g [anomaly = 859 µg/g – (4.77% Al (72.9) + 115) = 396 µg/g] dates to about 1988 ± 2 years. This anomaly is equivalent to a residue of 0.08% barite from drilling mud with 53% Ba (Trefry et al., 2007). Drilling activity in the area of Harrison Bay sampled during 2006 is within the area of western Harrison Bay where drilling occurred on State lease blocks in 1985 and 1986. The closest State/Federal lease blocks were exploratory drilling occurred are Mukluk, drilled to the east of station 7E (the red dot in Figure 2-1 south of Mars in central Harrison Bay) in 1983, and Mars, drilled to the north in 1986 (Table 1-1 and Figure 2-1). Furthermore, samples collected in western Harrison Bay during 1989 had Ba anomalies in the top 2 cm of sediment at stations 7A and 7G. The sediment at station 7G was hard and not penetrable for coring in 2006; therefore, cores were collected at stations 7A, 7C and 7E. The results for Ba in the core from station 7E (Figure 3-34) suggest that the peak concentration from the mid-1980s may have been preserved at this site. However, the sediments in the top 6 cm at station 7E contain high levels of TOC at 2-4%; therefore, a diagenetic explanation for the observed Ba profile cannot be ruled out. More detailed study of the sediment column is needed to resolve natural from anthropogenic layers of Ba-rich sediment.

Concentrations of metals in Beaufort Sea sediments have been monitored frequently during the last three decades as part of MMS and oil industry monitoring programs. Tables 3-22 and 3-23 summarize sediment metals data collected between 1984 and 2008 at a large number of locations throughout the Beaufort Sea (Neff, 2010). Most samples were collected distant, in time and space, from exploratory drilling activities, so the concentrations can be considered to represent the natural background**.**

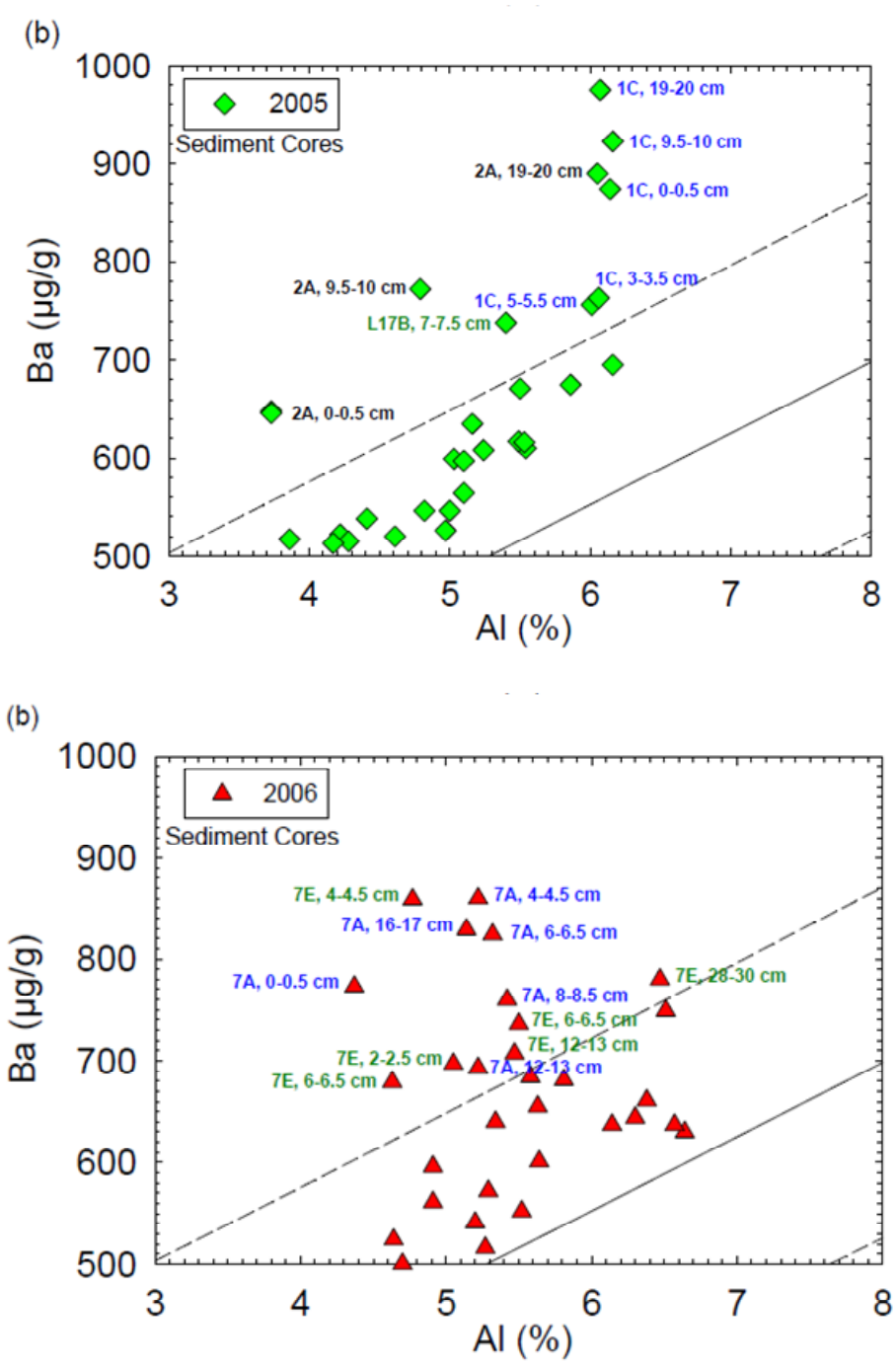


Figure 3-33. Concentrations of Aluminum (Al) versus barium (Ba) in sediment core samples collected in 2005 (top) and 2006 (bottom), showing the sediment samples that plotted above the upper prediction interval. Most of the anomalous Ba concentrations were in cores from Camden Bay in 2005 and Harrison Bay in 2006. From Brown et al. (2010).

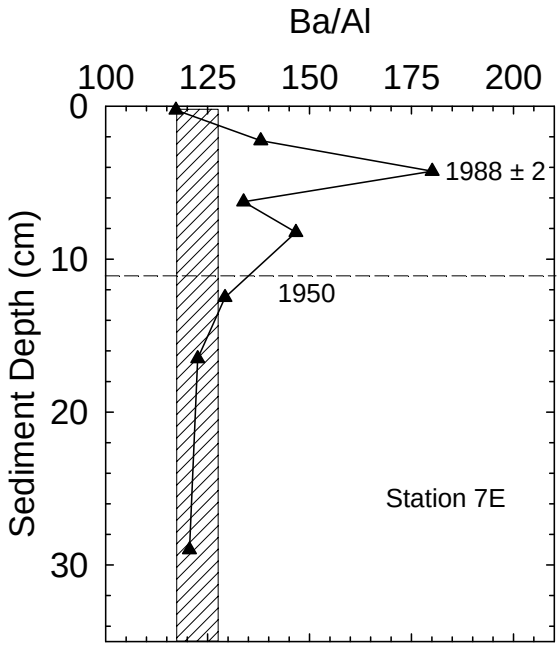


Figure 3-34. Vertical profile of the Ba/Al concentration ratio in a sediment core collected in 2006 at station 7E in Harrison Bay. Exploratory drilling occurred on State leases near this site in 1985-6 and the Ba/Al peak probably is from drilling muds discharged during exploratory drilling. From Brown et al. (2009).

Grain size distribution and concentrations of organic carbon and trace metals are variable in sediments in coastal and offshore waters of the western Beaufort Sea. Trefry et al. (2003) reported that nearly all samples of surface sediments and age-dated cores contain natural concentrations of several metals, with metal/Al ratios that have been constant for many decades. Metal concentrations in river-suspended matter entering the Beaufort Sea in spring runoff compare well with metal concentrations in coastal and offshore sediments. Overall, the constancy of metal/Al ratios in river-suspended sediment, the surface layers of bottom sediments, and deeper, older layers in bottom sediments show that anthropogenic inputs of trace metals have not significantly elevated metals concentrations in sediments in areas of offshore oil exploration and production in the coastal Beaufort Sea.

Concentration ranges of metals in water based drilling mud (WBM) used and discharged offshore in the Beaufort Sea between 1979 and 1982 are also included in Tables 3-22 and 3-23 for comparison (Neff, 2010). The only metals in historic Beaufort Sea WBM that sometimes are present at higher concentrations than those in Beaufort Sea sediments are barium, chromium, lead, and zinc. There are no area-wide trends in metal concentrations that might be associated with ocean discharges of WBM and cuttings from more than 50 exploration, delineation, and development wells.

Table 3-22. Concentrations of arsenic, barium, cadmium, chromium, and copper in sediments collected throughout the Alaskan Beaufort Sea between 1984 and 2008 and in water based drilling muds (WBM) used in the Beaufort Sea for exploratory wells between 1979 and 1982. Concentration ranges are mg/kg dry wt (ppm). From Neff (2010).

Year(s)	Arsenic	Barium	Cadmium	Chromium	Copper	Reference
Beaufort Sea Sediments						
1984-86	---	128-704	0.06-0.27	22-89	7.6-30	Crecelius et al. 1991
1993	10-43	---	0.06-0.43	77-110	11-63	Valette-Silver et al. 1999
1997-99	7-16	116-569	0.11-0.27	13-63	7-27	Naidu et al. 2001
1999-01	1.0-23	142-863	0.03-0.75	13-104	3.6-46	Trefry et al. 2003
1999-02[a]	4.2-28	155-753	0.03-0.82	13-104	3.6-50	Brown et al. 2010
2001-2	15-31	525-631	0.14-0.20	91-188	31-37	Naidu et al. 2003
2003	6.9-20	329-649	0.08-0.45	56-84	16-55	Naidu et al. 2006
2004-06	4.7-25	142-863	0.03-0.77	15-100	3.9-46	Brown et al. 2010
2008	9.5-22	456-714	0.16-0.31	59-96	15-27	Trefry & Trocine, 2009
2008[b]	10-21	585-18,300	0.15-0.24	73-135	21-53	Trefry & Trocine, 2009
Water Based Drilling Muds - Beaufort Sea - 1979 - 1982						
1979-82	---	520-36,000	<0.2-1.8	17-1300	1.5-88	NTS 1981, 1982, 1983

[a] Brown et al. (2010) summarizes data for 1999 to 2002 of the MMS ANIMIDA Program; Trefry et al. (2003) summarizes data for 1999 to 2001 for the same program.

[b] Surface sediment samples collected near the Hammerhead exploratory drilling site in Camden Bay in 2008.

Concentrations of barium, chromium, copper, and lead in some samples collected near the site of the Hammerhead exploratory drilling site, drilled in 1985/6 were higher than metals concentrations elsewhere in the Camden Bay area. Concentrations of these four metals were slightly elevated over a small area at the drill site. There was no evidence of spread of metals over a larger area of sediments in the 24 years since drilling. Thus, the concentrations of sediment metals summarized in Tables 3-22 and 3-23 can be used as background concentrations for comparisons with metals concentrations in sediments collected near historic exploratory drill sites shortly after drilling.

Table 3-23. Concentrations of mercury, nickel, lead, vanadium, and zinc in sediments collected throughout the Alaskan Beaufort Sea between 1984 and 2008 and in WBM used in the Beaufort Sea for exploratory wells between 1979 and 1982. Concentration ranges are mg/kg dry wt (ppm). From Neff (2010).

Years	Mercury	Nickel	Lead	Vanadium	Zinc	Reference
Beaufort Sea Sediments - 1984 - 2008						
1984-86	---	---	5.7-19	37-142	37-123	Crecelius et al. 1991
1993	0.04-0.15	21-75	11-26	---	65-160	Valette-Silver et al. 1999
1997-99	0.008-0.02	7-34	6-15	24-117	18-96	Naidu et al. 2001
1999-01[a]	0.003-0.11	---	2.8-22	27-173	15-136	Trefry et al. 2003
1999-02[a]	0.003-0.20	6.0-48	3.2-22	27-173	15-157	Brown et al. 2010
2001-02	0.05-0.10[b]	45-52	16-26	147-211	114-146	Naidu et al. 2003
2003	0.005-0.09	26-54	11-29	87-136	48-111	Naidu et al. 2006
2004-06	0.003-0.11	6.9-46	4.3-20	87-156	64-108	Brown et al. 2010
2008	0.03-0.08	---	9.9-18	87-156	64-108	Trefry & Trocine 2009
2008[c]	0.04 - 0.06	---	14 - 49	113 - 131	64 - 108	Trefry & Trocine 2009
Beaufort Sea Water Based Drilling Muds - 1979 - 1982						
1979-82	<0.01-0.08	44-88	16-106	160-235	130-380	NTS 1981, 1982, 1983

[a] Brown et al. (2010) summarizes data for 1999 to 2002 of the MMS ANIMIDA Program; Trefry et al. (2003) summarizes data for 1999 to 2001 for the same program.

[b] Concentration of methylmercury ranged from 0.00001 to 0.00013 ppm. [c] Surface sediment samples collected near the Hammerhead exploratory drilling site in Camden Bay in 2008.

3.2.1.7 Hydrocarbons in Surficial Sediments

Saturated Hydrocarbons (SHC). Concentrations of TSHC in surficial sediments ranged from 1,100 to 57,000 ng/g dry wt (parts per billion) during the summer 2006 survey, 200 to 38,000 ng/g during the summer 2005 survey, and 1000 to 33,000 ng/g during the summer 2004 survey. Outliers of 100,000 ng/g at Station N14 in 2005 and 85,000 ng/g at Station N08 in 2004 may have been influenced by the presence of recent organic material (i.e., peat). The TSHC concentrations at Stations N08 and N14 ranged from 600 to 24,000 ng/g in 1999, 2000, and 2002, respectively. By comparison, TSCH concentrations ranged from 320 to 25,000 ng/g in river sediments (Table 3-12) and from 8700 to 260,000 ng/g in peat (Table 3-13). The highest TSHC concentration in peat (260,000 ng/g = 2.6%) was in a sample from Arey Lagoon.

The means and ranges of TSHC concentrations in sediments from the Northstar, Liberty, and BSMP areas were highly variable between 2000 and 2006 (Table 3-24). Both the lowest and highest concentrations were in sediments collected in the Northstar area in 2005. The ranges of TSCH concentrations in sediments were similar in the three areas and in each of the five years.

There was no significant relationship between TSHC concentrations in sediments and concentrations of either %TOC or % silt+clay.

There was an increase in the mean concentration of TSHC in sediments at Northstar between the summer 1999 pre-construction survey and the post-construction surveys in the summers 2000 through 2006. This increase remained statistically significant when the silt+clay variable was used as a covariate in the regression equation. However, when the concentration of TSCH was normalized to perylene (a PAH associated with biogenic but not petrogenic hydrocarbon sources) in the full statistical model, no significant Northstar*construction interaction effects were noted.

The composition of SHC in offshore surface sediments was similar to that in the river sediments, indicating a possible common TPHC source for the river sediments and the nearshore surficial sediments. For example, Colville River, Northstar station 6, and BSMP station 3A sediments have a similar SHC profile. Also, the composition of the SHCs in surficial sediments in 2000, 2002, 2004, 2005, and 2006 are similar to that in the 1999 sediment samples, indicating that no new sources of SHC were introduced into these sediments during construction of the Northstar facility.

The most abundant SHC surficial sediments from the development are in the range of C17 to C30, similar to the SHC profiles for river sediments (Figure 3-24) and coastal peat (Figure 3-25). The SHC assemblage is a mixture of primarily terrestrial biogenic hydrocarbons and lower concentrations of petroleum hydrocarbons. This assemblage is clearly dominated by plant wax normal (i.e., straight-chain) alkanes in the n-C27 through n-C33 carbon range. This is further demonstrated by carbon preference index (CPI) values that range from two to seven for most samples, which is characteristic of sediments influenced by terrigenous plant inputs (Wakeham and Carpenter, 1976; Boehm, 1984). Two sediment samples have CPI ratios of less than two (BSMP 5B [2004] and Northstar N15 [2004]). The lower CPI ratios at stations 5B and N15 are due to low SHC concentrations (i.e., trace levels), combined with corresponding low TOC, which contribute to CPI ratio uncertainty and potential inaccuracy.

Traces of lower-molecular-weight alkanes (LALK – n-C9 through n-C20 alkanes), indicative of a petroleum source, are visible as additional components relative to the plant wax alkanes in the river and offshore sediment. This characteristic petroleum alkane signature in the sediments has been well documented by previous studies in the region (Boehm et al., 1987; Steinhauer and Boehm, 1992; Boehm et al., 1990; Brown et al., 2004). In 1999, an unresolved complex mixture (UCM) characteristic of diesel fuel hydrocarbons was observed in the GC/FID chromatogram for the surface sediment sample collected at Liberty station L08. The diesel fuel pattern was somewhat weathered, indicating a recent source of diesel fuel contamination at this station. Triplicate field replicates collected from L08 in 2000 revealed a similar diesel fuel pattern in one of the three field replicates and a visible but less pronounced diesel signature in the other two replicates. The diesel fuel pattern was identified in the 2005 L08 sample and was either not present or at trace levels in the L08 samples collected in 2002, 2004 and 2006. The absence of a similar diesel fuel signature in samples from adjacent stations and the 2002, 2004 and 2006 samples suggest a very limited or patchy area of sediment contamination. These results warrant continued evaluation and monitoring in future field surveys.

Polycyclic Aromatic Hydrocarbons. Concentrations of TPAH in surficial sediments ranged from 25 to 1,800 ng/g dry wt during the summer 2006 survey, 31 to 1,600 ng/g during the summer 2005 survey, and 13 to 1,100 ng/g during the summer 2004 survey.

The means and ranges of TPAH concentrations in sediments from the Northstar, Liberty, and BSMP areas were highly variable between 2000 and 2006 (Table 3-24). Mean TPAH concentrations ranged from 460 to 810 ng/g in Northstar sediments, 280 to 710 ng/g in Liberty sediments, and 200 to 726 ng/g in BSMP sediments sampled in 2000, 2002, 2004, 2005, and 2006. TPAH concentrations in individual sediment samples ranged from 13 ng/g to 1800 ng/g, with highest concentrations in sediment collected at Northstar station 5A, about 2 km west of the production island, in 2000, and at BSMP station 7E, the site of earlier exploratory drilling, in 2006 (Table 3-24).

Table 3-24. Mean and Range of concentrations of total PAH, total SHC, total StTr, TOC, and Silt+clay in sediments collected in the Northstar, Liberty, and BSMP areas between 2000 and 2006 in the ANIMIDA and cANIMIDA Programs. Hydrocarbon concentrations are ng/g dry wt (parts per billion) and TOC and silt+clay (mud) are % dry wt. Data from Brown et al. (2005, 2009).

Year	Total PAH (ng/g)	Total SHC (ng/g)	Total SrTr (ng/g)	TOC (%)	Silt+Clay (%)
Northstar					
2000	810 (80 - 1800)	14,000 (1000 - 27,000)	78 (2.9 - 180)	1.3 (<0.1 - 4/4)	61 (2.2 - 91)
2002	520 (61 - 940)	10,000 (3200 - 22,000)	55 (5.7 - 110)	0.85 (0.3 - 1.8)	63 (3.4 - 92)
2004	460 (13 - 1100)	15,000 (1000 - 85,000)	53 (7.5 - 110)	0.58 (0.05 - 1.7)	45 (0.4 - 89)
2005	560 (72 - 950)	17,000 (600 - 100,000)	99 (6.7 - 660)	1.4 (0.1 - 6.4)	34 (10 - 45)
2006	640 (170 - 1100)	10,000 (1200 - 22,000)	55 (13 - 90)	0.91 (0.23 - 1.4)	63 (10 - 95)
Liberty					
2000	340 (99 - 610)	8600 (1900 - 12,000)	39 (11 - 62)	0.76 (0.24 - 1.0)	49 (5.3 - 94)
2002	290 (84 - 420)	6000 (2900 - 10,000)	29 (11 - 52)	0.70 (0.18 - 1.2)	31 (6.4 - 58)
2004	640 (270 - 960)	17,000 (7300 - 26,000)	52 (21 - 88)	1.0 (0.47 - 2.4)	63 (47 - 91)
2005	710 (310 - 1100)	15,000(7800 - 23,000)	85 (30 - 140)	0.94 (0.28 - 1.6)	52 (21 - 84)
2006	280 (25 - 650)	7200 (2000 - 16,000)	25 (3.3 - 60)	0.60 (0.02 - 0.8)	35 (1.2 - 62)
BSMP					
2000	370 (26 - 630)	7500 (4100 - 8100)	36 (7.8 - 100)	0.71 (<0.1 - 2.0)	44 (1.2 - 85)
2002	200 (12 - 500)	4400 (440 - 8300)	20 (1.5 - 49)	0.62 (0.14 - 1.26)	37 (0.9 - 84)
2004	310 (18 - 1100)	8500 (1100 - 25,000)	31 (1.8 - 91)	0.44 (0.08 - 0.91)	43 (0.1 - 100)
2005	430 (45 - 1400)	8000 (230 - 38,000)	32 (2.1 - 68)	0.67 (0.05 - 1.7)	37 (3.1 - 92)
2006	726 (92 - 1800)	12,500 (1100 - 27,000)	55 (8.0 - 170)	1.1 (0.08 - 2.8)	46 (4.6 - 94)

Most of the sediments containing high TPAH concentrations also contained high concentrations of perylene, a biogenic hydrocarbon. There was a strong relationship between concentrations of TPAH minus perylene and percent silt+clay in sediments collected throughout the development area between 1999 and 2006 (Figure 3-35). There were a few outliers with TPAH concentrations higher or lower than predicted by the regression.

There was a small increase in the mean concentration of TPAH in sediments from the Northstar area between the 1999 pre-construction measurements and the combined 2000 through 2006 post-construction measurements. This increase remained statistically significant when the silt+clay variable was used as a covariate in the regression equation (Figure 3-35). When the concentration of TPAH minus perylene was normalized to perylene in the full statistical model, no significant Northstar*construction interaction effects were noted.

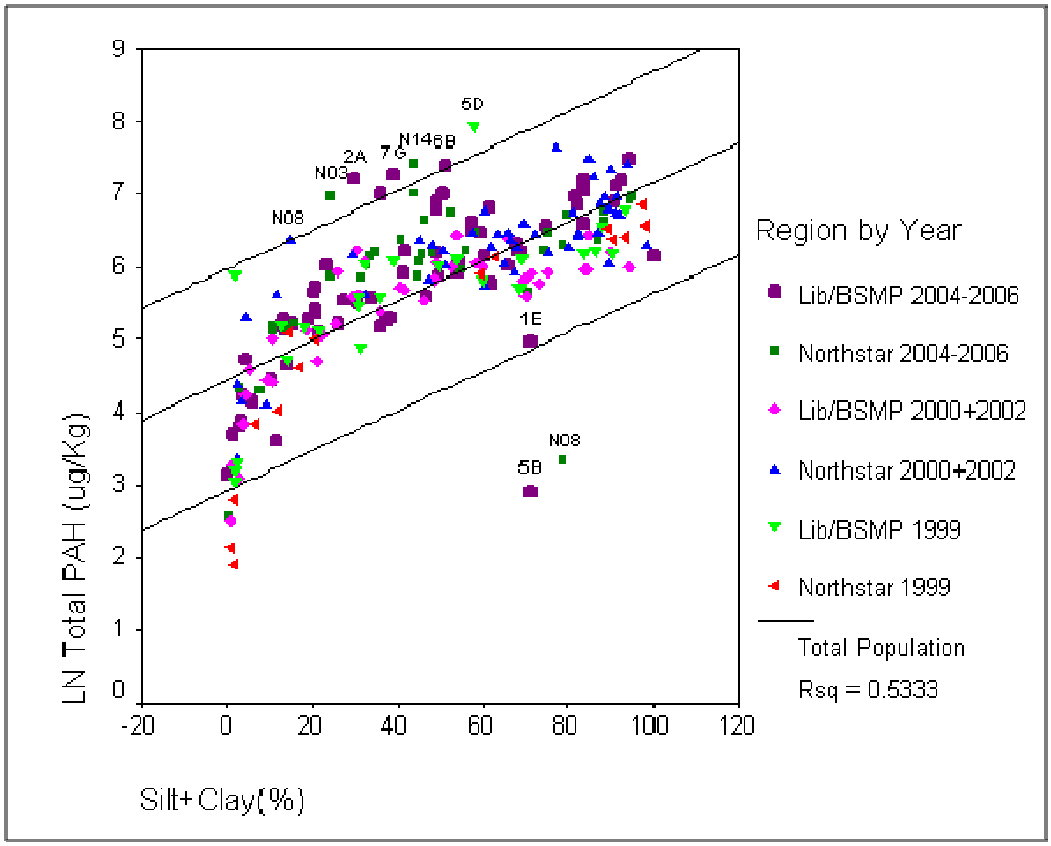


Figure 3-35. Regression plot of the concentration of total PAH (µg/kg = ng/g) minus perylene versus %silt+clay for all sediment samples collected between 1999 and 2006 in the Northstar, Liberty and BSMP areas. The R^2 and 99% prediction intervals are shown. Most ratios fall within the 99% prediction intervals. From Brown et al. (2009).

As noted with the SHC composition profiles, the composition of TPAH assemblage in the river sediment and peat samples was similar to that in surficial sediments, indicating a common PAH source relationship between the river sediments and the nearshore surficial sediments. Also, the composition of the TPAH assemblage in surficial sediments collected from Northstar in 2000, 2002, 2004, and 2005 was similar to that in the 1999 Northstar sediment samples (Figure 3-36), indicating that no new source of PAH was introduced into these sediments. For example, similar patterns are noted in the PAH distribution histograms for station N06 in 1999, 2000, 2002, 2004, and 2005 (Figure 3-36).

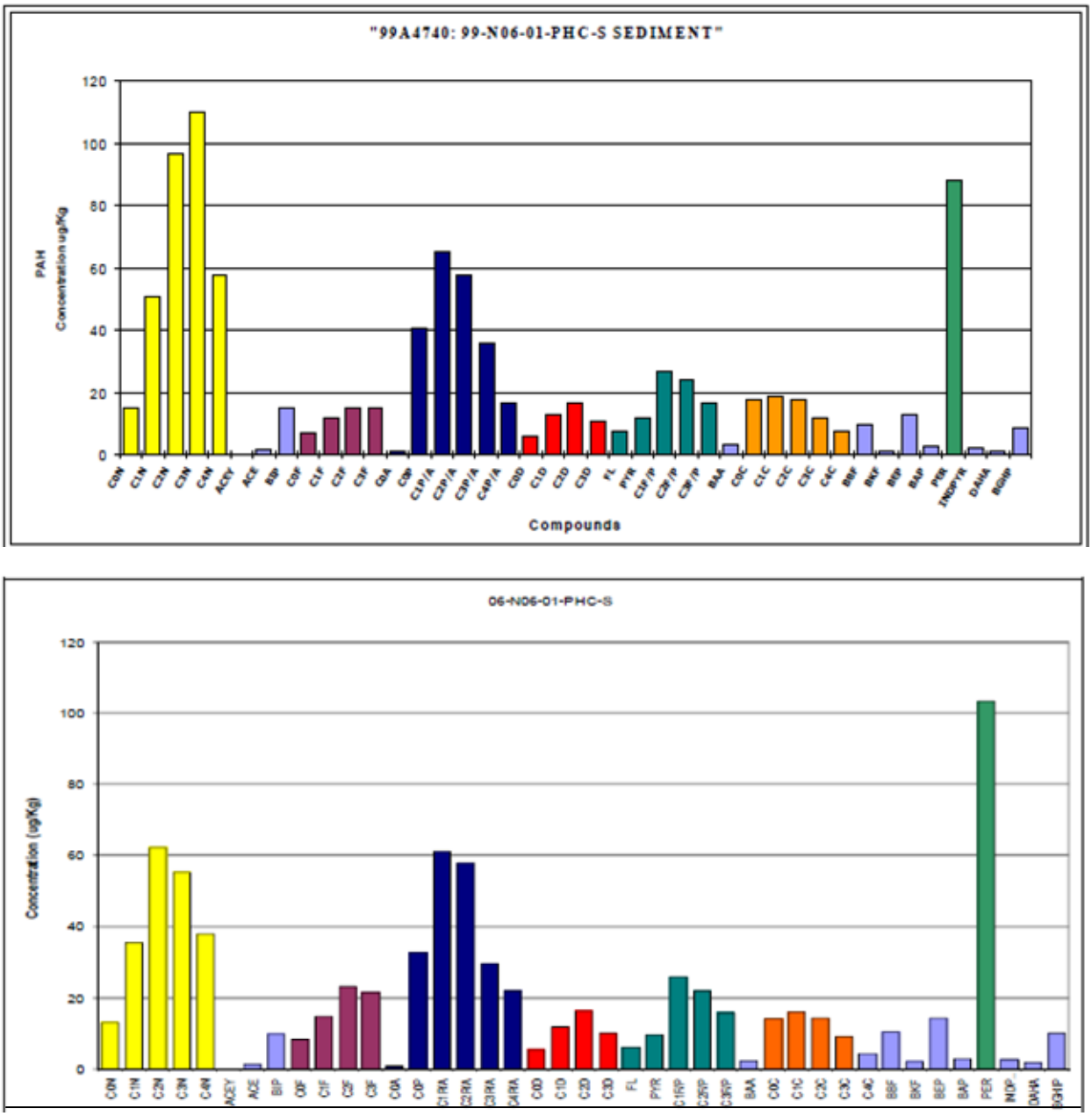


Figure 3-36. PAH profiles of surface sediments collected at Northstar station N06 in 1999 (top) and in 2006 (bottom). Construction of the Northstar production facility occurred in the winter of 1999-2000. The PAH profiles are similar, but the concentrations of all individual PAH except perylene are lower in 2006 than in 1999. From Brown et al. (20010).

The PAH profiles for most of the offshore surficial sediments indicate that the PAHs are primarily of a combined fossil fuel origin (i.e., petroleum, peat, kerogen, and coal) with a biogenic component (perylene), and lesser contributions of combustion-source, pyrogenic PAH (e.g., 4-, 5-, and 6-ring PAHs). The petrogenic PAHs account for approximately 90 percent of

the TPAH minus perylene in sediments throughout the study area. Perylene, a biogenic PAH, was abundant in surficial sediments and the regional peat samples and often was the most abundant single PAH in the overall PAH assemblages (Figures 3-24, 3-25, and 3-36). Although perylene is biogenic, it also is present at low concentrations in some crude oils. Northstar crude oil contains about 100 ng/g perylene, compared to about 40 ng/g in Colville River Peat. Perylene was found in peat at comparable concentrations to those in Beaufort Sea sediments in earlier studies in the BSMP area (Boehm et al., 1990 and 1991).

The PAH profiles usually are similar in sediments throughout all the regions of the development area and are characterized by the presence of a full suite of relatively "unweathered" petroleum PAHs (i.e., naphthalenes $\geq$ phenanthrenes) similar to the PAH distribution seen in Northstar crude oil and a typical North Slope crude oil. Perylene is found at equal or greater relative abundance in the river sediments and peat (Figures 3-24 and 3-25), indicating that the rivers are a source of the hydrocarbons in the nearshore sediments, as noted previously for the SHCs.

The PAH distribution in station L08 sediment from 1999, 2000, 2004 and 2005 shows a clear increase in the abundance of 2- and 3-ring petroleum PAHs, particularly the naphthalenes, relative to the other sediment samples. This further supports the GC/FID evidence of diesel fuel contamination at this station. A slight increase in the abundance of the 2- and 3-ring petroleum PAHs also was observed in the 2002 and 2006 samples from L08; however, the increase was not as evident as in previous years. Two samples that were identified as potentially being enriched in petroleum hydrocarbons based on SHC results in 1999 (sediments from BSMD stations 5D and 5E) do not show evidence of a corresponding enrichment in PAH or change in PAH distribution in subsequent years. In 2000 and 2004, the PAH concentration at 5E (260 and 190 ng/g, respectively) was comparable to the levels in 1999, but the concentration in 2002 was substantially lower at 46 ug/Kg, due to a corresponding decrease in fine-grained sediment. At 5D, the PAH concentrations were substantially lower in 2000 and 2002 but present at moderate levels in 2004, with no apparent change in overall PAH distribution. These results indicate a highly variable sediment substrate at stations 5D and 5E. Additionally, the source of hydrocarbon enrichment observed at 5D in 1999 appears to be depleted in PAH versus SHC, relative to the regional petroleum hydrocarbon background present in other sediments, suggesting an alternate hydrocarbons source in 1999 (e.g., coal or peat).

Steranes and Triterpanes. Concentrations of TStTr in surficial sediments from the development area ranged from 3.3 to 173 ng/g in 2006, 2.1 to 98 ng/g in 2005, and 1.8 to 110 ng/g in 2004. One outlier at 660 μg/Kg was detected at Station N14 in 2005.

The means and ranges of TStTr concentrations in sediments from the Northstar, Liberty, and BSMP areas were highly variable between 2000 and 2006 (Table 3-24). Mean TStTr concentrations ranged from 20 ng/g in BSMP sediments collected in 2002 to 99 ng/g in Northstar sediments collected in 2005. StTr concentrations in individual samples ranged from 1.5 ng/g in sediment sample collected at BSMP station 4C in 2002 to 660 in a sediment sample collected at Northstar station N14, about 3 km southeast of the Northstar facility, in 2005. Mean and range of StTr concentrations tended to be lower in BSMP sediments than in Northstar and Liberty sediments in most years.

In general, the StTr distributions in the sediment samples are indicative of a petroleum pattern, with varying abundances of a suite of recent organic material StTr markers. For example, North

Slope Crude oil contains a characteristic petroleum triterpane pattern dominated by norhopane (T15) and C30-hopane (T19). The StTr distributions for most sediment samples include a mixture of these characteristic petroleum biomarkers, along with recent organic or biogenic markers such as diploptene and other unnamed triterpanes (Peters and Moldowan, 1993). The greater abundance of T22 than T21 in some samples provides further evidence of substantial recent organic matter inputs to the surficial sediments. In general, the surficial sediment samples appear to show a greater abundance of these recent organic materials or biogenic biomarkers, suggesting a greater terrestrial influence (e.g., river runoff) to the sediments. Many of the sediment samples contain trace levels of oleanane (T18), indicating the presence of a non-North Slope Crude, post-Cretaceous/Tertiary petroleum source; i.e., T18 is absent in bulk North Slope Crude oil (Bence et al., 1996) and Northstar crude Oil (Figure 3-26). The origin of this petroleum signal is unknown, but it probably is from regional background inputs. Seep oils from Kavik and Angun may have trace oleananes, as part of their biodegraded biomarker signature. The presence of oleanane has also been reported in Canadian McKenzie Delta crude oils to the east of the study area (Banet, 1995).

The StTr distributions in Colville River sediments (Figure 3-24) and peat (Figure 3-25) have the same mixture of recent organic matter and petroleum hydrocarbon patterns as observed in many of the offshore sediment samples This similarity suggests that there is a strong link between Colville River hydrocarbon sources – mostly erosional inputs of regional shales, coal, peat, etc. (i.e., natural background) and the sediments. However, given the documented current transport regime of East to West in the study area, it is likely that rivers to the East, particularly the McKenzie River (Yunker et al. 1991, 1993), as well as the Canning River, influence the hydrocarbon abundance and composition in offshore surficial sediments. For example, the StTr distribution of Canning River sediment collected to the east of the development area in 2002 is dominated by a suite of recent organic markers with a different StTr biomarker pattern that is found at greater abundance in some samples in the eastern study area. The importance of different Arctic rivers as sources of metals and hydrocarbons in nearshore Beaufort Sea sediments depends mainly on the relative concentrations of metals and hydrocarbons in suspended sediments and colloidal organic matter from the different rivers.

The Kuparuk and Sagavanirktok River sediments contain many of the same recent organic matter StTr biomarkers, but generally have different distributions than the Colville River sediments. In particular, the ratio of T21/T22, where T22 is an order of magnitude higher than T21, is characteristic of an immature or recent hydrocarbon source, identified in a 2006 Sagavanirktok peat sample, possibly indicative of coal. This predominant T22 pattern is also found in several of the surficial sediment samples from stations near the Sagavanirktok River delta and near the mouth of the Kuparuk River, indicating the influence of these rivers to the deposition of surficial sediments at these stations. The presence of the predominant T22 pattern at station BSMP station 5D is of particular interest, since the high TSHC and TPAH concentrations indicate hydrocarbon contamination at this station. The observed T22 pattern indicates that coal particles, possibly from the Kuparuk River, may be one of the sources of the hydrocarbon enrichment.

Several surficial sediment samples have distinctly different StTr distributions. Sediments from several stations have StTr distributions more characteristic of a petroleum source, i.e., a predominance of hopanes (T15 and T19). In the case of L08, this is not surprising since other

organic data clearly indicate diesel fuel contamination. However, the abundance of petroleum StTr also indicates a petroleum product "heavier" than diesel, as triterpanes are typically removed from diesel-range fuels during the distillation process. This result suggests that the observed petroleum contamination at L08 is a complex mixture of hydrocarbons including diesel and heavier hydrocarbons, such as heavy fuel oil or crude oil. This could be the result of drilling mud/cutting residues from historic exploratory drilling nearby (i.e., Tern Island), Exploratory wells were drilled from the gravel Tern Island in 1982 and 1987 and an estimated 2380 m^3 of water based drilling muds and cuttings were discharged to the water (Table 1-3), as permitted by the NPDES permit. The cuttings could have contained small amounts of formation oil or kerogens. This hypothesis is supported by the elevated barium concentrations (when normalized to Al) observed in the sediment from L08 (1999 only). The petroleum StTr in the surficial sediment at 5B are at trace levels (7.8 ug/Kg TSTTr), whereas the StTr distribution at 5E further confirms the presence of low levels of a heavy petroleum hydrocarbon source shown by the SHC and PAH results, but the specific origins of these "contaminants" are not known.

3.2.1.8 Temporal and Spatial Trends in Hydrocarbons in Surface Sediments

One technique for examining the spatial trends (variability between stations) in hydrocarbon concentrations and compositions in sediments involves examining the relationship between the hydrocarbon parameter of interest and percent silt + clay or TOC content. The natural background concentrations of nonpolar organic compounds often varies as a function of fine-grained sediment (silt + clay) and TOC concentrations. Thus, samples enriched in organics from anthropogenic sources can be identified by normalizing the target organic parameter and generating a linear regression line and prediction interval on a cross-plot.

This regression plot technique was used effectively for the 1999 (pre-construction) sediment hydrocarbon data to identify sediments enriched in hydrocarbons and data outliers (Boehm et al., 2001b). For 1999 data, good linear correlation was established between concentrations of TPAH minus perylene and TSHC with silt + clay ($R^2 = 0.83$ and 0.69 respectively – station 5D was determined to be a statistical outlier and was not included in the regression calculation). The value TPAH minus perylene was used to reduce variability introduced to the TPAH data by perylene, which can vary widely in abundance based on sediment type.

These regressions defined the natural geological/geochemical background. In both TPAH and TSHC plots, the data point for station 5D was well outside the calculated 99 percent prediction interval of the regression line indicating that station 5D sediment was enriched in TPAH relative to the expected background for the region. As noted previously, station 5D sediments were identified as being contaminated with hydrocarbons, although the source of this contamination is still unclear (i.e., coal versus petroleum sources). In the TSHC plot, sediment samples L08 and 5E were found to fall slightly above the upper 99 percent prediction interval. Based on the analytical data, these two samples were also previously identified as being enriched in petroleum hydrocarbons. Diesel contamination with possible crude oil was identified in L08 and a heavy hydrocarbon product depleted in PAH was identified as a possible source in 5E.

Overall, these regression techniques provided a sensitive baseline process to measure temporal trends of anthropogenic inputs into the system from Northstar, given the radial sampling design around the production facility and regional BSMP station coverage. As noted earlier, statistical analyses of the 1999 through 2006 data were performed to determine if there were significant

differences in the measured key diagnostic organic parameters due to the development of Northstar. The results of the statistical analyses indicated that the key bulk hydrocarbon parameters (i.e., TPAH, TSHC, pyrogenic PAH, etc.) increased significantly in post-1999 sediments from Northstar. The results of the statistical analyses probably are best summarized in a TPAH minus perylene versus silt + clay regression plot for 1999, 2000, 2002, and 2004 - 2006 Northstar stations (Figure 3-37). In this plot, the regression lines and 95% prediction intervals do not overlap, indicating a significant increase in TPAH minus perylene concentrations in sediments from Northstar in 2000, 2002, and 2004 - 2006 after adjusting for fines (silt + clay). A simple plot of the TPAH normalized to fines clearly shows this trend of increasing PAH concentrations at the Northstar stations in 2000 with lower levels in 2002 and 2004 - 2006, but still generally higher than 1999. Station N15 in 2002 and 2004 and N11 in 2004 appear to be outliers on this plot due to a very low % fines (4.3%, 0.4%, 2.7%, respectively). The concentration of TPAH minus perylene at Station N03 in 2004 appears elevated compared to previous years, however, the concentration of perylene at this station is also correspondingly higher indicating the source of PAH in sediment from this station is from the regional background.

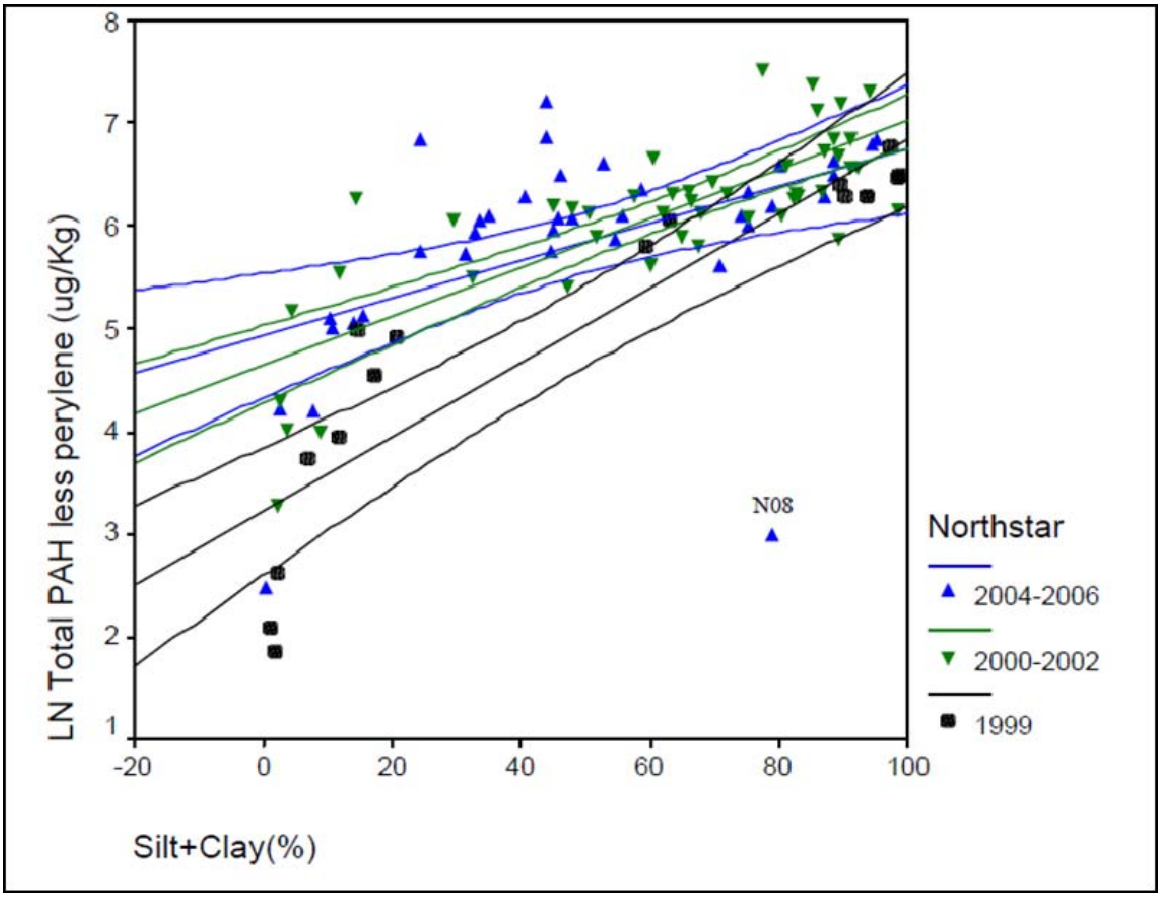


Figure 3-37. Scatterplot of % silt+clay versus TPAH minus perylene in surficial sediments at Northstar collected in 1999 through 2006. The 95% confidence interval for the mean regression and related statistical calculations for Northstar stations by year are included. Station N08 from year 2004 was an outlier and was excluded from this graph. From Brown et al. (2010).

However, a closer examination of the PAH data show that although PAH concentrations in Northstar sediments increased post-construction (2000, 2002, and 2004 - 2006 combined), the distribution and composition of the PAH assemblage remained relatively unchanged. The composition of the sediment hydrocarbons at Northstar is best summarized by a comparison of the pyrogenic to petrogenic PAH ratios in 1999, 2000, 2002 and 2004 - 2006. A comparison for this ratio for all paired Northstar stations (Figure 3-38) reveals no significant difference between years 1999 and 2000 indicating that there were no incremental additions of anthropogenic hydrocarbons to the Northstar area as a result of construction activities in 2000. The pyrogenic to petrogenic PAH ratios for Northstar stations in 2002 and 2004 show an increasing trend (Figure 3-38) which then decreases in 2005 and 2006. The statistical comparisons of PAH data (Table 3-24) show a significant increase in the pyrogenic to petrogenic PAH ratio region-wide for years 2000 through 2004. A subsequent ANOVA revealed that pyrogenic to petrogenic ratios for Northstar in 2002 and Liberty/BSMP in 2002 were not significantly different from each other, but that the ratios for Northstar in 2004 were significantly greater than Liberty/BSMP in 2004 and Northstar in 2002. Also, the Northstar 2004 petrogenic PAH concentrations (with perylene as a covariate) were significantly less than Northstar 2002 and Liberty/BSMP 2004 concentrations, while no significant differences were noted for pyrogenic PAHs between regions or years. These results suggest that the observed shift to a greater relative proportion of pyrogenic hydrocarbons in 2002 and 2004 could be the result of a subtle increase in pyrogenic PAH; possibly related to Northstar area inputs (flaring, boat and vehicle traffic, etc.) However, this shift in inputs is clearly variable (as shown by the decreased values in 2005 and 2006) and not currently of sufficient magnitude to result in a statistically significant increase in concentrations of PAH parameters. However, the observed potential of such a shift warrants continued sediment hydrocarbon monitoring in the area.

In 2005 and 2006, sediments from only eight of the 23 previously sampled Northstar stations were resampled. The differences in the pyrogenic to petrogenic ratio for this subset of Northstar stations were evaluated; the 2005 - 2006 pyrogenic to petrogenic ratio was not significantly different from 1999 or 2000 ratios but was significantly lower than the 2002 and 2004 ratios. However, it is uncertain if this reduction in the pyrogenic to petrogenic ratio occurred throughout the Northstar region due to the limited Northstar sampling in 2005 and 2006.

Another evaluation of the sources of the PAH was performed using a dibenzothiophene to phenanthrene source ratio plot, which has been used in similar investigations of PAH sources in the environment (Brown and Boehm, 1993; Page et al., 1998; Boehm et al., 2001a). An examination of the source plot for all ANIMIDA and cANIMIDA surficial sediments and source samples (Figure 3-39) reveals that the source composition of PAH in the Northstar 2000, 2002, and 2004 - 2006 sediments is in the same range as the 1999, 2000, 2002, and 2004 - 2006 BSMP and Liberty stations which are representative of the regional hydrocarbon background. Several of the Northstar 1999 sediments in the source ratio plot have ratios substantially higher than the "regional background" which is likely due to two factors: 1) the very low TPAH concentrations found at some of the 1999 Northstar sediments, which introduces variability into the ratio and generally results in a ratio increase, and 2) the localized influence of the Kuparuk river which has a ratio higher than the "regional background."

The Northstar production oil, which was first analyzed in 2002, contains relatively low concentrations of organo-sulfur compounds and has a resulting dibenzothiophene to

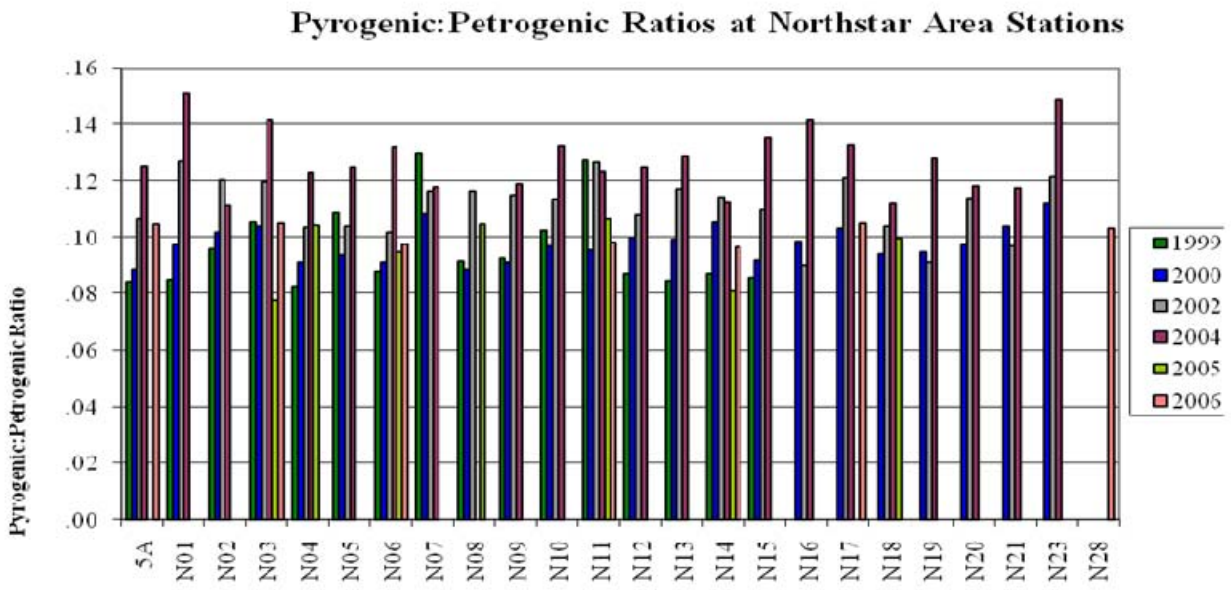


Figure 3-38. Pyrogenic:petrogenic ratios of Northstar surficial sediment samples collected in 1999 through 2006. From Brown et al. (2010).

phenanthrene source ratio similar to the "regional background" (Figure 3-26). Most other North Slope field crude oils have dibenzothiophene to phenanthrene source ratios that are substantially higher and are easily distinguished from the background hydrocarbons. This observation limits the use of this evaluation technique since the potential contribution of Northstar crude oil could not be determined in the case of an accidental release or incremental chronic inputs. However, another source ratio plot of the 20S to 20R epimers of steranes and triterpanes (5α,14α,17α-24-methylcholestane [S25/S28] versus 17α,21β(H)-30-homohopane [T21/T22]) shown in Figure 3-40, clearly differentiates all of the North Slope field crude oils and the Northstar production oil from the regional background signature in the surface sediments and river source samples. This ratio, which is a relative measure of the petroleum hydrocarbon maturity, relies on the relative immaturity of the biomarker compounds in the sediments versus the crude oils and provides another tool to evaluate potential additions of anthropogenic hydrocarbons to the region in the future.

The earlier observation that the Northstar 1999 sediments may be depleted in hydrocarbons relative to the other sediments is further supported by a TPAH minus perylene versus silt + clay regression plot for all the 1999, 2000, 2002, and 2004 - 2006 sediment data. In this plot (Figure 3-37), the regression and 95% prediction intervals are shown for all data. The plot shows a small cluster of Northstar 1999 samples which are be low the 95% prediction interval, indicating that these samples have significantly lower TPAH versus silt + clay ratios than the overall population of sediment samples. This result corroborates the observed trend of lower hydrocarbon levels in Northstar 1999 sediment samples. In addition, as part of the statistical analyses, a regression model comparing Northstar 1999 samples to 1999 BSMP and Liberty samples for all key parameters revealed that Northstar 1999 sediments were significantly lower

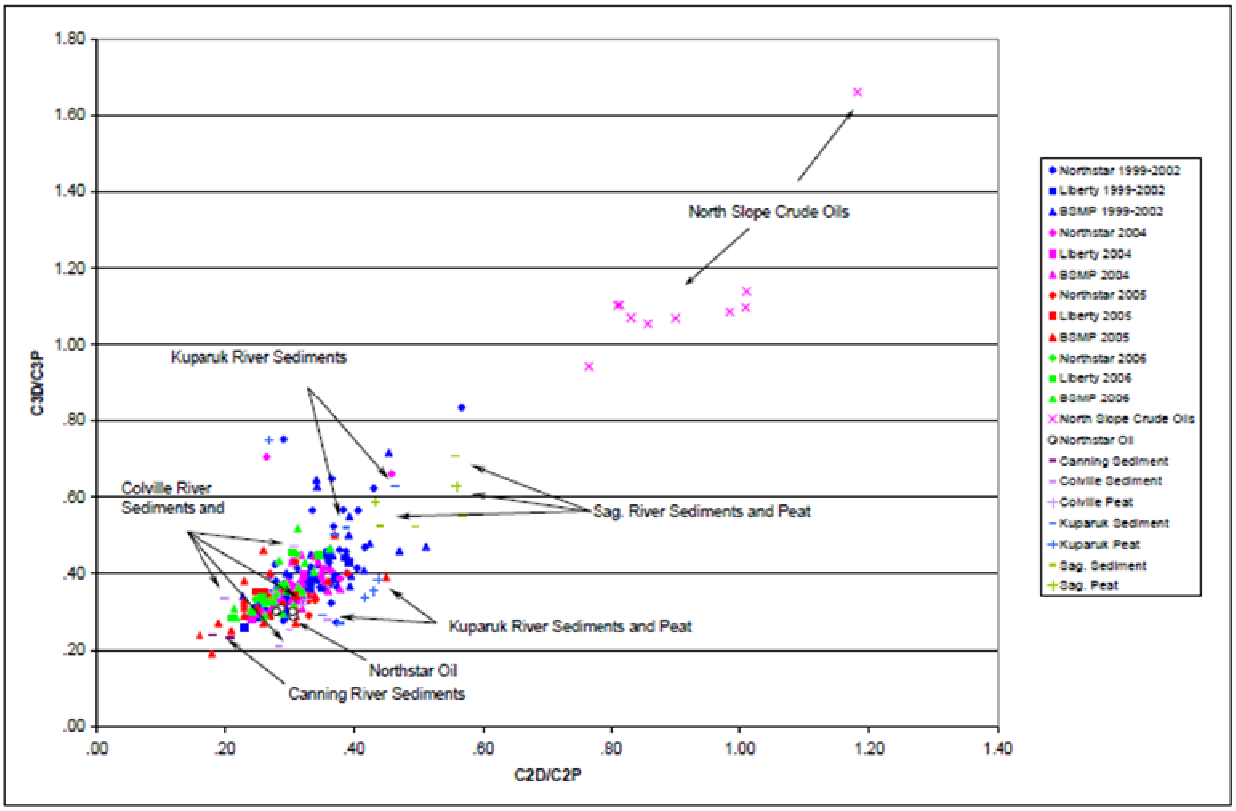


Figure 3-39. Double Ratio Source Plot of C2D/C2P vs. C3D/C3P for surface sediments from BSMP, Liberty, Northstar, and Arctic rivers collected between 1999 and 2006 and North Slope and for Northstar crude oils. From Brown et al. (2010).

in all bulk hydrocarbon parameters (e.g., Total PAH, TPHC, Petrogenic PAH, etc.) than 1999 BSMP and Liberty sediments. A further regression comparison of the Northstar 2000, 2002 and 2004 samples versus the BSMP and Liberty 2000, 2002, and 2004 samples resulted in no significant difference for all bulk hydrocarbon parameters and most of the diagnostic ratios. The results of this analysis are further illustrated by a PAH regression plot that shows overlap between the regression lines and 95% prediction intervals (i.e., no significant difference) for the Northstar, BSMP, and Liberty sediments for 2004 - 2006.

As noted previously, the initial statistical comparisons revealed that Northstar 1999 sediments were significantly lower in all bulk hydrocarbon parameters (e.g., Total PAH, TPHC, Petrogenic PAH, etc.) than 1999 BSMP and Liberty sediments which resulted in a positive Northstar and Northstar/construction effect (i.e., a significant increase in these parameters associated with Northstar construction). However, a subsequent, improved statistical model with perylene as a

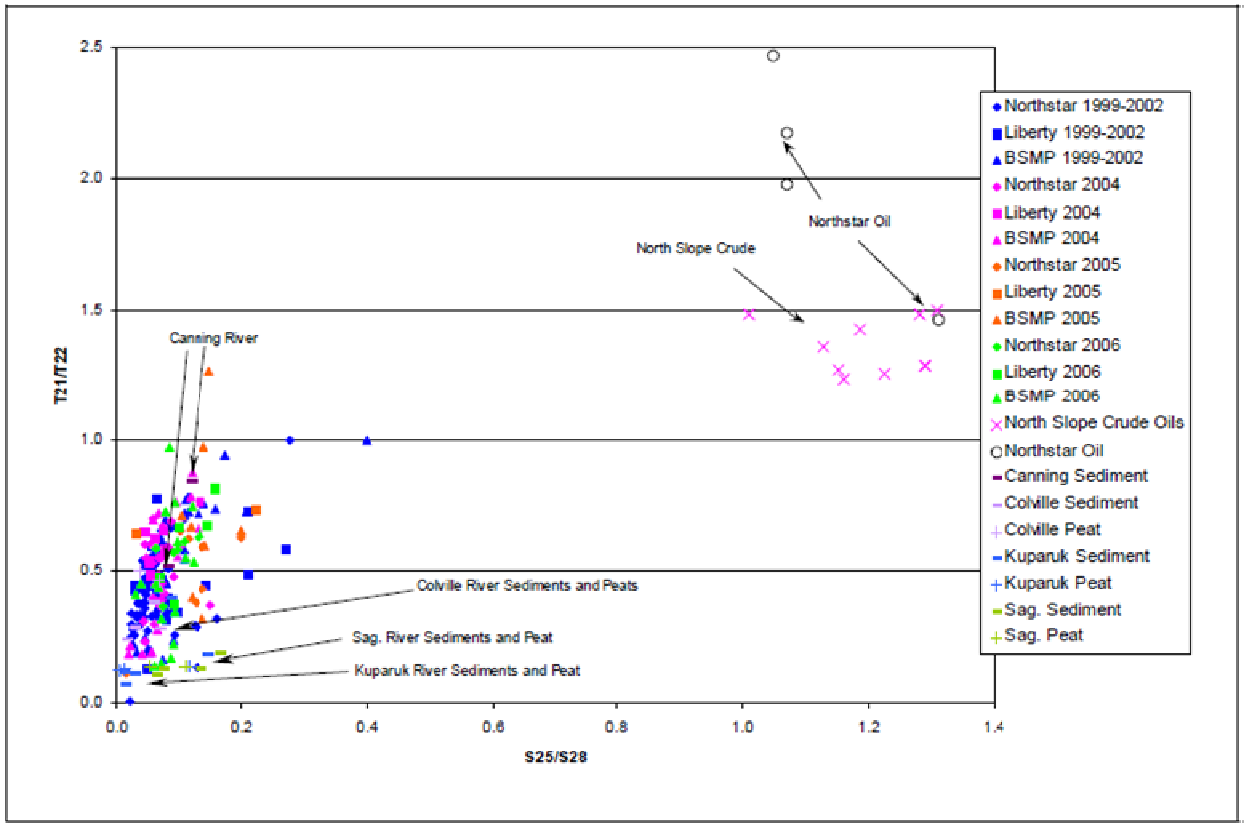


Figure 3-40. Double Ratio Source Plot of S25/S28 vs. T21/T22 steranes and triterpanes in BSMP, Liberty, Northstar, and River Sediment Samples collected in 1999 through 2006. From Brown et al. (2010).

covariate resulted in no significant increases in any of the key diagnostic hydrocarbon parameters due to Northstar or Northstar/construction effects. The use of perylene as a covariate parameter to normalize sediment data is particularly effective due to the absence or only trace levels of perylene in the anthropogenic sources of hydrocarbons to the region (petroleum and pyrogenic hydrocarbons), and the relative enrichment of perylene in the regional background (river and sediment sources). .

As was noted in the statistical analyses using perylene as a covariate, this plot shows no significant increase in PAH due to Northstar or Northstar/construction effects, and six stations fall outside the prediction intervals. Sediments from stations N11 and N14 appear to be slightly enriched in perylene, possibly due to the proximity to the Kuparuk River, which contains sediments rich in perylene. Station 1A sediments also appear to be enriched in perylene. Station 4A and 2G sediments appear to be somewhat depleted in perylene relative to TPAH, but had no signs of petroleum contamination. Petroleum hydrocarbon contamination was previously identified in Station L08 using other interpretative techniques. The relationship of perylene to other hydrocarbons in surface sediments clearly warrants further investigation, however, these results indicate that normalization of PAH and other hydrocarbon parameters to perylene is another valuable tool capable of identifying anthropogenic hydrocarbons inputs into the surface sediments of this dynamic coastal region.

Based on the results of the data evaluations, we considered three hypotheses for the observed absolute increase in sediment hydrocarbon concentrations in the Northstar area after 1999 with no corresponding change in source or composition: 1) the increase could be related to deposition of very fine-grained material associated with the gravel used to construct Northstar Island and disturbances from the pipeline construction; 2) the ice roads made during the Northstar construction may have diverted suspended sediments from the Kuparuk river flow during break-up, and increased the deposition of fine-grained hydrocarbon-bearing sediments in the Northstar area; and 3) that the Northstar sediments in 1999 were depleted in fine-grained sediment and hydrocarbons during the 1999 sampling period.

The first two hypotheses would require that the source of fine-grained material deposited in the Northstar area after 1999 (e.g., Northstar construction gravel and/or Kuparuk river sediment) was enriched in PAH and other hydrocarbons relative to the fine-grained material in the existing surface sediment. This is not the case. Analyses of the Kuparuk river sediments reveal that the river sediment is not enriched in hydrocarbons relative to the Northstar area sediments, and is thus unlikely to account for the observed increase. It is possible that the very fine-grained fraction of Northstar construction gravel could be enriched in hydrocarbons due to burial and compaction of the historic Kuparuk river sediments, which were the source of the gravel (the construction gravel was mined from the Kuparuk river delta). However, subsequent analysis of "source material" from the Kuparuk river gravel mine (borrow pit) revealed results similar to the previously analyzed Kuparuk River sediments.

The most likely explanation is the third hypothesis that the Northstar surface sediments were depleted in hydrocarbons in 1999. The organic analyses and resulting statistical comparisons of the 1999, 2000, 2002, and 2004 Northstar, BSMP and Liberty data, support this explanation. In addition, during the 1999 sampling survey, nearly all the Northstar stations were sampled within 24 hours after a six-day gale (peak winds in excess of 25 knots). This storm resuspended substantial amounts of surface sediments into the water column (Boehm et al., 2001b) and would account for the observed depletion of hydrocarbons in the 1999 Northstar sediments and corresponding lower abundance of fine-grained sediment. Regardless of the mechanism for the observed increase in hydrocarbon concentrations at Northstar, it is critical to recognize that the hydrocarbon assemblage identified at Northstar in 1999, 2000, 2002, and 2004 - 2006 represents the natural background (both in composition and concentrations) and is not indicative of anthropogenic inputs in spilled oil or drilling muds/cuttings. Although oil based and synthetic based drilling muds were used to drill deeper sections of some of the production and disposal wells at the Northstar facility, no mud or cuttings were discharged to the ocean. However, equally important is the recognition that the monitoring techniques and data evaluation approaches used in this study are very sensitive and capable of identifying incremental anthropogenic inputs to the system, if they occur.

Summary. The hydrocarbon measures do not reveal any detectable contaminant input, except possibly from gas flaring at Northstar, which can be attributed to the Northstar operations, when viewed against the pre-construction levels in the sediments and the pre-construction hydrocarbon composition and regional distribution.

3.2.1.9 Geochronology of Hydrocarbons in Sediment Cores

SHC, PAH, and StTr were analyzed in the ten core samples collected in 2005 and 2006. The hydrocarbon dataset for the core sediments from 2005 and 2006 data from ten core samples collected. Nine of the cores also have reliable deposition rates and detailed geochronology. Hydrocarbons were analyzed at several depth intervals in the cores in an effort to better understand the temporal pattern of hydrocarbon deposition in sediments of the Beaufort Sea deposition area. The available geochronology data indicate that most of the sediments in the area represent pre-development (i.e., pre-1970) sediment deposition and probably are much older.

Saturated Hydrocarbons. Most of the SHC profiles in sediments from different depths in the cores are consistent with a mixture of primarily terrestrial biogenic hydrocarbons and lower contributions of petroleum hydrocarbons. This assemblage is clearly dominated by plant wax normal alkanes in the n-C27 through n-C33 carbon range. This is further demonstrated by carbon preference index (CPI) values for all sediment core samples that range from 4.6 to 6.9, which is characteristic of sediments influenced by terrigenous plant inputs (Wakeham and Carpenter, 1976; Boehm, 1984). The SHC profiles in the sediment core samples closely resemble those in surface sediments from the same locations.

Traces of lower molecular weight alkanes (LALK; n-C9 through n-C20 alkanes), possibly indicative of petroleum sources, are visible as minor components relative to the plant wax alkanes in the core sediments and in the river sediment samples. This natural "background" petroleum alkane signature in the sediments has been well documented by previous studies in the region, including earlier ANIMIDA work (Boehm et al., 1987; Steinhauer and Boehm, 1992; Boehm et al., 1990; Boehm et al., 2001b; Brown et al., 2002). These cores confirm the presence of "petroleum" alkanes prior to North Slope development.

TSHC concentrations often are correlated with %silt+clay at different depths in sediment cores. This is consistent with the hypothesis that much of the SHC originates from terrestrial plant material delivered to offshore sediments in spring river runoff.

Polycyclic Aromatic Hydrocarbons. The PAH distributions in sediments at different depths in the cores show that the PAH are primarily petrogenic (i.e., petroleum, peat, and coal) with smaller contributions of pyrogenic PAH (e.g., 4-, 5-, and 6-ring PAHs), with a variable biogenic component (perylene). The petrogenic PAH account for approximately 90 percent of the TPAH minus perylene throughout the core samples, including the surface sediment layer, as discussed above. Perylene was abundant in the core sediments and often was the most abundant single PAH (Figure 3-41). Several cores showed a clear trend in increasing perylene concentrations with depth (Figure 3-42), likely a product of diagenesis in the deeper sediment strata. Perylene concentration often increases with depth in the sediment, because diagenesis of perylene precursors to perylene occurs primarily in deeper, suboxic and anoxic sediment layers (Wakeham and Farrington, 1980).

The main effect of discharge of drilling muds and cuttings on nearby sediments is organic enrichment of surface layers. This is caused by microbial degradation of organic matter in the discharged solids, leading to oxygen depletion in the sediments (Neff, 2010). Sediment cores through a layer of drilling wastes on the sea floor often show elevated concentrations of PAH,

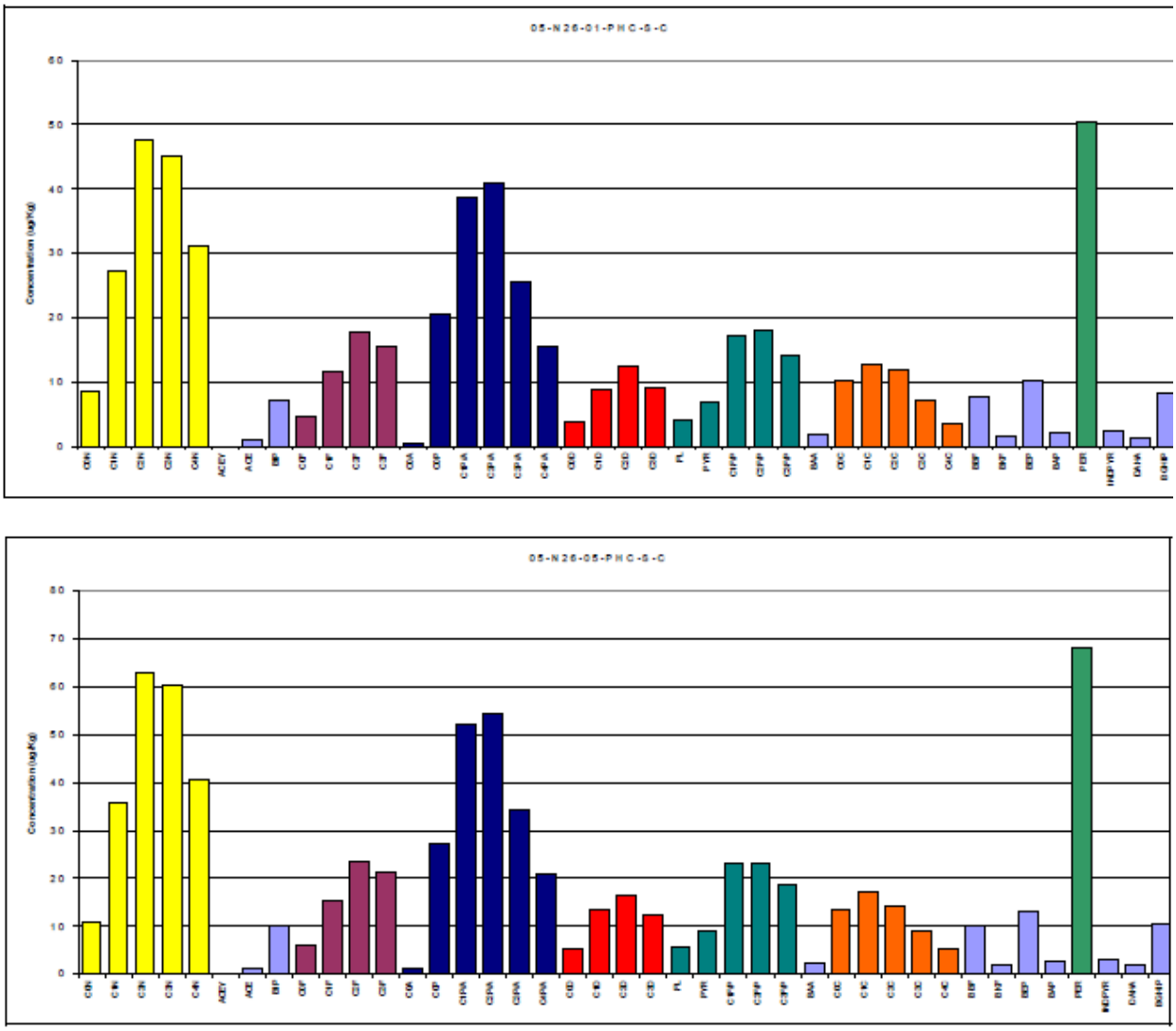


Figure 3-41. PAH profiles for the 0-2 cm (top) and 8-10 cm intervals in a sediment core collected at Northstar station N26 in 2005. From Brown et al. (2010).

including perylene, and SHC in near surface sediment layers. These hydrocarbons probably are from the organic-rich shallow (top few hundred meters) sediment layers cored and then deposited directly on the sea floor during drilling of the top hole (Neff, 2010). This is the pattern in a sediment core from BSMP station 7E, where there is other evidence of former drilling activities (Figure 3-43). Highest concentrations of TPAH and perylene were at about 3 cm below the surface and concentrations of TSHC reached a maximum at about 5 cm, where % silt+clay is lowest.

