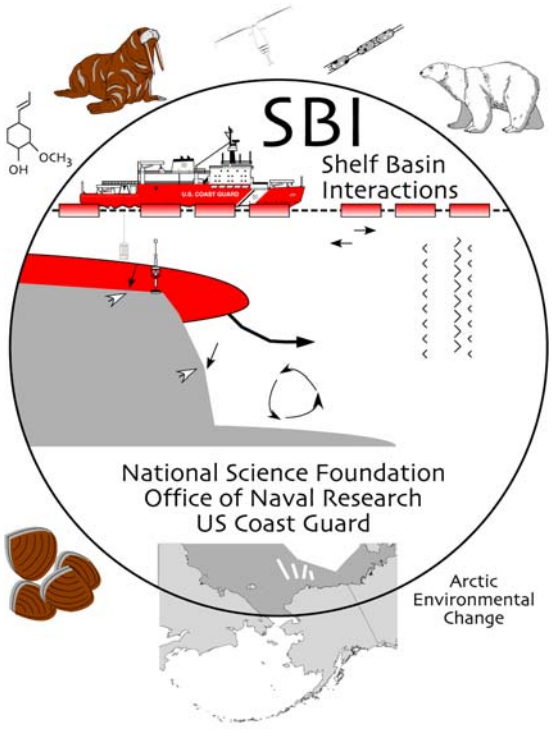
The Western Arctic Shelf–Basin Interactions Project

This article was prepared by Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Department of Ecology and Evolutionary Biology, The University of Tennessee, on behalf of all the SBI Phase II participants, who provided many of the concepts and results outlined in this article.

Further information on the overall SBI project can be found on the SBI web site (http://sbi.utk.edu) or by contacting Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Marine Biogeochemistry and Ecology Group, Department of Ecology and Evolutionary Biology, The University of Tennessee, 10515 Research Drive, Suite 100, Bldg A, Knoxville, TN 37932; phone: 865-974-2592; fax: 865-974-7896; email: jgrebmei@utk.edu.

The National Science Foundation and the Office of Naval Research are supporting an interdisciplinary global change research study known as the Western Arctic Shelf–Basin Interactions (SBI) project. This project is part of the Ocean–Atmosphere–Ice Interactions component of NSF's Arctic System Science program. The goal of the SBI project is to improve our ability to assess the impacts of global change on the physical and biogeochemical connections among the western Arctic shelves, slopes, and deep basins. The SBI project focuses on shelf, shelf break, and upper slope water mass and ecosystem modifications, material fluxes, and biogeochemical cycles. The geographical focus is on the Chukchi and Beaufort Seas and adjacent upper slopes. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the Arctic shelves and the adjacent ocean basins. SBI therefore focuses on the outer shelf, shelf break, and upper slope, where it is believed that key processes control water mass exchange and biogeochemical cycles and where the greatest responses to climate change are expected to occur.



The SBI project consists of three phases over a 10-year period. Phase I (1998–2001) involved analyses of historical data, opportunistic field investigations, and modeling of specific regions and processes. SBI Phase II constitutes the field program taking place in the Bering Strait region and over the outer shelf, shelf break, and slope of the Chukchi and Beaufort Seas into the Arctic Ocean. Phase III will focus on the development of pan-Arctic models suitable for simulating scenarios of the impacts of climate change on shelf–basin interactions.

The SBI field program has been developed to focus on:

- Physical modifications of North Pacific and other waters on the Chukchi shelf and slope, and exchanges of these waters across the shelf and slope;
- Biogeochemical modifications of North Pacific and other waters over the Chukchi and Beaufort shelf and slope areas, with an emphasis on carbon, nutrients, and key organisms that represent the suite of trophic levels; and
- Comparative studies over the wide Chukchi and narrow Beaufort shelves and adjacent slopes to facilitate extrapolation and integration of the Western Arctic work to a pan-Arctic perspective. Integrated process and modeling studies of shelf–basin exchange processes and their sensitivity to global change will be an important methodology in this extrapolation. A physical–biological coupled model is being undertaken as part of the SBI study.

Through integrated field and modeling efforts, the SBI project is investigating the effects of glo-

The USCGC Healy *anchored against an ice flow for SBI work.*

bal change on production, cycling, and shelf–slope exchange of biogenic matter, both seasonally and spatially. To this end, there are five study objectives deemed both timely and essential to improving our understanding of the effects of global change on productivity as it contributes to shelf–basin interactions within the Arctic Ocean ecosystem:

- Understanding the roles of physical processes in the transport and modification of water and biogenic materials across the shelf and into the interior basin;
- Identifying mesoscale oceanographic features that support locally elevated concentrations of benthic and pelagic biota;
- Quantifying upper ocean (water column and sea ice) primary productivity in relation to the biomass and diversity of benthic and pelagic primary and secondary consumers;
- Assessing the relative importance of top-down as compared to bottom-up controls over pelagic–benthic coupling, biotic complexity, and carbon partitioning among different trophic levels; and
- Assessing food web changes consequent to the impacts of changing ice cover and hydrographic parameters on remineralization of organic matter, recycling efficiency, and biogeochemical fluxes.

