

INVITED REVIEW

SCICEX Investigations of the Arctic Ocean System

Margo H. Edwards^{1,*} and Bernard J. Coakley²

¹Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii USA

²Geophysical Institute, University of Alaska, Fairbanks, Alaska USA

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Abstract

In 1993 the United States Navy and the marine research community embarked on an ambitious program to study the Arctic Ocean using nuclear-powered submarines. The program, termed **SC**ience **IC**e **EX**ercise (SCICEX), was designed to simultaneously sample and map the ice canopy, physical, chemical, and biological water properties, seafloor and seabed subsurface. The small size of the Arctic Basin relative to Earth's other oceans and the unique capabilities of the nuclear submarines, high speed coupled with the ability to operate independently of the sea ice cover, combined to allow the first holistic investigation of an entire ocean basin. The data acquired during eight submarine cruises helped refine hypotheses and models for the broad spectrum of subdisciplines that comprise arctic science and, perhaps more importantly, illuminated the linkages between the various components of the Arctic Ocean system. This paper presents an overview of the SCICEX program, summarizing the results published to date and briefly describing each submarine deployment and the instruments used to acquire various datasets, to demonstrate the important contribution of this collaborative venture to arctic science.

Key words: Arctic Ocean, SCICEX, oceanography, ice canopy, seafloor morphology, biogeography

* **Corresponding address:** Margo H. Edwards, Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA
Tel.: ++1-808-956-5232; Fax: ++1-808-956-6530; email: margo@soest.hawaii.edu

Introduction

Surrounding Earth's northern pole, the Arctic Ocean is a unique, extremely inhospitable environment. For two centuries this region has captured the imaginations of explorers and researchers, who have slowly but persistently investigated it. Results of these expeditions illustrate the extraordinary characteristics of the Arctic Ocean, where rock, water, ice, air and organisms all have important and inextricably linked roles. For example, the weak stratification of the Arctic Ocean below a few hundred meters water depth helps to reveal how the Atlantic and Pacific Oceans mix at their northern boundaries (Steele and Boyd 1998; Morison et al. 1998; Boyd et al. 2002); when combined with arctic bathymetric data, physical and chemical water properties also validate previously published hypotheses (e.g., Aagaard 1989; Rudels et al. 1994) describing how seafloor morphology regulates the movement of deep and intermediate arctic water masses (Mikhalevsky et al. 1995; Smith et al. 1999; Smethie et al. 2000; Boyd et al. 2000; Gunn and Muench 2001). Perennial ice cover is an exclusive feature of the Arctic Ocean that both influences and is influenced by ocean temperature and circulation (McPhee et al. 1998; Smith and Morison 1998; Björk et al. 2002). The ice canopy affects how much light penetrates the Arctic Ocean, regulating biological growth (Gosselin et al. 1997). Furthermore, the distribution of the arctic ice canopy plays a significant role in the present-day global climate (Clark 1990, and references therein; Aagaard and Carmack 1994, and references therein). Although interconnections between the arctic ice cover and the seabed may seem insignificant given the vertical distance between them in much of the present-day Arctic Basin, arctic ice has in fact provided evidence of ancient climates through apparent and well-preserved evidence of interaction with the seafloor (Polyak et al. 2001). Recognizing the systemic nature of the Arctic Ocean, scientists have developed an array of programs, many of them multidisciplinary, to study the region and describe its contributions to global and local processes.

The primary reason cited for studying the present-day Arctic Ocean is to understand its contribution to the global climate. From a planetary perspective, the Arctic Ocean influences both Earth's surface heat balance and the thermohaline circulation of its oceans (e.g., Johannessen et al. 1994, and references therein). Much of Earth's atmospheric circulation is generated by gradients that result from heat gain near the equator and heat loss near the poles. The presence of arctic ice cover hinders the heat exchange between the atmosphere and the ocean, effectively suppressing summer heat gain and winter heat loss (Clark 1990). Arctic snow and ice cover also impact Earth's albedo, reflecting solar energy back into the atmosphere and influencing atmospheric circulation. In the case of thermohaline circulation, the Arctic Ocean modulates the salinity of the northern Atlantic Ocean, affecting the formation of North Atlantic Deep Water (NADW), an important component of the global ocean conveyor (Broecker 1991). NADW results, in part, from the enhanced salinity of the northern Atlantic Ocean produced by the disequilibrium of evaporation and precipitation in the Atlantic and Mediterranean seas. In combination with cold temperatures, the higher salinity yields North Atlantic water that is very dense and thus contributes to deep, cold-water production. Broecker et al. (1985) hypothesize that melting arctic ice would lower salinity in the northern Atlantic and consequently reduce NADW production. The result would be less ocean-to-atmosphere heat flux that could, when combined with other influences on global climate such as

orbital forcing factors, lead to cooler temperatures and increased snow and ice production. The overall effect would create a global climate that cycles between colder and warmer periods, the type of climatic change that has already been documented for Earth.

Studies of such a singular environment as the Arctic Ocean are also important because they provide unique perspectives and/or information for a wide variety of scientific disciplines. For example, the Arctic Basin is the only ocean basin that is predominantly landlocked. Because of the movement of Earth's tectonic plates, the Arctic Ocean was likely isolated or nearly isolated from the rest of Earth's oceans for tens of millions of years between the late Mesozoic and the Early Tertiary (Marincovich et al. 1990, and references therein). Deep-water communication between the Arctic and North Atlantic Oceans was not established until the middle Miocene, ~ 15 mybp, and the Arctic Ocean remained unconnected to the Pacific Ocean until ~ 3 mybp. This isolation is significant to marine biologists as it could result in unique fauna associated with recently discovered hydrothermal venting on Gakkel Ridge (Edmonds et al. 2003).

Despite all of the compelling reasons to study the Arctic Ocean, it is an inhospitable place where established procedures can only rarely be used to acquire data. Historically, scientists have studied the Arctic Ocean from the air, from ice islands or from ice-breaking surface ships, but none of these approaches are ideally suited for arctic operations. Although planes and helicopters can cover large research areas, use of these platforms is highly dependent on the weather, fuel supply and distance to the nearest safe landing point. Airborne surveys typically employ only remote sensing instruments as it is time consuming and frequently unsafe to land and acquire physical samples. Ice camps have collected excellent oceanographic data, but they operate at the mercy of the elements, drifting where winds and currents dictate. Even icebreakers, with reinforced hulls to help move through the ice, cannot move freely and are unable to access some parts of the Arctic Ocean. Additionally, the interaction between ice and vessel can degrade the quality of the data collected by icebreakers; for example, the noise generated while underway in ice-covered water interferes with acoustic signals received by towed and hull-mounted sonar systems.

Nuclear-powered submarines, which are able to move independently and swiftly below the arctic ice canopy, are well suited as surveying and sampling platforms for arctic research (Newton 1994). For decades submarines have been exploring arctic regions, but the data that they collected could not be made available to the general public for reasons of national security (Newton 2000). Although portions of these historical submarine datasets have recently been declassified and released (e.g., Jakobsson et al. 2000), they were acquired during operations focused first on national security and as such did not collect the type of systematic, detailed datasets that arctic scientists prefer to use when addressing specific research questions.

The SCICEX program began in January 1993 when the U.S. Navy announced that a nuclear-powered submarine would survey the Arctic Ocean in the summer of that year and invited the U.S. academic community to help plan and participate in the cruise (Langseth et al. 1993). In contrast to standard operating procedures for naval nuclear submarines, the U.S. Navy agreed to allow data collected during 1993 to be published and disseminated in the public domain after completion of the survey. Based on the success of this proof-of-concept program, the U.S. Navy and the U.S. National Science Foundation signed a Memorandum of Agreement (MOA) that resulted in five more dedicated-science deployments to the Arctic Ocean using Sturgeon-class submarines (Pyle et al. 1997). These cruises took

place annually between 1995 and 1999 and each included extensive science-driven planning and civilian science riders. In October 1998 the U.S. Navy informed the civilian science community that it would no longer be able to conduct dedicated-science surveys of the Arctic Ocean for a number of reasons, the most pertinent being that the U.S. Navy's nuclear submarine force was being drastically reduced (Rothrock et al. 1999b). As an alternative to completely terminating the SCICEX collaboration, naval and academic personnel agreed to "accommodation missions" that set aside some time for the acquisition of unclassified data during otherwise classified submarine exercises. Two SCICEX accommodation missions were conducted aboard the *USS L. Mendel Rivers* in October 2000 (Gossett 2000) and aboard the *USS Scranton* in 2001 (Gossett 2001). Since SCICEX-2001 three additional accommodation missions have been scheduled but cancelled due to naval priorities (J. Gossett, pers. comm.). Appendices 1 and 2 contain detailed summaries of the eight SCICEX deployments and the instruments used during the cruises.

Reported Results

Data collected by the SCICEX submarines have been and are being used by dozens of scientists to investigate regions ranging from above the ice canopy to below the seafloor of the Arctic Ocean, from the continental shelves to the deep interior basins and ridges. SCICEX-derived publications have contributed to almost every field of marine science, providing important, novel observations as well as testable hypotheses and an increased understanding of both arctic and global processes (Dickson 1999; Morison et al. 2000). For example, SCICEX investigators were among the first to report on the pronounced changes in Arctic Ocean hydrography during the 1990's (Morison et al. 1998; Steele and Boyd 1998), to produce a detailed description of the physical and chemical properties within an eddy in the Canada Basin (Muench et al. 2000), to present evidence for an almost kilometer-thick ice shelf covering parts or the entirety of the Arctic Ocean during Pleistocene glacial maxima (Polyak et al. 2001), and to show that recent volcanic eruptions had occurred along Gakkel Ridge (Edwards et al. 2001a). In some instances findings based on SCICEX data have supported widely held hypotheses, while in other cases investigators have demonstrated that existing models and theories need to be re-evaluated, ultimately guiding and initiating subsequent arctic investigations. What follows is a summary of the publications produced using SCICEX data. Subjects are loosely organized by discipline; where appropriate, multidisciplinary topics are presented to underscore the links between the different components of the Arctic Ocean system. The discussion begins with the arctic seabed and works its way upward through the water column to the ice canopy.

Arctic Geology

Prior to the SCICEX program, topographic maps of the Arctic Basin had been painstakingly and somewhat subjectively pieced together by combining ice island, icebreaker and submarine bathymetric profiles from a variety of international programs with varying degrees of reliability (Jakobsson et al. 2000). During SCICEX-98 and SCICEX-99 swath bathymetry data collected by the SCAMP system (Appendix 2) signif-

icantly increased the number of depth soundings available for the Arctic Basin, acquiring 2–3 orders of magnitude more data in about ten weeks than had been acquired in all preceding years (Edwards et al. 2001b). SCAMP sidescan data provide an even higher resolution perspective of the seabed textures in the basin. In combination with subbottom data depicting upper (50–100 m deep) stratigraphic layers, SCAMP swath data yielded an unprecedented three-dimensional picture of the arctic seafloor, especially over three topographic highs that were systematically surveyed: Gakkel Ridge, Lomonosov Ridge and Chukchi Borderland.

Physiographically, the Arctic Basin is subdivided into four sub-basins by topographic ridges oriented approximately perpendicular to the long axis of the ocean. These ridges are: Gakkel (or Arctic Mid-Ocean) Ridge, the slowest spreading mid-ocean ridge on Earth (DeMets et al. 1994), Lomonosov Ridge, a continental sliver rafted away from Eurasia ~60 mybp (Ostenso and Wold 1973; Vogt et al. 1979) and Alpha-Mendelev Ridge, which has the distinction of having more hypotheses describing its formation than almost any other feature in Earth's oceans (Langseth et al. 1993). The sub-basins bounded by the ridges, from the Atlantic to the Pacific side of the Arctic Ocean, are the Nansen, Amundsen, Makarov, and Canada basins. A fourth topographic high, Chukchi Borderland, extends into the Canada Basin from the continental margin north of the Bering Strait but does not continue all of the way across the basin to the opposing Canadian continental shelf (Figure 1). The Nansen Basin-Gakkel Ridge-Amundsen Basin region is referred to more generally as the Eurasian Basin, grouped together through the seafloor spreading process that created all three areas. Features on the opposite side of Lomonosov Ridge (Makarov Basin, Alpha-Mendelev Ridge, Canada Basin and Chukchi Borderland) are correspondingly referred to as the Amerasian or Canadian Basin. To avoid confusion with the smaller Canada Basin, we adopt the former nomenclature for this paper.

Although the existence of Arctic Ocean ridges and basins has been recognized since the late 1940's and 1950's (Johnson et al. 1990, and references therein), their formation and evolution remained controversial (Chukchi Borderland, Alpha-Mendelev Ridge, Amerasian Basin) or were described in general terms (Lomonosov and Gakkel ridges, Amundsen and Nansen basins) due to the lack of high-resolution morphological data. "Lawn-mowing" surveys conducted over Chukchi Borderland, Lomonosov Ridge and Gakkel Ridge using the SCAMP system during SCICEX-98 and SCICEX-99 provided the detailed depictions of these topographic highs necessary to discuss the fine-scale volcanic, tectonic and erosional processes that contributed to their formation and evolution.

- Gakkel Ridge

Gakkel Ridge extends 1800 km across the Eurasian basin from the Spitzbergen transform system near the northeastern tip of Greenland to the continental margin of Siberia (Figure 1). It is categorized as an ultra-slow spreading Mid-Ocean Ridge (MOR) with full spreading rates ranging from ~1.3 cm/yr near Greenland to 0.6 cm/yr at the Laptev Shelf (DeMets et al. 1994). Gakkel Ridge has a deep axis (4700–5300 m) compared to other MORs (Kristoffersen 1982; Cochran et al. 2003; Michael et al. 2003), supporting a model of primarily tectonic formation; the contribution of volcanism to Gakkel Ridge topography remained controversial until the SCICEX SCAMP swath-mapping surveys of the ridge in 1998 and 1999.

Twelve days during the SCICEX-98 and SCICEX-99 surveys focused on collecting data to resolve the debate regarding volcanism at Gakkel Ridge. Lineated magnetic anomalies (Vogt et al. 1979; Coles and Taylor 1990) and bathymetric profiles across the axis of Gakkel Ridge (Kristoffersen 1982) support the theory that volcanism occurs in this ultra-slow spreading environment; however, modeling predicts that melt production might be inhibited at spreading rates < 1.5 cm/yr (Reid and Jackson 1981; Chen 1992; Sparks et al. 1993; Bown and White 1994). Coakley and Cochran (1998) interpret gravity

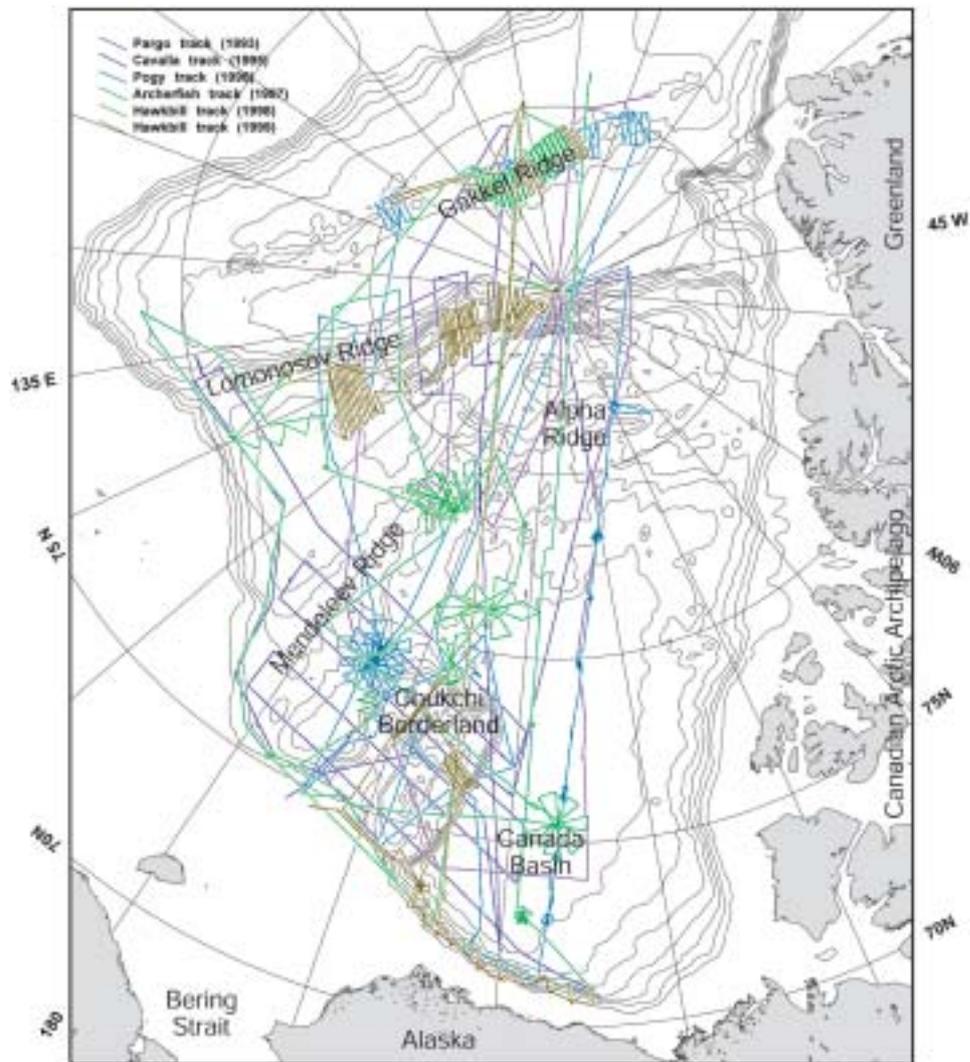


Fig. 1. Map of the Arctic Basin showing tracklines for SCICEX-93 through SCICEX-99 (SCICEX-2000/2001 navigation data are not available at this time). Contours are derived from the International Bathymetric Chart of the Arctic Ocean digital data set; contour interval is 500 m. Major physiographic provinces are labeled.

data collected during SCICEX-96 as indicative of Gakkel Ridge having anomalously thin crust, supporting a hypothesis of diminished volcanism. SCICEX-98 and SCICEX-99 SCAMP bathymetry and sidescan data for Gakkel Ridge resolved the issue, providing evidence of two young volcanoes covering approximately 20% of a 3750 km² region surveyed along the eastern Gakkel Ridge (Edwards et al. 2001a), which spreads at a full-rate of < 1.0 cm/yr.