The PAH distributions usually are similar in all the cores at surface and at depth, and are characterized by the presence of a full suite of petroleum PAH similar to the PAH distribution seen in the Northstar crude oil. Perylene is found at equal or greater relative abundance in the river sediments and peat (Figures 3-12 and 3-13) compared to abundance in surface and

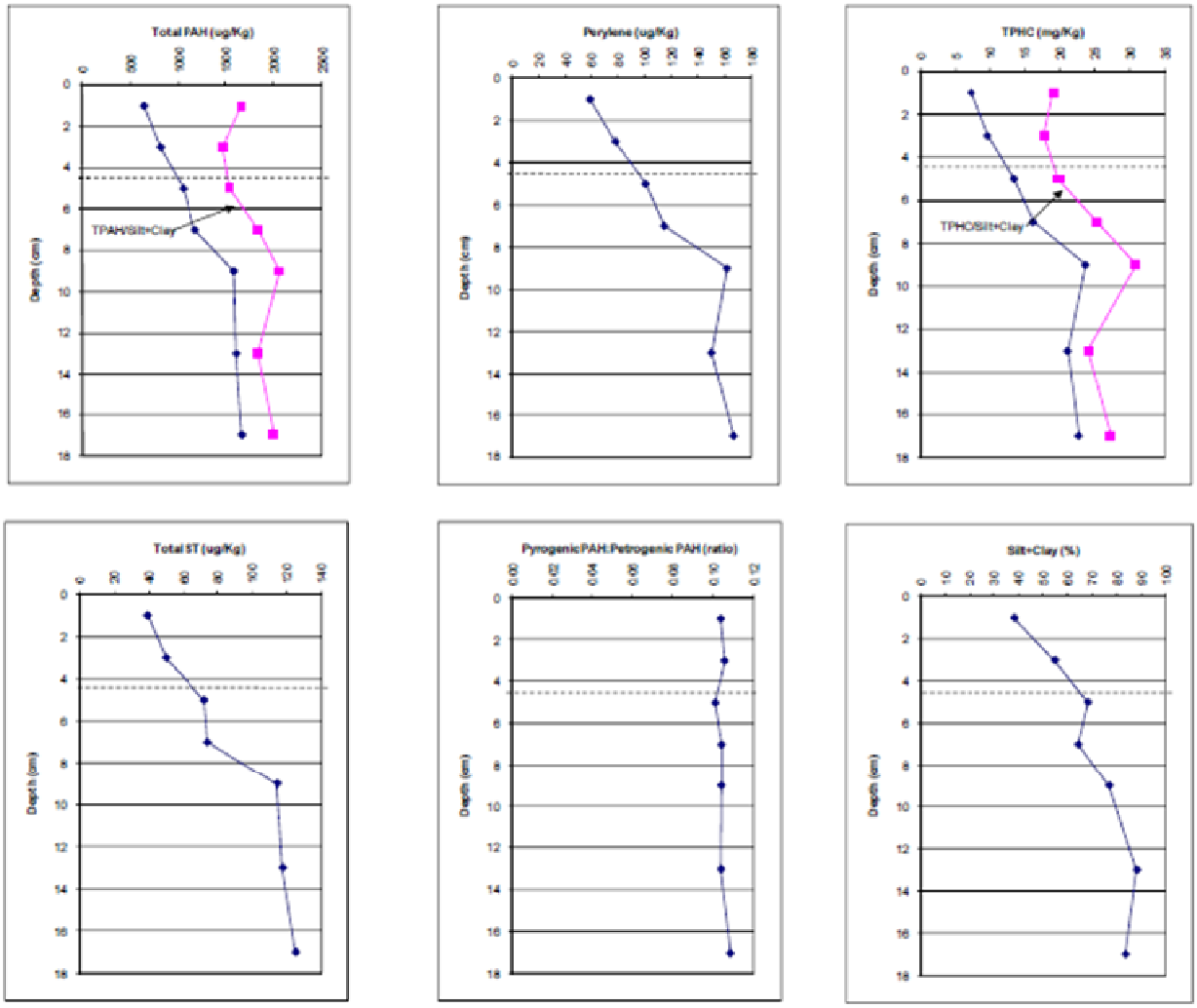


Figure 3-42. Profiles of TPAH, perylene, TSHC (TPHC), TStTr (Total ST) concentrations, pyrogenic/petrogenic PAH ratios, and % silt+clay in a sediment core from BSMP station 7A. From Brown et al. (2010).

subsurface layers of offshore sediment, which supports the relationship of the rivers and peat erosion as sources of most of the hydrocarbons in the nearshore sediments. Low levels of 4-, 5-, and 6-ring combustion PAHs also are also present, but are generally only a minor component of the overall PAH composition in the sediments.

Steranes/Triterpanes . In general, the StTr distributions in the sediment core samples are indicative of a petroleum source (Figures 3-42 and 3-43), with varying abundances of a suite of recent organic material triterpane markers. For example, Northstar crude oil has a characteristic petroleum StTr pattern dominated by 13β,17α-diacholestane-20S (S4), 17α(H),21β(H)-hopane (T19), C_{23}-diterpane (T4), and 22S-17α(H norhopane (T21) (Figure 3-26). The triterpane distributions for the core sediment samples are composed of a mixture of some of these characteristic petroleum triterpanes, as well as recent organic or biogenic markers such as diploptene and other unnamed triterpanes.

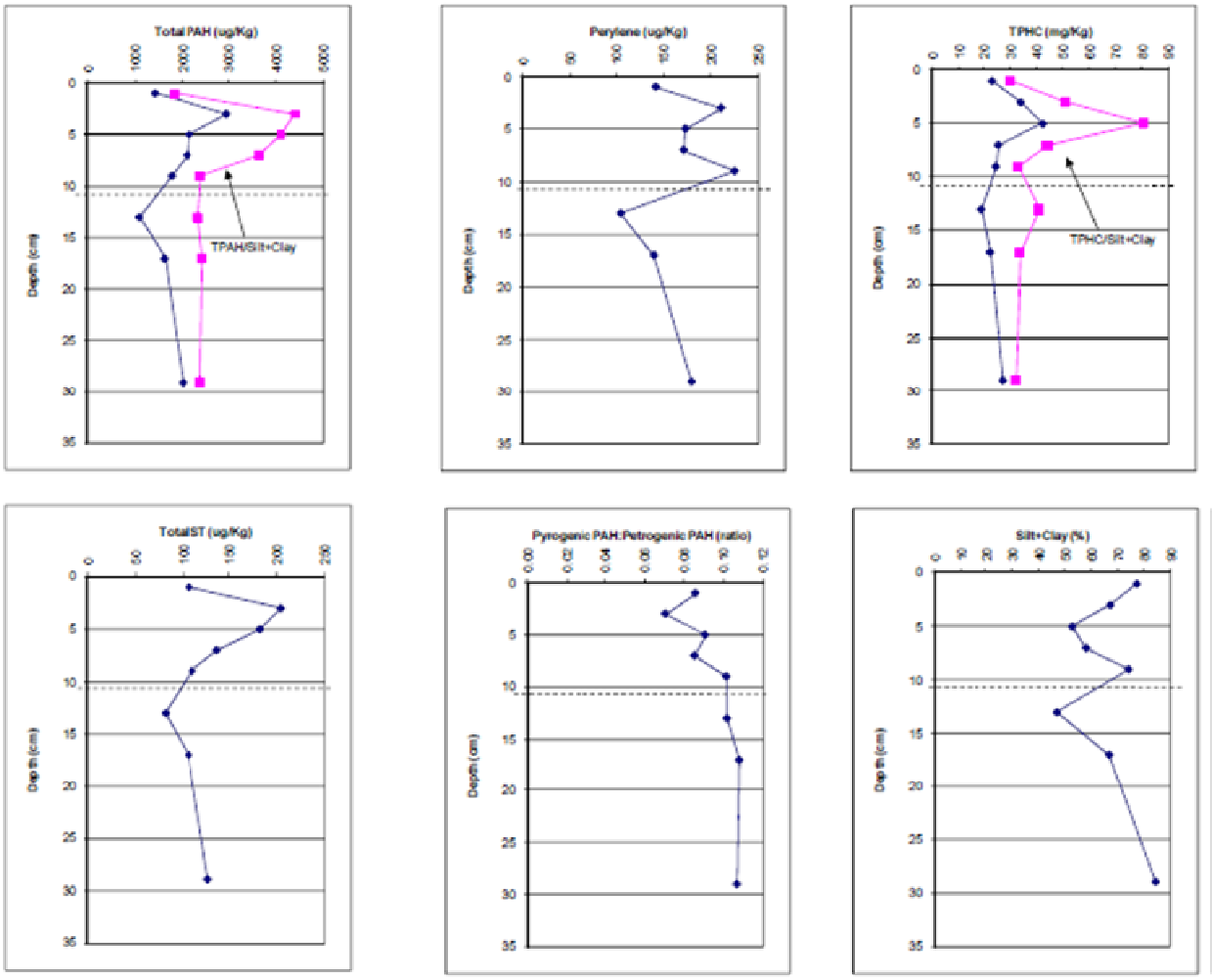


Figure 3-43. Vertical profiles of TPAH, perylene, TSHC (TPHC), TStTr (Total ST) concentrations, pyrogenic/petrogenic PAH ratios, and % silt+clay in a sediment core from BSMP station 7E, where there is evidence of exploratory drilling activities in the 1980s. From Brown et al. (2010).

The StTr distributions in river sediments and peat contain recent organic matter and petroleum hydrocarbon StTr patterns (Figure 3-24 and 3-25) with some similarities to those observed in the offshore sediment samples. This similarity suggests that there is a strong link between the river hydrocarbon sources – mostly erosional inputs of regional rock (shale) coal, peat, etc. (i.e., natural background) and the offshore sediments over time.

Comparisons of Hydrocarbons over Time. The key diagnostic organic parameters calculated for sediment core sections are important in examining the historical trends of hydrocarbons in the sediment record. As discussed earlier, reliable geochronology could be established for nine sediment cores Comparisons of selected key diagnostic parameters in the form of core profiles in conjunction with simple statistical treatments, allow an assessment of pre- and post-development hydrocarbon trends over time.

In general, comparisons of the core profiles for key diagnostic organic parameters for all of the cores do not show any clear trends that would indicate an increase in petroleum hydrocarbon inputs over time. The core profile from station 7C where geochronology could not be established (likely representing a historical pre-development record) is generally uniform and shows little variability of the hydrocarbon parameters over time. The cores for which pre- and post-development dates can be established generally show uniform distributions of key parameters throughout the cores, with some variability in specific core sections, such as that for station 7E (Figure 3-43). However the overall composition of the three classes of hydrocarbons analyzed are all similar throughout the cores and are consistent with the regional background hydrocarbon sources identified in the surface sediments (Figure 3-41).

In examining hydrocarbon trends in all of the cores, one useful technique involves examining the relationship between the organic parameter of interest and TOC content or alternatively, the %silt plus clay or perylene concentration. The natural background concentrations of TOC in the study area tend to co-vary with perylene concentration. Thus, samples enriched in organics from anthropogenic sources can be identified by normalizing the target organic parameter and generating a linear regression line and prediction interval on a cross-plot. A regression of TPAH minus perylene versus perylene concentration for all sediment core data for 2005 and 2006 demonstrates that most TPAH minus perylene/perylene ratios in different sediment layers in the cores fall within the 95% prediction intervals, indicating that the 2005 and 2006 core sediment samples usually do not have a TPAH concentrations different from the historical natural background for the region.

Another evaluation of the sources of PAH in the core samples was performed using a dibenzothiophene-to-phenanthrene source ratio plot, which was used earlier is this study to investigate PAH sources in surface sediments. Figure 3-44 is a source plot for all the 2001, 2005 and 2006 core sediments and additional source samples (i.e., field oils, river sediments and peat). The plot reveals that the source compositions of PAH in the core samples are generally similar (i.e., the data points cluster together on the plot) with some variability that can be attributed to local riverine source influences. For example, data points from core 2A (just east of the Canning River delta) tend to cluster below and to the left of the main grouping of data points and near the Canning River sediment data. The sediment core ratios cluster separately from the ratios for North Slope crude oil samples, but near the ratio for Northstar crude oil. However, Northstar crude oil has low concentrations of dibenzothiophenes, so it is unlikely that the PAH in sediment cores, which usually include abundant dibenzothiophenes (Figure 3-41), are derived from Northstar crude oil.

Another source ratio plot of the 20S to 20R epimers of steranes and triterpanes (5α,14α,17α-24-methylcholestane [S25/S28] versus 17α,21β(H)-30-homohopane [T21/T22]) of all the 2001, 2005 and 2006 core samples and sources samples (Figure 3-45) shows that the core data fall well within the range defined by the cluster of all of the surface sediment samples from the area. This provides further evidence that the sediment core data are representative of the regional hydrocarbon background, and do not indicate any substantial influence from post-development anthropogenic hydrocarbon inputs from the Northstar or Prudhoe Bay area, as indicated by the distance on the plot between the data points for Northstar and North Slope crude oils and the sediment cores.

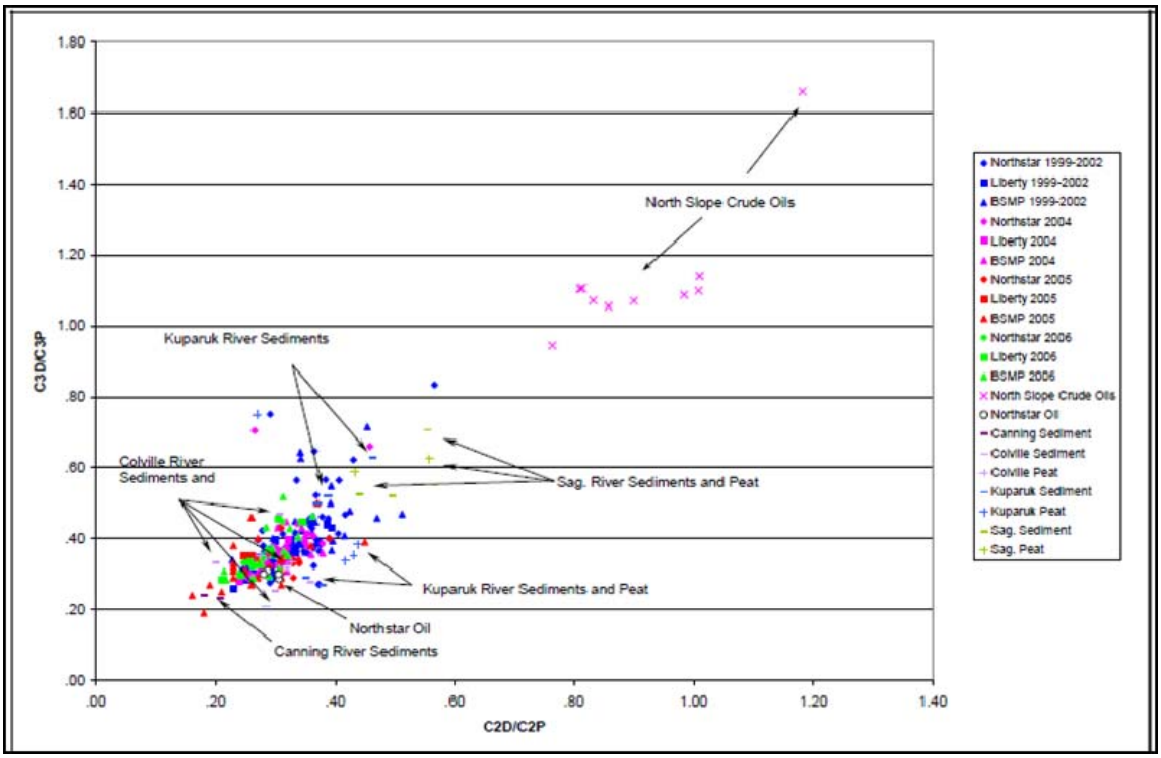


Figure 3-44. Double Ratio Source Plot of C2D/C2P vs. C3D/C3P for sediment core samples collected in 2001, 2005, and 2006, Northstar crude oil, river sediments, and peat. From Brown et al. (2010).

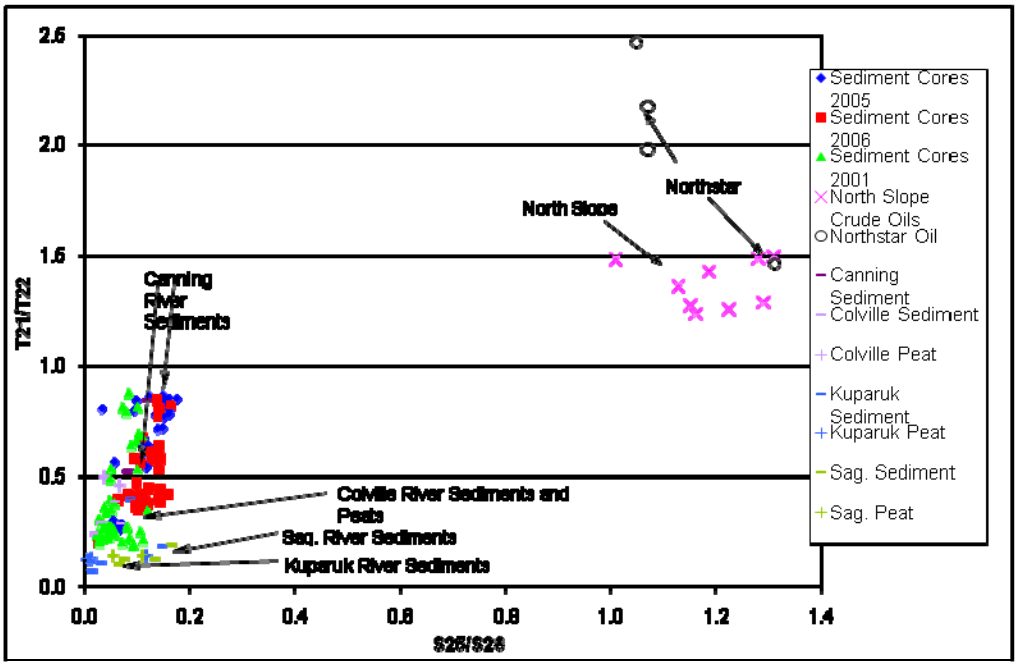


Figure 3-45. Double ratio source plot of S25/S28 versus T21/T22 petroleum biomarkers for BSMP, Liberty, Northstar sediment core samples. From Brown et al. (2010).

Overall, the organic analyses of the sediment cores collected during 2005 and 2006 have provided an important historical perspective on hydrocarbons in the sediments from the study area. The results have shown that the concentrations and sources of hydrocarbons are generally uniformly consistent over the past 50 or more years and represent a regional background assemblage. For most hydrocarbon parameters, there are no significant increases (after geochemical normalization) of hydrocarbon concentrations in the sedimentary record after the onset of oil and gas development in the Prudhoe Bay area.

3.3 Characterization of Metals and Hydrocarbons in Tissues of Marine Animals in the ANIMIDA/cANIMIDA Study Area

Large numbers of indigenous marine invertebrates (bivalve mollusks, amphipods, isopods, and mysids) and marine/anadromous fish were collected at a large number of stations in the Northstar, Liberty, and BSMP in 2004, 2005, and 2006 for analysis of tissue metals and hydrocarbons (Tables 2-1 and 2-2, Figure 2-3) (Neff et al., 2009). Mussels and sempermeable membrane devices (SPMDs) were deployed in cages at several stations in the same areas in an attempt to measure concentrations of bioavailable PAH in the water column. Marine animals had been sampled and mussels deployed at many of these stations one or more times in 1999 through 2002 for analysis of tissue metals and hydrocarbons as part of the Phase 1 and 2 ANIMIDA Project (Boehm et al., 2001; Spies et al., 2003; Brown et al., 2004). The objective of this sampling was to characterize bioavailability of several metals and three hydrocarbon classes (SHC, PAH, and StTr) to marine animals living in the oil and gas development area of the Alaskan Beaufort Sea and to determine if there were regional differences or temporal changes in tissue residues of metals and hydrocarbons that could be linked to exploration and development activities.

3.3.1 Metals in Tissues of Marine Animals

3.3.1.1 Fish

Concentrations of 13 metals were measured in the whole tissues of eight species of marine or anadromous fish indigenous to the nearshore Beaufort Sea between 2000 and 2006 (Table 3-25). Concentrations of metals for which comparison data were available (Table 3-26) were in the normal range in fish from the Beaufort Sea. The metals of greatest toxicological concern (As, Cd, Cr, Cu, Hg, Pb, and Zn) were present in fish tissues at concentrations well below potentially toxic values.

Concentrations of most metals were similar in different species of fish (Table 3-27). Arctic cod, four horn sculpin, and Arctic flounder are marine fish and Arctic char, Arctic cisco, least cisco, broad whitefish, and humpback broad whitefish are anadromous. There were no consistent trends in concentrations of metals in fish tissues. Demersal species, such as four horn sculpin tended to contain higher concentrations of metals than the more pelagic species. An anadromous species, arctic char, tended to contain lower concentrations of several metals (As, Ba, Cr, Fe, Ni, and V) than the other species did, perhaps from ingestion of fine grained suspended sediments from river water (Trefry et al., 2009).

Table 3-25. Concentration ranges of several metals in fish, mussels, amphipods, and clams collected in the Beaufort Sea between 2000 and 2006 as part of the ANIMIDA and cANIMIDA Programs, compared to the National Status and Trends median concentration ranges for mussels or oysters collected in US coastal waters between 1986 and 2003 (From O'Connor and Lauenstein, 2006). Concentrations are μg/g dry wt (ppm). Tissue metals data from Brown et al. (2005) and Neff et al. (2009).

Metal	Fish	Mussel	Amphipod	Clam	NS&T Medians
Silver (Ag)	0.01 – 0.35	0.05 – 2.5	0.8 – 4.0	0.04 – 0.13	---
Aluminum (Al)	---	131 - 2000	96 - 1200	98 - 2200	---
Arsenic (As)	0.55 – 16	6.2 - 13	4.0 – 17	8 - 16	8.1 – 9.6
Barium (Ba)	0.30 – 47	2.9 - 20	7.4 - 59	7 - 40	---
Beryllium (Be)	---	0.01 – 0.06	0.01 – 0.03	0.03 – 0.08	---
Cadmium (Cd)	0.01 – 0.37	0.29 – 5.4	0.3 – 2.4	0.53 – 13	2.1 – 2.9
Cobalt (Co)	---	0.46 – 2.6	0.6 – 2.9	0.8 – 4.0	---
Chromium (Cr)	0.04 – 3.8	0.65 – 7.3	---	---	---
Copper (Cu)	1.1 – 21	5.4– 9.40	41 - 210	7.0 - 24	(8.0 – 10)[a] (91 – 140)[b]
Iron (Fe)	19 - 1200	200 - 2000	100 - 950	770 - 3600	---
Mercury (Hg)	0.02 – 0.5	0.01 – 0.45	0.02 – 0.19	0.0 – 0.13	0.09 – 0.11
Manganese (Mn)	---	5.8 - 260	10 - 71	47 - 640	---
Nickel (Ni)	0.03 – 4.4	1.1 – 4.9	0.8 – 6.7	1.92 – 5.34	1.6 – 2.2
Lead (Pb)	0.01 – 2.6	0.22 – 1.1	0.05 – 0.7	0.18 – 1.9	0.63 – 0.98
Antimony (Sb)	---	0.01 – 0.03	0.01 – 0.04	0.01 – 0.06	---
Selenium (Se)	0.94 – 5.7	---	---	---	2.3 – 3.0
Tellurium (Tl)	---	0.01 – 0.04	0.01 – 0.03	0.01 – 0.03	---
Vanadium (V)	0.05 – 5.1	0.91 – 6.7	0.5 – 3.4	1.3 – 6.9	---
Zinc (Zn)	36.0 – 120	47 – 130	54 - 170	62 - 130	(110 – 140)[a] (1600 – 2400)[b]

[a] Mussels

[b] Oysters

Table 3-26. Concentrations of several metals and total polycyclic aromatic hydrocarbons (TPAH) in whole or muscle tissues of marine bivalve mollusks, crustaceans, and fish from unpolluted marine environments throughout the world. Concentrations are µg/g dry wt. From Neff (2002).

Chemical	Bivalve Mollusks		Crustaceans		Fish	
	Geomean	Range	Geomean	Range	Geomean	Range
Arsenic	11	0.13 – 214	15	<0.1 – 270	6.1	0.05 – 450
Barium	4.4	0.09 – 179	3.4	0.02 – 202	0.13	0.007 – 49
Cadmium	1.18	0.05 – 26.1	1.85	0.14 – 117	0.10	0.001 – 5.8
Mercury	0.17	0.004 – 11.7	0.45	0.02 – 6.2	0.77	0.01 – 115
Chromium	3.5[a]	0.1 – 10.0	2.6[a]	0.12 – 10.1	2.1[a]	0.03 – 5.8
Copper	51.8[a]	6.4 – 150	75.4[a]	8.8 – 241	3.9[a]	0.6 – 26
Lead	4.5[a]	<0.1 – 21.4	4.5[a]	0.03 – 17.5	7.09[a]	0.02 – 55.9
Zinc	290[a]	40 – 1315	68.6[a]	23.9 – 96.5	28.8[a]	4.1 – 58.8
TPAH	0.65	0.003 – 1729	0.17	0.004 – 13.4	0.19	0.002 – 23.4

[a] arithmetic mean.

Table 3-27. Concentrations of 13 metals in whole samples of seven species of fish collected from the Beaufort Sea study area during the summer of 2004. n = number of replicates. Concentrations are µg/g dry wt. Metals concentrations that were significantly different in a fish species at different sampling locations are highlighted.

Metal	Parameter	Arctic Char (n= 2-3)	Arctic Cisco (n= 4-5)	Arctic Cod (n= 4-5)	Arctic Flounder (n= 2)	Broad White-fish (n=2)	Four Horn Sculpin (n=5-6)	Least Cisco (n= 6)
Ag	Mean±SD	0.04±0.01	0.02±0.01	0.10±0.03	0.03±0.01	0.07±0.06	0.19±0.10	0.02±0.01
	Range	0.03-0.05	0.01-0.03	0.06-0.14	0.02-0.03	0.02-0.11	0.06-0.35	0.01-0.04
As	Mean±SD	2.51±0.80	3.05±0.52	9.45±5.33	5.74±0.88	1.43±0.44	4.87±2.32	2.98±0.91[a]
	Range	1.59-3.03	2.57-3.79	2.07-16.2	5.12-6.36	1.12-1.74	3.40-9.47	1.56-3.94
Ba	Mean±SD	1.9±0.3	2.5±4.3[b]	4.0±2.3	5.6±2.1	2.7±0	9.3±4.1	1.3±1.0
	Range	1.7-2.1	0.3-8.9	1.7-6.9	4.1-7.0	2.7-2.7	3.0-14.2	0.5-3.0
Cd	Mean±SD	0.10±0.04	0.07±0.04	0.17±0.11	0.04±0.02	0.05±0.03	0.18±0.09	0.06±0.06
	Range	0.05-0.13	0.03-0.14	0.05-0.27	0.03-0.06	0.03-0.07	0.05-0.32	0.02-0.18
Cr	Mean±SD	0.12±0.04	0.19±0.20	0.53±0.40	0.57±0.12	0.32±0.07	0.34±0.54	0.11±0.03
	Range	0.09-0.17	0.05-0.54	1.14±0.12	0.48-0.65	0.27-0.37	0.22-1.17	0.16±0.07
Cu	Mean±SD	4.5±0.3	3.0±0.5	4.5±2.2	3.4±0.9	3.7±0.7	11.1±4.1	2.3±0.5
	Range	4.2-4.7	2.4-3.6	2.2-7.9	2.7-4.0	3.2-4.2	6.1-18.2	1.5-2.9

Table 3–27. Continued.

Metal	Parameter	Arctic Char (n= 2-3)	Arctic Cisco (n= 4-5)	Arctic Cod (n= 4-5)	Arctic Flounder (n= 2)	Broad White-fish (n=2)	Four Horn Sculpin (n=5-6)	Least Cisco (n= 6)
Fe	Mean±SD	54.5±17.3	63.0±30.1	172±165	90.4±68.7	162±26.2	252±161	56.7±15.5
	Range	37.7-72.2	40.0-112	37.2-424	41.8-139	143-180	114-541	44.5-87.1
Hg	Mean±SD	0.06±0.02	0.06±0.02[b]	0.03±0.02	0.17±0.09	0.07±0.04	0.21±0.13	0.14±0.06
	Range	0.05-0.09	0.04-0.08	0.02-0.06	0.11-0.23	0.05-0.10	0.10-0.45	0.05-0.20
Ni	Mean±SD	0.06±0.02	0.19±0.10	0.60±0.24	0.36±0.16	0.20±0.03	0.48±0.33	0.19±0.10[a]
	Range	0.05-0.08	0.11±0.37	0.30-0.91	0.24-0.47	0.18-0.22	0.17-0.92	0.09-0.35
Pb	Mean±SD	0.19±0.13	0.07±0.04	0.30±0.19	0.11±0.06	0.11±0.10	0.22±0.09	0.10±0.05
	Range	0.11-0.33	0.02-0.12	0.09-0.57	0.07-0.15	0.03-0.18	0.07-0.32	0.04-0.18
Se	Mean±SD	3.69±1.23	1.94±0.46[b]	3.34±0.99	3.19±0.27	2.64±0.45	4.10±1.03	2.30±0.23
	Range	2.71-5.07	1.57-2.53	1.73-4.12	3.0-3.38	2.32-2.96	2.49-5.66	1.89-2.59
V	Mean±SD	0.14±0.05	0.15±0.15	1.12±1.18	0.55±0.14	0.57±0.09	1.32±1.08	0.13±0.06
	Range	0.10-0.19	0.05-0.40	0.19-3.02	0.45-0.65	0.50-0.63	0.34-3.38	0.05-0.19
Zn	Mean±SD	72.0±22.3	58.8±21.2[b]	82.9±22.1	91.6±16.1	50.5±12.3	94.0±13.1	66.5±26.1
	Range	53.1-96.6	36.0-82.5	44.5-97.8	103-80.2	41.8-59.2	70.8-106	38.7-109

[a] Northstar > Liberty; [b] Liberty > Northstar.

Concentrations of all metals were similar in all species collected at Liberty and Northstar in 2004, 2005, and 2006. Figure 3-46 summarizes the concentrations of 13 metals in tissues of several fish collected at Northstar and Liberty in 2006. When fish tissue data for 2005 and 2006 were combined, concentrations of Ag and Cu were significantly higher in fish from Northstar than in those from Liberty. The concentration of Se was significantly higher in fish collected in 2006 than in those collected in 2005. However, when combined fish tissue data for 2004, 2005, and 2006 were compared, there were no significant differences by year or location.

3.3.1.2 Marine Crustaceans

Amphipods (usually *Anonyx nugax*) were collected from several stations throughout the development area in all years of the ANIMIDA and cANIMIDA Projects for analysis of tissue metals and hydrocarbons (Table 2-1). Metals also were measured in isopods (*Saduria sabini*) collected at four BSMP stations and three Liberty stations in 2005. The amphipods contained higher concentrations of most metals than the fish did (Table 3-25). The amphipods and isopods contained similar concentrations of most metals.

Differences were relatively small for concentrations of metals in amphipods from the Northstar, Liberty, and BSMP areas in 2004, 2005, and 2006. Table 3-28 summarizes the mean concentrations of 18 metals in amphipods collected in 2004. There were significant differences among locations or year in concentrations of 9 metals in amphipod tissues (Table 3-29). Most significant differences were by year. None of the differences were large or ecologically significant.

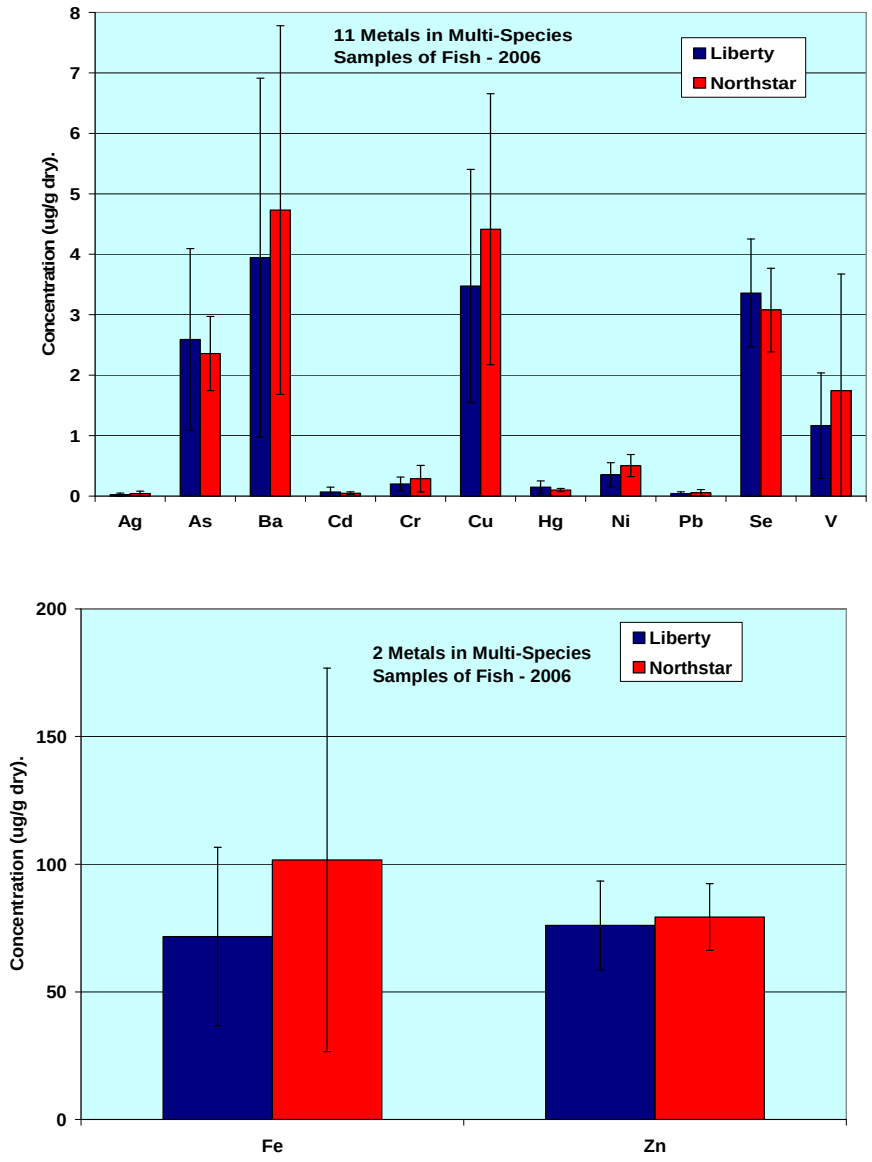


Figure 3-46. Mean ± SD concentrations of 13 metals in whole soft tissues of mixed assemblages of fish collected in the Liberty and Northstar areas in 2006. Concentrations are µg/g dry wt. From Neff et al. (2009).

Annual mean concentrations for each of 18 metals in amphipods from the coastal Beaufort Sea were plotted with their respective standard deviations (square root of the variance). Plots for the metals most likely to enter the marine environment as a result of offshore oil and gas operations or that pose the greatest ecological hazard are included in Figures 3-47 and 3-48. Table 3-30 shows the grand means and standard deviations for the 1999-2006 data along with the relative standard deviations [RSD = (mean/SD) x 100%], maximums and minimums. The 1999-2006 data sets were used to create Table 3-30 so that the same time interval would be used for all metals. Identification of any future changes in metal concentrations in amphipods relies on (1) a relatively low RSD or (2) low enough absolute metal values that changes can be distinguished before an adverse impact occurs.

Table 3-28. Concentrations of 18 metals in amphipods (*Anonyx nugax*) collected from three locations in the Beaufort Sea in 2004. n= number of samples. Concentrations are μg/g dry wt (ppm).

Metal	Parameter	Northstar (n= 3)	Liberty (n= 2)	BSMP (n= 3)
Ag	Mean±SD	4.05±1.69	2.98±0.07	2.41±0.51
	Range	2.75 - 5.96	2.91 - 3.04	1.85 - 2.84
Al	Mean±SD	444±257	531±33	278±101
	Range	271 - 740	494 - 555	164 - 358
As	Mean±SD	12.79±2.98	7.24±0.57	7.44±1.58
	Range	9.97 - 15.9	6.59 - 7.57	6.39 - 9.26
Ba	Mean±SD	34.8±14.1	23.9±1.1	20.1±13.5
	Range	22.8 - 50.4	23.0 - 25.1	10.7 - 35.6
Be	Mean±SD	0.011±0.007	0.011±0.002	0.008±0.003
	Range	0.007 - 0.019	0.010 - 0.013	0.005 - 0.01
Cd	Mean±SD	0.805±0.460	0.590±0.019	1.124±0.808
	Range	0.434 - 1.32	0.569 - 0.605	0.559 - 2.05
Co	Mean±SD	2.62±0.74	2.36±0.13	1.82±0.78
	Range	2.16 - 3.48	2.21 - 2.44	0.95 - 2.44
Cr	Mean±SD	0.62±0.21	0.86±0.17	0.46±0.13
	Range	0.43 - 0.85	0.66 - 0.96	0.35 - 0.6
Cu	Mean±SD	238±83	156±8	135±25
	Range	176 - 333	147 - 160	108 - 158
Fe	Mean±SD	299±122	326±26	184±71
	Range	218 - 439	297 - 345	103 - 237
Hg	Mean±SD	0.052±0.007	0.071±0.009	0.104±0.076
	Range	0.045 - 0.059	0.063 - 0.08	0.053 - 0.191
Mn	Mean±SD	61.1±33.2	43.0±2.3	35.5±23.3
	Range	39.7 - 99.4	40.9 - 45.5	10.3 - 56.2
Ni	Mean±SD	3.11±2.09	2.56±0.17	1.81±0.66
	Range	1.7 - 5.51	2.37 - 2.69	1.05 - 2.2
Pb	Mean±SD	2.01±2.11	0.294±0.010	0.221±0.144
	Range	0.371 - 4.39	0.285 - 0.305	0.097 - 0.379
Sb	Mean±SD	0.025±0.008	0.015±0.002	0.014±0.004
	Range	0.02 - 0.034	0.013 - 0.016	0.009 - 0.017
Tl	Mean±SD	0.013±0.005	0.011±0.001	0.016±0.010
	Range	0.008 - 0.018	0.01 - 0.012	0.009 - 0.028
V	Mean±SD	2.13±1.18	2.58±0.21	1.70±0.47
	Range	1.3 - 3.48	2.34 - 2.73	1.16 - 2.02
Zn	Mean±SD	145±60	103±2	122.6±41.3
	Range	103 - 214	101 - 105	94.8 - 170

Table 3-29. Statistical comparison of metals concentrations in amphipods (*Anonyx* sp) from BSMP, Liberty, and Northstar in 2004, 2005, and 2006. Only metals for which statistically significant differences were detected are included. Differences were considered statistically significant for p-values ≤ 0.05 (Sokol and Rohlf, 1994) and are highlighted.

Metal	Source	DF	p-value	Approach
Ag – Rank	Year	2	0.0217	Two-Way
	Location	2	0.0549	Two-Way
	Year x Location	3	0.6824	Two-Way
Al – Log	Year	2	0.0362	Two-Way
	Location	2	0.9723	Two-Way
	Year x Location	3	0.1378	Two-Way
Be - Rank	Year	2	<0.001	Two-Way
	Location	2	0.6945	Two-Way
	Year x Location	3	0.0818	Two-Way
Co – Log	Year	2	0.0023	Two-Way
	Location	2	0.3564	Two-Way
	Year x Location	3	0.0204	Two-Way
	Location x Year	7	0.0041	One-Way
Cu – Rank	Year	2	0.5339	Two-Way
	Location	2	0.0039	Two-Way
	Year x Location	3	0.1146	Two-Way
Fe - Log	Year	2	0.2842	Two-Way
	Location	2	0.7292	Two-Way
	Year x Location	3	0.0442	Two-Way
Pb – Rank	Year	2	0.0030	Two-Way
	Location	2	0.0054	Two-Way
	Year x Location	3	0.1759	Two-Way
Sb	Year	2	0.0003	Two-Way
	Location	2	0.9385	Two-Way
	Year x Location	3	0.0847	Two-Way
V – Log	Year	2	0.0082	Two-Way
	Location	2	0.9022	Two-Way
	Year x Location	3	0.1561	Two-Way

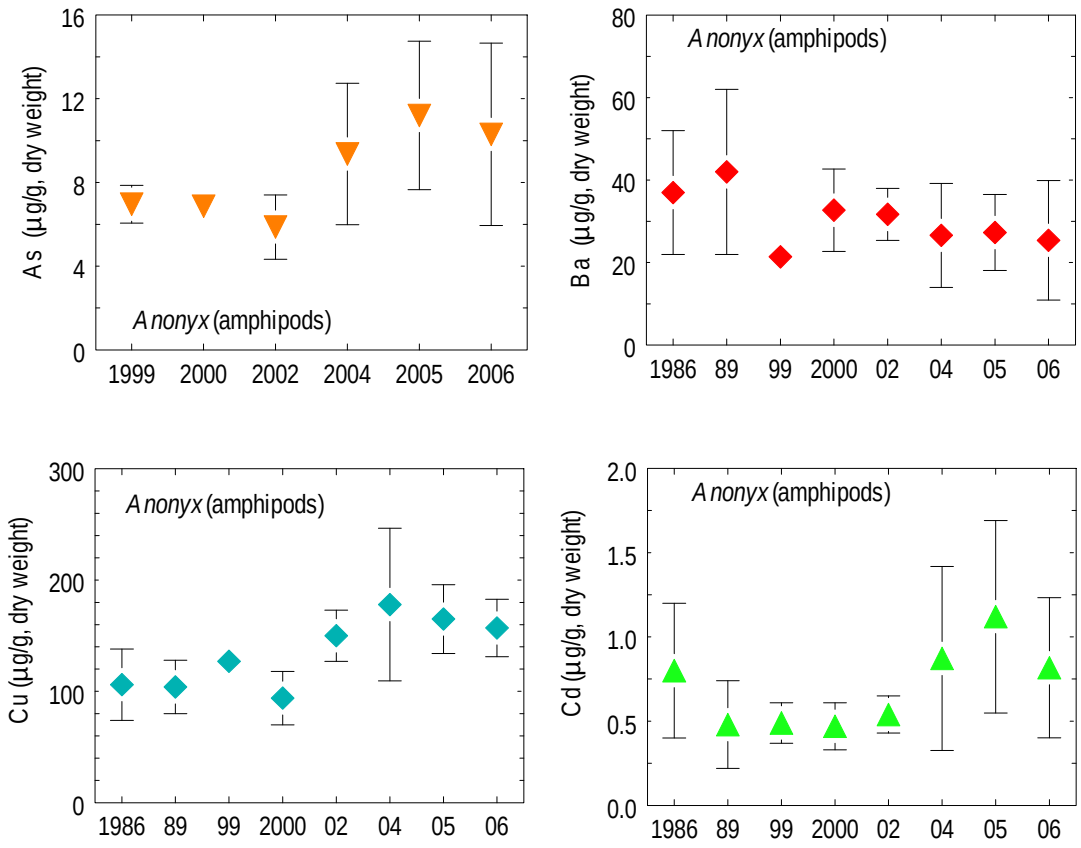


Figure 3-47. Concentrations of arsenic (As), barium (Ba), copper (Cu), and cadmium (Cd) in amphipods (*Anonyx nugax*) collected from nearshore waters of the Beaufort Sea between 1986 and 2006. Markers show the annual mean concentrations and lines show ± 1 standard deviation. Markers with no lines have an SD that is smaller than the marker. From Neff et al. (2009).

Concentrations of Cu and Zn in amphipods were the most uniform in the database with RSDs of 25% and 20%, respectively, for the complete data set of 54 samples collected between 1999 and 2006 (Table 3-30 and Figures 3-47 and 3-48). This uniformity for Cu and Zn is most likely due to ion regulation of these essential metals that helps control their concentrations in the amphipods. The other metals show a variety of values for the RSD that range from 26% for Ag and Co to 62% for Al (Table 3-30). Assuming that an increase of 2 standard deviations above the mean (for replicate samples) is required to identify changes in metal values, then a 40 to 52% increase in the absolute concentrations of Ag, Co, Cu and Zn would be needed to support a significant increase (Table 3-29). Similarly, increases in metal concentrations in amphipods of 64 to 70% (2 SDs) would be needed to identify changes in concentrations of Mn, Sb, Tl, As and Ni (Table 3-30).

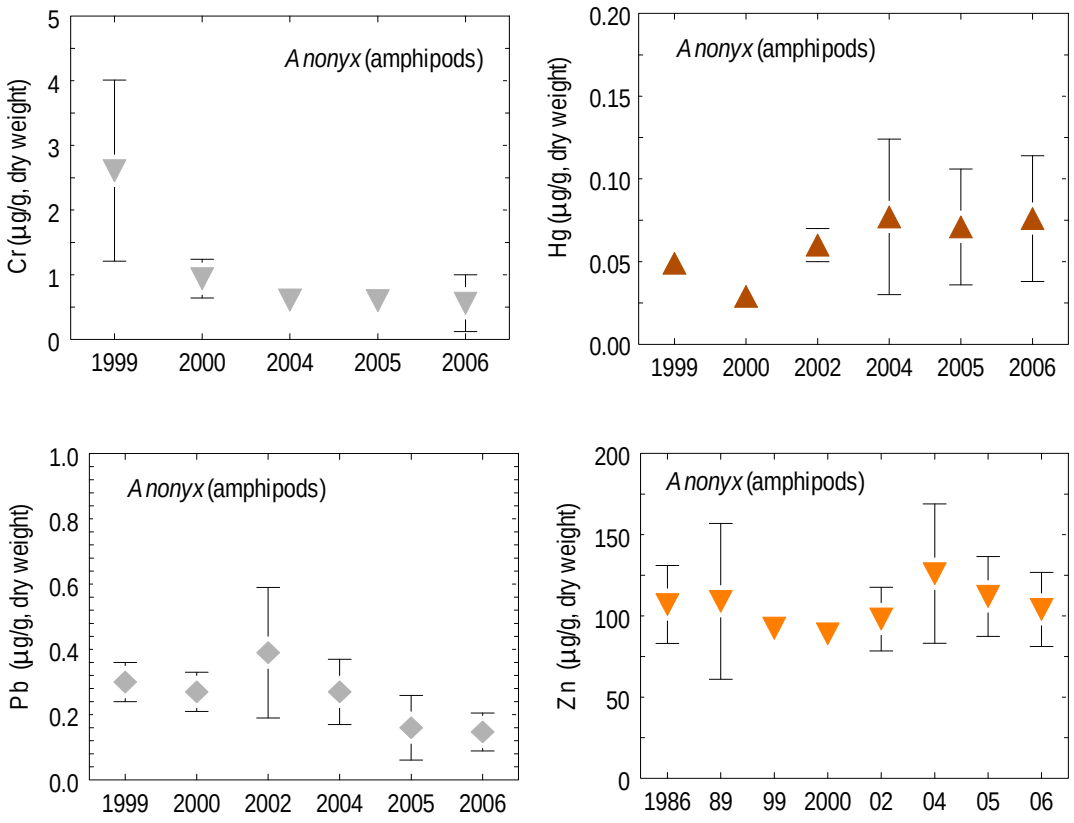


Figure 3-48. Concentrations of arsenic chromium (Cr), mercury (Hg), lead (Pb), and Zinc (Zn) in amphipods (*Anonyx nugax*) collected from nearshore waters of the Beaufort Sea between 1986 and 2006. Markers show the annual mean concentrations and lines show ± 1 standard deviation. Markers with no lines have an SD that is smaller than the marker. From Neff et al. (2009).

Because average metal concentrations for several metals were <1 µg/g, the absolute magnitude of any increase in metal values could be small, yet easily detected. For example, concentrations of Be ranged from 0.002 to 0.031 µg/g (i.e., 2 to 31 parts per billion) with a mean of 0.012 ± 0.007 µg/g; thus, an increase of just 0.030 µg/g (30 parts per billion) would be equivalent to an increase of >4 standard deviations.

3.3.1.3 Bivalve Mollusks

Bivalve mollusks, *Astarte montagui*, that occupies nearshore sandy marine sediments, and *Cyrtodaria kurriana*, that occupies fine grained sediment in river estuaries, were collected from several stations in the Liberty and BSMP areas in most years of the ANIMIDA and cANIMIDA Projects for analysis of tissue metals and hydrocarbons (Table 2-1). Because of difficulty in collecting sufficient tissue biomass of these small clams for metals and hydrocarbons analysis, relatively few tissue samples were available for metals analysis. Only a single sample of clams was available from Liberty in 2004 and 2005, and two samples were available in 2006. Concentrations of most metals, except Fe and Mn, were similar in clam and amphipod tissues (Table 3-25), and comparable to concentrations in bivalves from uncontaminated environments and the National Mussel Watch sites in the US and Europe (Tables 3-25 and 3-26).

Table 3-30. Means, standard deviations (SD), relative standard deviations [RSD = (mean/SD) x 100], maximums and minimums for metals in 54 samples of amphipods (*Anonyx*) from the ANIMIDA and cANIMIDA study areas for combined data from 1999-2001, 2003 and 2004-2006.

Metal	Mean ± SD (µg/g, dry wt.)	RSD (%)	Maximum (µg/g, dry wt.)	Minimum (µg/g, dry wt.)	(Max/Mean)
Ag	2.5 ± 0.6	26	4.0	0.8	1.6
Al	391 ± 242	62	1220	96	3.1
As	9.4 ± 3.8	40	17.4	4.0	2.4
Ba	26.1 ± 10.6	41	59.0	7.4	3.5
Be	0.012 ± 0.007	57	0.031	0.002	2.6
Cd	0.79 ± 0.45	57	2.4	0.3	3.0
Co	1.7 ± 0.4	26	2.9	0.6	1.7
Cu	149 ± 37	25	206	41	1.4
Fe	293 ± 156	53	949	103	3.2
Hg	0.067 ± 0.033	49	0.19	0.02	2.8
Mn	40 ± 13	32	71	10	1.8
Ni	2.9 ± 1.2	40	6.7	0.8	2.3
Pb	0.23 ± 0.14	60	0.7	0.05	1.7
Sb	0.022 ± 0.008	37	0.04	0.01	1.8
Tl	0.011 ± 0.004	39	0.028	0.005	2.5
V	1.6 ± 0.7	43	3.4	0.5	2.1
Zn	105 ± 21	20	170	54	1.6
% H_2O	75.5 ± 2.3	3	80.0	71.0	1.06

Clams from Liberty and the BSMP contained similar concentrations of most metals in 2004 and 2005 (data for 2005 are summarized in Table 3-31). There were statistically significant differences between the two locations or among the three years for four metals in tissues of the clams (Table 3-32). The most significant difference (Pr>F = 0.0009) was for mercury (Table 3-33). The significant differences in concentrations of this metal and the other metals was caused by the small numbers of replicates and the narrow range of concentrations among replicates. All mercury concentrations and concentrations of the other metals were well below concentrations that could be toxic to the bivalves or their consumers, including man.

Annual mean concentrations for eight of the 18 metals in clams (*Astarte montagui*) from the coastal Beaufort Sea are plotted with their respective standard deviations (square root of the variance) in Figures 3-49 and 3-50. Table 3-34 shows the grand means and standard deviations for the 1999-2006 data along with the relative standard deviations [RSD = (mean/SD) x 100], maximums and minimums. The 1999-2006 data sets were used to create Table 3-34 so that the same time interval would be used for all metals. As discussed above with the amphipod data, identification of any future changes in metal concentrations in clams relies on (1) a relatively low RSD or (2) low enough absolute metal values that changes can be distinguished before an adverse impact occurs.

Table 3-31. Concentrations of 18 metals in indigenous clams (*Astarte montagui* and *Cyrtodaria kurriana*) collected from two locations in the Beaufort Sea in 2005. n= number of samples. Concentrations are μg/g dry wt (ppm).

Metal	Parameter	Liberty (n= 1)	BSMP (n= 5)
Ag	Mean±SD	0.066	0.085±0.031
	Range		0.052 - 0.137
Al	Mean±SD	1220	623±495
	Range		98.5 - 1320
As	Mean±SD	16	13.0±2.6
	Range		11.3 - 17.4
Ba	Mean±SD	24.8	17.3±13.0
	Range		7.9 - 39.5
Be	Mean±SD	0.085	0.046±0.020
	Range		0.019 - 0.066
Cd	Mean±SD	3.88	4.34±3.45
	Range		1.13 - 9.55
Co	Mean±SD	1.67	1.16±0.35
	Range		0.75 - 1.68
Cr	Mean±SD	3.7	2.46±1.60
	Range		0.91 - 5.15
Cu	Mean±SD	11.1	14.0±2.5
	Range		12.0 - 17.1
Fe	Mean±SD	1910	1227±592
	Range		771 - 2110
Hg	Mean±SD	0.081	0.042±0.007
	Range		0.030 - 0.047
Mn	Mean±SD	65.5	128±57.4
	Range		78.4 - 205
Ni	Mean±SD	4.45	4.05±1.27
	Range		2.04 - 5.34
Pb	Mean±SD	0.707	0.5274±0.426
	Range		0.184 - 1.24
Sb	Mean±SD	0.045	0.046±0.011
	Range		0.031 - 0.059
Tl	Mean±SD	0.021	0.022±0.006
	Range		0.015 - 0.030
V	Mean±SD	3.37	2.41±1.49
	Range		0.97 - 4.72
Zn	Mean±SD	73.1	70.8±9.2
	Range		57.8 - 79.3

Table 3-32. Statistical comparison of metals concentrations in clams (*Astarte montagui* and *Cyrtodaria kurriana*) from Liberty in 2004, 2005, and 2006 and the BSMP stations in 2004 and 2005. Only metals for which statistically significant differences were detected are included. Differences were considered statistically significant for p-values ≤ 0.05 (Sokol and Rohlf, 1994) and are highlighted. From Neff et al. (2009).

Metal	Source	DF	p-value	Approach
Co – Log	Year	2	0.0220	Two-Way
	Location	1	0.0577	Two-Way
	Year x Location	1	0.3827	Two-Way
Fe	Year	2	0.0678	Two-Way
	Location	1	0.0392	Two-Way
	Year x Location	1	0.2692	Two-Way
Hg	Year	2	0.0868	Two-Way
	Location	1	0.0015	Two-Way
	Year x Location	1	0.0139	Two-Way
	Location_Year	4	0.0009	One-Way
Mn – Log	Year	2	0.0247	Two-Way
	Location	1	0.3780	Two-Way
	Year x Location	1	0.0570	Two-Way

Table 3-33. Concentrations of mercury (Hg) in soft tissues of clams (*Astarte montagui* and *Cyrtodaria kurriana*) from Liberty and BSMP stations in 2004, 2005, and 2006. Concentrations are µg/g dry wt. (parts per million). Data from Neff et al. (2009).

Year	Liberty			BSMP		
	n	Mean ± SD	Range	n	Mean ± SD	Range
2004	1	0.075	0.075	3	0.067 ± 0.005	0.062 - 0.072
2005	1	0.081	0.081	5	0.042 ± 0.007	0.030 - 0.047
2006	2	0.068 ± 0.002	0.066 - 0.069	0	---	---

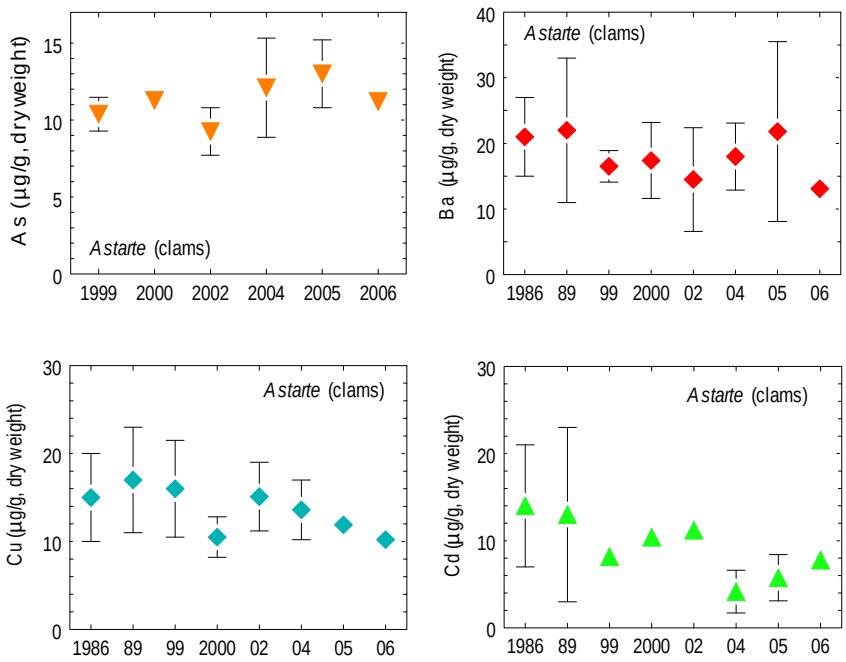


Figure 3-49. Concentrations of arsenic (As). barium (Ba), copper (Cu), and cadmium (Cd) in clams from the coastal Beaufort Sea in 1986 through 2006. Markers show the annual mean concentrations and lines show ± 1 standard deviation. Markers with no lines have an SD that is smaller than the marker. From Neff et al. (2009).

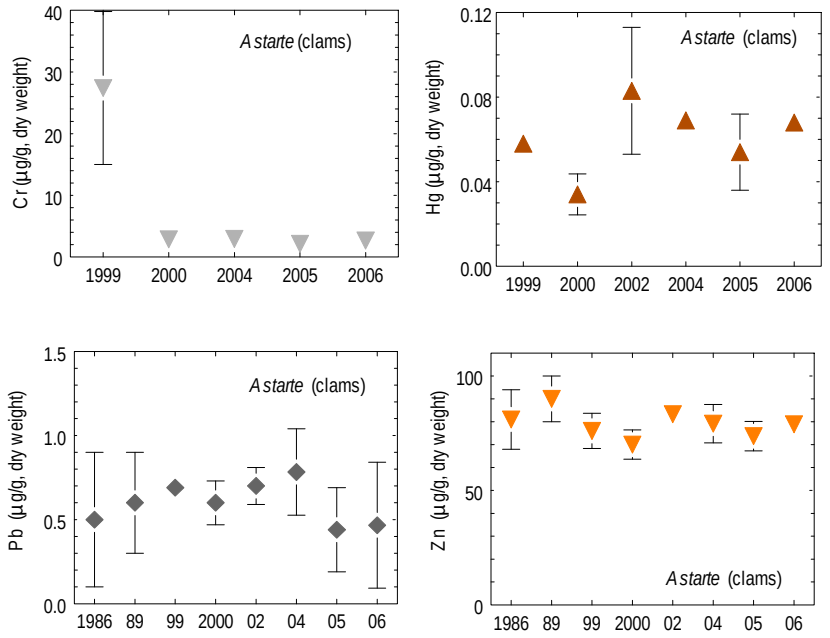


Figure 3-50. Concentrations of chromium (Cr), mercury (Hg), lead (Pb), and Zinc (Zn) in clams (*Astarte montagui*) collected from nearshore waters of the Beaufort Sea between 1986 and 2006. Markers show the annual mean concentrations and lines show ± 1 standard deviation. Markers with no lines have an SD that is smaller than the marker. From Neff et al. (2009).

Table 3-34. Means, standard deviations (SD), relative standard deviations [RSD = (mean/SD) x 100], maximums and minimums for metals in 22 samples of clams (*Astarte montagui* and *Cyrtodaria kurriana*) from the ANIMIDA and cANIMIDA study areas for combined data from 1999-2001, 2003 and 2004-2006.

Metal	Mean ± SD (µg/g, dry wt.)	RSD (%)	Maximum (µg/g, dry wt.)	Minimum (µg/g, dry wt.)	(Mean/Min)
Ag	0.07 ± 0.02	32	0.13	0.04	1.8
Al	1000 ± 454	45	2150	98	2.2
As	11.2 ± 2.1	19	16	8	1.4
Ba	17.2 ± 7.2	42	40	7	2.3
Be	0.052 ± 0.015	29	0.085	0.029	1.6
Cd	7.9 ± 3.1	39	13.1	0.5	1.6
Co	2.1 ± 1.0	47	4.0	0.8	1.9
Cu	13.0 ± 3.6	28	24	7	1.8
Fe	1555 ± 672	43	3640	771	2.3
Hg	0.060 ± 0.021	35	0.127	0.025	2.1
Mn	235 ± 163	69	637	47	2.7
Pb	0.62 ± 0.22	35	1.2	0.2	1.9
Sb	0.034 ± 0.015	43	0.059	0.010	1.7
Tl	0.018 ± 0.006	33	0.028	0.008	1.6
V	3.4 ± 1.4	42	6.9	1.3	2.0
Zn	79.9 ± 14.1	18	125	62	1.6
% H_2O	84.4 ± 2.9	3.5	92	78	1.18

Concentrations of As, Cu and Zn in clams were the most uniform in the data base with RSDs of 19%, 28% and 18%, respectively, for the complete data set of 22 samples collected between 1999 and 2006 (Table 3-34 and Figures 3-49 and 3-50). The other metals show a variety of values for the RSD that range from 29% for Be and Co to 69% for Mn (Table 3-34). If an increase of 2 standard deviations above the mean (for replicate samples) is assumed to be required to support a change in metal values, then a 36 to 58% increase in the absolute concentrations of As, Be, Cu and Zn would be needed to identify a significant increase (Table 3-34). Similarly, increases in metal concentrations in clams of 64 to 70% would be needed to identify changes in concentrations of Ag, Hg, Pb and Tl (Table 3-34).

Because average concentrations for several metals are <1 µg/g, the absolute magnitude of any increase in metal values could be small, yet easily detected. For example, concentrations of Ag ranged from 0.04 to 0.13 µg/g with a mean of 0.07 ± 0.02 µg/g; thus, an increase of just 0.10 µg/g (100 parts per billion) would be equivalent to an increase of >5 standard deviations.

3.3.1.4 Deployed Mussels

Concentrations of 18 metals were measured in soft tissues of the zero-time reference mussels (*Mytilus trossulus*) (from a mariculture facility in Port Chatham, AK, near the entrance to Cook Inlet) and mussels that had been deployed for approximately two weeks near the Northstar

Development, the Liberty prospect, and at BSMP stations in 2004, 2005, and 2006. Mussels also were deployed at Prudhoe Bay in 2005 and at the Endicott SDI (where slant drilling into the Liberty prospect is planned) and West Dock in 2006 (Table 3-33). Concentrations of most of the metals were higher in mussels that had been deployed for about two weeks in the Beaufort Sea than in zero-time reference mussels. Table 3-35 summarizes metals concentrations in reference (time zero) and deployed mussels in 2006).

Concentrations of most metals in zero time reference mussels were similar in 2004, 2005, and 2006 (Figure 3-51). Interannual differences rarely were more than two-fold. Largest differences were for abundant metals, such as Fe and Mn. Thus, the zero time mussels serve as a good reference for the mussels that were deployed at locations in the Beaufort Sea.

Mussels were deployed at Liberty, Northstar, and BSMP in 2004, 2005, and 2006, so statistical comparisons can be made for all 18 metals in mussels deployed in three years and in three locations. There were statistically significant differences in concentrations of nine metals in the three years of the study: Ag, As, Cd, Co, Mn, Ni, Pb, and V (Table 3-36). Significant differences also were observed for Mn and Tl for location and year x location and for Ni for year x location. None of the differences in metal concentrations in mussels deployed in 2004, 2005, and 2006 at BSMP, Liberty, and Northstar were large.

Ag and Pb concentrations were significantly higher in deployed mussels in 2004 than in 2005 and 2006; As and Cd concentrations were lower in 2004 than in 2005 and 2006. V concentration was higher in 2005 than in 2004 and 2006. Co, Mn, and Ni concentrations were significantly higher in mussels deployed at BSMP in 2006 than in mussels deployed at other locations and years. Hg and Tl concentrations were very low in all mussels, but concentrations varied among years and deployment locations.

Twelve metals (Ag, As, Ba, Be, Cd, Cu, Fe, Hg, Pb, Tl, V, and Zn) were measured in the soft tissues of reference mussels and mussels deployed near the Northstar Development as part of Task 2 of the ANIMIDA Project (Brown et al., 2005). These 12 metals and an additional six metals were analyzed in mussels in 2004 through 2006 as part of the cANIMIDA Project.

Concentrations of Ba, Be, Cu, Fe, and Zn were higher in reference mussels and mussels that had been deployed at the Northstar Development in 2002 than in 2004, 2005, and 2006 (Table 3-37). Concentrations of Ag and As were slightly lower in mussels deployed at the Northstar Development in 2002 than in those deployed there in 2004, 2005, and 2006. In all cases, the differences were small and the number of replicates in each year was small, indicating that the differences were not ecologically significant. In each year, the concentration of each metal was similar in reference mussels and mussels that were deployed at the Northstar Development, indicating the metals were accumulated primarily at the reference site, Port Chatham.

Table 3-35. Concentrations of 18 metals in Mussels (*Mytilus trossulus*) following deployment in five regions of the Beaufort Sea, compared to the time zero reference animals in 2006. n= number of samples. Concentrations are µg/g dry wt. From Neff et al. (2009).

Metal	Parameter	Liberty (n= 3)	Northstar (n= 2)	BSMP (n= 1)	SDI (n= 1)	West Dock (n= 1)	Time Zero (n= 1)
Ag	Mean±SD	0.075±0.010	0.065±0.004	0.103	0.069	0.05	0.07
	Range	0.064-0.081	0.062-0.067				
Al	Mean±SD	1182±448	328±74.2	1910	1860	1690	474
	Range	665-1450	275-380				
As	Mean±SD	10.9±0.2	8.97±0.47	11.7	10.8	10.1	10.8
	Range	10.8-11.1	8.63-9.30				
Ba	Mean±SD	10.4±2.86	3.34±0.59	8.72	17.9	14.4	3.75
	Range	7.09-12.1	2.92-3.76				
Be	Mean±SD	0.028±0.005	0.012±0.004	0.021	0.038	0.038	0.011
	Range	0.022-0.032	0.009-0.014				
Cd	Mean±SD	4.23±0.22	3.14±0.37	5.27	4.16	3.72	4.07
	Range	3.98-4.39	2.88-3.4				
Co	Mean±SD	0.87±0.08	0.556±0.062	1.56	1.2	1.08	0.803
	Range	0.77-0.93	0.512-0.599				
Cr	Mean±SD	2.32±0.49	1.19±0.11	7.32	4.17	3.24	2.09
	Range	1.75-2.64	1.11-1.27				
Cu	Mean±SD	7.3±0.6	5.75±0.49	7.4	7.9	8.2	6
	Range	6.9-8.0	5.4-6.1				
Fe	Mean±SD	976±273	424±81	2010	1790	1470	659
	Range	669-1190	366-481				
Hg	Mean±SD	0.095±0.006	0.062±0.003	0.104	0.112	0.121	0.086
	Range	0.091-0.102	0.06-0.064				
Mn	Mean±SD	18.0±3.9	13±2.8	61.5	29.8	29.6	21.3
	Range	13.8-21.4	11-15				
Ni	Mean±SD	2.08±0.33	1.63±0.08	4.94	3.4	3.12	2.1
	Range	1.70-2.33	1.57-1.68				
Pb	Mean±SD	0.697±0.170	0.457±0.030	0.795	0.933	0.631	0.587
	Range	0.513-0.849	0.435-0.478				
Sb	Mean±SD	0.007±0	0.011±0.030	0.011	0.011	0.013	0.005
	Range	0.007-0.007	0.009-0.013				
Tl	Mean±SD	0.016±0.004	0.009±0.002	0.019	0.024	0.011	0.012
	Range	0.012-0.019	0.007-0.01				
V	Mean±SD	4.06±1.39	1.88±0.24	6.74	5.27	4.48	2.98
	Range	2.68-5.46	1.71-2.05				
Zn	Mean±SD	103.6±9.05	91.9±6.0	95	110	105	85.9
	Range	97.9-114	87.6-96.1				

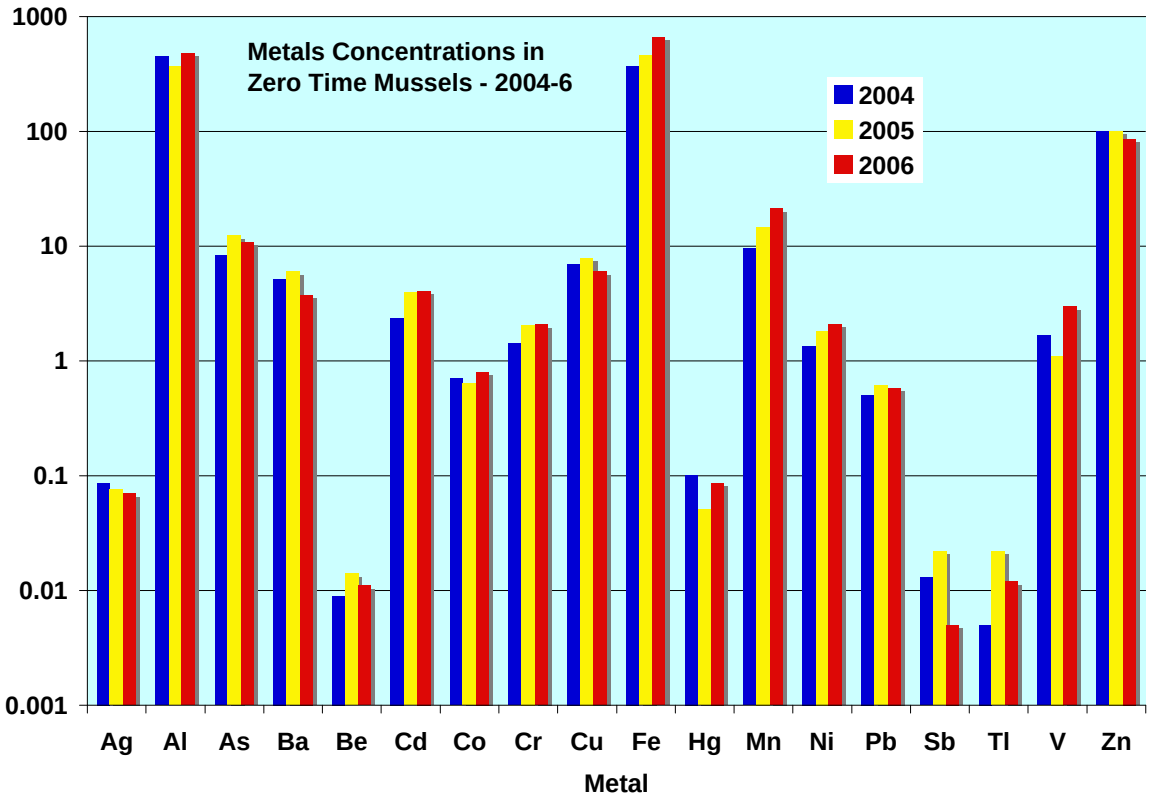


Figure 3-51. Mean metals concentrations in reference mussels collected at Port Chatham in 2004, 2005, and 2006. Note that the y-axis is log scale. From Neff et al. (2009).

3.3.1.5 Integration of Metals Concentrations in Tissues of Indigenous Marine Animals and Deployed Mussels in the Beaufort Sea

Concentrations of 18 metals in tissues of several species of fish, amphipods, isopods, and clams collected near the Northstar Development, in the Liberty Prospect area, and in other reference areas were similar in 2004, 2005, and 2006, and comparable to metals concentrations in the same species collected in the ANIMIDA Project. When statistically significant differences were detected among years or locations, the differences were small. Northstar is the only offshore area where a large amount of development drilling has occurred and where oil production currently is occurring. A few metals concentrations were higher in marine animals from Northstar than in the same species from the other sampling sites (Pb in amphipods and Ag and Cu in fish); however, there were no consistent differences by year or location.