Further details on the SBI project can be found in the SBI Science Plan and the Implementation Plan.

The 2002 SBI Field Program

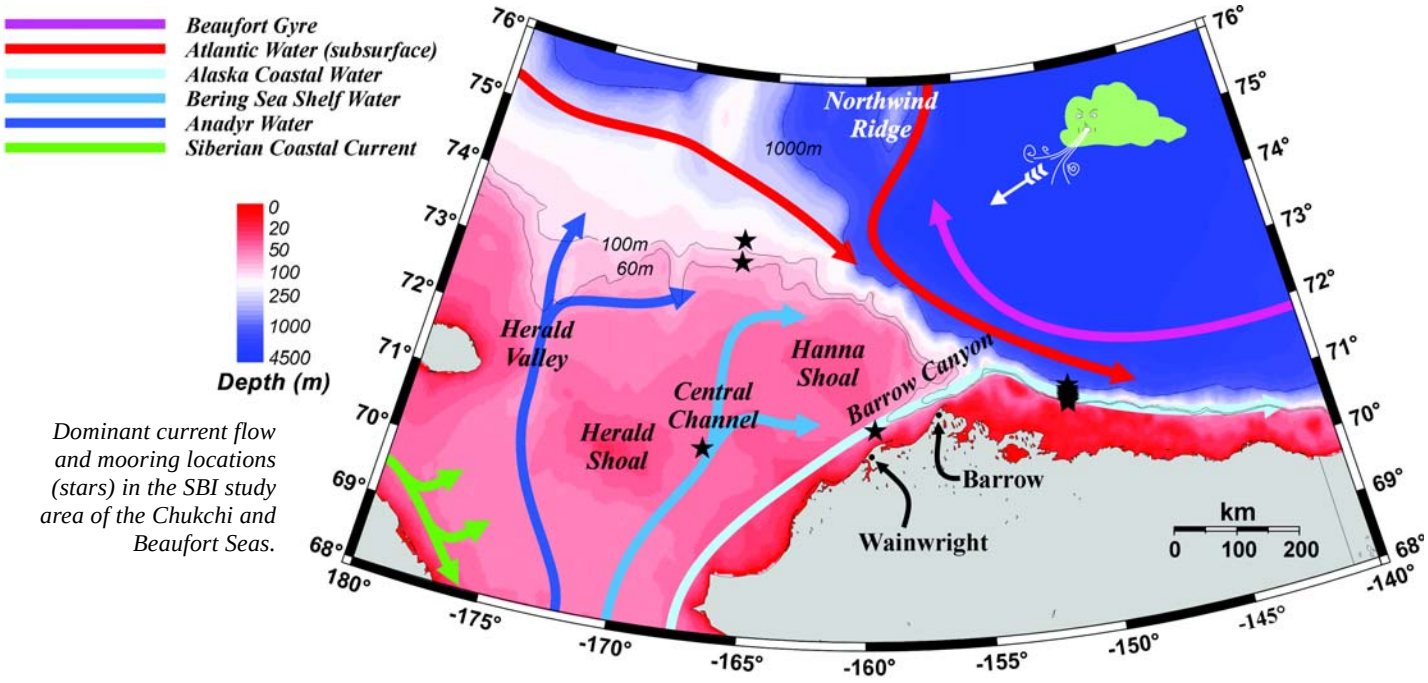
In 2002 the field phase of the SBI project included four successful scientific missions to the Arctic using three vessels: the USCGC *Healy* (5 May–15 June and 17 July–26 August), the USCGC *Polar Star* (15 July–13 August), and the RV *Alpha Helix* (20–29 June). Up to 39 scientists from 19 institutions in the U.S., Bermuda, Canada, and Europe participated in any one cruise, depending on the ship and its objectives. During the field program the SBI project applied a broad array of physical, biogeochemical, and biological measurements from May through September (and year-round with the moorings) that are almost unprecedented in scope for the Arctic. The spring cruise on the new *Healy* icebreaker was the first interdisciplinary research cruise to this region by a science vessel at this time of year.

SBI Hydrographic and Mooring Cruises

The current structure in the SBI study area includes three northward-flowing water masses passing through Bering Strait: Anadyr Water in the west, Alaska Coastal Water in the east, and Bering Sea Shelf Water occurring between these two water masses. These water masses move across the shelf to the north, then east as they meet the eastward-flowing slope boundary current at the interface with the Atlantic water and are carried eastward as well as offshore to the Arctic Basin.