In January 1999 global seismic networks detected the initiation of an earthquake swarm on Gakkel Ridge centered near one of the young volcanoes at 86°N, 85°E (Müller and Jokat 2000; Tolstoy et al. 2001; Figure 2). Seismic activity was vigorous for the first three months and persisted at a reduced rate for four additional months. A total of 252 events were recorded. The *USS Hawkbill* passed over the area in May 1999, during the waning stages of the earthquake swarm, imaging highly reflective lava flows that overprinted tectonic features (Figure 2). Since historical seismic records indicate this is the only earthquake swarm detected on Gakkel Ridge in ~100 years (Müller and Jokat 2000), Edwards et al. (2001a) theorize the SCICEX-99 program imaged an eruption on Gakkel Ridge shortly after its occurrence. Cochran et al. (2003), Michael et al. (2003) and Jokat et al. (2003) subsequently present evidence for extrusive volcanism in other, isolated locations along Gakkel Ridge. The most compelling confirmation of Gakkel Ridge volcanism to date has been the discovery of hydrothermal venting along the ridge axis (Edmonds et al. 2003) in association with fresh-looking basalts (Michael et al. 2003). Edmonds et al. (2003) report that the most vigorous hydrothermal plume, as indicated by thickness, height of rise and magnitude of signal, was discovered at 85°E, proximal to the young volcano (Edwards et al. 2001a) and locus of teleseismically-detected earthquake epicenters (Müller and Jokat 2000; Tolstoy et al. 2001).

- Lomonosov Ridge

Lomonosov Ridge is a narrow, high-standing ridge that extends across the Arctic Ocean, separating the Eurasian and Amerasian basins (Jokat et al. 1992; Figure 1). The ridge formed ~60 mybp when Gakkel Ridge rifted off a sliver of the Barents-Kara margin during the formation of the Eurasian Basin (Wilson 1963; Vogt et al. 1979; Kristoffersen 1990). Prior to the SCICEX program, studies of the morphology and structure of Lomonosov Ridge were limited to ~300 km of ridge between 87°40'N, 140°E and 89°N, 120°W using data collected from ice islands (Weber 1979) and icebreakers (Ostenso and Wold 1977; Sweeney et al. 1982; Mair and Forsyth 1982; Forsyth and Mair 1984; Weber and Sweeney 1990; Jokat et al. 1992; 1995). These studies describe Lomonosov Ridge as a flat-topped structure comprised of tilted en echelon fault blocks with steeper flanks facing the Eurasian Basin than the Amerasian Basin. Its continental nature was confirmed by seismic refraction lines during the Lomonosov Ridge Experiment (LOREX; Mair and Forsyth 1982; Forsyth and Mair 1984), which indicated a 5 km-thick crustal layer with velocity of 4.7 km/s overlaying another 20 km-thick crustal layer with a 6.6 km/s velocity, analogous to sections from the Barents and Kara shelves.

Although the continental character of Lomonosov Ridge is widely accepted, the first comprehensive mapping of the feature during SCICEX-99 revealed that the flanks of the ridge vary greatly along its length (Cochran et al. submitted; Coakley submitted). This variability permits the evaluation of several competing models that describe the formation of the poorly understood Amerasian Basin (Lawver and Scotese 1990). Cochran et al. (submitted) suggest these variations reflect different styles of rifting. They cite an

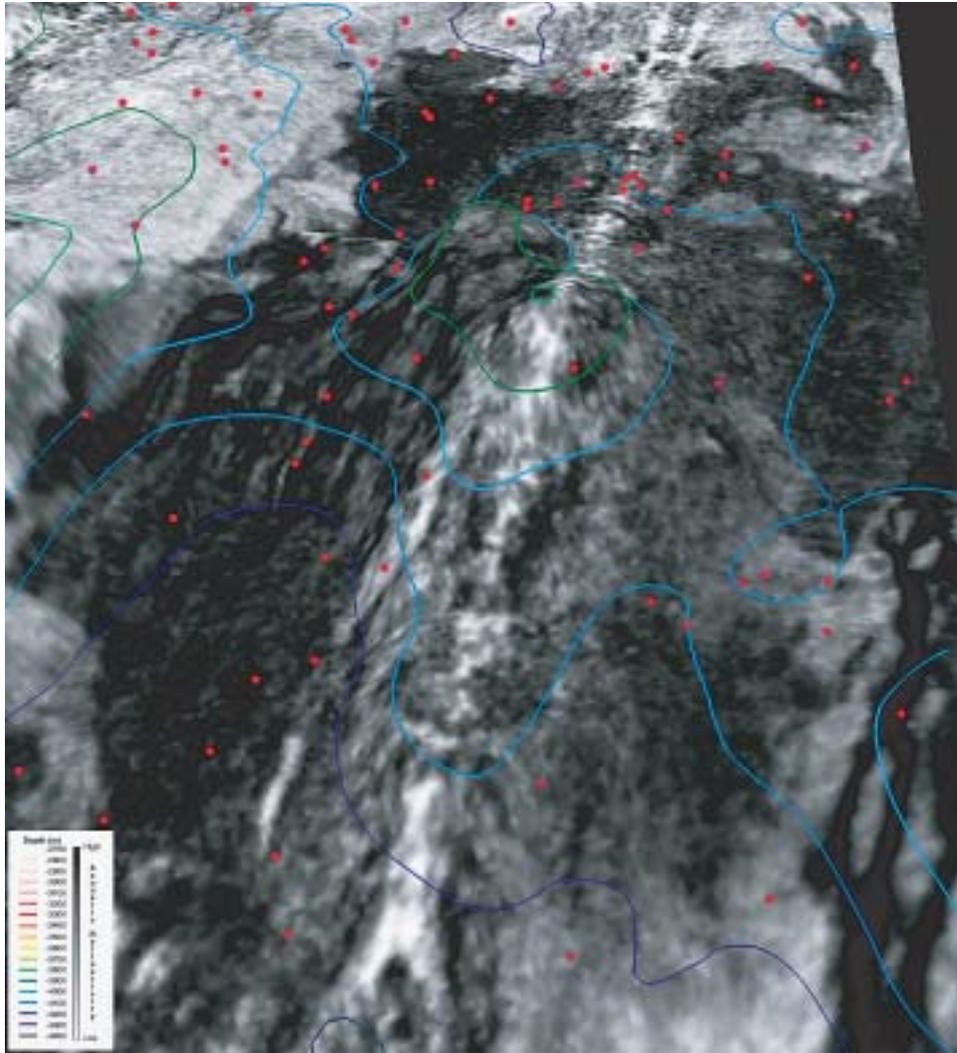


Fig. 2. Three-dimensional view of a volcano on Gakkel Ridge imaged by the SCAMP system during SCICEX-99. The perspective view is from east (bottom) to west (top). In this image sidescan data are overlain on a digital terrain model derived from SCAMP bathymetry. Color-coded contours (left) indicate depth; strong acoustic returns are dark while low acoustic returns are light. The dark, reflective terrain is centered about a close-contoured high having a maximum vertical relief of 500 m. Lava channels spill down slope from the volcano, ponding against fault scarps or terminating in flow toes that are characteristic of eruptive processes. Lava on this volcano exhibits little faulting; a few faults on the southern flank appear as dark lineations cutting through a small saddle-shaped rise. These faults abruptly terminate to west and east of the saddle suggesting that they have been volcanically overprinted. Red dots indicate the locations of earthquake epicenters for a teleseismically-detected event swarm that occurred from January until September 1999 (Müller and Jokat 2000; Tolstoy et al. 2001). The correlation between the earthquakes and the unteutonized lava flow is interpreted to indicate that this area recently erupted (Edwards et al. 2001; Tolstoy et al. 2001). After Edwards et al. (2001a).

apparent change in bathymetry, gravity and magnetic data near 88°N on the Siberian side of Lomonosov Ridge as reflecting an along-axis change in the tectonics shaping the former (i.e., pre-Eurasian Basin initiation) northern margin of Eurasia. Since seafloor spreading magnetic anomalies in the Eurasian Basin are continuous and parallel to the overall trend of Lomonosov Ridge (Vogt et al. 1979), Cochran et al. (submitted) infer that the variability in the structure of the ridge is related to the rifting that formed the Amerasian Basin. They propose that the opening along the northern Eurasian margin to create the Amerasian margin was strike-slip in nature from Greenland to ~88°N, becoming progressively oblique toward Siberia. This created the wider zone of oblique ridges and fault-bounded basins that now make up the Siberian end of Lomonosov Ridge. This interpretation, if sustained by ongoing analysis of geophysical data collected during SCICEX-99, supports a rotational model for the origin of the Amerasian Basin.

- Chukchi Borderland and Other Shallow Regions:
Interactions between Ice and the Arctic Seafloor

SCICEX surveys of Chukchi Borderland were not designed to investigate the formation of this topographic high, but rather to determine whether Pleistocene glaciations had modified this terrain, as well as other elevated portions of the Arctic Ocean floor. It has been hypothesized that during major glaciations, thick ice shelves covered the Arctic Ocean (Mercer 1970; Lindstrom and MacAyeal 1989; Grosswald and Hughes 1999). This theory contrasts with a more conventional view that throughout the Quaternary the Arctic Ocean was covered by just a few-meters-thick perennial sea ice with scattered icebergs (Clark 1982; Phillips and Grantz 1997; Spielhagen et al. 1997). To resolve the debate, SCAMP seafloor mapping surveys were developed for the SCICEX-99 program focusing on shallow regions including the Chukchi margin and borderland (Chukchi Cap and Northwind Ridge) and the crest of Lomonosov Ridge. Swath sonar images of the Chukchi region show a variety of glacigenic bedforms including parallel lineations, ridges, and scours to depths of 700+ m on Chukchi Borderland (Figure 3; Polyak et al. 2001; Edwards et al. submitted). These features are consistent with stratigraphic evidence of seafloor erosion from chirp records and sediment cores (Polyak et al. 2003). From the morphology and orientation of bedforms, Polyak et al. (2001) conclude there was major ice-shelf flow over Chukchi Borderland that originated from the northwestern part of the Canadian Arctic Archipelago. They hypothesize this westward-flowing ice was deflected towards the interior of the Arctic Ocean by Chukchi Rise's steep slopes or by a grounded ice sheet on the Chukchi shelf. Evidence of margin-parallel glacigenic lineations on the Alaska margin (Phillips and Grantz 1997; Engels et al. 2003; Edwards et al. submitted) supports the conclusion that a major source of ice was the Canadian Arctic Archipelago.

Another startling discovery from the SCICEX-99 SCAMP data was evidence of grounded ice to depths of almost 1000 m on the central portion of Lomonosov Ridge. Although erosional truncation has been previously reported for Lomonosov Ridge (Jakobsson 1999), the SCAMP chirp sonar records, showing erosionally planed ridge tops with rough micro-relief that includes parallel lineations and sub-parallel gouges (Figure 4) represent the first compelling evidence for widespread scouring and molding of seafloor by grounded ice at these depths in the central Arctic Ocean (Polyak et al. 2001). Based on the SCICEX findings, Polyak et al. (2001) suggest that a vast ice shelf advanced from the Barents Sea shelf and eroded parts of the top of Lomonosov Ridge to depths of almost 1 km.

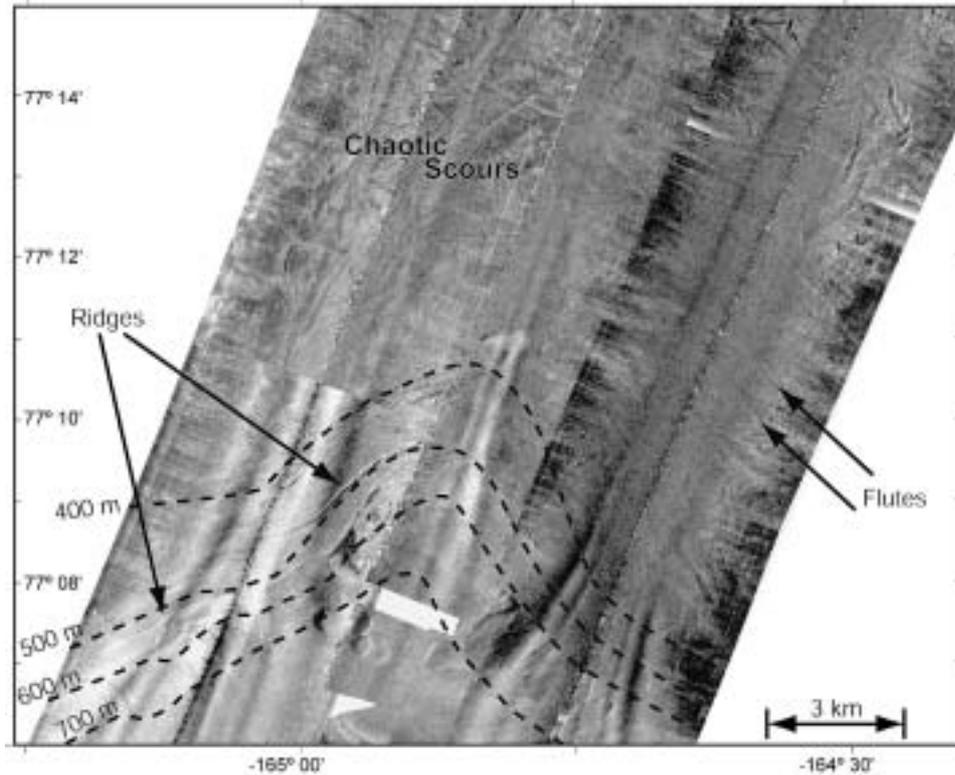
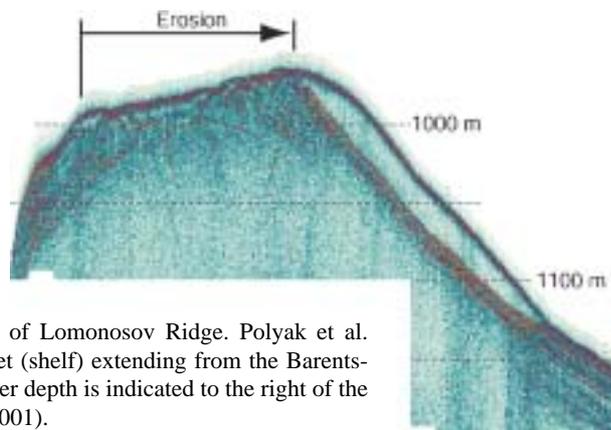


Fig. 3. Sidescan sonar image from the southern slope of Chukchi Plateau with overlain depth contour lines. In this figure, acoustic shadows are black and strong returns are white. Spatial resolution of gridded data is 16 m. NW-trending glacial lineations (flutes) indicate ice flow from the Canadian Arctic Archipelago. Transverse ridges, parallel to isobaths, mark the back-stepping of an ice-shelf grounding line with rising sea level during deglaciation. Chaotic scours cover the <400-m-deep portions of seafloor, cross-cutting and obscuring the lineations. These scours reflect unrestricted movement of icebergs driven by winds and/or currents after ice-shelf removal.

Fig. 4. SCAMP HRSP profile of Lomonosov Ridge in a location where SCAMP bathymetry and sidescan data show evidence of glacial erosion. The peneplained top of the ridge tilts toward the Eurasian Basin; a lens of transparent, reworked sediments has been deposited on the Amerasian flank of Lomonosov Ridge. Polyak et al. (2001) suggest that a large ice sheet (shelf) extending from the Barents-Kara shelf caused this erosion. Water depth is indicated to the right of the cross-section. After Polyak et al. (2001).



Kristoffersen et al. (submitted), describe massive erosion of the Yermak Plateau, located at the exit for ice export from the Arctic Ocean. This erosion, discovered by Vogt et al. (1994), is depicted in more detail in seismic records and SCICEX-99 SCAMP data. Based on this evidence, Kristoffersen et al. (submitted) concur with Polyak et al. (2001) that very thick ice must have been present in the Arctic; however, they dispute the existence of continuous ice shelves covering large portions of the Eurasian Basin. Kristoffersen et al. (submitted) point out that there are locations on Lomonosov Ridge shallower than the planated portion of the ridge described by Polyak et al. (2001) that exhibit undisturbed stratigraphy in seismic cross-section. They argue that the existence of these shallow, uneroded features does not support the inference of a continuous ice shelf over the Eurasian Basin and instead present a model in which an armada of large icebergs entrained in sea ice modified the arctic seabed.

Although the form and extent of thick arctic ice shelves remain controversial and the timing of their presence is not well constrained (Polyak et al. 2001; Kristoffersen et al. submitted), the discovery of glacial bedforms in the central Arctic Ocean will require substantial revision of models describing the Earth's major glaciations and related paleoclimate. The SCICEX-99 sonar images provide wide spatial coverage for circum-oceanic correlation of mapped terrains (Edwards et al. submitted) and will serve as the basis for future surveys to directly sample and date glacial features.