Although there were interannual differences in concentrations for several metals, the differences were small and all concentrations were in the range for marine animals from clean marine environments (Table 3-26). Concentrations of most metals were higher in clams and mussels than in amphipods and fish. Aluminum and iron concentrations tended to be higher in clams than in crustaceans and fish, possibly indicating that the clams are retaining sediment particles in the gut and gills.

Table 3-36. Statistical comparison of metals concentrations in mussels (*Mytilus trossulus*) that were deployed at BSMP, Liberty, and Northstar in 2004, 2005, and 2006. Only metals for which statistically significant differences were detected are included. Differences were considered statistically significant for p-values ≤ 0.05 (Sokol and Rohlf, 1994) and are highlighted. From Neff et al. (2009).

Metal	Source	DF	F Value	p-value
Ag	Year	2	5.65	0.0187
	Location	3	2.93	0.0770
	Year x Location	6	2.00	0.1451
As	Year	2	13.20	0.0009
	Location	3	0.37	0.7758
	Year x Location	6	2.46	0.0871
Cd	Year	2	30.10	<0.0001
	Location	3	0.56	0.6540
	Year x Location	6	2.12	0.1266
Co – Rank	Year	2	4.55	0.0339
	Location	3	0.28	0.8406
	Year x Location	6	6.88	0.0024
Hg	Year	2	2.56	0.1183
	Location	3	1.46	0.2755
	Year x Location	6	6.84	0.0024
Mn – Log	Year	2	6.76	0.0108
	Location	3	4.47	0.0251
	Year x Location	6	3.25	0.0392
Ni – Rank	Year	2	4.00	0.0466
	Location	3	0.61	0.6241
	Year x Location	6	3.15	0.0428
Pb	Year	2	4.60	0.0329
	Location	3	0.23	0.8755
	Year x Location	6	095	0.4971
Tl	Year	2	13.29	0.0009
	Location	3	7.50	0.0044
	Year x Location	6	3.87	0.0220
V	Year	2	13.72	0.0008
	Location	3	1.66	0.2285
	Year x Location	6	2.94	0.0528

Table 3-37. Mean (± Sd) concentrations of 12 metals in tissues of reference mussels from Port Chatham, AK, and mussels from Port Chatham that had been deployed for 2 to 3 weeks near the Northstar Development in 2002 (ANIMIDA Project), 2004, 2005, and 2006 (cANIMIDA Program). n= number of samples. Concentrations are µg/g dry wt. From Neff et al. (2009).

Metal	Reference Mussels				Mussels Deployed at Northstar			
	2002 (n = 2)	2004 (n = 3)	2005 (n = 2)	2006 (n = 1)	2002 (n = 2)	2004 (n = 3)	2005 (n = 1)	2006 (n = 2)
Ag	0.08±0.01	0.09±0.01	0.08±0.01	0.07	0.08±0.01	0.12±0.02	0.09	0.06±0.00
As	6.9±0.6	8.4±1.4	12.4±1.1	10.8	6.7±0.10	10.2±1.11	11.3	8.97±0.47
Ba	18±3	5.2±3.5	6.0±0.70	3.75	17±2	13.0±5.7	7.2	3.34±0.59
Be	0.04±0.01	0.01±0.01	0.01±0.01	0.01	0.04±0.00	0.03±0.01	0.02	0.01±0.00
Cd	3.9±0.4	2.4±0.71	4.69±1.05	4.07	3.9±0.30	2.32±1.51	4.77	3.14±0.37
Cu	9.9±1.4	7.0±1.3	7.9±0.40	6.0	9.1±0.10	8.3±0.97	7.0	5.75±0.49
Fe	1300±80	374±265	460±0.7	659	1370±130	865±341	265	424±81
Hg	0.11±0.01	0.10±0.01	0.05±0.00	0.09	0.09±0.01	0.09±0.01	0.25	0.06±0.00
Pb	0.75±0.10	0.88±0.33	0.61±0.02	0.59	0.71±0.05	0.99±0.11	0.52	0.46±0.03
Tl	0.02±0.004	0.01±0.00	0.02±0.00	0.01	0.02±0.00	0.02±0.00	0.04	0.01±0.00
V	4.2±0.01	1.67±1.15	1.11±0.06	2.98	4.0±0.50	3.65±0.94	0.99	1.88±0.24
Zn	114±4	99.7±33.7	101±2.0	85.9	106±2.0	93.3±34.2	95.6	91.9±6.0

There were no consistent trends in concentrations of metals in fish tissues. Demersal species, such as four horn sculpin, tended to contain higher concentrations of metals than the more pelagic species. The anadromous species, such as arctic char, tended to contain lower concentrations of metals than the other species did, perhaps because they spend much of the year in fresh water where dissolved concentrations of most metals are lower than in the ocean.

The concentrations of metals in the tissues of most of the bivalve mollusks, crustaceans, and fish sampled in this project were in the range expected for the same or similar species in relatively unpolluted marine environments throughout the world (Table 3-26). Concentrations of different metals vary widely in tissues of different taxa of marine animals. Zinc is particularly abundant in mollusks (particularly oysters); copper often is abundant in crustaceans and oysters. Mercury tends to be more abundant in fish tissues, particularly muscle, than in tissues of marine invertebrates. Most of the mercury in fish muscle is methylmercury. This pattern of distribution of metals was evident in bivalve mollusks, crustaceans, and fish in the Alaskan Beaufort Sea.

The National Status and Trends Mussel Watch Program median metals concentrations in mussels and oysters can be considered normal values (Table 3-25). A few fish, mussel, amphipod, and clam samples from the Beaufort Sea contained higher than the NS&T median concentrations of the 8 metals for which median NS&T values are available. As expected, amphipods contained copper at concentrations that exceeded the median value for copper in mussels, but not oysters. Crustaceans often contain naturally high concentrations of copper in their blood pigment. As discussed above, fish muscle often contains slightly elevated concentrations of mercury, as methylmercury. Some fish collected in the Beaufort Sea contained greater than the mussel

median value for mercury of 0.24 μg/g. The mercury concentration in Beaufort Sea fish is well below the 1 μg/g wet wt (~ 5 μg/g dry wt) screening concentration for edible tissues of fishery products consumed by man set by the Food and Drug Administration (FDA, 2001). Most marine fish from elsewhere contain mercury concentrations similar to or higher than concentrations reported in this investigation for Beaufort Sea fish. These concentrations of metals in tissues are not harmful to the animals themselves or to consumers of these species, including man.

3.3.2 Hydrocarbons in Tissues of Marine Animals

3.3.2.1 PAH in Fish Tissues

A total of 171 fish were collected 2004, 2005, and 2006 in the Northstar, Liberty, and the BSMP areas for chemical and biomarker analysis (Table 2-1). An additional 125 fish were collected in 2001 as part of the ANIMIDA Project. A total of 28 fish samples of seven species were analyzed in 2004, 21 samples of six species were analyzed in 2005, and 20 samples of five species were analyzed in 2006.

TPAH concentrations in fish tissues varied widely among both locations and years (Table 3-38). Mean TPAH concentrations in all species combined were higher at both Northstar and Liberty in 2001 than in 2004 through 2006. Mean TPAH concentrations in all species combined were highest at Liberty in 2001 (64.1 ± 65.9 ng/g dry wt) and lowest at Northstar in 2005 (9.44 ± 6.85 ng/g). TPAH concentrations in tissues of all eight species of fish combined were lower in 2005 than in 2001, 2004, and 2006. The same pattern was observed for TPAH and all other hydrocarbon concentrations in crustaceans, indigenous clams, and deployed mussels (Table 3-38). These differences may have been caused by analytical error or natural interannual variation in hydrocarbon concentrations in the environment.

TPAH concentrations were quite variable in the eight species of fish sampled (Table 3-38). Arctic cod, an important food web species, contained higher concentrations of TPAH than the other species collected at Northstar and Liberty in 2004. Arctic cod were not collected in 2005 and 2006, and four horn sculpin, a demersal species, usually contained the highest TPAH concentrations.

The PAH assemblage in all fish samples was dominated by naphthalene and alkyl naphthalenes, sometimes with smaller amounts of phenanthrenes (Figure 3-52). Fish have an inducible enzyme system, the cytochrome P450 mixed function oxygenase that efficiently metabolizes PAH. CYP1A metabolizes higher molecular weight PAH more efficiently than low molecular weight PAH; this may explain the relative abundance of 2- and 3-ring PAH and the low concentrations of TPAH in fish tissues. In all years, the PAH profile in fish tissues is indicative of a primarily petrogenic source, but this pattern is obscured somewhat by the preferential metabolism of higher molecular weight, pyrogenic PAH. The fish tissue PAH residue data for 2001 through 2006 also are consistent with chronic, low-level exposure to PAH in water, sediments, and food throughout the study area, with no clear point source of bioavailable PAH in the coastal environment.

Table 3-38. Mean Concentrations of total polycyclic aromatic hydrocarbons, dibenzothiophenes, and dibenzofuran (TPAH), total saturated hydrocarbons (TSHC), pristane, and steranes/triterpanes (StTr) in tissues of indigenous fish, clams, amphipods, isopods, and mysids collected at several locations in the Alaskan Beaufort Sea in 2004 through 2006. From Neff et al. (2009).

Taxon	Analytes	Location	Mean (SD) Concentration (ng/g)		
			2004	2005	2006
Fish (8 species)	TPAH	Northstar	38.8 ± 20.7	9.44 ± 6.85	52.4 ± 12.8
		Liberty	47.8 ± 25.3	10.1 ± 6.45	24.8 ± 6.4
		Tigvariak Island	30.4 ± 7.7	No data	No data
Amphipods	TPAH	Northstar	83.3 ± 52.7	13.8 ± 8.96	41.3 ± 27.4
		Liberty	73.6 ± 10.3	39.5 ± 10.1	81.5 ± 23.9
		BSMP	49.5 ± 16.7	23.6 ± 9.24	60.9 ± 14.4
	TSHC	Northstar	31,458 ± 2784	18,003 ± 1746	26,681 ± 17,987
		Liberty	26,203 ± 2010	44,625 ± 14,523	85,152 ± 41,029
		BSMP	28,704 ± 3948	26,914 ± 9980	43,679 ± 31,008
	Pristane	Northstar	26,968 ± 3237	16,598 ± 8736	24,749 ± 18,785
		Liberty	24,634 ± 2488	42,127 ± 17,377	81,071 ± 47,234
		BSMP	27,254 ± 5160	24,644 ± 14,816	39,986 ± 3397
	StTr	Northstar	12.7 ± 4.37	0.57 ± 0.25	1.09 ± 2.40
		Liberty	8.10 ± 0.40	4.88 ± 2.27	8.38 ± 6.53
		BSMP	3.70 ± 1.93	0.52 ± 0.32	13.4 ± 17.8
Isopods	TPAH	Northstar	No data	No data	67.6 ± 12.8
		Liberty	No data	67.0 ± 9.83	88.5
		BSMP	No data	73.37 ± 4.36	114
Mysids	TPAH	Northstar	No data	No data	89.3 ± 24.4
Clams	TPAH	Liberty	91.85	No data	141 ± 57.8
		BSMP	97.1 ± 52.5	38.4 ± 12.3	No data
	TSHC	Liberty	1644	No data	5276 ± 666
		BSMP	1922 ± 621	1510 ± 634	No Data
	Pristane	Liberty	80.2	No data	96.6 ± 36,0
		BSMP	152 ± 40.6	434 ± 629	No data
	StTr	Liberty	8.99	No data	0
		BSMP	8.40 ± 6.20	1.72 ± 2.98	No data

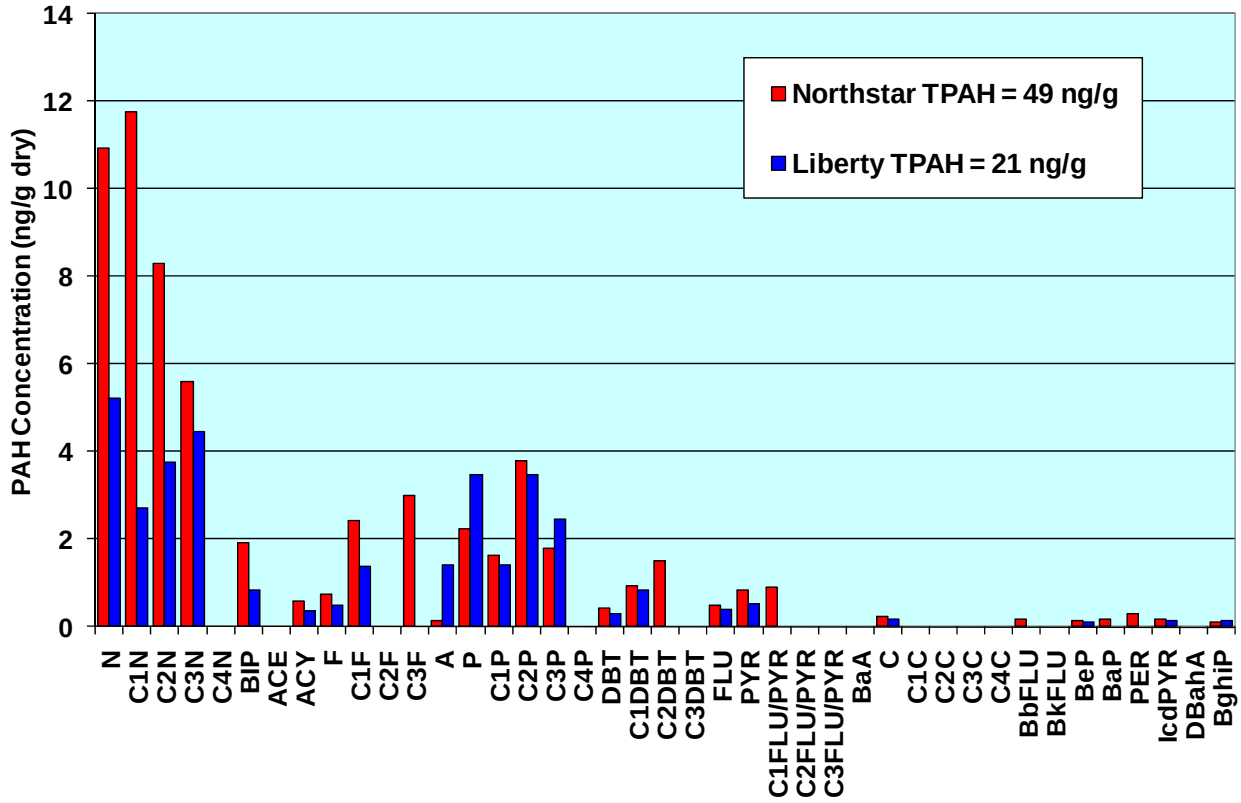


Figure 3-52. Profiles of mean concentrations of individual PAH in tissues of fish from Northstar and Liberty collected in 2006. From Neff et al. (2009).

3.3.2.2 Exposure Biomarkers in Fish Tissues

CYP1A staining in fish tissues. Several species of fish from Liberty and Northstar were analyzed by immunohistochemistry for CYP1A activity in 2004 and 2006. Several fish tissues stained for CYP1A but there were significant differences in staining intensity only in hepatocytes of some species (Table 3-39). Highest CYP1A staining scores in hepatocytes were in Arctic cisco from Liberty in 2004 and in humpback broad whitefish and four horn sculpin in 2005. All scores were low (2 or lower with a test score range of 0 to 15).

Fish tissues from 5 sites (2 sites near Northstar, 2 near Liberty, and 1 reference site east of Liberty) were stained for CYP1A activity in 2001(Spies et al., 2003). There was low to moderate staining of hepatocytes and gut mucus epithelium, but not other tissues, in most fish from all 5 sites. Hepatocyte staining scores were highest in four horn sculpin from Point Brower (near Liberty) and Stump Island (near Northstar). Staining scores in gut mucous epithelium were highest in four horn sculpin from Point Brower and Bullen Point (reference site). Highest mean staining score was in gut mucous epithelium of four horn sculpin from Point Brower (mean score ~ 6.0). CYP1A staining intensity in arctic cod hepatocytes was correlated to concentrations of PCBs in whole fish tissues. CYP1A staining intensity in four horn sculpin gut mucus epithelium was correlated to concentrations of total low molecular weight PAH in the whole fish tissues. There were no other statistically significant correlations.

Table 3-39. Immunohistochemical staining for CYP1A of hepatocytes of fish collected in 2004 at three Liberty, Northstar, and Tigvariak Island (reference site) and in 2005 at Liberty and Northstar. Scaled score range is 0 – 15. n = number of samples. From Neff et al. (2009).

Fish Species	Station	Tissue	CYP1A Staining		Sig. Diff.
			n	Mean Scaled Score ± SD	
2004					
Arctic cisco	Liberty	Hepatocyte	3	2.00 ± 0.87	Liberty > Northstar
	Northstar	Hepatocyte	8	0.0	
Least cisco	Liberty	Hepatocyte	5	0.60 ± 0.82	Liberty > Tigvariak, Northstar
	Northstar	Hepatocyte	8	0.0	
	Tigvariak	Hepatocyte	7	0.0	
Arctic cod	Northstar	Hepatocyte	4	0.0	NS
	Liberty	Hepatocyte	3	0.0	
	Tigvariak	Hepatocyte	6	0.17 ± 0.41	
Four Horn Sculpin	Liberty	Hepatocyte	6	0.50 ± 1.22	NS
	Tigvariak	Hepatocyte	10	1.50 ± 1.87	
2005					
Humpback broad whitefish	Northstar	Hepatocyte	9	1.5 ± 1.3	Northstar > Liberty
	Liberty	Hepatocyte	7	0.21 ± 0.57	
Four horn sculpin	Northstar	Hepatocyte	2	1.5 ± 2.1	NS
	Liberty	Hepatocyte	1	3.0	

NS, no significant difference.

The CYP1A staining data for 2001, 2004, and 2005 are consistent in showing low-level staining in several fish tissues, with no significant trends among fish species or sampling locations. Fish throughout the ANIMIDA study area apparently are being exposed to very low levels of CYP1A-inducing chemicals, possibly of several types and sources, including petroleum PAH and several organochlorine compounds (Spies et al., 2003).

Fluorescent aromatic compounds (FACs) in fish bile. When fish metabolize PAH and certain other nonpolar organic compounds, the polar metabolites are complexed with soluble compounds and excreted in the bile. The PAH metabolites are aromatic and fluoresce strongly at wavelengths characteristic of different conjugated aromatic structures. Thus, concentrations of fluorescent aromatic compounds (FACs) in bile are good biomarkers of exposure of fish to PAH in the water or food. Two-ring (e.g., naphthalenes), three-ring (e.g., phenanthrenes), and four- through six-ring PAH metabolites (e.g., benzo(a)pyrene) fluoresce at different wavelengths and usually are quantified as naphthalene equivalent, phenanthrene equivalent, and benzo(a)pyrene equivalent FACs.

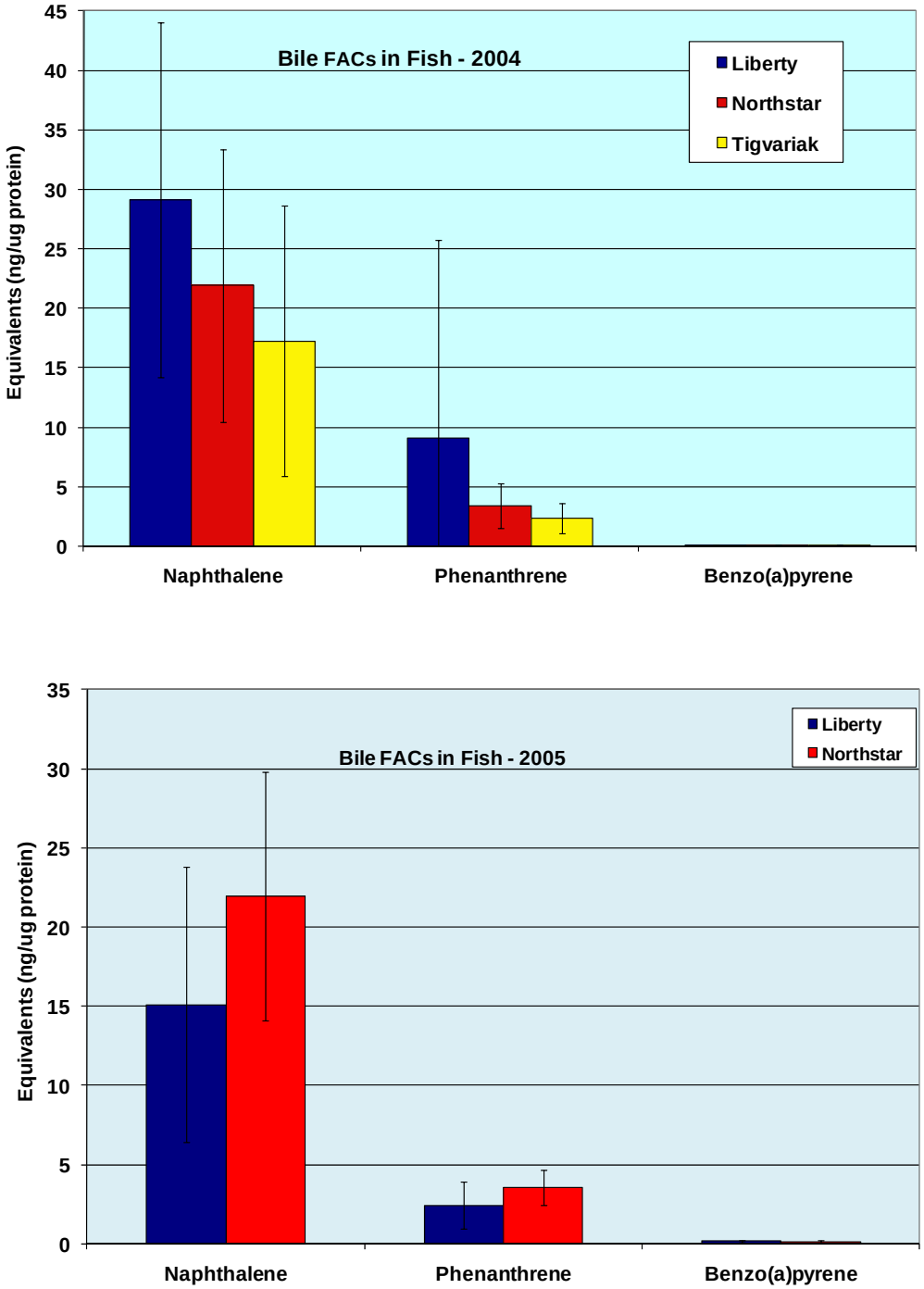


Figure 3-53. Mean and SD concentrations of fluorescent aromatic compounds (FACs) in bile of fish collected in three areas in the Beaufort Sea in 2004 (top) in the Northstar and Liberty areas in 2005 (bottom). Concentrations of naphthalene, phenanthrene, and benzo(a)pyrene equivalents are ng/µg bile protein (= µg/mg protein).

Concentrations of FACs were low in most of the 56 fish bile samples analyzed in 2004 (Figure 3-53). The protein-normalized metabolite concentrations have a much smaller range of variation, particularly for samples that have relatively higher naphthalene-equivalent metabolite concentrations. The protein-normalized naphthalene-equivalent concentrations ranged from 1.9 to 57 µg/mg protein. Normalized values for phenanthrene and benzo(a)pyrene (BaP) equivalents ranged from 0.14 to 77 µg/mg protein and 0.01 to 0.23 µg/mg protein, respectively (Figure 3-51).

Concentrations of naphthalene-equivalent and phenanthrene-equivalent bile FACs were lower in most of the 30 fish bile samples analyzed in 2005 than in those analyzed in 2004 (Figure 3-53). BaP-equivalent concentrations in bile of fish collected in 2005 were slightly higher than in bile of 2004 fish. Protein-normalized naphthalene-equivalent bile FACs ranged from 0.8 to 36.2 µg/g protein, normalized phenanthrene equivalents ranged from 0.1 to 5.2 ng/µg protein, and BaP equivalents ranged from 0.03 to 0.38 µg/g protein. There was not a significant difference in concentrations of the three bile FACs concentrations in fish from Liberty and Northstar. As with the 2004 FAC data, the protein-normalized bile FAC concentrations in fish collected near Northstar and Liberty in 2005 were similar to bile FAC concentrations in fish from contaminated and clean marine areas of the Pacific Northwest (Meador et al., 2008; Myers et al., 2008).

Phenanthrene-equivalent and BaP-equivalent bile FACs were measured in 57 samples of bile from 5 species of fish collected in 2001 at 5 locations in the Beaufort Sea as part of Task 8 of the ANIMIDA Project (Spies et al., 2003). FAC concentrations were not normalized to bile protein. Mean concentrations of phenanthrene-equivalent and BaP-equivalent FACs ranged from 0.05 to 12 µg/g and 0.02 to 0.32 µg/g, respectively, in the different fish species. The highest mean phenanthrene-equivalent FAC concentration was in arctic cod from Liberty; the highest mean BaP-equivalent FAC concentration was in arctic cisco from Stump Island (between Northstar and West Dock). Both phenanthrene-equivalent and BaP-equivalent bile FAC concentrations in Beaufort Sea fish were lower in 2001 than in 2004 and 2005. The bile FAC data for the 3 years indicate that fish in coastal waters of the Beaufort Sea development area are being exposed to low concentrations of low and high molecular weight PAH.

3.3.2.3 Hydrocarbons in Tissues of Indigenous Clams, Amphipods, Isopods, and Mysids

Soft tissues of clams (*Astarte montagui* and *Cyrtodaria kurriana*) and amphipods (*Anonyx nugax*) collected at different locations in the Beaufort Sea during cANIMIDA in 2004, 2005, and 2006 were analyzed for PAH, saturated hydrocarbons (SHC), and sterane/triterpane biomarkers (StTr). Isopods (*Saduria sabini*) and mysids (*Mysis* sp) were collected opportunistically and were analyzed for PAH.

PAH. Indigenous clams (*Astarte montagui* and *Cyrtodaria kurriana*) and three taxa of crustaceans (amphipods, isopods, and mysids) collected at Liberty, Northstar, and at reference stations contained similar concentrations of TPAH in any one year of the project, with lowest concentrations in all species in 2005 (Table 3-38). As expected, mean TPAH concentrations in whole fish tissues were lower each year than in the four taxa of marine invertebrates, because of the greater ability of fish than mollusks and crustaceans to metabolize and excrete PAH (Neff, 2002a). The mean TPAH concentration in amphipods from Liberty was higher than that in amphipods from Northstar in 2005; the mean TPAH concentration was significantly higher in amphipods from Liberty than in those from BSMP and Northstar in 2006 (Table 3-38).

The PAH assemblage in amphipods, isopods, mysids, and clams was dominated by alkylnapthalenes and alkylphenanthrenes, consistent with a predominantly petroleum source for the PAH in the invertebrate tissues (Figures 3-54 and 3-55). The most abundant five- through six-ring PAH in tissues of all four taxa was perylene, a predominantly biogenic PAH derived from diagenesis of organic matter of plant origin in anoxic sediments (Venkatesan, 1988). This may indicate that eroding coastal peat (high in perylene) may be important in the food web leading to these mollusks and crustaceans.

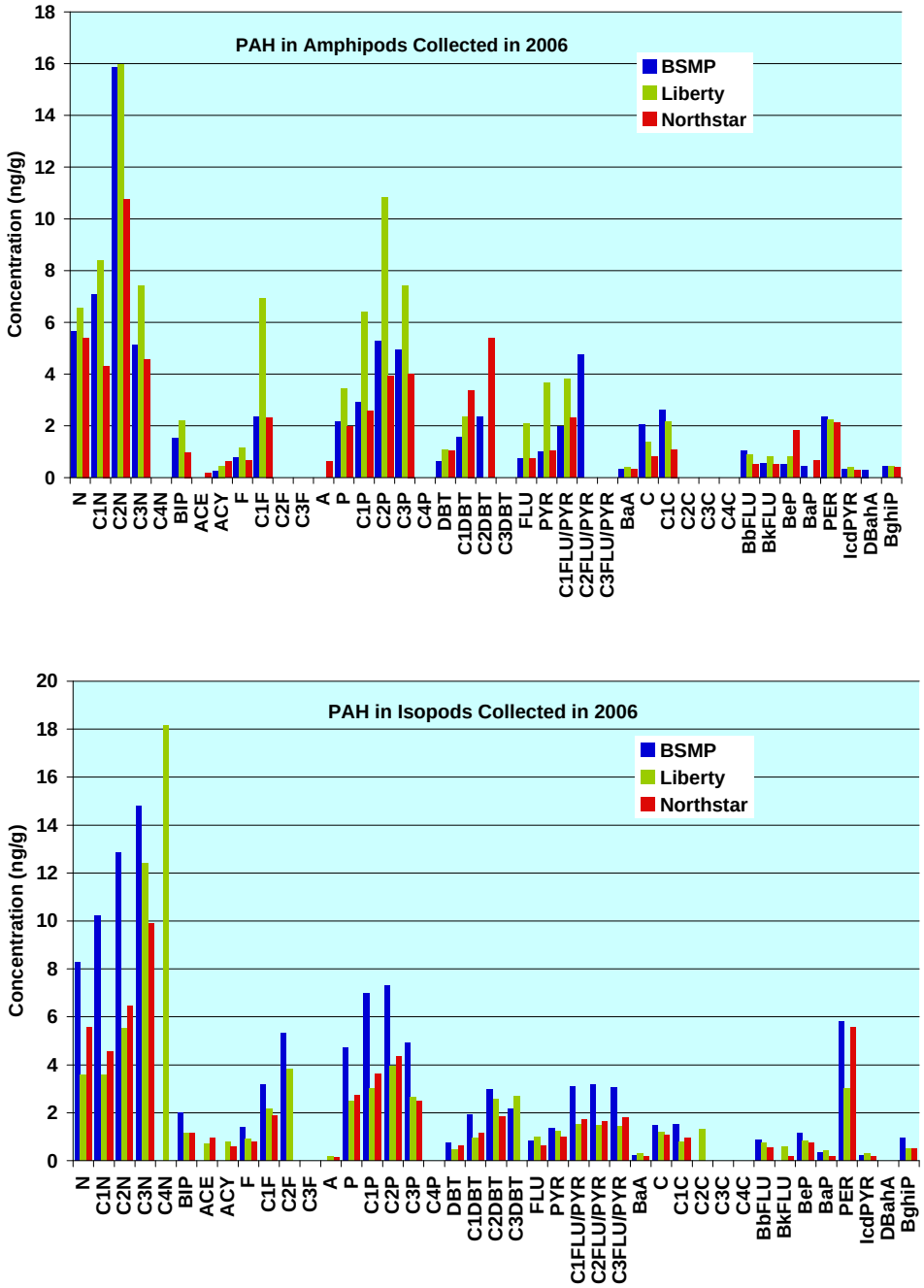


Figure 3-54. The PAH profile in tissues of amphipods and isopods collected at BSMP, Liberty, and Northstar in 2006. From Neff et al. (2009).

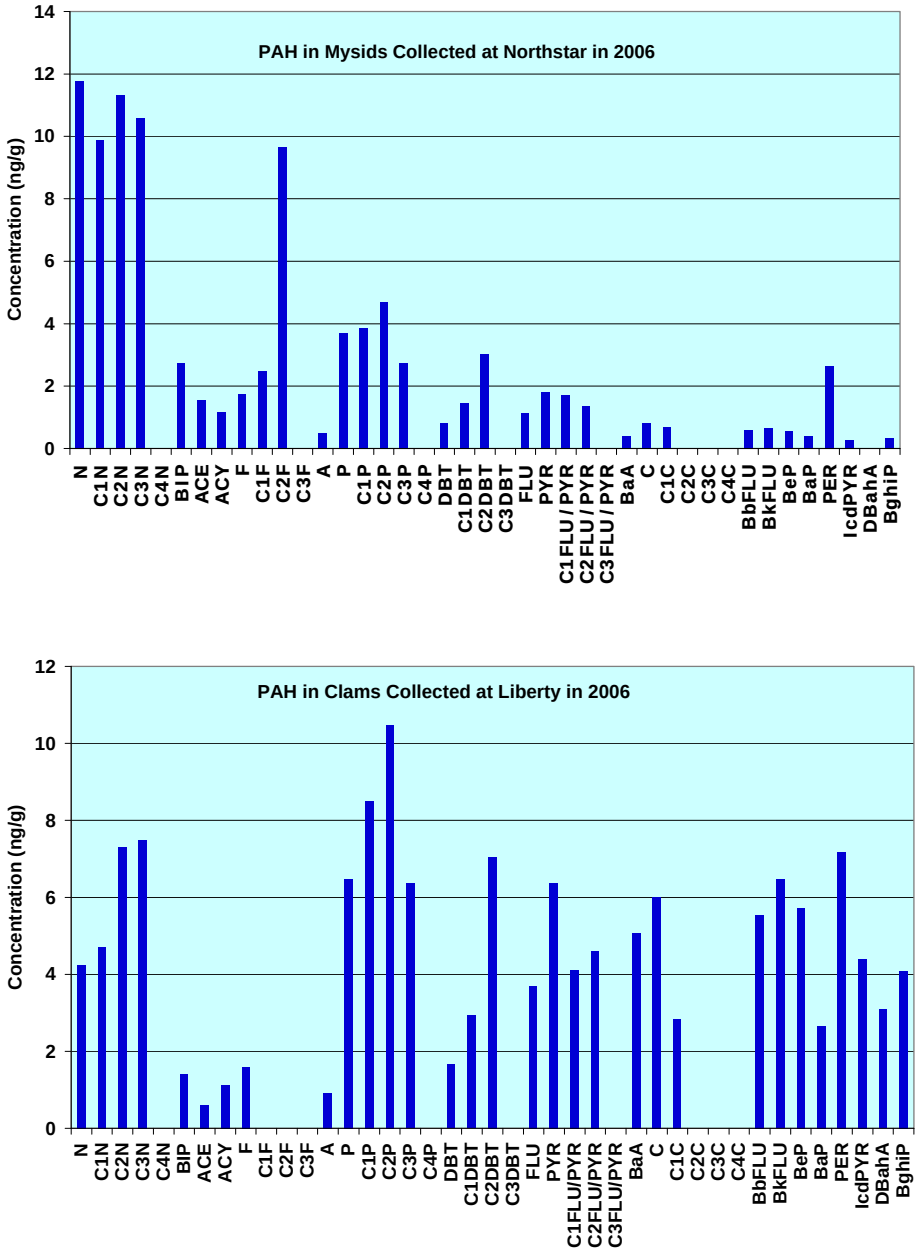


Figure 3-55. The PAH profile in tissues of mysids collected at Northstar (top) and clams collected at Liberty (bottom) in 2006. From Neff et al. (2009).

SHC. The saturated hydrocarbon data yielded some information that, with the TPAH and St/Tr data, was useful in the food chain conceptual model that was developed as part of this task. Total SHC concentrations were very high in tissues of amphipods, clams, and deployed mussels (Tables 3-38 and 3-40). Most of the SHC in amphipods, but not in clams or deployed mussels, was a single isoprenoid hydrocarbon, pristane. Pristane is present in petroleum, but its main source in the marine environment is from zooplankton, particularly copepods of several genera, including *Neocalanus* and *Pseudocalanus*, the dominant zooplankton in Beaufort Sea waters in most seasons (Horner and Murphy, 1985).

Table 3-40. Concentrations of total PAH, total SHC, and total St/Tr in amphipods (*Anonyx nugax*) sampled at 23 sites in 5 monitoring areas in 2006. n = number of samples. Concentrations are ng/g dry wt. From Neff et al. (2009).

Hydrocarbon	n	Location	Mean	SD	Range
Total PAH	2	Liberty	92.2	26.6	73.4 – 111
	10	Northstar	41.3	27.4	19.7 – 114
	2	West Dock	103	19.6	83.6 – 123
	2	Boulder Patch	70.9	16.5	54.4 – 87.4
	7	BSMP	60.9	14.4	34.8 – 80.1
Total SHC	2	Liberty	66,400	37,700	39,700 – 93,100
	10	Northstar	33,800	20,100	13,700 – 71,700
	2	West Dock	25,900	732	25,200 – 26,700
	2	Boulder Patch	145,500	8,300	137,000 – 154,000
	7	BSMP	90,800	77,600	26,100 – 249,000
Pristane	2	Liberty	48,100	36,600	22,300 – 74,000
	10	Northstar	24,700	18,800	6,400 – 61,000
	2	West Dock	15,600	1,020	14,600 – 16,600
	2	Boulder Patch	114,000	22,600	91,400 – 136,600
	7	BSMP	34,000	34,000	1,970 – 88,500
Total StTr	2	Liberty	6.70	3.74	2.96 – 10.45
	10	Northstar	1.09	2.28	0 – 7.48
	2	West Dock	0	---	0
	2	Boulder Patch	10.5	6.66	3.39 – 16.7
	7	BSMP	13.42	16.45	0 – 52.6

Calanoid copepods bioaccumulate phytol, a monounsaturated diterpenyl alcohol that is esterified with chlorophyll, in their phytoplankton food and convert it to pristane; the pristane accumulates to high concentrations in lipid droplets in the copepods (Avigan and Blumer, 1968). Pristane is readily bioaccumulated by the many species of marine invertebrates, fish, birds, and mammals that rely on copepods or their predators for food (Short, 2005). Short (2005) showed that mussels in Prince William Sound, AK, bioaccumulate pristane from fecal material produced by juvenile pink salmon that feed primarily on *Neocalanus* and not from copepod feces or dissolved pristane in the ambient water. *Neocalanus* from Prince William Sound contain 4000 to 8000 μg/g pristane (Short, 2005). Pristane does not accumulate in marine sediments, but apparently is biodegraded rapidly at the sediment/water interface (Prahl and Carpenter, 1984). The amphipods sampled in this study (*Anonyx nugax*) are carnivores/scavengers that consume any carrion that settles to the sea floor and have been observed preying directly on pelagic copepods near the ice edge in the Barents Sea (Werner et al., 2004). Highest pristane concentrations were in amphipods collected in the Boulder Patch, a highly productive and biodiverse area north of the Liberty Prospect (Table 3-40). Lowest concentrations were in amphipods from Harrison Bay, suggesting that the pristane in amphipods doesn't come primarily from peat in river runoff.

Amphipods also may bioaccumulate pristane from ingestion of detritus that accumulates at the sediment/water interface. Pristane is present at low concentrations in peat, which is eroding into coastal waters from shoreline sediments and upland soils (Steinhauer and Boehm, 1992). Peat collected from four rivers emptying into the Beaufort Sea contained 22 to 84 ng/g pristane. The amphipods probably accumulate pristane from ingestion of copepods and detritus, derived from dead copepods and zooplanktivorous fish, and from eroded peat. Clams may be feeding on a different fraction of the benthos. The indigenous clams, *Astarte* and *Cyrtodaria*, occupy sandy nearshore sediments and finer shallow bay and river mouth sediments, respectively, and may be feeding on organic particles in interstitial water and at the water/sediment interface (Bernard, 1979).

StTr. Concentrations of St/Tr, often used as tracers of crude oil sources, were low in all benthic invertebrates analyzed; amphipods, clams, and deployed mussels. The small amounts present may be from terrestrial plant materials, detritus, peat, or petroleum. The StTr profiles in the invertebrate tissues had some resemblance to the StTr profiles in Colville River peat, but little resemblance to the StTr in Northstar crude oil. Both recent and fossil biomarkers were present in the tissues, indicating that they were bioaccumulating hydrocarbons from organic detritus, peat, and possibly petroleum. Amphipods, mysids and clams also contained high concentrations of the biogenic PAH, perylene, which is abundant in Coleville River peat (Figure 3-23). The tissue residue data for PAH, SHC, and StTr indicate that hydrocarbons in tissues of nearshore benthic animals from the development area are derived in part from organic matter entering the Beaufort Sea from nearby rivers and also from coastal erosion. Contributions from the Northstar Development are negligible.

Hydrocarbons in Amphipods and Clams from ANIMIDA (2000 and 2002). PAH, SHC, and StTr were measured in soft tissues of amphipods (*Anonyx nugax*) and clams *(Astarte montagui* and *Cyrtodaria kurriana*) in 2000 and 2002 as part of Task 2 of ANIMIDA (Brown et al., 2004). Sampling locations were similar to those used in this investigation and were primarily near the Northstar Development, the Liberty Prospect, and at a few locations in the BSMP. The results of these analyses are compared to those for 2004, 2005, and 2006 in Table 3-41.

Mean concentrations of TPAH were similar in all years except 2005 in tissues of amphipods and clams from the Beaufort Sea development area (Table 3-41). TPAH concentrations in both taxa were lower in 2005 than in other years. The mean TPAH concentration in amphipods declined each year between 2000 and 2006; this trend was not observed in clams. Clams (*Cyrtodaria kurriana*) collected off the Kuparuk River in Gwydyr Bay (station 5F) in 2000 and 2002 contained higher TPAH concentrations (195 and 175 ng/g dry wt) than the *Astarte montagui* collected in 2000 and 2002 further offshore.

Mean concentrations of TSHC were high and extremely variable, both within a year and from one year to another, in tissues of both amphipods and clams (Table 3-41). Highest TSHC concentrations in both taxa were in animals collected in 2004 and lowest concentrations were in animals collected in 2005. In any year, TSHC concentrations were higher in amphipod tissues than in clam tissues. Most of this difference was due to much higher pristane concentrations in amphipods than in clams.

Mean StTr biomarker concentrations were roughly similar in all years except 2005 in amphipods (Table 3-41). Mean biomarker concentrations tended to decline with time in clam tissues and were not detected in 2006.

Table 3-41. Mean, SD, and range of concentrations of TPAH, TSHC, and StTr in soft tissues of amphipods (*Anonyx nugax*) and clams (*Astarte montagui* and *Cyrtodaria kurriana*) collected from the Beaufort Sea in 2000 and 2002 (ANIMIDA Task 2) and 2004, 2005, and 2006 (cANIMIDA Task 5). Concentrations are ng/g dry wt (data for 2000 and 2002 were converted from wet wt. by multiplying by 5, based on ~89% moisture). From Brown et al. (2005) and Neff et al. (2009).

Hydrocarbon	Year	Amphipods		Clams	
		Mean ±SD	Range	Mean (SD)	Range
TPAH	2000	85.8 ± 18.4	60.0 – 115	90.4 ± 54.4	37.0 - 195
	2002	95.6 ± 41.6	55.0 – 175	80.6 ± 47.8	48.0 - 175
	2004	68.2 ± 33.8	39.6 – 143	95.8 ± 52.6	42.7 - 168
	2005	25.4 ± 13.5	8.25 – 50.0	38.4 ± 15.1	21.8 – 51.2
	2006	59.6 ± 29.8	19.7 – 123	141 ± 40.9	100 - 182
TSHC	2000	55,800 ± 45,300	0 – 130,000	6000 ± 8580	0 – 22,000
	2002	113,000 ± 71,800	23,500 – 260,000	14,100 ± 1390	12,500 – 16,000
	2004	444000 ± 8540	29800 - 54100	26,800 ± 14,400	678 – 39,700
	2005	31,600 ± 18,400	5171 – 67,100	1510 ± 517	1030 - 2230
	2006	63,000 ± 57,100	13,700 – 249,000	12,600 ± 2410	10,200 – 15,000
StTr	2000	18.8 ± 10.2	10.0 – 40.5	14.8 ± 3.67	10 - 20
	2002	10.8 ± 2.46	7.5 – 16.0	8.40 ± 3.97	5.00 – 15.5
	2004	12.2 ± 3.45	8.36 – 17.8	8.54 ± 5.37	2.92 – 17.1
	2005	6.22 ±1.89	4.53 – 8.02	1.72 ± 2.43	0 – 5.16
	2006	29.0 ± 11.8	20.7 – 55.0	0	0

3.3.2.4 Hydrocarbons in Deployed Mussels and SPMDs

Deployed Mussels. Mussels (*Mytilus trossulus*) collected each year from a mussel mariculture operation, certified by the state for mussel harvesting, in Port Chatham at the mouth of Lower Cook Inlet, were deployed for approximately two weeks at Northstar, Liberty, and BSMP, to monitor bioavailability of PAH, SHC, and StTr in the water column. Unfortunately, reference mussels (collected at Port Chatham with mussels destined for deployment, but frozen for analysis immediately or after shipment to the North Slope), contained PAH, SHC, and StTr at concentrations similar to those in mussels following deployment in the Beaufort Sea (Table 3-42). In each year, the mean TPAH concentration in reference mussels was higher than that in mussels that were deployed for about two weeks at the three Beaufort Sea locations. Mean concentrations of TSHC and pristane were higher than or about the same as in deployed mussels. StTr concentrations were low in both reference and deployed mussels.

Table 3-42. Mean Concentrations of total polycyclic aromatic hydrocarbons (TPAH), total saturated hydrocarbons (TSHC), pristane, and steranes/triterpanes (StTr) in tissues of reference and deployed mussels and of TPAH in blank and deployed SPMDs used to monitor bioavailability of hydrocarbon concentrations in the water column of the Alaskan Beaufort Sea in 2004 through 2006. From Neff et al. (2009).

Matrix	Analytes	Location	Mean (SD) TPAH Concentration (ng/g dry wt or ng/SPMD)		
			2004	2005	2006
Deployed Mussels	TPAH	Reference	227 ± 34.9	32.8 ± 27.0	164 ± 36.2
		Northstar	148 ± 45.8	13.0	91.6 ± 5.18
		Liberty	92.8	24.8 ± 14.7	134 ± 6.74
		BSMP	157 ± 46.8	31.5 ± 1.46	52.7
	TSHC	Reference	6051 ± 522	3632 ± 151	23,159 ± 2294
		Northstar	7624 ± 2494	3381	21,024 ± 3599
		Liberty	5725	2689 ± 384	16,040 ± 3145
		BSMP	6246 ± 123	3137 ± 380	16,033
	Pristane	Reference	637 ± 63.4	270 ± 10.9	627 ± 86.0
		Northstar	365 ± 79.5	273	671 ± 180
		Liberty	337	146 ± 29.1	1153 ± 214
		BSMP	413 ± 162	290 ± 106	850
	StTr	Reference	12.2 ± 3.79	5.87 ± 5.87	ND
		Northstar	27.2 ± 16.2	6.9	ND
		Liberty	13.5	ND	ND
		BSMP	14.1 ± 6.43	ND	ND
SPMDs	TPAH	Blank	699 ± 55.0	No data	No data
		Northstar	750 ± 182	No data	No data
		Liberty	945	No data	No data
		BSMP	606 ± 155	No data	No data

ND, not detected.

Concentrations of individual PAH in the PAH assemblage in the deployed mussels were different than that in the reference mussels, indicating that some exchange of PAH between Beaufort Sea water and suspended particles and the mussel tissues had occurred during the deployment.

The limited net bioaccumulation of PAH, SHC, and StTr by deployed mussels could have been due to a too short deployment period to allow for equilibration between Beaufort Sea water and mussel tissues or to stressful environmental conditions for Cook Inlet mussels in the Beaufort Sea. A deployment period of at least one month usually is recommended to allow tissue concentrations of non-polar organic chemicals, such as PAH, to equilibrate with concentrations in the ambient water and mussel food, particularly in cold water (Salazar and Salazar, 1995;

Durell et al., 2006). The deployment period for mussels in the Beaufort Sea in 2004, 2005, and 2006 was limited to approximately two weeks because of logistic constraints. This may have been insufficient time for equilibration of some PAH, particularly 3- through 6-ring PAH that equilibrate slowly because of their low aqueous solubilities (Neff, 2002a). However, mussels were deployed near Northstar and at a reference site for three weeks in 2002 as part of the ANIMIDA Project. TPAH concentrations in the mussels from the longer 2002 deployment were similar to those in mussels deployed for 2 weeks in 2004, 2005, and 2006. Thus, a short deployment period doesn't completely explain the lack of bioaccumulation of PAH by the deployed mussels.

The short deployment period probably combined with unsatisfactory environmental conditions to limit PAH equilibration between mussel tissues and Beaufort Sea water. Ambient water temperature and salinity in July and August within a few meters of the bottom at the locations where mussels were deployed usually was in the range of -1.5ºC to +2ºC and 20‰ to 32‰, respectively. *Mytilus trossulus* is the most cold-tolerant of the mytilid bivalves; they can tolerate temperatures at least as low as -2ºC (Cusson et al., 2005). However, clearance rate, food absorption efficiency, and metabolic rate, measured as the scope for growth, decreases to low levels in *M. trossulus* at a temperature of - 1˚C; mussels transferred from + 4 or + 8˚C to - 1˚C decreased respiration and required more than 5 days to recover (Cusson et al., 2005). Feeding also is depressed markedly by high suspended sediment concentrations and low phytoplankton concentrations (Thompson, 1984). The salinity of the near-bottom water of the Beaufort Sea is in the optimum range for *M. trossulus* and similar to what it is at Port Chatham. Thus, since the Port Chatham mussels were not acclimated for more than a few days to Beaufort Sea conditions before deployment, low ambient temperature and high suspended sediment loads, probably coupled with a short deployment time may have limited PAH bioaccumulation (and depuration) in the deployed mussels. However, mussels from Port Chatham that were deployed near Northstar and at a reference area in 2002 as part of the ANIMIDA Project exhibited byssal thread growth, an indication that they were active during deployment. Activity probably was slowed enough to slow equilibration of hydrocarbons between Beaufort Sea water and food and tissues of deployed mussels. Future deployments should be for longer periods of time (preferably one month or more) with mussels that have been acclimated to low Beaufort Sea water temperatures for a few weeks.

SPMDs. SPMDs were deployed at three locations in the Beaufort Sea in 2004 to measure PAH in the water column. They produced little useful data because blank (unused) SPMDs contained about as much TPAH as deployed ones (Table 3-42). As with the deployed mussels, there was some evidence of exchange of some PAH between the ambient Beaufort Sea water and the SPMDs. PAH exchange probably was slowed by the low ambient temperatures and short deployment period. As with mussels, SPMDs and other passive samplers require deployment times of a month or more to reach equilibrium with dissolved PAH, particularly the higher molecular weight PAH, in the water column (Cornelissen et al., 2008). The dominant PAH in both blank and deployed SPMDs were naphthalenes; very little high molecular weight PAH were present, indicating limited equilibration and low concentrations of high molecular weight PAH in Beaufort Sea water. Therefore, SPMDs showed no advantage over mussels and they were not used in subsequent years.

SPMDs were deployed in 2002 at locations near the Northstar Development and at a reference site to the east as part of the ANIMIDA Project. Blank SPMDs from 2002 contained more than twice the amount of PAH contained in blank SPMDs from 2004 (1604 ng/SPMD versus 699 ng/SPMD). As in 2004, naphthalenes were the dominant PAH in both blanks and deployed SPMDs in 2002. Concentrations of most PAH in the SPMDs deployed in 2002 were higher than the concentrations of the corresponding PAH in SPMDs deployed in 2004, confirming that the blank PAH were masking any PAH analytes accumulated during deployment.

The combined SPMD and deployed mussel PAH data indicate that PAH concentrations were very low (probably lower than at Port Chatham) in Beaufort Sea water and suspended fine particulate matter. Amounts of PAH in SPMDs following deployment in the Beaufort Sea were lower than amounts in most SPMDs that had been deployed in the vicinity of offshore production platforms in the North Sea (Durell et al., 2006). Estimated TPAH concentrations in North Sea water, estimated from amounts of individual PAH in SPMDs that had been deployed for a month in the North Sea, range from about 4 to 25 ng/L at locations where the SPMDS contained amounts of TPAH similar to those in the SPMDs deployed in the Beaufort Sea. The background concentration of TPAH in coastal estuarine and marine waters is about 5 to 10 ng/L (Neff, 2002a). Beaufort Sea water probably contained similar or lower TPAH concentrations.

Summary. As discussed above, the PAH, SHC, and StTr profiles in animal tissues and SPMDs from the Beaufort Sea are consistent with a primarily petrogenic source. Thus, marine biota from throughout the production area of the Beaufort Sea are being exposed to low concentrations of fossil hydrocarbons. These PAH, SHC, and StTr may be coming from aerial deposition (arctic haze and combustion plumes offshore and onshore oil and gas operations), small boat fuel leaks, small releases from production activities on and offshore, and runoff from land, mainly via rivers (Steinhauer and Boehm, 1992), particularly from erosion of peat from river banks and the shore. TPAH concentrations were not higher in marine animals collected near the Northstar Development than at other areas of the Beaufort Sea, indicating that the offshore operations were not a significant source of PAH in the animal tissues. The TPAH concentrations in tissues of Beaufort Sea invertebrates and fish are well below concentrations that might pose a health risk to fish, wildlife, and humans that might consume marine foods from the Beaufort Sea (Neff et al., 2006).

3.4 Conceptual Model of Bioaccumulation and Trophic Transfer of Chemicals in the Beaufort Sea Food Web

A conceptual food web model is useful as a tool for designing scientifically defensible studies of the sources and distribution of chemical contaminants in biological communities in the coastal Alaskan Beaufort Sea. It provides the basis for development of testable null hypotheses about relationships among physical and chemical disturbance of marine ecosystems by offshore oil development and production operations, climate change, and ecological changes.

3.4.1 Contaminant Sources in the Beaufort Sea

Metals and hydrocarbons (SHC, PAH, St/Tr) are natural ingredients of the Alaskan Beaufort Sea environment. Large amounts of metals and hydrocarbons enter the Beaufort Sea each year associated with suspended particles in river runoff (See Section 3.1.1 above) (Yunker et al., 1991, 1996; Yunker and MacDonald, 1995; Steinhauer and Boehm, 1992; Trefry et al., 2003,

2004a,b, 2009; Rember and Trefry, 2004). Additional metals and hydrocarbons enter coastal waters and sediments of the Beaufort Sea from dry and wet deposition from the atmosphere. The arctic aerosol over northern Canada and Alaska contains relatively high concentrations of metals, PAH, SHC, and other persistent organic pollutants (POPs) (Matsumoto et al., 1998; Muir et al., 1999; Cheng and Schroeder, 2000). Climate change in the Arctic results in changing wind patterns that in turn alter the patterns and masses of contaminants deposited to the Arctic seas from aerosols (MacDonald, et al., 2005).

Metals and petroleum hydrocarbons also may enter coastal and offshore waters of the Beaufort Sea from coastal and offshore oil and gas operations (Steinhauer and Boehm, 1992; Trefry et al., 2003). The major sources of metals in Beaufort Sea sediments from oil development activities are causeway and drilling island construction and drilling mud and cuttings discharges (Northern Technical Services, 1982; Naidu et al., 2001; Neff, 2002b, 2010). Island construction material usually has a metal concentration similar to that of natural soils and sediments, but sometimes may contain elevated concentrations of some metals (e.g., Crippen et al., 1980).

The metals frequently found in drilling muds and cuttings that are of greatest concern because of their potential toxicity and/or abundance in drilling muds include arsenic, barium, chromium, cadmium, copper, iron, lead, mercury, nickel, and zinc. Only barium, chromium, iron, lead, and zinc, sometimes are present in drilling mud/cuttings solids at concentrations significantly higher (> 100-fold) than concentrations in clean marine sediments (Neff, 2005, 2010). However, most of these metals are present as insoluble sulfide inclusions in drilling barite and are not bioavailable to marine animals (Neff, 2008).

PAH also have natural and anthropogenic sources (Neff, 2002a). The major sources of the complex PAH assemblages found in most North Slope and Beaufort Sea soils and sediments are combustion soot and fossil hydrocarbon mixtures (peat, coal, and petroleum). There are vast peatlands, covering an area larger than the area of the state of California, on the Alaskan North Slope (Jones and Yu, 2010). Most of this peat is more than 8900 years old. These peat deposits gradually erode or decompose to POC and DOC, and are carried to the Beaufort Sea in river flows and coastal erosion. The rate of loss of tundra peat is expected to increase with global warming. PAH from these sources enter the Beaufort Sea in natural seeps, petroleum spills, river runoff, coastal erosion, and aerial deposition.

Oil development and production activities on the North Slope also contribute PAH to coastal waters of the Beaufort Sea. In the past, the major sources of PAH inputs to the environment from oil and gas activities were permitted discharges of drilling mud/cuttings and produced water (Neff, 2002a, 2005, 2010). However, produced water is not discharged to coastal waters of the Alaskan Beaufort Sea; it is reinjected. Currently, water based drilling muds are the only ones used and discharged offshore in the Beaufort Sea. The current NPDES permit for Alaska allows discharge of water based drilling muds and cuttings to Federal waters of the Beaufort Sea if they meet effluent limitation guidelines. Drilling mud discharges usually are limited to winter discharges onto the ice in deep water. The most recent drilling mud and cuttings discharges to State/Federal lease tracts in the Beaufort Sea probably were from the McCovey exploratory well, drilled in 2002 northeast of the Northstar production facility. An estimated total of 939 m^3 of water based drilling muds and cuttings were discharged from McCovey to the ice (Table 1-3). Drilling muds and cuttings were not discharged during development drilling at Northstar.

Water based drilling muds, if used and discharged in accordance with regulations; contribute only small amounts of hydrocarbons to the local marine environment. Completion fluids that usually are used to drill the hydrocarbon-bearing formation are not permitted for discharge because they often contain free oil. They may be reinjected if a suitable geologic formation is available or transported to shore for upland disposal.

PAH also are emitted to the atmosphere by flaring waste gases at production platforms or gas-treatment facilities. A total of 162,321 million standard cubic feet (mscf) of waste gas was flared at Northstar in 2004, almost sevenfold lower than peak flaring of more than 1,100,000 mscf in 2002. (Alaska Oil and Gas Conservation Commission, 2005). The PAH concentration in the flare exhaust is not known. Hydrocarbons, including PAH, may also be emitted in diesel exhaust and fugitive emissions from oil industry support vessels. Accidental drilling mud/cuttings, petroleum, and wastewater releases also are a potential source of PAH to the Beaufort Sea.

3.4.2 Bioaccumulation and Trophic Transfer of Metals and Hydrocarbons in the Beaufort Sea Food Web

There is concern that offshore oil and gas development may harm the Beaufort Sea marine environment by habitat alteration and by contamination of the local food web with harmful chemicals from accidental or intentional discharges from development and production activities. Marine invertebrates, fish, birds, and mammals living in the Beaufort Sea are able to bioaccumulate metals and PAH from the ambient seawater, from contaminated sediments, and from their food (Neff, 2002a). The concentrations of metals and PAH in tissues of marine animals are assumed to be at equilibrium with concentrations in the ambient water and food. Benthic invertebrates bioaccumulate contaminants primarily from solution in sediment pore water, overlying bottom water, and ingestion of sediment particles; benthic carnivores may also bioaccumulate contaminants from their food. Demersal and pelagic invertebrates, fish, birds, and mammals bioaccumulate the contaminants primarily from their food. Thus, a local increase in concentrations of metals and PAH in water or sediments due to oil development and production discharges may lead to an increase in the concentration of the contaminants in tissues of marine organisms in the local food web. As discussed above, the ANIMIDA/cANIMIDA Project has monitored intensively between 1999 and 2006 and has found no evidence of ecologically significant increases of concentrations of metals and hydrocarbons in Beaufort Sea sediments and tissues of marine animals.

None of the target PAH or metals is known to biomagnify in marine food webs (with the possible exception of arsenic and methylmercury) (Neff, 2002a,b; Dehn et al., 2006a,b). Some metals, such as cadmium, bioaccumulate continuously in certain tissues, such as kidneys, during the life of marine animals (Dehn et al., 2006a,b). The accumulated metals usually are in solid, non-bioavailable concretions, such as mercuric selenide in cetacean liver and solid cadmium concretions in walrus liver; this is not considered biomagnification (Neff, 2002a,b). This means that the concentrations of bioavailable metals and hydrocarbons do not increase “up the food chain” with highest concentrations in the top consumer, usually a marine bird or mammal. However, all the target contaminants are transferred through marine food webs; measured concentrations are lower in the whole predator tissues than in the whole prey tissues.

Arctic marine animals are about as sensitive as or slightly more sensitive than temperate and tropical species to petroleum and metals toxicity (Neff, 2002a; Perkins et al., 2003; Chapman

and Riddle, 2005). Thus, if chemicals from offshore oil development activities are bioaccumulated to high enough concentrations, they may cause adverse effects in the Beaufort Sea food web.

This conceptual model of bioaccumulation, trophic transfer, and effects was used as a basis for developing the objectives and study design for Task 5 of cANIMIDA. A major focus of this task is to develop the information needed to protect indigenous people and the subsistence resources upon which they rely from injury due to chemical contamination from offshore oil and gas operations. This conceptual model is being used to evaluate the possible bioaccumulation and food web transfer of metals and PAH derived from offshore oil and gas development activities in the Beaufort Sea. Sediments, benthic invertebrates (lower trophic level), and fish (higher trophic level) from the Beaufort Sea development area have been analyzed in the ANIMIDA and cANIMIDA Projects for several metals and PAH that are associated with oil development activities (See Section 3.3 above). Marine mammals and birds (the apex consumers: Figure 3-56) from the Beaufort Sea and other Arctic marine environments have not been analyzed for PAH. However, there is a large amount of data available on concentrations of several metals and organochlorine compounds in several species of marine birds and mammals from the Beaufort Sea (e.g., Honda et al., 1990; Zeisler et al., 1993; Mackey et al., 1995, 1996; Krone et al., 1999; Woshner et al., 2001, 2002; Hoekstra et al., 2002, 2003, 2005; Kucklick et al., 2002; Borga et al., 2004; Franson et al., 2004; Dehn et al., 2005, 2006a,b; Riget et al., 2005; O'hara et al., 1999, 2006). However, there are no published data on the concentrations of PAH in tissues of Arctic marine mammals from Arctic offshore oil development areas (i.e., Arctic Alaska, Canada, Greenland, the Norwegian and Russian Barents Sea, and the Russian Far East).

3.4.3 The Beaufort Sea Food Web

The harsh marine environment of the Beaufort Sea, with wide seasonal variations in light intensity, ice cover, freshwater input from rivers, and nutrient concentrations results in wide seasonal cycles of primary production, and complex, seasonally variable food webs (Walsh et al., 2005). Food web structure and carbon flow on the inner continental shelf of the Alaskan Beaufort Sea are different in the nearshore (inside the barrier islands) and offshore environments and are weakly linked (Figure 3-56). For example, although terrestrially derived peat makes a substantial contribution to available particulate organic carbon (POC) in the nearshore marine environment (lower left side of Figure 3-56), it contributes much less to offshore organic carbon fluxes (right side of Figure 3-56) (Schell, 1983; Dunton et al., 2006). For example, arctic cod in Beaufort Sea lagoons may derive up to 70 percent of their carbon from terrestrial carbon (mostly peat); offshore populations derive most of their carbon from zooplankton (Dunton et al., 2006).

The Beaufort Sea food web is a relatively simple one with relatively few abundant taxa at each trophic level (Figures 3-56 and 3-57). Nutrients to support primary production in the Alaskan Beaufort Sea are derived primarily from inflows from the Bering Sea, Anadyr Water (from the Russian Chukchi Sea), the Canadian Beaufort Sea, and upwelling from the Arctic Basin (Dunton et al., 2003, 2004). Primary production is pelagic (phytoplankton), epontic (living on the underside of sea ice), and benthic (micro- and macro-algae living on the sea floor: e.g., the Boulder Patch - See section 3.5 below). The epontic community along the seasonal ice edge may contribute substantially to overall pelagic production. Epontic microalgae support diverse communities of ice-associated meiofauna that help support spring zooplankton blooms (Carey and Montagna, 1982).

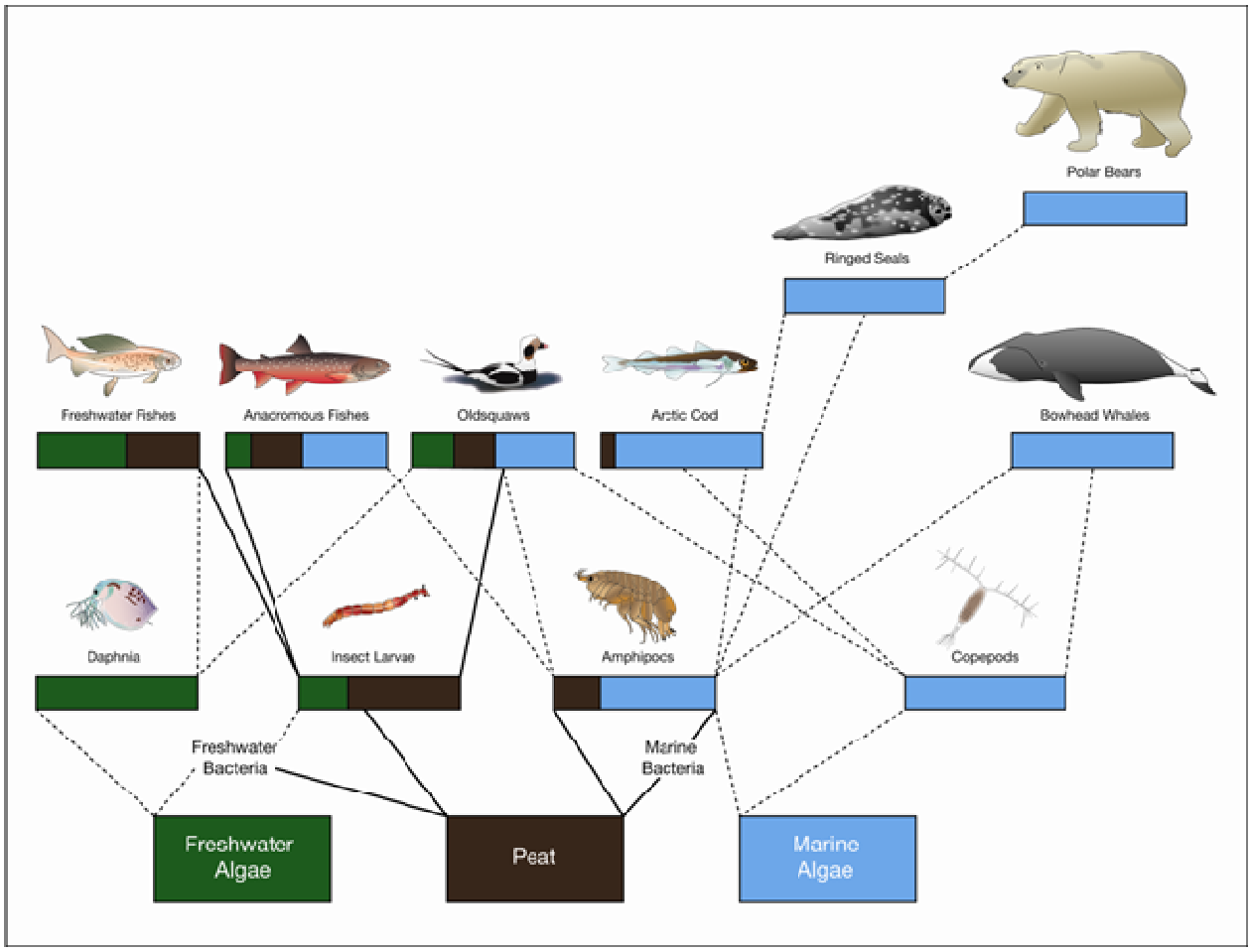


Figure 3-56. A generalized food web structure showing the sources of organic carbon, including peat, in the Alaskan Beaufort Sea coastal ecosystems. The shading of the rectangles below each taxon shows the relative contribution and pathway of carbon from freshwater algae, terrestrial peat, and marine algae in the food web. Food chain structure grades from near-shore, freshwater/estuarine on the left to offshore marine on the right. Modified from Schell et al. (1982).

Primary production, measured as chlorophyll *a* concentrations in surface waters, is lower in the Beaufort than in the Chukchi Sea (Dunton et al., 2003, 2004). Near-shore areas east of Barrow and off the Coleville River and Mackenzie River have the highest primary production in coastal and continental shelf waters of the Beaufort Sea. This probably is caused mainly by the large flux of organic carbon into the Canadian and Alaskan Beaufort Sea from rivers (Yunker et al., 2005; Elmquist et al., 2008; Holmes et al., 2008; Trefry et al., 2009; Magen et al., 2010). These regions of high productivity are import to fall-migrating bowhead whales.

Particulate organic carbon (POC), produced by primary producers (phytoplankton) or in runoff from land, may be consumed by primary consumers (mostly zooplankton), or exported to sediments or off the shelf (Wasserman et al., 2003; Moran et al., 2005). The POC supports blooms of zooplankton communities, dominated by calanoid copepods and euphausiids, which are consumed by bowhead whales.

In the nutrient rich northeastern Chukchi Sea, the fraction of primary production that is exported from the water column increases from about 15 percent in the spring to about 32 percent in the summer (Moran et al., 2005). POC flux to the benthos probably is lower in the nutrient-depleted Beaufort Sea (Dunton et al., 2003, 2004, 2006). Because of the lower POC flux, benthic biomass in the Beaufort Sea (average 33 g/m^2) is much lower than that in the Chukchi Sea (167 g/m^2) (Dunton et al., 2003, 2004). POC in sediments supports development of a rich benthic fauna that supports benthic feeders, such as some seals and many species of demersal fish, and results in strong benthic/pelagic coupling of nutrients (Figure 3-56). Sediments in the Beaufort Sea contain organic matter from both marine and terrigenous sources (Yunker et al., 2005; Trefry et al., 2009; Magan et al., 2010). This organic matter tends to sequester metals and hydrocarbons and is ingested by benthic fauna, facilitating bioaccumulation and trophic transfer of contaminants in the Beaufort Sea food web.

Global warming may dramatically change ecosystem dynamics, including the distribution of marine organisms and chemical contaminants in the Chukchi Sea. Environmental changes may include: 1) increased pelagic primary and secondary production during extended open-water conditions in the summer (based on surplus nutrients, currently underutilized); 2) reduced benthic and pelagic biomass in coastal/shelf areas (due to increased river runoff and resulting changes in salinity and turbidity; and 3) increased pelagic grazing and recycling in open-water conditions at the expense of the current benthic/pelagic coupling in part of the ice-covered shelf regions (due to increased pelagic consumption versus vertical flux) (Bluhm and Gradinger, 2008). These changes may benefit pelagic feeders, such as bowhead whales and some pinnipeds and marine birds, and harm benthic feeders such benthic-feeding pinnipeds and fish. It will also affect the trophic transfer and cycling of chemical contaminants in the Chukchi Sea food web.

Grainger (1965) identified two zooplankton communities in waters less than 100 m deep in the Alaskan Beaufort Sea. The community occupying Arctic surface water is dominated by coelenterates, ctenophores, and copepods. Dominant copepods include *Calanus hyperboreus, Calanus glacialis, Pseudocalanus minutus, Metridia longa,* and *Oithoma similes.* The second zooplankton community is associated in summer with warmer, less saline nearshore waters, primarily inside the barrier islands. Dominant copepods include *Limnocalanus macrouris, Acartia clausi, Eurytemora herdmani,* and *Derjugina tolli.* Calanoid copepods, primarily *Pseudocalanus,* are abundant under the sea ice during winter and early spring; they are replaced in early summer by cyclopoid and harpacticoid copepods, hydrozoans, amphipods, larvaceans and larval stages of planktonic and benthic invertebrates (Horner and Murphy, 1985). Griffiths and Thompson (2002) identified three zooplankton communities in waters out to 200 m off the eastern Alaskan Beaufort Sea (Camden Bay and eastward to the Canadian border). Copepods are dominant in all three communities, accounting for 50 to 75% of the total zooplankton biomass. Three species represent more than 85% of the total copepod biomass: *Calanus hyperboreus, C. glacialis,* and *Limnocalanus macrourus.* Calanoid copepods are the main prey of bowhead whales in the central and eastern Beaufort Sea.