The physical oceanographic and mooring component of SBI was undertaken during two cruises: one in June on the *Alpha Helix* and from mid-July to mid-August on the *Polar Star*. The primary aims of this component are to identify and understand the transport of water through Bering Strait and to understand the water masses and mechanisms by which shelf waters ventilate the western Arctic halocline. The major goals of the SBI June cruise were to emplace three mooring arrays in Bering Strait to capture the inflow characteristics of water transiting both the eastern and western channels of Bering Strait. The SBI summer 2002 goals were to deploy a system of moorings that will measure the outflow from the Chukchi shelf; to deploy a high-resolution moored array across the Beaufort slope, downstream of the outflows, to determine how these waters are fluxed into the interior; and to conduct a hydrographic survey encompassing locations along the Chukchi and Beaufort shelf edge.

The moored instruments will measure currents, temperature, and salinity numerous times per day until September 2003 (when they will be turned around for a second year-long deployment). A combination of discrete sensors and profiling instruments are being used. In addition, some mooring arrays in Bering Strait and the Central Chukchi Channel are outfitted with a fluorometer, a nitrate analyzer, and a turbidity meter. Nearly all



Dominant current flow and mooring locations (stars) in the SBI study area of the Chukchi and Beaufort Seas.

hydrostations during the cruise included water sample measurements of salinity and nutrients. The conductivity/temperature/depth package was also outfitted with a turbidity sensor, a fluorometer, and a lowered acoustic doppler current profiler measuring absolute horizontal velocity. These additional sensors provided invaluable information on the origin and magnitude of the currents in the region. Finally, the Beaufort Sea array consisted of eight moorings spaced 5 km apart, with an additional whale-listening mooring deployed by the National Marine Mammal Laboratory.

Hydrographic surveys completed during the mooring cruise represented the first systematic coverage of the three outflow branches of the Chukchi Sea: Herald Valley, the Central Channel, and Barrow Canyon. Additionally, sections were occupied downstream of both the Herald Valley and Barrow Canyon outflows, and the cruise included the first high-resolution crossings of the shelf and upper slope in this area of the western Arctic. Preliminary data on the origin and fate of the shelf-edge boundary currents indicate that the outer shelf of the Herald Valley outflow site is filled with cold, dense, Pacific-origin winter water as it flows eastward, forming a shelfbreak jet. The bottom water in this region has high turbidity, likely due to sediments drawn into this water mass as it crosses the shelf. Small lenses of water observed at the shelf edge are likely the beginnings of eddies. At the eastern end of the domain in the Beaufort Sea, a transect revealed the presence of a fully developed subsurface anti-cyclonic eddy comprising cold, turbid, Pacific-origin winter water. This is the same type of eddy that has been observed repeatedly throughout the interior of the Canada Basin, a result that suggests that these eddies emanate from the shelf-edge boundary current.

SBI Process Cruises

Thirty to fifty stations were occupied each cruise over five transect lines: one line over the shelf and slope of Herald Valley in the Chukchi Sea, two shelf-to-basin lines from the Chukchi outer shelf to the Arctic Basin (one west of Hanna Shoal and one east of Hanna Shoal), a transect down Barrow Canyon, and a shelf-to-basin line east of Barrow. Additional stations were also occupied near the Alaska coastline.

During the spring process cruise, ice observations were carried out from the ship's bridge at two-hour intervals when the ship was underway and once at every station along the entire cruise transect. Observations included prevailing ice types, ice thickness, snow depth, and distribution of open water, as well as estimates of ice colonized by ice algae ("brown ice") and containing sediment entrained during ice growth ("dirty ice"). Towards the north, both sediment-laden ice and bottom communities exhibited a distinct (though not quite coincident) boundary with clean ice northwards of roughly 73°40'N (on the west Hanna Shoal line). The northernmost stations of the