Arctic Oceanography

As significant as the contributions of the SCICEX program have been to arctic geology, the submarine cruises have had an even greater impact in oceanography. The mobility of SCICEX submarines, ranging from rapidly traversing long survey lines across the entire Arctic Basin to maintaining a constant station while moving up and down through the water column, facilitated investigations of physical, chemical and biological properties of the Arctic Ocean that could not have been accomplished using any other type of research platform. The SCICEX oceanographic data have provided not only new 2- and 3-dimensional perspectives of the Arctic Ocean, but because of repeated surveys like the cross-basin transects, yielded valuable time-series data that depict how the ocean is changing on annual and, in combination with existing climatologies, decadal scales.

In terms of oceanographic characteristics and processes, the Arctic Ocean can be divided into different regimes. The Arctic Ocean's vertical density structure can be subdivided into the upper mixed layer (~0–100 m deep), the halocline (~100–200 m deep), the intermediate water (~200–1700 m deep) and the remainder of the water column, most often referred to as deep and bottom waters (Aagaard and Carmack 1994; Rudels et al. 1994; Morison et al. 1998; Smethie et al. 2000). The halocline is characterized by its vertical stratification in salinity (Aagaard et al. 1981; Rudels et al. 1996). Beneath the halocline is the salty and warm intermediate water, which supplies most of the heat content in the central Arctic Basin (Morison et al. 1998). Atlantic water is the major source of intermediate waters, as the latter are too dense to be derived from the Pacific Ocean water that enters through the Bering Strait (Smethie et al. 2000). Processes including convection, mixing by eddies, and lateral admixture of low salinity water from the shelves affect this vertical structure.

The Arctic Ocean also has a complex horizontal structure. For example, the Amerasian Basin is more strongly stratified than its Eurasian counterpart. Water in the Amundsen Basin, which comprises the northern half of the Eurasian Basin, is cooler and less saline than in the

Nansen Basin, its southern equivalent (Rudels et al. 1994). Circulation in the Arctic Ocean is broadly divided into three large cyclonic cells, one flowing around the Eurasian Basin, the second around the Makarov Basin, and the third around the Canada Basin (Aagaard 1989; Rudels et al. 1994). Factors contributing to the circulation of the Arctic Ocean include: asymmetric interactions with the Atlantic and Pacific Oceans, with the Atlantic providing two-way heat and mass exchange with the Arctic while the Pacific provides only inflow; boundary currents affecting the flow of deep and intermediate waters in predominantly counterclockwise, but frequently reversing, directions; and long-lived eddies, especially in the Amerasian Basin (Aagaard and Carmack 1994). Thanks to the SCICEX submarines, oceanographers conducted nearly synoptic investigations of many oceanographic features by mapping and sampling water over a range of distances and depths. Their findings reveal both large- and small-scale characteristics of the Arctic Ocean, illuminating how this body of water both influences and is affected by the environment around it.

- Vertical Stratification of the Arctic Ocean

- **Intermediate Water:** During the first half of the 1990's several arctic field programs, including Oden-91, LARSEN-93 and SCICEX-93, led to reports of widespread changes in the Arctic Ocean's upper water column (Anderson et al. 1994; Carmack et al. 1995; McLaughlin et al. 1996; Morison et al. 1998). In particular, the Atlantic Layer (AL; ~200–800 m deep) was observed to be extending farther into the Arctic Basin and becoming warmer. Compared to existing climatologies (Levitus 1982; 1994; Gorshkov 1983) data collected during the early 1990's indicated that the front between the eastern AL, characterized by a warm temperature of 2–3 °C, and the western AL, slightly cooler at 0.5 °C (McLaughlin et al. 1996), shifted from Lomonosov Ridge westward to the Alpha-Mendeleev Ridge (McLaughlin et al. 1996; Morison et al. 1998). The AL also shoaled by about 40 m within the Amundsen Basin between the Oden-91 and SCICEX-95 expeditions (Steele and Boyd 1998). The change was recognized as enduring for several years, but whether it was a long-term trend or an isolated change could not be determined from data available in the early 1990's (Morison et al. 1998). Beginning with SCICEX-95 and continuing through the SCICEX-2001 deployment, cross-basin transects were undertaken to collect the chemical and physical oceanographic data necessary to monitor changes in the water column and investigate this issue. Several SCICEX-related studies focused on the Atlantic Water (AW) layer (Gunn and Muench 2001), also known as Arctic Intermediate Water (AIW; Mikhalevsky et al. 1999; 2001; Mikhalevsky 1999), the boundaries of which are defined to cross the 0 °C isotherms above and below the AL temperature maxima (Mikhalevsky et al. 2001).

Gunn and Muench (2001) examine AW layer mean and maximum temperatures collected from 1995–1999 to show that warming continued from 1995 until 1998, but was replaced by a slight cooling during 1998–1999. This result is illustrated in average temperature profiles generated from SSXCTD data collected during the SCICEX cross-basin transects (Figure 5; P. Mikhalevsky and M. Moustafa, unpublished data). Examining four temperature cross-sections systematically approaching the North Pole, Gunn and Muench (2001) demonstrate the variability of temperature change as a function of location; for example, temperature changes on Lomonosov Ridge are generally less than in the basins on either side. They propose northward currents along the flanks of the arctic ridges as mechanisms for advecting warm Atlantic water from the Eurasian continental margin into the central Arctic Ocean.

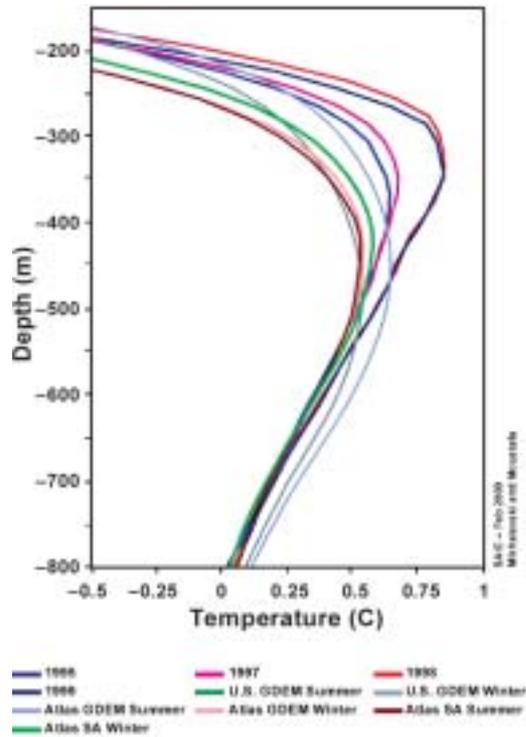


Fig. 5. These curves show average temperatures along cross-basin transects of the Arctic Ocean. Focusing on the 300 m depth level, the five curves on the left were derived from historical data; the four curves on the right represent SCICEX SSXCTD data (see key at the bottom of the figure). In general the SCICEX data show a warming trend relative to the historical data although there is a slight cooling in the upper part of the AL from 1998 to 1999. (Courtesy of P. Mikhalevsky and M. Moustafa).

Mikhalevsky et al. (2001) examine the SCICEX SSXCTD data (Appendix 2) through the 2000 *USS L Mendel Rivers* deployment and find that the warming trend did not stop during 1998–1999, it continued between 1999 and 2000. They confirm these results using acoustic thermometry data collected during the Transarctic Acoustic Propagation Experiment (TAP; Mikhalevsky et al. 1995; 1996; 1999) and ACOUS (Mikhalevsky 1999). The thermometry data show a slight cooling from October 1998 through March 1999, consistent with the observation of Gunn and Muench (2001), followed by a large warming between March and December 1999. Gunn and Muench (2001) suggest that the observed changes in the Arctic Ocean temperature structure may be correlated with atmospheric forcing that causes changes in sea level pressure (SLP; Proshutinsky et al. 1999). As will be discussed in the following section, there is strong evidence that upper ocean circulation is correlated with SLP (Boyd et al. 2002).

- **Cold Halocline Layer:** The strong vertical stratification of the Arctic Ocean is largely responsible for the existence of the ice canopy that covers the ocean (Aagaard and Carmack 1994). The halocline suppresses vertical mixing and may also serve as a heat sink, effectively isolating the upper ocean and ice cover from the underlying warm Atlantic water (Aagaard et al. 1981; Rudels et al. 1996). However, the arctic halocline exhibits horizontal variability that changes over time. In the central Arctic Ocean a cold halocline layer (CHL), characterized by its approximately constant, near-freezing temperature and strong vertical stratification in salinity (Boyd et al. 2002) historically protected

the surface waters of the Makarov and Eurasian Basins from the Atlantic water. Alternatively, the Canada Basin exhibits what Steele and Boyd (1998) referred to as a “cool halocline” layer due to the contributions of warmer Bering Sea water to the halocline. Because the CHL is a better insulator than a cool halocline, decreases in the extent of the CHL have the potential to cause a corresponding decrease in the extent of the ice canopy and a subsequent increase in global temperatures. With their ability to map and sample the upper water column of a large cross-section of the Arctic Basin, the SCICEX submarines were ideally suited to undertake detailed time-series investigations of the CHL. Steele and Boyd (1998) and Boyd et al. (2002) used the SCICEX data to track the evolution of the CHL during the 1990's while Björk et al. (2002) considered the potential impact of the CHL evolution on sea ice mass balance.

Steele and Boyd (1998) compare CTD data collected during SCICEX-93 and SCICEX-95 with a winter climatology compiled by the joint U.S.-Russian Environmental Working Group (EWG 1997) to demonstrate that the extent of the CHL decreased during the first half of the 1990's, retreating from an area covering the combined Amundsen and Makarov basins into just the Makarov Basin. They infer that throughout much of the Eurasian Basin in 1995, the upper mixed layer was in direct contact with the AL, which would yield higher heat fluxes and reduced ice formation during the winter. Although Steele and Boyd (1998) had insufficient oxygen isotope profiles to quantify the role of rivers in this retreat, they use salinity as a proxy to infer that less freshwater was delivered to the Eurasian Basin between 1991 and 1995. They suggest that the increased saltiness of the upper layers of the Arctic Ocean in the Eurasian Basin is due to a shift of Siberian river runoff from the Amundsen to the Makarov Basin, and that this shift, in turn, resulted from the Eurasian Low pressure cell extending farther into the Arctic Basin during the 1990's than in previous years.

Boyd et al. (2002) expand upon the analyses of Steele and Boyd (1998), adding data from SCICEX-98, SCICEX-99 and SCICEX-2000 to the comparison of Oden-91 and SCICEX-95 changes in the CHL. Using salinity at the top of the halocline (~80 m water depth) as a measure of halocline development, they demonstrate that between 1991 and 1998 upper ocean salinity increased as the CHL disappeared. Similar to the trend observed for the AIW, the CHL began to recover in 1998, but in the case of the shallower CHL, the recovery continued into 2000. To investigate the atmospheric contribution to the observed change, Boyd et al. (2002) examine IABP (International Arctic Brog Program) sea level pressure averaged over three time periods (1979–1987, 1988–1995, and 1998–1999). They find that during the first and last time periods a strong SLP high was centered over Chukchi Plateau, forcing an anticyclonic upper ocean circulation regime. Between 1988 and 1995 the SLP high weakened and retreated into the Canada Basin, which led to a decrease in ice flux from the Laptev Sea into the Amundsen Basin (Steele and Boyd 1998). Was the CHL sufficiently weakened to account for the observed reduction in sea ice during the 1990's reported by Rothrock et al. (1999a)? Following the approach of Rudels et al. (1996) to estimate upward heat flux, Boyd et al. (2002) conclude that enhanced heat flux through the weakened CHL was not sufficient to account for the freshening observed during the last half of the 1990's (McPhee et al. 1998) and therefore did not unilaterally cause the decrease in sea ice thickness. Björk et al. (2002) suggest that the recent return of the CHL described by Boyd et al. (2002) could increase the mass balance of sea ice; their model computations predict increased winter sea ice growth of 0.25 m when the CHL is present versus when it is absent.

- Water Circulation in the Central Arctic Ocean

Understanding the circulation of the Arctic Ocean and how it exchanges water with the oceans adjacent to it is a necessary component of understanding global climate (Smethie et al. 2000). To accomplish this goal a number of arctic oceanographic expeditions systematically sampled the arctic water column, primarily in the Eurasian Basin, during the early 1990's (Anderson et al. 1994; McLaughlin et al. 1996; Swift et al. 1997; Schauer et al. 1997; Morison et al. 1998). Using hydrographic and tracer data collected during the Oden-91 expedition, Rudels et al. (1994) expanded on the earlier ideas of Aagaard (1989) and developed a conceptual circulation model for intermediate water in the Arctic Ocean with three primary cyclonic cells circling the Eurasian, Makarov and Canada Basins. They estimated average renewal times for intermediate water in these cells ranging from one decade in the Eurasian Basin to two decades in the Amerasian Basin. By the mid-1990's the Rudels et al. (1994) circulation scheme had generally been confirmed, except in the Makarov and Canada Basins where limited data existed. During the SCICEX-96 program, data were collected along a line of surface stations from Lomonosov Ridge to the Chukchi margin (Smethie et al. 2000) to evaluate the predictions of Rudels et al. (1994) model for the Canada Basin.

Smethie et al. (2000) analyze data and samples collected by the *USS Pargo* from surface cast CTDs and Niskin bottles deployed to depths of 1600 m. Included in their analyses are temperature, salinity, oxygen and nutrient measurements as well as the tracers tritium, ^3He and chlorofluorocarbon (CFC). They find the most saline intermediate waters were located at the northern end of the Canada Basin, just south of Alpha-Mendeleev Ridge, associated with low transient tracer concentrations. Contrastingly, the highest tracer concentrations occurred in the central Canada Basin and the Makarov Basin where the intermediate water is relatively low in salinity. Using tritium/ ^3He ages to determine the time of formation of the water mass and calculating a dilution factor from CFC data, Smethie et al. (2000) develop a timescale describing the flow of intermediate water into the Canada Basin. Their results show the presence of well-ventilated Atlantic water in the central Canada Basin, with renewal times on the order of 1–2 decades. Smethie et al. (2000) conclude that the presence of this well-ventilated water indicates that intermediate water does not flow around the Canada Basin in one large cyclonic gyre according to the model of Rudels et al. (1994), which predicts the oldest intermediate water should be found in the interior of the basin. Smethie et al. (2000) suggest instead that intermediate water is rapidly transported into the interior of the Canada Basin in the vicinity of the Chukchi Rise. They contend that the presence of the oldest, least-ventilated intermediate water at the northern end of the Canada Basin could indicate the existence of a small gyre that isolates this part of the Arctic Ocean, or alternatively, could be the result of circulation changes introduced by the observed influx of Atlantic water into the Arctic Ocean (Anderson et al. 1994; McLaughlin et al. 1996; Morison et al. 1998).

Smith et al. (1999) use measurements of tracer radionuclides ^{129}I and ^{137}Cs in seawater samples collected during the SCICEX-95 and SCICEX-96 deployments to examine the circulation of both the halocline and intermediate water. These radionuclides derive from the discharges of nuclear fuel reprocessing plants located in the United Kingdom (Sellafield, England) and France (La Hague) and are transported into the Arctic via the Fram Strait and Barents Sea. Based on high ^{129}I levels measured in the interior of the Canada Basin relative to the northern part of the basin, Smith et al. (1999) conclude that ventilation of the intermediate water layer in the central Canada Basin is rapid, consistent with

the result subsequently reported by Smethie et al. (2000). Smith et al. (1999) interpret very low levels of ^{129}I sampled over the northern Canada Basin and Alpha-Mendelev Ridge as evidence for ventilation ages >25 years for intermediate water in these regions. They use the ^{129}I and ^{137}Cs data to estimate transit times of 6.5–7 years (± 0.5 years) for transport of upper AL water from the Norwegian Coastal Current to the continental slope of the Makarov Basin, with transport into the interior of both the Makarov and Amundsen basins having a lower limit of eight years.

Examining halocline water between 59 and 134 m depth, Smith et al. (1999) find markedly different ^{129}I levels between water originating in the Atlantic ($>100 \times 10^7$ atoms L^{-1}) and in the Pacific ($<5 \times 10^7$ atoms L^{-1}). The latter levels derive primarily from fallout and hence are significantly lower than levels derived from European reprocessing plants. The ^{129}I data show that the front between the Pacific and Atlantic coincides with the Alpha-Mendelev Ridge, consistent with previously published findings (Carmack et al. 1995; Morison et al. 1998), and it is displaced toward the Canada Basin with increasing depth. Between the 1995 and 1996 SCICEX cruises, the radionuclide analyses of Smith et al. (1999) show little evidence of change in the front between the Atlantic and Pacific haloclines. With regards to transport, Smith et al. (1999) estimate that $^{129}\text{I}/^{137}\text{Cs}$ transit times for the halocline at 59 and 134 m water depths are, on average, 0.5 years lower than those for AL water at 240 m water depth.