Euphausiids (*Thysanoessa inermis* and *T. raschii*) are much less abundant than calanoid copepods in the eastern Beaufort Sea. However, they are seasonally abundant in the Chukchi Sea and western Beaufort Sea. Euphausiids are transported by deep-water currents from the Bering Sea, through the Chukchi Sea to waters off Barrow, and then into the western Beaufort Sea

(Berline et al., 2008). They are the main prey of bowhead whales that aggregate to feed off Barrow and in the Chukchi Sea during the fall migration.

The abundance and distribution of zooplankton is extremely variable in different seasons and years. Total zooplankton wet biomass in waters of the eastern Alaskan Beaufort Sea ranges from 170 to more than 383 mg/m^3 in different years; biomass is greater at depths of more than 10 m than at the surface (Griffiths and Thomson (2002). Wet biomass of zooplankton can be as high as 3,500 mg/m^3 in dense patches. The feeding threshold for bowhead whales may be as high as 800 mg zooplankton wet biomass/m^3 of seawater (Griffiths et al., 2002; MMS, 2006), highlighting the importance of dense zooplankton patches to bowhead whales.

These primary consumers are preyed on by a variety of secondary consumers (carnivores), including several species of anadromous and marine fish, marine birds, and marine mammals, including some ice seals (e.g., ringed, ribbon, and bearded seals) and baleen whales (bowhead whales) (Figure 3-57). Other marine fish, birds, and mammals consume primarily fish or other marine mammals (beluga whales, polar bears). Crustaceans, such as copepods, euphausiids, amphipods, isopods, and mysids, are abundant in coastal, estuarine waters where they are preyed upon heavily by several species of fish (Table 3-43). Many of the coastal fish in the Beaufort Sea feed primarily on small fish, particularly arctic cod (Frost and Lowry, 1984).

Table 3-43. Anadromous and marine fish collected for Task 5 of the cANIMIDA program from coastal waters of the Beaufort Sea and their food preferences. Data from Thorsteinson and Wilson (2006) and Craig et al. (1984).

Common Name	Scientific Name	Food Preferences
Marine Fish		
Arctic cod	*Boreogadus saida*	Mysids, amphipods, copepods
Four horn sculpin	*Myxocephalus quadricornis*	Amphipods, isopods, polychaetes
Arctic flounder	*Liopseta glacialis*	Demersal & benthic crustacea, polychaetes
Anadromous Fish		
Arctic char	*Salvelinus alpinus*	Mysids, small fish
Arctic cisco	*Coregonus autumnalis*	Mysids, larval & juvenile fish
Least cisco	*C. sardinella*	Mysids, amphipods
Broad whitefish	*C. nasus*	Chironomids, amphipods
Humpback broad whitefish	*C. pidschian*	Chironomids, amphipods

Arctic cod (*Boreogadus saida*) is considered a key species in the Beaufort Sea marine ecosystem (Lowry and Frost, 1981; Bradstreet et al., 1986). They are a major link between lower trophic level benthic and pelagic primary consumers and upper trophic level apex consumers, such as several species of marine birds, seals, and mammals (Figures 3-56 and 3-57; Tables 3-44, 3-45, and 3-46). They consume primarily gammarid amphipods, copepods, and mysids, and are consumed by many birds and mammals, including black kittiwakes, arctic terns, thick-billed murres, black guillemots, and glaucous gulls.

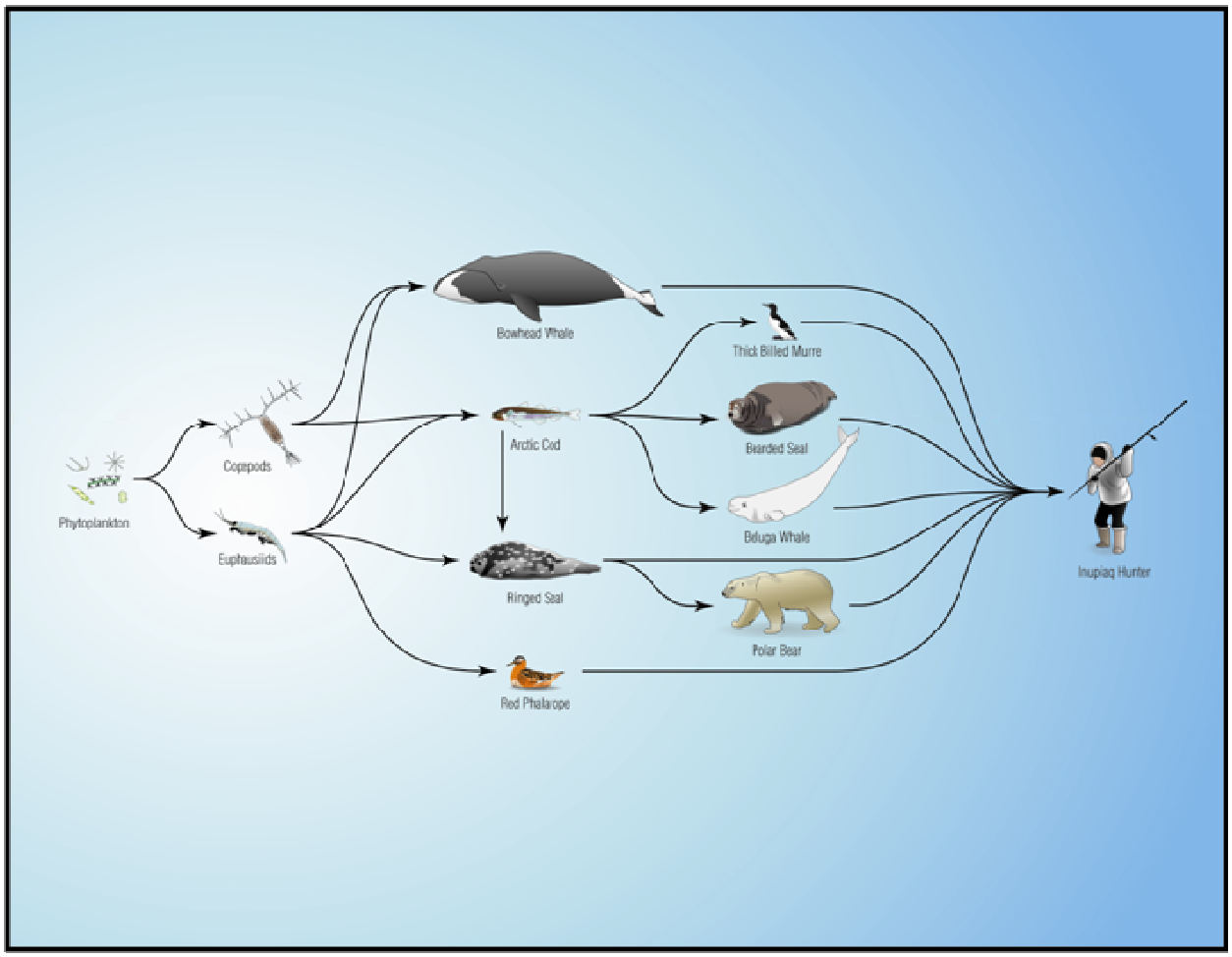


Figure 3-57. The importance of zooplankton and arctic cod in the Arctic pelagic food web leading to mammalian consumers, including man. Based on Macdonald et al. (2005).

Bowhead whales and some marine birds and seals also rely on marine crustaceans, particularly copepods and euphausiids, for food. (Tables 3-44, 3-45, and 3-46). The amphipods, mysids, and isopods that are such important foods for many fish, birds and mammals, consume primarily smaller benthic crustaceans and polychaetes, diatoms, and peat (Craig et al., 1984).

Bowhead whales feed on pelagic euphausiids, copepods, mysids, hyperiid amphipods, and occasionally small fish (Lowry and Frost, 1984; Richardson et al., 1995; Lowry et al., 2004). Bowhead whales feed throughout the Alaskan Beaufort Sea during both the spring (eastward) and fall (westward) migrations between the Bering/Chukchi Seas and the Canadian Beaufort Sea. They feed less during the spring than the fall migration (Lowry et al., 2004). Carroll et al. (1987) reported large numbers of bowheads feeding near Point Barrow during the 1985 spring migration. The dominant prey in the whale stomachs were calanoid copepods and euphausiids. They also feed extensively during their fall, nearshore migration through the Alaskan Beaufort Sea to northeastern Chukchi Sea (Lowry et al., 2004). (Landino et al., 1994) reported a large

aggregation of bowhead whales feeding near Point Barrow in late October 1992. Calanoid copepods were the dominant prey in bowhead whales collected off Kaktovik (eastern Beaufort Sea) and euphausiids were the dominant prey in whales collected off Point Barrow (western Beaufort Sea) (Table 3-44).

Table 3-44. Diet composition (% of stomach contents) in arctic cod, bowhead whales, beluga whales, and ringed seals in the Alaskan Beaufort Sea. From Frost and Lowry (1984) and Lowry and Sheffield (2002).

Prey	Arctic Cod	Bowhead Whales		Beluga Whale	Ringed Seal		
		E. Beaufort	W. Beaufort		Nov-Mar	Apr-Jun	Aug-Sep
Isopod						16	
Hyperiid Amphipod	1				0 – 17		44
Gammarid Amphipod	12					32	
Copepod	50	60	8				
Euphausiid	3	37	92			20	21
Mysid	20	1				19	
Arctic Cod	5			80	75 - 90	6	30
Other Fish		1		10			
Misc.	9	1		10		7	5

Table 3-45 . Diet composition in black kittiwakes, red phalaropes, Sabine's gulls, and arctic terns feeding in nearshore and offshore waters of the Alaskan Beaufort Sea. From Frost and Lowry (1984).

Prey	Black Kittiwake		Red Phalarope	Sabine's Gull		Arctic Tern	
	Offshore	Nearshore	Offshore	Offshore	Nearshore	Offshore	Nearshore
Isopod							
Hyperiid Amphipod	1	67	1	54	6	1	
Gammarid Amphipod		14	49		49		31
Copepod			11				
Euphausiid			5	13	4	35	23
Mysid		11	13		24		
Shrimp	1			3			
Mollusks							
Arctic Cod	95	5		13	4	64	20
Other Fish			1				12
Misc.	3	3	20	17	13		14

Table 3-46. Diet composition in long-tailed ducks, common and king eiders, thick billed murres, black guillemots, and glaucous gulls feeding in nearshore and offshore waters of the Alaskan Beaufort Sea. From Frost and Lowry (1984).

Prey	Long-tail Duck	Comm. Eider	King Eider	Thick-bill Murre	Black Guillemot	Glaucous Gull	
	Nearshore	Nearshore	Nearshore	Offshore	Offshore	Offshore	Nearshore
Isopod		83	89				12
Hyperiid Amphipod				1		1	1
Gammarid Amphipod	23	1	2				
Copepod							
Euphausiid	17						13
Mysid	20	15					
Shrimp							
Mollusks	22	1	2				
Arctic Cod				99	100	17	60
Other Fish							
Misc.						75	

Lee and Schell (2002) compared carbon isotopes in zooplankton to those in bowhead whale muscle and estimated that 10 to 26% of annual bowhead feeding activity was in the eastern and central Beaufort Sea. Thomson et al. (2002) estimated that they may obtain approximately 2.4% of their annual energy requirements feeding in the Alaskan Beaufort Sea. Although bowheads feed extensively in the Alaskan Beaufort Sea, the times, extent, and locations of feeding vary widely from year to year. The variation is due in large part to variations in the temporal and spatial distribution of dense patches of zooplankton upon which the whales depend, which are controlled by ocean conditions, particularly inputs of primary nutrients in river runoff and upwelling from the continental shelf and ice edge (Asjian et al., 2009).

Beluga whales (*Delphinapterus leucas*) migrate annually through the Alaskan Beaufort Sea, usually further offshore than bowhead whales, between summer feeding areas in the Canadian Beaufort Sea and wintering areas in the Bering Sea and feed heavily on pelagic and demersal fish (Treacy, 2002). The dominant prey of beluga whales, because of its abundance in offshore waters, is the arctic cod (Table 3-44).

Some ice-associated seals, such as the bearded seal (*Erignathus barbatus*) and ribbon seal (*Phoca faciata*), which feed in coastal waters of the Beaufort Sea in some seasons, feed heavily on benthic invertebrates and demersal fish, such as shrimp, crabs, arctic cod, and sculpins (Wynne, 1997). Ringed seals (*Phoca hispida*), the principal food of polar bears, are common in all seasons in the Beaufort Sea. Their diet varies seasonally from primarily isopods, amphipods, euphausiids, and mysids in spring during retreat of the sea ice, to amphipods, euphausiids, and arctic cod during the summer open-water season, to primarily arctic cod during the winter when the seals occupy the sea ice (Table 3-44).

The protected spectacled eider (*Somateria fischeri*) and king eider (*Somateria spectabilis*) that breed along the arctic coastal plain from Barrow to the Canadian border, feed primarily on benthic isopods and mysids, as well as small numbers of mollusks that they gather in shallow coastal waters (<30 m) (Dau and Kistchinski, 1977; Frost and Lowry, 1984) (Table 3-46). Several species of marine birds in the Alaskan Beaufort Sea, including black kittiwakes, arctic terns, thick-billed murres, black guillemots, and glaucous gulls, feed heavily on arctic cod, which, in turn, feed mainly on mysids, copepods, and amphipods (Frost and Lowry, 1984) (Figure 3-57; Tables 3-44, 3-45, and 3-46). The copepods that are the principal foods of bowhead whales also are consumed by red phalaropes, Sabine's gulls, arctic terns, long-tailed ducks, and glaucous gulls (Tables 3-45 and 3-46).

Contaminants introduced into the marine environment from offshore oil and gas operations are likely to accumulate in this Beaufort Sea food web. Although none of the contaminants measured in tissues of Beaufort Sea animals in cANIMIDA Task 5 are known to biomagnify (with the exception of arsenic and methylmercury), they all can be spread through trophic transfer through the food web. The tissue residue data collected to date in Task 5 of the cANIMIDA Project has not identified any metal or PAH contaminants from offshore oil and gas operations that are present at elevated concentrations in selected representatives of the Beaufort Sea food web. Some of the petroleum PAH in the tissues of invertebrates and fish could have been derived from offshore operations; however, concentrations are very low, mostly in the range of natural background, indicating a lack of significant risk to the local ecosystem.

An example of the distribution of total mercury in selected components of the Beaufort Sea food web is shown in Figure 3-30. The mercury data, collected from several sources, including cANIMIDA (Trefry et al., 2009; Semmler, 2006), show that there is a large increase in total mercury concentrations from the ambient water, to phytoplankton, to zooplankton (Table 3-17). The apparent biomagnification factor (BF= concentration in consumer/concentration in prey) for the transfer of total mercury and methylmercury from phytoplankton to zooplankton is 2.8 and 7.1, respectively. Mercury concentration then decreases from zooplankton to arctic fish (BF = 0.54). Highest concentrations of total mercury are in liver of the marine mammals in Table 3-18. The apparent BFs for total mercury concentration from whole soft tissues of prey to liver tissue of bowhead whales, beluga whales, and ringed seals are 3.6, 2000, and 586, respectively. Thus, apparent biomagnifications of mercury from zooplankton to bowhead whales is much less than biomagnification from arctic cod to beluga whales or ringed seals. Polar bears from the Beaufort Sea contain liver total mercury concentrations ranging from 7500 to 272,000 ng/g dry wt (Table 3-18); the BF for total mercury from prey (ringed seal) liver to polar bear liver is 3 to 4.

Because of their low trophic status, bowhead whales contain low concentrations of metals, including mercury in all tissues (Table 3-47). Mercury concentrations are highest in liver and kidney, as are concentrations of cadmium and selenium. The presence of mercury and selenium in liver and kidney indicates that the mercury in these organs probably is present as an insoluble, inert mercury-selenium complex.

Table 3-47. Range of concentrations of selected metals in tissues and organs of bowhead whales (*Balaena mysticetus*) collected by subsistence hunters near Barrow, Alaska. Concentrations are mg/kg wet wt (ppm: can be converted to approximate dry wt concentration by multiplying by five). From O'Hara et al. (2006).

Organ/ Tissue	Cd	Cu	Se	Zn	Hg
Kidney	0.47-70.2	1.13-2.20	0.77-2.04	12.7-57.2	0.003-0.18
Liver	0.28-42.2	3.08-8.96	0.50-1.79	23.6-65.1	0.01-0.19
Muscle	0.007-0.212	0.36-0.76	0.13-0.25	24.7-62.8	0.003-0.04
Heart	0.03-3.64	0.90-1.36	0.24-0.92	21.8-30.3	0.006-0.031
Intestine	0.04-1.52	0.45-1.47	0.18-0.63	14.3-31.7	0.004-0.014
Tongue	0.005-0.22	0.11-0.35	0.045-0.18	1.10-15.7	0.003-0.046
Blubber	0.009-0.015	0.10-0.16	0.06-0.14	0.70-1.16	0.005-0.008
Epidermis	---	0.22-0.72	0.39-0.86	9.88-18.7	0.004-0.037

Biomagnification of total mercury in marine food chains usually is attributed to selective accumulation and retention of methylmercury. Mason et al. (1995, 1996) showed that the preferential bioaccumulation of methylmercury in pelagic marine food webs occurs primarily at the level of phytoplankton. Phytoplankton are able to bioaccumulate both inorganic mercury and methylmercury from water. The inorganic mercury binds to cell membranes of the plants in a relatively non-bioavailable form, whereas the methylmercury accumulates in the cytoplasm. Zooplankton that feed on phytoplankton assimilate more methylmercury than inorganic mercury (Table 3-17). Marine animals that feed on the zooplankton also assimilate more methylmercury than inorganic mercury; they also are able to eliminated inorganic mercury more rapidly than methylmercury from their tissues, facilitating the greater accumulation of methylmercury, particularly at higher trophic levels in marine food webs.

Mercury concentrations in marine waters of much of the Arctic are higher than concentrations in temperate and tropical waters due in large part to deposition of metallic and inorganic mercury from long-range transport and deposition from the atmosphere (Skov et al., 2004). There is no evidence that significant amounts of mercury are coming from oil operations around Prudhoe Bay (Snyder-Conn et al., 1997).

Less than 3.5% of the total mercury in Beaufort Sea coastal water is methylmercury (Trefry et al., 2009; Semmler, 2006). Methylmercury in the water column and in tissues of marine organisms is derived from microbial methylation of inorganic mercury in suboxic layers in the water column and sediments (Rolfhus and Fitzgerald, 1995; Gagnon et al., 1996). The methylmercury in Beaufort Sea coastal water probably is from upwelling of offshore water near the edge of the pack ice (Semmler, 2006). The percent of total mercury that is methylmercury increases from 3% in phytoplankton, to 7.6% in zooplankton, and more than 90% in arctic cod (Semmler, 2006), indicating that methylmercury is preferentially biomagnifying in this part of the Beaufort Sea food chain. Methylmercury was not measured in bowhead whale liver; because of the high selenium/total mercury ratio, most of the mercury in bowhead liver probably is present as an insoluble mercury-selenium complex (Dehn et al., 2006a). Three to 10% of the total mercury in ringed seal and polar bear liver is methylmercury; the remainder probably is

present as mercury-selenium complex (Woshner et al., 2001). Mercury concentrations in liver are much higher than those in other tissues of marine mammals. Thus, much of the methylmercury accumulated from zooplankton by bowhead whales and from arctic cod by beluga whales and ringed seals is demethylated and stored as a mercury-selenium complex, probably solid mercuric selenide, primarily in the liver (Khan and Wang, 2009). Thus, the apparent biomagnification of mercury in the trophic step from water-breathing prey to air-breathing predator is the result of assimilation of bioavailable methylmercury and chemical transformation of methylmercury to inorganic mercury and sequestration as solid mercuric selenide.

3.5 Ecology of the Kelp Community in the Stefansson Sound Boulder Patch

3.5.1 Study Design.

The primary objective of cANIMIDA Task 6 was to use synoptic and long-term measurements of photosynthetically active radiation (PAR: the total radiation in the 400 to 700 nm wavelength interval), light attenuation coefficients, total suspended solids (TSS) concentration, and indices of benthic diversity and kelp biomass to determine the impact of sediment resuspension on kelp productivity and ecosystem status in the Stefansson Sound Boulder Patch (Dunton et al., 2009). This research project was designed to address ecosystem change as related to anthropogenic activities from offshore oil and gas development, particularly in the vicinity of the Liberty prospect. The initial effort in the ANIMIDA Project was focused on establishing a quantitative relationship between total suspended solids (TSS) and benthic kelp productivity (Aumack et al., 2007). In cANIMIDA, the specific objectives included efforts to:

- define the spatial variability in annual productivity and biomass of kelp
- monitor incident and *in situ* ambient light (as photosynthetically active radiation [PAR]) and TSS;
- establish the quantitative relationship between TSS, light attenuation, and kelp productivity;
- measure benthic faunal community diversity;
- incorporate historical datasets related to kelp productivity, ambient PAR measurements (both surface and underwater), and benthic diversity into ANIMIDA datasets to establish a long-term record available in digital format; and
- develop a rationale and strategy for future Boulder Patch contaminant monitoring.
- Thirty sites across the monitoring area (Figure 2-4) were sampled, in order to describe the spatial extent and patterns of TSS, light attenuation, chlorophyll, nutrients, and physiochemical properties across Stefansson Sound.

3.5.2 Light Attenuation

Because it is important to understand how changes in the light environment affect kelp productivity, we used surface light and underwater light to quantify the relationship between TSS and the attenuation coefficient, k (m^{-1}). The light attenuation coefficient (k) is the fraction of radiant energy removed from light by either absorption or scattering per unit distance passed through the water column. k was derived from coincident *in situ* measurements of surface and

underwater PAR at 2 and 4 m depths collected at 30 stations (Figure 2-4) on three different occasions each summer. Attenuation was consistently elevated in coastal zones with highest *k* values (1.4 m^{-1}) observed near Endicott Island and the SDI, indicating more turbid water closer to shore (Figure 3-58). Lower *k* values (0.4 m^{-1}) were recorded offshore along the eastern and northeastern sides of Stefansson Sound. In summer 2004, *k* ranged from 0.43 – 1.34 m^{-1} (mean 0.73 ± 0.14) throughout Stefansson Sound. In 2005 *k* ranged from 0.47 – 1.32 m^{-1} (mean 0.69 ± 0.03) and in 2006, *k* was 0.54 – 1.08 m^{-1} (mean 0.72 ± 0.01). The majority of the Boulder Patch, including areas with dense kelp populations (> 25% rock cover), were found predominantly in offshore waters where attenuation measurements were consistently less than 1.0 m^{-1}.

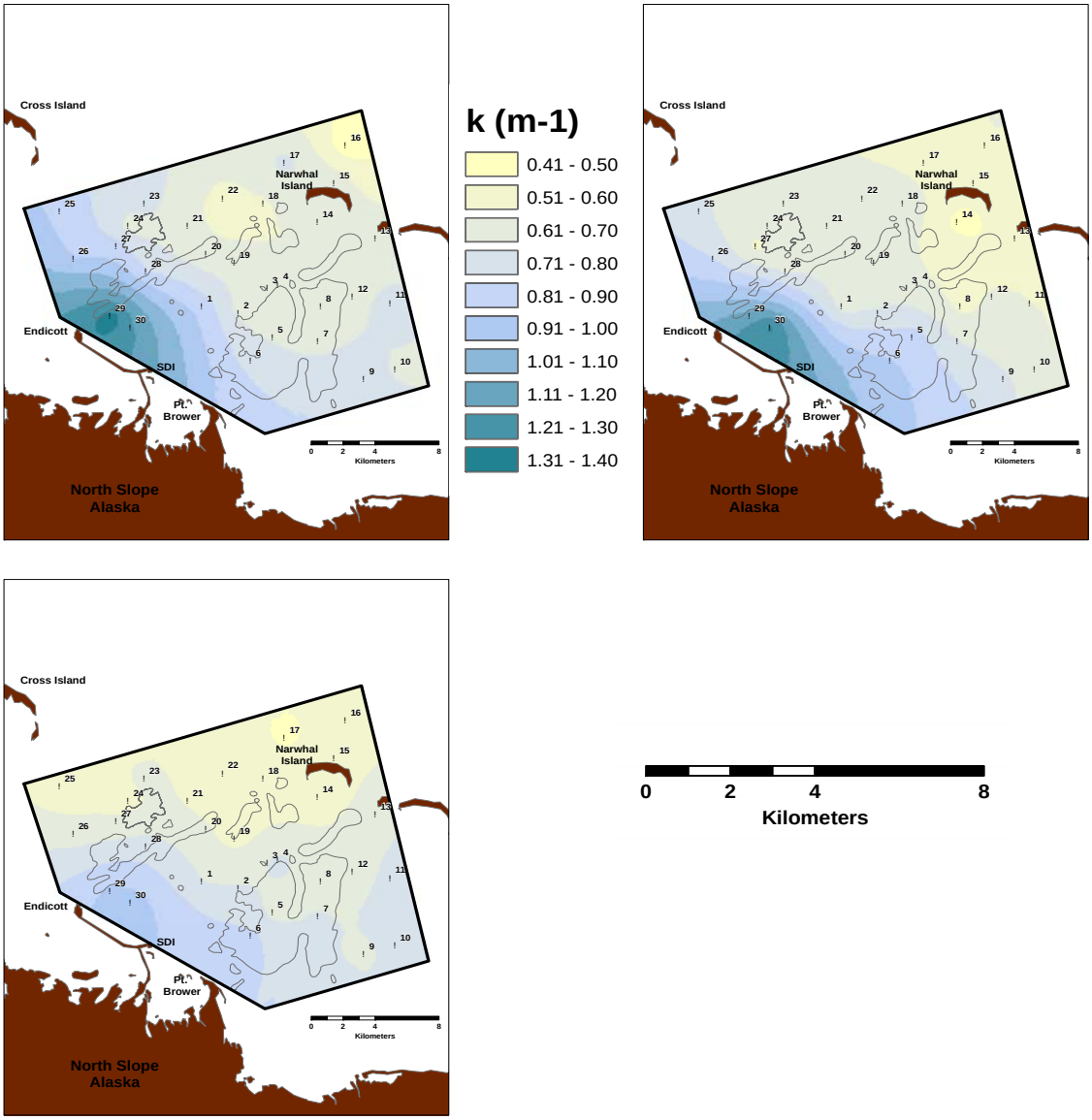


Figure 3-58. Combined mean attenuation coefficient (*k*) values calculated from measurements collected at 2 m and 4 m water depths in summers 2004, 2005 and 2006. Areas of >10% rock cover are outlined in black. From Dunton et al. (2009).

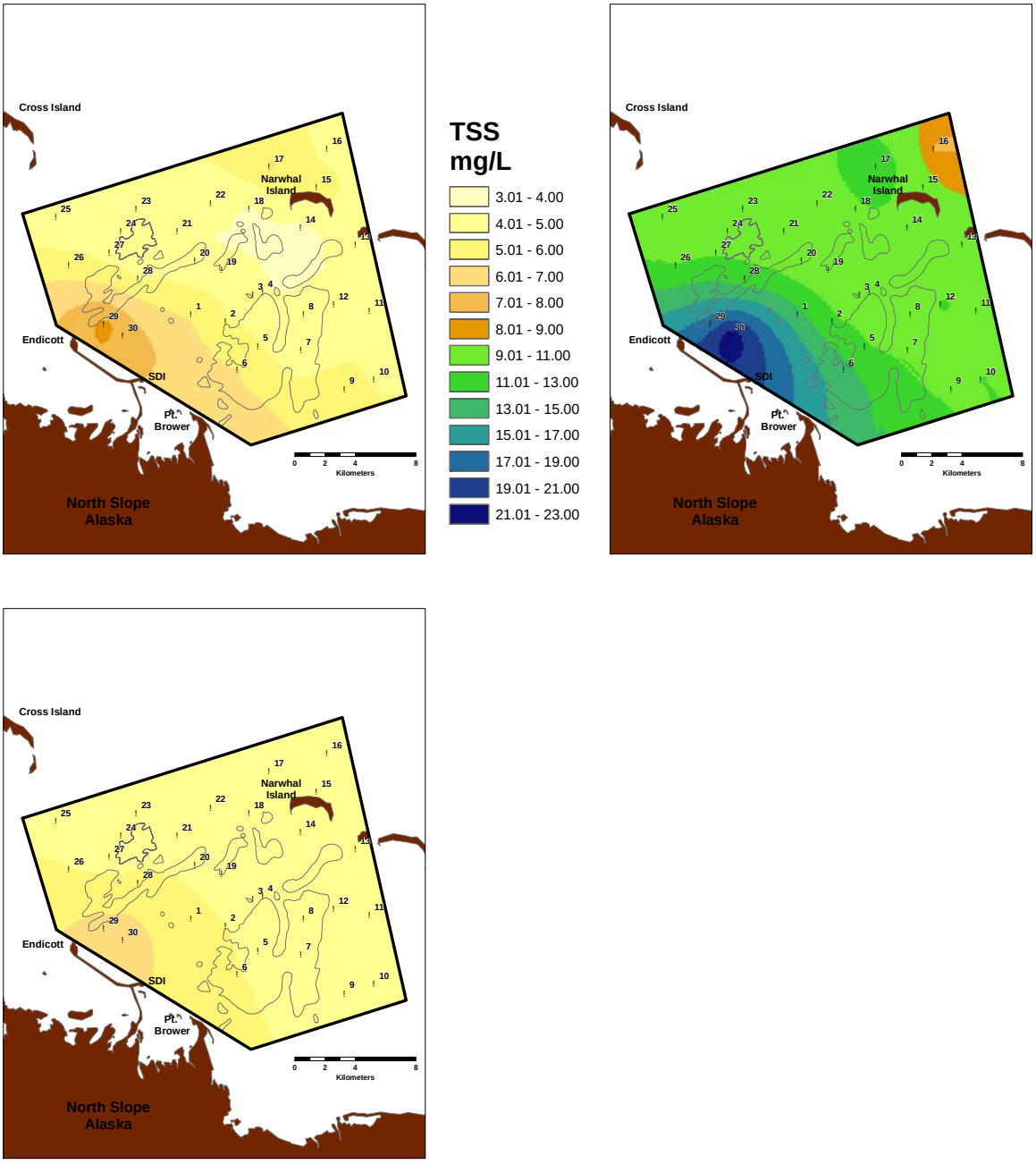


Figure 3-59. Combined mean total suspended solids (TSS) mg/L from samples collected at 2 m and 4 m water depths in 2004, 2005 and 2006. Areas of >10% rock cover are outlined in black. From Dunton et al. (2009).

3.5.3 Total Suspended Solids (TSS)

TSS concentrations were much lower in the summers of 2004 and 2006 (generally all <7.0 mg/L) than in 2005 (generally >7.0 mg/L), but the general trend of decreasing TSS with distance offshore was observed in all three years (Figure 3-59). Since a paired t-test indicated that the TSS values measured at 2 and 4 m depths were not significantly different in either 2004 and 2005 (2004 $p = 0.065$; 2005 $p = 0.156$) the means of the two depths are displayed in Figure 3-59. In 2004, highest TSS concentrations (7.6 - 8.3 mg/L) were found near Endicott Island and SDI and in a turbid area just north of Narwhal Island (5.7 – 6.1 mg/L). TSS concentration ranged from 3.8 – 7.6 mg/L (mean 5.0 mg/L) outside the Boulder Patch. Inside the Boulder Patch TSS concentration ranged from 4.0 to 8.3 mg/L (mean 5.0 mg/L); the overall site average was 5.0 ± 1.8 mg/L.

TSS measurements were much higher and variable throughout Stefansson Sound during the summer of 2005 (7.5 – 23.8 mg/L; mean 11.1 ± 1.1 mg/L). Highest values (17.6 – 23.8 mg/L) were located nearshore, adjacent to Endicott Island, SDI, and Point Brower. Outside the Boulder Patch, TSS concentrations ranged from 7.5 to 23.8 mg/L (mean 11.2 mg/L). Inside the Boulder Patch, concentrations ranged from 9.0 to 17.6 mg/L (mean 11.0 mg/L).

TSS concentrations in 2006 were similar to those measured in 2004 (range 3.5 - 6.9 mg/L; mean 4.7 ± 0.2 mg/L). The highest concentrations again were adjacent to Endicott Island, SDI and Point Brower. Outside the Boulder Patch, TSS concentration ranged from 3.6 to 6.9 mg/L (mean 4.6 ± 0.2 mg/L). TSS ranged from 3.5 to 5.9 mg/L inside the Boulder Patch with a mean of 4.6 ± 0.2 mg/L.

3.5.4 Chlorophyll a Concentrations

Chlorophyll *a* measurements from 2 and 4 m depths were significantly different from each other in 2004 ($p = 0.00006$), 2005 ($p = 0.008$), and 2006 ($p = 0.0000004$). In all three years, 4 m chlorophyll concentrations were higher than the 2 m measurements. The 2005 chlorophyll means were the highest, followed by 2004 means, with the lowest values occurring in 2006. In 2004 chlorophyll measurements ranged from 0.11 to 2.63 µg/L (mean 0.39 ± 0.2 µg/L). In summer 2005, values ranged from 0.11 to 3.54 µg/L (mean 0.76 ± 0.08 µg/L) compared to 0.11 – 0.41 µg/L (mean 0.18 ± 0.01 µg/L) in 2006. Highest concentrations were north of Narwhal Island in 2004 and in nearshore waters adjacent to Endicott and SDI in 2005 (Figure 3-60). Chlorophyll *a* concentrations were low and quite uniform throughout the study area in 2006.

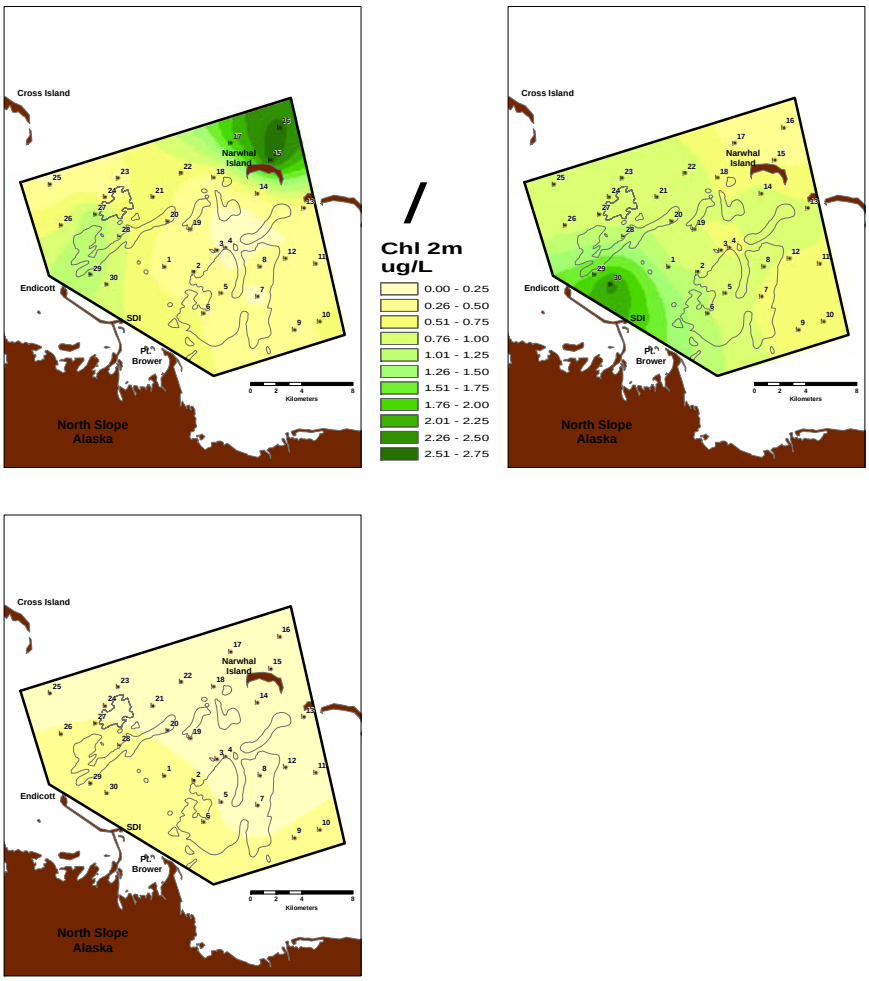


Figure 3-60. Chlorophyll *a* concentrations (µg/L) measured in 2004, 2005 and 2006. Samples were collected at 4 m water depth. Areas of >10% rock cover are outlined in black. From Dunton et al. (2009).

3.5.5 Nutrient Concentrations

Ammonium, phosphate, silicate, and nitrate + nitrite nutrients were analyzed in 2- and 4-m water samples collected in the three times in July and August 2004, 2005 and 2006 (Table 3-48). **A**mmonium concentrations were significantly lower in water samples collected at 2 m than in those from 4 m in 2004 and 2005, and significantly higher in 2006 ($p = 0.024$; $p = 0.00009$; $p = 0.00005$) All mean concentrations were low, ranging from 0.12 to 0.65 µM. Highest concentrations were water samples at sites adjacent to barrier islands.

Table 3-48. TaConcentrations the primary nutrients, ammonium, phosphate, silicate, and nitrate + nitrite at two depths in the water column at 30 sites in Stefansson Sound, measured on three occasions annually in July and August 2004 - 2006. Values are mean ± SE in µM. From Dunton et al. (2009).

Inorganic Nutrient	Depth (m)	2004	2005	2006
Ammonium (NH_4^+)	2	0.12 ± 0.06	0.40 ± 0.04	0.25 ± 0.05
	4	0.17 ± 0.07	0.65 ± 0.05	0.12 ± 0.02
Phosphate (PO_4^{-3})	2	0.24 ± 0.03	0.29 ± 0.01	0.17 ± 0.01
	4	0.19 ± 0.05	0.35 ± 0.01	0.20 ± 0.01
Silicate (SiO_4^{-4})	2	1.76 ± 0.18	5.64 ± 0.19	7.05 ± 0.14
	4	1.84 ± 0.26	5.19 ± 0.16	6.89 ± 0.16
Nitrate + Nitrite ($NO^{-3} + NO^{-2}$)	2	0.14 ± 0.10	0.21 ± 0.04	0.07 ± 0.01
	4	0.15 ± 0.01	0.29 ± 0.08	0.10 ± 0.02

Mean phosphate concentrations were low throughout the study area, ranging from 0.17 to 0.35 µM (Table 3-48). Highest concentrations were in water samples collected at sites adjacent to Endicott. The lowest concentrations were in water samples from sites seaward of Narwhal Island. Phosphate concentrations were slightly lower in water from 4 m than from 2 m in 2004 and slightly higher in water from 4 m than 2 m in 2005 and 2006.

Mean silicate concentrations in water from both 2 and 4 m increased between 2004 and 2006 (Table 3-48). Mean concentrations ranged from 1.76 µM at 2 m in 2004 to 7.05 µM at 2 m in 2006.

Concentrations of $NO_2^- + NO_3^-$ were low throughout Stefansson Sound (Table 3-48). Concentrations ranged from 0.07 µM at 2 m in 2006 to 0.29 µM at 4 m in 2005.

3.5.6 Physicochemical parameters

The four physiochemical parameters measured during synoptic water sampling included temperature, salinity, dissolved oxygen, and pH (Table 3-49). Mean seawater temperature at 2 m and 4 m increased throughout the Boulder Patch each year between 2004 and 2006. Summer 2004 was characterized by frequent storm activity which was reflected to depressed surface water temperatures that were negative at some sites. The mean temperatures at 2 m and 4 m in 2006 were more than 2-fold and 4-fold, respectively, higher than the mean temperatures at 2 and 4 m in 2004.

Salinity measurements were homogeneous across the Boulder Patch and means were consistent among the summers 2004 and 2005 at both 2 m and 4 m depths, but salinities dropped precipitously in 2006 (Table 3-49). In 2004, salinity ranged from 20.4 to 27.4‰ at 2 m and 23.5 to 31.7‰ at 4 m. In 2006, salinity dropped to 11.3 to 23.5‰ at 2 m and 12.3 to 30.0‰ at 4m. Salinity was slightly lower at 2 m than at 4 m in all three years.

Table 3-49. Average temperature, salinity, dissolved oxygen, and pH at two depths in the water column at 30 sites in Stefansson Sound, measured on three occasions annually in July and August 2004 - 2006. Values are means ± SE. From Dunton et al. (2009).

Parameter	Depth (m)	2004	2005	2006
Temperature (°C)	2	2.11 ± 0.55	2.62 ± 1.07	4.64 ± 0.16
	4	0.88 ± 0.75	1.97 ± 1.32	4.21 ± 0.22
Salinity (‰)	2	23.80 ± 0.99	23.85 ± 1.66	16.91 ± 0.35
	4	26.81 ± 1.16	26.65 ± 1.36	20.67 ± 0.49
Dissolved O_2 (mg/L)	2	13.18 ± 0.35	11.48 ± 0.45	11.45 ± 0.02
	4	14.22 ± 0.38	11.53 ± 0.39	11.57 ± 0.05
pH	2	8.19 ± 0.05	No sample	7.90 ± 0.01
	4	8.22 ± 0.04	No Sample	7.88 ± 0.01

pH data were recorded in 2004 and 2006, but not in 2005, because the pH meter malfunctioned during the 2005 field season (Table 3-49). In 2004, Mean pH was remarkably constant at approximately 8.2 at both 2 and 4 m in 2004. Mean pH also was consistent between 2 and 4 m in 2006, but pH was lower at about 7.9, about 0.3 pH units more acidic than in 2004.

Mean dissolved oxygen concentrations were higher in 2004 than in 2005 and 2006 at both 2 and 4 m water depths (Table 3-49). Mean dissolved oxygen concentrations ranged from 13.2 to 14.2 mg/L at 2 and 4 m in 2004. Mean dissolved oxygen concentrations were lower in 2005 and 2006, about 11.5 mg/L at both 2 and 4 m. The higher concentrations of dissolved oxygen in 2004 than in 2004 and 2005 probably are related to the lower water temperatures recorded in 2004 than in 2005 and 2006. However, the dissolved oxygen concentrations in all three years are at or above saturation at ambient salinity and temperatures. Oxygen saturation at the ambient seawater temperatures and salinities range from about 11.8 to 12.5 mg/L (Murray and Riley, 1969). Oxygen saturation may be caused by high primary production during the long daylight hours of the Arctic summer in the shallow Boulder Patch.

3.5.7 Continuous Light Measurements

PAR measurements were collected during summer 2004, 2005 and 2006 at three historic sampling stations in the Boulder Patch. PAR followed a typical cyclical pattern with terrestrial surface irradiances peaking between 1200 – 1400 µmol photons/m^2/sec. Surface irradiance maxima always occurred between 1300 and 1400 hrs. The highest underwater PAR values measured by the underwater spherical quantum sensors also normally occurred around 1400 in all three summers. Between 31 July and 6 August, 2004, underwater irradiance dropped to near zero at all three sites (DS-11, E-1, and W-1) in conjunction with a series of intense storms. Extremely low underwater PAR concentrations continued through 9 August followed by four days of slightly higher values, at which point the dataloggers were removed. Prior to the storm, underwater cosine sensors measured peak downward irradiances ranging from 180 to 200 µmoles photons/m^2/sec. In 2005, underwater PAR measurements were lowest between 15 July and 1 August although the surface irradiance was high on most days. In 2006, underwater PAR was lowest at W-1 but was generally consistent across all sites with no sustained periods of low

PAR. Values recorded from both surface and underwater PAR sensors are similar to irradiance measurements made in Stefansson Sound during earlier studies (Dunton, 1990).

Overall, water transparency, as reflected by consistently low *k* values (generally < 1.0/m) and high light transmission (> 55%/m) at all three sites, was highest in 2006, probably due to the absence of significant storm events during the study period. In all three years, mean irradiance was significantly ($p<0.05$) lower at site W-1, the station farthest to the west, compared to all other sites for the period 26 July to 10 August although the surface irradiance was high on most days. Values recorded from both surface and underwater PAR sensors are similar to irradiance measurements made in Stefansson Sound during earlier studies (Dunton, 1990). Lowest light transmission (< 10%/m) and highest *k* values (2-3/m) were observed at all three sites in 2004. Conditions in 2005 improved considerably, with just one peak in water turbidity occurring in late July as noted earlier. The shallower depth at E-1, compared to W-1 and DS-11 amplifies the *k* values at this site for similar levels of underwater PAR recorded at all three sites.

3.5.8 Kelp Measurements

3.5.8.1 Kelp Linear Growth

Blade elongation in *Laminaria solidungula* displayed large spatial and temporal variability as reflected in measurements from eight sites between 1996 and 2006 (Figure 3-61). Growth was measured per growth year, defined as the period beginning on 15 November one year and ending on 15 November the following year. At these high latitudes, kelp stores nutrients produced by photosynthesis during the summer high solar irradience period and then uses the nutrients for new biomass growth during the dark winter months. Mean site blade growth was lower at every site in growth year 2003 compared to growth in all other growth years between 2000 and 2006, reflecting the exceptionally poor weather conditions in summer 2003 that produced extremely low levels of ambient PAR. Kelp collected in the three years of cANIMIDA (growth years 2003, 2004, and 2005) had annual blade growth rates comparable to those recorded in earlier studies (LGL Alaska Research Associates Inc. and Dunton, 1992; Martin and Gallaway, 1994; Dunton and Dayton, 1995). An interannual comparison of growth years 1998 – 2005 at DS-11 and E-1 indicated that linear growth was lowest during growth year 2003, highest in growth year 2000, and that 2005 was similar to 1998-2000. Changes in local climatology clearly have an important role in regulating kelp growth through increased cloud cover and sustained winds that negatively impact kelp growth (Figure 3-62).

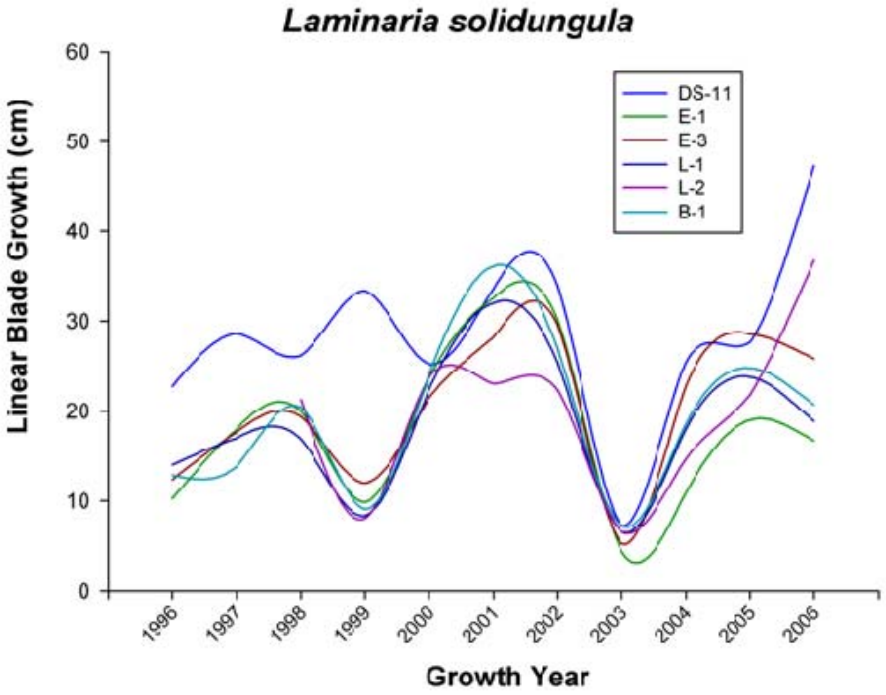


Figure 3-61. Variation in annual growth in *Laminaria solidungula* from 1996 to 2006 at sites in the Stefansson Sound Boulder Patch. Measurements are based on blade lengths of plants collected between 2001 and 2006 under the ANIMIDA project. Values are means. From Dunton et al. (2009).

3.5.8.2 Kelp Biomass

In the summer of 2005, *Laminaria solidungula* plants were measured *in situ* along four 25 m transects at sites DS-11 (n = 226) and E-1 (n = 53). A correlation coefficient between basal blade dry weight (g) and basal blade length (cm) developed for the Stefansson Sound Boulder Patch from specimens collected between 1980 and 1984 (n = 912) was used to obtain an estimate of kelp biomass at these sites. Biomass at DS-11 (> 25% rock cover) ranged from 5 to 45 g/m^2 (mean 23 g/m^2) compared to a range of 0.5 to 2.7 g/m^2 (mean 1.7 g/m^2) at site E-1 (10-25% rock cover). The range of biomass at DS-11 is within the estimates reported by Dunton et al., (1982). Estimates of benthic biomass at the ANIMIDA sites in Stefansson Sound are critical for calculation of realistic basin-wide benthic production models in relation to changes in PAR.

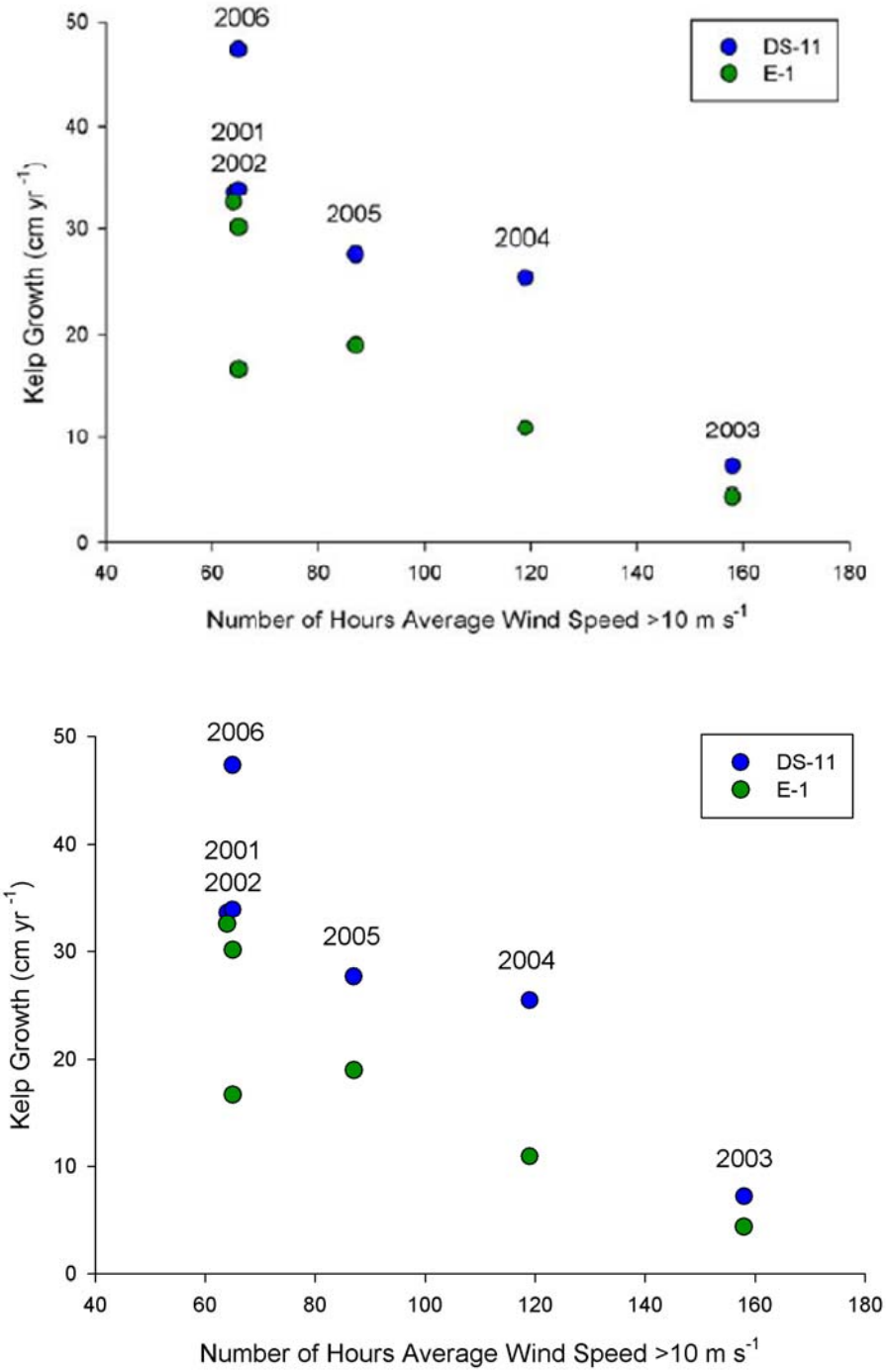


Figure 3-62. Annual mean linear growth of *Laminaria solidungula* as a function of the number of hours that wind speed exceeded 10 m/s at SDI in July and August, 2001 to 2006. Wind speed data from Veltcamp and Wilcox, 2007. Sites DS-11 (blue) and E-1 (green) are located in the Stefansson Sound Boulder Patch. From Dunton et al. (2009).

3.6 Monitoring the Boulder Patch: Biodiversity Assessments

3.6.1 Introduction

Marine biodiversity can be defined as the variety of living organisms within a particular marine ecosystem and the ecological communities they form. Biodiversity often is used as a measure of ecosystem health, though this sometimes is not the case, as in harsh Arctic marine environments. The seafloor of the nearshore Beaufort Sea is typically dominated by soft sediments (Barnes and Reimnitz 1974; Trefry et al., 2009). The benthic faunal communities in those sandy, silty or muddy sediments have a low biodiversity, dominated by bivalve mollusks, polychaete worms, and benthic amphipods (Feder and Schamel 1976, Carey and Ruff 1977, Carey et al. 1984). There are local hotspots of abundant and diverse marine life amidst these relatively low-diversity areas, where boulders provide rare hard substrates for colonization by macroalgae and sessile epibenthic (epilithic) macrofauna. One of these regions is the Boulder Patch in eastern Stefansson Sound. One of the main reasons why this area has been identified as a focus area within the cANIMIDA project is the need to protect these sensitive, biologically productive regions, while allowing oil exploration in the surrounding areas (Figure 3-63) (MMS, 2007).

A variety of brown and red macroalgae have colonized the boulders in the Boulder Patch, forming one of the few known macroalgal beds along the Alaskan Arctic coast. Sessile fauna such as sponges, encrusting bryozoans, hydroids, soft corals, and tube worms thrive on the rocky and macroalgal substrates (Dunton et al. 1982, Dunton 1992, Konar and Iken 2005). This three-dimensionally structured, epilithic community provides habitat for a number of associated macro-organisms. More than 150 species of macroalgae, invertebrates and fishes were found in the Boulder Patch in the late 1970s (Dunton et al. 1982; Dunton and Schonberg 2002), while only about 30 infaunal species, mainly polychaetes and amphipods, have been recorded from the adjacent soft-bottom areas in Prudhoe Bay (Feder and Schamel 1976). Thus, the Boulder Patch is a unique area of high biodiversity in the otherwise silt-mud dominated system of the Beaufort shelf that is devoid of the majority of these faunal and floral groups.

The uniqueness of the Boulder Patch ecosystem made it a center-piece of Task 6 of both the ANIMIDA and cANIMIDA Projects (Dunton et al., 2004, 2009). The biodiversity assessment was introduced in the cANIMIDA Project. Biodiversity is one potential measure of ecosystem health and of biological interactions such as competition, disturbance, facilitation, predation, recruitment, and productivity of a system (Petraitis et al. 1989, Worm et al. 1999, Mittelbach et al. 2001, Paine 2002). The goal of this study was to establish the recent level of biodiversity of epilithic communities within the Boulder Patch with the purpose of evaluating further monitoring mechanisms for this sensitive habitat.

A total of seven Boulder Patch sites, established by Martin and Gallaway (1994), were sampled (Figure 3-64). Biodiversity samples were taken and processed between 30 July – 3 August 2005, and between 21 July – 31 July 2006. Sites were sampled following the standardized sampling protocols developed within the NaGISA program (Natural Geography in Shore Areas: Rigby et al. 2007), a field project within the Census of Marine Life (http://www.coml.org/). See Dunton et al. (2009) for additional details.

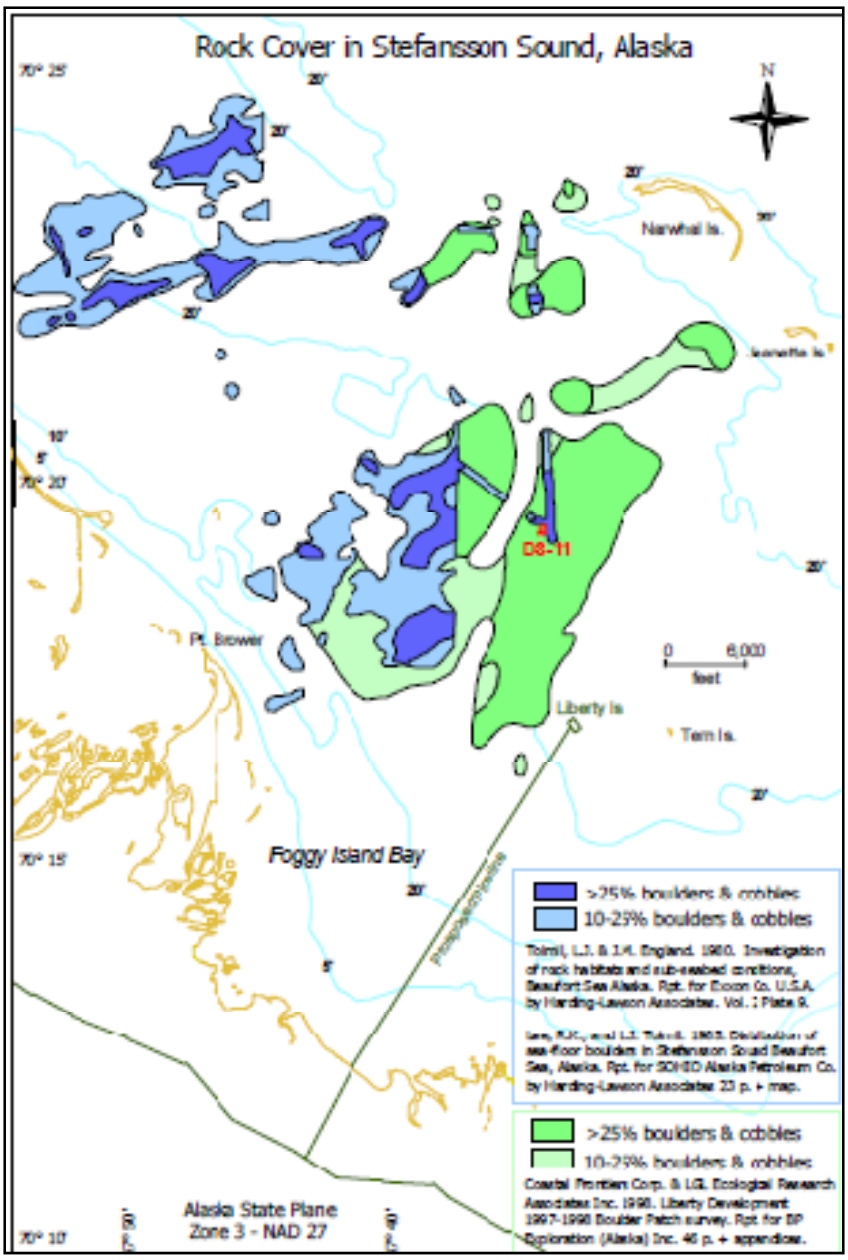


Figure 3-63. Stefansson Sound, showing the Boulder Patch area in relation to the Liberty prospect and the Endicott and SDI production facilities. From MMS (2007).

3.6.2 Macroalgal Communities

Percent macroalgal cover at station DS11 was significantly different in the two years of the study. This difference was driven mainly by the abundance of red algae in both years (30% of dissimilarity between years). Percent cover also differed among sites (DS11, W3, E3) sampled in 2006, which was due mainly to differences between E3 and the two other sites. This difference was based on a much higher percentage of gravel and lower rock cover at E3 compared to other sites.

Fifteen macroalgal species were collected in the Boulder Patch in both 2005 and 2006 (Table 3-50). New records for the area include the brown algae *Sphacelaria plumosa* and *Sphacelaria arctica*, and the red algae *Rhodomela tenuissima* and *Scagelia* cf *americana*. Also, the red alga *Phyllophora trucata* often was infested with what has been identified so far as an endophytic Chlorochytrium. The sampling protocol was suitable to exhaustively measure macroalgal biodiversity as species accumulation curves reached asymptote with 4-6 replicates.

Table 3-50. Species and distributions of major taxa of macroalgae in the Boulder Patch in 2005 and 2006. From Dunton (2009).

Division	Species	2005 sites	2006 sites	Comments
Chlorophyta (green algae)	*Chaetomorpha melagonium* (Weber et Mohr) Kützing	E1, E2, W3	E1, E2	
Rhodophyta (red algae)	*Phycodrys riggii* NL Gardner	DS11, E1, E2, E3, W1, W2, W3	DS11, E1, E2, E3, W1, W2, W3	
Rhodophyta (red algae)	*Phyllophora truncata* (Pallas) Zinova	DS11, E1, E2, E3, W1, W2, W3	DS11, E1, E2, E3, W1, W2, W3	
Rhodophyta (red algae)	*Dilsea socialis* (Postels et Ruprecht) Perestenko	DS11, E1, E2, E3, W1, W2, W3	DS11, E1, E2, E3, W1, W2, W3	
Rhodophyta (red algae)	*Odonthalia dentata* (Linnaeus) Lyngbye	DS11, E1, E2, E3, W1, W3	DS11, E1, E2, E3, W1, W2, W3	
Rhodophyta (red algae)	*Rhodomela sibirica* Zinova et KL Vinogradova	DS11, E1, E2, E3, W1, W2, W3	DS11, E1, E2, E3, W1, W3	
Rhodophyta (red algae)	*Rhodomela tenuissima* (Ruprecht) Kjellman	E2	E1	
Rhodophyta (red algae)	*Ahnfeltia plicata* (Hudson) Fries	E1, W3	DS11, E1, E2, E3	
Rhodophyta (red algae)	*Scagelia* cf *americana* (Harvey) Athanasiadis	DS11	DS11	
Rhodophyta (red algae)	*Lithothamnium* sp	DS11, E2, E3, W1, W2, W3	DS11, E2, E3, W1, W2, W3	Particularly prominent at DS11, E3 and W3
Ochrophyta (brown algae)	*Laminaria solidungula* (C Agardh)	DS11, E1, E2, E3, W1, W2, W3	DS11, E1, E2, E3, W1, W2, W3	
Ochrophyta (brown algae)	*Laminaria saccharina* (C Agardh)	W3	DS11, E3, W1, W3	Was observed but not quantitatively collected at DS11 in 2005
Ochrophyta (brown algae)	*Alaria esculenta* (Linnaeus) Greville	-	DS11	Was observed but not quantitatively collected at DS11 in 2005
Ochrophyta (brown algae)	*Sphacelaria plumosa* Lyngbye	E1, E2, W2	DS11, E1, W1, W2, W3	
Ochrophyta (brown algae)	*Sphacelaria arctica* Harvey	E1, E2	E1, E2	

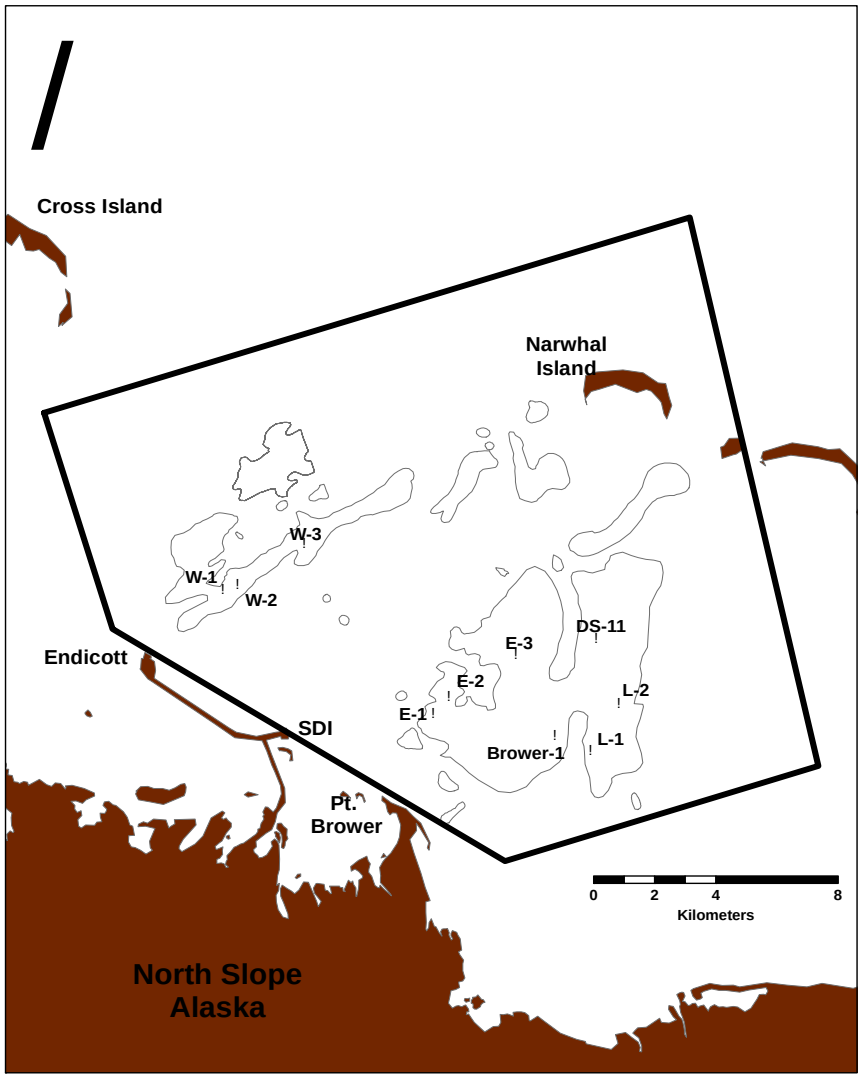


Figure 3-64. Map of the cANIMIDA Task 6 study area. The labeled stations are historic Boulder Patch stations that have been visited repeatedly since 1984, and resampled for biodiversity in 2005 and 2006. During summers 2004, 2005 and 2006, long-term light was measured at sites DS-11, E-1, and W-1; kelp blade length data were also collected at these sites.

The main contributors to total biomass in both years and at all stations were the red algae *Phycodrys riggii* and *Phyllophora truncata* and the brown alga *Laminaria solidungula*. Smaller amounts of biomass were usually contributed by the three red algae *Dilsea socialis*, *Odonthalia dentata* and *Rhodomela sibirica* (Figure 3-64).

Total macroalgal biomass was higher in 2006 than in 2005 at all sites (Figure 3-64, $p<0.001$, t-test), although relative proportions among sites were similar in both years. This higher biomass was particularly obvious at stations W2 and W3, that was driven mainly by significantly higher biomass contributions of *P. riggii* and *P. truncata* ($p=0.033$ and 0.005, t-tests) and also *L. solidungula* (ns, t-test), in 2006.

Overall algal community structure based on biomass did not differ among sites within a year. If averaged by sites, none of the sites differed significantly in 2005 ($p>0.05$, SIMPROF test) but DS11 and W3 clustered differently from other sites in 2006 (Figure 3-65). In an interannual comparison (2-way crossed ANOSIM with sites and years as factors), sites had a larger influence on overall differences than year (R_{global} between years (across sites) = 0.103; R_{global} between sites (across years) = 0.31).

3.6.3 Epibenthic and Epilithic Invertebrate Communities

A total of 86 invertebrate species or higher taxonomic groups were identified in 2005 and 120 in 2006. Of the 86 taxa in 2005, 21 were not found in 2006 and of the 120 taxa in 2006, 47 were not found in 2005. In the two collection years combined, 141 invertebrate taxa were identified. Taxa encountered in only one year were always rare and never dominant in either biomass or abundance. Invertebrates belonged to eight major phyla: Porifera, Cnidaria (Anthozoa, Hydroidea), Mollusca (Polyplacophora, Gastropoda, Bivalvia), Annelida (Polychaeta), Arthropoda (Pycnogonidae, Amphipoda, Isopoda, Cumacea, Decapoda, Cirripedia, [in 2006 also Copepoda, Insecta and Acari]), Bryozoa, Echinodermata (Asteroidea), and Tunicata (Ascideacea).

Average invertebrate biomass (across all sites) was very similar between both years (15.96 g wet/m^2 in 2005; 14.77 g wet/m^2 in 2006). Invertebrate biomass in both years was clearly dominated by sponges, bryozoans and hydrozoans (Figure 3-66).

Invertebrate abundance averaged across sites within a year was much higher in 2006 (56.08 ind/m^2 in 2005 versus 207.26 ind/m^2 in 2006) than in 2005, which was entirely driven by the very large numbers of barnacles in some replicates at sites E1 and E2. Abundance was dominated by polychaetes, bivalves and barnacles (Figure 3-65). Within the first two groups, it was one taxon each that caused high abundances, the serpulid worm, *Spirorbis* sp., and the mussel, *Musculus* sp. This overall pattern does not include non-countable encrusting and colonial organisms such as sponges, bryozoans, hydrozoans, and ascidians, which made up much of the biomass. Sites E1 and E2 differed most from other sites in both years because of high abundances of bivalves (*Musculus* sp) in 2005 (Figure 3-67a) and high abundances of barnacles in 2006 (Figure 3-67b).

Invertebrate community composition based on biomass did fall into distinct groupings in 2005, but all station E-sites were distinctly different from other sites in 2006. This separation of station E-sites in 2006 was mostly due to the high biomass of barnacles and bivalves at these sites, as well as a lower biomass of polychaetes compared to the other sites. Community composition based on abundance differed most between sites E1 and E2 and the other sites in both years. In 2005, these two station groupings were similar only at a 30% similarity level, and in 2006 at a 35% similarity level. In both years, this dissimilarity between E1 and E2 and the other sites was driven by the high abundance of barnacles and bivalves.

Dissimilarity between invertebrate communities (based on biomass) at different sites was mainly driven by the following species: *Eucratea loricata* (Bryozoa), *Sertularia albimaris* and *S. cupressoides* (both Hydrozoa), *Haliclona gracilis* and *H. panicea* (Porifera), and to a lesser extent the two polyplacophorans *Ishnochiton albus* and *Amicula vestita*. Community

composition based on abundance was mainly distinguished by *Balanus crenatus* (Cirripedia), *Musculus* spp. (Bivalvia), and *Spirorbis* sp. and *Exogone* spp. (Polychaeta).