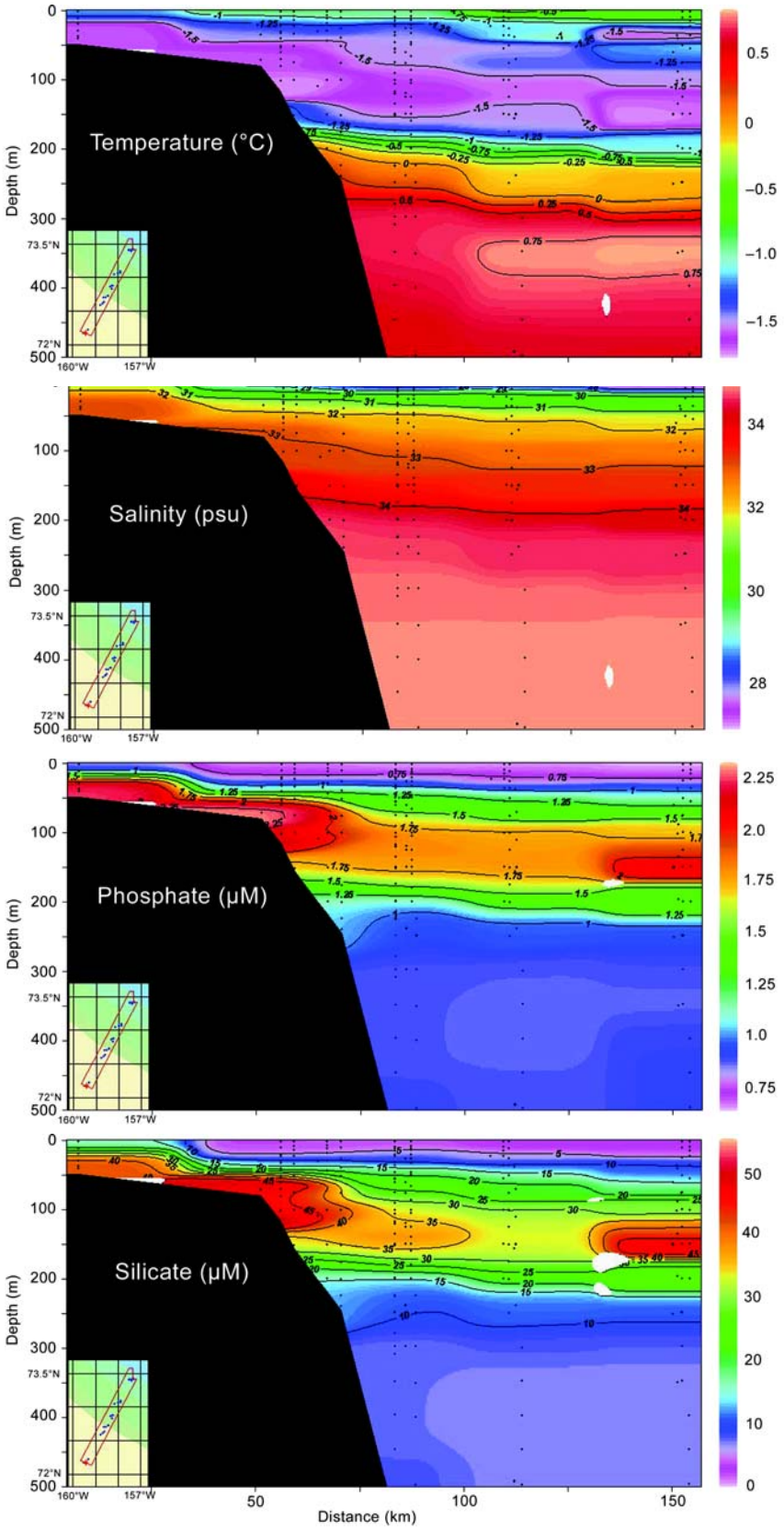
Cruise reports for both process and mooring cruises are available on the SBI web site (http://sbi.utk.edu).

west and east Hanna Shoal transects were located in predominantly second- or multi-year ice, corresponding well with information on last summer's minimum pack ice extent obtained from satellite data.

Hydrographic collections were made during both the spring and summer process cruises using a conductivity/temperature/depth (CTD) and bottle rosette. Bottle samples were analyzed for salinity, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, dissolved silicon, urea, and chlorophyll. Surface salinities of less than 30 psu were recorded as the ship moved eastward and offshore into the Beaufort Sea, presumably because of a general freshening of the surface waters as the ship departed the region under the direct influence of the Bering Strait inflow and because of the accumulated effects of icemelt and river runoff. Temperature and salinity vs. depth profiles in Barrow Canyon varied more from station to station than they did in the sections outside of the canyon, indicative of the dynamic nature of the offshore and onshore current flow within this canyon. In addition, the western Chukchi Sea showed two regions of increased southeastward flow near the shelf edge: one right at the shelf break transporting shelf-origin water and one a bit offshore and deep transporting warm Atlantic water. An eddy-like feature was found centered near a depth of 100–150 m on the east Hanna Shoal line, with a warm center and cold water on either side of it, indicating a strong shoaling of Atlantic water properties onshore. Understanding these features will aid in investigating how physical and biochemical products are transported from the shelf to the basin.

The nutrient regime measured on three transects during the spring cruise indicated high initial nutrient concentrations over the shelf near Bering Strait, decreasing eastward and seaward. Although high nitrate levels are characteristic of the study region in spring, conditions encountered

Detailed USCGC Healy *cruise track plot from the SBI 2002 process cruises. The locations of moorings and past, present, and future measurement stations are shown. The map background is a combination of USGS elevation data and bathymetry data from the International Bathymetric Chart of the Arctic Ocean.*