Guay et al. (1999) analyze physical and chemical water properties along the Beaufort, Chukchi, East Siberian and Laptev shelves to identify sites where river waters cross the shelves and join the circulation of the upper Arctic Ocean water column. Their datasets include temperature, salinity, chlorophyll *a*, Ba, total organic carbon (TOC) and dissolved organic carbon (DOC) derived from *in situ* measurements of fluorescence, all of which were collected at a keel depth of 58 m along a 2900-km transect. Regions where river waters cross the shelves and enter into the interior of the Arctic Ocean are identified by the coincidence of local salinity minima with local maxima in Ba, DOC and TOC. Although the Mackenzie River and Eurasian arctic rivers are enriched in Ba and DOC compared to the marine waters, relative to each other the Mackenzie River is lower in DOC and higher in Ba than water derived from Eurasian arctic rivers. Guay et al. (1999) are thus able to define three major regimes along the shelf transect: the Canada Basin and Chukchi Cap regime, which is dominated by mixing between Pacific inflow, discharge from the Mackenzie River and ice melting; a transition zone centered over the Alpha-Mendelev Ridge corresponding to the front between Pacific and Atlantic waters observed by Morison et al. (1998); a Makarov and Amundsen Basin regime dominated by discharge from Eurasian arctic rivers and Atlantic water.

- Detailed Mapping of an Arctic Eddy

Eddies were first documented in the Arctic Ocean in the middle 1970's (Newton et al. 1974). Since that time they have been recognized as nearly ubiquitous features of the Amerasian Basin, originating near the margins of the Arctic Ocean and having life spans of several years (Aagaard and Carmack 1994, and references therein). Despite their prevalence, detailed observations of individual arctic eddies are unusual (Muench et al. 2000) because systematic mapping of these features is difficult to accomplish from icebreakers or bottom-moored sensors. During SCICEX-97, embarked researchers seized an unprecedented opportunity to map a cold core mesoscale eddy by collecting oceanographic data and samples to characterize the feature both horizontally and vertically. In

addition to describing the eddy's physical properties, Muench et al. (2000) use chemical tracers to examine the age and source region of the feature.

The cold core eddy was encountered ~150 km north of Alaska, recognized when real-time data acquired by the sail-mounted CTDs showed anomalously low temperature and salinity values (Muench et al. 2000). To map the eddy, the *USS Archerfish* undertook ten transects across the feature ranging in length from ~25–55 km. Seven transects were completed at a depth of 218 m; the remaining three were completed at 118 m depth. During the survey the sail-mounted CTDs recorded data continuously, 15 SXXCTDs were launched, 19 through-hull water samples were collected and one 8-depth spiral station was completed near the eddy center. In addition to continuous underway measurements of temperature, salinity, density and dissolved oxygen (DO) concentrations, vertical distributions of chemical and tracer variables including silicate, nitrate, phosphate, ammonium, chlorophyll *a* concentrations, phaeopigment concentrations and dissolved organic nitrogen (DON) concentrations were derived from the spiral cast samples. $\delta^{18}\text{O}$ values and tritium concentrations were used to investigate eddy source while tritium/ ^3He provided age constraints. Vertical profiles of current speed were computed from SXXCTD data.

Muench et al. (2000) describe the eddy as ~20 km in diameter, extending from the base of the upper mixed layer (~40 m depth) to ~400 m depth. Core temperatures in the eddy are cooler than in the surrounding ambient water with the greatest temperature difference occurring at ~230 m depth. The eddy core exhibits excess salt from the top of the eddy to depths of ~185 m; at deeper depths salinity is less than ambient values. Maximum current speeds recorded in the eddy are 20 cm/sec. At the 218 m survey depth, DO concentrations are substantially higher than the surrounding water. Vertical gradients in the chemical and tracer variables in water <100 m deep show nutrient depletion in the upper ocean, probably the result of productivity processes.

Analyzing the distributions of inorganic nutrients, DO and tracer concentrations, Muench et al. (2000) conclude that the likely source of the eddy was a polynya along the Alaskan Chukchi coast. They infer that water densification from surface ice formation, followed by the development of frontal instabilities, created the eddy. The tritium/ ^3He ages place an upper limit of 2 years on the mean age of the eddy core waters. Muench et al. (2000) estimate that if the eddy formed along the Alaskan Chukchi coast during the early winter ten months prior to the SCICEX-97 encounter, it migrated northward at ~1 cm/sec, transporting $2 \times 10^3 \text{ m}^3$ of shelf water per second. They further suggest that if eddies are the sole mechanism for venting water from the shelves, volume considerations would imply that ~250 eddies form and migrate annually.

Muench et al. (2000) speculate that cold core eddies contribute to the maintenance of the halocline and describe a possible feedback relationship between the formation of eddies and the extent of the arctic ice cover. In the scenario where eddies form primarily in open water polynyas, as the amount of open water increases, there should be a corresponding increase in the formation of eddies. The existence of more cold core eddies would strengthen the halocline, effectively limiting upward heat flux from deeper water which in turn would produce increased ice cover. As the extent of the ice cover increased, fewer eddies would form, the halocline would weaken and the cycle would reverse. This model presents a testable hypothesis as scientists carefully monitor the extent of arctic ice cover (Maslanik et al. 1996; Parkinson et al. 1999); namely, that more eddies should be found as ice cover decreases.

- Beaufort Slope Oceanography: Fine-scale Interactions between Complex Continental Shelf-slope Seafloor Topography and Currents

The influence of large-scale topographic features such as Gakkel Ridge, Lomonosov Ridge and Alpha-Mendelev Ridge on the Arctic Ocean were documented prior to the SCICEX program (Aagaard and Carmack 1994, and references therein), but SCICEX investigators demonstrated for the first time that smaller-wavelength topography also has a measurable effect on water properties (Okkonen et al. 2000). Okkonen et al. (2000) compare power spectra for underway measurements of temperature, salinity, DO and topographic profiles collected during a shelf-parallel transect along the Beaufort Sea slope (Figure 6). The topography at the western end of this survey is incised by an extensive submarine canyon system with vertical scales of hundreds of meters and along-slope scales of tens of kilometers. At the eastern end of the survey, the slope topography is significantly less rugged at km-scale wavelengths. Okkonen et al. (2000) find the amplitudes and scales associated with the horizontal variations in upper halocline temperature, salinity and DO are strongly correlated with along-slope morphology on the western end of the survey whereas at the eastern end there is no significant correlation. Mixing within the halocline is enhanced near the undulating canyon topography, demonstrating a strong link between topography and the overlying water column at scales of a few tens of kilometers.

- Nutrient-Biological Productivity Export from the Beaufort-Chukchi-East Siberian-Laptev Shelves to the Basin

The SCICEX program has provided some of the first detailed information on the pathways by which organic matter from the shelves is transported to the Arctic Basin (Rothrock et al. 1999b). Alongshore transects were undertaken on SCICEX-95, SCICEX-97 and SCICEX-99 that covered a most of the productive period of the Arctic seasonal cycle. Especially during SCICEX-95, which occurred in April, nitrate and chlorophyll transport was detected in the upper halocline at 50 m depth at four different locations along the edge of the Beaufort and Chukchi shelves (Figure 7; Whitley 1999). It was particularly useful to observe the relative changes of chlorophyll:phaeopigments, which indicated three regions contained relic pigments and one region near Herald Canyon where recent phytoplankton pigments were leaving the Western Arctic shelf. This information provided valuable guidance to the development and sampling design of the Shelf-Basin Interactions in the Western Arctic (SBI) program. The alongshore sampling also contributed to validation of recent biological modeling (Walsh et al. submitted).

- Biogeography of Bacterioplankton

The Arctic Ocean receives organic matter (OM) from several sources including riverine inflow from the surrounding continents, phytoplankton production and ice-algal production (Ferrari and Hollibaugh 1999). The relative significance of the flux of terrigenous dissolved organic matter (DOM) to the Arctic Ocean from rivers is higher than corresponding fluxes to the adjacent Pacific and Atlantic Oceans, and this flux may be increasing due to changes in the global climate (Opsahl et al. 1999). Water samples collected during the SCICEX program presented an unprecedented opportunity for biologists to study OM on a basin-wide scale and in different parts of the water column to track

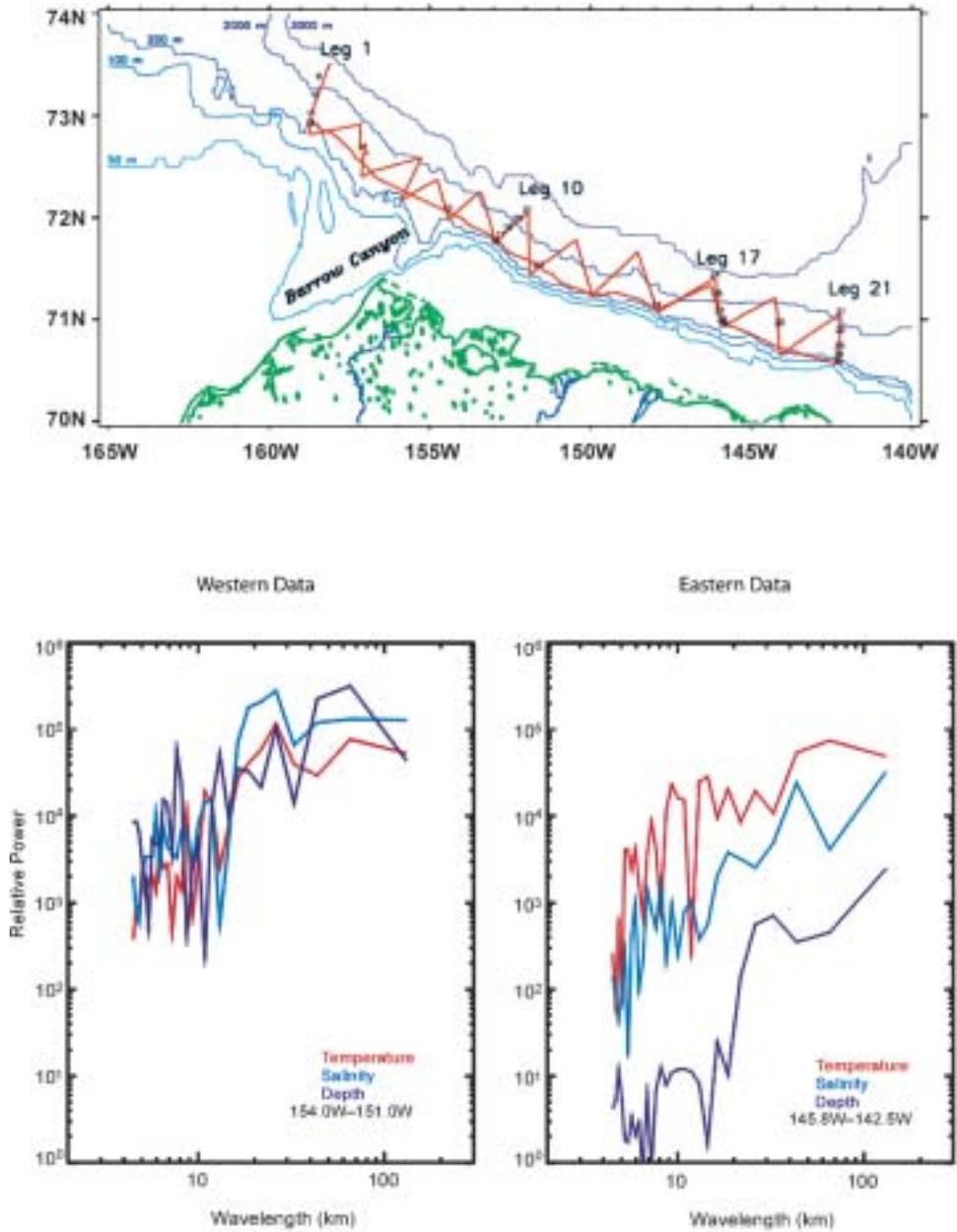


Fig. 6. Top: Track lines for Beaufort Slope survey conducted during SCICEX-99. SXXCTD launch sites are numbered. Bottom left: Power spectra for the western end of the survey, showing local maxima in T, S and depth at ~26 km. Okkonen et al. (2000) infer this correlation represents the influence of bathymetry on length scales of T and S variability in this area. Bottom right: Power spectra for T, S and depth at the eastern end of the survey show little correlation. (Courtesy of S. Okkonen and T. Weingartner).

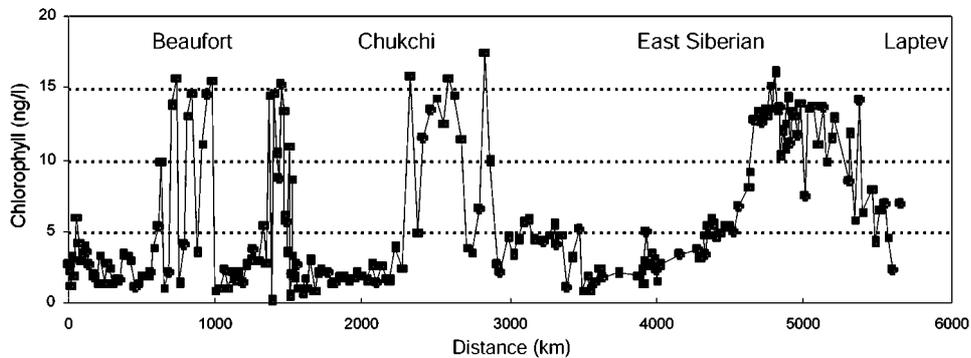


Fig. 7. Chlorophyll concentrations along the Beaufort, Chukchi, East Siberian and Laptev shelves showing the export of particulate organic matter at four locations during SCICEX-95. This track follows the shelf break from about 70.9°N , 142.7°W in the Beaufort Sea to 80.2°N , 141.8°E in the Laptev Sea. It is striking that the transport across the shelf occurs in such confined plumes that appear to be related to canyons or other depressions in the shelf topography. Likely sources for the maxima are: Beaufort Canyon (leftmost two peaks), Herald Canyon in the Chukchi Sea (central peak) and the East Siberian Sea (broad peak on the right). (Courtesy of T. Whitledge).

water inflow and outflow. Opsahl et al. (1999) examined the abundance of lignin, a macromolecule unique to vascular plants, to study the inflow and outflow of DOM in the Arctic Ocean, while Bano and Hollibaugh (2000; 2002) and Hollibaugh et al. (2002) investigated local, regional and global bacterioplankton biogeography using molecular biological techniques to analyze signature sequences in bacterial DNA from material collected on SCICEX cruises.

In order to analyze the large bacterial datasets yielded by SCICEX, biologists first had to develop a methodology to circumvent the laborious (and highly biased) process of isolating, purifying and culturing samples to describe physiology and determine taxonomy. Ferrari and Hollibaugh (1999) accomplished this goal by using denaturing gradient gel electrophoresis (DGGE) to resolve the products of polymerase chain reaction (PCR) amplifications of 16S rRNA gene fragments from DNA samples collected on SCICEX cruises. After sample analysis, they used an image processing program to examine DGGE images and statistically compare banding patterns in different gel samples. Using 100 samples collected at 59 m water depth in the Canadian Basin, Ferrari and Hollibaugh (1999) demonstrated that the PCR/DGGE method provides useful qualitative information on spatial and temporal variations in the composition of microbial communities. They recommend that the approach be used in combination with sequence information to determine the distribution of organisms.

Bano and Hollibaugh (2000) use the PCR/DGGE technique, in combination with cloning amplified 16S rRNA gene fragments, to study the distribution of ammonia-oxidizing bacteria in the Arctic Ocean. They analyzed 246 samples collected at 5, 55, 133 and 235 m water depth during SCICEX-95, SCICEX-96 and SCICEX-97. They found that ammonia oxidizers are more prevalent in halocline waters (80% of samples from 55 m and 88% of samples from 133 m) than in shallower and deeper waters. Bano and Hollibaugh (2000) suggest that the high abundance of ammonia oxidizers in this water layer is the result of organic matter accumulating at the pycnocline and decomposing to

release ammonium. They found that a *Nitrosospira*-like ammonia oxidizer, previously thought to be important only in terrestrial and fresh water environments, was the dominant ammonia oxidizer in the Arctic Ocean. They also observe differences in the diversity and species composition of the ammonia oxidizing bacterial community, with higher diversity and more frequent occurrence of a *Nitrosomonas*-like species in western Arctic Ocean regions influenced by inflow from the Pacific Ocean. Hollibaugh et al. (2002) found that the unique *Nitrosospira*-like organism was also the dominant ammonia oxidizer in 42 samples from the Southern Ocean, which they infer to indicate a transpolar, and possibly a global, distribution of this organism.

Bano and Hollibaugh (2002) expand on their earlier PCR/DGGE based analyses and lay the foundation to answer the fundamental questions of whether bacterial communities that evolved in perennially cold oceans have diverged from communities in temperate and tropical waters and whether the polar oceans exhibit similarities or differences in their bacterioplankton species. They establish phylogenetic affiliations of 16S rRNA gene fragments in DGGE bands by cloning 16S rRNA genes; screening the clone libraries by comparing DGGE bands from cloned fragments with DGGE bands from the original sample; then sequencing cloned genes and fragments extracted from the DGGE bands and comparing them to sequences in the GenBank database. Bano and Hollibaugh (2002) found that the diversity of the Arctic bacterioplankton assemblage was comparable to temperate oceans. Most of the sequences they obtained were not closely related to previously described organisms. The Arctic bacterioplankton community was composed of a mixture of uniquely polar and cosmopolitan phylotypes, many of them most similar to sequences of barophiles obtained from abyssal samples.

- DOM Biogeochemistry

Opsahl et al. (1999) use biogeochemical markers to investigate sources of DOM in the Arctic Ocean and to evaluate the quantitative significance of terrigenous DOM exported to the Arctic Ocean. They characterize the terrigenous component of ultra-filtered DOM (UDOM) by the chemical composition of products that result from CuO oxidation of lignin and by its stable carbon isotope composition ($\delta^{13}\text{C}$). Opsahl et al. (1999) estimate that terrigenous sources contribute between 5–33% of the UDOM observed in the upper water column of the Arctic Ocean. They further suggest that if the rest of Arctic Ocean DOM has a composition similar to the UDOM fraction, 12–41% of the terrigenous DOM discharged by rivers to the Arctic Ocean is exported to the North Atlantic through the surface waters of the East Greenland Current. In contrast, low concentrations of UDOM are observed in Arctic Deep Water, which Opsahl et al. (1999) interpret as indicating that very little terrigenous DOM from around the Arctic Ocean is incorporated into NADW and distributed globally through deep thermohaline circulation.