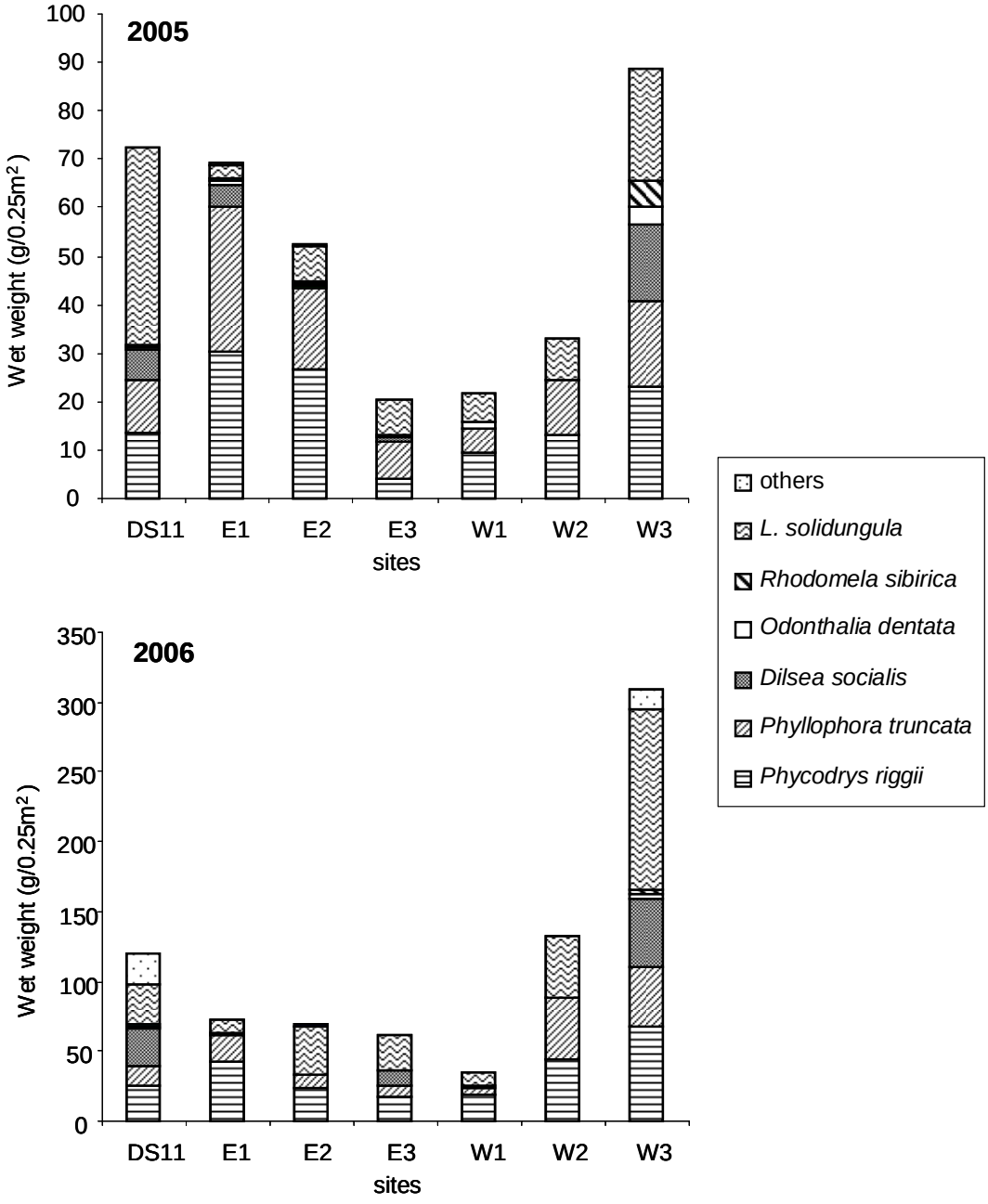


Figure 3-65. Absolute contribution of species to total macroalgal biomass (g ww/0.25m^2) across sites in 2005 and 2006. Note difference in scale in the two years.
From Dunton et al. (2009).

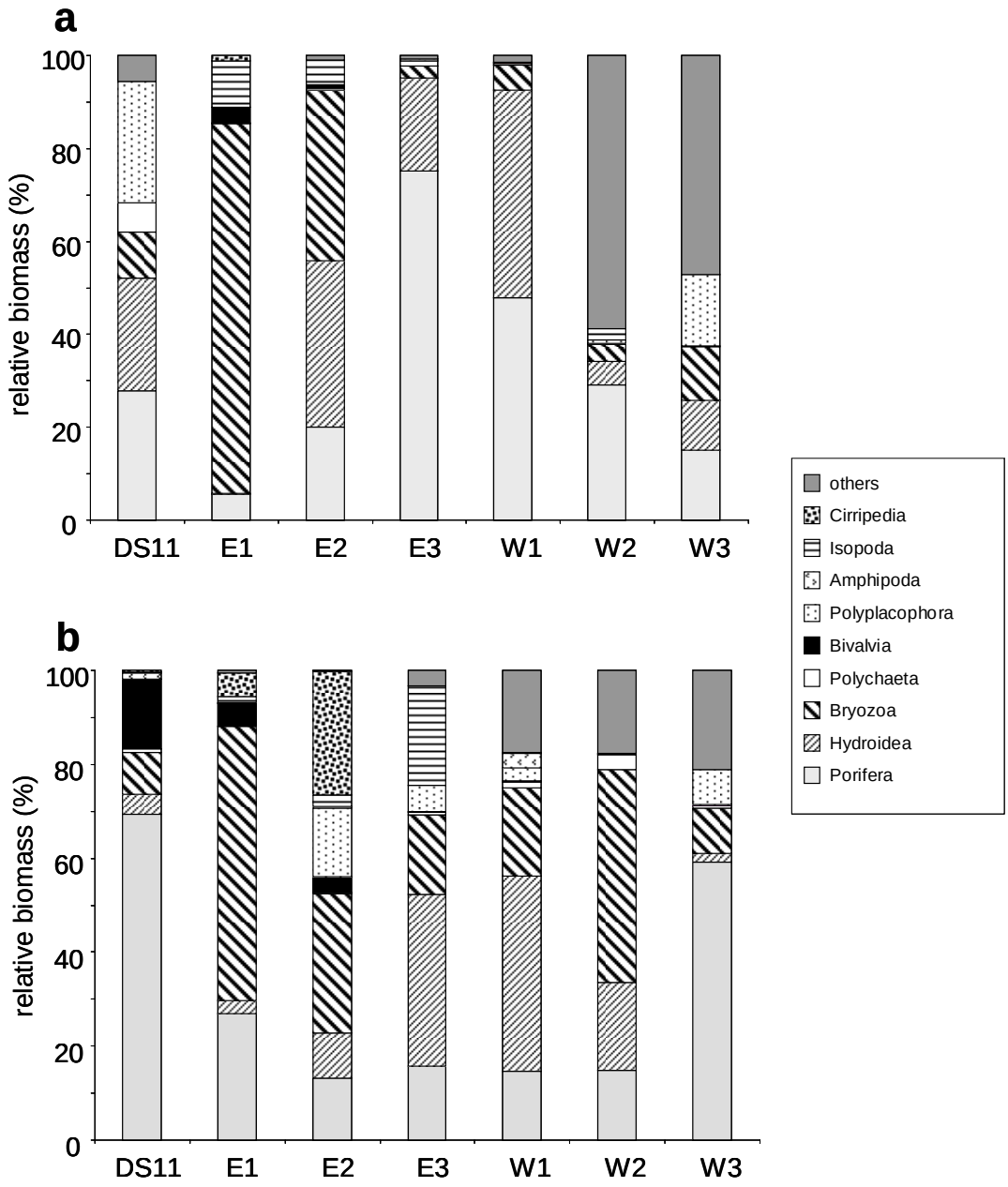


Figure 3-66. Relative biomass contributions of major invertebrate taxa in a) 2005 and b) 2006. "Others" includes Anthozoa, Crustacea, Echinodermata and Nemertea. From Dunton et al. (2009).

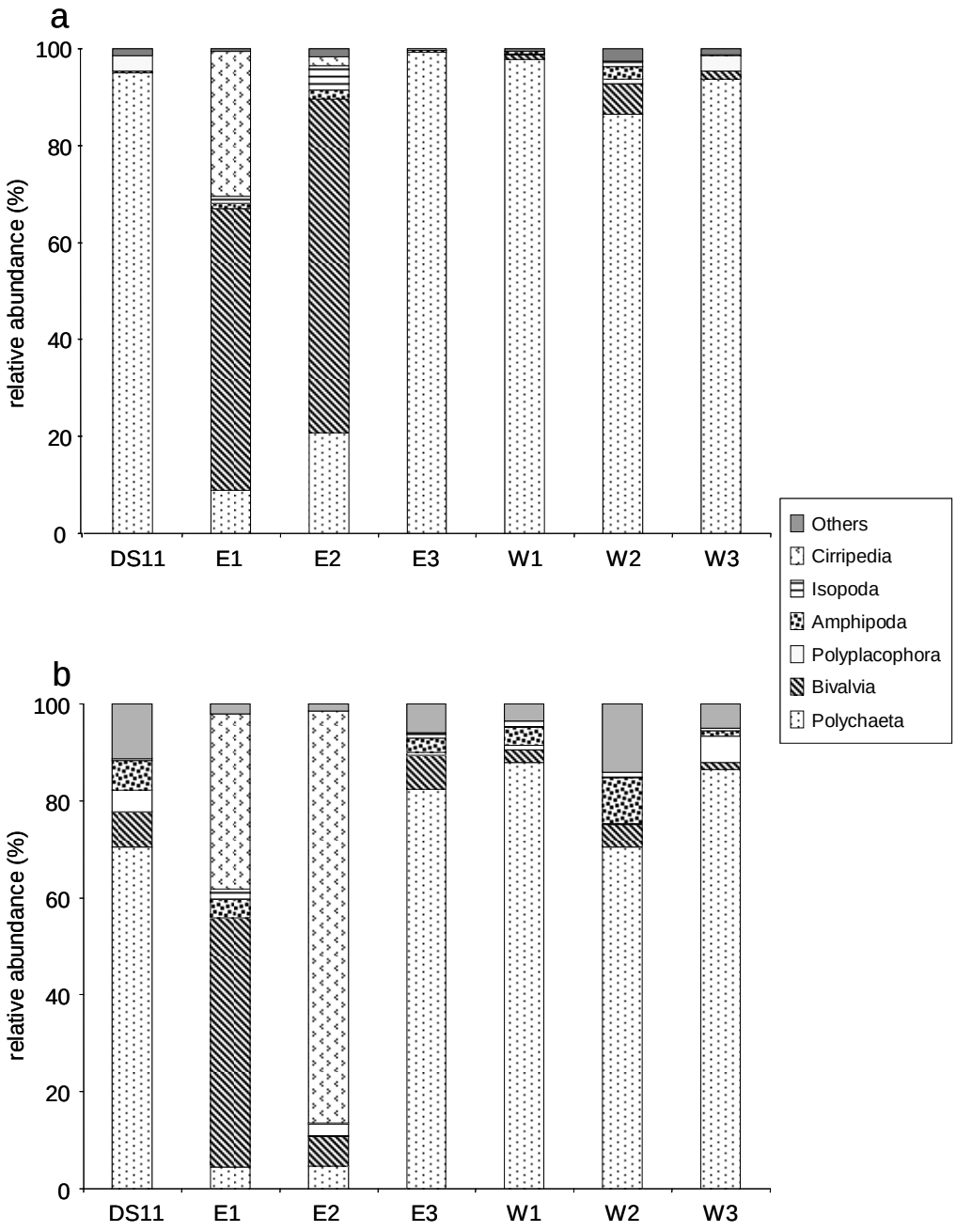


Figure 3-67. Relative abundance contributions of major invertebrate taxa in a) 2005 and b) 2006. Encrusting and colonial taxa are excluded. "Others" includes Anthozoa, Crustacea, Echinodermata and Nemertea. From Dunton et al. (2009).

3.6.4 Biodiversity of the Benthic Community of the Boulder Patch

Algal and invertebrate biomass was not significantly correlated (Pearson correlation, α=0.05) in either year. Separation of invertebrates into functional groups (mobile, sessile) also did not yield any significant relationship with macroalgal biomass.

Diversity measures based on combined invertebrate and algal biomass data did not differ among sites within a year or between years (Table 3-51). Maximum possible Shannon-Woener diversity indices are 1.99 for 2005 and 2.17 for 2006, indicating that Shannon diversity values encountered in our samples were intermediate. Similarly, Simpson dominance indices also were about half the maximum possible values (0.99 in both years). Evenness (Pielou's index), which is always constrained between 0 and 1, had values that were in the lower range owing to the fact that most species, especially among the invertebrates, had a highly uneven abundance distribution.

Table 3-51. Shannon-Wiener diversity index, Simpson dominance index, and Pielou's evenness index for epilithic (living on hard substrates) communities (invertebrates and algae) in the Boulder Patch in 2005 and 2006. From Dunton et al. (2009).

Site	2005			2006		
	Shannon	Simpson	Pielou	Shannon	Simpson	Pielou
DS11	1.118±0.47	0.640±0.37	0.449±0.18	1.298±0.39	0.623±0.17	0.431±0.10
E1	1.061±0.28	0.579±0.16	0.446±0.12	1.169±0.19	0.609±0.08	0.449±0.07
E2	0.777±0.40	0.457±0.26	0.372±0.17	1.107±0.45	0.569±0.20	0.444±0.16
E3	0.821±0.28	0.616±0.31	0.391±0.12	1.021±0.32	0.554±0.15	0.429±0.19
W1	1.037±0.26	0.668±0.15	0.493±0.12	1.081±0.38	0.612±0.29	0.391±0.14
W2	1.119±0.27	0.619±0.16	0.473±0.11	0.889±0.34	0.479±0.18	0.287±0.11
W3	1.057±0.46	0.641±0.38	0.467±0.21	1.097±0.23	0.570±0.13	0.401±0.08
Annual average	0.999±0.14	0.603±0.07	0.442±0.04	1.095±0.13	0.574±0.07	0.405±0.04

While overall diversity indices did not differ among sites or between years, diversity of algae and invertebrates differed within each year. In both years, the Shannon diversity was significantly higher for invertebrates than for algae ($p<0.001$ for both years), although Pielou's evenness index was higher in algae than in invertebrates (not significant in 2005, $p<0.001$ in 2006). Therefore, while the invertebrate portion of the community was much more diverse than the algal portion, the abundance of algal taxa was much more evenly distributed than invertebrate.

Core samples generally contained few species, low biomass, and low abundance of invertebrate species in both years. Several core replicates did not contain any organisms in 2005 (54%) and no invertebrates were found in any of the cores at W1 in 2005. More infauna were found in 2006 when only 3 replicates (8.5%) did not contain any invertebrates and invertebrates were found in at least several of the replicates at all sites. Only 17 taxa were found in 2005; 11 were polychaetes and 3 were bivalves. In contrast, 42 taxa were identified from core samples in 2006; 28 were polychaetes and 7 were bivalves. Core biomass in both years was dominated mainly by bivalves (Figures 3-68 and 3-69). Abundance in 2005 was dominated by polychaetes and at some stations by anthozoans and tanaids, and in 2006 by polychaetes, amphipods and tanaids.

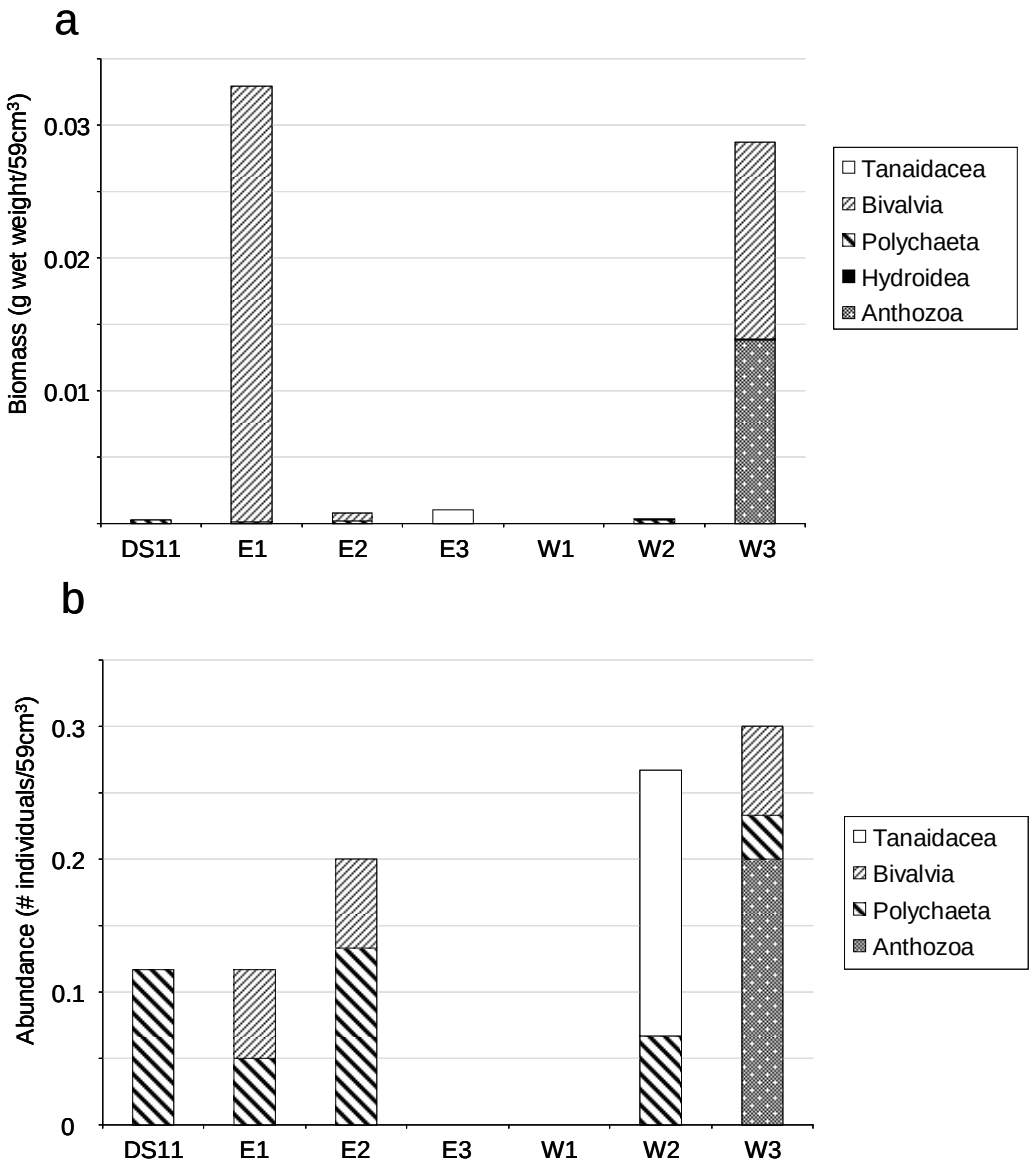


Figure 3-68. Biomass (a) and abundance (b) of invertebrate taxa in sediment cores collected in the Boulder Patch in 2005. From Dunton et al. (2009).

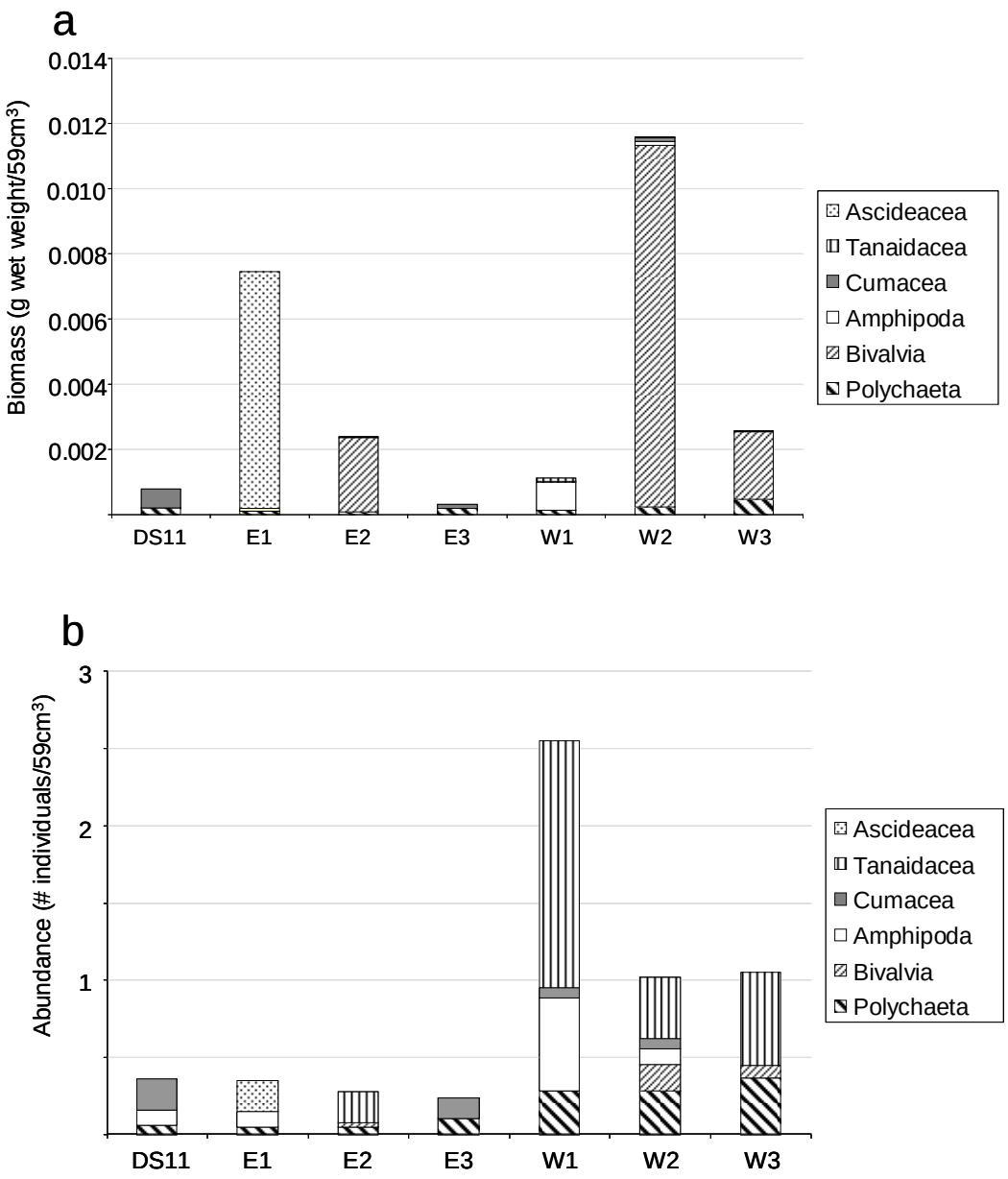


Figure 3-69. Biomass (a) and abundance (b) of invertebrate taxa in sediment cores collected in the Boulder Patch in 2006. From Dunton et al. (2009).

3.6.5 Discussion

The Boulder Patch is an isolated macroalgal-dominated rocky bottom habitat within the usually soft-sediment environment of the nearshore Beaufort Sea. Such algal systems are known to fulfill many diverse habitat functions in other regions of the world's coastal oceans, such as providing three-dimensional space, protection, food, and nursery areas for juvenile life stages (e.g., Iken 1999; Iken et al. 1997; Dean et al. 2000; Beck et al. 2003). These habitat provisions often

increase the number of associated fauna within such algal habitats (Taylor, 1998). In the Boulder Patch, for example, an important portion of carbon channeling through the Boulder Patch food web is derived from macroalgae (Dunton and Schell 1987). However, the lack of correlation between algal and invertebrate biomass found here indicates that flora and fauna are at least in part responding to different environmental drivers.

Environmental factors influencing macroalgae in general are mostly light, nutrients, sedimentation, competitive interactions, and grazing pressure (Worm et al. 1999; Burkepile and Hay 2006; Liess and Kahlert 2007; Gruner et al. in press), all of which can work at the adult or early life history stages of algae. In the Boulder Patch, low light limits growth of kelp in the winter when nutrient levels are high and low nutrients limit summer growth when light levels are high (Dunton and Schell 1986). However, even in summer, light levels can be severely compromised locally by high loads of suspended particles in the water column from river discharge or resuspension due to storm events (Aumack et al. 2007). Sedimentation rate in the Boulder Patch can be high, as can be observed from the large build-up of fine sediments on top of boulders and algal thalli (Iken, pers. obs.). Detrimental effects of sedimentation for macroalgae include light reduction, smothering of small stages, and abrasion of microscopic life stages important for dispersal and recolonization (Kendrick 1991, Konar and Robert 1996, Airoldi and Cinelli 1997). Macroalgae also are under competitive constraints for space as many other encrusting organisms (mainly invertebrates) are competitively dominating in these interactions (Konar and Iken 2005). Grazers can have strong structuring effects on macroalgal communities in temperate and tropical ecosystems (e.g., Schiel and Foster 1986) but little is known about their influence on algal community structure in the Arctic (Konar 2007). In the Antarctic, several invertebrate and fish species are known to be algal consumers with the potential to influence biomass and species distribution (Iken 1999, Iken et al. 1997). Unique to polar environments, ice gouging also can have a considerable impact on algal communities as grounding ice can overturn large boulders and bury attached organisms but also expose new substratum (Conlan et al. 1998). In the Boulder Patch, such overturning events can be inferred from the occurrence of bleached (dead) encrusting coralline algae at the underside of boulders (Dunton et al. 1982).

The diversity indices reported here are subject to change based on final confirmation of the taxonomic identity of some of the red algae. For example, there has been debate and considerable uncertainty regarding the genera *Rhodomela, Phycodrys* and *Dilsea*. The changes in species names between this report and those reported by Dunton et al. (1982) and Dunton and Schonberg (2000) include *Rhodomela sibirica* and/or *R. tenuissima (*from *R. confervoides), Phycodrys riggi (*from *P. rubens),* and *Dilsea socialis* (from *D. integra*). These changes either reflect (1) a definite shift in species composition over the last two decades which can be interpreted as possible effects of climate change or simply (2) disagreement among algal taxonomists regarding these particular genera (confirmation by S. Lindstrom here vs. R.T. Wilce in previous studies; note that in contrast, S. Schonberg has participated in all the taxonomic studies of the Boulder Patch fauna to date).

The macroalgal community in the Boulder Patch in 2005 and 2006 was characterized by high biomass compared to invertebrate biomass, relatively even distribution (high Pielou's index) and relatively low diversity measures. This pattern was caused mainly by the high occurrence of the two dominant red algae at all sites, *Phycodrys riggii* (possibly *P. rubens*) and *Phyllophora*

truncata. It seems that these species are competitively dominants and are able to capitalize on the available space (Konar and Iken 2005). It also may indicate higher reproductive success in these species, possibly through vegetative regrowth in addition to sexual reproduction. The abundance of *Phycodrys riggii* (or *P. rubens*) and *Phyllophora truncata* at all sites and independent of year indicates that environmental conditions for the most part are suitable to sustain these species. In contrast, some of the rarer species may not only be less competitive but may also be more limited by physiological constraints in the environment, such as low growth and reproduction due to low light or high sedimentation (Dunton and Schell 1986, Dunton and Dayton 1995).

The algal species that showed distinct differences among sites was the kelp, *Laminaria solidungula*. This may indicate that kelp is more sensitive than other species to local environmental conditions. While overall environmental conditions in the Boulder Patch are relatively similar, there are distinct local differences in light and sedimentation regime, which probably are reflected in differences in kelp biomass. *Laminaria solidungula* is a perennial species but produces distinct annual blade sections during the winter, which are indicative of the light conditions experienced the previous summer (Dunton and Schell, 1986). If conditions were to change over time, this probably could be traced by diminished or increased kelp biomass. It has to be cautioned, however, that recruitment patterns and inter-annual variability in recruitment and post-recruitment mortality may influence adult distribution patterns. Current knowledge is that recruitment of all taxa is very slow in the Boulder Patch (Dunton et al., 1982; Konar 2007). It is suggested here that *L. solidungula* may be particularly suitable as an environmental indicator for monitoring purposes, as also investigated by other activities within cANIMIDA Task Order 6 (for example, see Aumack et al. 2007).

Compared to other geographical regions, macroalgal biomass and diversity are lower than occurs in cold-temperate waters along south-central Alaskan coasts in the northern Gulf of Alaska (Konar et al. 2009). There, macroalgal biomass at the same depth as the Boulder Patch is about an order of magnitude higher with about 100 g wet weight 0.25 m^{-2}, compared to an average of about 10 g wet weight 0.25m^{-2} in the Boulder Patch. Also macroalgal diversity is higher in the Gulf of Alaska with 20-50 macroalgal species at 5 m depth, depending on location (Konar et al. 2009). Comparative quantitative macroalgal data from other Arctic regions are rare, but species diversity in the Boulder Patch seems to be similar to that encountered along the Russian Arctic coast where kelps like *Saccharina latissima*, *Laminaria digitata, Alaria esculenta* and *Saccorhiza dermatodea* dominate the subtidal community (Tzetlin et al. 1997) and red algae such as *Phycodrys rubens* as well as *Odonthalia dentata*, *Ahnfeltia plicata, Palmaria palmata*, and *Devaleraea ramentacea* build much of the understory (Makarov et al. 1999). Also, the seaweed flora of the Canadian high Arctic, mainly the Baffin Bay area, are similar to that found in the Boulder Patch sublittoral kelp zone contains *Saccharina latissima*, *Laminaria solidungula* and also the red algae *Dilsea integra*, *Devaleraea ramentacea*, *Rhodomela confervoides*, other brown algae such as *Punctaria glacialis*, *Desmarestia* sp. and *Chorda* sp, and green algae of the genus *Chaetomorpha* (Ellis and Wilce 1961; Cross et al. 1987). In comparison, species diversity in western Svalbard is much higher, likely because of the strong influence of Atlantic species carried in by the Gulf Stream (Hop et al. 2002).

The epilithic invertebrate community in the Boulder Patch had distinctly different characteristics than the macroalgal community. Invertebrate biomass was much lower than for algae; however, this is not unusual in systems where algae are the foundation taxon. The invertebrate community

had significantly higher diversity and lower evenness indices than the algal community. This is caused by the patchy distribution of invertebrates in the Boulder Patch with many rare taxa and some taxa being extremely abundant on small spatial scales. This small scale can be at the size of individual boulders, as exemplified by the two orders of magnitude higher barnacle abundance in two replicates at E2 in 2006 than in any other sample. Similarly, high patchy abundances in some but not all replicates per site were found for the bivalve, *Musculus* sp. at the E1 site in both years. Other invertebrate taxa seem to vary on slightly larger spatial scales than barnacles and bivalves. For example, sponges, hydroids and bryozoans always contributed considerably to invertebrate biomass at all sites and usually occurred regularly in most replicate samples within a site.

Some bryozoans, hydroids, and sponges were identified in the present study to be major drivers of differences in invertebrate community composition among sites (*Eucratea loricata*, *Sertularia* spp., *Haliclona* spp.). Similarly, some polychaetes, bivalves, and barnacles were important in differentiating among sites when invertebrate abundances were regarded. As discussed above for macroalgae, it is these differentiating species that probably will make good monitoring species (indicator species) as they probably are responding to different environmental conditions on the scale of sites within the Boulder Patch, and may respond to changing environmental conditions. As the kelp *Laminaria solidungula*, these invertebrates are long-lived, which should dampen some of the effects that inter-annual variability in recruitment and post-recruitment mortality have on adult abundance. However, more information is needed on the specific effects that environmental conditions have on recruitment processes and how this could influence patterns detected from monitoring adult populations. If cost-effective monitoring efforts are to be developed, especially the sessile species should be considered as likely candidates as they can be distinguished readily *in situ*, thus avoiding labor-intensive scrape collections and time-consuming identifications in the laboratory. It is suggested here that feasible monitoring efforts can be done effectively by quantitative percent cover estimates using SCUBA. Naturally, the details of such monitoring design would need to be rigorously tested in future work.

In a larger geographical comparison, a similar invertebrate taxon composition was found to be associated with macroalgae in an Arctic fjord in Spitsbergen (Lippert et al. 2001). While actual species were different, sponges, hydroids and bryozoans were important sessile taxa and were represented in similar species numbers as in the Boulder Patch. Among the mobile fauna, polychaetes, bivalves and amphipods were the most speciose groups in Spitsbergen, which is similar to our results from the Boulder Patch, although amphipods seemed to be more species rich in Spitsbergen. Similarly high amphipod species numbers were found in Bjornøya, close to Spitsbergen (Weslawski et al. 1997). It may be that amphipods may be more dominant in Arctic regions under Atlantic influence, or that local differences in habitat structure (e.g. high abundance of filamentous green algae, Lippert et al. 2001) favor amphipods in the Spitsbergen regions.

Infaunal abundance in the Boulder Patch was very low and there were distinct differences between the two sampling years. It is suggested here that these interannual differences likely stem from methodological differences applied in both years. The sediment in the Boulder Patch is highly consolidated and contains a high percent clay, which presented difficulties during the sieving process when clay portions were broken up. We assume that organisms were lost during the sieving process in 2005. In 2006, we employed a more gentle method by slowly stirring sediments in large volumes of water until clay clumps dissolved. While we believe this has

resulted in much better capture of the infaunal community, it is not a feasible method that could be employed routinely for large sample quantities. It also is possible that much of the infauna of these fine-grained, consolidated sediments were smaller than the 500 μm screen used to collect infauna. Thus, the total infauna were undersampled.

3.6.6 Comparison with Pre-ANIMIDA Data

Both epilithic taxon composition as well as relative contributions of different taxa to the overall community are similar to what has been reported previously (Dunton and Schonberg, 2000) with mollusks and polychaetes being dominant taxa based on abundance. Sponges, hydroids, bryozoans and ascideans are major contributors to invertebrate biomass, as also identified by Dunton and Schonberg (2000). The total number of epilithic invertebrate taxa identified here (~140) was much higher than previously found by Dunton et al. (1982) and Martin and Gallaway (1994), which is mainly due to the lack of polychaetes reported in those studies. The taxon number was similar though to those reported by Dunton and Schonberg (2000) for "between rocks infauna", which included a significant amount of epifaunal organisms. In all studies, however, the main biomass and abundance contributors were the same and differences existed mainly for the rarer taxa.

Infaunal species biomass was similar to earlier results for infauna between rocks (Dunton and Schonberg, 2000). In both studies, mollusks (mainly bivalves) were the main biomass contributor (only 2006 results considered here), followed by polychaetes. Remaining taxonomic groups differed between studies but this was likely due to the very low presence of other taxa, which may be too patchily distributed to be sampled effectively by a limited number of small cores. However, overall infaunal taxon richness was only about half of what was found during the Dunton and Schonberg (2000) study. Sampling effort was larger in the previous study as a much larger core ($0.01m^2$ area versus $0.001m^2$ area) was used and sampled with an airlift, likely contributing to some of the observed differences. Mesh size, another important factor when comparing community composition, was the same in both studies (500 μm) and thus did not contribute to differences in infaunal diversity between the studies.

In summary, the Boulder Patch is characterized by high diversity, abundance and biomass of macroalgae and invertebrates compared to the surrounding soft sediments. Both macroalgal and invertebrate components of the community are dominated by few, very common species. Interestingly, some of these species have distinct site distributions within the Boulder Patch, and if these distributional patterns can be linked to major environmental factors such as light availability or sedimentation, then these species may be good candidates for monitoring purposes.

3.7 Monitoring Subsistence Bowhead Whaling near Cross Island, 2001-2007

3.7.1 The Bowhead Whale *Balaena mysticetus*

Bowhead whales are found only in Arctic and subarctic regions. They spend much of their lives in and near the pack ice, migrating to the high Arctic in summer, and retreating southward in winter with the advancing ice edge (Allen and Angliss, 2009).

The International Whaling Commission (IWC) currently recognizes four stocks: Bering-Chukchi-Beaufort Seas (northern Alaska, western Canada, and eastern Russia); Hudson Bay-

Foxe Basin (Canada) and Davis Strait-Baffin Bay (Denmark (Greenland) and Canada) [now: East Canada-West Greenland stock]; Svalbard-Barents Sea (Spitsbergen) (Denmark (Greenland), Norway, and western Russia); and the Okhotsk Sea (Russia and Japan) (OSPAR, 2010).

The Bering-Chukchi-Beaufort Seas stock of bowhead whales is distributed in seasonally ice-covered waters of the Arctic and near-Arctic, generally north of 60°N and south of 75°N in the western Arctic Basin (Allen and Angliss, 2009). This stock occupies marine waters from Chaunskaya Guba (Russia) in the western Chukchi Sea east to the Amundsen Gulf (Canada), and from the northern Bering Sea south to Karaginskiy Zaliv (Russia), St. Matthew Island, and Norton Sound (OSPAR, 2009). The size of the Bering-Chukchi-Beaufort Seas stock has grown steadily since the ban on commercial whaling to an estimated size of 10,545 (CV 0.128) individuals in 2001 and an annual rate of population increase of about 3.5% (Brandon and Wade, 2006; Allen and Angliss, 2009).

3.7.2 Objectives

Monitoring of subsistence bowhead whaling near Cross Island was initiated as Task 4 of the ANIMIDA Project (Galginaitis, 2004; Galginaitis and Funk, 2004) and has continued as Task 7 of the cANIMIDA Project (Galginaitis, 2009). Data were collected for the fall whale hunts of 2001 through 2007. The overall objective of this project was to describe subsistence whaling as currently conducted near Cross Island by residents of Nuiqsut. The project was designed as a collaborative effort among MMS (through M. Galginaitis, Applied Sociological Research), the subsistence whalers, and the Alaska Eskimo Whaling Commission (AEWC). This project was designed to measure basic parameters of Cross Island whaling so that observed changes (if any) in subsistence whaling activities could be analyzed in relation to such factors as offshore oil and gas activities, weather and ice conditions, climate change, or other variables.

3.7.3 Contemporary Subsistence Whaling in Alaska

This report concentrates on fall whaling by Nuiqsut residents, currently conducted from and near Cross Island, due to the specific interest in the potential effects of offshore oil and gas activities on subsistence whaling. Cross Island is the closest whaling site to most of the past offshore exploratory drilling in the Alaskan Beaufort Sea and the current development and production activities at Endicott, Northstar, and Liberty (Figure 2-3). The island lies at the western border of Stefansson Sound and a short distance west of the Boulder Patch and about 16 km northwest of Endicott production island (Figure 3-63).

The Inupiat of the North Slope maintain and live a vital culture -- with kinship, dependence on hunting wildlife resources, and a respectful relationship to the land as fundamental values. Hunting provides most of the meat consumed by Inupiat. Whaling not only provides a significant part of this food, but also is a key social organizational activity for North Slope Inupiat. Whaling also is a central ideological idiom for the expression of key cultural values, and an important vehicle for the transmission of those values (Worl 1979; Rexford 1997). Subsistence whaling has been (and continues to be) a key focus for Inupiat and Yupik culture and society (Bering Straits area, Northern coastal Alaska) for at least 1,000 to 1,500 years (Dumond 1984; Krupnik and Stoker 1993; McCartney 1994). This discussion focuses on a general description of some key aspects of the organization of subsistence whaling, within the context of its management regime, that are important for an understanding of this project's methods and results.

In Alaska, eleven coastal communities (Point Lay recently being allocated a quota of one bowhead whale per season) currently field whaling crews and are members of the AEWC. Subsistence whaling in Alaska occurs in the spring (generally April-May) in the Bering Straits/Chukchi Sea and the fall (generally September-October) in the Beaufort Sea, when the bowhead whale migration brings them reasonably close to the whaling communities in those areas. Barrow, located where the Chukchi Sea and the Beaufort Sea meet, has historically whaled in both seasons. In the spring, bowhead whales migrate north through the Bering Straits into the Chukchi Sea, past Barrow into the Alaskan Beaufort Sea, and then, into the Canadian Beaufort Sea and Amundsen Gulf, where they spend the summer feeding (some may also go west from the Chukchi Sea into Russian waters). In the fall they reverse this course. Figure 3-70 is a map showing these migratory routes and the locations of the 11 Alaskan (and six Russian) whaling communities and the seasonal availability of bowhead whales to each of the whaling communities. Use areas for Point Lay and the Russian communities are not indicated on Figure 3-70, because whaling for bowhead whales has only recently resumed from those locations.

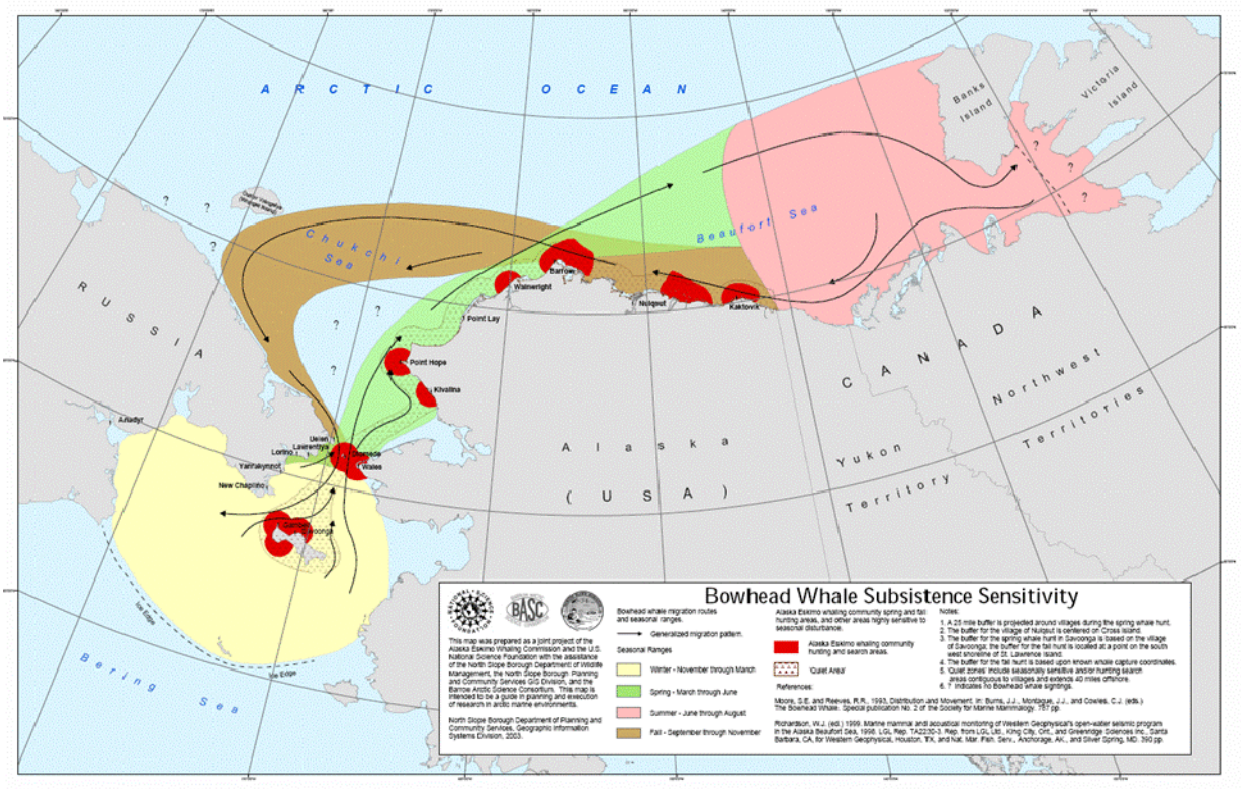


Figure 3-70. . A map showing the generalized spring (eastward) and fall (westward) bowhead whale migration routes and locations of Alaskan subsistence whaling communities. The draft map was prepared by the National Science Foundation, the Barrow Arctic Science Consortium, and the North Slope Borough. From Galginaitis et al. (2009).

Spring whaling differs from fall whaling. In the spring, whales migrate through relatively narrow open leads in the ice, whereas in the fall, the water usually is more open (although there often are

large areas of thick floating ice). Spring leads do not open up close enough to Nuiqsut or Kaktovik along the central Alaskan Beaufort Sea coast to allow these communities to whale in the spring. In the fall, because whales are not confined by leads, it is difficult in most years for whaling communities southwest of Barrow to whale (although St. Lawrence Island and Wainwright whalers have taken a few whales in the fall), because the whales are so far offshore at those points. Thus, most whaling communities whale in the spring, while Barrow can hunt whales in both the spring and the fall, and Nuiqsut and Kaktovik whale only in the fall. Spring whalers have traditionally and historically used only skin boats (until recently), whereas fall whalers use more durable wood, aluminum, and fiberglass boats. This is related to three general seasonal differences: the greater need to avoid unnecessary noise in the spring, the harsher environmental conditions of fall whaling (rougher seas, more floating ice), and the greater need for speed in the fall to find and pursue whales in more open water.

In 1978, the International Whaling Commission (IWC) set a low quota of bowheads that could be harvested, because of concern that the bowhead population was too small to sustain a regular harvest and subsistence whaling methods were too wasteful. The quota was accompanied by a monitoring program to measure and monitor the bowhead whale population and the efficiency of the subsistence whaling harvest. The monitoring program demonstrated the robust size and health of the bowhead whale population (Figure 3-71) and has resulted in an increase in quotas and in the number animals harvested each year (Figure 3-72). It has also created an incentive for the reduction of "struck and lost" whales that has been quite successful. Currently AEWC co-manages the Alaskan subsistence bowhead whale hunt with the United States Government, and this management regime is consistently cited as one of the most successful examples of such management.

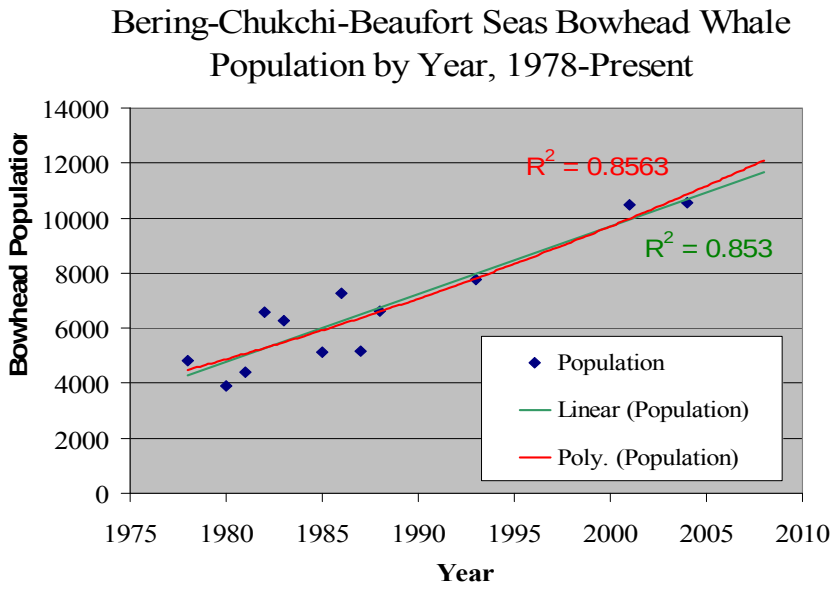


Figure 3-71. Estimated population size of the Bering-Chukchi-Beaufort Sea stock of bowhead whales between 1978 and the present. From Gakginaitis et al. (2009).

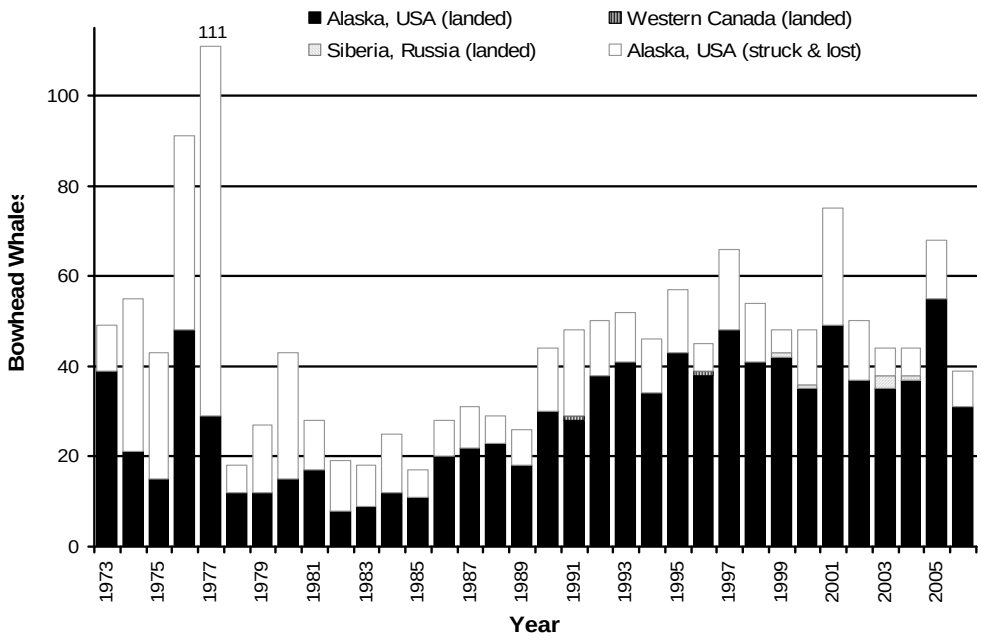


Figure 3-72. Number of bowhead whales struck in the annual subsistence hunt by year and country. Whales landed and struck and lost are indicated. From Galginaitis et al. (2009).

The AEWC Management Plan for the subsistence bowhead whale hunt provides definitions, rules or guidelines of conduct, and management mechanisms for subsistence whaling. It states that all subsistence whaling must be conducted in "the traditional harvesting manner," meaning that only "traditional" weapons may be used. The first strike on a bowhead whale must be made with a harpoon or a darting gun with line and float attached, which also fires an explosive projectile (or "bomb") into the whale at the same time. A fuse that is lit by a percussion hammer mechanism when the bomb first hits the whales is timed so that the bomb explodes only after it has penetrated the whale. A shoulder gun may be used to fire additional bombs into the whale (without additional harpoons and floats) only after a line has been secured to a whale, or when pursuing a wounded whale with a float already attached to it. A lance may be used after a line has been secured to the whale (AEWC 1995:7).

The AEWC Management Plan defines a "whaling crew" as "…those persons who participate directly in the harvest or attempted harvest of the bowhead whale and are under the supervision of a captain" (AEWC 1995). This will be distinguished in this report from "boat crew," since it is not uncommon for Nuiqsut whaling crews to consist of several boat crews, all under the supervision of a single captain. Further, some whaling crew members never go out in the boat, but provide other important services (help in butchering, provision and maintenance of equipment, logistical support or other services such as cooking). "Boat crew" is thus a subset or a part of a larger whaling crew. A typical Nuiqsut boat crew consists of three or four crew members in an aluminum or fiberglass boat. The usual position for the harpooner is at the front of the boat where the darting gun and holder are located. The harpoon line is always rigged on the right side of the boat.

For this report, "whaling crew" refers to all those persons on Cross Island directly under the supervision of a whaling captain. "Boat crew" will refer to those persons who actually go out in a given boat on a given day, and will generally be a subset of a whaling crew, even for those whaling crews with only one boat. In recent years most Nuiqsut whaling crews have used more than one boat, although this was evidently not as common in the past when more whaling captains (and whaling crews) were active.

3.7.4 The Historic Context of Cross Island Whaling

The present community of Nuiqsut has a relatively short history, having been resettled in 1973. However, Inupiat use and occupation of the Nuiqsut area has a very long history, which is the basis for Nuiqsut's status as a village recognized under the Alaska Native Claims Settlement Act (ANCSA). Nuiqsut is located about 12 miles inland on the west bank of Nickalik Channel, the westernmost distributory of the Colville River (Figures 3-70 and 3-73), which is not a typical location for a whaling community. However, its residents trace their ancestry to people who whaled in the mid-Beaufort Sea (including near Cross Island) in the first half of the twentieth century, as well as prior to that time.

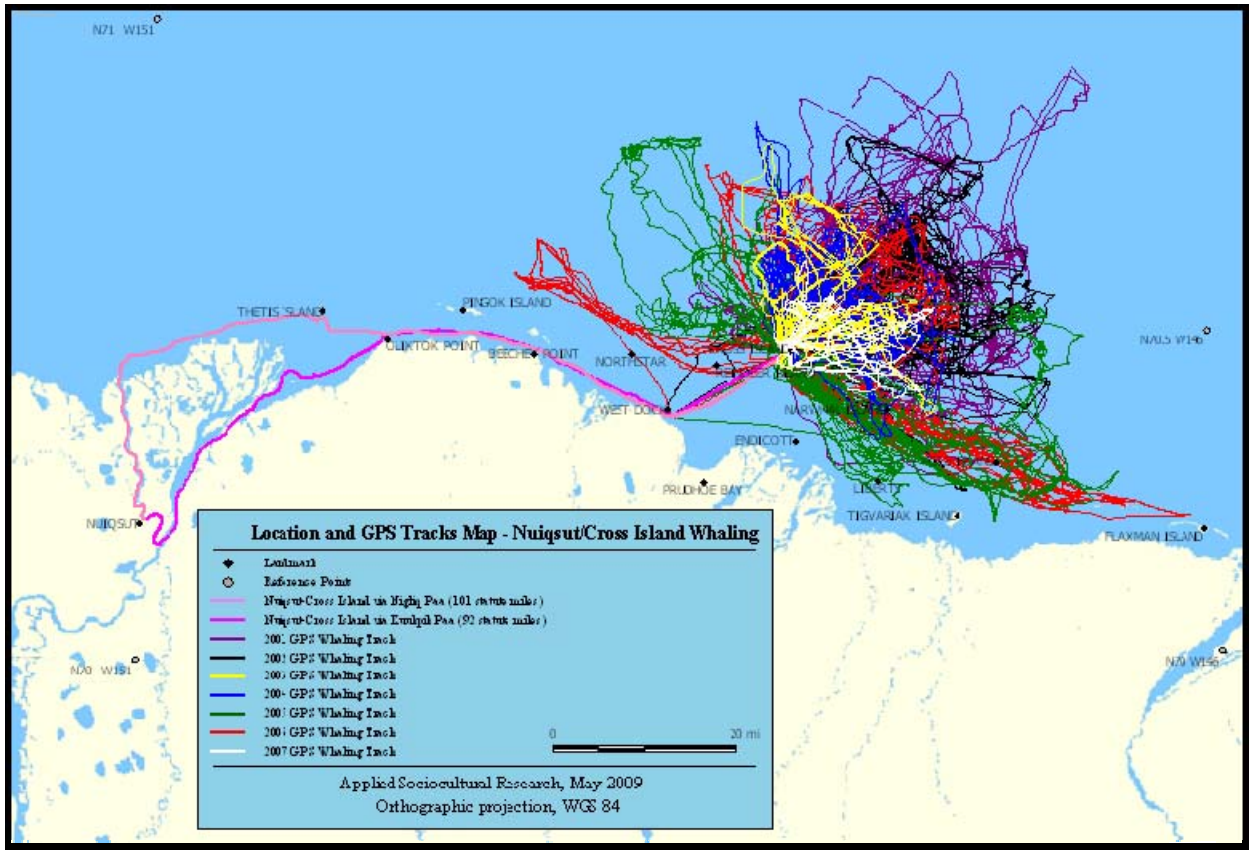


Figure 3-73. Map showing the location of Nuiqsut and Cross Island, the routes taken by whalers to move to and from the island and a GPS tracks map for whale hunts performed each fall between 2001 and 2007. From Galginaitis et al. (2009).

Figure 3-71 shows the location of Nuiqsut on the Colville River and Cross Island in the Beaufort Sea. It also shows typical routes between Nuiqsut and Cross Island, some significant landmarks in-between, and GPS tracks for all documented whaling trips ("scouting" for whales) for 2001-2007. This indicates how far from Nuiqsut whalers must travel in order to set up their whaling camps, and also the year-to-year variability in how far they must go from Cross Island to find and land whales. Describing and explaining this variability is the primary focus of the body of this report. The community of Nuiqsut was built recently, with a regular rectangular grid of streets and modern facilities, located on a river channel. The structures on Cross Island are contemporaneous with those of Nuiqsut, but are typical of those at hunting or fishing camps.

Cross Island is about 117 km northeast of Nuiqsut "as the crow flies" and from 148 to 163 km away by boat, depending on which channel of the Colville River can be used to reach the ocean. The shorter, more protected route is passable during periods of high river water level. The roughest part of the trip tends to be the passage through deeper and potentially rougher water from West Dock to Cross Island. Cross Island is about 18 km offshore but, more important from a logistic point, it is about 16 km from the Endicott causeway and 24 km from West Dock. Endicott is about 23 km east of West Dock, adding significantly to any trip between Nuiqsut and Cross Island in adverse conditions Figure 3-73.

Prehistoric use of Cross Island has not been well documented or investigated archaeologically, but several families used the island seasonally as a whale hunting base during the first half of the twentieth century. Taaqpak hunters used Cross Island as a whaling base from the early twentieth century through the late 1940s. Many current Nuiqsut whalers learned from Taaqpak's crewmembers (or those who had learned from such people). Taaqpak maintained that Inupiat had hunted whales near Cross Island for centuries, supporting the cultural continuity of Cross Island whaling.

Cross Island is now a low sandy barrier island with an artificial higher area built from gravel. When the Nuiqsut whalers started to use Cross Island as a logistical base in the 1980s, there were areas of tundra and vegetation, and the remains of old sod houses, on the island. The tundra and any obvious signs of past habitation have since disappeared. The higher area was constructed for earlier oil and gas exploratory drilling. Cross Island is about 4.8 km long and 137 m wide, and is constantly changing due to erosion and redeposition. Logistical support for whaling on Cross Island was very difficult, especially in the earlier years. The oil and gas industry (and especially BPXA since the development of the Northstar production facility and Shell since they have ramped up their exploration program nearby in Camden Bay) has been providing a variety of logistical support to Nuiqsut whalers as a mitigation measure for potentially disrupting subsistence whaling by seismic, exploration and development activities.

Approximately 55 bowhead whales were harvested by Nuiqsut whaling crews from Cross Island between 1973 and 2007 (Table 3-52). Incomplete records indicate that eight whales were harvested by whaling crews from Cross Island between 1921 and 1940. Poor success in the early years was attributed to poor weather and ice conditions in some years and to the difficult logistics conditions. Later difficulties were attributed in some cases to interference by oil industry operations as well as weather conditions. Weather and ice factors are also evident in the three years with the greatest incidence of "struck and lost" whales (1989- 1991 or 1992).

Table 3-52. Documented harvest and struck & lost bowhead whales near Cross Island between 1973 and 2007. Years with no documented landed or struck& lost whales are not included. From Galginaitis et al. (2009).

Year	Whales			Notes
	Quota	Landed	Struck & Lost	
1973	NA	1	0	
1982	1	1	0	
1986	2	1	0	
1987	2	1	0	
1989	3	2	2	Oil industry vessel disturbance noted
1990	3	0	1	Oil industry disturbance, also rough seas
1991	3	1	2	Poor weather, bad ice conditions
1992	3	2	1	
1993	3	3	0	Very favorable conditions
1995	4	4	0	
1996	4	2	0	
1997	4	3	1	
1998	4	4	1	
1999	4	3	0	
2000	4	4	0	Very favorable conditions
2001	4	3	0	Little ice, whales relatively distant and skittish
2002	4	4	1	Little ice, whales closer than in 2001
2003	4	4	0	Poor weather, whales close to Cross Island
2004	4	3	0	Poor weather, whales close to Cross Island
2005	4	1	0	Very poor weather, bad ice conditions, disruption
2006	4	4	0	Ice restrictions first half of season
2007	4	3	1	No ice, generally poor weather and rough sea conditions, whales close to Cross Island

Once Cross Island was established as a logistical center for Nuiqsut whaling, and current Nuiqsut whalers gained experience there, harvest success became much more regular – although other factors contributing to that success are more moderate ice conditions since 1992 and the logistical support provided through the Conflict Avoidance Agreement (CAA) between the whalers and industry. With the development of Northstar, a new CAA for the Beaufort Sea was negotiated and signed each year. The CAA process has been incorporated into the Incidental Harassment Authorization (IHA) and Letter of Authorization (LOA) permitting processes administered by the National Marine Fisheries Service and the Fish and Wildlife Service when proposed industry activities may have potential effects on the subsistence use of marine mammals.

At the most basic level, the CAA provides for the constant communication between industry and the whalers about all of their respective ongoing activities, so that each can avoid interfering with the other. The mechanism for this mutual communication is the Whaling Communication Center (WCC – also referred to as the Conflict Avoidance Communication Center or the Oil/Whalers Communications Center) in Deadhorse. The Deadhorse WCC operates during each fall whaling season and is staffed by bilingual radio operators, usually with at least one from Nuiqsut and one

from Kaktovik. All industry and whaling vessels are required to report their activities to the WCC in real time (purpose, time left, time returned, significant events as they occur), and the WCC maintains a log of these reports which is archived by the AEWC. This provides a record of activities as they take place, and also documents to some extent the whaling activities. It also allows the WCC to advise industry of planned industry activities that may interfere with ongoing whaling, or to suggest windows of opportunity (when whaling is not taking place) when industry activity may have minimal potential effects. Unfortunately, vessel activity not associated with the oil and gas industry (for example, commercial barge traffic) need not coordinate with the WCC in the same way, so that this is not a totally effective mechanism for mitigation.

Other sorts of logistical support have been supplied at least in part by industry. These have included low-cost connex units (converted into seasonal cabins on Cross Island); a winch to help haul whales up at Cross Island; assistance with a steadier supply of gasoline; a generator system to supply electricity to the cabins during the whaling season; diesel fuel (for the winch and generator); water, and other supplies; help with transporting the butchered whale to Nuiqsut; at least limited phone service for one or two whaling crews; help with mobilization and demobilization; and the assurance of available emergency assistance. Alaska Clean Seas (ACS) or a contractor with similar capabilities is the industry's contractor for much of this OWA support, as a small part of its overall responsibilities (which are mainly logistical and/or related to oil spill response). BPXA, Shell, and ConocoPhillips provided most of the funding for implementing the CAA, but BPXA and more recently Shell bear the majority of CAA-related costs since ConocoPhillips has relatively few offshore interests in the Beaufort Sea. The AEWC does pay for some of the services provided under the CAA, but the amount and exact services are not reported. Neither industry nor the whalers disclose the financial terms of the CAA. In recent years some industry proposals for exploratory and development activities have created some tensions that have complicated the negotiations for the annual CAA, with some oil and gas companies indicating that they may not wish to participate in or support the CAA process in the future.

Preparations for whaling, in one form or another, take place during the entire year. This report focuses only on the actual harvest activities at and near Cross island during the fall whaling season, and does not describe or discuss in much detail the extensive support activities and celebratory and distribution events that take place throughout other parts of the year. During the period discussed by this report, 2001-2007, a minimum of three whaling crews, and a maximum of five, whaled from Cross Island in any one season, with an average and a median of four whaling crews per season. Seven different whaling crews were active for at least one season during this period. Only one whaling crew was active during all seven seasons. The final preparation of boats and equipment for whaling happens in Nuiqsut in August, and a meeting of the NWCA in late-July to late-August is usually conducted to set a date for the start of the hunting effort and to review the rules and regulations. Labor Day, the first Monday in September, is the normative date for all whaling crews to go to Cross Island, but whalers say it is not unusual for individual whaling crews to go out earlier, especially if Labor Day is "late." Whalers also state that normatively all whaling crews would go out to (and come back from) Cross Island together, on the same day. For the 2001-2007 seasons, as discussed below, patterns were clearly different, although Labor Day is a significant time marker for the start of whaling. Most whaling crews did leave Cross Island to return to Nuiqsut on the same day, but did not

necessarily travel together. For two seasons, one whaling crew stayed on Cross Island one day longer than the others.

Usually, one day is spent in transit to and from Cross Island, unless a boat encounters mechanical or other difficulties. Once on Cross Island, the focus is on whaling, with little effort devoted to other subsistence activities. There were a few instances of seal harvest, the taking of nuisance polar bears, and incidental bird hunting. None of these other subsistence activities took place every season, and only polar bear were perceived as a "likely" other harvest to occur. This was clearly due to the fact that polar bears are attracted to Cross Island by the whales that the whalers butcher. The bears represent both a nuisance and potential hazard as well as a possible opportunity for harvest, if a hunter wants to take a bear. Most of Nuiqsut's polar bear harvest takes place at Cross Island during whaling, but the understanding is that a hunter needs his whaling captain's permission to kill a polar bear and, if he does so, the captain has the right to claim the skin. This effectively limits the take of polar bears to those commonly perceived as nuisance/hazardous bears. If a whaling crew member can make a case for how he will use a bear, and that it will not detract from his whaling effort, permission may be given to kill a non-nuisance bear, but there were few instances of this during 2001-2007.

Nuiqsut whalers usually will go scouting for whales on any day when the weather is suitable for finding and striking whales, unless a whale was taken the prior day, in which case butchering usually has priority. However, this pattern may be changing. In 2003, whalers landed three whales in two days (September 5 and September 6) to complete their quota during a rare period of good whaling conditions (Galginaitis and Funk, 2005). In 2004, they landed two of their whales on successive days (September 5 and 6), again to take advantage of good conditions (2006). In 2006, Nuiqsut whaling crews landed single whales on three successive days, apparently because the whales were relatively small and the whalers wanted to take advantage of a period of good weather for scouting (Galginaitis, 2007). In 2007, they purposely landed two whales on one day in order to complete their quota and close their season due to the uncertainty of future conditions for whaling (Galginaitis, 2009).

Whalers invariably use the term "scouting" rather than "hunting" to describe looking for whales to strike. Good whaling weather is determined more by wind speed and sea conditions than anything else. Whalers prefer days with no wind, but winds up to 8 to 16 km/h (5-10 mph), or even higher, can be acceptable. Sea conditions generally correspond with wind speed, but scouting can occur even with higher winds, depending on the circumstances. Ice cover, especially when the ice edge is not too far from shore but also to some extent floating ice floes, generally moderates the effect of wind by dampening wave height. During the period of this report, 2001-2007, the ice edge has always been quite distant from shore, and significant ice floes have been mostly absent. There were some large ice floes present in 2001 (Galginaitis and Funk, 2003a), fewer in 2002 (Galginaitis and Funk, 2003b, 2004), and almost none of significance since then. In 2005 and 2006, localized consolidated pack ice along the north shore of Cross Island limited the area where Nuiqsut whalers could hunt for whales (Galginaitis, 2007, 2008).

Boats typically scout for whales with a complement of three or four people, although since 2001 boat crews ranged in size from two to seven (average 3.9). Although solitary boats do take whales on occasion (for example the first two strikes by Nuiqsut whalers in 2007 were conducted by boats scouting alone), it is not encouraged. Nuiqsut boats almost always scout for whales

with at least one other boat, in case of mechanical break down or other emergencies. Whaling crews with two or three boats are willing to whale without the support of other whaling crews, and this is one reason for a single whaling crew to use more than one whaling boat. It is still commonly agreed that five to seven boats is a preferable number to have available for scouting whales on a given day, and this was generally the case once three of four whaling crews were at Cross Island. The availability of fewer boats decreases the efficiency, safety, and overall chance for success of the hunt. For 2001-2007 the average number of boats out scouting for whales was actually 4.2, reflecting periods when only one or two whaling crews were at Cross Island, mechanical problems, or other particular circumstances.

Once Nuiqsut whalers spot a whale and determine that it is a proper whale to take (generally 7.6 to 10.7 m [25 to 35 ft] long, and not a mother with a calf), they will approach it at high speed so that it dives. They will then estimate where it will reappear (usually in 5 to 10 min, but sometimes longer) and once they reach that area will wait and search at low speed until the whale surfaces and is spotted. They will then repeat the process. The objective is to tire the whale so that it must stay on the surface for longer periods of time, until one of the boats can get close enough to strike the whale on its left side with the darting gun. The whale is killed by the delivery of whale "bombs", which are in essence very large bullets with timed fuses (generally 4 to 8 s) that explode inside the whale. Inupiat whalers adopted this technology from the commercial Yankee whalers. The whale bombs are delivered to the whale via two methods: a darting gun attached to a harpoon, or a shoulder gun.

During fall whaling, the first bomb is delivered via a darting gun, which at the same time deploys a harpoon with an attached float. The harpoon and darting gun are both attached to a long wooden handle. This is thrown from the boat at the whale, usually at a distance of no greater than 3 or 4.6 m (10 or 15 ft), and ideally closer. Once the whale is struck, the harpoon separates from the handle. A trigger rod fires the darting gun and shoots the bomb into the whale. An internal hammer ignites the bomb's fuse once it hits and penetrates the whale's skin and the bomb explodes 4 to 8 s later (depending on how long a fuse was used). The darting gun remains on the handle and thus floats in the water until it can be recovered. It must be dried and cleaned before being used again. In extreme cases, this can be done on the water, but is usually done on shore. Thus, most darting guns are effectively one-shot weapons. Each whaling boat has at least one, and sometimes two, darting guns on board. The second weapon used to deliver whale bombs is the shoulder gun—a very heavy, short barreled, high caliber "rifle" used to shoot the same sort of black-powder bomb as is used in the darting gun, only with fletches or fins to help stabilize its flight in the air. In the fall, the shoulder gun can only be used after a float has been attached to a whale with a darting gun. The first bomb kills some whales. However, when multiple bombs are required, the shoulder gun is useful because it can be used to fire more than one shot.

Until recently, all Nuiqsut whalers used the "traditional" black powder bombs – technology adopted from the commercial Yankee whalers. All captains, or a trusted member of a captain's whaling crew, loaded and assembled these bombs each year, often only after reaching Cross Island, due to the hazards involved. As discussed above, the darting gun and shoulder gun black powder projectiles are essentially the same. The more recently developed "super bomb" can only be used on a darting gun, with a specially modified barrel. It is manufactured in Norway, uses penthrite instead of black powder, and is designed to kill whales faster than a black powder

bomb. It is a product in the interest of developing more efficient weapons for subsistence whaling, but development has been somewhat delayed due to the relatively small demand and its somewhat complicated operation compared to the black powder bomb (Øen 1995; Sadler and Grønvik, 2003; AEWC 2006).

The darting gun is always thrown from the right side of the boat, since it is attached to a line and the float, and this line is always rigged on the right side of the boat. If the darting gun were thrown to the left of the boat, the float line would then stream across the boat at high speed, endangering the boat crew and the structural integrity of the boat. Thus the whale is usually approached and struck on the whale's left side, since the boat normally "catches up" to the whale from behind it in order to achieve a striking position. Nuiqsut whalers report that whales are sometimes approached and struck from the front, but that this is unusual and has not been documented for this research.

When a whale is taken, it is towed to Cross Island, usually by all the boats that had participated in the chase. Depending on the size of the whale, the distance back to Cross Island, weather conditions and sea-state, and how many whales had already been landed that season, boats that had not gone scouting that day may be called in help with the tow or boats that had participated in the hunt may be given the option of trying to strike a second whale on the same day. Once at Cross Island, the whale is hauled up on the gravel beach using a loader that is on Cross Island for the duration of the whaling season and/or a diesel-powered winch, and butchered.

The first cuts into the whale are made by the captain of the whaling crew that landed it (or his designated representative) and are used to delineate the *tavsi*, or captain's belt (share). This belt can vary in width from perhaps 12 to 18 inches, and some captains will designate two such belts on large whales. The back boundary of the *tavsi* is usually the "bellybutton" of the whale with the other edge forward of that, although some captains may adjust this based on the size and body configuration of the whale landed. The *tavsi* essentially divides the whale into two parts, the *uati* (forward of the *tavsi*, composed of the upper torso of the whale) and the *ningiq* (backward from the bellybutton of the whale to the tail). The *ningiq* is used for whaling crew shares and is divided equally among the whaling crews that helped land and butcher the whale. The *uati* is reserved for sharing with the community at large, primarily at celebratory feasts (Thanksgiving, Christmas, and *Nalukataq*). The tongue is divided equally between *uati* and *ningiq*. Half of the baleen belongs to the captain of the whaling crew that landed the whale, and the other half is divided among the whaling crews (generally including the whaling crew that landed the whale) that helped to tow the whale to Cross Island. One flipper belongs to the harpooner who first struck the whale, and the other flipper is available to be shared by any and all whaling crew members of all crews. In practice, since Cross Island is fairly remote from Nuiqsut, most whaling crew members do not take portions of this flipper and it is generally processed as part of the *uati* after it has been available to all crew members for several days. Usually all whaling crews will help with the primary butchering of the whale – taking off all the usable parts and dividing them into *tavsi*, *uati*, and *ningiq*. The whaling crew that landed the whale is then responsible for the further processing of the *uati* so that it can be packed and transported to Nuiqsut. All other whaling crews, other than the one that landed the whale, are responsible for processing the *ningiq* into smaller portions that can then be divided equally among the whaling crews helping with landing and butchering the whale. The first whale is a special case, in that the *ningiq* is divided equally among all the crews that whale at Cross Island

that season, even if they were not on Cross Island when the first whale was landed and did not assist in the hunt or butchering of that whale.