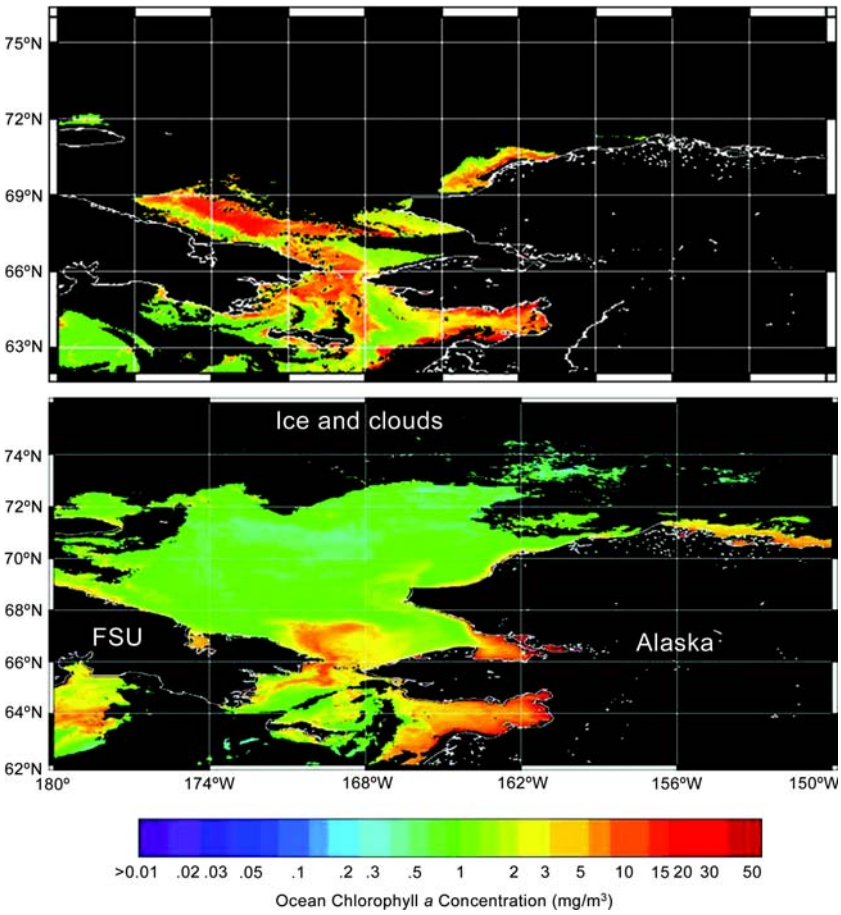


Vertical distribution of key variables on the East Hanna Shoal line during the summer of 2002.

during this period suggested the initiation of an inshore phytoplankton bloom on the Barrow Canyon line. While a strong decrease in nutrients was expected as the ship departed the region under the direct influence of the Bering Strait inflow, the lack of nitrate in surface waters at the offshore stations was somewhat surprising since this was early in the "growing" season. Preliminary observations indicate that the spring bloom may have already occurred, at least in the surface layer, at the offshore sites. Observations and comments on productivity in this region are scarce, so it is uncertain whether this early blooming is "normal" or related to the recent warming of the Arctic. As the ship entered deep water, the expected nutrient maximum was found at about 125 m associated with Bering Strait/Chukchi waters that form the upper halocline. Nutrient concentrations in this maximum appear to be a bit lower than in the past, but determining whether this is correlated with the recent warming and freshening of the Bering Strait inflow or is simply a normal space- or time-related difference between our data and past experiments will require further analysis.

During the summer SBI process cruise, all transects could be sampled because of the low ice cover in the study region for this time of year. Primary production was either occurring or at the end of its bloom period. In contrast with the spring SBI cruise, when several stations had surface nitrate concentrations in excess of 10 micromolar (pre-bloom conditions), surface nutrient concentrations were low during the summer cruise, with the highest water column chlorophyll near the bottom, suggesting post-bloom conditions. Microscopic analyses of phytoplankton supported these post-bloom conditions throughout the study region during the summer cruise.

Additional subsamples from multiple CTD and rosette casts were used to measure primary production, particulate carbon, inorganic carbon, biomarkers, microzooplankton, and radioisotope content. Shipboard sensors and measurements indicated that the colored dissolved organic matter (cDOM) had its maximum at 140–160 m on the slope and in the Canada Basin, just below the upper halocline maintained by Bering Strait inflow water. In addition, cDOM and physical oceanographic data support the occurrence of an eddy along the Chukchi slope on the east Hanna Shoal line. Anomalous concentrations of radium-224 (a signature of shelf products) and total dissolved nitrogen were measured in the core of the eddy feature. These observations were augmented



Satellite coverage of chlorophyll a in the SBI study area during June 2002 (top) and August (bottom) 2002.

by expendable CTD deployments and close-spaced CTD profiling undertaken along the east Hanna Shoal line. Eddies are one proposed mechanism for shelf–basin exchange.

In the spring, numerous clear days with good satellite coverage in the southwestern margins of the study area were sufficiently ice- and cloud-free for extensive ocean color observations from space. Primary production experiments and satellite data indicated that blooms occurred north of Bering Strait and to a lesser degree along the northwestern Alaskan coast and in areas of ice retreat. Of particular note were the large concentrations of ice algae in the water column at the shallow water stations in the spring. Shipboard measurements will assist in calibrating remote satellite observations seasonally over the study region and will enhance the annual coverage of the SBI study region.