Arctic Ice Canopy

Of all of the components of the Arctic Ocean system, the arctic ice canopy was studied in perhaps the most detail prior to the SCICEX program. The development of Earth-orbiting satellite systems provided nearly continuous mapping of the surface of the ice canopy, allowing researchers such as Maslanik et al. (1996) and Parkinson et al. (1999) to measure ice canopy extent and demonstrate its noticeable decrease since the late 1970's. Sea ice thickness had also been studied using ice draft data collected by pre-

SCICEX nuclear-powered submarines (McLaren et al. 1994; Wadhams 1994); however, the coverage of the pre-SCICEX datasets was limited as was the quantity of ice-draft data collected (Rothrock et al. 1999a). The SCICEX program provided a significantly improved set of ice draft measurements, mapping the bottom of the ice canopy throughout the central Arctic Basin and acquiring an unprecedented volume of data. Ice draft surveys were repeated over periods of weeks as well as interannually to document changes in the canopy over different time scales and provide the data necessary to improve models predicting changes in the thickness of the ice pack.

- Arctic Ice Thickness

Near the initiation of the SCICEX program, a number of studies reported that the Arctic ice canopy was thinning (McLaren 1989; Wadhams 1990; McLaren et al. 1994, and references therein; Wadhams 1994, and references therein). These studies, based largely on declassified ice draft data collected by nuclear-powered submarines, faced inherent difficulties in comparing draft measurements in different datasets. Sampling of the ice pack rarely occurred at the same time of year or in the same location, and the time between observations was quite variable. The pre-1990's data were often provided as mean ice draft values averaged over distances ranging from 50 to 500 km (Rothrock et al. 1999a). Uncertainty also resulted from analyzing data that were originally recorded as analog records on paper charts and subsequently digitized (Rothrock et al. 2003). Determining a reliable sea-level datum was difficult if no open water was present. Although it was generally accepted that the pack ice was thinning, the ambiguities introduced by the historical datasets, combined with the dynamic character of the moving, deforming ice canopy, obfuscated the spatial and temporal scales of the effect. The SCICEX program improved on the historical data in several ways, for example by digitally recording all data and oversampling parts of the ice canopy to determine spatial sampling error estimates (Rothrock et al. 1999a). More importantly, SCICEX provided data for a larger cross-section of the Arctic Ocean, facilitating more comprehensive analyses of changes in the ice canopy.

Initial analysis of SCICEX ice draft data yielded a disturbing result; comparing data from SCICEX-93, SCICEX-96 and SCICEX-97 with historical data from 1958–1976 Rothrock et al. (1999a) estimate that the mean ice draft decreased by 1.3 m in most of the deep water portion of the Arctic Ocean (Figure 8). Possible causes suggested to explain the decrease include enhanced export of ice through Fram Strait, a change in the fraction of ridged ice due to the pattern of ice circulation within the Arctic Ocean, and more open water during the arctic summer allowing increased absorption of solar radiation (Rothrock et al. 1999a; 2003; Tucker et al. 2001). Using non-SCICEX submarine profiles acquired in 1976 and 1986–1994, Tucker et al. (2001) conclude that rapid thinning of sea ice was evident in the western Arctic Ocean at the end of the 1980's, but a decrease in ice thickness was not observed at the North Pole during the same time period. They suggest that the observed thinning north of Alaska was caused by ice dynamics associated with the Beaufort Gyre. Using a combination of SCICEX and non-SCICEX profiles collected during the 1990's, Winsor (2001) concurs with the finding that mean ice thickness remained almost constant at the North Pole from 1986 to 1997 but reports only a small decrease in ice thickness in the Beaufort Sea. Contributing to the differing assertions are fairly large mean draft error estimates (~10% of ice thickness; Rothrock et al. 1999a), the use of different datasets in the studies, and complications intrinsic to comparing data collected during different seasons, years and regions.

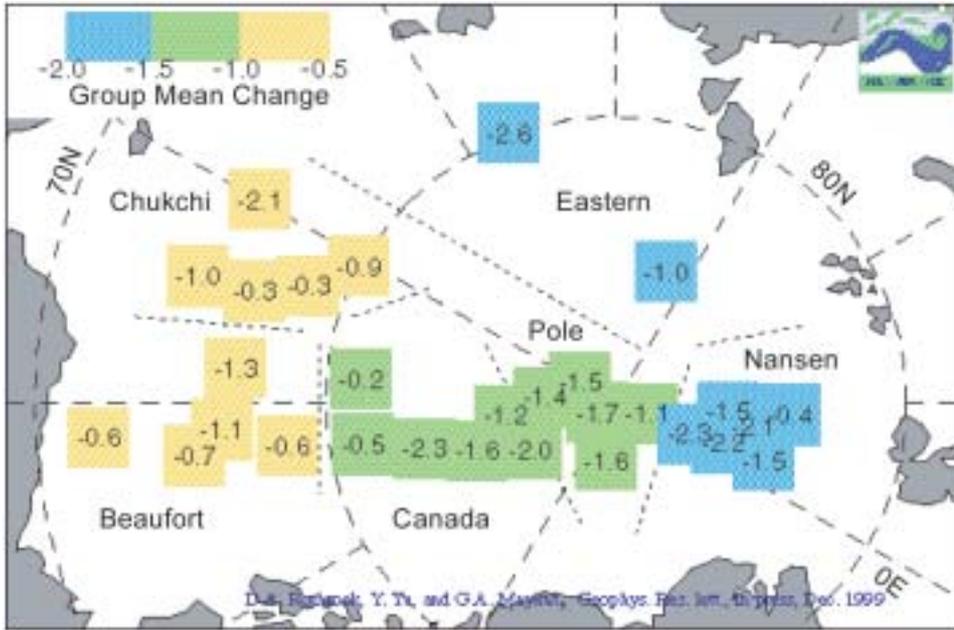


Fig. 8. Changes in mean ice draft from historical data collected in 1958–1976 to the SCICEX-93, SCICEX-96 and SCICEX-97 cruises. The change at each ship crossing is shown numerically. The crossings within each regional group are given the same shading equivalent to their group mean. Each square covers about 150 km, the typical sample size (Rothrock et al. 1999).

To resolve the debate regarding changes in observed ice thickness between the late 1980's and 1997, Rothrock et al. (2003) limited their analysis to digitally recorded ice draft data collected between 1987 and 1997 and compared their findings with previously reported results for three regions: an angular swath between the Beaufort Sea and the North Pole; a region centered about the North Pole; and the entire SCICEX data release box. They conclude that the general trend in the observed 1987–1997 data is an approximate decrease in ice draft of 0.1 m/yr, except at the North Pole where little change is observed.

SCICEX data were also used to evaluate the theory of Thorndike et al. (1975), which predicts temporal changes in ice draft thickness as a function of thermodynamic growth, divergence (or convergence) and mechanical processes such as ridging and rafting. Although this ice thickness distribution theory was developed a quarter century ago, prior to the SCICEX deployments it had not been directly tested due to lack of data. Babko et al. (2002) used SCICEX-96 data collected during two ice surveys carried out 40 days apart, between September 14th–18th and October 24th–28th, to examine changes in one portion of the arctic ice canopy and test the ice distribution model; a buoy was deployed at the center of the first ice survey to enable the *USS Pogy* to find the same patch of ice, which had drifted ~70 km south by the time of the second survey. Babko et al. (2002) found that the model results were in good agreement with the SCICEX observations. They also improved on the theory of Thorndike et al. (1975) by modifying it to include ice rafting as equally important to ridging as a mechanism for redistributing ice thickness.

The Future of SCICEX

Although the final dedicated SCIENCE SCICEX cruise sailed from Pearl Harbor in March 1999, contributions of the program to the international arctic community are just beginning. For example, SCICEX hydrographic and ice draft data are freely available online (see Supplemental Resources below). This availability has facilitated ongoing scientific discussions, e.g., whether the thickness of the arctic ice canopy is decreasing (Rothrock et al. 1999a; 2003; Winsor 2001). SCICEX bathymetric profiles from various submarines' fathometers have been incorporated into the IBCAO dataset already (Jakobsson et al. 2000) and the SCAMP swath bathymetry data will be included in the next IBCAO data release. SCICEX gravity data have been added to the Arctic Gravity Project, an international effort to produce a freely available gravity map of the region. In addition to enhancing web-based datasets, SCICEX data have contributed to the success of subsequent field programs. In 2001 SCICEX geophysical data were used to support the Arctic Mid-Ocean Ridge Expedition (AMORE), a collaboration between U.S. and German academics aboard the icebreakers *USCGC Healy* and *PFS Polarstern* (Michael et al. 2003; Jokat et al. 2003). SCICEX maps of Gakkel Ridge were provided to AMORE principal investigators before the onset of the program to facilitate their mapping and sampling efforts; in return, one of the SCICEX-98 civilian riders was invited to participate in the AMORE program to compare the SCICEX and AMORE bathymetric datasets (Kurras et al. 2001). SCICEX data are also part of the data bank presently being used to plan a future International Ocean Drilling Project leg to Lomonosov Ridge.

Perhaps as a consequence of the expanding availability and utility of SCICEX data and results, the enthusiasm engendered by the program continues to flourish even though the dedicated-science missions have, for the foreseeable future, been discontinued. The countries of Denmark/Greenland and Norway have extended invitations to SCICEX to operate in their Exclusive Economic Zones; negotiations to develop a similar invitation from the government of Canada are presently underway (G. Newton, pers. comm.). These invitations, if accepted by the U.S. Navy, will expand the operational area defined for SCICEX by approximately 50%. While the international science community values the achievements of SCICEX and would welcome further dedicated cruises, the rapid decommissioning of the entire Sturgeon-class has severely limited the ability of the U.S. Navy to support scientific missions. Even though the U.S. Navy might welcome further SCICEX cruises, military demands for submarine time ultimately take precedence, and the feasibility, frequency and duration of future dedicated-science SCICEX cruises remain undefined (Newton 2000). Alternative approaches for SCICEX-like investigations of the Arctic Ocean involve using autonomous underwater vehicles or nuclear-powered submarines from other nations (Newton 2000); however, these programs are unlikely to achieve the scope of the SCICEX program within the next decade. The political process could potentially allocate resources and direct deployment of submarines in service of U.S. national needs. The results summarized in this paper present compelling scientific reasons to accomplish this goal, and there are other benefits that would result from future dedicated-science SCICEX cruises including: defining the outer limits of juridical continental shelf under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS; Newton 2003), assisting in oil exploration efforts along arctic continental margins, and enhancing the operational capability of U.S. Navy Los Angeles-class submarines for arctic programs. Whether the political process will revive the collab-

orative effort of the U.S. Navy and the U.S. academic community to better understand the Arctic Ocean system is still undecided at the time of this writing.

Supplemental Resources

There are a number of websites that provide more information about SCICEX cruises, including charts and graphs of data, plus raw and processed data files. Following is a list of portals for SCICEX-related sites with a brief description of the information available at each:

<http://www.ldeo.columbia.edu/SCICEX/> provides cruise information such as dates and participants for each deployment, a list of SCICEX publications and abstracts of funded SCICEX projects. It also presents detailed information describing the SCAMP system.

<http://boreas.coas.oregonstate.edu/scicex/scicex.html> provides track maps of each SCICEX deployment showing the locations where SSXCTD probes were deployed. Includes all of the XCTD data in various stages of processing, several cruise reports and links to other relevant websites.

<http://wood.jhuapl.edu/SOARED/> is a relational database presently under development that includes SCICEX CTD profiles, bathymetry and ice keel data, plus historical profiles from the National Ocean Data Center, and General Digital Environmental Model temperature, salinity and sound speed profiles.

http://www.soest.hawaii.edu/HMRG/SCAMP/Archive/Archive_Frame.htm contains maps produced from SCAMP SSBS data.

<http://psc.apl.washington.edu/scicex/main.html> includes the SCICEX 2000 meeting report.

http://arcss.colorado.edu/data/arcss_projects.html contains dissolved barium and hydrographic data collected on SCICEX deployments.

<http://nsidc.org/data/catalog.html> mirrors the data listed in the ARCSS website and provides additional snow, ice and hydrographic data for the Arctic and Antarctic.

http://www.nima.mil/GandG/agp/hist_agp.htm describes the ongoing effort to develop a uniform gravity grid for the Arctic Ocean using data collected from a variety of sources including the SCICEX submarines.

<http://www.ims.uaf.edu/scicex/> provides the CTD data collected during the SCICEX-99 survey of the Beaufort Sea slope, along with downloadable pictures of the SCICEX-99 program.

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References

- Aagaard K, Coachman LK, Carmack E (1981) On the halocline of the Arctic Ocean. *Deep Sea Res A*, **28** (6), 529–545
- Aagaard K (1989) A synthesis of the Arctic Ocean circulation. *Rapp P-V Reun Cons Intl Explor, Mar* **188**, 11–22
- Aagaard K, Carmack EC (1994) The Arctic Ocean and climate: A perspective. In *The Polar Oceans and their role in shaping the global environment* (eds Johannessen OM, Muench RD, Overland JE), The Nansen Centennial Volume, Geophysical Monograph **85**, Washington, DC (Am Geophys Union), 5–20
- Anderson LG, Björk G, Holby O, Jones EP, Kattner G, Koltermann KP, Liljeblad B, Lindegren R, Rudels B, Swift J (1994) Water masses and circulation in the Eurasian Basin – Results from the Oden 91 Expedition. *J Geophys Res* **99** (C2), 3273–3283
- *Babko O, Rothrock DA, Maykut GA (2002) Role of rafting in the mechanical redistribution of sea ice thickness. *J Geophys Res* **107** (C8), art. no. 3113
- *Bano N, Hollibaugh JT (2000) Diversity and distribution of DNA sequences with affinity to ammonia-oxidizing bacteria of the β subdivision of the Class *Proteobacteria* in the Arctic Ocean. *Appl Environ Microbio* **66** (5), 1960–1969
- *Bano N, Hollibaugh JT (2002) Phylogenetic composition of bacterioplankton assemblages from the Arctic Ocean. *Appl Environ Microbio* **68** (2), 508–518
- Beal MA (1969) Bathymetry and Structure of the Arctic Ocean, PhD Thesis, Oregon State University, 188 pp.
- Bell RE, Watts AB (1986) Evaluation of the BGM-3 sea gravity meter system onboard R/V Conrad. *Geophys* **51** (7), 1480–1493
- *Björk G, Söderkvist J, Winsor P, Nikolopoulos A, Steele M (2002) Return of the cold halocline layer to the Amundsen Basin of the Arctic Ocean: Implications for the sea ice mass balance. *Geophys Res Lett* **29** (11), art. no. 1513

- Bown JW, White RS (1994) Variation with spreading rate of oceanic crustal thickness and geochemistry. *Earth Planet Sci Lett* **121** (3–4), 435–449
- *Boyd TJ, Moustafa MS, Steele M (1997) Submarine-based hydrographic observations of the Arctic Ocean March – May 1995. OSU Data Report 165, Ref 97-3, pp. 84
- *Boyd TJ, Muench RD, Gunn JT (2000) A strong front over the Arctic Mid-Ocean Ridge. *EOS, Trans Am Geophys Union* **80**, OS181
- *Boyd TJ, Steele M, Muench RD, Gunn JT (2002) Partial recovery of the Arctic Ocean halocline. *Geophys Res Lett* **29** (14), art. no. 1657
- Broecker WS (1991) The great ocean conveyor. *Ocean* **4** (2), 79–89
- Broecker WS, Peteet DM, Rind D (1985) Does the ocean-atmosphere system have more than one stable mode of operation? *Nat* **315** (6014), 21–26
- Carmack EC, Macdonald RW, Perkin RG, McLaughlin FA, Pearson RJ (1995) Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 expedition. *Geophys Res Lett* **22** (9), 1061–1064
- *Chayes DN, Coakley BJ, Langseth MG, Anderson RM, DiBella G, Rognstad MR, Davis RB, Edwards M, Kosalos JG, Szender SJ (1996) SCAMP: An enhanced geophysical mapping system for Arctic submarine cruises. *EOS, Trans Am Geophys Union* **77** (46), F315
- *Chayes D, Kurras G, Edwards M, Anderson R, Coakley B (1998) Swath mapping the Arctic Ocean from US Navy submarines; Installation and performance analysis of SCAMP operation during SCICEX 1998. *EOS, Trans Am Geophys Union* **79** (45), F854
- *Chayes DN, Anderson RM, Ar dai JL, Coakley BJ, Davis RB, Edwards MH, Rognstad MR (1999) SCAMP performance. *EOS, Trans Am Geophys Union* **80** (46), F1001
- Chen YJ (1992) Oceanic crustal thickness versus spreading rate. *Geophys Res Lett* **19** (8), 753–756
- Childers VA, McAdoo DC, Brozena JM, Laxon SW (2001) New gravity data in the Arctic Ocean: Comparison of airborne and EPS gravity. *J Geophys Res* **106** (B5), 8871–8885
- Clark DL (1982) Origin, nature, and world climate effect of Arctic Ocean ice cover. *Nat* **300** (5890), 321–325
- Clark DL (1990) Arctic Ocean ice cover; Geologic history and climatic significance. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 53–62
- *Coakley BJ (1998) Forty days in the belly of the beast. *Sci Am Presents* **9** (3), 36–37
- *Coakley BJ, Cochran JR (1998) Gravity evidence of very thin crust at the Gakkel Ridge (Arctic Ocean). *Earth Planet Sci Lett* **162** (1–4), 81–95
- *Coakley BJ, Chayes D, DeLaca T, Grindlay N, Klinkhammer G, Maslowski W, Polyak L, Preller R, Rothrock D, Smith J (2001) White paper on the renewal of dedicated data collection cruises by US Navy nuclear submarines in the Arctic. Tulane University, New Orleans, 29 pp.
- *Coakley B (submitted) The Lomonosov Ridge, top to bottom. 4th Intl Congress on Arctic Margins, submitted
- Cochran JR, Fornari DJ, Coakley BJ, Herr R, Tivey MA (1999) Continuous near-bottom gravity measurements made with a BGM-3 gravimeter in DSV Alvin on the East Pacific Rise crest near 9° 31' N and 9° 50' N. *J Geophys Res* **104** (B5), 10, 841–10, 861
- *Cochran JR, Kurras GJ, Edwards MH, Coakley BJ, (2003) The Gakkel Ridge: Bathymetry, gravity anomalies, and crustal accretion at extremely slow spreading rates. *J Geophys Res* **108** (B2), art. no. 2116
- *Cochran JR, Edwards M, Coakley B (submitted) Structure of the Lomonosov Ridge: Implications for the nature of continental rifting in the Eurasian and Amerasian Basins. 4th Inter. Congress on Arctic Margins, submitted
- Coles RL, Taylor PT (1990) Magnetic anomalies. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 119–132
- *Davis, RB, Edwards MH, Rognstad MR, Appelgate, TB, Chayes, DN (2001) New tools for processing sidescan & bathymetry data. *Sea Tech* **42** (8), 21–27
- DeMets C, Gordon RG, Argus DF, Stein S (1994) Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions. *Geophys Res Lett* **21** (20), 2191–2194
- *Dickson B (1999) Oceanography – All change in the Arctic. *Nat* **397** (6718), 389–391
- Edmonds HN, Michael PJ, Baker ET, Connelly DP, Snow JE, Langmuir CH, Dick HJB, Mühe R, German CR, Graham DW (2003) Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic. *Nat* **421** (6920), 252–256