Select parts of the whale from the *tavsi* (captain's belt) are sent to Nuiqsut via whaling boat the same or the next day "to feed the village." The rest of the meat, muktuk, organs, and baleen is packed into containers (either plastic fish totes or more recently heavy cardboard boxes) and transported to West Dock and then to Nuiqsut (most recently via ACS barge and air freight). What is left of the whale is taken to the bone yard. Once the quota is taken or conditions threaten to prevent boats returning to Nuiqsut (formation of ice), the whalers clean up the island, pack, and leave. Most will leave for Nuiqsut on the same day. Captains who have taken whales that season will fly their flags. Whaling will generally be completed by mid- to late-September (an apparent change from the past, discussed below). In Nuiqsut, each whaling crew will process their total crew shares into smaller portions, divide each sort of item (several types of *muktuk*, meat, etc.) into the number of equal individual crew shares determined by the captain, and apportion a share to each crew member or other individual. Each whaling crew that landed a whale will store its *uati* in the captain's ice cellar.

Nuiqsut whalers first used wood boats and relatively small motors. Although they remember these vessels with fondness, and long for the economy of those motors, they also remember that they were limited in terms of speed and towing capability. Currently Nuiqsut whalers all use aluminum or fiberglass boats, 18 to 24 feet long, with motors of 80 to 225 horsepower. It is possible that a 16-foot boat may be used as a whale boat on occasion, but it would not be considered a primary boat. A few boats have cabins, but most are open. Boats typically scout for whales with a complement of three or four people, although some boat crews are as small as two and as large as eight.

In the recent past, Nuiqsut had as many as eleven active whaling captains. Currently, the number is smaller than that. Some captains who do not expect to go whaling do not register with the AEWC each year, and others have retired. When eight or more whaling crews went out whaling there was little reason for captains to run multiple whaling boats. When relatively few (three or four) captains go whaling, the number of boats available to assist in chasing and towing the whale are too limited unless some whaling crews use more than one whaling boat. Also, the only way that a whaler who is not registered as a whaling captain can take his boat out whaling is as a boat (usually a second or third boat) for a registered captain. This is one way that people with the goal of becoming whaling captains acquire the experience to support their eventual application to their local WCA and the AEWC to become a registered whaling captain. Thus, part of the reason that most whaling crews (63 percent) during the study period used more than one whaling boat was probably due to the fact that only three to five whaling crews were active during any given season.. Whaling crews with two or three boats are willing to whale on their own, but it is commonly agreed that five to seven boats is a preferable number to have available for whaling on a given day. More boats would be useful, and the availability of fewer boats decreases the efficiency, safety, and overall chance for success of the hunt.

3.7.5 Trends in Nuiqsut Bowhead Whale Harvest

Table 3-52 summarizes the strikes for Nuiqsut whalers since 1973 (the date the community was resettled). The first whale landed by residents of the current community of Nuiqsut was struck near the Flaxman Island/Canning River area, well east of Prudhoe Bay and Cross Island.

Whaling continued in subsequent years, but success from 1973 until at least the mid-1980s was intermittent, with the next whale landed in 1982 and the one after that in 1986. Starting in 1986, whales were landed on a more regular basis and Nuiqsut whalers first used their full quota of strikes (plus a "transferred" strike) in 1989. They first landed their full quota of whales in 1993 and have done so on a regular basis since then. For the period 1973-1992, they landed 9 whales and had 6 struck and lost, for a landed percentage of 60 percent. A quota was only established in 1978, so a comparison with possible harvest is not possible. For the period 1978-1992 (fully covered by a quota assigned to Nuiqsut), Nuiqsut whalers landed 8 whales, struck and lost 6 (a landed percentage of 57 percent) and had a quota of 25 strikes over the period. They used only 56 percent of the strikes and landed only 32 percent of their quota. For the period 1993-2007, Nuiqsut whalers had an aggregate quota of 55 whales and landed 45 (82 percent of their quota) and had only 4 struck and lost whales (a landed percentage of 92 percent of the strikes used). Nuiqsut whalers used 49 strikes during this period (89 percent of their quota). This demonstrates a clear improvement in efficiency, both in terms of an increased percentage of landed whales versus struck and lost whales, as well as in terms of more fully using their quota and satisfying the community's need. Most Nuiqsut whalers indicate that four whales, each about 25 to 35 feet in length, provide enough meat and muktuk for everyone in the community, with enough left over to share with people in other villages. Three whales, if they are larger than 35 feet, can be enough and in some years Nuiqsut whalers have foregone landing a fourth whale for this reason.

Whalers report that, during the fall migration, the smaller whales reach Cross Island before the larger ones, and that they have a preference to land smaller whales (35 feet or less). This preference is consistent with the AEWC management guideline for whalers to strike only sexually immature animals (generally less than 38 feet). There has been a trend, not statistically significant, for size of whales landed to decline between the 1980s and 2007 (Figure 3-74). The trend may be skewed because most of the whales taken in the 1980s and early 1990s were landed

in late September or October, when larger animals may have composed more of the animals present than in early- to mid-September, when Nuiqsut whalers currently whale. Current whalers may have more of a preference for smaller whales than did whalers in the past (some whalers state it the other way – that past whalers may have had more of a preference for larger whales). Another factor is that current whalers use larger boats with more powerful motors, and have more reliable gas supplies and logistical support, than whalers in the 1980s and early 1990s. While they are not able to wait for long periods of time for a "preferred" whale, they can at times decide not to chase a whale that is "too big" early in the season, with the expectation that they will have other opportunities later in the season. Nuiqsut whalers in the 1980s and early 1990s did not have the same degree of freedom and tended to chase and strike whatever whale made itself available.

Smaller whales seem to be more likely to be landed earlier in the season than are larger whales – but the same skewing effect of current whalers hunting earlier in September than did past whalers may apply (Figure 3-75). There is little question that whalers are whaling, and landing whales, earlier than in the past. Whalers say that, in the past, it was common to hunt caribou on the way to Cross Island, or to make trips to the mainland from Cross Island to hunt caribou, to support themselves while whaling. They also say that whaling crews often took fish nets to Cross Island, and would hunt seals for food. The captain who landed the first whale for Nuiqsut in

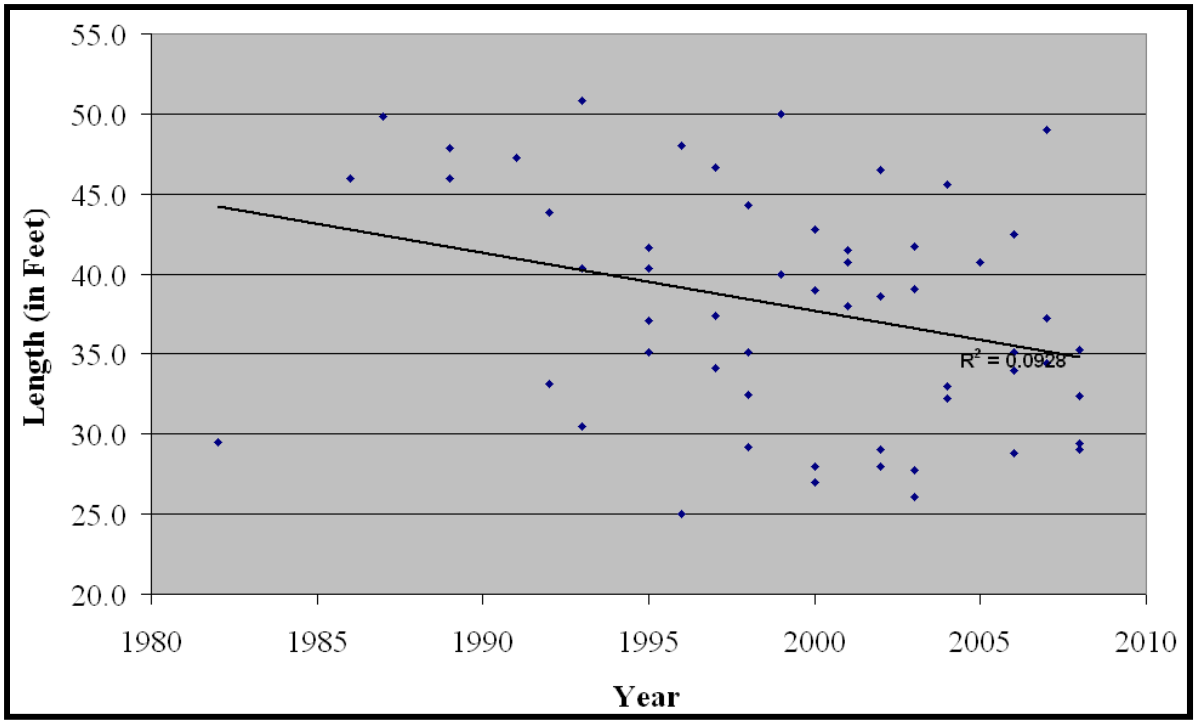


Figure 3-74. Historic trend in length in feet of bowhead whales landed by Nuiqsut whalers from Cross Island between 1982 and 2007. From Galginaitis et al. (2009).

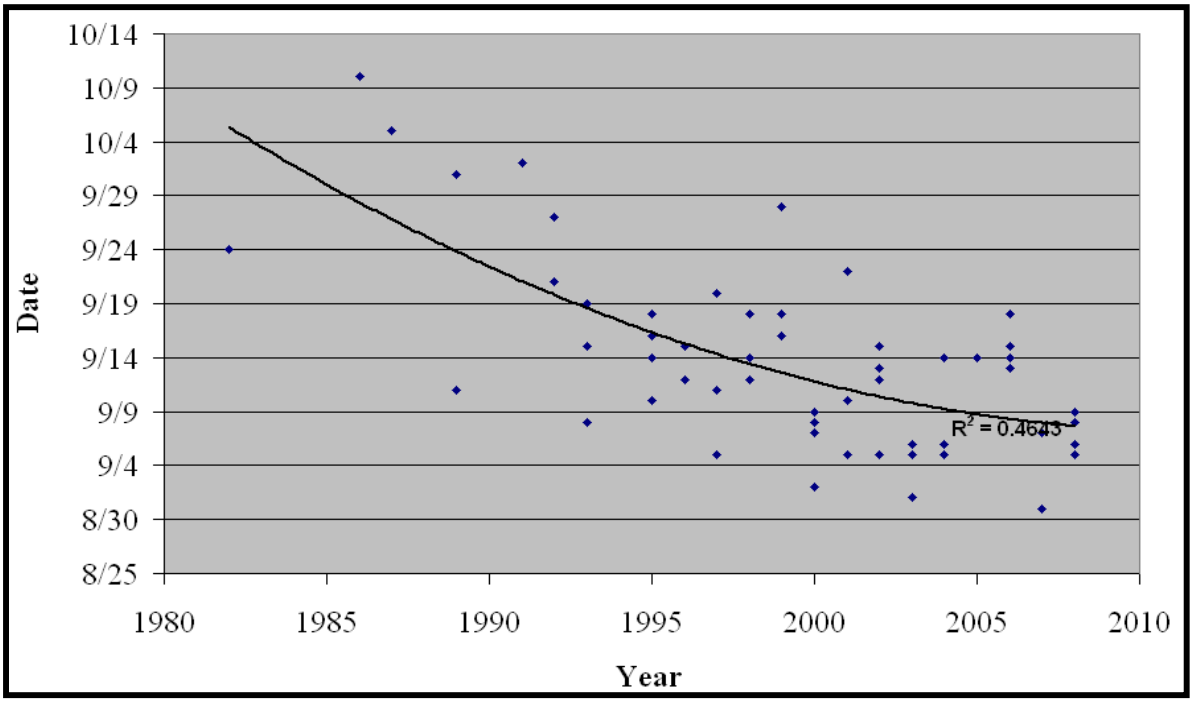


Figure 3-75. Historic trend in date of bowhead whale landings by whalers from Cross Island between 1982 and 2007. From Galginaitis et al. (2009).

1973 often told the story of how, after two weeks, he and his crew had run out of food except for some salt and tea, and how they lived for weeks on nothing but seal. In those days they not only hunted for food to support their whaling activities, but also for gas. Because of past military and industry activities, drums of various materials were left at numerous locations all along the coast, and Nuiqsut whalers made use of the fuel that they could find. They were very limited in what they could bring from Nuiqsut, and could not always rely on being able to buy what they needed. What they did have more of in the past than they do currently is time. In many ways, increased access to economic resources and improved technology is used to decrease the time required to successfully harvest subsistence resources, in this case bowhead whales. Nuiqsut whaling captains commonly remark that it is very expensive to be a whaling captain, and that to field a whaling crew on a regular basis one needs a good job or a wide and strong support network, or preferably both.

3.7.6 Methods

Three main types of information were collected in this project: systematic GPS observations of whale hunts, systematic observations of various components of subsistence whaling activity; and whalers' observations on whale behavior (and especially changes in such behavior). This last sort of information is often accompanied by perceptions of possible causes for such changes and the implications such changes may have for subsistence whaling activities.

The objective of this work was to determine if subsistence whaling activity and behaviors in the vicinity of Cross Island are significantly adversely changed by offshore oil developments at Northstar and/or Liberty and if general subsistence activities on/near Cross Island are significantly adversely changed by oil and gas activities associated with Northstar and/or Liberty. The MMS Cross Island project was intended to describe Cross Island whaling using measures that document year-to-year variability in whaling and, when sufficient time series data are available, will allow tests of hypotheses on the causes of this variability. Concern about potential effects of oil and gas development on whaling is the prime motivation for the MMS project, but it is recognized that other factors can strongly affect Cross Island whaling and thus need to be considered as well. These other factors include weather and ice conditions, equipment problems, whalers' decisions, and non-industrial human activities. During the MMS-sponsored project, information was collected on level of hunting effort, including how many boats go out each day, boat crew size, how much time is spent on the water, lengths of trips in miles, and furthest point away from Cross Island during each trip. Information is also collected on the abundance and distribution of whales, including the number and location of whales observed and/or struck by the whalers. This information will be applied to internal MMS management leasing plans and decisions, as well as stipulation requirements, and has also been recognized as important for the management decisions for other agencies.

Information on the level of hunting effort was collected by systematic observations by Dr. Galginaitis, who was on Cross Island for most of the whaling season in each of 2001–2007. This information was supplemented by conversations with all of the boat crews. Further information on the hunting effort, and on the abundance and distribution of whales, was obtained by issuing Garmin handheld GPS (Global Positioning System) units on all boats. The whalers were given instructions on how to record the GPS coordinates (track) of the boat's trip, and how to mark waypoints of significance, including whale sightings and strikes, sightings of vessels other than whaling vessels, and other pertinent observations. This information was then mapped. Whalers

tended to mark relatively few points when on the water, and the points they do mark represent the boat's position at the time a whale or group of whales was seen. These whales may be quite close or miles away.

This information was supplemented by subsequent conversations with each boat crew, while reviewing the mapped GPS information on a laptop computer with them. When reviewing tracks after their return, boat crew members would often identify locations where they saw whales, and these points were added to the GPS information. Some of these points were boat positions, and some were estimated positions of whales (and thus not on a boat track). Other points were reference coordinates and may represent past whale sightings, so they also may not be on boat tracks. Galginaitis did not accompany the whalers in their boats while they were hunting, since it is not permissible for any non-native to participate actively in hunting marine mammals.

What has become clear from an examination of the seven field seasons of data is that, at least during the period of study, there does not appear to be any clear way to demonstrate any adverse effects of oil and gas activities on Cross Island subsistence whaling. There are several possible components to this result. First is the existence of the CAA between the whalers and industry. The CAA, for the most part, has minimized adverse effects of industry activities on whaling activities and vice versa. The CAA has had a positive effect in its logistical support provided to the Cross Island whalers. This does not mean that there is no disagreement between industry and the whalers, or that specific conflict incidents did not occur during the period of the research. Such incidents were singular in nature, however, and not amenable to generalization or statistical treatment. Second, obtaining detailed information on the timing and geospatial location of oil and gas activities was not part of this project and has not been systematically compiled by BOEMRE/MMS or others. The MMS Human Activities Database documents only the period before 2000, and not in great detail. Thus, it is difficult to articulate possible mechanisms of articulation between oil and gas activities and subsistence whaling. Third, oil and gas activities are only a subset of commercial activities that can potentially affect subsistence whaling. Commercial barge and other vessel traffic is a great concern to subsistence whalers, and the one major incident that occurred during the period of the research involved an encounter between whaling vessels and a commercial (non-oil and gas) tug and barge in 2005. At present, there are few if any reporting requirements for such commercial (or non-commercial) vessel traffic. Fourth, many subsistence whalers are most concerned about the potential effects of events or activities that have not yet taken place, such as offshore oil spills, or offshore development to the east (rather than the west) of Cross Island, for example. The data collected on the 2001-2007 whaling seasons cannot address concerns about future hypothetical impacts, other than to provide comparative information that may be useful to gauge or measure future effects.

It is clear that Cross Island subsistence whaling is quite variable, and that the seven years of data are quite useful in describing this variability. Factors that seem to account for most of this variability are the weather (especially wind speed), ice conditions, the decision-making characteristics of individual whaling captains, and other activities going on in the vicinity of Cross Island. As discussed above, the last factor was either largely absent, or to the degree present largely undocumented, and so is not explicitly treated at any great length in this report. To the extent that these activities do take place and are documented, the variability of Cross Island whaling documented here may be attributable to them to some degree.

3.7.7 Results

Results are discussed in this section in terms of the quantitative observations designed as measures of subsistence whaling activity and the less quantifiable observations and perceptions of Nuiqsut whalers about whale behavior in the 2001-2007 Cross Island whaling seasons. The primary focus is on year-to-year comparisons and the discussion of variability.

3.7.7.1 Quantitative Measures

Detailed quantitative data will not be presented here. Rather, the following discussions are based on the summary and comparison of these data presented in Table 3-53. Some of the discussions will reformulate portions of these data, or present supplemental details. Quantitative measures that are considered significant are included in Table 3-53. When composing discussions of various aspects of the 2001-2007 Cross Island whaling seasons, it became clear that other available measures were also pertinent to the discussion. Most if not all of the data for 2001-2007 was developed for this project, but of course most of the data for seasons prior to 2001 comes from other sources (although they were perhaps obtained or processed as part of this project).

All of the measures discussed in this section relate in some way to the "success" of any given season, but "success" is a relative term and may mean different things for different people. In the final analysis, Nuiqsut whalers define "success" as landing sufficient whales to satisfy the community's needs (which include a percentage for sharing with residents of other communities). Whalers will note seasons with poorer weather more often than others, and certainly prefer shorter seasons over long ones, but ultimately judge a season by the number of whales landed. Perhaps this is because so many factors that clearly influence the subsistence bowhead hunt are beyond the control or influence of the hunters – weather, ice conditions, and the timing and path of the bowhead migration, among other possible factors. More anthropogenic factors, such as other vessel traffic, oil and gas activities in general, mechanical and equipment failures, and accidents, also potentially influence the course of the hunt and possibly "success" in landing whales, but can at least in theory be minimized by proper planning and management. Whalers seem to differentiate the two categories of factors. Seasons may be characterized as "poor weather" years (2003, 2004, 2005, 2007) or "bad ice" years (2005, 2006) or years when the whales were farther out or behaving in a different way making the hunt more difficult (2001 and to some extent 2002). Any of these conditions, or a combination of them, can result in not landing sufficient whales for the village – but if 3 or 4 whales are landed, whatever the natural conditions have been, the season is considered successful. The one project field season during which the whalers experienced direct disruption of their hunt by non-whaling vessel traffic (a commercial, but not petroleum industry, tug and barge) was 2005, a "bad ice" and "poor weather" season and the only project season when the Nuiqsut whalers landed fewer than 3 whales (only 1). While a single case is not sufficient to establish an argument one way or the other, Nuiqsut whalers characterized this season as much by this disruption incident as by the ice and weather conditions. As will be discussed below, absent this incident, they indicated they may have been able to land at least one more whale (but would never claim that this was certain, as that would not be showing proper respect for the animals).

Table 3-53. Selected measures of Cross Island subsistence bowhead whaling, 2001 through 2007. From Galginaitis et al. (2009).

Metric	Type	2001	2002	2003	2004	2005	2006	2007	Mean
Whales Taken/Whales Stuck&Lost	Count	3/0	4/1	4/0	3/0	1/0	4/0	3/1	3.1/0.3
Active Whaling Crews on Cross Island (Max)	Count	4	3	4	4	5	4	5	4.1
Active Whaling Crews on Cross Island (Mean/day)	Mean	3.8	2.5	2.8	2.6	4.1	4.0	4.0	3.3
Scouting Boats on Cross Island (Max)	Count	7	9	10	8	8	7	9	8.3
Cross Island Population (Max/Ave/day)	Mean	35/27.7	39/26.6	33/20.4	33/18.9	43/29.8	38/29.2	36/26	24.8
Length of Season[1]	Count	24	23	19	30	27	21	13	22.4
Mean Length of Season/Crews (days on Island)	Mean	22.5	19.3	13.2	19.2	21	21	10.4	18.1
Weather Days	Count	8-9	4	8	10	11-15	4	3	7.6
No. Days Scouting[2]	Count	12	15	7	12	9	10	5	10.0
No. Days Whales Seen[3]	Count	9	9	7	6	7	8	4	7.1
Boats Scouting/Day	Mean	4.8	4.3	4.9	3.4	4.0	4.8	3.2	4.2
No. Boat Days[4]	Count	57	65	34	41	35	48	16	42.3
Boat Days/Whale	Mean	19	16.2	8.5	13.7	35	12.0	5.3	13.4
No. Boat Trips (Possible No. GPS Tracks)[5]	Count	59	67	42	46	48	53	22	48.1
Actual No. GPS Tracks Collected	Count	49	52	37	44	48	51	20	43.0
Length of Trip (Miles)	Mean	84.0	64.3	37.2	45.3	60.7	60.8	30.1	58.5
Duration of Trip (Hours:Minutes)	Mean	9:43	7:58	4:31	6:51	7:07	8:13	5:39	7:32
Furthest Point from Cross Island (Miles)	Mean	23.6	19.5	11.6	12.1	19.1	22.2	10.4	18.1
Strike Distance from Cross Island (Miles)	Mean	19.5	13.4	9.3	9.7	25.9	17.0	12.0	13.9
Strike Direction from Cross Island (Degrees)	Mean	64°	67°	56°	36°	82°	59°	80°	62°
Boat Crew Size	Mean	3.9	3.6	2.9	3.6	4.4	4.3	4.2	3.9
Total Seasonal Boat Effort (Boat-Hours)[6]	Sum	573	534	163	301	341	427	124	352
Boat Hours/Whale	Mean	191	133	41	100	341	107	42	112
Bout Hours/Strike (Landed + Struck&Lost)	Mean	191	107	41	100	341	107	31	103

[1]Number of days with at least on whaling crew on Cross Island, including days of arrival and departure from Cross Island.

[2]Number of days when at least one whaling boat went out scouting for whales.

[3]Number of days when at least one whaling crew saw whales while scouting from a boat. Blows were seen from Cross Island on a few non-scouting days, but are not included in these totals.

[4]Each boat scouting for whales on any given day counts as one "boat day", regardless of the duration of the trip or if whales were seen or not.

[5]Some boats made more than one scouting trip on a single day.

[6]Yearly total equals aggregate sum of duration of all whaling trips by all boats.

That said, whalers will indicate that some seasons are "better" than others, and generally "better" means "shorter" in terms of days spent out at Cross Island (with the caveat that 3 or 4 whales were landed). Good weather is preferred, but not a necessary condition, for a "better" season. The shortest seasons documented by the project were those with arguably the worst weather (2007, 2003) but other factors (whales close to Cross Island and the adaptive behavior of the whalers) allowed the whalers to use their full quota of strikes in both years. Thus these finer distinctions of what makes some seasons "better" than others – the evaluation of the variability between and among seasons - is recognized by Nuiqsut whalers. Thus the measures discussed below make sense to the whalers, but some they accept as factors they cannot change but need to adapt to (weather, sea conditions, ice conditions, whale migration) and others (anthropogenic) to which the whalers mostly (in present conditions) need to adapt. In principle, the anthropogenic factors could be (and through "mitigation" or other management practices actually are) influenced or minimized, at least in terms of timing or where they take place (oil and gas activities, other vessel traffic). The CAA between the whalers and industry is the one mechanism for reducing the potential effects of such anthropogenic factors, as are lease stipulations and lease deferral areas. It may be the sense that these factors can be limited or controlled that makes the cases where they occur, or mitigation measures fail, so salient to the whalers. The following discussions focus on specific measures, followed by a more general examination of variability in Cross Island whaling.

3.7.7.2 Whales Landed in Relation to Quota

The most obvious indicator of whaling success is the number of whales taken. The quota for Nuiqsut during the project years has been four strikes per season. This usually is expressed as "four whales" not because the whalers expect to land four whales or take this for granted, but because each strike counts as a dead whale in the bowhead population model, whether it is landed or not. This suggests two other measures of degree of whaling success – the number of whales landed versus the total number that could have been landed, and the number of whales landed versus the number of whales "wasted" or "struck and lost." Nuiqsut whalers could have landed 28 whales for the years 2001-2007. They actually landed 22, or 79 percent. They had two struck and lost whales in this period, so they landed 22 of the 24 whales they struck, or 92 percent. Both represent high rates of success, and probably Kaktovik is the only other Alaskan whaling community that may match or surpass them.

For four of the seasons in the period 2001-2007, Nuiqsut whalers completed their quota of four whales – 2002, 2003, 2006, and 2007 (Table 3-53). In both 2003 and 2006 they landed four whales, with no struck and lost. In both 2002 and 2007 they had one struck and lost whale, and landed three whales in 2007 and four in 2002 (one strike was transferred from the AEWC "bank" of unused strikes). The first three whales landed in 2002 were fairly small, so that a fourth one was desired to ensure that community needs were satisfied. In 2007 the three whales landed were sufficiently large that a fourth whale was perceived as unnecessary and potentially wasteful. It is interesting to note that the four years when Nuiqsut whalers completed their quota are also the four shortest seasons in terms of number of days for the study period – 13, 19, 21, and 23 days. This compares to the "average" season over this period of 22.4 days, and the other three seasons of 24, 27, and 30 days. Not coincidentally, the four seasons when the Nuiqsut whalers completed their quota are also the four seasons with the fewest weather days – 3, 4, 4, and 8 (although one of the other three seasons had "only" 8 weather days as well).

Although Nuiqsut whalers state that three whales can be sufficient for the needs of the community, they clearly have a preference for landing four whales. The longest seasons documented by this project are those for which the quota was not completed, whether they were seasons when only three whales were landed (2004, 2001) or only one (2005). The median case of 2002 is interesting in this regard, as the whalers requested (and received) a fifth strike to use to land a fourth whale, as they had struck and lost an earlier whale. As will be discussed in the following section, Nuiqsut whalers stay out at Cross Island until they land sufficient whales for the village or until the conditions in their judgment become untenable for whaling.

As a measure of level of effort, the number of whales landed (or strikes used) does not appear to be a very useful measure. For all but one of the seasons discussed in this report, Nuiqsut whalers landed either three or four whales, and considered the seasons successful. The number of whales landed, combined with their size, is a measure of the ultimate success of any given season. The AWEC allocates a quota to each Alaskan whaling community based on that community's needs, based on a number of factors (Braund, Stoker, and Kruse,1988; Braund & Associates 1997, 2007), and fulfilling that quota is each community's goal for any given season. Nuiqsut whalers prefer to target whales 25 to 35 feet in length, but if the first three whales they land are larger than this (as in 2007, for example) they may choose to forego trying to land a fourth. In other years, Nuiqsut whalers may essentially run out of time before completing their quota, as in 2001, 2004, and 2005. In 2001 and 2004 they landed three whales, with no struck and lost, and felt that at least the basic needs of the community were fulfilled. In 2007, Nuiqsut whalers landed three whales and also had a struck and lost whale, but the three landed whales averaged near 40 feet each and were judged to more than fulfill the community's needs. In 2005, only one whale was landed due to very adverse weather and ice conditions, and possible disruption from a commercial barge, and the whalers were forced to end their season with only this limited harvest. The whalers considered 2005 a poor whaling season due to this limited harvest (results of the season), attributed by the whalers to the conditions of the season (weather, ice, vessel encounters). The whalers distinguish between conditions and results, however. Overall physical conditions were good for whaling in 2001 and 2002, but because of the distance of whales from Cross Island more effort was expended to land each whale in those years than in other years (2003, 2004, 2007) when physical conditions were poorer but whales were more plentiful and closer.

3.7.7.3 Timing and Length of Season

This section will begin with a general discussion of the timing and the length of the 2001-2007 Cross Island subsistence whaling seasons. It will conclude with a discussion of the effectiveness of "length of season" as a measure of level of effort or a characterization of the season as a whole.

As mentioned above, Nuiqsut whalers state that they usually go to Cross Island after Labor Day (the first Monday in September) and that ideally, all whaling crews would travel together and on the same day. For the seven seasons documented by this project, this was never the case, although the 2006 season came very close (Table 3-54). For most seasons (five of seven), the first whaling crew left for Cross Island alone. In one season two whaling crews left for Cross Island on the same day, and in another season three whaling crews left for Cross Island on the same day. In only one case did the first whaling crews actually leave for Cross Island on Labor Day. On average, these "first whaling crews" left for Cross Island 6.4 days before Labor Day.

Table 3-54. Timing and duration of Cross Island subsistence whaling seasons, 2001 through 2007. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Average
Date Labor Day (LD)	9/03	9/02	9/01	9/06	9/05	9/04	9/03	9/03
Date 1st Crews Out (FCO)	9/03	8/30	8/23	8/15	8/30	9/02	8/30	8/28
FCO-LD[1]	0	-3	-9	-21	-6	-2	-4	-6.4
Date 2nd Crews Out (SCO)	9/06	9/01	8/29	8/30	9/04	9/03	8/31	9/02
SCO-LD[1]	3	-1	-3	-6	-1	-1	-3	-1.7
Date 3rd Crews Out (TCO)	NA	9/05	8/31	9/04	9/05	NA	9/03	9/03
TCO-LD[1]	NA	3	-1	-2	0	NA	0	0
Length of Season (Days)	24	23	19	30[2]	27	21	13	22.4

[1]A negative number represents the number of days a date occurs before Labor Day. A positive number similarly represents the number of days a date occurs after Labor Day.

[2]Not included in this total are an additional 5 days when no one was present on Cross Island. The whaling crew that had gone out early returned to Nuiqsut to wait out a period when extremely bad weather was expected.

One season was clearly anomalous in this regard (one whaling crew leaving for Cross island a full 21 days before Labor Day, but only being able to scout for whales five times before Labor Day, with no whales seen). Not counting this season, "first whaling crews" still left for Cross Island an average of 4 days before Labor Day. In five of the seven seasons whaling crews traveled to Cross Island on three different days, and on two different days for the other two seasons. On average, the "second whaling crews" left for Cross Island 1.7 days before Labor Day, and "third whaling crews" on Labor Day. The behavioral generalization would seem to be that whaling crews try to be at Cross Island by Labor Day, with variation due to the individual characteristics of the captains making the decision for each whaling crew. Labor Day is an accepted date because the temperature tends to be lower in September than in August, which is better for maintaining the quality of the butchered products. As the first Monday in September, at the start of the week, Labor Day seems to serve as a marker for the start of September – explicitly recognized by whalers when they say that they go out to Cross Island before Labor Day when Labor Day is "late."

Examining whaling crew departure dates for Cross Island strictly in terms of calendar date (and not in relation to Labor Day), there is a clear trend for "first whaling crews" to arrive on Cross Island in late August (8/28), and for all whaling crews to have arrived by early September (9/03). During the seasons documented by the project, Labor Day occurred, on average, on 9/03. This is perhaps more support for Labor Day being used as a convenient, already labeled, reference point rather than as a definitive one – or perhaps its use as a date that applied to past whaling behavior and not as much to current behavior. As will be clear when the data on Nuiqsut whaling since 1973 are presented below, whaling occurred later in the year before 1993 than it does currently. Factors that may help account for such a change will be discussed at that time.

The whale migration, at least in the past, has also been fairly predictable in terms of timing to reach Cross Island on or about September 1, or Labor Day. Some captains are now of the view that the bowhead whale migration is starting earlier in the fall than before, and this may simply be another way of stating that they know bowhead whales are usually present in the Cross Island

area in August (precisely when in August is their question). Since the small whales tend to migrate first and the whalers prefer the small whales, this is an incentive to some captains to leave for Cross Island sometime in August, before Labor Day. Also, although whaling is a cooperative endeavor, some captains seek at least a temporary "competitive advantage" by being the first whaling crew out at Cross Island (and once on Cross Island, the first whaling crew to leave the island to go out scouting for the day). Other factors also influence the decision of when a whaling crew leaves for Cross Island – when the boat(s) and crew members are actually ready to leave, the other obligations (usually work or meetings of some sort) that the captain and crew members may have that may limit the span of time they can stay at Cross Island, and the perception that the weather after September 20 has increasingly become more unpredictable and poor for whaling. Most Nuiqsut whalers now seem to typically "budget" two weeks for whaling at Cross Island, although historically (from whalers' accounts) most seasons have been longer than that. Recent seasons exhibit a number of characteristics that support the conclusion that Nuiqsut whalers currently incorporate more time constraints (wage employment, travel and meeting obligations) into their whaling decisions than was required in the past (also discussed below).

The relationship between the date whaling crews first go out to Cross Island and the length of the season is not clear – except for the obvious that a later start implies a season with fewer possible days than does an earlier start. The longest season documented by the project was that with the earliest starting date, 8/15 in 2004. This was probably an experiment in response to the experience of the 2003 season. In 2003, the first whaling crew arrived on Cross Island on 8/23 (the second earliest during the project), with other whaling crews arriving 8/29 and 8/31. All whaling crews were on hand when the weather broke on 9/01 and conditions were good for whaling. The whalers completed the quota on 9/06, and left for Nuiqsut on 9/10 – a season of 19 days, the second shortest documented by the project. In 2004 a captain may have hoped to duplicate this but to avoid the first week of bad weather experienced in 2003 by going out even earlier than in 2003. Instead, this whaling crew encountered worse weather than in 2003 and saw no whales on the few days they were able to go boating. Once other whaling crews arrived on Cross Island (8/29, 9/04) two whales were quickly landed (9/05, 9/06) but conditions again deteriorated and even when boats could go out few or no whales were seen. A third whale was taken 9/14 and a decision was made to call an end to the season. If the first whaling crew had not gone out so early, this would have been a fairly "typical" season in terms of duration and other factors. All other seasons were very similar in terms of the date that the first whaling crew(s) left for Cross Island, ranging from 8/30 to 9/03. The duration of these seasons ranged from 13 days (the shortest documented by the project) to 27 days (the second longest documented by the project). Clearly many factors interact and influence the duration of a Cross Island whaling season, but the available "window of opportunity" when whales are present, temperatures are fairly cool, and weather and ice conditions are acceptable is fairly well delimited as late August through middle-to-late September. This is also a change from the documented historical past, as some whales were taken by subsistence whalers in the mid-Beaufort in October.

Table 3-55 summarizes measures related to whale strikes for each season that are consistent with and support these conclusions. The first whale of the season was struck during the five seasons with no unusual ice conditions no sooner that 8/31 and no later than 9/06. The first whale of the season was struck later in 2005 and 2006 because the whalers were prevented from reaching the whales by ice conditions that blocked them from boating beyond the barrier islands. As soon as

they found a way through this ice to the whales in the open water beyond the ice, they were able to strike and land a whale (the only whale for 2005, the first of 4 for 2006). Ice conditions in 2005 and 2006 clearly made these years different from the other five documented by the project. The "average strike date" for 2005 and 2006 was September 15, whereas for the other five seasons the average strike date was September 8 (and September 10 for all seven seasons).

Table 3-55. Selected measures related to bowhead whale strikes by Cross Island whalers, 2001 through 2007. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Average
Average Distance	19.5	13.4	9.3	9.7	25.9	16.8	12.0	13.9
Average Bearing	64	67	56	36	82	59	80	62
Date 1st Strike	5-Sep	5-Sep	1-Sep	5-Sep	14-Sep	13-Sep	31-Aug	6-Sep
Date Last Strike	22-Sep	15-Sep	6-Sep	14-Sep	14-Sep	18-Sep	7-Sep	14-Sep
End of Season	26-Sep	21-Sep	10-Sep	18-Sep	25-Sep	22-Sep	11-Sep	19-Sep
Date Average Strike	13-Sep	10-Sep	5-Sep	9-Sep	14-Sep	15-Sep	5-Sep	10-Sep
Note: "Average Strike Date" (ASD) must be an integer value. For example, the computed ASD for 2001 of September 12.333 is a calendar date of September 13.								

The last whale of the season was struck over a wider range of dates, from as early as 9/06 to as late as 9/22. As would be expected, the last whale of the season was struck earliest for the two shortest seasons documented by the project, and also the two seasons when whales were arguably closest to Cross Island. Whalers reported that whales were close to Cross Island in both these years. All seasons ended either a few days after the quota was filled (to allow for butchering and packing) or if the quota had not yet been filled, when the whaling captains determined that conditions were such that it was not wise to remain at Cross Island any longer (freeze-up imminent or weather inclement). Of the project seasons, only in 2001 was the day the last whale was struck for that season after the average day for the end of the season for all seven seasons. 2001 was also the season with the latest ending date.

Table 3-56 summarizes some measures that one might expect to influence or be related to the duration of Cross Island whaling seasons – mainly weather conditions (number of "weather days") and measures of the relative number and distance of whales in the proximity of Cross Island. Missing from this table is a quantitative measure of ice conditions. Ice as a factor will be discussed in a later section in qualitative terms, because ice was a factor mainly due to its absence. "Weather days" is a label mainly for days when the wind was too strong for the boats to go out looking for whales. In the absence of ice, any wind over 10 miles per hour (mph) can create sea conditions making seeing and striking a whale, and then towing it to Cross island, difficult. The presence of the edge of the shelf ice dampens the height of waves and swells created by wind. Nuiqsut whalers will go out scouting for whales when winds are over 10 mph and there is little or no ice, but such conditions are marginal and whalers scout in such conditions only when prospects for improved conditions are slight. Floating ice floes may have been a factor in 2001, and local ice conditions were certainly a factor in 2005 and 2006.

Table 3-56, Measures related to weather and whale distribution affecting the Cross Island subsistence whale hunt, 2001 through 2007. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Average
Duration (days)	24	23	19	30[1]	27	21	13	22.4
# Weather Days	8	4	8	13[1]	13	4	3	7.5
# Days Scouting	12	15	7	12	9	10	5	10.0
# Days Whales Seen	9	9	7	6	7	8	4	7.1
Av Length of Trip (miles)	83.9	64.3	37.2	45.3	60.7	60.8	30.1	58.5
Duration of Trip (Hr:Min)	9:43	7:58	4:31	6:51	7:07	8:13	5:57	7:32
Av Farthest Point from Cross Island (miles)	23.6	19.5	11.6	12.1	19.1	22.3	10.4	18.1
Average Strike Distance from Cross Island (miles)	19.5	13.4	9.3	9.7	25.9	17.0	12.0	13.9

[1]Not included in this total are an additional 5 days when no one was present on Cross Island. The whaling crew that had gone out early returned to Nuiqsut to wait out a period when extremely bad weather was expected.

Of course Nuiqsut whalers' observations of whales near Cross Island are only representative of the area where they are actually looking for whales, and are by no means a measure of the total bowhead population or of the migration route in general. The whalers report that prior to oil and gas development, the whale migration passed close to Cross Island and even inside of the barrier islands sometimes. They no longer see many whales inside the barrier islands and note that, in some years, whales are closer to Cross Island than they are in other years.

The number of "Weather Days" – days when all Nuiqsut whaling captains decided that conditions were not suitable to go out whaling – have an obvious relationship to the total length of a whaling season. They are only one factor, and not the entire story, however. While the longer duration seasons tend to have had more weather days, seasons with relatively few weather days (3-4) ranged in duration from 13 to 23 days. Overall conditions may be good for scouting, but whales may not be present. Whales could be present, but in low numbers and/or at relatively great distances so that they are relatively hard to find. The whales that are seen could be behaving in ways that make them difficult to follow and approach. Thus, season length can be expected to be quite variable and dependent on a number of factors, of which weather is just one.

The number of "Scouting Days" (days when the whalers go out looking for whales) is also clearly related to the duration of the season, and is not independent of "weather days." The normative expectation, as reported by whaling captains and experienced whaling crew members, is to take one whale on any given day that boats go out scouting, although in recent years two whales are not uncommonly landed at Cross Island on the same day. Thus, the minimum number of scouting days expected for a Cross Island season would be 2-4. Any number over 4 represents an extension over the ideal "shortest season". The number of scouting days does seem to correspond well with the duration of the overall season. The shortest season (2007, lasting 13 days) had 5 scouting days and 3 weather days. The next shortest season (2003, lasting 19 days) had 7 scouting days and 8 weather days. Both of these seasons had a high percentage of scouting days on which whales were actually seen (80 percent for 2007, 100 percent for 2003). The difference between the two seasons seems to be relatable to weather. The three seasons ranging

from 21 to 24 days in duration (2001, 2002, 2006) had far more scouting days than the shortest two seasons, ranging from 10 to 15. Two of these seasons (2002 and 2006) had relatively few weather days while 2001 had a relatively high number of weather days. Whales were seen on only 60 percent of scouting days in 2002, and on 75 and 80 percent of such days in 2001 and 2006. The two longest seasons (2004, 2005 of 30 and 27 days in duration) had 12 and 9 scouting days, but whalers actually saw whales on only 50 and 78 percent of those days, respectively. Furthermore, each had 13 weather days. Seasons differ in the number of days on which whalers saw whales but were not able to strike one, from 1 in 2007 (the shortest season) to 6 for 2001 and 2005, one a long season but the other close to "average" in length. The longest season, 2004, had only 3 days when whales were seen that a strike was not made, but only had 6 total scouting days and 10 weather days. There are two or three factors that would seem to contribute to this sort of variation. A larger number of days when whalers go out looking for whales but do not report seeing any may be due to the relative local scarcity of whales, scouting in conditions marginal for seeing whales, or a combination of the two, for that season. A larger number of days when whales are seen but a strike is not made may be due to more difficulty in following or approaching whales for that season than for seasons with fewer such days, and could be due to weather and ice conditions, "skittish" whale behavior, or a combination of the two. An estimate of the overall "skittish" behavior of whales is difficult if not impossible to quantify, but whalers made many more comments about skittish whale behavior in 2001 than for any other season, and also commonly remarked on such behavior in 2002.

The measures related to the distance whales were found from Cross island generally support the discussion above – although the 2005 season has some unique characteristics that must be taken into account. "Average Length of Trip" and "Average Farthest point from Cross Island" seem to be the better measures of the distance of whales from Cross island for a specific whaling season. Whalers in general do not travel further from Cross Island to find whales than necessary for a number of reasons. One is the often cited "principle of least effort" but at least equally as importantly is a concern for safety. Whalers constantly remind less experienced whalers (and the researcher) that the weather is very changeable and that the further from Cross Island boats travel, the more danger they are in if conditions change and the more difficult towing a whale would be. Resources at Cross Island are also finite (fuel, food, water) and whalers have made an explicit effort in recent years to whale efficiently. There has been an increased willingness on the part of Nuiqsut whalers to land more than one whale on the same day, or multiple whales on successive days, than in the past. Good whaling conditions cannot be assumed for the future, so the most is made of current conditions when they are favorable. "Average Duration of Trip" is affected by the time required for tows (for 2007 in particular) as well as by the average speed during the other parts of the trip (some trips are almost all at "scouting speed" while others have significant periods of high speed travel). "Average Strike Distance from Cross Island" is generally not as reliable a measure since it is an average of only 3 to 5 (or in the case of 2005 only 1) boat trip versus all boat trips for the year for the first two measures discussed above.

Comparing each of the seasonal average values to the overall average value for these first two measures (58.5 miles for the average boat trip, 18.1 miles as the farthest point from Cross Island) seem to indicate that whales were closer to Cross Island in 2007 than in previous years – which supports the observations frequently made by the whalers in 2007 that the whales were closer to Cross Island than in previous years. The average strike made in 2007 was further out than for two other seasons (2003 and 2004), at 12.0 miles, however, because of the number of shorter

scouting trips in 2007. 2003 had an average boat trip of 37.2 miles and an average farthest point of 11.6 miles, with the average strike at 9.3 miles from Cross Island. 2004 had an average boat trip of 45.3 miles and an average farthest point of 12.1 miles, with an average strike distance of 9.7 miles. Both were years when weather conditions were quite poor. Whales were relatively difficult to spot and follow, but more so in 2004 than in 2003. Whales were seen on all scouting days in 2003, but only on 50 percent of scouting days in 2004. 2004 would have been about the same in terms of measures as 2003 if the first part of the season, when only one whaling crew was out at Cross Island from 8/15-8/19 and then back in Nuiqsut for 8/20-8/24 were excluded.

The 2002, 2005, and 2006 seasons are all similar in terms of average mileage of boat trip and average farthest point reached from Cross Island, ranging from 60.7 to 64.3 miles for the first and 19.1 to 22.3 miles for the second. The three seasons were quite different, however, or at least each had a different distribution of whales and other factors they had to deal with. The difference in "Average Strike Distance from Cross Island" values for the three seasons reflect these differences. In 2002 whalers reported that the whales were closer than they had been in 2001, but still farther out than "normal." There also were far fewer whales than the whalers expected to see. Whalers only saw whales on 60 percent of the days they went out scouting. Whales were sparse and somewhat skittish (but again, not as much as in 2001). Thus in 2002, whalers had to cover a relatively big area and long distance to find whales, but when they did find them they were relatively close to Cross Island. The average strike in 2002 was 13.4 miles from Cross Island. In 2006 whales were somewhat easier to find, but also somewhat farther from Cross Island and the average strike distance was 17.0 miles. In 2005 localized ice conditions – packed floating ice against the north side of Cross Island – made it impossible for the whalers to travel beyond the barrier islands except for two days. On one of these days, sea state conditions made it hazardous to boat into open water beyond the ice. On the other day, whales were seen and one was landed, but the whalers also encountered a tug and barge that they believe hindered their hunt (discussed below). When the whalers were confined within the barrier islands, they were limited in where they could travel. The one whale they struck and landed, at 25.9 miles, was understandably well beyond the average trip they made in 2005. The whaling crew that took this whale did so because it might have been their only chance to take a whale. Other whaling crews, thinking that this area was too far from Cross Island, had returned to the island before this whale was struck. These whaling crews then scouted to the NW of Cross Island and found whales at a closer distance – but only after the whale had already been struck to the east. The senior Nuiqsut whaling captains did not want to risk striking two whales on the same day, given the distances and ice conditions involved for the first whale.

2001 was the year for which average trip distance was greatest (83.9 miles) and boats on the average went farthest from Cross Island (23.6 miles). The average strike was also the farthest from Cross Island than for all other years except 2005 (when only one whale was taken) at 19.5 miles. This reflects the whalers' reports that 2001 was the year when whales were farthest from Cross island, were difficult to find because there were not many of them, and hard to approach because they were skittish and already traveling fast before the whalers saw them.

In summary, weather is one determinant of season length, but whalers are patient enough to wait for opportunistic "breaks" when they can go out looking for whales. Whalers cannot control the weather, but in most seasons they can expect at least a minimal number of days suitable for whaling. When those days occur, seasons during which whales are more numerous and/or closer

to Cross Island tend to result in shorter seasons than when whales are fewer and/or farther away. If there is a second complicating factor, such as the ice conditions of 2005 (and the first half of 2006) that limited where the whalers (and other maritime traffic) could go, seasons are likely to longer and the chances of success are greatly diminished. The length of the season, in terms of days, is not really an estimate of the level of effort required to land whales; however whales were taken for that season, but only the length of time that Nuiqsut whalers had to spend at Cross Island that year. The next section considers some other gross measures of Cross Island whaling activities that also may reflect more the relatively remote location of Cross Island as a whaling site from Nuiqsut than the actual level of effort required to land whales there in any one specific season. The section discussing Effort Per Unit Catch, following the next section, attempts to define a measure that is comparable for all whaling communities, and essentially defines "whaling effort" as the time spent on the water looking for and landing whales – from the time a boat leaves shore until the whale is hauled out of the water. While this measure also has deficiencies and could be improved, it seems to serve the purpose of providing a rough measure to compare the seven seasons documented by this project, and potentially for other whaling communities as well, should comparable information be available for those communities.

3.7.7.4 GPS Information

All whaling crews agreed to carry and use GPS units. The level of information obtained has varied from boat to boat, but for most boats and for all whaling crews, at least partial tracking information (where most boats went each day) was obtained, along with the locations where whales were observed (or struck), from the start of the project. The quality of GPS information collected since the 2002 season is actually quite high (Table 3-57). Examples of GPS tracks for individual boats on a single day have been presented above (Figure 3-76) and complete tracks for all seasons are included in Figure 3-73.

Table 3-57. Percent of scouting trips by Cross Island whale boats that had GPS track documentation, 2001 through 2007. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Total
Boat Trips	59	67	42	46	48	53	22	337
GPS Tracks	49	52	37	44	48	51	20	301
% of Trips with GPS Tracks	83%	78%	88%	96%	100%	96%	91%	89%

Figure 3-77 shows the locations of the 10 whales landed and the 4 whales struck-and-lost by Nuiqsut whalers during 1986-1992. It does not display the locations of the first two whales landed by Nuiqsut whalers, in 1973 and 1982. The first was struck near Flaxman Island, within the barrier islands. The location of the second has not been identified. The information in Figure 3-77 was published previously (Long 1996). The locations for the 23 whales landed by Nuiqsut whalers during 1993-2000 may be known to the NSB and AEWC, but permission to publish that information has not been obtained. The locations of whales struck by Nuiqsut whalers during 2001-2007, as documented by this project, are discussed below.

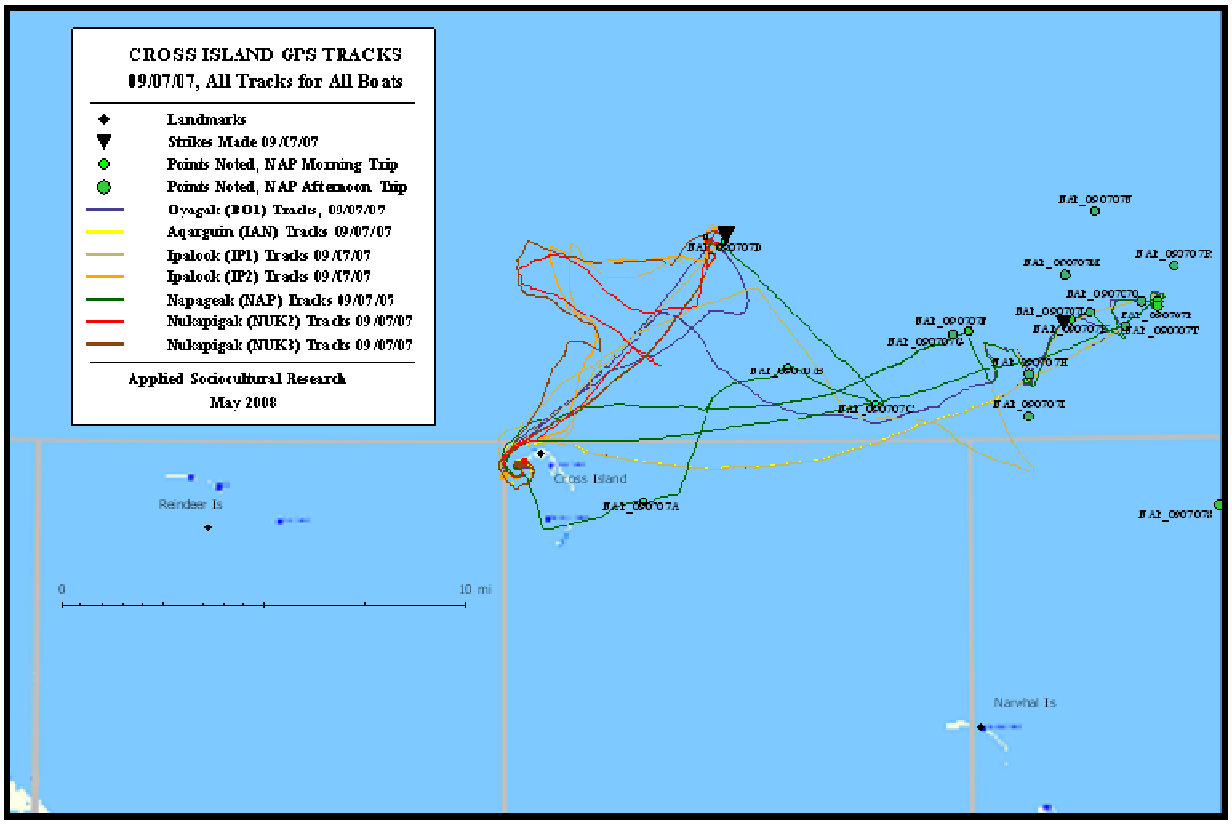


Figure 3-76. GPS tracks for all bowhead whale scouting trips from Cross Island on September 7, 2007. From Galginaitis et al. (2009).

Figure 3-77 is included primarily for historical purposes and to highlight two main points. First, the quadrant NE of Cross Island is where these strikes are concentrated, and those strikes not within this quadrant are either just south or just west of this quadrant. Second, 9 strikes occurred within 20 miles of Cross Island, of which only 1 was struck-and-lost. Of the 5 strikes beyond 20 miles, 3 were struck-and-lost. At least one of these was struck in good weather conditions, but was cut loose during the tow when conditions changed and the tow could not be continued safely. The whalers attributed this at least in part to the distance of the strike from Cross Island – and said that a whale struck closer to Cross Island on that day might have been landed at Cross Island.

Figure 3-73 shows all the GPS tracks collected for all the whaling boats for all years, coded by year. This comparison readily shows the variability from year-to-year. The relatively "normal" years in terms of distance traveled from Cross Island and direction of travel were 2003 (yellow), 2004 (blue), and 2007 (white). Whalers reported that in a "normal" year, whales could be found within 15 to 20 miles of Cross Island, and that they generally searched for whales in the quadrant NE of Cross Island. The patterns for these three years generally meet these conditions. All were years when there was little or no ice.

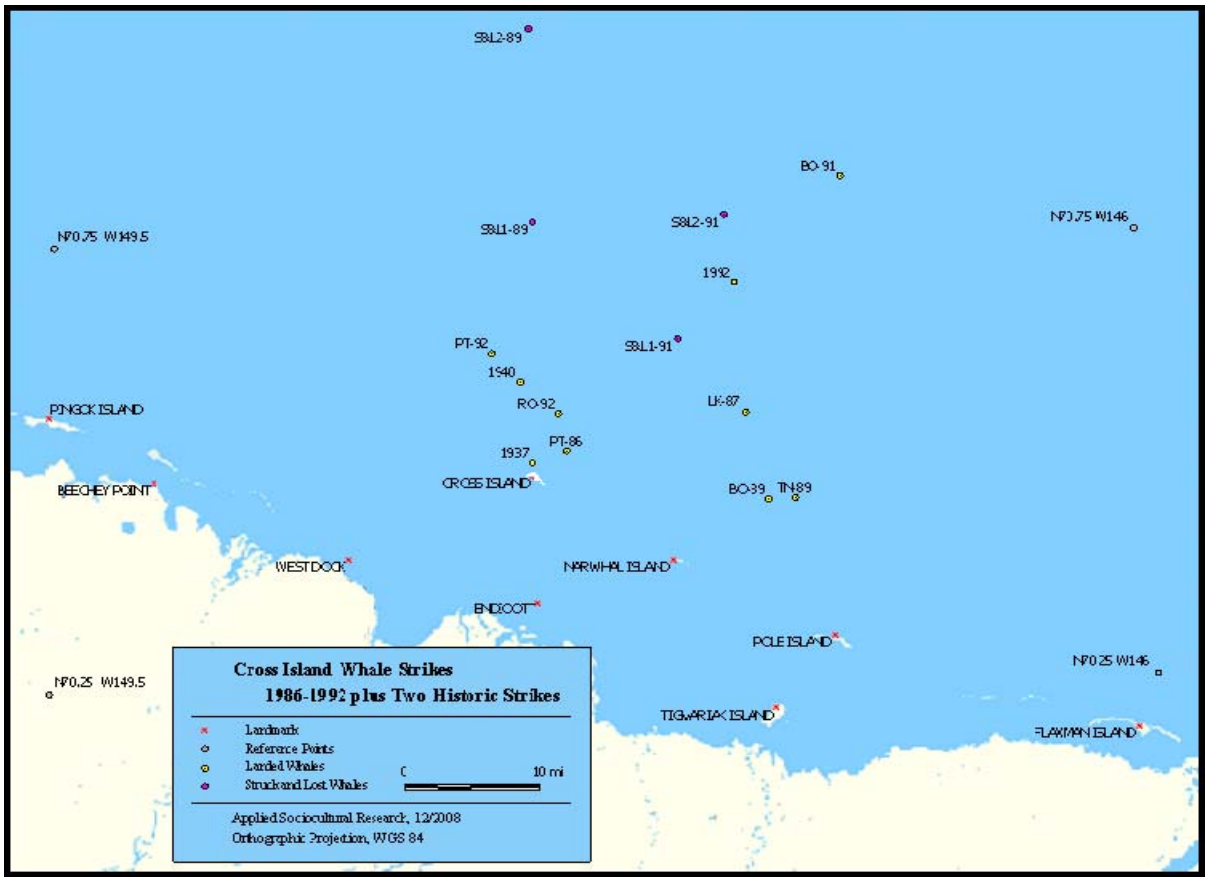


Figure 3-77. Historic bowhead whale strike locations in the Cross Island/Prudhoe Bay area between 1987 and 1992. From Long (1996) as presented in Galginaitis et al. (2009).

The track patterns for 2001 (purple) and 2002 (maroon) are essentially the three "normal" years except that the tracks extend farther from Cross Island, especially for 2001 (Figure 3-73). Whalers reported that the whales were the further from Cross Island in 2001 than they had been in quite a while, and the measures reported in this document bear them out. Whales were not quite as far from Cross Island in 2002 as in 2001, but were still farther from Cross Island than in any year documented for the project other than 2001. In both 2001 and 2002 the whalers indicated that the whales were not behaving in a normal manner, but were "spooky" – traveling fast, difficult to approach, and few in number. Both 2001 and 2000 were relatively ice free, although there was more floating ice in these two years than in 2003, 2004, and 2007. Scouting effort for these years was also concentrated in the quadrant NE of Cross Island.

Ice posed a severe constraint to whaling in 2005 (green), but was a localized pack of floating ice jammed against the north shore of the barrier islands (Figure 3-73). The ice shelf itself was located relatively far offshore. The whalers could not find a way through this jammed floating ice for most of the 2005 season. Winds were also relatively high on most days, which also contributed to limiting scouting activity to inside of the barrier islands. This explains the pattern of mostly SE and NW tracks within the barrier islands. Relatively few whales were seen on these scouting trips, and whales within the ice were impossible to approach. One whale was landed on

one of the two days when boats could find a way through the ice to open water beyond the barrier islands. The whalers also encountered a commercial barge on this same day, which may have contributed to their only being able to land one whale on this day. On the only other day when whalers were able to penetrate through the ice to open water, high swells prevented their being able to safely travel beyond the ice, and made spotting whales (let alone following and striking them) very difficult in any event. These two days account for all 2005 tracks beyond the barrier islands. 2005 was the first year documented by the project during which the whalers traveled west of Cross Island to any extent, mainly because the ice prevented them from going NE.

The first half of the 2006 (red) season duplicated the conditions of 2005, and the NW to SE pattern of tracks within the barrier island is even more evident than in 2005. When ice conditions moderated during the second half of the 2006 season, the track patterns were similar to those of a "normal" season except that the tracks extended slightly farther from Cross Island, and a few tracks stray somewhat west of the quadrant NE of Cross Island. The whalers were able to land their full quota of whales in 2006. Of the seasons discussed in this report, Nuiqsut whalers did not fill their quota in 2001, 2004, and 2005. In 2001 the whales were relatively distant from Cross Island and not very locally abundant, and the whalers essentially ran out of time and landed "only" three of their quota of four. In 2004 the whales were relatively close to Cross Island, but poor weather restricted whaling activities and the whalers again ran out of time. In 2005 ice and weather conditions allowed the whalers only two days of potential scouting beyond the barrier islands before time ran out on their season (potential freezeup) and they landed only one whale. In six of the seven years, Nuiqsut whalers landed either three or their full quota of four whales.

Figure 3-78, showing the whale sighting points for 2001 through 2007, demonstrates several main points, and then some comparative points of one year versus another. First, whales were seen where the whalers went and looked for them. Whales could very well have been where the whalers did not go, but the whalers were not there to see them. Second, the number of points for any given year roughly reflects the whalers' assessments of the numbers of whales they saw, but can be taken only as a minimum number of whales seen. As discussed in the methodology section, not all whales seen by the whalers were marked, and some points represent more than one whale. Third, there tended to be one or two days in each season (other than 2001 and 2002) when whale sightings were much more frequent than on other days. These sightings tend to form clusters (even though duplicate sightings have been eliminated as far as possible). Fourth, whale sightings are concentrated in the quadrant NE of Cross Island, where whalers search for whales most frequently and where the tracks are concentrated, but sightings are also located NW and SE of Cross Island, with some inside of the barrier islands.

Discussing the whale sighting points in comparative terms can only be done in a qualitative and speculative way, since the points do not represent all the whales seen for any given year, and may represent a different percentage or sample of the whales seen for year. With that understanding, the points were collected with the same methodology and from many of the same observers from year-to-year, so that they are at least in some sense comparable.

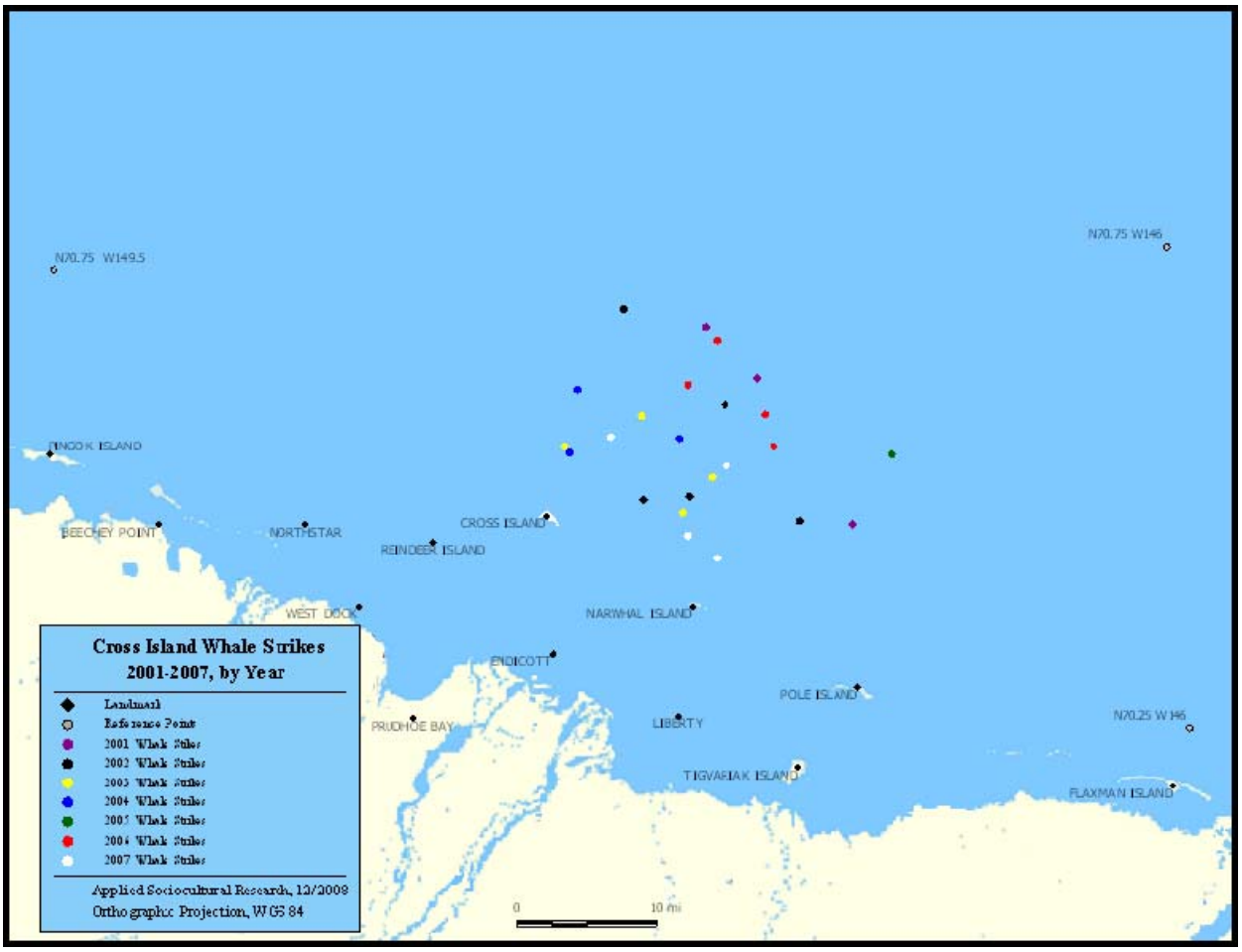


Figure 3-78. Bowhead whale strike locations near Cross Island between 2001 and 2007. From Galginaitis et al. (2009).

It does appear that the whale sighting points for the "normal" years of 2007, 2003, and 2004 are closer to Cross Island than form the other years. This does not mean that for those three years that whales were not also present in the locations noted for other years of the project, since for the three years in question the whalers did not go out that far. It does indicate that for the other years of the project, not as many whales were seen close to Cross Island as for these three years, even though whalers had to traverse those waters closer to Cross Island on their way to the locations where they did note seeing whales.

Note that there are some whale sightings relatively close to Cross Island for both 2002 and 2001, but that most whale sighting points for those years are farther out (and especially for 2001). Once ice conditions moderated in 2006, whales were located somewhat farther out than during the three "normal" years. The whales seen on the two days when whalers were able to travel beyond the ice (and the barrier islands) in 2005 were also located at this general distance, both to the NW and NE of Cross Island. Comparing the 2005 and 2006 whale sighting points, it is interesting that far more whales were reported along and within the barrier islands in 2005 than in 2006, although there was far more searching effort in this area in 2006 than in 2005.

Figure 3-78 displays the strike locations for each of the seasons, coded by year. Nearly all strikes were within the quadrant NE of Cross Island, with the only exceptions being those slightly south of this quadrant. The average strike distance for all strikes for all years was 13.9 miles from Cross Island – which corresponds with the whalers' reports that for most years they land whales 10 to 15 miles from Cross Island, and that in "good" years they find and land whales within 10 miles of Cross Island. The years with the closest average strikes were, as might be expected, the three "normal" years of 2003, 2004, and 2007 – although strikes in 2003 and 2004 were significantly closer to Cross Island (9.3 and 9.7 miles) than those in 2007 (12.0 miles). The atypical season of 2005, when only one whale was landed, and the 2007 season were the only seasons for which the average strike distance for the season was greater than the average greatest distance away from Cross Island reached on all whaling trips. For 2005 this reflects that only one struck was made, relatively far from Cross Island. For 2007 it probably reflects the generally poor weather encountered for most of the season and the inability to follow and strike whales except on days with somewhat better conditions, when whalers were able to travel a bit farther from Cross Island. On the other hand, weather was also poor for the 2003 and 2004 seasons, so there were probably some idiosyncratic or chance factors in play as well. The average strike distance for 2002 was also less than the average for all seasons, at 13.4 miles from Cross Island.

The three seasons for which the average strike distance was greater than the average for all seasons all had some characteristics that set them apart from the other seasons. Ice restricted where the whalers could go for most of the 2005 season, and the one strike was made when they finally could get beyond the ice, nearly 26 miles from Cross Island. According to many Nuiqsut whalers, this is near the limit where a prudent Cross Island whaler will make a strike (25 to 30 miles), since beyond this range the tow becomes too long. The average tow speed under even ideal conditions is 3 to 4 miles per hour, and sea and weather conditions can change too quickly to willingly risk many long tows. In 2005, much of the tow could take place with the protection of floating ice, which dampens the effect of wind and sea state, but can present its own problems for towing a whale. In any event, in 2005 whalers could not reach whales any closer than about 26 miles from Cross Island. In 2001, the whalers reported that most whales they saw were farther from Cross Island than "normal," were traveling at a greater speed than usual, and seemed "skittish" or behaviorally disturbed even before they encountered the whalers' boats. The measures of the 2001 season bear this out, as the whalers' trips for 2001 were the longest both in terms of distance and time duration of all the season documented. The average strike distance for 2001 was 19.5 miles from Cross Island. The 2006 season started out as did the 2005 season. Floating pack ice jammed against the north shore of the barrier island and prevented the whalers from reaching open water beyond the barrier islands for the first half of the season. Ice conditions moderated for the second half of the 2006 season, but whales were encountered and struck at greater distances from Cross Island than the 2002-2004 and 2007 seasons. Whether this was a residual effect of the ice conditions of the first half of the season or due to other factors was not clear. As discussed above, the whalers reported seeing whales at about the same distance from Cross Island in both 2005 and 2006, once they could travel outside the barrier islands.

3.7.7.5 Effects of Weather on Subsistence Whaling at Cross Island

The next seven figures are graphical summaries of key characteristics for each of the Cross Island subsistence whaling seasons documented by this report, 2001-2007. Each figure presents the information for one season. The factors that influence the success and length of a Cross Island subsistence whaling season, and how they interact, may perhaps be best understood by

explaining and discussing each in turn. The X-axis for each diagram represents the length of the Cross Island whaling season for the year in question, with units of 1 calendar day. Since seasons differed in length as well as starting and ending dates, the scales for the figures are not the same. The starting date of the whaling season was defined as the date that the first whaling crew arrived at Cross Island, and the ending date was the date the last whaling crew left Cross Island. The Y-axis for each figure is used to display two scales. The one on the right side of each figure denotes wind speed in miles per hour, while the left scale denotes barometric pressure in inches of mercury. Six sorts of data are plotted on each figure, except for 2001 which only has four data series plotted since there was no weather station at Cross Island in 2001:

- Wind speed from the Deadhorse weather station (average hourly values) – in blue
- Wind speed from the Cross Island weather station (readings every 4 minutes) – in teal
- Barometric pressure from the Deadhorse weather station – in black
- Barometric pressure from the Cross Island weather station – in light purple
- Periods when Cross Island whalers were out on the water whaling, from when the first whaling crew left the island on a given day until the last whaling crew returned for the day, plotted at the value of the average wind speed for that period of time as measured by the Cross Island weather station (or if that information was lacking, the Deadhorse weather station) – in red.
- Whale strikes, plotted at the time of the strike and the wind speed at the time of the strike, as measured by the Cross Island weather station (or in its absence, the Deadhorse weather station) – yellow triangles.

The plotted information does not provide a complete description of each season, but provides the most essential information – the length of the season, when whalers were out whaling, the time and date of strikes, and wind speed and barometric pressure when whaling could take place and when it could not. Wind direction and temperature information are also available and are included in the data appendices provided electronically for each annual report, but are not plotted as they did not seem to have much explanatory power.