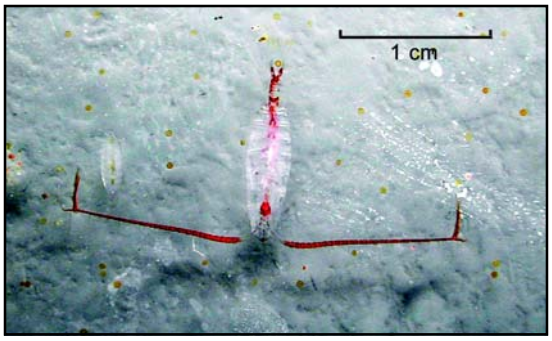
Water column particulate organic matter was greatest at the 50-m shelf stations, became reduced at the 100-m stations, and was negligible at deeper stations. An exception was Barrow Canyon, where extraordinarily cloudy water was collected at the 100- and 200-m stations because of high plankton productivity in the water.

In-situ pumps were also used to measure the activities of the naturally occurring, particle-reactive radionuclide thorium-234 to trace particulate carbon in combination with its parent, uranium-238, which is soluble in seawater. Particle export is enhanced in the shelf–slope region compared to the deep interior stations. There appears to be a subsurface scavenging signature near the shelf sediments that extends into the deep water, an indication of shelf–basin interactions.

Bacterial abundance was determined using a shipboard epifluorescence microscope. Preliminary results indicated roughly 50% lower counts than found in low-latitude oceanic waters. Both bacteria and bacterivorous flagellates were common in the upper water column, whereas there were many occurrences of a deeper chlorophyll maximum layer of large diatoms. The accumulation and decay of diatoms suggests that plankton grazers are not able to consume most of the spring bloom and that instead the bulk of the bloom is decomposed by heterotrophic microbes or sinks to the benthos. Coincident measurements of microzooplankton grazing rates also indicated very low metabolic rates during this spring, ice-covered season. Bacterial abundance was highest in the surface waters, where the amount was twice as high in the summer as in the spring. Bacterial production was ten times higher in the summer than in the spring.

Various nets were used to collect size fractions of micro-, macro-, and mesozooplankton for both population and experimental purposes. Plankton nets were often clogged by chain-forming diatoms in the spring at the shallow stations. At the deeper stations, phytoplankton abundance was much reduced, and different species of both chain-forming and centric diatoms were most important. For mesozooplankton, Pacific water copepod and euphausid species were observed in the Chukchi shelf stations, indicative of the water type they transited in. In general, Pacific-type copepods were the most important shelf species, whereas Arctic- and Atlantic-type copepods were more important in deeper waters.

In addition to standard net collections, a special zooplankton sensor was used on the cruise for video recording of plankton in the water. Preliminary analysis of the digital files suggests a higher density of plankton on the shelf, which, according to shipboard grazing and egg production measurements, was likely caused by the occurrence of the phytoplankton bloom and high feeding and egg production of key copepod species.



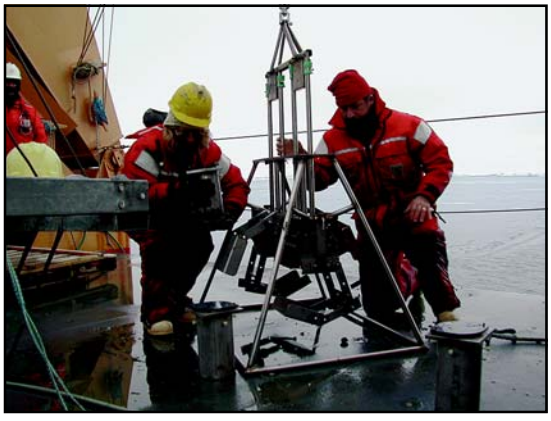
Using a vertical net for collecting zooplankton (near right) and a calanoid copepod with red antennae and yellow eggs (far right).

Benthic grabs and cores were used to collect benthic fauna and sediment samples for population, community structure, food web, chemistry, and metabolism studies. A variety of sediment processes indicate patterns of sediment focusing and recycling in the SBI study region. Sediments collected with benthic coring devices indicated that sediment oxygen uptake and nutrient flux (an indication of carbon supply), along with denitrification, occur on the shelves. A regular pattern of high to low rates was observed from the shelf to the deep basin. Both radioisotope and sediment tracer studies indicate that phytodetritus is rapidly deposited to depths as great as 1000 m along the Barrow Canyon and East Barrow transect lines since the time of the spring cruise. It is notable that higher sediment uptake rates occurred at deeper depths in Barrow Canyon than along the other transect lines, probably because of a focusing of organic carbon down the axis of the canyon.