- *Edwards M, Coakley B, Chayes D, Okkonen S, Stockwell D, Whittedge T, Rognstad M, Gossett J, Ray R (1999) Cruise Report: SCICEX99 USS Hawkbill. 30 pp.
- *Edwards MH, Kurras GJ, Tolstoy, M, Bohnenstiehl DR, Coakley BJ, Cochran, JR (2001a) Evidence of recent volcanic activity on the ultraslow-spreading Gakkell ridge. *Nat* **409** (6822), 808–812
- *Edwards M, Anderson R, Chayes D, Coakley B, Cochran J, Jakobsson M, Kurras G, Polyak L, Rognstad M (2001b) SCICEX sonars chart new topographies, new theories. *Witness the Arctic* **9** (1), 1–2
- *Edwards MH, Davis RB, Anderson RM (2003) Swath mapping the base of the arctic ice canopy. *Cold Reg Sci Technol* **36** (1–3), 93–101
- *Edwards MH, Polyak L, Engels JL, Coakley BJ (submitted) Seafloor surveys provide circum-basin evidence for thick Pleistocene ice in the Arctic Ocean. 4th Intl Congress on Arctic Margins, submitted
- *Engels JL, Edwards MH, Polyak L (2003) New sidescan sonar evidence for the westward flow of ice across the Alaska margin, Arctic Ocean, XVI INQUA Congress, Reno, Nevada, July 23–30, 195
- Environmental Working Group (1997) Joint U.S.-Russian Atlas of the Arctic Ocean [CD-ROM]. Natl Snow Ice Data Cent, Boulder, CO
- Ewing M, Worzel JL, Shubert GL (1957) Gravity observations at sea in U.S. submarines Barracuda, Tusk, Conger, Argonaut and Medregal. In *Gedenboek* (ed Vening Meinesz, FA), Koninkl Ned Geol-Mijnbkw, Gen Verh, Geol Ser Part **18**, 49–115
- *Ferrari VC, Hollibaugh JT (1999) Distribution of microbial assemblages in the Central Arctic Ocean Basin studied by PCR/DGGE: analysis of a large data set. *Hydrobiologia* **401**, 55–68
- Forsyth DA, Mair JA (1984) Crustal structure of the Lomonosov Ridge and the Fram and Makarov Basins near the North Pole. *J Geophys Res* **89** (NB1), 473–481
- Gorshkov SG (1983) Arctic Ocean. In *The World Ocean Atlas Series* (Pergamon) Oxford, England
- Gosselin M, Lvasseur M, Wheeler PA, Horner RA, Booth BC (1997) New measurements of phytoplankton and ice algal production in the Arctic Ocean. *Deep Sea Res II* **44** (8), 1623–1644
- *Gossett J (1996) Arctic Research Using Nuclear Submarines. *Sea Tech* **37** (3), 33–40
- *Gossett J (2000) Cruise Report: USS L. Mendel Rivers – PACSUBICEX 3-00: SCICEX accommodation. Arctic Submarine Laboratory, San Diego, CA, 12 pp.
- *Gossett J (2001) SCICEX accommodation data: USS Scranton (SSN 756) LANTSUBICEX 1-01. Arctic Submarine Laboratory, San Diego, CA, 3 pp.
- Grosswald MG, Hughes TJ (1999) The case for an ice shelf in the Pleistocene Arctic Ocean. *Polar Geography* **23** (1), 23–54
- *Guay CK, Klinkhammer GP, Falkner KK, Benner R, Coble, PG, Whittedge TE, Black B, Bussell FJ, Wagner TA (1999) High-resolution measurements of dissolved organic carbon in the Arctic Ocean by in situ fiberoptic spectrometry. *Geophys Res Lett* **26** (8), 1007–1010
- *Gunn JT, Muench RD (2001) Observed changes in Arctic Ocean temperature structure over the past half decade. *Geophys Res Lett* **28** (6), 1035–1038
- *Hollibaugh JT, Bano N, Ducklow HW (2002) Widespread distribution in polar oceans of a 16S rRNA gene sequence with affinity to Nitrosospira-like ammonia-oxidizing bacteria. *Appl Environ Microbio* **68** (3), 1478–1484
- *Hopkins TS, Moustafa MS, Kinder CA, Cook MO (1998) SCICEX-96 Hydrographic Data Report USS POGY SSN 647 Polar Cruise 27 August – 12 November 1996. MEAS/NCSU Tech Report **98-1**, 22 pp.
- *Jakobsson M, Cherkis N, Woodward J, Macnab R, Coakley B (2000) New grid of arctic bathymetry aids scientists and mapmakers. *EOS, Trans Am Geophys Union* **81** (9), pp. 89, 93, 96
- *Jakobsson M (1999) First high-resolution chirp sonar profiles from the central Arctic Ocean reveal erosion of Lomonosov Ridge sediments. *Mar Geol* **158** (1–4), 111–123
- Johannessen OM, Muench RD, Overland JE (1994) The polar oceans and their role in shaping the global environment. *Geophysical Monograph* **85**, Washington, DC (Am Geophys Union), 525 pp.
- Johnson GL, Grantz A, Weber JR (1990) Bathymetry and physiography (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 63–77
- Jokat W, Uenzelmann-Neben G, Kristoffersen Y, Rasmussen TM (1992) Lomonosov Ridge – A double-sided continental margin. *Geol* **20** (10), 887–890
- Jokat W, Weigelt E, Kristoffersen Y, Rasmussen T, Schöne T (1995) New insights into the evolution of the Lomonosov Ridge and the Eurasian Basin. *Geophys J Int* **122** (2), 378–392
- Jokat W, Ritzmann O, Schmidt-Aursch MC, Drachev S, Gauger S, Snow J (2003) Geophysical evidence for reduced melt production on the Arctic ultraslow Gakkell mid-ocean ridge *Nat* **423** (6943), 962–965
- *Jung W, Vogt PR, Jewett IF (2002) Bathymetric error evaluation for submarine cruises in the Arctic Ocean based on track crossover differences, Naval Research Laboratory report NRL/FR-MM/7420-02-10 012, 22 pp. (including CD)

- Klinkhammer GP, Chin CS, Wilson C, Rudnicki MD, German CR (1997) Distributions of dissolved manganese and fluorescent dissolved organic matter in the Columbia River estuary and plume as determined by in situ measurement. *Mar Chem* **56** (1–2), 1–14
- Kristoffersen Y (1982) The Nansen Ridge, Arctic Ocean – Some geophysical observations of the rift valley at slow spreading rate. *Tectono* **89** (1–3), 161–172
- Kristoffersen Y (1990) Eurasia Basin. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 365–378
- *Kristoffersen Y, Coakley B, Jokat W, Edwards M, Brekke H, Gjengedal J (submitted) The Arctic Ocean during glacial extremes: How much deep draught glacial ice? *Sci* (submitted)
- Kurras GJ, Edwards MH, Anderson RM, Michael P, Cochran JR, Coakley BJ (2001) Comparison of Seabeam 2112 and SCAMP bathymetry data along the Gakkel Ridge: Preliminary mapping results from the Healy0102 Arctic cruise. *Proc MTS/IEEE Conf and Exhibition* **3**, Honolulu, Hawaii, Nov 6–9, 1496–1499
- *Langseth M, Delaca T, Newton G, Coakley B, Colony R, Gossett J, May C, McRoy P, Morison J, Smethie W, Steele D, Tucker W (1993) SCICEX-93: Arctic cruise of the United States Navy nuclear powered submarine *USS Pargo*. *MTS Journal* **27** (4), 4–12
- Lawver LA, Scotese CR (1990) A review of tectonic models for the evolution of the Canadian Basin. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 593–618
- Leary WM, Nicholson, JH (1999) *Under Ice: Waldo Lyon and the development of the arctic submarine*. Texas A&M Univ Press **62**, 320 pp.
- Levitus S (1982) *Climatological Atlas of the World Ocean*. US Dept of Commerce, NOAA Pub Rep **12**, 173 pp.
- Levitus S (1994) *World Ocean Atlas 1984 CD-ROM data sets*. Natl Ocean Data Cent, US Dept of Commerce, Washington, DC
- Lindstrom DR, MacAyeal DR (1989) Scandinavian, Siberian, and Arctic Ocean glaciation: Effect of Holocene atmospheric CO₂ variations. *Sci* **245** (4918), 628–631
- Mair JA, Forsyth DA (1982) Crustal structures of the Canada Basin near Alaska, the Lomonosov Ridge, and adjoining basins near the North Pole. *Tectonophysics* **89** (1–3), 239–253
- Marincovich Jr. L, Brouwers EM, Hopkins DM, McKenna MC (1990) Late Mesozoic and Cenozoic paleogeographic and paleoclimatic history of the Arctic Ocean Basin, based on shallow-water marine faunas and terrestrial vertebrates. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 403–426
- *Martinson DG, Steele M (2001) Future of the Arctic sea ice cover: Implications of an Antarctic analog. *Geophys Res Lett* **28** (2), 307–310
- Maslanik JA, Serreze MC, Barry RG (1996) Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophys Res Lett* **23** (13), 1677–1680
- McLaren AS (1989) The under-ice thickness distribution of the Arctic Basin as recorded in 1958 and 1970. *J Geophys Res* **94** (C4), 4971–4983
- McLaren AS, Bourke RH, Walsh JE, Weaver, RL (1994) Variability in sea-ice thickness over the North Pole from 1958 to 1992. In *The Polar Oceans and their role in shaping the global environment* (eds Johannessen OM, Muench RD, Overland JE), *The Nansen Centennial Volume, Geophysical Monograph* **85**, Washington, DC (Am Geophys Union), 363–371
- McLaughlin FA, Carmack EC, Macdonald RW, Bishop JKB (1996) Physical and geochemical properties across the Atlantic Pacific water mass front in the southern Canadian Basin. *J Geophys Res* **101** (C1), 1183–1197
- McPhee MG, Stanton TP, Morison JH, Martinson DG (1998) Freshening of the upper ocean in the Arctic: Is perennial sea ice disappearing? *Geophys Res Lett* **25** (10), 1729–1732
- Mercer JH (1970) A former ice sheet in the Arctic Ocean? *Palaeogeogr Palaeoclimatol Palaeoecol* **8** (1), 19–27
- Michael PJ, Langmuir CH, Dick HJB, Snow JE, Goldstein SL, Graham DW, Lehnert K, Kurras G, Jokat W, Mühe R, Edmonds HN (2003) Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. *Nat* **423** (6943), 956–961
- Mikhalevsky PN, Baggeroer AB, Gavrilov A, Slavinsky (1995) Experiment tests use of acoustics to monitor temperature and ice in Arctic Ocean. *EOS Trans Am Geophys Union* **76** (27), 265–269
- *Mikhalevsky PN, Keenan RE, Baggeroer AB (1996) Measured transarctic travel time and model comparisons. *Proc. 3rd European Conf Underwater Acoustics* **2**, Heraklion, Crete, Greece, June 24–28, 773–777
- *Mikhalevsky PN, Gavrilov AN, Baggeroer AB (1999) The Transarctic Acoustic Propagation experiment and climate monitoring in the Arctic. *IEEE J Ocean Eng* **24** (2), 183–201

- *Mikhalevsky PN (1999) Arctic Climate Observations using Underwater Sound (ACOUS). Proc Intl Symp on Acoustic Tomography and Acoustic Thermometry, Japan Marine Science and Technology Center, Toyko, Japan, Feb 8–9, 1999
- *Mikhalevsky P, Gavrilov A, Moustafa MS, Sperry B (2001) Arctic Ocean warming: Submarine and acoustic measurements. Proc MTS/IEEE Conf and Exhibition **3**, Honolulu, Hawaii, Nov 6–9, 1523–1528
- *Morison J, Aagaard K, Steele M (2000) Recent environmental changes in the Arctic: A review. *Arctic* **53** (4), 359–371
- *Morison J, Steele M, Andersen R (1998) Hydrography of the upper Arctic Ocean from the nuclear submarine U.S.S. Pargo. *Deep Sea Res* **45** (1), 15–38
- *Muench RD, Chayes DN, Kurras GJ, Ardai JL (1998) SCICEX 98 cruise report. 46 pp.
- *Muench RD, Gunn JT, Whitedge TE, Schlosser P, Smethie W (2000) An Arctic Ocean cold core eddy. *J Geophys Res* **105** (C10), 23, 997–24, 006
- Müller C, Jokat W (2000) Seismic evidence for volcanic activity discovered in central Arctic. *EOS Trans Am Geophys Union* **81** (24), 265–269
- *Newton GB (1994) The nuclear submarine as an ocean research platform. *MTS Journal* **28** (4), 47–52
- *Newton GB (2000) The Science Ice Exercise Program: History, achievements, and future of SCICEX, Arctic Research of the United States **14** (fall/winter), 2–7
- *Newton GB (2003) Arctic Ocean research: Progress and requirements. *Sea Tech* **44** (7), 39–42
- Newton GL, Aagaard K, Cochman LK (1974) Baroclinic eddies in the Arctic Ocean. *Deep Sea Res Ocean Abstr* **21** (9), 707–719
- *Okkonen SR, Edwards M, Weingartner T, Muench RD (2000) Associations between water properties and bottom topography on the Beaufort-Chukchi Shelf and Slope. *EOS, Trans Am Geophys Union* **80**, OS220
- *Opsahl S, Benner R, Amon RMW (1999) Major flux of terrigenous dissolved organic matter through the Arctic Ocean. *Limnology and Ocean* **44** (8), 2017–2023
- Ostenso NA, Wold RJ (1973) Aeromagnetic evidence for origin of Arctic Ocean Basin. In *Arctic Geology* (ed Pitcher MG), *Am Assn Petroleum Geologists Mem* **19**, 506–516
- Ostenso NA, Wold RJ (1977) A seismic and gravity profile across the Arctic Ocean. *Tectonophysics* **37** (1–3), 1–24
- Parkinson CL, Cavalieri DJ, Gloersen P, Zwally HJ, Comiso JC (1999) Arctic sea ice extents, areas, and trends, 1978–1996. *J Geophys Res* **104** (C9), 20, 837–20, 856
- Phillips RL, Grantz A (1997) Quaternary history of sea ice and paleoclimate in the Amerasia basin, Arctic Ocean, as recorded in the cyclical strata of Northwind Ridge. *GSA Bull* **109** (9), 1101–1115
- *Polyak L, Edwards MH, Coakley BJ, Jakobsson M (2001) Ice shelves in the Pleistocene Arctic Ocean inferred from glaciogenic deep-sea bedforms. *Nat* **410** (6827), 453–457
- *Polyak L, Brachfeld S, Darby DA, Bischoff J, Phillips RL, Febo LA, Coakley BJ, Edwards MH, Engels JL (2003) Multiple glacial erosion on the Chukchi Borderland, Arctic Ocean, as indicated by preliminary data on sediment stratigraphy and sea-floor morphology. XVI INQUA Congress, Reno, Nevada, July 23–30, 195
- Proshutinsky AY, Polyakov IY, Johnson MA (1999) Climate states and variability of Arctic ice and water dynamics during 1946–1977. *Polar Res* **18** (2), 135–142
- *Pyle TE, Ledbetter M, Coakley B, Chayes D (1997) Arctic Ocean science. *Sea Tech* **38** (10) 10–15
- Reid I, Jackson HR (1981) Oceanic spreading rate and crustal thickness. *Mar Geophys Res* **5** (2), 165–172
- *Rothrock DA, Yu Y, Maykut GA (1999a) Thinning of the Arctic sea-ice cover. *Geophys Res Lett* **26** (23), 3469–3472
- *Rothrock D, Maslowski W, Chayes D, Flato G, Grebmeier J, Jackson R, Sambrotto R, Smethie W, Sternberger W, Swift J, Tarduno J, Thorndike A (1999b) Arctic Ocean science from submarines – A report based on the SCICEX 2000 workshop. University of Washington, Seattle, WA, 31 pp.
- *Rothrock DA, Zhang, J, Yu Y (2003) The arctic ice thickness anomaly of the 1990s: A consistent view from observations and models. *J Geophys Res* **108** (C3), art. no. 3083
- Rudels B, Jones EP, Anderson LG, Kattner G (1994) On the intermediate depth waters of the Arctic Ocean. In *The Polar Oceans and their role in shaping the global environment* (eds Johannessen OM, Muench RD, Overland JE), *The Nansen Centennial Volume, Geophysical Monograph* **85**, Washington, DC (Am Geophys Union), 33–46
- Rudels B, Anderson LG, Jones EP (1996) Formation and evolution of the surface mixed layer and halocline of the Arctic Ocean. *J Geophys Res* **101** (C4), 8807–8821
- Schauer U, Muench RD, Rudels B, Timokhov L (1997) The impact of eastern Arctic shelf waters on the Nansen Basin intermediate layers. *J Geophys Res* **102** (C2), 3371–3382
- *Smethie Jr., WM, Schlosser P, Bönisch G., Hopkins TS (2000) Renewal and circulation of intermediate waters in the Canadian Basin observed on the SCICEX 96 cruise, *J Geophys Res* **105** (C1), 1105–1121