The approximate nature of the time and location that whale strikes occur has been noted above. They are not precise in terms of exact time and place, but are quite close approximations based on the best reconciliation of various sorts of information – Communication Center log records of whaler reports, field notes of radio communications, and whaler GPS information. The available weather information is also only a proxy for the weather as experienced by the whalers. Wind speeds at Cross Island and Deadhorse tend to correspond with each other, especially in terms of overall patterns of increase and decrease, but as the figures show, can also often greatly diverge at times. Similarly, wind speed as experienced "on-the-water" by the whalers can differ from either of these time series records, although the whalers report that the wind speed at Cross Island does tend to correspond with what they experience while whaling. While they are out whaling they are careful to monitor the wind speed at Cross Island, however, as changes (and especially wind increases) that take place there and are not evident further offshore where they are whaling can signal sudden changes that indicate they should think about returning to the island. Barometric pressure for the two weather stations tended to correspond well, but the Deadhorse data covered a much longer part of each season. In the interests of clearer figures, the

Cross Island barometric pressure data is plotted in a light color so that it can be compared with the Deadhorse information without cluttering up the display of the other information. Increasing barometric pressure was usually associated with reduced wind speed, and vice versa, but not always. Since winds could be calm for a period of hours for any large change in pressure or weather system, whalers would sometimes whale during a period of decreasing barometric pressure, knowing that they would have a short period of good scouting conditions before facing a likely longer period when they could not go scouting.

In 2001 (Figure 3-79), the first whaling crews arrived on Cross Island on September 3 during a period of low winds, but wind speed increased and prevented any scouting for whales until the middle of September 5. This allowed the two whaling crews on Cross Island to land the first whale of the season on September 5 in moderate winds (about 8 miles per hour). The two other whaling crews traveled to Cross Island on September 6 as winds continued to be moderate at 10-15 mph. The whaling crew that had landed the whale the previous day stayed in to butcher, but the other crew already on Cross Island sent one of their two boats out to scout for whales while the rest of their crew stayed on the island to help butcher. On September 7, winds were moderate and remained so through September 10, below 15 mph for the most part, with barometric pressure peaking about September 9 and only starting to decrease sharply around September 11. All whaling crews went out scouting on all days from September 7-10 and a whale was landed on September 10, during a period when wind speeds were low (5 or 6 mph). All whaling crews stayed in to butcher the next two days, during a period of decreasing barometric pressure and fluctuating winds. All whaling crews went out scouting on September 13, as butchering had been completed and winds were moderate, although increasing. Two whaling crews each sent one boat out scouting the next day, but most captains chose to stay onshore, thinking that winds would increase still more. Instead, winds calmed late in the day and the barometric pressure was rising, so all whaling crews sent boats out scouting on September 15. Winds increased, however, and the boats experienced rough seas, so most came in after relatively short trips. All boats stayed onshore the next three days as winds remained above 15 mph for the most part, and peaked at just under 30 mph. Winds decreased on September 19 and two whaling crews sent boats out scouting, and all whaling crews sent boats out on September 20. On both these days conditions were not good for whaling, however, perhaps because of standing swells remaining from the past windy period. Winds peaked over 30 mph September 21 and all boat stayed onshore. On September 22 winds were less (below 10 mph, even though barometric pressure was decreasing) and all whaling crews sent out boats and a third whale was landed. All boats stayed onshore to butcher the next day (when it was windy in any event) and it remained windy (close to 25 mph) for September 24-25. With three whales landed and fully processed, and the prospects of deteriorating weather and possible freezeup, the whalers called an end to their season and reserved their last strike for a future season. They left for Nuiqsut on September 26, on a day with calm winds and had an uneventful and easy trip back to Nuiqsut.

One of the reasons this season was longer than average, even though the weather was not notably bad, was that the whale migration was relatively far from Cross Island, and the whales were difficult to find and approach. The whalers used only three of their four strikes in 2001, but went scouting on 12 different days. They saw no whales on three of these days. The whalers stated that there seemed to be fewer whales in the area, and those that were there were farther from Cross Island than “normal” and were swimming faster and acted in a “skittish” manner. The further from Cross Island the whalers go, the rougher sea conditions for the same wind speed

tend to become. In 2001 there was some floating ice offshore, but not enough to moderate the effect of the wind. Most scouting in 2001 took place when winds were 10 mph or below, and trips except on one day were when winds were below 15 mph (and that day may have been a calculated gamble). All strikes took place when wind speed was 7 mph or less.

In 2002 (Figure 3-80) the overall wind pattern was similar to that of 2001, at least superficially. Overall wind speed varied within the same range, but did not maintain high speeds for the periods of time it had in 2001 – until the end of the season. There were no spans of several days when scouting activity was not possible. Most scouting activity took place at wind speeds of less than 10 mph, as in 2001, again with only one day of scouting when the wind speed was over 15 mph (by only one boat). The first whaling crew arrived on Cross Island August 30, earlier than in 2001 and was probably an explicit decision in order to try to avoid poor weather at the end of the season, and to have some "extra" time after the experience of the year before when the whaling crews had to leave before completing their quota. They did not see many "early" whales, but did not consider this a failed experiment in that the season did not extend past September 20.

The whalers used five strikes (their quota and the unused strike from the year before) and landed four whales, with one struck-and-lost. Two of their landed whales sank after being struck and were recovered as "stinkers." After they sink, natural processes within a stinker create gas and bloat the carcass, so that it floats to the surface. The meat and internal organs from such animals are not edible, but the *muktuk* is still good (and preferred by some Inupiat), as is the baleen. Of the five strikes, three were made when wind speeds were 7 mph or less, and all were landed (although one sank and was recovered as a stinker). The struck-and-lost whale was struck when the wind speed was about 12 mph, and the other whale that sank when the wind speed was just under 15 mph. At the time, the whalers did not indicate that wind speed or sea state was a factor in either case. When asked, they had no standard explanation for why struck whales sometimes sink, other than water entering the lungs and body cavity. The Nuiqsut whalers used their fifth strike on September 15, but did not leave Cross Island until September 20. This is explained by two of their whales sinking and not being recovered until September 17 and 18 (and this also explains the "scouting" activity for two days after the whalers used their last strike). They also endured the only period of sustained high winds while recovering the second of these whales, and would not have been able to physically leave Cross Island until September 20 anyway.

The 2002 season was, like the 2001 season, just a little longer than the average for the seven seasons documented by this report. There was less floating ice than in 2001, but still some ice present. Whales were somewhat closer to Cross Island than in 2001, but not as close as the Nuiqsut whalers had come to expect them. The combination of the wind at generally moderate (but not low) conditions, and whales at relatively low densities and farther from Cross Island than in some other years combined for even more days of scouting activity without a strike (and number of scouting days without seeing a whale) in 2002 than in 2001. The 2002 season had the highest number of both such days of any of the seven seasons discussed in this report, and also the most days of scouting effort overall (15).

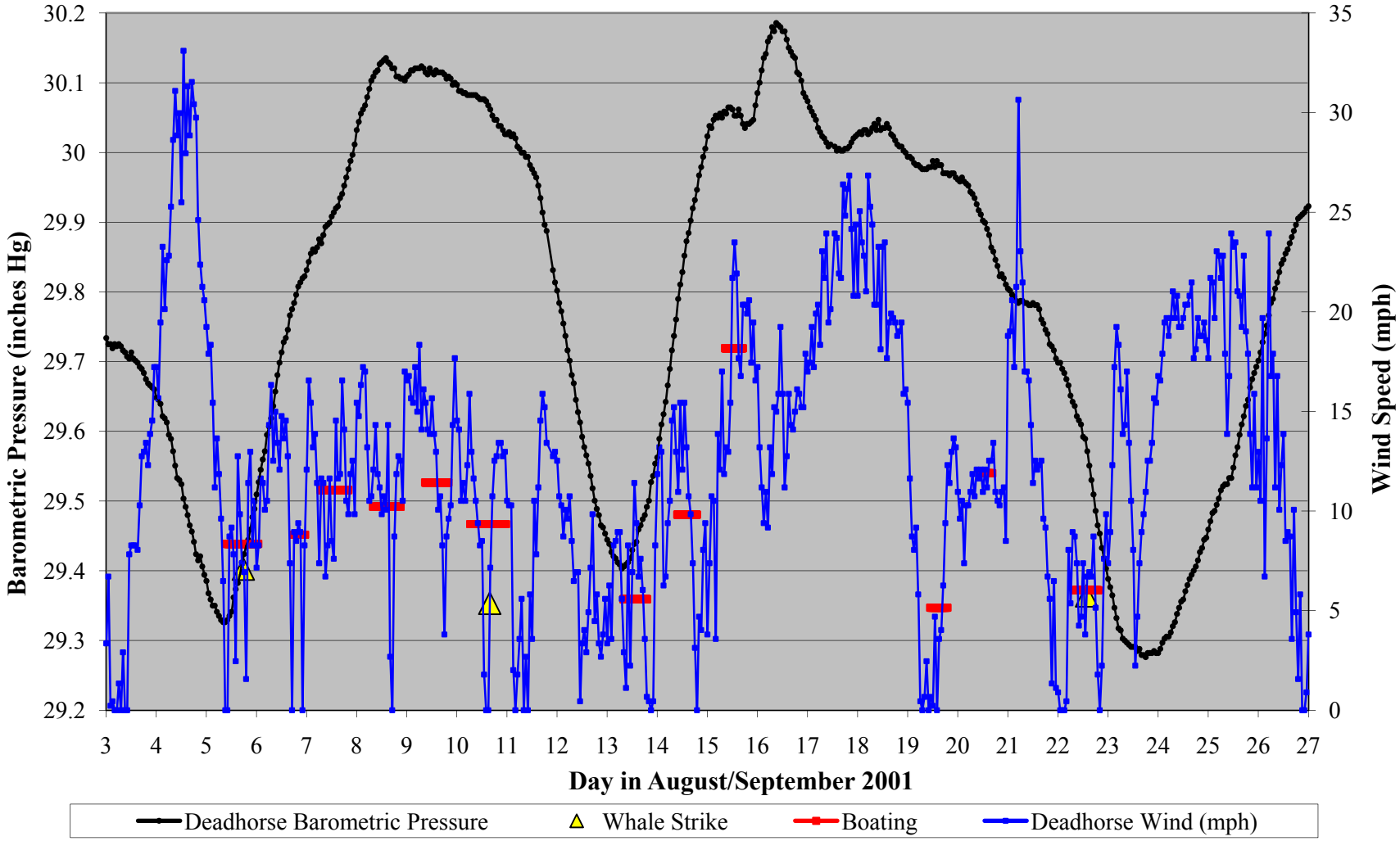


Figure 3-79. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2001. From Galginaitis et al. (2009).

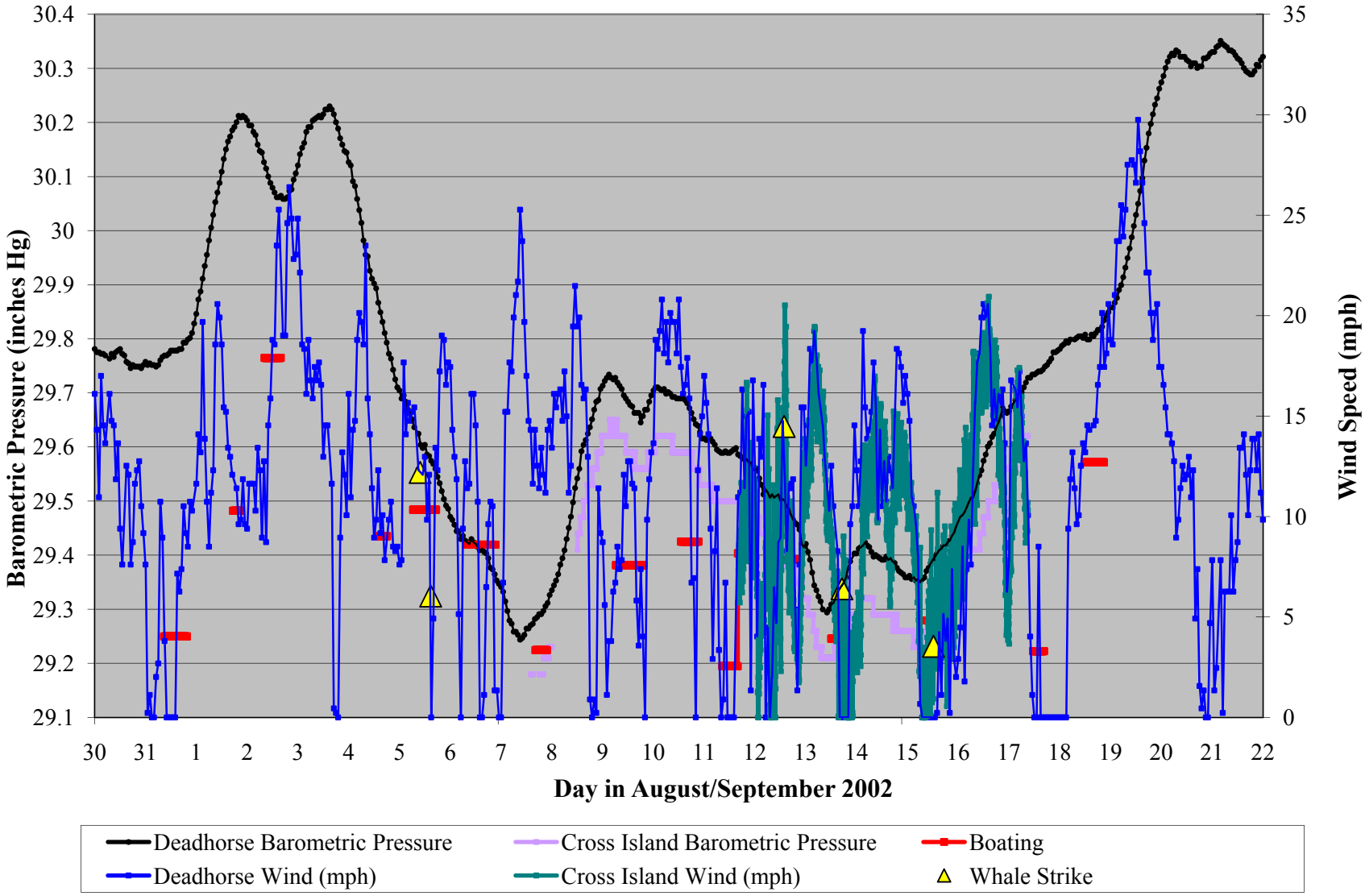


Figure 3-80. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2002. From Galginaitis et al. (2009).

The 2003 season (Figure 3-81) was the second shortest of the seven discussed in this report. It was characterized by the whalers as one of poor weather, with whales "close" to Cross Island. The first whaling crew arrived on Cross Island August 23, again as an experiment to avoid poor weather in September and to determine if whales were present near Cross Island that early. Weather conditions, mainly wind over 20 mph, prevented scouting on all but two days through August 31 (winds moderated on August 25 to below 10 mph, and an attempt was made to scout on August 27 even though winds were 15-20 mph). Conditions still allowed two other whaling crews to reach Cross Island during this period. All whaling crews went scouting on September 1, with winds moderated to below 10 mph, and landed a whale close to Cross Island. Including the tow, the trip was a little over four hours for the successful whaling crew. Winds increased to almost 25 mph once this whale had arrived at Cross Island, but then decreased to less than 5 mph late on September 2 and all whaling crews except the one who had landed the whale the day before went out scouting. These trips were short, due to lack of daylight. The next day, September 3, increased winds of 10 to 15 mph kept all but one whaling crew onshore, and that crew scouted for less than 3 hours before returning to Cross Island. On September 4 winds were over 30 mph and no whaling crews went scouting. Winds decreased early on September 5 to less than 10 mph and all whaling crews took advantage of the conditions to go scouting, and, once one whale was struck and landed the captains decided to take advantage of conditions and try for a second on the same day, and were successful in doing so. Winds increased to nearly 20 mph once these whales reached Cross Island, but the wind again decreased to nearly calm very early on September 6, then increased throughout the day to almost 20 mph, and decreased to nearly calm late in the day. The captains again decided to take advantage of the period of calm, knowing that the whales were close to Cross Island, and three whaling crews went out scouting, including the crew that had landed one of the whales the day before. Butchering on both these whales had advanced reasonably far, but the whalers were also anxious not to "waste" the little good weather they were having. They landed and towed their fourth whale with winds of 5-10 mph, and again winds increased once the whale reached Cross Island. Winds remained high (15 mph or more) until September 9, when all but one whaling crews left for Nuiqsut. The last whaling crew stayed another day and left for Nuiqsut September 10. The whalers had been out scouting on only seven different days, seeing whales all seven days and striking whales on three of those days. Although winds were consistently high during the 2003 season, the whalers were able to take advantage of relatively brief (4 to 6 hour) periods when the wind speed was lower, shifting, or variable. These periods tended to correspond with peaks in the barometric pressure prior to steep decreases. If whales had not been relatively close to Cross Island, these "weather breaks" may not have been long enough to strike, land, and tow a whale back to Cross Island.

Most scouting trips in 2003 took place during winds of 10 mph or less, with one day of scouting by one whaling crew when winds were 15-20 mph. All strikes took place when the wind speed at Cross Island was 7 mph or less, three of the four with wind speeds of less than 5 mph, and one at near dead calm.

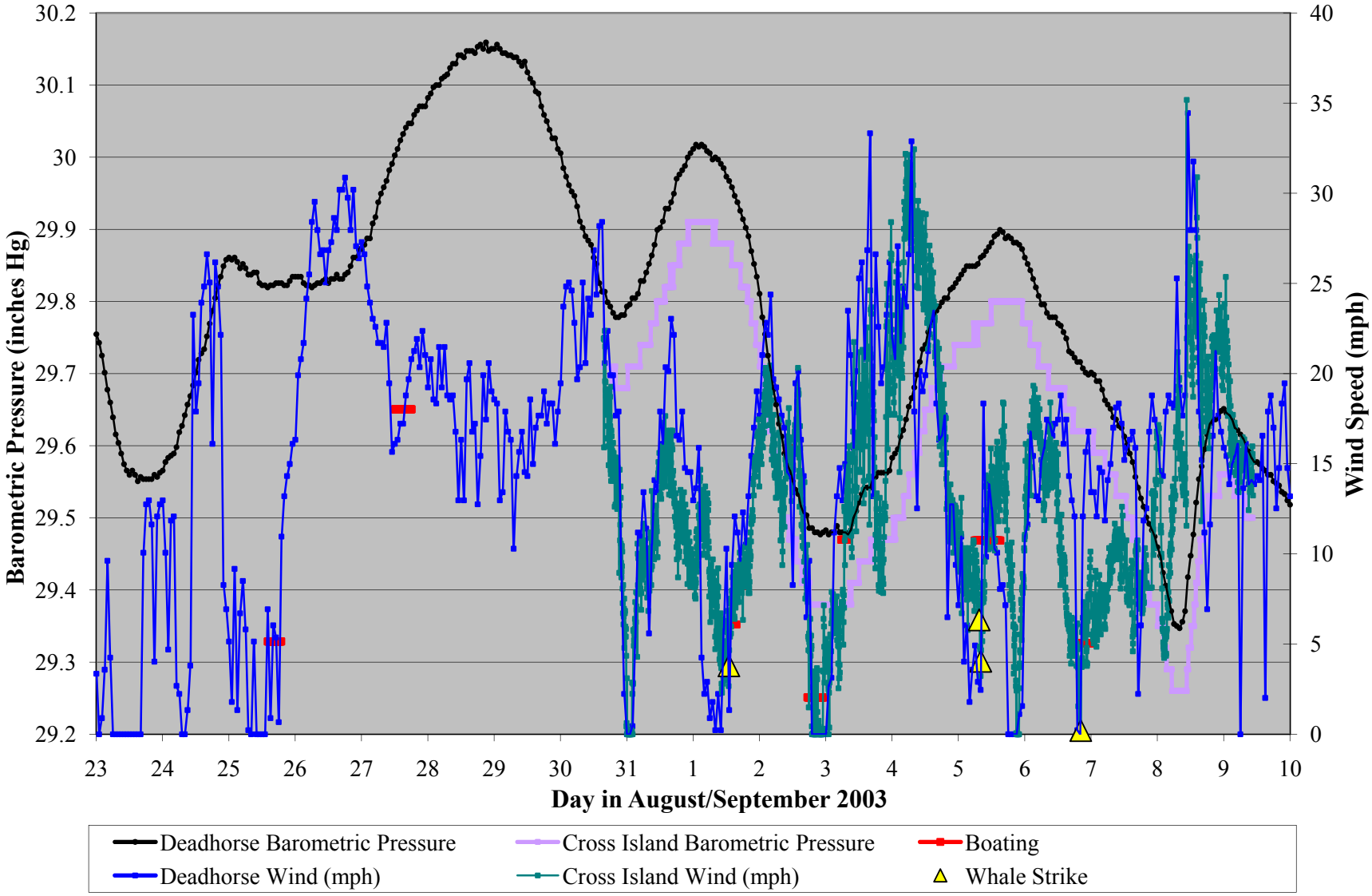


Figure 3-81. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2003. From Galginaitis et al. (2009).

The 2004 season (Figure3-82) was the longest season for the seven discussed in this report, but primarily because one whaling crew went out to Cross Island on August 15, encountered high winds and poor scouting conditions through August 26. They were only able to scout one day, on August 17, when winds were 10-15 mph. In the face of a forecast of extended poor weather and high winds, having only one boat since their second boat had been disabled and no other whaling crews were at Cross Island yet, they returned to Nuiqsut August 19. They returned to Cross Island August 25 (with winds still 20 mph or more), and were shorebound August 26. They then repaired their second boat but encountered more mechanical problems and adverse wind and weather through September 4. Of the ten days from August 26 through September 4, they were able to scout on four days, and on three of these days their trips were relatively short because the wind increased after they had gone out and conditions became too rough. This was primarily due to winds of 20 mph and more. A second whaling crew had arrived on Cross Island August 30, when there was a lull in the wind, but then was shorebound for five days through September 4. This second whaling crew did not try to scout in the marginal conditions of September 4, even though the first whaling crew did make an attempt. On September 4 two additional whaling crews were able to travel to Cross Island.

All four whaling crews scouted for whales on September 5, as winds had moderated to 5 mph or so, and a whale was landed (struck when the wind speed was close to zero). Three whaling crews scouted on September 6, even though winds had increased to 10-15 mph, as the thought was that this was perhaps as good as conditions were likely to be for the rest of the season. A second whale was struck and landed in about 10 mph winds. September 7 was too windy (winds above 20 mph) to whale and people stayed onshore to butcher. Conditions were marginally better (winds 10-15 mph with stronger gusts) on September 8 and the two whaling crews who had not landed whales went out scouting, but saw no whales. The other two whaling crews stayed onshore and continued to butcher their whales. On September 9 conditions were much the same and only one whaling crew scouted for whales, but did not see any. The wind decreased late on September 9 and was still moderate enough so that all whaling crews went out to scout on September 10, but winds increased while they were at sea and, even though they saw whales, no strikes were made. All boats were then shorebound for the next three days (September 11-13) by winds that peaked at 35 mph. All four whaling crews went scouting on September 14, as winds were below 10 mph, and a third whale was landed. The wind increased to more than 20 mph soon after this whale was towed to Cross Island, and many of the whalers were quite discouraged by the conditions. One captain, having landed a whale while only being able to go out on the water three of the fifteen days he had been on Cross Island, decided on season was over. All whaling crews were shorebound by high winds on September 15, and the captains jointly decided that if conditions were suitable on September 16, those whaling crews who wished to could try to complete the quota. If a whale were landed, all whaling crews would stay to help butcher it. Otherwise, all whaling crews would leave for Nuiqsut as soon as the whales already landed were butchered and packed for transport. Winds did decrease to 5-10 mph and two whaling crews decided to go scouting (one crew had already decided not to hunt anymore that season while the crew that had taken the third whale stayed in to butcher). These two whaling crews saw whales, but made no strikes. Three whaling crews finished packing on September 17 and left for Nuiqsut. The fourth whaling crew stayed on Cross Island an extra day and left September 18.

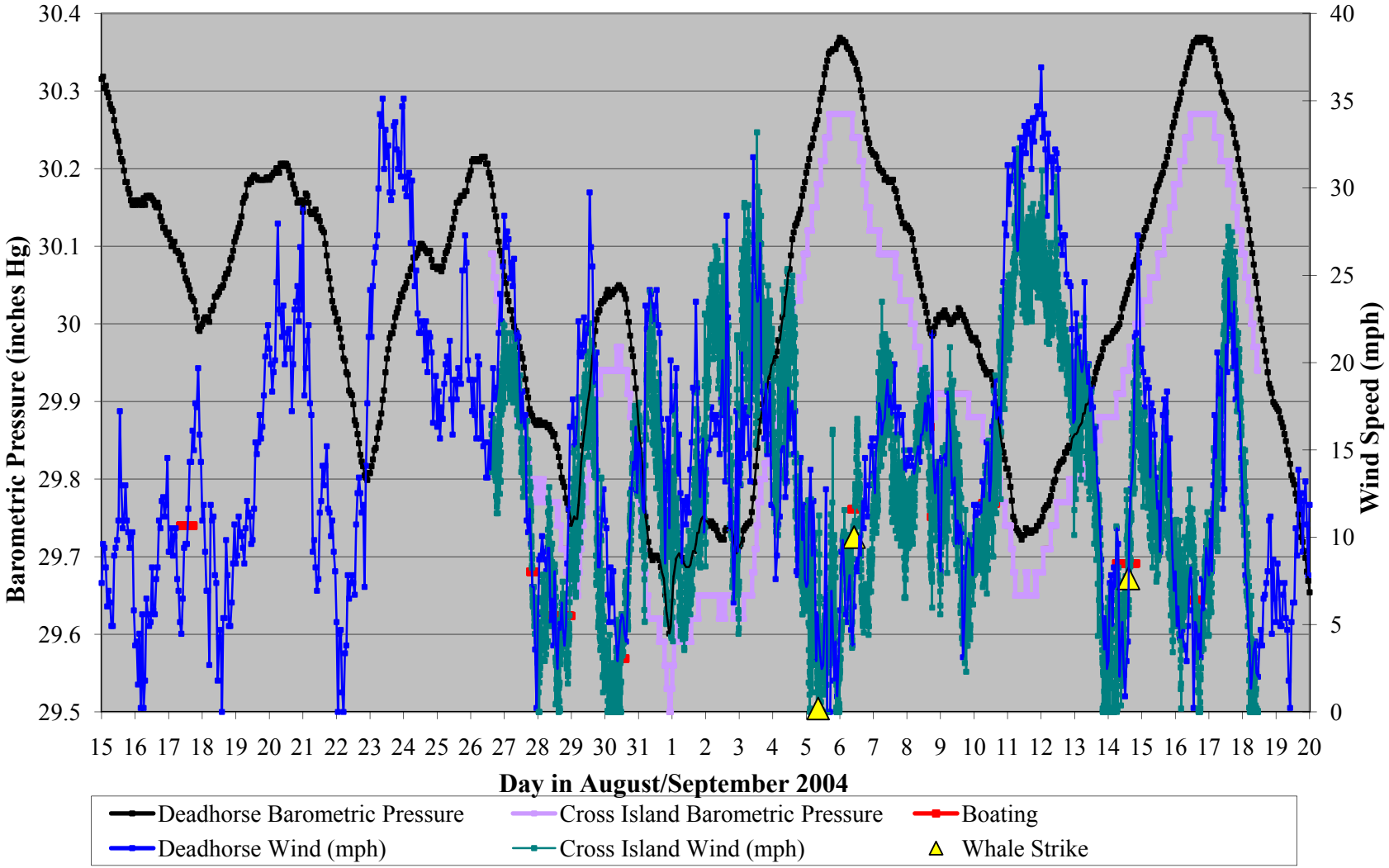


Figure 3-82. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2004. From Galginaitis et al. (2009).

The 2004 whaling season had 10 weather days, when no scouting could take place. There were 12 days when at least one boat did go scouting, but no whale were seen on 6 of these days (the same number as in 2002). Whalers noted that whales were close to Cross Island in 2004, but that the weather was poor. They again took advantage of relatively brief periods when wind speed abated, with all strikes taking place is conditions when the wind speed was 10 mph or less. Whalers do not necessarily predict how long a lull in windy conditions will be, but consider, when they out on the water, how far they can risk traveling from Cross Island and when conditions dictate they should head back in. If the first whaling crew had not gone out to Cross Island so early compared to the other whaling crews, the 2004 season would have very similar to the 2003 season.

The 2005 season (Figure 3-83) was another long season characterized by very poor weather (high and variable winds) and a pack of floating ice jammed on the north shore of the barrier islands that prevented the whalers from traveling beyond the barrier islands on all but two days. There were nine days when at least one boat went scouting, but on three of these days only one boat went scouting since the first whaling crew arrived on Cross Island August 30 (with only one boat) and the second and third whaling crews did not follow until September 4 (and the fourth September 6, the fifth September 8). Weather conditions were reasonably suitable for scouting prior to September 9, but the ice prevented the whalers from traveling beyond the barrier islands and although whales were seen on trips within the barrier islands, no strikes were made. After September 8 through September 25 there were only three days suitable for scouting. Winds were generally at least 20-25 mph except for September 13-14 and September 21. Ice prevented whalers from reaching open water beyond the barrier islands on September 13, but on September 14 they were able to reach open water both to the SE and NW of Cross Island. A whale was struck about 26 miles ENE from Cross Island and due to the distance and ice conditions the whaling captains decided that a second whale should not be struck by the boats following whales to the NW of Cross Island. The trip to land this whale, from leaving the beach to bringing the whale in, lasted about 19 hours. The boats to the ENE of Cross Island had encountered a commercial barge prior to finding and striking the whale that they landed, and were of the opinion that the presence of the barge contributed to the time it took them to locate and land a whale. There is also the possibility that if they had landed a whale quicker that they may have decided to try for a second whale on the same day.

Thus effort was followed by another six days of 20 to 40 mph winds, and then perhaps a 6-hour window of 0-10 mph wind within a 24-hour window of 15-20 mph wind on September 21. All five whaling crews went out scouting but made no strikes. High swells and wind prevented them from being able to safely travel beyond the ice into open water, so that they were not able to approach any whales. High winds kept all boats shorebound for September 22-24 and the whalers called an end to their season and escaped from Cross Island on September 25. This is the one season when conditions made it all but impossible for a whale to be landed. There were 11-15 weather days, and 9 days on which scouting were made. However, ice conditions made it impossible to find or approach whales on 7 of these days, and heavy swells in the open water on 1 of them, so that there was only 1 day in 2005 on which Nuiqsut whalers had an opportunity to land a whale.

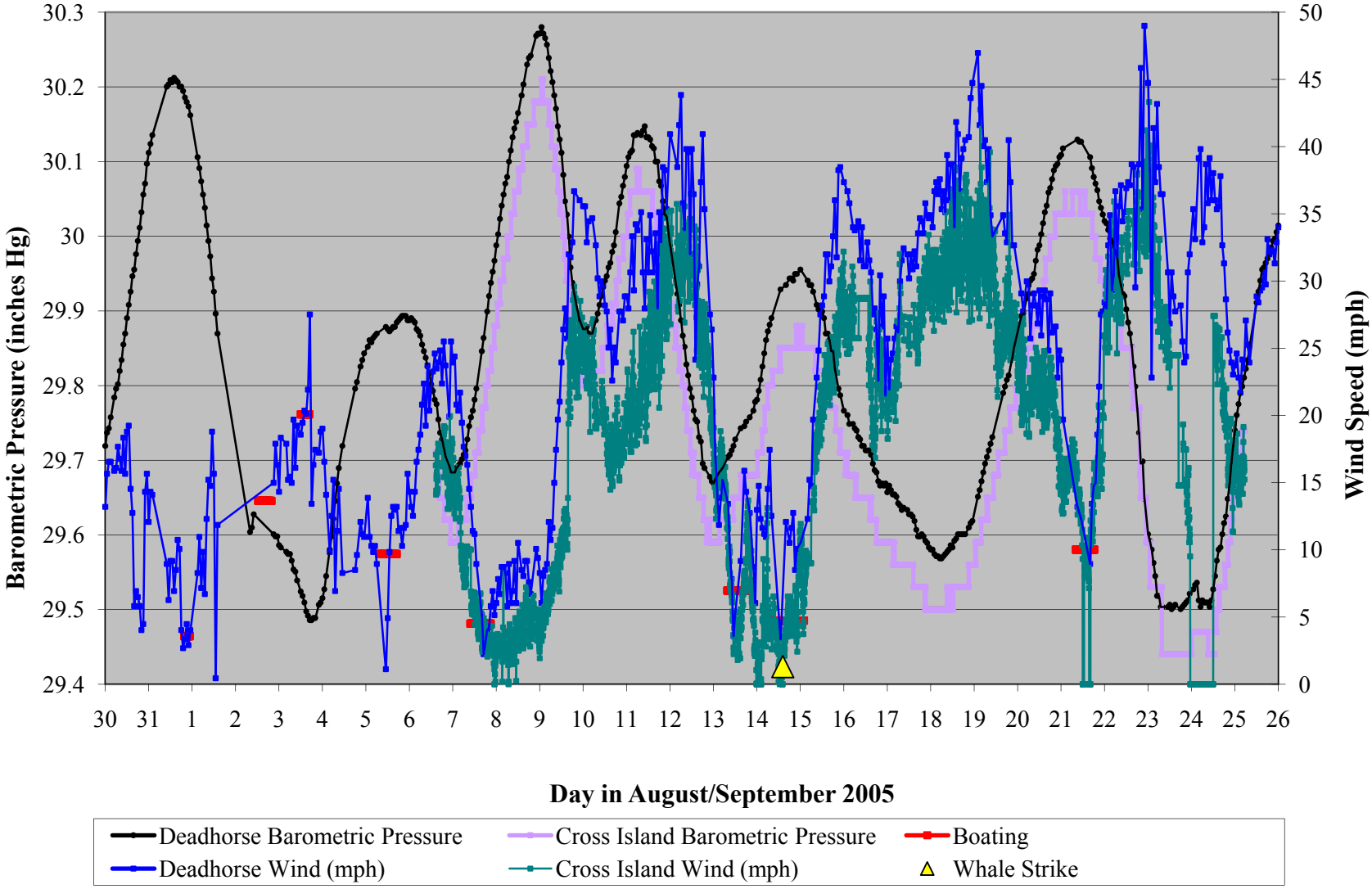


Figure 3-83. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2005. From Galginaitis et al. (2009).

The 2006 season (Figure 3-84) began in much the same way as had the 2005 season, with floating pack ice jammed against the northern shore of the barrier islands and preventing the whalers from reaching open water. While winds were not light, they were suitable, for the most part, for scouting. Three of the four whaling crews went to Cross Island on the same day, September 2 and the fourth on September 4. All spent September 3 making final preparations to whale and from September 6 through September 12 all whaling crews went scouting the same 6 of the 9 days, with winds generally below 10 mph for those 6 days (1 day of 10-15 mph). There were 3 weather days due to higher winds. The main problem was that the whalers were confined within the barrier islands, and could not reach the open water where most of the whales were. They could see whales, but not approach them in the ice, and could not get through the ice to the open water.

The higher winds of September 12 (no scouting that day) may have blown the ice off the barrier islands, as the whalers were able to reach open water and scout for whales for the next three days, and landed a whale on each of those days (September 13-15). The experience of the most recent past had been that poor conditions were more the rule than good conditions, and that the most should be made of good conditions. Therefore, the captains made the decision to land as many whales as they could take care of in as short a time as possible. All three whales were struck and landed in 5-10 mph winds. After the third whale was landed it was decided that scouting had to be deferred at least one day to catch up on butchering, and conditions were marginal for scouting on September 16-17 in any event. On September 18 all four whaling crews went scouting and the fourth whale was landed. Three more days, September 19-21, were devoted to butchering and packing and all whaling crews left for Nuiqsut on September 22.

The 2006 season was not one affected by weather a great deal, as there were only 4 weather days. Ice conditions, however, made whaling ineffective from September 2 through September 12. The functional whaling season in 2006 was September 13-18, after which they whalers had to finish butchering and then go back home to Nuiqsut. Most scouting and all strikes were conducted in conditions of 5-10 mph winds and although whales were seen on 8 of the 10 days when boats went scouting, whales could only be approached in the open water beyond the barrier islands September 13-18.

The 2007 season (Figure 3-85) was quite unusual in that while the whalers characterized the weather as generally poor and the sea conditions as rough, they completed their quota and it was by far the shortest season, in terms of days, of the seven documented for this report. The key characteristic of the season seemed to be that whales could be found close to Cross Island and that there were local areas that were not as rough as others. Whalers reported that they could see and follow whales close to Cross Island, but then had difficulty if the whales went more than 8 to 10 miles from Cross Island. Since the average strike distance in 2007 was 12 miles, whalers were able to follow some whales farther, but the general point was that beyond a certain point the whalers could not see or follow whales, let alone approach to strike. Yet, only five scouting days were required to use the Nuiqsut quota of four strikes, and on 2 of these 5 days only three of the five whaling crews went scouting, as the other two captains thought that conditions were too marginal (winds 15-20 mph) and no strikes were made on those days.

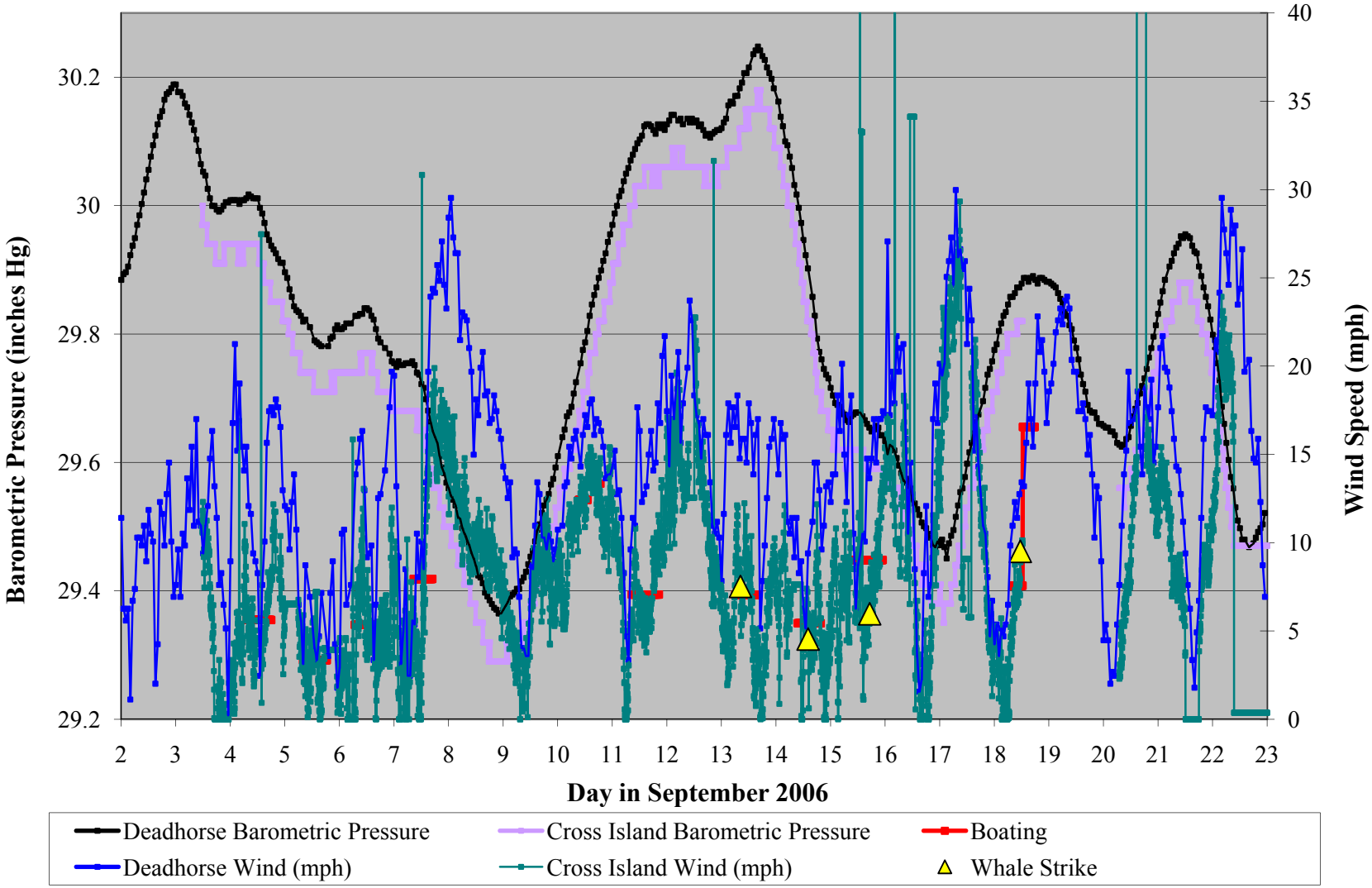


Figure 3-84. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2006. From Galginaitis et al. (2009).

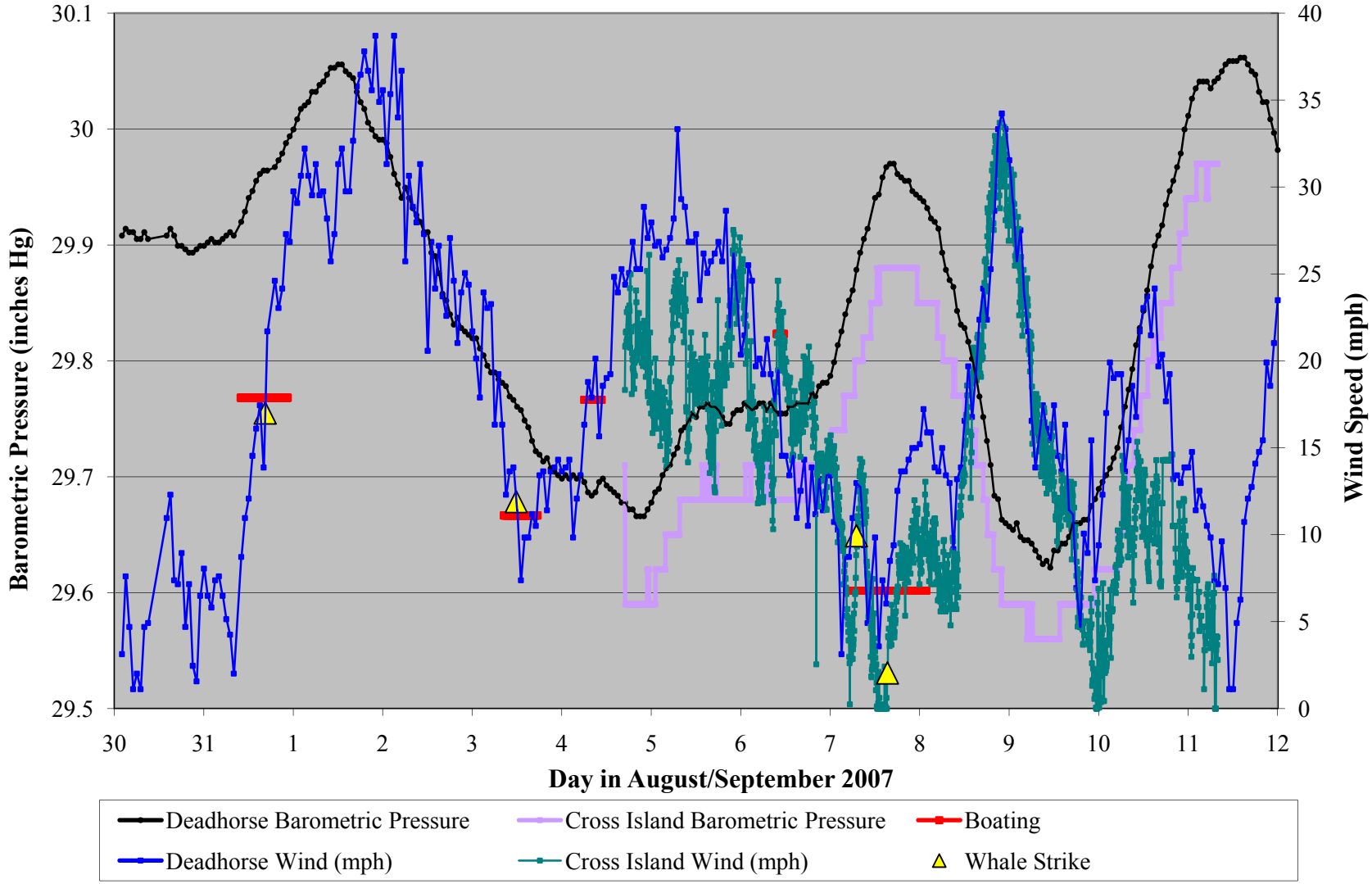


Figure 3-85. Relationships between weather conditions, bowhead whale scouting trips, and strikes in 2007. From Galginaitis et al. (2009).

The first two strikes were used when only two whaling crews were on Cross Island, the first to land a whale on Aug 31 when the wind may have been 15-20 mph (Deadhorse) and the second on September 3 when winds appear to have been 10-15 mph (Deadhorse). The last two strikes were both landed on September 7, the only day that all five whaling crews scouted for whales in 2007 (and the only day of scouting for two of them). The wind peaked near 35 mph on September 9 but no boats had considered scouting as the whales landed on September 7 were not completely butchered until September 10. The captains met and decided that since the three landed whales were all fairly large, they did not need to land a fourth. If they had desired to do so, they could have requested an additional strike from the AEWC. As it was, they finished packing on September 10 and left for Nuiqsut on September 11.

The 2007 season had only 3 days lost to weather, and whalers only had to go out 5 days (2 of them with marginal conditions) to use their quota of 4 strikes. Sea conditions and wind speeds were not particularly favorable, compared to previous years, according to the measures developed for this project and the accounts from the whalers. They did report more localized variability in the degree of swells in some areas than others, but made no generalizations about which areas were rougher than others. Whalers also indicated that whales were closer to Cross island than in previous years, but that beyond a certain distance they seemed to vanish. Clearly winds of 10 mph or less are conducive to Cross Island whaling success, but they are not essential given the right set of circumstances. If whales are not too far from Cross Island, whales can be landed even in winds of 15-20 mph – but this may rely on the whalers finding the localized areas where the effects of wind and swells are not as pronounced. The most general statement Nuiqsut whalers make about this is that the farther one goes from Cross Island, the rougher it gets.

3.7.7.6 Whaling Effort - Number of Whaling Crews, Number of Boats, Boat Crew Size

The relationship between "whaling crew" and "boat crew" was briefly discussed above. The "whaling crew" includes everyone who supports a captain is his whaling effort, and all members will usually receive some sort of crewshare once the whaling season is over. The number of support crewmembers who do not actually go out to Cross Island varies from one whaling crew to another – some have relatively few such members while others have quite a few. Of those crewmembers that go out to Cross Island, all are expected to help with butchering and on-island work. For some whaling crews, all members who go out to Cross Island may potentially go out in the boat scouting for whales – and for one whaling crew the captain encouraged all crew members to go out every trip (and there were usually 6 to 8 crew members on Cross Island for this crew). Most other whaling crews took no more than 5 or perhaps 6 crew members in a boat for scouting, and the more typical number is 3 or 4. On occasion a boat will go out looking for whales with a boat crew of only two. For some whaling crews, there may crew members who go out to Cross Island and never go out in the boat.

As discussed above, boats will often go out with more than the minimum of three crew members. A number of factors were advanced by whalers to explain their boat crew composition. For example, when conditions were rougher or more marginal, or on days when a captain felt a greater need for speed than other days, he would go out with fewer crew members in each boat. When conditions were optimal or when a captain wished to act more in support of other boats rather than to more aggressively seek a first strike, he may take more crew members in a boat. Those whaling crews with younger crew members not fully proficient in skills required for whaling tended to be larger, to facilitate the transmission of whaling knowledge. When a crew

member slept late, he was left on shore. None of these relationships or reasons was determinant, however. Many interacting factors affected how many crew members went scouting in each boat on any given day.

There is no real "typical" whaling crew on Cross Island – all have unique characteristics that contribute to their size and composition. Many captains state the rule that when someone asks if he (or she) may go whaling "I never say no." The reality is that space in the boats to go out to Cross Island are limited, since the boat must carry not only the whaling crew members but most of what they will need on Cross Island - although this is less true than in the past, due to the logistical support and help supplied through the CAA. Under terms of the CAA, almost all of the gas and diesel fuel have been provided by industry and barged to the island just before or when the whalers get there, along with a generator, water tanks, and large boxes and other materials to pack and ship the butchered whale. Some whaling captains (and the researcher) ship food and other supplies from Anchorage (or Fairbanks) to Deadhorse, so that they can also be transported to Cross Island on this barge, and so save some space on their boats. Still, space in the boats and cabins is limited. Those captains with bigger boats, and bigger cabins, are less limited than others in terms of whaling crew size. This is one reason that most whaling captains are constantly thinking of ways to improve their cabins on Cross Island.

Table 3-58 presents measures related to the number of whaling crews and boats physically present on Cross Island during the seasons documented by the project, as well as the average total population of Cross Island and the average boat crew size during that period. As the table shows, there was a minimum of 3 whaling crews on Cross Island (2002) and a maximum of 5 (2003, 2007) in this period, an average of 4.1 per season. To some extent this is a number without much meaning – the more meaningful number is the number of whaling boats present on Cross Island. Most Nuiqsut whaling crews (18 of 29, or 62 percent) used more than one whaling boat (and many also use additional support boats for hauling people and supplies that are not used to hunt or tow whales). This allows experienced whalers who do not want to, or are not yet able to afford to, register as a captain to essentially run a boat under the overall management of a registered whaling captain. Some individuals may have whaled as captains in the past but be currently unable or unwilling to assume the economic responsibilities of fielding a whaling crew in a particular year (which include hosting the attendant public events if their whaling crews should land a whale). Others may be individuals looking to amass more experience and equipment, so that they can eventually field an independent whaling crew. Others may have other reasons.

However that may be, the number of boats capable for whaling has varied from 7 to 11 for 2001-2007, or an average of 1.9 whaling boats per whaling crew. The numbers from Table 3-58 indicate that Nuiqsut whalers try to have at least 8 boats available for whaling at Cross Island. In 2002, with only 3 whaling crews, each crew operated 3 boats (whereas in most years only 1 3-boat whaling crew would be expected). In 2007, two whaling boats were disabled on the way to Cross Island and never used for looking for whales, and so were not counted as whaling boats. One reached Cross Island and was used as a support vessel. One was left (and repaired) at West Dock and was used on the trip back to Nuiqsut. This leaves only 2006 as a season when Nuiqsut whaling captains knew before they reached Cross Island that there would be fewer than 8 whaling boats. 2006 was a transitional season for one whaling crew, when one captain sat out the whaling season and reorganized his whaling crew from a multi-boat to a single-boat operation.

Table 3-58. Information on the number of whaling crews and boats physically present on Cross Island during the 2001 through 2007 whaling seasons, as well as the average total population of Cross Island and the average boat crew size during that period. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Total	Average
# of 1-Boat Whaling Crews	1	0	1	1	3	2	3	11	1.6
# of 2-Boat Whaling Crews	2	0	1	2	1	1	2	9	1.3
# of 3-Boat Whaling Crews	1	3	2	1	1	1	0	9	1.3
Total Whaling Crews (Max. #)	4	3	4	4	5	4	5	29	4.1
Average Whaling Crews on Cross Island (average for the full season)	3.8	2.5	2.8	2.6	4.1	4.0	4.0		3.3
Total Boats (Max.)	8	9	9	8	8	7	7	56	8.0
Average Boats Scouting/Day[1]	4.8	4.3	4.9	3.4	4.0	4.8	3.2		4.2
Average Boats Scouting/Strike[2]	5.3	4.8	6.3	5.7	8.0	3.8	4.3		5.1
Average Cross Island Pop	27.7	26.6	20.4	16.2	29.8	29.2	26.0		24.8
Average Whaling Crew Size	7.3	10.6	7.3	6.2	7.3	7.3	6.5		7.5
Average Boat Crew Size	3.9	3.6	2.9	3.6	4.4	4.3	4.3		3.9

[1]Average number of boats out scouting for whales for all scouting day

[2]Average number of boats participating in the hunt that resulted in a struck whale

The 2005 season was exceptional in that only one strike was made, on a day when all the whaling boats on the island were available to go out scouting. Even excluding 2005, however, there is some evidence for a trend of fewer boats available for whaling over the period of 2001-2007. There is also an apparent declining trend for the maximum number of boats present on Cross Island potentially able to whale from 2001 to 2007. This is a gross indication that total level of effort may have similarly declined. Other measures examined in the next section may indicate this is not a strong trend.

The "Average Boats Scouting/Day" numbers indicate why captains may prefer to have eight or more boats available for whaling. Not all captains will necessarily whale on any given day. Some captains are more willing to try to whale in marginal conditions than others, but this is usually a concern only on a limited number of days. Most whaling crews will not whale the day after landing a whale, especially if they have only one boat, since they have butchering responsibilities. However, if they are using multiple boats they may send out a boat while keeping other crew members onshore to butcher. Whaling crews other than that who landed a whale will often seek to go out scouting for whales the next day, if conditions are good and the successful captain indicates that he has the butchering in hand. In the more general case, however, it is likely that at any given time there will be one or two boats that are experiencing some sort of mechanical or other problem. The overall average for each season also reflects scouting days before all whaling crews reached Cross Island. It is instructive that for all season except 2006 the average number of boats out scouting and participating in a hunt that resulted in a struck whale was larger than the general average for all scouting days of the season. What may be more remarkable is the magnitude of the difference between the number of boats on Cross

Island and the number that, on average, actually go out scouting. This reflects mechanical problems that keep boats onshore, but also cases where a whaling crew needs to stay onshore to butcher while other whaling crews go out to scout, the need for captains to send a boat to Nuiqsut with their *tavsi* after a whale is landed, or the use of boats for other errands such as trips to West Dock.

The average number of people physically present on Cross Island did not vary much from one season to another, and only roughly reflects the number of whaling crews on Cross Island. In 2003, for example, when the number of whaling crews decreased to three, each whaling crew used three boats. Some crew members who would normally whale for captains who did not whale in 2003 joined other crews for that year. The increase in the average size of whaling crews in 2003 (and not in the overall number of boats at Cross island) is consistent with a minimum number of boats being available to scout for whales, and a minimum number of people being required to go out in the boats and butcher the whales that are landed. It also reflects the dynamic that new whaling crews are created when an experienced co-captain "hives off" from an existing whaling crew to form a whaling crew of his own. The apparent lower Cross Island populations for the 2003 and 2004 seasons actually reflect the relatively long periods of time when only one whaling crew was physically present on Cross Island (6 days in 2003 and 9 days in 2004) and the relatively few days when all whaling crews were physically present on Cross Island (58 percent in 2003 and 50 percent in 2004). This is also evident in the difference between the values of the maximum number of whaling crews at Cross Island for any given season (by necessity an integer value) and the actual average number of whaling crews present at Cross Island over the entire season. This difference, in terms of percentage, ranged from 35 percent for 2004 to 0 percent for 2006. The 2001 season is the only other season with a difference as low as 5 percent – all the others have differences that are 15 percent or greater.

3.7.7.7 Whaling Effort - Boat Days, Boat Hours, and Effort per Unit Catch (EPUC)

Table 3-59 summarizes the information that will be used to ground the discussion on different approaches for estimating the effort per unit catch (EPUC) for Cross Island whaling, and the comparison of these metric across seasons.

The best approach seems to be to compare whaling-crew-days with boat-days and simple length of season (Table 3-59). Looking at the number of whaling-crew-days, 2007 appears to be quite similar to 2003 and even 2002, as seasons with the lowest values. The overall range is only 52 to 105, basically a factor of 2. The largest value is for 2005, with only 2004 near the average value, and 2006 and 2001 with above average values. Whaling-crew-days/Whale would seem to indicate that 2003 and 2002 were the most efficient seasons, with 2007 not too far behind, followed by 2006, 2004, 2001, and finally 2005. Looking at boat-days, however, 2007 has by far the lowest value, with 2003 and 2005 each having about twice the 2007 value, followed by the other four seasons pretty much evenly spaced at intervals of about half the total 2007 value. The range is 16 to 65, about a factor of 4. The boat-days/whale ratio indicates that 2007 was the most efficient season, followed by 2003 and 2006 with values below the average for all season, and the other four seasons above the average (2004, 2002, 2001, and 2005). In terms of the overall length of the season, 2007 was the shortest by far at 13 days, followed by four seasons ranging from 19 to 24 days long (2003, 2006, 2002, and 2001), and then 2005 and 2004 at 27 and 30 days. When the seasons are ranked by the average number of days each whaling crew was

actually present at Cross Island, 2007 again was by far the shortest at 10.4, followed by 2003 at 13.25, and then the other five seasons with values of 19.34 to 22.5.

Table 3-59. Measures of Subsistence Whaling Effort by Cross Island Whalers between 2001 and 2007. From Galginaitis et al. (2009).

Season	2001	2002	2003	2004	2005	2006	2007	Average
# of Whales landed	3	4	4	3	1	4	3	3.1
Struck-and-Lost	0	1	0	0	0	0	1	0.3
Length of Seasons, Days	24	23	19	30	27	21	13	22.4
# of Whaling Crews (Max)	4	3	4	4	5	4	5	4.1
Average Days on Cross Island/Whaling Crew	22.5	19.3	13.3	19.3	21	21	10.4	18.1
Whaling Crew Days (total)	90	58	53	77	105	84	52	75
Whaling Crew Days/Whale	30	14.5	13.3	25.7	105	21	17.3	23.6
# of Boat-Days	57	65	34	41	35	48	16	42.3
Boat-Days/Whale	19.0	16.3	8.5	13.7	35.0	12.0	5.3	13.5
Boat-Days/Strike	19.0	13.0	8.5	13.7	35.0	12.0	4.0	13.6
Average Duration of Scouting Trip	9:43	7:58	4:31	6:51	7:07	8:13	5:57	7:32
Total Seasonal Effort (Boat-Hours)	572.9	533.6	162.9	301.2	341.3	427.1	124.9	351.9
Boat-Hours/Strike	191	107	41	100	341	107	31	103
Boat-Hours/Whale	191	133	41	100	341	107	42	112

It can be argued that the way "whaling-crew-days" and "boat-days" are defined above makes them two different sorts of measures and thus not comparable. "Whaling-crew-days" aggregates the total number of days each whaling crew was present on Cross Island, whether they went out looking for whales or not. "Boat-days" aggregates the total number of days each boat went out scouting for whales. However, a measure for whaling-crew-days calculated the same way, aggregating the total number of days each whaling crew actually went out whaling, would suffer from the same defects of whaling crew composition and size variability discussed above, and boat-days calculated as the aggregate number of days each boat was present on Cross Island would basically represent the length of season measure (already directly known) rather than a measure of active whaling effort. Another way to approach this is to recognize these as measures of two different sorts of effort. One is a measure of the total time (including "down time" for whatever reason – weather, mechanical, support chores) devoted to an activity, while the other focuses on the time spent doing the productive aspects of the activity ("on-the-water" activities).

The question remains of how best to discuss the seasonal variability of whaling effort. Length of season and "whaling-crew-days" as discussed encompass all whaling activities (travel, daily chores, scouting and landing whales, towing, butchering and packing) as well as bad weather periods, mechanical problems, and so on. While all are significant components of the whaling experience of any one season and in combination characterize each season, not all represent "effort" in the same way or are as easy to measure.

Butchering is clearly a component of the total level of whaling effort on Cross Island, but also clearly has a direct relationship with the number of whales landed, and no relationship to struck-and-lost whales. The work required to butcher a whale is a function of its size, but to accurately record the actual labor that is devoted to butcher any given whale is quite difficult. The number of people present at the butcher site is constantly in flux, as is the number of people actually engaged in the work of butchering. The labor requirements of butchering also clearly influence the length of any given whaling season. However, given that Nuiqsut whalers have landed 3 or 4 whales in all but one of the seasons discussed in this report, the butchering component of the whaling effort is relatively constant from one season to the next. It could be argued that if fewer people were available to butcher, butchering would take longer, and the length of the whaling season would increase. In empirical terms, this has not been the case for the 2001-2007 seasons. Individual whales have typically been butchered in 1 to 2 days, with most whaling crews participating to some extent in butchering most whales. Because of this logical consistency of butchering effort from one season to the next, the difficulty of actually measuring butchering effort in any systematic and detailed fashion, and the apparent limited effect on the variability of the length of the overall subsistence whaling season, butchering has not been included in the EPUC measure discussed below.

While it can be argued that butchering is certainly a necessary component of processing the whale after it is landed, it is not really a component of "catching" the animal – essentially a restatement of the argument above. It is the actual level of effort out on the water that is variable from one season to another, given a relatively equivalent level of harvest. It is also precisely this "on-the-water" aspect of the hunt that is comparable (although not precisely the same) for both "landed" and "struck and lost" whales. There is no tow for a "struck-and-lost" whale, and the chase for a struck-and-lost whale may be, but is not necessarily, shortened from that of a landed whale. Thus, there is a legitimate question as to whether "catch" should refer to "landed whales" or "strikes used." In the strict sense, only "landed whales" are productive results of effort. However, it is not uncommon for whalers to indicate that they did nothing different for a landed whale than for one that was struck-and-lost. Considering only landed whales as "catch" would automatically increase the EPUC in any year with a struck-and-lost whale. However, as is evident in Table 3-59, it makes relatively little difference in terms of how seasons compare to each other which definition of "catch" is used since Nuiqsut whalers had only two struck-and-lost whales in the seven whaling seasons considered here. Ultimately, however, it makes most intuitive sense to define "catch" as "landed whales." While the difference in the calculations of the EPUC measure using both possible definitions of "catch" would be a measure of struck-and-lost whales as a percentage of all strikes used, this is arrived at far more simply by the direct ratio of struck whales actually landed. Since the subsistence bowhead hunt is managed in terms of strikes, however, and not landed whales, there may be some justification for calculating Effort Per Strike, even if "strike" is not defined as "catch." That is, the hunt is limited to the number of animals that the whalers are allowed to land, and they end their effort when they either reach their quota and decide that they have satisfied the community's need and do not need to ask for a fifth strike, or when it is late in the season and they judge that conditions for whaling are poor or dangerous and not likely to improve. In the past, if Nuiqsut whalers had not filled their quota, they would sometimes stay out at Cross Island waiting for whales until the ocean froze. They no longer do so, since in such a case they must leave their boats and retrieve them later. The whalers have also noted that weather conditions after September 20 or so generally make whaling very difficult near Cross Island.

It will be argued here that the easiest component of whaling effort to measure, and the one that varies the most from season-to-season, is the "on-the-water" effort of scouting, striking, and landing whales. While it is possible to calculate the aggregate number of days each boat is present on Cross Island, and to easily identify the subtotals of days boats went out whaling and days they did not, it has been quite difficult to always identify exactly why boats did not go out whaling. Sometimes it was for mechanical reasons, or because of adverse weather conditions, or the need to use the boat for something else. Sometimes the whaling crew had onshore chores to complete. Other cases were less clear, however. Sometimes it could have been one of several such reasons. On the other hand, when a boat goes out whaling, it is clear that it has done so. It is also clear that the completion of the quota is the limiting factor on determining the length of the season. Nuiqsut whalers do not stay at Cross Island any longer than they need to after they fill their quota or determine that it is not likely that they will be able to do so. "Boat-days" is a direct measure of the on-the-water activities required for them to fill their quota. All other onshore activities (butchering, packing, chores) are in support of and a result of landing whales. Thus, boat-days would appear to be a good proxy measure for overall seasonal whaling effort (and can be adjusted if necessary for season length due to poor weather, ice, or other conditions).

It is possible to measure the level of effort "on the water" in several different ways, with different degrees of precision or intuitive validity. Whaling-crew-days and boat-days have been discussed above, and while boat-days appear to be a reasonably good measure, the available information allows a more refined and precise measure to be developed. From Table 3-53, it is clear that the average boat-trip varies significantly both in terms of time duration and total distance from season-to-season, so that a "boat-day" does not represent the same amount of whaling effort each season (for instance, 4 hours 31 minutes and 37.2 miles in 2003 compared to 9 hours 43 minutes and 84 miles in 2001). A "boat-day" includes both the temporal and spatial aspects of effort, and to refine the measure one could focus on one or the other (or a combination of the two). As a measure of effort, time appears to be a better unit than distance. Nuiqsut whalers generally scout for whales at 4 or 5 miles per hour and reserve high-speed for traveling to a likely place to spot whales or for returning to Cross Island after not deciding to stop looking for whales on any given trip. On many trips Nuiqsut whalers will maintain "scouting speed" for the entire trip, as whales can be found very close to Cross Island and could be missed if they were traveling at high speed. A measure of effort based on distance would result in larger values for seasons when whales were more distant from Cross Island, regardless of the speed of travel. A measure of effort based on time would also appear to result in larger values for seasons when whales were more distant from Cross Island, and this does appear to be the case in general, but for those seasons when whales were generally more distant from Cross Island than other seasons (2001 and 2002), whalers tended to travel at high speeds until they were out to where they had been seeing whales before they slowed to "scouting speed." Distance appears to represent more where whales were found than effort as such, and is incorporated into the time measure. Further, travel at higher speeds (when scouting for whales is less effective) contributes less to a time-based measure than to a distance-based measure, so time rather than distance may be preferable for a measure.

Table 3-59 shows values for total seasonal effort in terms of boat-hours, and clearly indicates that 2007 was the season of least on-the-water effort (124.9 boat hours), with the 2001 season having the most on-the-water effort (572.9 boat hours). Because of the high seasonal effort in 2001 and 2002, the effort for the 2003 through 2007 seasons was below the average for all seven

years of this study (351.9). The 2006 season had about 30 percent more effort than the average season, and both the 2002 and 2001 seasons had roughly 70 to 90 percent more effort than the average season. In terms of effort per whale landed, the 2007 and 2003 seasons were about the same (42 and 41 boat-hours/whale, respectively), since 4 whales were landed in 2003 but only 3 in 2007 (with one struck and lost). The 2004 season has a value about 150 percent greater the 2007/2003 values, with the 2006 season value only a little higher (but again, 4 whales landed in 2006 and only 3 in 2004). The 2002 seasonal value for effort/whale is somewhat higher than for the 2006 season, but is about the same for effort/strike, because of a struck-and-lost in 2002. The 2001 season has the highest effort/whale value for seasons when 3 or more whales were landed (191 boat-hours/whale), at somewhat less than twice the values for the 2004/2006/2002 seasons. This was the year when whalers (and other measures) indicated that whales were farther from Cross Island and seemed to be less numerous than for other seasons. The value for effort/whale is of course highest for the 2005 season (341 boat-hours/whale), when only one whale was landed due to very poor weather and ice conditions.

3.7.7.8 Non-Whaling Boat Activity

In addition to searching for whales, Nuiqsut whaling vessels made trips between Cross Island and West Dock on a fairly regular basis. These trips were to pick up packages and supplies, or to do other errands. Generally, after a whale is butchered, one of the boats from the whaling crew that landed it made the trip between Cross Island and Nuiqsut to transport the meat and muktuk from the captain's *tavsi* to feed the village. Only a few other boats went to Cross Island from Nuiqsut other than the whaling boats. These boats were to bring help to butcher one of the whales in one case, and in several other cases were to bring or take away whaling crew members during the season. There were visitors of other sorts in different years – tourists, adventurers, polar bear researchers, and industry representatives on various missions or just on a sight-seeing visit. The people from these boats generally stayed for the day, or perhaps a night or two. Visitors from Nuiqsut generally stayed a bit longer - a day or two before returning to Nuiqsut, and helped with whatever tasks needed to be done (especially the butchering of the second whale in 2001). New whaling crew members generally stayed for the rest of the season.

This project focuses explicitly on Cross Island whaling activity, so little attempt was made to collect systematic information on these non-whaling activities or visitors. Also, information on preparation, support, or other whaling crew member activities that occurred elsewhere (primarily in Nuiqsut, one would assume) were not documented as part of this project. That remains for a larger project. There were two "landline" phones on the island during each whaling season (which, like the generator, operate only during Cross Island's whaling season), as well as a FAX. Thus, important business need not be put on hold while corporation and other officials are whaling on Cross Island. Contacts and interactions through telephone, FAX, or non-whaling non-Nuiqsut vessel were not fully documented, and such information was only collected as contextual background. Whaling crew members increasingly have cell phones that work from Cross Island, but no attempt has been made to measure how this has changed patterns of behavior on Cross Island (except through opportunistic observations). Similarly, the pattern of use of video-players, DVD players, computers, gameboys and other gaming systems, and other such electronic equipment has not been systematically explored.

3.7.7.9 Other Subsistence Activities

All things considered, very little non-whaling subsistence activity was reported or observed over the course of the project at Cross Island during 2001-2007. The most consistent activity of this sort is the harvest of polar bears that are attracted to Cross Island by the remains of the butchered whales. The skulls of most of the whales landed by Nuiqsut whalers are lined up on the island some distance east of the butcher site, and somewhat further is where the rest of whale is disposed of, after butchering for human consumption is finished. Sometimes the polar bears approach too closely to the butchering activities or to the cabins where the whaling crews live while on Cross Island. If non-lethal hazing does not deter these bears sufficiently, they are shot. On average, perhaps one polar bear a year is shot for being a nuisance bear. Some years, no bears are shot. Other years more than one may be shot, but this would be uncommon. There are cases where a whaling crew member will come to Cross Island with the intention to kill a polar bear, but to do so he must first obtain the permission of his whaling captain. Most whaling captains consider whaling as the first priority while out at Cross Island, and butchering a polar bear and taking care of its hide is a great deal of work that would take a crew member away from whaling duties. A whaling crew member also has to be aware that even if he kills a polar bear and takes care of the butchering and hide, his whaling captain can claim the hide for himself, should he wish to do so.

Some sealing has taken place during a few years, but not every year. Whalers will sometimes look for a seal on the way back from scouting for whales, if a whale has not been landed, or will make a trip looking for seals around the island on a day when conditions are not suitable for scouting for whales. Most such attempts have not resulted is a harvested seal, however – perhaps three or four over the seven years described in this report. Some whaling crews will try to harvest bearded seal should one appear opportunistically on the boat's return trips to Cross Island, and perhaps two have been taken in this way over the course of seven years. Similarly, one whaling crew took a walrus that happened to present itself, some 20 or more miles west of Cross Island. The boat crew members in the boat that actually shot the walrus were all young and had never taken a walrus before. They did not realize how difficult the tow back to Cross Island would be, nor how hard it is to butcher a walrus for the first time. Another walrus with a calf beached on Cross Island and died. It was disposed of, after salvaging its tusks. One young walrus followed the whalers' boats into Cross Island one year, and was eventually shot. Vocalizations of other walrus have been heard from Cross Island, but only in one or two of the seasons discussed here, and walrus are not commonly encountered by Cross island whalers.

One whaling crew did take a fish net out to Cross Island during one or two of the seasons described in this report, but it was never deployed. Whalers say that in the past they fished while out on Cross Island at whale camp, and that they would also sometimes go hunting for caribou on the mainland, either while traveling to Cross Island or while they were out there. Of course, in the past, and especially before the mid-1990s, Cross Island whaling seasons tended to be longer and whalers tended to be, or needed to be, more self-sufficient than they are currently. Much more can be transported to Cross Island now than in the past, and whalers have more resources with which to purchase supplies. Also, current whalers feel more of a time crunch than did whalers of the past. Whalers with jobs must often fit their whaling season into a two-week envelope of vacation or subsistence leave, whereas whalers of the past could comfortably spend more time.

Some bird hunting also took place, but again only in one or two seasons. For the most part, the subsistence food consumed on Cross Island, other than whale, is brought to the island from Nuiqsut. The typical whaling crew will bring frozen caribou, frozen fish, perhaps some moose, and a wide assortment of "store" food, much of it canned. Perishable food is most often kept in coolers on the roofs of the cabins, but a few captains have bought and transported freezers to their cabins at Cross Island, to take advantage of the generator provided under the terms of the CAA. It may be that the implementation of the CAA has reduced the need for whalers to engage in subsistence activities other than whaling while out at Cross Island, and increased their focus on whaling and thus shortened the time required for them to fill their quota, than would be the case in the absence of the CAA.