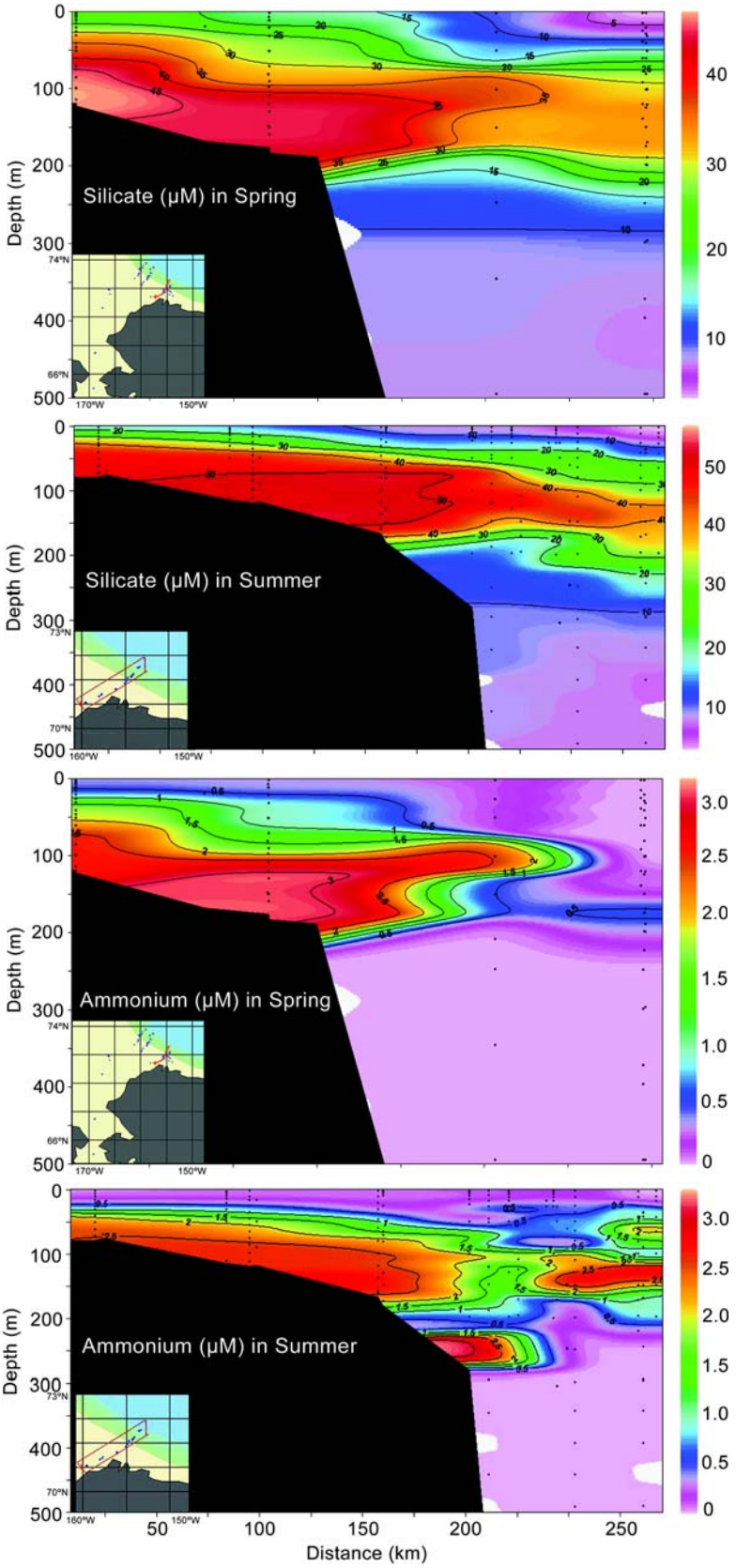
Benthic macrofaunal populations also follow the trend in carbon deposition to the benthos. Shelf water column plankton samples also contained large numbers of young forms of bottom-dwelling invertebrates (such as marine worms, crabs, clams, and tunicates) coincident with high phytoplankton, indicating that this region acted as a nursery for various benthic species that release their larval stages into the water column at this time of year. Benthic biomass and diversity were greatest at the 50- to 100-m stations, declining down to 500 m deep, and negligible at water depths of 1000 m and greater. The species collected from the greater depths were small and limited to foraminifera, clams, and marine worms. The Barrow Canyon stations had well-sorted cobbles and gravel and a greater number of filter-feeding animals than at other stations.

Shallow oxygen penetration in sediments in Barrow Canyon sections also suggests sediment focusing and off-shelf carbon transport in the Barrow Canyon area. In contrast, the East Hanna shoal section to the east of Barrow Canyon had deep oxygen penetration, likely a reflection of low relative productivity and consequently low carbon rain rate to the sediments.

Modification of waters over the shelf and transport of biogenic signals from the shelf to the



Sediment sampling using a HAPS benthic corer (near right) and the resultant sediment core with animals from Barrow Canyon (far right).