- Smith DC, Morison JH (1998) Nonhydrostatic haline convection under leads in sea ice. *J Geophys Res* **103** (C2), 3233–3247
- *Smith JN, Ellis KM, Boyd T (1999) Circulation features in the central Arctic Ocean revealed by nuclear fuel reprocessing tracers from Scientific Ice Expeditions 1995 and 1996. *J Geophys Res* **104** (C12), 29, 663–29, 677
- Sparks DW, Parmentier EM, Morgan JP (1993) 3-dimensional mantle convection beneath a segmented spreading center: Implications for along-axis variations in crustal thickness and gravity. *J Geophys Res* **98** (B12) 21, 977–21, 995
- Spielhagen RF, Bonani G, Eisenhauer A, Frank M, Frederichs T, Kassens H, Kubik PW, Mangini A, Norgaard-Pedersen N, Nowaczyk NR, Schaper S, Stein R, Thiede J, Tiedemann R, Wahsner M (1997) Arctic Ocean evidence for late Quaternary initiation of northern Eurasian ice sheets. *Geo* **25** (9), 783–786
- *Steele M, Boyd T (1998) Retreat of the cold halocline layer in the Arctic Ocean. *J Geophys Res* **103** (C5), 10, 419–10, 435
- Sweeney, JF, Weber JR, Blasco SM (1982) Continental ridges in the Arctic Ocean: LOREX constraints. *Tectonophysics* **89** (1–3), 217–237
- Sweeney JF, Sobczak LW, Forsyth DA (1990) The continental margin northwest of the Queen Elizabeth Islands. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 227–238
- Swift JH, Jones EP, Aagaard K, Carmack EC, Hingston M, Macdonald RW, McLaughlin FA, Perkin RG (1997) Waters of the Makarov and Canada basins. *Deep Sea Res II* **44** (8), 1503–1529
- Thorndike AS, Rothrock DA, Maykut GA, Colony R (1975) The thickness distribution of sea ice. *J Geophys Res* **80**, 4501–4513
- *Tolstoy M, Bohnenstiehl DR, Edwards MH, Kurras GJ (2001) Seismic character of volcanic activity at the ultraslow-spreading Gakkel Ridge. *Geol* **29** (12) 1139–1142
- Tsuboi C (1983) *Gravity*. George Allen and Unwin, London, 254 pp.
- Tucker (III) WB, Weatherly JW, Eppler DT, Farmer LD, Bentley DL (2001) Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s. *Geophys Res Lett* **28** (14), 2851–2854
- Uttal T, Curry JA, McPhee MG, Perovich DK, Moritz RE, Maslanik JA, Guest PS, Stern HL, Moore JA, Turenne R, Heiberg A, Serreze MC, Wylie DP, Persson OG, Paulson CA, Halle C, Morison JH, Wheeler PA, Makshtas A, Welch H, Shupe MD, Intrieri JM, Stannnes K, Lindsey RW, Pinkel R, Pegau WS, Stanton TP, Grenfeld TC (2002) Surface heat budget of the Arctic Ocean. *Bull Am Meteorol Soc* **83** (2), 255–2
- Vening Meinesz FA (1932) *Gravity Expeditions at Sea, 1923–1930. – Vol. I: The expeditions, the computations and the results*. Publ Neth Geod Comm. Waltman, Delft, 109 pp.
- Vening Meinesz FA (1948) *Gravity Expeditions at Sea, 1923–1938 – Vol. IV: Complete results with isostatic reduction, interpretation of results*. Publ Neth Geod Comm, Waltman, Delft, 233 pp.
- Vogt PR, Taylor PT, Kovacs LC, Johnson GL (1979) Detailed aeromagnetic investigation of the Arctic Basin. *J Geophys Res* **84** (B3), 1071–1089
- Vogt PR, Crane K, Sundvor E (1994) Deep Pleistocene iceberg plowmarks on the Yermak Plateau: sidescan and 3.5 kHz evidence for thick calving ice fronts and a possible marine ice sheet in the Arctic Ocean. *Geo* **22** (5), 403–406
- Wadhams P (1994) Sea ice thickness changes and their relation to climate. In *The Polar Oceans and their role in shaping the global environment* (eds Johannessen OM, Muench RD, Overland JE), *The Nansen Centennial Volume, Geophysical Monograph* **85**, Washington, DC (Am Geophys Union), 337–361
- Wadhams P (1990) Evidence for thinning of the Arctic ice cover north of Greenland. *Nat* **345** (6278), 795–797
- *Walsh JJ, Dieterle DA, Maslowski W, Whitledge TE (submitted) Decadal shifts in biophysical forcing of Arctic marine food webs: the numerical consequences. *J Geophys Res* (submitted)
- Weber JR (1979) The Lomonosov Ridge experiment; “LOREX 79.” *EOS Am Geophys Union Trans* **60** (42), 715–721
- Weber JR, Sweeney JF (1990) Ridges and basins in the central Arctic Ocean. In *The Arctic Ocean region* (eds Grantz A, Johnson L, Sweeney JF), *The Geology of North America L*, Boulder, CO (Geol Soc Am), 305–336
- *Whitledge TE (1999) Arctic biology: Recent results and future directions. In: *Arctic Ocean science from submarines – A report based on the SCICEX 2000 workshop*. University of Washington, Seattle, WA, 31 pp.
- Wilkins, Sir Hubert (1931) *Under the North Pole: The Wilkins-Ellsworth submarine expedition*. New York, NY (Brewer, Warren & Putnam) 347 pp.
- Wilson JT (1963) Hypothesis of the Earth's behavior. *Nat* **198** (4884), 925–929
- *Winsor P (2001) Arctic sea ice thickness remained constant during the 1990s. *Geophys Res Lett* **28** (6), 1039–1041

* SCICEX-related publication.

Appendix 1: Submarine Cruise Summaries.

Pre-SCICEX Use of Submarines for Science

Submarines were first employed for science by Dutch geodesist Vening Meinesz, who used Dutch diesel submarines during the period 1923 to 1938 to make the first gravity measurements at sea (Vening Meinesz 1932; 1948). Vening Meinesz employed a pendulum apparatus on a neutrally buoyant submarine hovering at depth. This apparatus was also used extensively on U.S. Navy submarines after World War II by a group at Lamont-Doherty Geological Observatory, resulting in a number of papers (e.g., Ewing et al. 1957 and references therein).

Hubert Wilkins was the first person to attempt to adapt a submarine for science (Wilkins 1931). The Wilkins-Ellsworth Trans Arctic Submarine Expedition obtained the former USS O-12 from the United States Navy for a nominal fee and renamed her *Nautilus*. With the help of submarine inventor and designer Simon Lake, he modified the boat for its proposed under ice mission by removing the sail and installing rails to permit the sub to “skate” along the underside of the ice. An ice drill was installed to enable the *Nautilus* to penetrate the ice, run the diesel engine, recharge the batteries and refresh the sub’s atmosphere. The undertaking failed at the ice edge, when the ice drill failed. This failure made it clear that extensive sub-ice exploration of the Arctic would await the development of a submarine with a longer submerged range than diesel submarines.

Data collection by nuclear submarines operating under sea ice started with the deployment of the *USS Nautilus* in the western Arctic Ocean in 1958. During the late 1950s and early 1960s, U.S. Navy submarines traversed the Arctic Ocean, exploring the ocean basin and collecting valuable environmental data. These cruises were announced after the fact and extensively publicized through popular books and magazine accounts. However, by the middle 1960’s arctic submarine deployments became classified missions. Information regarding submarine location and activities were rarely discussed outside of the Navy and never made public, although the early bathymetric profiles collected by the first generation of nuclear-powered submarines were released, forming the basis of a doctoral dissertation (Beal 1969). During this time the U.S. Navy collected environmental data for its own use in understanding the Arctic and in fulfilling U.S. research and development data needs.

As it became clear the Cold War was ending, the submarine community faced reduced operational commitments, and it appeared that the U.S. Navy might support occasional deployments of pure civilian science in the Arctic Ocean. George Newton, a retired submarine captain acting as a consultant for the U.S. Arctic Research Commission (ARC), recognized this possibility and began work to bridge the gap between the civilian science community and the U.S. submarine fleet (Newton 2000). The first collaborations between the U.S. submarine and academic communities occurred during two classified missions in 1989 and 1990 when water samples were collected for a civilian researcher during arctic deployments (Newton 2000). Concurrently NSF and ARC continued to address the more comprehensive idea of dedicated Arctic Ocean science deployments. These discussions culminated in a meeting held in December 1991 at the Naval Postgraduate School in Monterey, California, sponsored by the University National Oceanographic Laboratory System (UNOLS). The report from this meeting, named “Scientific Opportunities Onboard a Nuclear Submarine” (known as the SOONS report), presented a variety of ideas for conducting dedicated-science submarine cruises, ranging from simple adaptations of equipment used on surface ships to installation of expensive instruments that would require extensive ship modifications. The UNOLS chair sent a copy of the SOONS report to the Secretary of the Navy. The initial reception of this report was not positive (Newton 2000); however, the U.S. Navy ultimately recognized that unclassified missions would produce benefits including more data for the Arctic Ocean,

continued arctic operational training for their crews and good public relations. These realizations led to the development of the first dedicated-science mission in 1993.

SCICEX-93

In August–September 1993 the *USS Pargo*, under the command of Commander (CDR) Brian Wegner, carried out the joint naval and academic proof-of-concept field program that would subsequently become known as SCICEX-93 (Langseth et al. 1993). The primary objective of the exercise was to evaluate the potential for conducting science onboard a U.S. Navy nuclear-powered submarine, but an equally important goal was to demonstrate operational compatibility between the U.S. Navy and the U.S. academic community (Coakley 1998). The survey consisted of a circumnavigation of the deep Arctic Basin (Figure 1). This lap around the basin was broken into transects for the purpose of constructing oceanographic sections; two long transects crossed the Amerasian Basin and four shorter traverses crossed from the Amerasian Basin into the Eurasian Basin over Lomonosov Ridge. Additionally, a detailed 100 km × 100 km survey mapped seafloor topography and the bottom of the ice canopy in the region where the Alpha and Mendeleev Ridges meet. From August 23rd through September 13th, the submarine operated under the arctic ice pack within the data release area (Figure 1). Five civilian scientists from three academic institutions participated: Chief Scientist Ted Delaca and marine biologist Peter McRoy, both from University of Alaska Fairbanks (UAF); geophysicist Bernard Coakley from Lamont-Doherty Earth Observatory (LDEO) of Columbia University; and ice dynamics specialist Roger Colony and oceanographer James Morison of University of Washington (UW). For all SCICEX missions civilian personnel from ASL assisted scientists from academic institutions in data acquisition; during SCICEX-93 the ASL participants were Jeff Gossett and Dan Steele.

Although SCICEX-93 was planned over a time period of only six months, the survey succeeded remarkably well, collecting a multidisciplinary dataset that included underway bathymetry and gravity profiles, conductivity, sound speed and temperature measurements plus upward-looking sidescan and video imagery of the ice canopy along 9,080 km of survey track (Langseth et al. 1993). The *USS Pargo* surfaced at 20 stations during the cruise, collecting water samples to 500 m depth (Morison et al. 1998) and deploying both expendable equipment and buoys designed to remain fixed in the arctic ice pack and telemeter data to land-based stations via satellite. While submerged, SCICEX-93 personnel collected through-hull water samples at 46 stations (Langseth et al. 1993) and launched 37 expendable oceanographic probes (Morison et al. 1998).

SCICEX-95

The first of five annual dedicated science missions agreed to in the SCICEX MOA took place aboard the *USS Cavalla* in the spring of 1995 (Gossett 1996) under the command of CDR Joe Leidig. SCICEX-95 included four civilian scientists, two of them repeat performers from the SCICEX-93 program, Chief Scientist Ted Delaca (UAF) and Bernard Coakley (LDEO). They were accompanied by oceanographers Dean Stockwell from University of Texas (UT) and Tim Boyd from Oregon State University (OSU). ASL participants were Jeff Gossett, Al Hayashida, and Dan Steele. The *USS Cavalla* commenced operations in the Chukchi Sea on March 26th and departed the Bering Strait on May 8th after 43 days of operations (Figure 1). The cruise consisted of reconnaissance surveys over Lomonosov Ridge and the combined Northwind Ridge, Chukchi Borderland and Mendeleev Ridge complex to determine the temperature and salinity variability in the halocline layer (Boyd et al. 1997). SCICEX-95 also executed the first arctic transect from the Beaufort Sea to a point north of the

Barents Sea to create a cross-section of the physical and chemical water properties along the long axis of the Arctic Ocean. Similar transects were undertaken during each subsequent SCICEX cruise.

Like SCICEX-93, the 1995 program was planned over a time period of only a few months, which meant that most of the equipment used on the *USS Cavalla* deployment had previously been developed and installed by ASL for naval operations (Gossett 1996). Data collected during SCICEX-95 included underway bathymetry and gravity profiles, conductivity, sound speed and temperature measurements plus upward-looking sidescan and video. Total trackline length during 43 days of operation was ~20,000 km. The *USS Cavalla* surfaced at five stations during the cruise, collecting water samples to 800 m depth (Smith et al. 1999) and deploying expendable equipment from a temporary ice camp. At 43 submerged stations personnel aboard the *USS Cavalla* collected through-hull water samples at depths of 59, 134 and 240 m (Smith et al. 1999). SCICEX-95 personnel also launched 121 expendable oceanographic probes while underway (Boyd et al. 1997).

SCICEX-96

Commanded by CDR Jim Reilly, the *USS Pogy* served as the platform for SCICEX-96, beginning and ending the survey in the Chukchi Sea on September 13th and October 28th, respectively, for a total of 45 operating days. SCICEX-96 included two detailed ice surveys near Chukchi Cap, one at the beginning and one at the end of the cruise (Rothrock et al. 1999a), several long oceanographic traverses of the Amerasian Basin including one cross-Arctic transect, and detailed geophysical surveys of four regions along Gakkel Ridge (Coakley and Cochran 1998) and over Lomonosov Ridge. Four civilian scientists from three academic institutions participated in the SCICEX-96 program: Chief Scientist Ray Sambrotto and engineer Jay Ardai (LDEO), Mark Cook from North Carolina State University and Jay Simkins from OSU. ASL participants were Jeff Gossett, Mike Hacking and Barry Campbell.

The *USS Pogy* covered ~23,500 km of track during SCICEX-96. Data collected during the deployment included underway bathymetry and gravity profiles, conductivity, sound speed and temperature measurements plus upward-looking current profiles and profiles of the base of the ice canopy, upward-looking sidescan and video. There were nine surface stations during the cruise where water samples were collected to ~1600 m water depth using a winch and gantry system provided by ASL (Smith et al. 1999; Smethie et al. 2000). Ice runup on the hull during SCICEX-96 surface sampling was a problem and led to the reduction of surface sampling on the later cruises (T. Whitledge, pers. comm.). While the *USS Pogy* was submerged 115 expendable oceanographic probes were launched (Hopkins et al. 1998). Similar to the previous year, SCICEX-96 included 44 sampling stations at water depths of 59, 134 and 240 m (Smith et al. 1999).

SCICEX-97

SCICEX-97 was a 30-day deployment aboard the *USS Archerfish*, under the command of CDR Steve Kremer, which began in the Eurasian Basin on September 3rd and ended in the Chukchi Sea on October 2nd. The cruise included an across-basin transect to continue the time-series investigation of physical and chemical water properties, an ice survey around a drifting buoy that was placed in 1996, a 27-hour survey of a cold core eddy that crossed through the feature seven times (Muench et al. 2000), an intensive water sampling survey along the Chukchi and Siberian margins, and an ice survey in support of the Surface Heat Budget of the Arctic Ocean (SHEBA) program (Uttal et al. 2002). The submarine surfaced twice during the cruise, once near the North Pole and the second time for operational purposes. Five civilian scientists from three academic institutions participated in the SCICEX-97 program: Chief

Scientist Terry Whitlege (UT), oceanographers Chris Guay (OSU), John Gunn from Earth and Space Research (ESR) in Seattle, WA, Erik Quiroz from Texas A&M University (TAMU) and microbiologist Grieg Steward from Scripps Institution of Oceanography (SIO). Barry Campbell, Randy Ray and Marshall Mosher participated from ASL.