Specific non-whaling subsistence activities that took place during each season are detailed in the annual reports for each season. Discussion of these activities was beyond the scope of this study.

4 INTEGRATION OF cANIMIDA PROJECT

4.1 Objectives of ANIMIDA/cANIMIDA

The primary objectives of the ANIMIDA and cANIMIDA Projects were to monitor and characterize the marine environment of the Northstar and Liberty development areas to evaluate potential and actual effects of these large offshore oil developments. cANIMIDA was an extension of ANIMIDA intended to examine temporal and spatial changes in the marine environment in the development area of the Beaufort Sea and to determine if any observed changes in chemical, including distribution and abundance of metals and hydrocarbons, and biological characteristics, including the ecology of the Boulder Patch and behavior and movements of bowhead whales near Cross Island during the fall Nuiqsut whale hunt, in the development area were related to the current Northstar development and production operations.

4.2 Offshore Oil and Gas Operations in the Beaufort Sea that Could Cause Long-Term Environmental Disturbance.

Many operations performed during evaluation, exploration, and development/production of offshore oil and gas resources may cause physical disturbance or chemical contamination of the marine environment. These include seismic exploration, offshore infrastructure construction, drilling and production waste disposal, blowouts and oil spills, and air emissions.

Seismic exploration may cause temporary disturbance to nearby marine mammals and birds, but, if performed properly with modern seismic survey equipment, does not cause any long-term damage.

The longest-lasting disturbance in the Beaufort Sea is from platform, gravel island, and subsea pipeline construction and emplacement during exploration, development, and production. These activities may cause physical disturbance at the sea floor and may interfere with other uses of the local marine environment. Most exploratory drilling and all development operations in the Alaskan Beaufort Sea were performed from artificial gravel Islands or grounded drilling structures. These structures cause considerable long-lasting physical disturbance to the sea floor, effectively smothering all benthic fauna in the area of the facility footprint. They also may alter ocean currents, mixing of water masses, and marine animal migratory routes. More than 20 gravel islands have been constructed since 1975 in waters less than 15 m deep on State and State/Federal lease tracts in the Alaskan Beaufort Sea for exploratory drilling and production. About 1.6 million metric tons of sand and gravel were used to construct Northstar production island. This is equivalent to about one-third of the mass of suspended sediments delivered to the Beaufort Sea each year from the Colville River (Trefry et al., 2004a). Most of these islands remain in some form. Some of the gravel islands erode away after completion of exploratory drilling, spreading coarse sediments over a large area. The gravel islands also may leach chemicals, particularly metals, from the gravel material used to construct the island or from small spills of drilling chemicals during drilling after the island is abandoned and erodes. Most exploration in deeper waters in the Arctic is done from platforms, such as drill ships and specialized ice resistant drilling platforms. These drilling structures are anchored to the sea floor and the anchors and anchor chains may cause serious sea floor scour. Similar physical

disturbance to the sea floor may be caused by pipeline emplacement. These physical disturbances to the sea floor resemble those from ice scour and spring river floods.

Large volumes of wastes are generated during drilling of exploratory, production, and workover wells. Some of these wastes may be permitted by NPDES permits for discharge into the marine environment where they have the potential to cause ecological damage. The wastes produced in largest volumes during drilling are drilling muds and drill cuttings. Water based drilling muds (WBM) are the only types that have been used and discharged offshore in the Alaskan Beaufort Sea.

Modern WBM are composed of a weighting agent, usually barium sulfate (barite), clay or organic polymers, and small amounts of additives suspended in freshwater, seawater, or a saline brine. The WBM ingredients of major environmental concern are metals and petroleum hydrocarbons. The drill cuttings generated by the drill bit when drilling with WBM also may contain metals and hydrocarbons, derived mainly from the geologic strata being penetrated by the drill, and usually at concentrations similar to those in local marine sediments.

Thirty-one exploratory wells were drilled over a period of 23 years (1981 to 2002) on State/Federal lease tracts administered by MMS between Barrow and Kaktovik in the Alaskan Beaufort Sea. Many additional wells were drilled on nearshore State lease tracts. WBM and cuttings were discharged to the Beaufort Sea from most of these wells. The total estimated volume of WBM and cuttings discharged from each exploratory well drilled in the Beaufort Sea between 1981 and 1997 ranged from about 940 to 2530 m^3/well. If it is assumed that the average mud/cuttings discharge from a Beaufort Sea exploratory well is about 1500 m^3/well containing an average of 600 metric tons/well of solids and that WBM and cuttings were discharged from about 50 wells drilled on State and State/Federal lease tracts since 1981, the total volume of drilling mud and cuttings discharged to the Beaufort Sea was about 75,000 m^3 and the total mass of solids discharged was about 30,000 metric tons.

The metals frequently found in drilling muds and cuttings that are of greatest concern because of their potential toxicity and/or abundance in drilling muds include arsenic, barium, chromium, cadmium, copper, iron, lead, mercury, nickel, and zinc. In the past, only barium, chromium, iron, lead, and zinc sometimes were present in drilling mud/cuttings solids at concentrations significantly higher (> 100-fold) than concentrations in clean marine sediments (Table 4-1). However, most of these metals are present as insoluble sulfide inclusions in drilling barite and are not bioavailable to marine animals (Neff, 2008). With the imposition of a limit on the concentrations of mercury (1 mg/kg) and cadmium (2 mg/kg) in drilling mud barite (EPA, 1993), concentrations of most metals have decreased in WBM and cuttings discharged offshore in the US; barium (from barite) is the only metal usually found at substantially higher concentrations in WBM than in marine sediments (Neff, 2010). All metals, with the exception of barium and chromium, were present in the historic Beaufort Sea drilling muds at concentrations similar to those in Beaufort Sea sediment and river particulate matter (Table 4-1).

Total petroleum hydrocarbons, including PAH, sometimes are present in WBM and cuttings at concentrations higher than those in river sediments (Table 3-12) and Beaufort Sea sediments (Table 3-24). For example, drilling mud and cuttings from several depths in a well drilled off Point Arguello, CA, contained 900 to 8000 µg/g total PAH, compared to a range of total PAH

Table 4-1. Ranges of metal concentrations in water based drilling muds (WBM) used and discharged offshore in the Beaufort Sea to drill five exploratory wells between 1973 and 1983. The exploratory wells were Reindeer Island, Sag Delta 8, Challenge Island, Mukluk, and Tern Island. Concentrations are µg/g dry wt. From Neff (2010). Metals concentrations in suspended particles in three Arctic Rivers and in Beaufort Sea sediments (Tables 3-2 and 3-20) are included for comparison.

Well	Barium	Cadmium	Chromium	Copper	Lead	Mercury	Zinc
Reindeer	720 - 7640	<0.01 - 1.5	28 - 176	2.8 - 17	2.4 - 117	0.017 - 0.22	42 - 397
Sag Delta 8	60,000	0.28	19.0	19.0	20	<0.01	380
Challenge Island	20,000-360,000	0.2	590 - 1300	14 - 17	17 - 20	0.04 - 0.08	95 - 140
Mukluk	9520 - 33,200	0.19 - 0.20	9.2 - 10	NA	NA	0.06 - 0.08	NA
Tern Island	113 - 259,000	1.7	28 - 37	13	16 - 106	<0.1	130
River Suspended Particles	358 - 1219	NA	NA	17.6 - 45.1	4.0 - 36	NA	81 - 264
Offshore Sediments	16 - 912	0.03 - 0.77	14.7 - 116	3.9 - 46.2	3.7 - 20.3	0.007 - 0.11	15.1 - 120

NA, not analyzed.

concentrations in North Slope river sediments and Beaufort Sea sediments of 8.6 to 2635 ng/g. By comparison, mean concentrations of total PAH in surficial sediment samples collected from the Beaufort Sea off the Mackenzie River, Canada, ranged from 1930 to 4580 ng/g (Yunker et al., 1996). The PAH in WBM and cuttings are primarily from hydrocarbon-rich organic matter (e.g., kerogens, shale, and petroleum) in geologic strata penetrated by the drill bit and from lubricants and other additives sometimes added to the drilling muds. Current NPDES permits prohibit discharge of drilling mud and cuttings containing free oil.

The PAH in river particulates and Beaufort Sea sediments are from combustion soot (pyrogenic), fossil hydrocarbon mixtures (peat, shales, coal, and petroleum) (petrogenic), and biogenic (perylene, retene, and simonellite from anaerobic diagenesis of organic matter) (Venkatesan and Kaplan, 1982; Anders and Magoon, 1985; Steinhauer and Boehm, 1992; Brown et al., 2004, 2010). PAH from these sources enter the Beaufort Sea in natural seeps, petroleum spills, river runoff, coastal erosion, and aerial deposition. Becker and Manen (1988) document six oil seeps on the shore of the Beaufort Sea and on the Chukchi Sea shore, just south of Barrow. The Beaufort Sea seeps are, from east to west, at Angun Point, Maning Point on Barter Island, the mouth of the Canning River, oil lake on the Colville River, and Cape Simpson. Anders and Magoon (1985) identified several additional oil seeps and oil-stained rock shale outcrops across the coastal plain of northeastern Alaska. They reported that the oil rich shales along the coast of the Alaskan National Wildlife Refuge (ANWR) contained 0.9 to 18.3% TOC and 41 to 4,200 mg/kg total hydrocarbons. The residues exhibited a wide range of petroleum biomarker ratios, indicating a wide diversity of source materials with different maturities. Hydrocarbons, including PAH, from these surface deposits probably are being transported into the Beaufort Sea with the spring river floods and coastal erosion.

Drilling muds and cuttings were not discharged to the Beaufort Sea during development of the Endicott, Northstar, and probably also the Oooguruk facilities. Some non-aqueous phase drilling muds (i.e., synthetic based and oil based muds) were used for development drilling at Endicott and Northstar and all drilling wastes were disposed of in waste disposal wells at the drill site or transported to shore for onshore disposal (Krieger et al., 2002). The Liberty prospect will be developed from the Endicott satellite drilling island (SDI) and probably will dispose of drilling muds and cuttings through a disposal well at Endicott or in the Prudhoe Bay field. Therefore, one of the original objectives of the BSMP and AMIMIDA Projects, to assess environmental impact of offshore drilling mud and cuttings discharges in the Alaskan Beaufort Sea, cannot be accomplished.

Ocean discharge of produced water during production of oil and gas has been a long-term environmental concern in most offshore oil and gas development areas in the world (Neff, 2002a). Historically, produced water from onshore and offshore production wells has not been discharged to the Alaskan Beaufort Sea. Most is treated and reinjected, primarily for water-flood to enhance production of oil. Therefore, produced water is not a source of contaminants, particularly PAH, to the Beaufort Sea.

4.3 Sources of Sediments, Metals, and Hydrocarbons in the Beaufort Sea

4.3.1 Sediments

Alaskan Arctic rivers typically transport 30 to 80% of their total annual discharge of water and >80% of their load of suspended sediments during spring (Rember and Trefry, 2004). During the 2 to 3 weeks of the spring floods, usually in late May and early June, about 60% of the annual water flow from the Kuparuk River and about one third of the annual flow of the Sagavanirktok River are carried to the Beaufort Sea (Trefry et al., 2004a). Peak flows, lasting three to about 12 days, range from about 300 m^3/sec in the Sagavanirktok River to about 8,500 m^3/sec in the Colville River (Table 4-2). The total annual river flow from the three rivers is about 22.7 km^3 (a km^3 is equivalent to one billion m^3).

Table 4-2. Rate of discharge of water and total solids from the three largest North Slope rivers and from coastal erosion into the development area of the central Alaskan Beaufort Sea. Peak flow and sediment discharge, representing 30 to 90% of the total annual discharge, occurs during 3 to 12 days in late May and early June each year. Data from Rember and Trefry (2004), Trefry et al. (2004), and Alkire and Trefry (2006).

River/Drainage	River Flow		Total Solids (Metric Tons/Year)
	Peak Range (m^3/sec)	Annual Rate (km^3/year)	
Sagavanirktok River	300 - 1200	~6.5	330,000
Kuparuk River	500 - 3500	~1.2	21,000
Colville River	~8500	~15	~5,000,000
Coastal Erosion	---	---	~1,000,000
Total	---	~22.7	~6,350,000

These three rivers also deliver about 6.35 million metric tons/year of suspended sediments to the coastal Beaufort Sea (Table 4-2). An additional 1 million tons/year of suspended sediments is from coastal erosion. By comparison, as discussed above, the total volume of drilling mud and

cuttings discharged to the Beaufort Sea during drilling of about 50 exploratory wells in the 1980s and 1990s was about 75,000 m^3 (0.000075 km^3) and the total mass of solids discharged was about 30,000 metric tons, about 0.00003% and 0.5%, respectively, of the solids discharged from the three rivers each year.

Sedimentation rates in the development area of the nearshore Beaufort Sea range from ~0.04 cm/yr to ~0.10 cm/yr, with several areas having little or no net accumulation of sediment during at least the past 50 years (Trefry et al., 2003, 2004a). Most of the area is considered erosional, with fluxes of suspended sediments from rivers and from offshore on the shelf being redistributed by storms during the open water seasons, as indicated by increases in concentrations of TSS and turbidity during high wind conditions in the open-water period.

The Sagavanirktok River, the major river carrying sediment into Stefansson Sound, is estimated to have an annual sediment load of about 330,000 metric tons (Table 4-2). The depositional area for this sediment in the coastal Beaufort Sea is about 1,000 km^2 (the approximate area bounded by the mainland to the south, the outer islands such as Cross Island to the north, and between 147.0° N and 148.5° W), yielding an estimated deposition rate of ~0.04 cm/year.

4.3.2 Metals

The river discharges also delivered large amounts of particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved and particulate metals to the coastal Beaufort Sea (Table 3-3 and 4-3). The 116,000 tons/year of POC and high concentrations of DOC (2 to 16 mg/L) play an important role in complexing with and transporting metals and hydrocarbons in the Beaufort Sea (Trefry et al., 2004a,b, 2009). There is some evidence that metals and hydrocarbons associated with POC and DOC are less bioavailable and toxic to marine organisms than dissolved metals and hydrocarbons (Neff, 2010). The particulate metals discharged from the three rivers in the largest amounts, Al, Ba, Ca, Fe, and Zn,, also are present in solution in river water (Tables 3-7 and 3-8) and Beaufort Sea water (Table 3-11), and are abundant in drilling muds (Table 4-1), river suspended sediments (Table 3-2), and Beaufort Sea Sediments (3-20). A regression of each metal versus aluminum concentrations in Beaufort Sea sediments yielded a good correlation for most samples, indicating that most metals in the sediments were associated with the clay (aluminosilicate) fraction. More than 85% of river sediments plotted along the metal/aluminum regressions for offshore sediments, supporting the hypothesis that most of the metals in offshore sediments were from the river suspended particles.

If the Tern Island drilling muds (Table 4-1) are considered representative of the drilling muds/cuttings discharged to the Beaufort Sea in the 1980s, then approximately 4.5 metric tons of barium and 0.002 metric tons of zinc were discharged to the Beaufort Sea with the 30,000 metric tons of drilling solids discharged from 50 exploratory wells. These masses represent 0.09% of the barium and 0.0003% of the zinc discharged in particulate matter to the Beaufort Sea each year in river discharges. Thus, river discharges are a major source of fresh water, total suspended solids, POC, DOC, and dissolved and particulate metals to the coastal Beaufort, and are a much larger source than discharges from all the drilling waste discharged to the Beaufort Sea in the last three decades.

4.3.3 Hydrocarbons

The PAH, SHC, and StTr profiles of typical river sediment samples indicate a mixed petrogenic, pyrogenic, and biogenic source (-23).Total PAH concentrations in river and shore peat ranged from 13 to 740 ng/g dry wt (parts per billion) (Table 3-13). As expected, total SHC concentrations in the peat were much higher, ranging from 8700 to 260,000 ng/g. Most peat samples contained comparatively low concentrations of total StTr; highest concentrations were in Kuparuk River sediments, probably because the Kuparuk River drains primarily Arctic tundra soils. There were no clear relationships among concentrations of PAH, SHC, StTr, and TOC in the Arctic peat. However, the high relative concentrations of PAH and SHC in peat, indicates that peat probably is a major source of hydrocarbons in river sediments delivered to the Beaufort Sea.

The SHC, PAH, and StTr profiles of Northstar crude oil (Figure 3-25) were quite different from those of river sediments (Figure 3-23) and river peat (Figure 3-24). Profiles of the SHC and PAH assemblages in the river sediment and peat samples was similar to that in surficial sediments, indicating a common PAH source relationship between the river sediments and the nearshore surficial sediments. Perylene, a biogenic PAH, dominates the overall PAH distribution as one of the most abundant individual PAHs in many offshore and river sediment samples. Perylene is found at equal or greater relative abundance in the river sediments and peat (Figures 3-24 and 3-25), which suggests the relationship of the rivers as a source of the hydrocarbons in the nearshore sediments. Perylene was absent from Northstar crude oil. There was no indication of Northstar crude oil PAH and SHC in Beaufort Sea sediments, even those near the Northstar production facility.

Steinhauer and Boehm (1992), Yunker et al., (1991, 1996), Naidu et al. (2003, 2006), Yunker and MacDonald (1995), and Elmquist et al. (2008) have concluded, based on the abundance of perylene in sediments from sites with and without a past history of exploratory drilling, that most of the PAH in Beaufort Sea, Barents Sea, and other Arctic sediments, including those from drill sites, comes from erosion of peat, coal, and black carbon deposits along the coast or into rivers emptying into the Arctic Ocean. PAH in sediments from the Norwegian and Russian regions of the Barents Sea also have been derived in part from eroding natural deposits of kerogens, oil shales, and coals (Dahle et al., 2003; Elmquist et al., 2008; Boitsov et al., 2009). A major source of PAH in marine sediments throughout the Arctic is diagenesis (early degradation/fossilization of plant material) to form peat, kerogens, immature bitumen, and lignitic coals (Yunker and MacDonald, 1995; Yunker et al., 1996; Steinhauer and Boehm, 1992; Naidu et al., 2006; Elmquist et al., 2008; Boitsov et al., 2009). These PAH-rich materials reach the Arctic Ocean in coastal erosion and river runoff. These tightly bound PAH have a low bioavailability and, therefore, are not toxic to marine plants and animals (Rust et al., 2004; Neff et al., 2005).

There also is a large flux of POC and DOC into the Alaskan and Canadian Beaufort Sea and Barents Sea from rivers (Trefry et al., 2004b, 2009; Yunker et al., 2005; Elmquist et al., 2008; Holmes et al., 2008; Magan et al., 2010). Much of the terrigenous organic matter is delivered to the Beaufort Sea in outflows from large Arctic rivers and from coastal erosion and often is enriched in metals and hydrocarbons.

4.4 Metals and Hydrocarbons in Beaufort Sea Water, Sediments, and Marine Animals

4.4.1 Metals

Concentrations of dissolved trace metals in coastal Beaufort Sea seawater were highly variable (Table 3-11). Concentrations of dissolved As, Cr, and Pb were lower than reported values for surface seawater worldwide. Lower As concentrations were found because dissolved As concentrations increase with increasing salinity and the salinity of nearshore water is lower than that of ocean water due to river runoff of freshwater containing low As concentrations. In contrast, concentrations of dissolved Cd, Cu, and Zn were higher than in typical surface seawater. Concentrations of dissolved Cd, at 14 to 18 ng/L, in rivers were lower than in seawater at any time of year. Concentrations of dissolved Ba were similar to those in typical surface seawater, except during 2000 and 2001, when more nearshore samples were collected. Dissolved Ba concentrations usually were lower in seawater (10 to 32 µg/L), than in river water because of precipitation of barium as barite during mixing of river water with seawater containing naturally high concentrations of sulfate.

Concentrations of particulate metals in the open-waters of the Beaufort Sea were variable as a function of the organic matter and clay content in the TSS and POC particles. The area-wide averages for 2000, 2001, 2002, 2004, 2005 and 2006 in Table 3-10 show some interannual variability; however, most of the variations are due to differences in the composition of the suspended sediments as shown by variations in concentrations of Al and Fe and generally comparable shifts in concentrations of trace metals.

Concentrations of metals in Beaufort Sea sediments were highly variable on both spatial and temporal scales. The variability was due partly to variations in % silt+clay, and concentrations in sediment of total organic carbon (TOC), aluminum, and iron (Table 3-19). Normalization of sediment metals concentrations to aluminum concentration reduced the variability and indicated that most metals in most sediments were associated with the clay (aluminosilicate) fraction. There were no large interannual variations in concentrations of any Al-normalized metals in Beaufort Sea sediments (Tables 3-20 and 3-21). With few exceptions, metals concentrations measured in cANIMIDA in Beaufort Sea sediments were similar to concentrations measured by others in sediments from throughout the Beaufort Sea (Table 22 and 23), but lower than concentrations in drilling muds and cuttings discharged during exploratory drilling in 1979 through 1982 (Tables 3-22, 3-3, 4-1).

Concentrations of 13 to 18 metals in tissues of several species of fish, amphipods, isopods, and clams collected near the Northstar Development, in the Liberty Prospect area, and in reference stations in the BSMP areas were similar in 2000 through 2006 (Table 3-25), and comparable to metals concentrations in the same or similar species collected in uncontaminated water throughout the world (Table 3-26).

Benthic amphipods and clams were collected at some of the same stations where surface sediments were collected between 1999 and 2006 (Table 2-1). Therefore, it is possible to determine if there is a significant relationship between metals and hydrocarbons concentrations in co-occurring sediments and benthic amphipods and clams in the development area of the Beaufort Sea. This cannot be done for fish, because sediments were not collected at most fish

sampling locations and fish are highly migratory, making it unlikely that there would be such a relationship.

The two most abundant metals (relative to their concentrations in clean marine sediments) in historic Beaufort Sea drilling muds (Table 4-1) are barium and chromium. Concentrations of these two metals were relatively high in Beaufort Sea sediments, but low in tissues of amphipods and clams (Figure 4-1). There was no relationship between concentrations of these two metals in sediments and concentrations in tissues of amphipods and clams collected concurrently from the same sediments between 1999 and 2006. R^2 values were less than 0.01 in all cases, indicating that barium and chromium concentrations in tissues were relatively constant over a wide range of barium and chromium concentrations in sediments. Concentrations of both metals in the tissues of both species were about one-tenth those in sediments in which they were residing. There was a single outlier (unexpectedly high metal concentrations) for both metals in both species of benthic invertebrates. The outliers were collected in 2002 and 2006 off the mouths of the three rivers. The amphipods containing elevated concentrations of chromium were collected in 2002 near the Northstar facility (station N03).

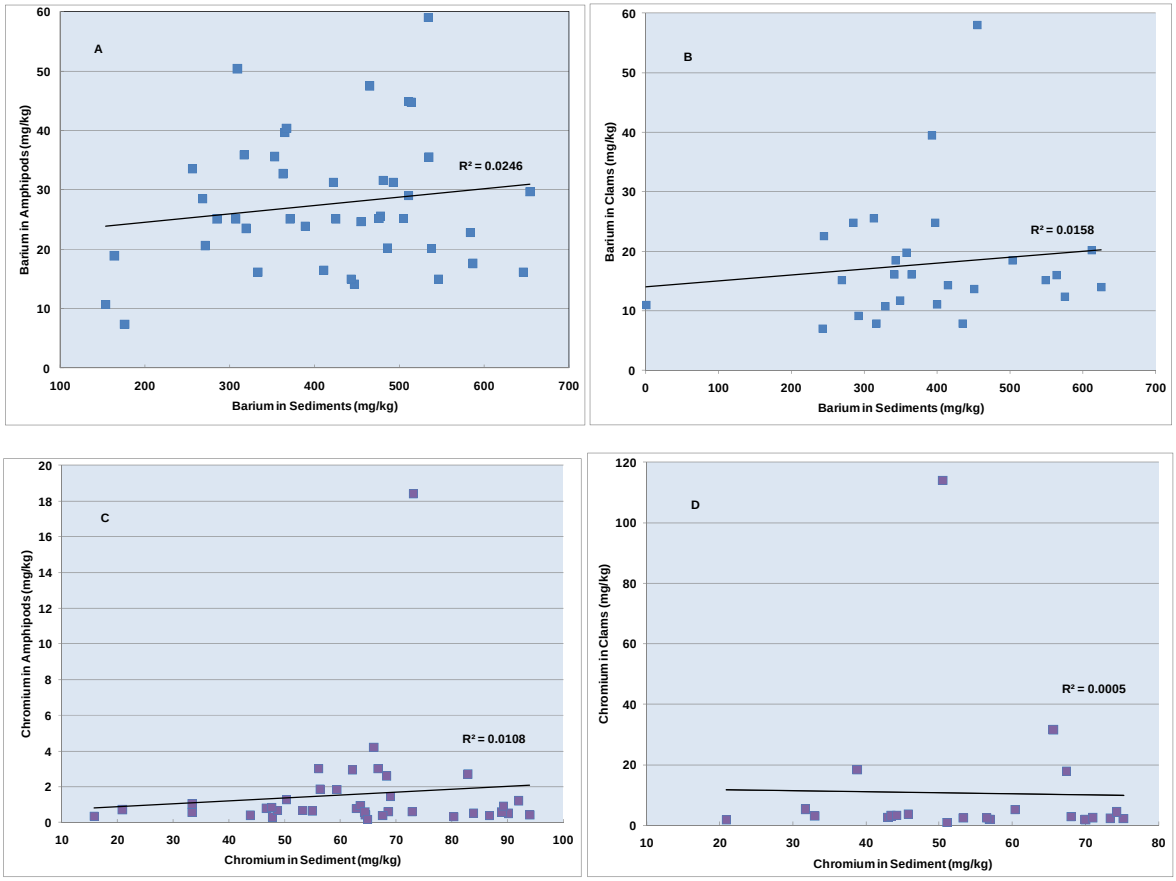


Figure 4-1. Regressions of barium and chromium concentrations in sediments and tissues of amphipods (A, C) and clams (B, D) collected at several stations in the Northstar, Liberty, and BSMP areas of the Beaufort Sea between 1999 and 2006. Approximately 40 sediment/amphipod and 25 sediment/clam concentration pairs were available (Table 2-1). Concentrations in sediments, amphipods, and clams are mg/kg dry wt (parts per million).

Concentrations of Ba, the best indicator of previous drilling water discharges, in surface sediments in the development area ranged from 16 mg/kg to 910 mg/kg between 2000 and 2006, with little difference in sediment Ba concentration in Northstar, Liberty, and BSMP sediments (Table 3-20). Thus, there is little evidence, with the exception of elevated Ba concentrations in sediment cores from a few locations, of past drilling discharges in the development area.

There were similar results for lead and zinc, also sometimes present at high concentrations in drilling discharges (Table 4-1). There was a slightly negative slope to the sediment/tissue concentration regressions for both metals and both species (Figure 4-2). However, the highest R^2 was only 0.18 (for zinc in clams), indicating that the relationships were not statistically significant. Both lead (a non-essential trace metal) and zinc (an essential trace metal) concentrations were relatively constant in tissues of both amphipods and clams over a wide range of lead and zinc concentrations in sediments. With only a few exceptions, lead concentrations in amphipods and clams were below 1.0 mg/kg over a sediment lead concentration range of about 3.0 to 16 mg/kg. Zinc concentrations in amphipods were about 100 mg/kg in sediments containing 10 to 120 mg/kg zinc. Zinc concentrations in most clams ranged from 60 to 90 mg/kg in sediments containing 30 to 85 mg/kg zinc. Again, there are single outliers for both metals and both species of marine invertebrates. Concentrations of both lead and zinc were elevated in amphipods collected in 2004 south of the Northstar facility (station N11). Clams collected in 2002 from off the mouth of the Kuparuk River (station 5F) and in the center of the liberty prospect (L08) contained elevated concentrations of lead and zinc, respectively.

Two of the metals of concern in the Beaufort Sea ecosystem, because of their potential to accumulate to potentially toxic concentrations n the Beaufort Sea food web, are arsenic and mercury. Regressions of concentrations of these two metals in sediments and benthic invertebrates were not significant (R^2 ranging from 0.001 for mercury in clams to 0.05 for arsenic in amphipods) (Figure 4-3). Arsenic concentrations were extremely variable in sediments, amphipods, and clams collected between 1999 and 2006 throughout the development area. Unlike all the other metals examined, concentrations of both arsenic and mercury in invertebrate tissues were not related to those in the sediments where they reside. Much of the arsenic in benthic invertebrates is in the form of arseno-sugars and arsenobetaine, probably converted from arsenate by microbes in suboxic sediments (Neff, 1997). These organo-arsenic compounds are highly bioaccumulative, but not toxic. More than 90% of the mercury in Beaufort Sea sediments is inorganic mercuric mercury (Semmler, 2006; Trefry et al., 2009), which is less bioaccumulative and toxic than methylmercury (Neff, 2002b). However, the lack of correlation between concentrations arsenic and mercury in sediments and tissues indicates that these metals probably are not being bioaccumulated from sediments.

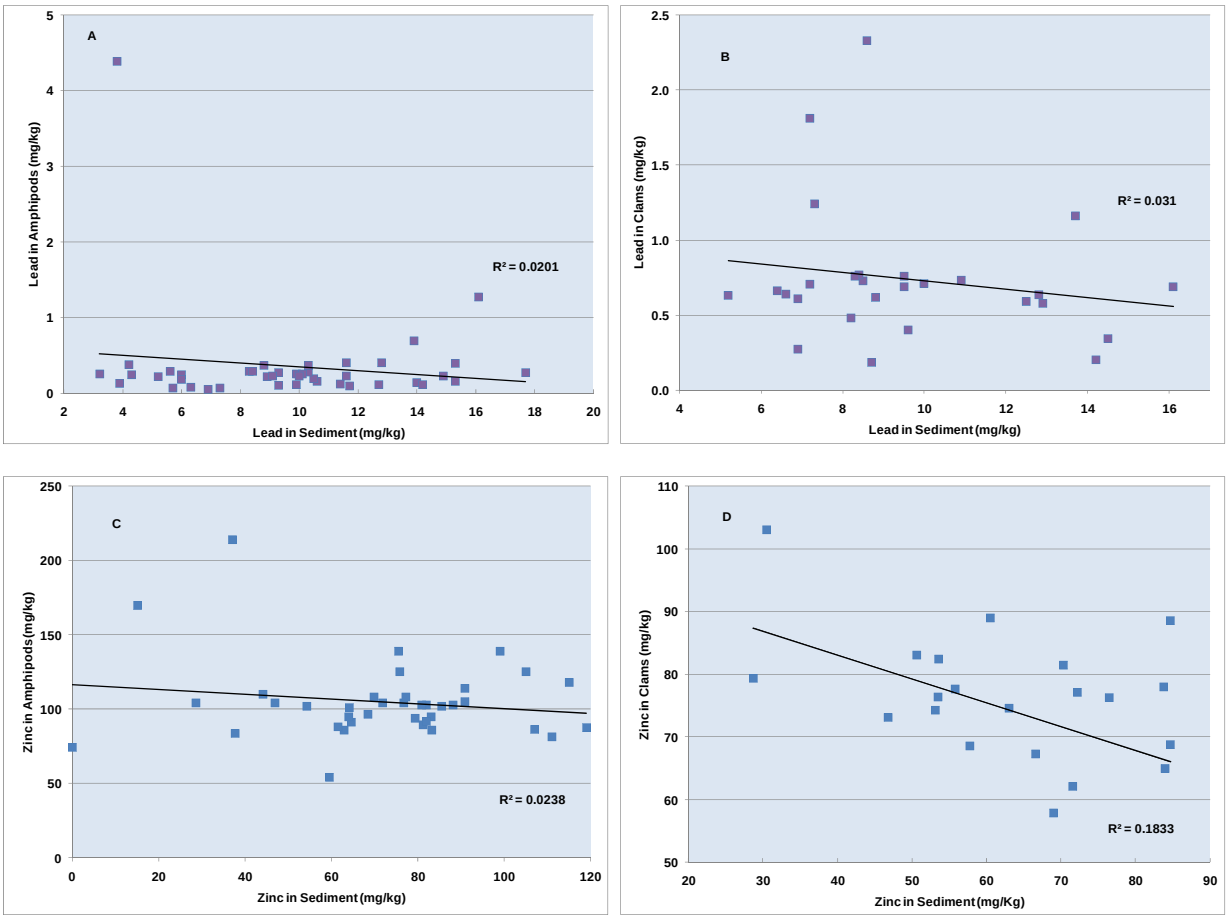


Figure 4-2. Regressions of lead and zinc concentrations in sediments and tissues of amphipods (A, C) and clams (B, D) collected at several stations in the Northstar, Liberty, and BSMP areas of the Beaufort Sea between 1999 and 2006. Approximately 40 sediment/amphipod and 25 sediment/clam concentration pairs were available (Table 2-1). Concentrations in sediments, amphipods, and clams are mg/kg dry wt (parts per million).

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The concentrations of all six metals discussed here are at concentrations in sediments, amphipods, and clams at concentrations similar to those in sediments and marine invertebrates from uncontaminated marine environments, worldwide (Neff, 2002a) and are well below concentrations that might be toxic to the benthic invertebrates or their consumers.

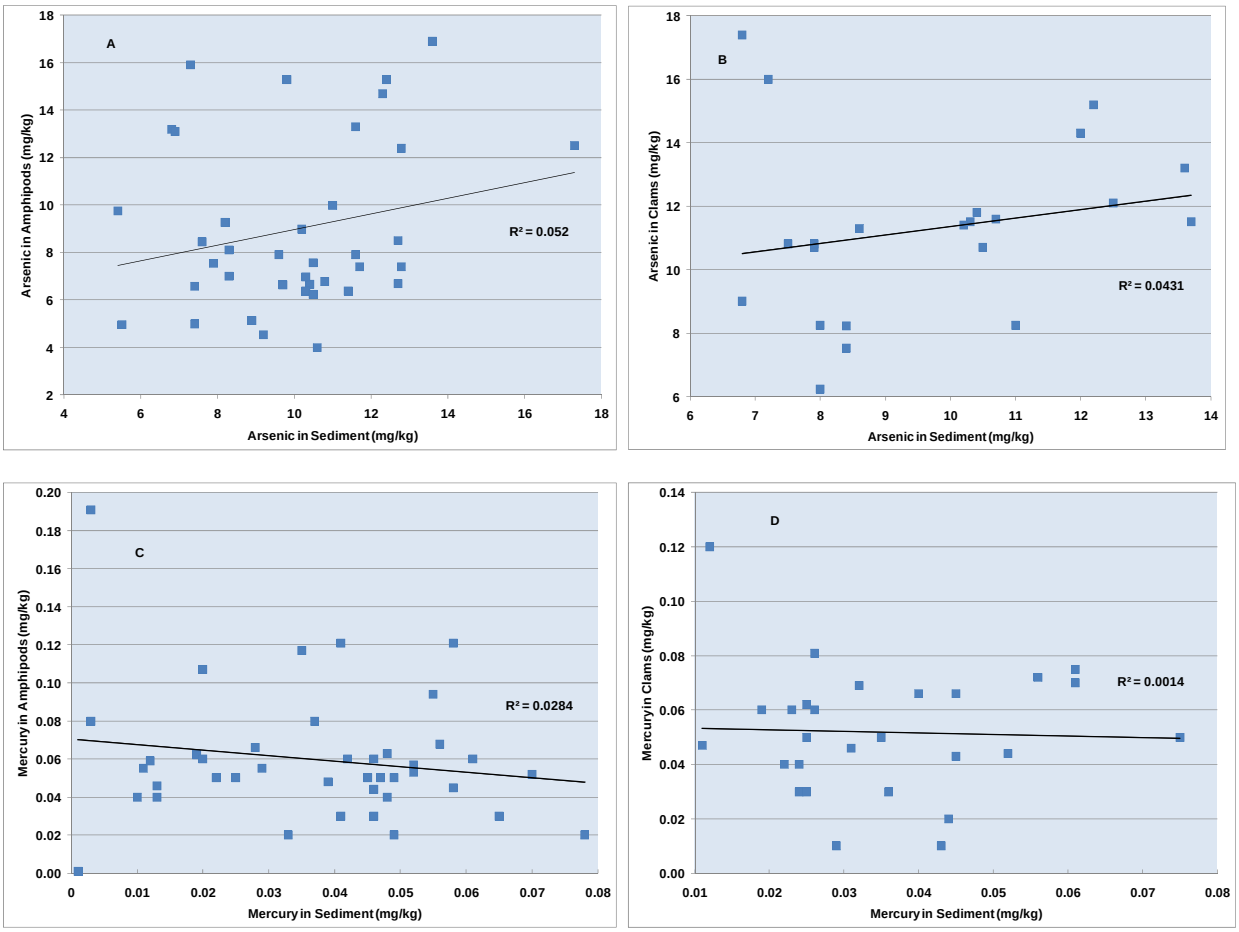

Figure 4-3. Regressions of arsenic and mercury concentrations in sediments and tissues of amphipods (A, C) and clams (B, D) collected at several stations in the Northstar, Liberty, and BSMP areas of the Beaufort Sea between 1999 and 2006. Approximately 40 sediment/amphipod and 25 sediment/clam concentration pairs were available (Table 2-1). Concentrations in sediments, amphipods, and clams are mg/kg dry wt (parts per million).

4.4.2 Hydrocarbons

Whole water samples from the three areas of the Beaufort Sea contained 37 to 69 ng/L (parts per trillion) TPAH (Table 3-14). Most of the PAH in whole water were associated with the particulate fraction. Concentrations of dissolved PAH ranged from 13 to 19 ng/L. The low molecular weight 2- and 3-ring PAH were much more abundant than the higher molecular weight 4- through 6-ring PAH in both the particulate and dissolved fractions, indicating that much of the PAH in surface waters were from a petrogenic origin. If the blank concentrations are considered, the actual TPAH concentrations in whole water and the particulate and dissolved fractions, ~15 - 40 ng/L, ~11 - 45 ng/L, and ~<1 - 6 ng/L, respectively, are in the range frequently reported for uncontaminated nearshore surface seawater (Neff, 2002a).

Concentrations of TPAH in surficial sediments collected between 2000 and 2006 from the Northstar, Liberty, and BSMP areas ranged from 0.01 to 1.80 mg/kg (Table 3-24). Much of the PAH appeared to be associated with POC in the silt+clay fraction of the sediments. Although mean TPAH concentrations increased in sediments from Northstar stations between 2000 and 2006, the mean TPAH concentrations in sediments collected between 2000 and 2006 combined from the three survey areas were similar. The PAH composition did not change between 2000 and 2006 in Northstar sediments, indicating that the sediment PAH probably did not come from Northstar operations. As discussed above much of the sediment PAH and SHC probably were derived from hydrocarbon-rich POC from Arctic rivers.

TPAH concentrations in tissues of eight species of fish combined were low in all years (Table 3-38). The fish tissue PAH residue data for 2001 through 2006, as well as the low levels of PAH exposure biomarker levels in fish tissues, are consistent with chronic, low-level exposure to PAH in water, sediments, and food throughout the study area, with no clear point source of bioavailable PAH in the coastal environment.

The tissue residue data for PAH, SHC, and StTr indicate that hydrocarbons in tissues of near-shore benthic invertebrates from the development area are derived in part from DOC and POC entering the Beaufort Sea from nearby rivers, as well as the Mackenzie River, and from coastal erosion. Contributions from the development of and oil production from Northstar facility appear to be low.

These conclusions are confirmed by regression analysis of TPAH and TSHC concentrations in sediments and tissues of amphipods and clams collected from the same stations between 1999 and 2006. The regression of TPAH concentrations in sediments versus concentrations in tissues of amphipods and clams collected from the same stations shows that there is no relationship between TPAH concentrations in sediments and the two benthic invertebrates ($R^2 = 0.0004$ and 0.072, respectively) (Figure 4-4a,b). With a few exceptions, TPAH concentrations in amphipods are less than 0.1 mg/kg over a range of 0.01 to 1.80 mg/kg TPAH in the sediments where they reside. The uniformly low concentrations of TPAH in amphipod tissues indicates that these crustaceans are able to metabolize and excrete bioaccumulated PAH, and that the sediment PAH have a low bioavailability.

Concentrations of TPAH in clam tissues was more variable, ranging from about 0.01 mg/kg to about 0.15 mg/kg, compared to a concentration range of about 0.05 to 0.75 mg/kg in the sediments where the clams reside (Figure 4-4b). The few outlier concentrations were in amphipod and clams collected in the Liberty prospect (stations L03 and L04) in 1999 and 2006. The lack of correlation between TPAH concentrations in sediments and clams and the limited ability of clams to metabolize and excrete bioaccumulated PAH (Neff, 2002a) confirms that sediment PAH have a low bioavailability. PAH tightly bound to peat, kerogens, and coal have a very low bioavailability and toxicity, as discussed above.

There also was no relationship between concentrations of TSHC in sediments and tissues of amphipods and clams ($R^2 = 0.15$ and 0.04, respectively) (Figure 4-4c,d). TSHC concentrations were highly variable in tissues of amphipods, ranging from 5 mg/kg to 249 mg/kg. Concentrations in sediments were much lower, ranging from 0.3 to 38 mg/kg. Most of the SHC in amphipods is pristane (Table 3-40), bioaccumulated from consumption of copepods or

animals that consume large numbers of copepods. Pristane concentrations in Beaufort Sea sediments is very low. Thus, the amphipods are not bioaccumulating SHC from sediments.

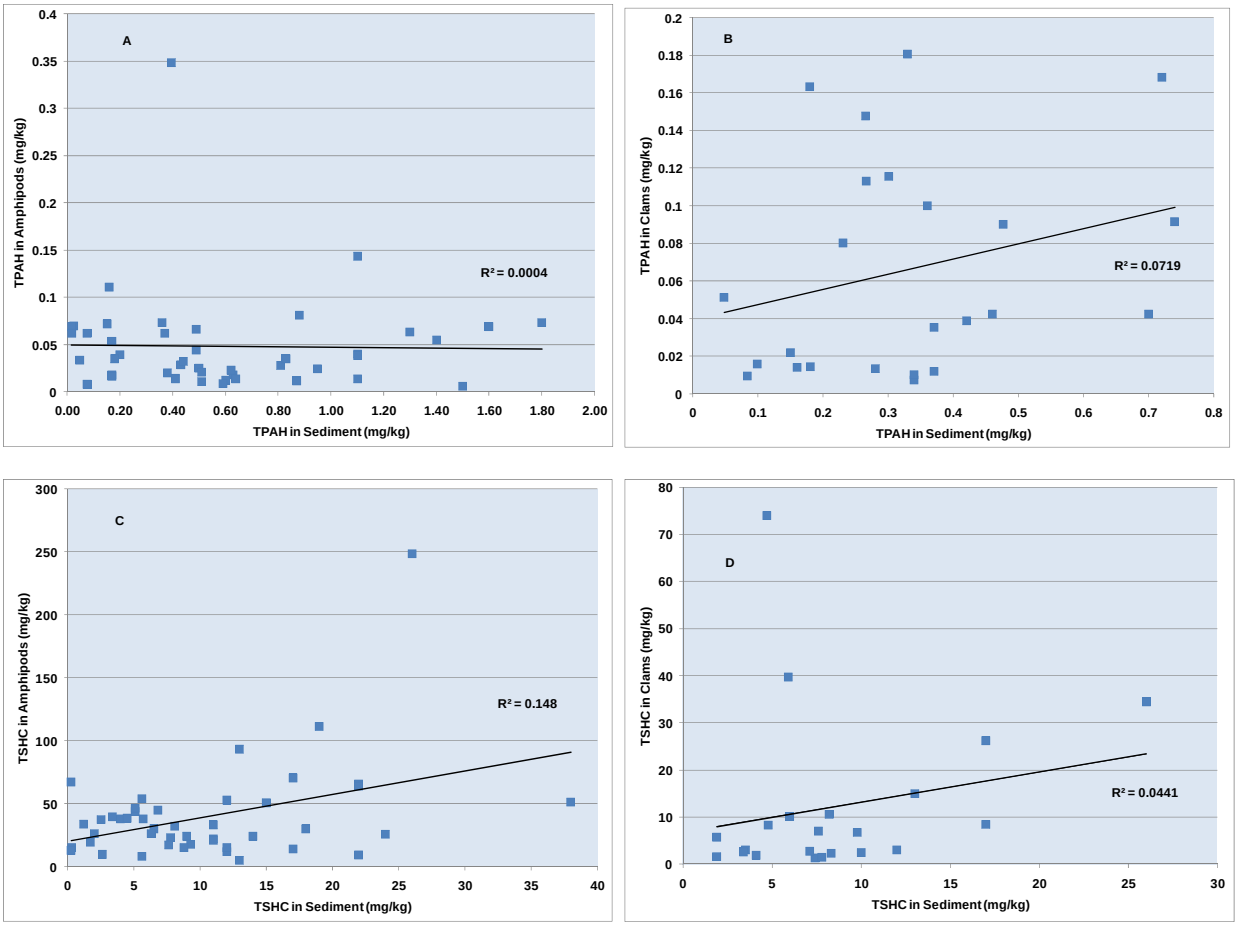

Figure 4-4. Regressions of total PAH (TPAH) and total SHC (TSHC) concentrations in sediments and tissues of amphipods (A, C) and clams (B, D) collected at several stations in the Northstar, Liberty, and BSMP areas of the Beaufort Sea between 1999 and 2006. Approximately 40 sediment/amphipod and 25 sediment/clam concentration pairs were available (Table 2-1). Concentrations in sediments, amphipods, and clams are mg/kg dry wt (parts per million).

With a few exceptions, TSHC concentrations in clams were below 20 mg/kg, compared to concentrations in sediments ranging from 1.9 to 26 mg/kg (Figure 4-4d). The SHC assemblage in clam tissues is dominated by higher molecular weight n-alkanes (>C_{24}), with no obvious odd/even carbon number preference. The SHC assemblage in Beaufort Sea sediments also is dominated by high molecular weight n-alkanes, with a pronounced odd/even carbon number preference, indicating that the sediment SHC are derived primarily from terrestrial plant material. The SHC assemblage in petroleum usually is dominated by low molecular weight alkanes. Thus, the SHC in clams probably are from marine and terrestrial biological sources.

4.5 Are Chemicals from Offshore Oil Operations Entering the Beaufort Sea Food Web?

The Beaufort Sea food web is a relatively simple one with relatively few abundant taxa at each trophic level (Figures 3-54 and 3-55). Nutrients to support primary production in the Alaskan Beaufort Sea are derived primarily from inflows from the Bering Sea, Anadyr Water (from the Russian Chukchi Sea), the Canadian Beaufort Sea, and upwelling from the Arctic Basin (Dunton et al., 2003, 2004). However, DOC concentrations are high in the spring floods from the Sagavanirktok, Kuparuk, and Colville Rivers (Trefry et al., 2004b, 2009; Holmes et al., 2008). About 20 to 40% of the DOC in the spring freshet is labile and is an important source of nutrient input to the Beaufort Sea (Holmes et al., 2008). Primary production, supported by these nutrient sources, is pelagic (phytoplankton), epontic (living on the underside of sea ice), and benthic (Dunton et al., 2009). The nutrient inputs from Arctic rivers during the spring breakup may stimulate the spring phytoplankton blooms. The epontic community along the seasonal ice edge may contribute substantially to overall pelagic production. Epontic microalgae support diverse communities of ice-associated meiofauna that help support spring zooplankton blooms (Carey and Montagna, 1982).

As discussed above, most of the hydrocarbons in river water, particularly during the spring floods, are associated with POC and DOC, whereas most of the metals are associated with suspended fine-grained sediments. These complexed metals and hydrocarbons accumulate in offshore sediments. Metals and hydrocarbons from offshore oil and gas operations, such as gravel island construction and drilling waste discharges, also tend to accumulate in Beaufort Sea sediments. The POC in the Arctic rivers is derived primarily from terrestrial plant matter and peat and is quite refractory (Magan et al., 2010). Metals and hydrocarbons adsorbed to terrestrial POC from the Arctic rivers in sediments from the development have a low bioavailability and toxicity to benthic and pelagic marine animals. Metals and hydrocarbons in tissues of benthic invertebrates and fish from the Beaufort Sea are at background levels similar to concentrations in tissues of the same or related species from clean marine environments throughout the world.

The metals and hydrocarbons associated with offshore oil and gas operations also have a limited bioavailability (Neff, 2005, 2010); a small fraction may be bioaccumulated by marine plants and animals and transferred through marine food webs. None of these chemicals, except possibly arsenic and mercury, biomagnifies in marine food webs. Their concentrations decrease with each trophic step.

Arsenic does seem to biomagnify in some steps of marine food webs because inorganic arsenic is converted to arseno-sugars and arsenobetaine, probably by sediment bacteria. These organo-arsenic compounds are much more bioavailable and slower to be released from tissues than inorganic arsenate and arsenite salts, so arsenobetaine, in particular, tends to bioaccumulate to high concentrations in marine animals that consume benthic fauna (Neff, 1997). Arsenobetaine is not toxic to consumers, including man. Arsenic tends to biomagnify to only a limited extent in the Beaufort Sea food web (Semmler, 2006). Arsenic concentrations are relatively high in ocean waters of the Beaufort Sea and probably is derived from upwelling of slope water onto the shelf (Trefry et al., 2009). Arsenic is present at expected concentrations in the Beaufort Sea food web. There is no evidence of bioaccumulation of arsenic from offshore oil and gas operations.

Methylmercury, but not inorganic mercury, tends to biomagnify in the Beaufort Sea food web. Because methylmercury tends to biomagnify in marine food webs, concentrations of total and methylmercury are high in high trophic level consumers in Arctic seas. Concentrations of total and methylmercury are high in liver and muscle tissues of several marine mammals collected off Barrow, AK (Table 3-18). Fish- and mammal-eating marine carnivores, such as polar bears, beluga whales, and some seals, contain high concentrations of total and methylmercury in liver, with lower concentrations in muscle and other organs. Bowhead whales do not bioaccumulate high concentrations of mercury because they feed at a lower trophic level on large copepods and euphausiids that contain low concentrations of methylmercury. Drilling discharges contain low concentrations of mercury that is tightly bound in insoluble forms in the drilling mud barite (Neff, 2002b). This insoluble mercury can not readily be converted to bioaccumulative, toxic methylmercury, so drilling discharges do not introduce bioavailable mercury into the Beaufort Sea food web.

As discussed above, concentrations of hydrocarbons, including toxic PAH, are low in Beaufort Sea water, sediments, and tissues of marine animals. There are no data on concentrations of PAH in top consumers in the Beaufort Sea food web. Beluga whales from off the Mackenzie River delta exhibited high levels of induction of the PAH exposure biomarker CYP1A, indicating exposure to relatively high concentrations of PAH or other inducers, such as halogenated aromatic hydrocarbons (Wilson et al., 2005). The PAH and halogenated aromatic compounds probably came from the river drainage that includes the vast heavy oil reserves in central Alberta. However, PAH concentrations are low in water, sediments, and marine animals from the Alaskan Beaufort Sea and marine mammals and birds are able to rapidly metabolize and excrete bioaccumulated PAH. Therefore, PAH concentrations in tissues of upper trophic level marine animals in the Beaufort Sea food web are expected to be low. There is no evidence of input of large amounts of PAH from offshore oil and gas operations into the Beaufort Sea; concentrations are at expected levels in water, sediments, and tissues of marine invertebrates and fish.

4.6 Is There Evidence of Physical, Chemical, or Biological Changes Caused by Construction and Production at Northstar?

Monitoring during ANIMIDA with vertical profiles and horizontal tows showed that there were no significant differences in turbidity or concentrations of TSS in proximity (within 100 to 500 m) of Northstar Island relative to other locations in the ANIMIDA study area (Trefry et al., 2004a,b). Variations in turbidity and TSS concentrations in the water column during the open water season are due largely to variations in wind speed and duration (Table 4-3). Arctic rivers also discharge massive amounts of TSS both onto and under the shorefast ice during the spring floods (Table 4-4). Some of this TSS persists well into the open water season and is repeatedly resuspended by summer storms.

Concentrations of dissolved and particulate metals were not significantly different in the water column of Northstar area than in the overall cANIMIDA study area. A few water samples collected near Northstar contained slightly elevated concentrations, compared to other parts of the development area, of particulate lead and cadmium, probably associated with plankton detritus, which sometimes contains elevated concentrations of some metals derived from

Table 4-3. Relationship between wind speed and total suspended solids (TSS) concentrations in surface waters of the Beaufort Sea development area during the open water speed. Under-ice TSS concentration range is included for comparison. From Trefry et al., 2004).

Wind Speed (Knots)	TSS Concentration (mg/L)
Calm to 5	~1 - 4
5 - 10	3 - 8
10 to 20	5 to 15
> 20	50 - >100
Under Ice	<0.1 - 0.5

Table 4-4. Estimated masses of suspended sediment (TSS), particulate metals and particulate organic carbon (POC) carried by the Sagavanirktok, Kuparuk, and Colville Rivers to the coastal Beaufort Sea. Masses are metric tons/year. Estimates for the Sagavanirktok and Kuparuk Rivers are based on 2001 data collected by Trefry et al. (2004) and for the Colville River are from Arnborg et al. (1967). From Trefry et al. (2004).

Parameter	Sagavanirktok River	Kuparuk River	Colville River	Total Discharge
TSS	330,000	21,000	5,000,000	5,350,000
POC	5000	1000	110,000	116,000
Arsenic (As)	3.5	0.3	70	73.8
Barium (Ba)	241	12	4900	5153
Copper (Cu)	11	0.7	200	212
Iron (Fe)	11	0.7	250	267
Lead (Pb)	6	0.3	120	126
Zinc (Zn)	41	2.4	650	693

upwelling of slope water onto the shelf. Concentrations of all dissolved metals were in the range of background values, which are well below the EPA water quality criteria for chronic effects in marine organisms (Table 3-11).

The TPAH concentrations and PAH compositions were similar in the dissolved and particulate phases of water samples collected in 2000 and 2002 near the Northstar production island, in the Liberty prospect, and at historic BSMP stations (Table 3-14). Much of the dissolved and particulate PAH in the development area were from the Arctic rivers (Yunker et al., 1991, 1996; Yunker and MacDonald, 1995; Steinhauer and Boehm, 1992; Trefry et al., 2003, 2004a,b, 2009; Rember and Trefry, 2004). Concentrations of dissolved and particulate TPAH were low at all locations and within the range reported by others for nearshore marine waters world-wide (Neff, 2002a).

Inter-annual shifts in the texture of surficial sediment were observed throughout the cANIMIDA study area between 1999 and 2006 (Brown et al., 2010). During 1999, surficial sediment from several stations near Northstar was composed almost exclusively of sand and gravel. Most surficial sediments collected from the same stations in 2000 contained more than 50% silt+clay. Although the exact mechanism for this shift is not known, the 1999 samples were collected after

a 6-day storm with winds in excess of 25 knots that may have eroded away finer-grained material. No such storms preceded collection of the 2000 samples that probably contained fine-grained sediments discharged from the Kuparuk River during the spring breakup of 2000. Fine grained sediments were more abundant in sediments collected in 1999 at a few stations close to Northstar than in sediments collected at the same locations in 2000. This shift may have resulted from inputs of coarser material at these stations in association with construction of the Northstar gravel island. There continued to be shifts in grain sized distributions at all stations in the Northstar area between 2000 and 2006. These shifts were associated with inter-annual variations in the concentrations of TSS in the spring river flood from the Kuparuk, Sagavanirktok, and Colville Rivers (Table 3-1). Thus, the Northstar area appears have a dynamic sedimentary environment, an observation that is consistent with difficulties in finding sediment cores with a useful radioisotope record of sediment geochronology.

Concentrations of 11 metals, of the types that are of concern in marine sediments because of their toxicity or association with offshore oil and gas development activities (Neff, 2010), were similar in surface sediments in the Northstar, Liberty, and BSMP areas in 2000 through 2006 (Tables 3-19, 3-20, and 3-21). None of the metals was consistently present at a higher range of concentrations in sediments from the Northstar production facility, than in sediments from the Liberty prospect or the historic BSMP stations.

Statistical analyses of TPAH, TSHC, and StTr concentrations in surface sediments collected throughout the development area between 1999 and 2006 indicated that hydrocarbon concentrations increased significantly at in post-1999 sediments from the Northstar area. However, a closer examination of the PAH data show that although PAH concentrations in Northstar sediments increased after construction (2000, 2002, and 2004 - 2006 combined), the distribution and composition of the PAH assemblage in sediments remained relatively unchanged. The composition of the sediment hydrocarbons in Northstar sediments is best summarized by a comparison of the pyrogenic to petrogenic PAH ratios in sediments from 1999, 2000, 2002 and 2004 - 2006. The pyrogenic/petrogenic ratio is the same in sediments collected at Northstar in 1999 and 2000, but then increases after 2000 (Figure 3-37), indicating that there were no incremental additions of petrogenic hydrocarbons to Northstar sediments from construction activities in the winter of 1999/2000. Some of the pyrogenic PAH may have come from flaring of waste gases on the production island during the early years of production. Apparently, the Northstar surface sediments were depleted in hydrocarbons in 1999, possibly by storm-driven bed transport of hydrocarbon-rich POC from the sediments. The organic analyses and resulting statistical comparisons of the 1999, 2000, 2002, and 2004 Northstar, BSMP and Liberty data, support this explanation. The hydrocarbon concentration and composition data do not reveal any detectable hydrocarbon input that can be attributed to the Northstar operations, when viewed against the pre-construction levels in the sediments and the pre-construction hydrocarbon composition and regional distribution.

Diagnostic ratio plots of sterane and triterpane petroleum biomarkers show that the hydrocarbon composition in sediment cores fall well within the range defined by hydrocarbon data for the surface sediment samples from the area (Figure 3-43). This provides further evidence that the sediment core data are representative of the regional hydrocarbon background, and do not indicate any substantial influence from anthropogenic hydrocarbon inputs from construction and

production in the Northstar or Prudhoe Bay areas, as indicated by the distance on the plot between the data points for Northstar and North Slope crude oils and the sediment cores.

TPAH and SHC concentrations were not higher in marine animals collected near the Northstar facility in 1999 through 2006 than in marine animals from other areas of the Beaufort Sea, indicating that the offshore operations were not a significant source of PAH in the animal tissues. All concentrations in marine animals tissues were well below concentrations that are considered hazardous to the marine animals or their consumers, including man (Neff et al., 2009).

4.7 Possible Effects of Offshore Oil Development on the Boulder Patch Ecosystem and Subsistence Whaling Near Cross Island

Offshore oil exploration and development in the Beaufort Sea could affect the Boulder Patch and areas northeast of Cross Island where the annual subsistence whale hunt takes place by changing (increasing) concentrations of suspended sediment, POC, and biodegradable DOC in the nearshore water column. Physical disturbance by vessel activity in the Boulder Patch or in areas along the coast where bowhead migrate westward each fall is perhaps the greatest threat to these biological resources. Construction and production operations offshore on artificial gravel islands could cause or contribute to increases in concentrations of TSS (and associated turbidity), POC, DOC, metals, and hydrocarbons in the water column, and tainting of the Beaufort Sea food web with potentially toxic chemicals.

TSS concentrations were much lower in the water column of the Boulder patch during the summers of 2004 and 2006 than in 2005 but the general trend of decreasing TSS with distance offshore was observed in all three years (Dunton et al., 2009) (Figure 3-57). Concentrations of the primary nutrients, ammonium, phosphate, silicate, and nitrate + nitrite nutrient also were higher in 2005 than in 2004 and 2006 (Table 3-48). Dissolved oxygen concentrations were at or above saturation in all years monitored, though concentration were slightly higher in 2004 than in 2005 and 2006, probably due to small differences in temperature and salinity among the three years.

Underwater light intensity dropped to near zero in the water column of some parts of the Boulder Patch during the summer of 2004, due to a series of intense storms. Water transparency was highest in 2006, probably due to the absence of significant storm events during the study period.

These interannual differences in water quality have a significant effect on the macroalgal community of the Boulder Patch which receives sufficiently intense solar radiation to support growth for only a few summer months each year (Dunton et al., 2009). Blade elongation in the kelp *Laminaria solidungula* displayed large spatial and temporal variability between 1996 and 2006 (Figure 3-59). Growth was measured per growth year, defined as the period beginning on 15 November one year and ending on 15 November the following year. Mean site blade growth was lower at every site in growth year 2003 compared to growth in all other growth years between 2000 and 2006, reflecting the exceptionally poor weather conditions in summer 2003 that produced extremely low levels of ambient photosynthetically active solar radiation (PAR). An interannual comparison of growth years 1998 – 2005 at two Boulder Patch stations indicated that linear growth was lowest during growth year 2003, highest in growth year 2000, and that 2005 was similar to 1998-2000. Changes in local climatology clearly have an important role in

regulating kelp growth through increased cloud cover and sustained winds that negatively impact kelp growth (Figure 3-60).

There is no evidence that these inter-annual variations in TSS, POC, DOC, and nutrients concentrations are caused or altered significantly by offshore oil operations. Much of this material comes from the Arctic rivers and most is delivered to the Beaufort Sea during a brief period during the spring floods accompanying breakup of the on-shore and offshore ice.

Concentrations of TSS in the spring flow water from the Sagavanirktok and Kuparuk Rivers in 2001, 2002, 2004, and 2006 and from the Colville River in 2001 and 2006 were highly variable both among years and within each annual spring flood (Table 3-1). Concentrations of POC (as a % of TSS) varied by factors of 2 to 5 in each of the rivers between 2001 and 2006, with the highest POC concentrations in Kuparuk River suspended sediments (Table 3-2).

Some links between river inputs of suspended sediments and local offshore TSS concentrations and sedimentation rates can be made with available data from the cANIMIDA Project. Concentrations of TSS declined sharply with distance offshore from the Sagavanirktok River, even during the spring floods. Sedimentation rates are very low throughout the development area and most areas are not considered depositional (Trefry et al., 2003). Surficial sediments from some sites in the Boulder Patch contain low concentrations of silt+clay, indicating that they probably are not depositional (Brown et al., 2010). Low sedimentation rates are important for growth, production, and biodiversity of the Boulder Patch. However, large storms can cause massive sediment resuspension and bed transport that can harm the macroalgal community.

River flow and discharge of TSS and POC are much lower during the summer than during the brief period of the spring flood. These discharges do not contribute much to offshore sedimentation but may contribute to local increases in water turbidity, particularly during summer storms and rain. Concentrations of TSS in the Kuparuk River during summers of 2004, 2005 and 2006 averaged 1.0 mg/L, about 25 to 60 times lower than during the spring floods (Table 3-6). Concentrations of TSS in the Sagavanirktok River were more variable during summer with a range of 0.5 to 53.4 mg/L (Table 3-5). An increase in TSS concentrations >1-2 mg/L was typically linked to a rain event that raised flow and TSS (Table 3-5). During 2004, a rain storm raised the water flow rate and concentrations of TSS to 53 mg/L in the Sagavanirktok River on August 3. This discharge of TSS may have contributed to the low light intensities in the Boulder Patch in the summer of 2004.

At typical concentrations of TSS in summer (~2 mg/L), concentrations of particulate metals and organic carbon in the Sagavanirktok River during the summer of 2004 were lower than in spring (Table 3-5) but close to results obtained during summer for previous years (Trefry et al., 2004a,b). After the 2004 rainstorm, the concentrations of particulate metals increased to levels that were closer to those for particulate metals in spring 2004, except for Pb (Table 3-5). The rain seems to have carried in particles that were slightly more Pb-rich than typically observed, perhaps representing a contribution from road runoff or deposition with rain.

Concentrations of dissolved and particulate metals and hydrocarbons in the open-waters of the Beaufort Sea were variable as a function of the organic matter and clay content in the TSS and POC particles. The area-wide averages for 2000, 2001, 2002, 2004, 2005 and 2006 in Tables 3-10 and 3-14 show some interannual variability; however, most of the variations are due to

differences in the composition of the suspended sediments as shown by variations in concentrations of Al and Fe and generally comparable shifts in concentrations of trace metals and hydrocarbons. These metals and hydrocarbons may get into the Boulder Patch and be bioaccumulated by the local plants and animals. However, all dissolved and particulate metals and hydrocarbon concentrations are at background concentrations, well below concentrations that could harm the biological communities of the Boulder Patch.

Concentrations of metals, TPAH, and TSHC in sediments, amphipods, and clams collected in the Boulder Patch in 1999 through 2006 were similar to concentrations in sediments, amphipods, and clams from elsewhere in the Beaufort Sea and in uncontaminated Arctic marine habitats elsewhere in the world. Thus, there is no evidence that the marine biological community of the Boulder Patch is being exposed to chemicals from offshore oil operations.

The success of the annual subsistence bowhead whale hunt is variable from year to year, depending mainly on the weather. Seasons may be characterized as “poor weather” years (2003, 2004, 2005, 2007) or “bad ice” years (2005, 2006) or years when the whales were farther out or behaving in a different way making the hunt more difficult (2001 and to some extent 2002) (Galginaitis, 2009). The only documented disturbance of the whale hunt was an incident of non-oil-industry vessel traffic in the area where whales were congregating during the fall migration, resulting in alterations of whale behavior, making the hunt more difficult. As discussed above, bowhead whales contain lower concentrations of most chemical contaminants in their tissues than most other marine mammals do. This is due to their lower trophic status, based on a diet consisting primarily of large copepods and euphausiids. Thus, there is a very low risk that whales are being contaminated with chemicals from offshore oil operations during their spring and fall migrations through the development area.

The abundance of suitably dense patches of zooplankton to support feeding of bowhead whales in the area offshore of Cross Island probably is influenced by the amounts of labile DOC and POC and primary nutrients being discharged from the Sagavanirktok and Kuparuk Rivers during the spring floods. As discussed above, concentrations of the primary nutrients in surface waters of the Boulder Patch were higher in 2005 than in 2004 and 2006 (Table 3-48). However, we don't know if the higher nutrient concentrations in 2005 stimulated growth of more bowhead food, because the 2005 harvest was poor because of bad weather, ice conditions, and interference from a motor vessel (Table 3-52). More work is needed to better characterize the relationships between nutrients influxes from rivers, primary productivity, and abundance of zooplankton prey of bowhead whales off Cross Island and Stefansson Sound.

5 RECOMMENDATIONS

With the continuing growth in concern about the possible harmful impacts of offshore oil and gas operations on the marine environment and the biological resources it supports, particularly in the Arctic, there is an urgent need for BOEMRE to continue intensive monitoring of environmental effects of offshore oil and gas exploration, development, and production. The ANIMIDA/cANIMIDA Project and physical oceanography projects have provided and excellent framework for understanding the physical/chemical dynamics of the Beaufort and Chukchi Sea continental shelf. This information is critical for predicting potential ecosystem disturbances from offshore oil and gas operations in Arctic Alaska. Such studies should continue, but as part of a program to better understand the dynamics of the benthic and pelagic ecosystems of the Alaskan Beaufort and Chukchi Seas and how physical and chemical disturbances of the types associated with offshore oil and gas operations can affect these ecosystems and their biological resources, particularly those of importance to the local Inupiat people.

The following topics could be a component of the BOEMRE environmental assessment program for the development area of the Beaufort Sea.

- ANIMIDA/cANIMIDA has made considerable progress in identifying and characterizing the sources of sediments, DOC, POC, metals, and hydrocarbons on the continental shelf of the Beaufort Sea. Additional information is needed on:
    - amounts and geochemistry of suspended sediments discharged all along the Alaskan and Canadian Beaufort Sea coast from rivers and coastal erosion.
    - sources and concentrations of primary nutrients (e.g., N, PO_4) in coastal and offshore waters.
    - the chemical characteristics of the different classes of POC and DOC from rivers and coastal erosion, how the chemistry differs among the different sources, the biodegradability of these organic materials and their contribution of nutrients to the pelagic and benthic food webs of the coastal Beaufort Sea.
    - the chemical composition and sources of the POC and DOC in Beaufort Sea sediments and possible source apportioning to different terrestrial (e.g., rivers and erosion in Alaska and Canada) and marine (e.g., water flows from the Chukchi Sea, upwelling from the outer shelf, and biodiverse Arctic communities, such as the Boulder Patch).
    - contributions of coastal peat, oil seeps, oil-rich shales, and upriver sources to the complex organic fractions in the waters and sediments of the Beaufort Sea.
    - identity unique diagnostic markers of the terrestrial and oceanic sources of the Beaufort Sea POC that can be used to help identify the sources of the POC in sediments, and rates of ingestion by different members of the pelagic and benthic ecosystem.

  This information will be useful for identifying the importance of terrestrial and offshore POC and DOC in the Beaufort Sea food web, particularly the contribution of nutrients to pelagic primary production, the first step in the pelagic food web leading to copepods that bowhead whales consume during their fall migration through the Alaskan Beaufort Sea.

- Limiting monitoring near past exploratory drilling sites in the Alaskan and Canadian Beaufort Sea has identified slightly elevated concentrations of hydrocarbons, particularly PAH, and some metals, such as barium, in surface sediments near the former drill sites. These hydrocarbons appear to be refractory, having persisted for up to two decades in surface sediments, and are not bioavailable to benthic organisms. There is a need to better characterize the chemical composition and phase associations of these hydrocarbon assemblages. They may be associated with fossil kerogens eroded from the vast fossil (~18,000 years old) peat bogs on the North Slope. Full characterization may help identify hydrocarbon discharges associated with current and future exploration and production activities in the Beaufort Sea.
- The ANIMIDA/cANIMIDA Project, though well designed and executed, missed part of its overall goal, because drilling wastes were not discharged during development of the Northstar facility, and Liberty was not developed at all during the project. There are plans to perform exploratory drilling in the Beaufort Sea in the next few years, particularly in the Camden Bay area. The industry is planning extensive monitoring projects to identify effects of drilling and long-term effects of any permitted discharges. BOEMRE should consider collaborating in the monitoring programs, providing additional studies not currently planned by industry. These studies could focus on region-wide assessment of key biological resources, such as zooplankton, marine fish, birds, and marine mammals, including bowhead whales.
- Monitoring of the Cross Island subsistence bowhead whale harvest should continue, particularly if plans go ahead for exploratory drilling in Camden Bay. More information should be collected, mainly from the whale boat captains and crews, on variations in behavior and abundance of whales near shore in different years, and the possible reasons for these variations. It would be extremely useful to, if possible, collect the contents of the stomachs of harvested whales to determine the extent of feeding off Cross Island and the composition of the food. It also would be valuable to collect zooplankton samples in the areas off Cross Island where the whales congregate during the fall migration. This information would contribute to a better understanding of the importance of terrestrial nutrient sources for the zooplankton community.

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APPENDIX A

ANIMIDA and cANIMIDA REPORTS, PUBLICATIONS, AND OTHER PRODUCTS

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cANIMIDA DATA MANAGEMENT PLATFORM

A Web site for the management of and access to the ANIMIDA and cANIMIDA field and analytical data, and a repository for the Program reports and other documents.

http://www.duxbury.battelle.org/CANIMIDA/

TECHNICAL REPORTS

cANIMIDA
(continuation of Arctic Nearshore Impact Monitoring in Development Area)

Task 1

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Task 3 and 4

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Task 6

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cANIMIDA Task 5 journal publication – being prepared.

cANIMIDA Task 7 journal publication – being prepared.

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Durell, G., Neff, J., Trefry, J., Brown, J., Hardin, J., Prentki, R. (2010). The cANIMIDA Project: Monitoring of Sediment and Biota in Nearshore Oil and Gas Development and Production Areas in the Arctic Beaufort Sea, Alaska. Presented at the Alaska Marine Science Symposium, January 18-22, 2010, Anchorage, Alaska.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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