Nutrient concentrations along the Barrow Canyon line for silicate and ammonium in spring and summer measured during the SBI field project in 2002.

basin were observed during all cross-shelf sections for every SBI cruise on the main transects (see the figure to the left). It is notable that when comparing spring vs. summer data from the same hydrographic sections, we see an increase of 5–10 micromolar in maximum silicate concentrations in the plume originating over the shelf in Barrow Canyon, as well as pulses of ammonium moving off the shelf to the deep basin. This observation suggests fairly rapid settling and remineralization of diatoms produced by the spring bloom over the shelf. By the time of the summer SBI process cruise, most of the production had settled downwards in the water column and undergone transformation in the water and sediments. Maxima in other variables had a tendency to peak offshore and to intersect the shelf break instead of the shallower portions of the shelf.

Marine mammal studies by the U.S. Fish and Wildlife Service during the 2002 SBI spring cruise recorded 291 sightings of seven species of marine mammals, with the following distribution by species and number of sightings (in parentheses): walrus (78), bearded seal (29), ringed seal (29), spotted seal (10), unidentified seals (96), polar bear (19), bowhead whale (6), gray whale (14), and unidentified whales (10). The 19 sightings of polar bears including five of mothers with one or two cubs. In mid-June two helicopter flights produced sightings of over 50 groups of walruses, and high-resolution vertical digital photographs were obtained from approximately 45 of these groups. Group size, area covered by groups, and group composition will be determined from the photographs and used to develop correction factors for future surveys using remote sensing systems.

SBI Data Support and Outreach Activities

In support of the SBI field program, the Joint Office of Science Support (JOSS) group maintained a shipboard field catalog during both process cruises on the *Healy* that provided real-time data to scientists on the ship. Some data were also made available to onshore PIs who were following the progress of the cruise. Field products included satellite images, ship tracking, weather, CTD data from the hydrographic group as well as associated bottle data, and shipboard event logs. The SBI field catalog (with maps and event information at sea) can be found on the JOSS web page (http://www.joss.ucar.edu/sbi/catalog/).

In addition to the research information available through the JOSS and SBI web sites, public outreach was provided to explain our research program during the summer cruises. A broadcast crew from *CBS News* and reporters from *USA Today* and the Associated Press were aboard the *Healy* during the summer cruise transit of Barrow Canyon. Interviews were also provided to a reporter for the *Nome Nugget* before the *Healy* left port and to KBRW-AM/FM, a National Public Radio affiliate in Barrow that broadcasts across the North Slope Borough, during the cruise using the Inmarsat telephone capabilities. An article was released by the Associated Press wire and

A herd of walruses observed in the SBI study area in the spring of 2002.

appeared in a number of newspapers, including the *Baltimore Sun*, *Orlando Sentinel*, *Fresno Bee*, and *Juneau Empire*. *CBS News* broadcast three stories on August 28, 29, and 31, 2002, on their national evening news program, and another piece was presented on the *CBS News Sunday Morning* program in January 2003. The repeat visits of the *Healy* to Nome this past summer were covered by the *Nome Nugget*, particularly in their issues of June 20 and August 29, 2002. Some of the media coverage is presented on the SBI project web site (http://sbi.utk.edu) as well as coverage of the mooring cruise operations (http://www.whoi.edu/arcticedge).

A valuable addition to the SBI research program was the participation during the summer SBI process cruise of Betty Carvellas, a Vermont high school teacher who provided daily updates on research and ship operations, including spotlights on individual research groups, explained in layperson's terms. These daily updates are accessible through the Teachers Experiencing Antarctica and the Arctic web site (http://tea.rice.edu, specifically http://tea.rice.edu/tea_carvellasfrontpage.html). While aboard the cruise, she also served as a team member with the group investigating water and sediment tracers, sediment metabolism, and benthic community structure. Outreach activities during the cruise included a tour of the *Healy* for students from the Anvil City Science Academy (a public magnet school in Nome) while the ship was anchored off Nome. Also during the cruise she made Inmarsat-telephone-aided Powerpoint presentations of cruise activities to a district-wide teachers in-service at Essex (Vermont) High School and to a public forum in Colchester, Vermont.

Future SBI Field Program

Plans for the 2003 SBI field season include a March helicopter survey and field sampling project, participation by some SBI PIs in an April ice camp sponsored by the Office of Naval Research, the annual June Bering Strait mooring project, a June–July hydrographic and sampling survey cruise to the Chukchi and Beaufort Seas, and a September–October mooring turnaround cruise to retrieve and redeploy both the Chukchi and Beaufort Sea mooring arrays. The 2004 field season will proceed with four cruises similar to those undertaken in 2002 to provide an interannual comparison of processes in the SBI sampling region. Phase II of SBI will continue through 2006 with data synthesis. The final Phase III of the SBI project (2007–2009) will focus on developing pan-Arctic models suitable for simulating scenarios of the impacts of climate change on shelf–basin interactions.

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