As with previous deployments, underway data collected during SCICEX-97 included bathymetry and gravity profiles, conductivity, sound speed, dissolved oxygen, fluorescence and temperature measurements plus profiles of the base of the ice canopy, upward-looking sidescan and video. SCICEX-97 was the first cruise to collect two additional kinds of underway data: upward-looking current profiles and dissolved organic carbon through fluorescence. SCICEX-97 also introduced a new type of submerged water sampling stations, known as a spiral hydrocast (Muench et al. 2000). Spiral stations involve having the submarine maintain approximately the same geographic position while slowly rotating up through the water column. Stations are maintained at a constant depth while samples are collected. After sampling for a particular depth is completed, the submarine rises to the next specified depth. During an eight-depth spiral station, onboard personnel collect through-hull water samples at standard depths of 56, 66, 89, 104, 119, 132, 165 and 226 m. The diameter of the submarine's trajectory while performing spiral hydrocasts is typically a few hundred meters. A total of 23 eight-depth spirals were performed during the survey with 425 water samples collected at 243 locations (T. Whitlege, pers. comm.). Beginning with this deployment and continuing through the rest of the dedicated-science SCICEX cruises, water samples were collected in the torpedo room through a specially modified valve. This allowed for sample collection by civilian scientists as well as ASL personnel (T. Whitlege, pers. comm.). *USS Archerfish* personnel launched 138 expendable oceanographic probes while underway. During 30 days of operation a total track of ~14,000 km was surveyed (J. Gossett, pers. comm.).

SCICEX-98

During the SCICEX-98 field program the *USS Hawkbill*, under the command of CDR Robert Perry, spent 31 days in the Arctic Ocean, beginning August 1st in the Chukchi Sea and ending September 2nd in approximately the same location (Muench et al. 2000). The survey was designed to continue documenting changes in the Arctic Ocean observed during previous SCICEX investigations and to map the topography and shallow sediment distribution of the Arctic Basin using a sonar system specially designed and built for SCICEX operations, the Seafloor Characterization and Mapping Pods (SCAMP). SCICEX-98 focused on several objectives: a cross-shelf transect of the Chukchi margin to determine oceanographic parameters of the region; two ice surveys near the SHEBA ice station (Uttal et al. 2002) to document changes in ice conditions over a period of weeks and for comparison with conditions observed a year previously; a comprehensive geophysical and topographic survey of a portion of Gakkel Ridge characterized by a distinctive change in orientation; geophysical surveys of Lomonosov Ridge and Chukchi Plateau; and a hydrographic survey of the Atlantic-Pacific frontal zone north of the Alpha-Mendelev Ridge. Four civilian scientists from three research institutions participated in SCICEX-98: Chief Scientist Robin Muench (ESR); engineers Dale Chayes and Jay Ardai from LDEO; and geophysics graduate student Gregory Kurras from University of Hawaii (UH). Sampling operations were supported by *USS Hawkbill* crewmembers C. Kiser, K.C. Shankland, J. Matthews and J. Mahan. Jeff Gossett and Randy Ray from ASL also participated in the program.

The *USS Hawkbill* traversed 16,500 km of survey track during the SCICEX-98 cruise, continuously collecting underway profiles of bathymetry and gravity, measuring conductivity, sound speed, temperature, dissolved oxygen and upward-looking current profiles, and acquiring upward-looking sidescan and video of the ice canopy. Sensors that measure fluorescence in and light transmission through the water column were mounted in the sail of the submarine, also

collecting data continuously. For the first time in the SCICEX program swaths of seafloor bathymetry and sidescan data, plus subbottom profiles in sedimented regions, were collected by the SCAMP system, eclipsing the amount of topographic data that existed for the entire arctic seafloor prior to SCICEX-98. The *USS Hawkbill* surfaced at four stations during the cruise, collecting water and biological samples in spite of 20–25 kt winds that sometimes made surface operations difficult. While submerged, SCICEX-98 personnel launched 152 expendable probes and performed 20 three-depth and eight-depth spiral stations; samples for the three-depth stations were collected at 104, 132 and 226m (Muench et al. 1998; Muench et al. 2000). An additional 130 through-hull water samples were also collected during SCICEX-98.

SCICEX-99

The 1999 cruise was unique among SCICEX programs for a number of reasons. It was the only survey to be carried out using a captain, crew and submarine that had participated in a previous SCICEX deployment: CDR Robert Perry, his officers and crew, and the *USS Hawkbill*. This repeat performance allowed a second deployment using the SCAMP system that had already been installed aboard *Hawkbill*. Additionally, it advantageously provided a SCICEX-experienced crew for the final dedicated science deployment. SCICEX-99 was also the only SCICEX cruise that involved rendezvous over a two-week period with personnel at an ice camp. Ice Camp Lyon, named after the man considered to be the father of the arctic submarine, Waldo Lyon (Leary and Nicholson 1999), was built and operated by members of ASL and UW's Applied Physics Laboratory. The ice camp was constructed ~130 miles north of Barrow, Alaska on multi-year pack ice (Figure A1-1). It served as a base camp for *USS Hawkbill* allowing personnel to be transferred to and from the submarine, as well as a staging area and laboratory for ancillary experiments. The ability to transfer personnel facilitated three other SCICEX firsts: the inclusion of a civilian media presence during parts of SCICEX-99, an overnight tour of the submarine by a dozen distinguished visitors and the historical participation, for the first time, of female personnel in a SCICEX deployment.

SCICEX-99 began April 2nd in the Chukchi Sea and ended May 14th in Norwegian territorial waters thanks to an invitation from the Norwegian government to survey the Yermak Plateau (Edwards et al. 1999). Based on the success of the SCAMP system in 1998, the 1999 program emphasized geophysics, undertaking detailed and systematic surveys of Lomonosov Ridge, Gakkel Ridge, Yermak Plateau and Chukchi Borderland. SCICEX-99 also included an oceanographic survey of the northern Alaska margin and a repeat cross-basin transect of the Arctic Basin. Seven civilian scientists from four academic institutions participated in SCICEX-99: Co-Chief Scientists Margo Edwards (UH) and Bernard Coakley (relocated to Tulane University); engineers Dale Chayes (LDEO) and Mark Rognstad (UH); and oceanographers Steve Okkonen, Dean Stockwell and Terry Whitlege (UAF). ASL participants Jeff Gossett and Randy Ray joined many members of the submarine's crew in completing their second *USS Hawkbill*-based SCICEX deployment.

The types of underway data collected during SCICEX-99 were analogous to those collected during SCICEX-98 (swath bathymetry and sidescan, bathymetric and gravity profiles, conductivity, sound speed, temperature, dissolved oxygen measurements, current profiles) except fluorometer and transmissometer data were not acquired during the later program. The *USS Hawkbill* acquired these data along ~22,750 km of survey track during 42 days of operation (J. Gossett, pers. comm.). The submarine surfaced at Ice Camp Lyon four times during the cruise, plus once at the North Pole, once during the survey of Lomonosov Ridge and once on the last day of the program. No surface station data were collected during SCICEX-99; the surfacings were used to transfer personnel, load equipment and obtain GPS fixes. While submerged, SCICEX-99 personnel launched 153 expendable probes and collected water samples at 200 stations, including three-depth and eight-depth spiral stations.



Fig. A1-1. Ice Camp Lyon, base camp for SCICEX-99. In addition to facilitating personnel transfers for the *USS Hawkbill*, the ice camp served as scientific research station under the direction of Chief Scientist Dr. Peter Mikhalevsky. Photo: Margo Edwards.

SCICEX-2000

SCICEX-2000 was an 8-day accommodation mission that took place from October 17th to October 24th during a U.S. Navy operation aboard the *USS L Mendel Rivers* under the command of CDR Dave Portner. At the behest of the SCICEX Science Advisory Committee, the goals of the SCICEX-2000 deployment were to repeat the cross-basin transect conducted on the earlier dedicated SCICEX missions to continue the time series investigation of arctic physical and chemical oceanography and to complete short oceanographic transects of the Chukchi Shelf and Margin in support of the Shelf Basin Interaction project (Gossett et al. 2000). In accordance with the new MOA, no civilian scientists from academic institutions participated in the survey; data were collected by ASL personnel Jeff Gossett, Randy Ray and Travis King, plus *USS L Mendel Rivers* Petty Officers Stanley Baker, Christopher Crook, Conan Meadows, and Rick Sarwal. Underway data collected continuously during SCICEX-2000 included conductivity, sound speed, temperature, and upward-looking ice profiles. Soundings were acquired every half-hour using the ship's fathometer. While submerged, SCICEX-2000 personnel launched 109 expendable probes and collected 123 through-hull water samples for scientific analysis.

SCICEX-2001

The most recent SCICEX mission took place on June 3rd–4th 2001 aboard the *USS Scranton* under the command of CDR Earl Carter. Although science time was limited, the *USS Scranton* completed a partial repeat transect of the Arctic Basin, augmenting the oceanographic time-series database for the entire Eurasian Basin and part of the Amerasian Basin (Gossett 2001). This was the first time a Los Angeles-class submarine undertook a SCICEX mission, hence many of the sensors used during previous deployments were not available. Three types of data were collected during the 2001 science operations: continuous underway ice draft measurements, bottom soundings at 30-minute intervals, plus physical and chemical water properties measured using expendable probes. A total of 31 expendable devices were launched while the *USS Scranton* was submerged (Gossett, 2001). ASL's Jeff Gossett and two Royal Navy officers, Lieutenant Commander (LtCdr) James Dixon and LtCdr Jeeves Toor, collected data.

Appendix 2: SCICEX Instrumentation.

Because planning for SCICEX-93 started a mere six months before the field program, the sensors available for that exercise were restricted to those already installed on the submarine, systems that had previously been installed on the same class of submarine, or instruments that could be incorporated into the *USS Pargo* without any modification of the submarine's structure or systems (Langseth et al. 1993). As the SCICEX dedicated-science program progressed, on-board instrumentation was adapted to fit the research goals of each survey and capitalize on the operational capabilities of Sturgeon-class submarines. By the SCICEX-98 deployment, engineers and researchers from several institutions and the private sector had collaborated with U.S. Navy personnel to make significant modifications to the *USS Hawkbill*, including the installation of pods on the outer hull that contained SCAMP's specialized swath-mapping and subbottom-penetrating sonars (Chayes et al. 1998; 1999). The combination of sensors deployed during the SCICEX surveys collected an unprecedented combination of cryogenic, oceanographic and geologic data, creating a multidisciplinary time series for the Arctic Ocean that has yielded, and will continue to yield, significant results for years.

Sensors used during SCICEX fall into three main categories: instruments deployed from a submarine when it was at the surface, instruments deployed from a submarine during under-ice operations, and surveying and sampling sensors that were installed onboard. Surface stations involved several types of operations including using a winch and gantry installed on the deck to lower and raise bottles and instruments on a wire through open water or a hole in the ice (Figure A2-1), using remotely operated vehicles to deploy expendable sensors, lowering baited traps to the seafloor and installing into the ice pack monitoring equipment capable of telemetering data to satellites after the submarine had departed from the surface station. Sensors deployed from a submerged submarine were launched by naval personnel (Figure A2-2) but remained attached via a very thin wire to the submarine for some of the free-fall period to allow oceanographic data to be recorded. Onboard devices used for underway surveying and measurement were located in the sail, foredeck or on the keel of a submarine. A gravimeter was installed in the torpedo room, which also served as the boat's scientific laboratory housing the instrumentation, computers and displays that scientists used to monitor system performance and data quality (Figure A2-3). During the 1997–1999 SCICEX programs the torpedo room also provided access via a through-hull penetrator to seawater outside of the submarine, allowing water samples to be collected for onboard analysis or storage for later shore-based research (Figure A2-4). Prior to SCICEX-97 naval personnel collected through-hull water samples at the aft end of submarines. Following are more detailed descriptions of the instruments and sampling methods used during various SCICEX deployments.



Fig. A2-1. Jay Ardai (LDEO) launches an Acoustic Doppler Current Profiler from the deck of the *USS Hawkbill* during SCICEX-98. The winch and gantry used for surface casts during this cruise were provided by ASL. Photo: Greg Kurras.



Fig. A2-2. Crewman “Ted” Groustra loads an SSXCTD for launching. These instruments were designed to measure physical and chemical water properties under the arctic ice canopy. Their operation is described in the text. Photo: ASL.

Submarine Data Recording System

The Submarine Data Recording System (SDRS), built and installed by Systems Integration Research, captured information from a number of sensors on a submarine and constructed a binary data stream composed of interleaved synchro, ASCII and binary data (Edwards et al. 1999). It was installed for each SCICEX cruise except the SCICEX-2001 deployment. The logged data consisted of submarine time, position and orientation plus environmental information acquired from the Ship's Inertial Navigation System (SINS) and, when the submarine surfaced, the GPS receiver. Environmental and orientation information included the keel depth, roll, pitch and heading of the submarine, water depth from the submarine's bottom sounder and the measured sound speed in water. Synchro data were typically provided at one-second intervals although there were intermittent gaps of longer duration when the SDRS malfunctioned. Approximately six months after SCICEX-93 was completed the six-minute sampled submarine data were provided by the Defense Mapping Agency. Software development conducted during SCICEX-95 permitted the direct real-time acquisition and display of SDRS data on a centralized logging computer.

Submarine Remote Video Systems (SRVS)

Low-light-level cameras were mounted in the top of each SCICEX submarine's sail to monitor the ice canopy during all deployments. Video systems included the Osprey/Simrad Inc. video camera mounted vertically in the *USS Cavalla's* sail during SCICEX-95 (Gossett 1996) and the Simrad "Nighthawk." Images of the overhead ice were continuously recorded, but to date these data have not been evaluated in any form.

Upward-looking sidescan sonar

Upward-looking Klein sidescan sonars were also mounted on the decks of SCICEX submarines to map the base of the arctic ice canopy, primarily for the purpose of locating surfaceable features (Gossett 1996). Type and location of the sonar systems varied depending on survey year and submarine. In 1993 and 1995 Klein model-595 100 kHz sonars were mounted on the foredeck of *USS Pargo* and *USS Cavalla* (Gossett 1996). Beginning in 1996 Klein model 2000 dual-frequency sonars were mounted aft of the weapons loading hatch on each SCICEX submarine. Full-swath widths of the sidescan data were 600 m for the model-595 and 800 m for the model 2000. Displays for the upward-looking sonars were installed in the torpedo room so that scientists could monitor the ice canopy. In early SCICEX deployments the upward-looking sidescan data were continuously recorded for further analysis (Gossett 1996); however, these data were not recorded during the SCICEX-99 mission (Edwards et al. 1999).

Digital Ice Profiling System

The Digital Ice Profiler System (DIPS; Gossett 1996) was used during the 1993 through 2000 SCICEX missions to detect, digitize and record ice draft when the submarine was operating beneath the arctic ice canopy. Developed by ASL, DIPS is a modification of the standard OD-161 ice profiler, which uses an upward-looking sounder with a half-power beam width of approximately 3°. Spatial resolution of the sonar depends on the distance between the transducer and its target (depth below the ice canopy). At a typical ice profiler operating depth of 100 m, the sonar maps a spot ~6 m in diameter on open water or shallow ice at the ocean surface. Assuming an average submarine speed of 16 kts and a repetition rate of six transmit cycles (or pings) per second, the sonar samples the base of the ice canopy every 1.3 m.

OD-161 profilers are analog electro-mechanical systems that use a stylus mounted on a rotating arm to record ice draft data. The recorder's stylus arm makes one revolution for a set number of clock cycles to allow each clock cycle to be correlated with ice draft measured in feet. Because the sonar operator typically chooses to have ten clock cycles per foot, the clock is referred to as the "0.1 foot clock". The data displayed on the paper chart records compensate for the transducer depth (as measured by a simple pressure gauge), so that the zero depth point, which occurs when there is open water, appears at the top of the recorder page. ASL modified the OD-161 analog approach to determine ice draft by using the returning echo from the ice profiler to start a counter that is clocked by the 0.1 foot clock. The counter stops upon receipt of a signal that was originally used to synchronize the phase of the rotating stylus arm with the position of the chart paper. The counter retains the ice draft value, measured to a precision of 0.1 ft. DIPS also acquires ship's speed, depth, and heading from either synchro or digital sources with a sampling rate of approximately once per second. A PC located in the torpedo room recorded and displayed DIPS data in real time for quality control.

Conductivity, Temperature, Depth (CTD) Sensors

Three types of CTD sensors were used during the SCICEX-93 field program. Morison et al. (1998) and Hopkins et al. (1998) present detailed descriptions of different categories of CTDs that are summarized here.

The first type of CTD was deployed from surface stations. These instruments were used for all SCICEX missions except the 1997 and 1999–2001 surveys, which did not include oceanographic data collection from surface stations. During SCICEX-93 Sea-Bird SBE-19 SEACATs equipped with pumps to flush the conductivity cells were lowered to depths of ~500 m; in SCICEX-96 CTDs were being lowered to depths of ~1600 m (Smith et al. 1999; Smethie et al. 2000). Data sample rates were typically 2 Hz with 12-bit resolution except during SCICEX-98 when a Sea-Bird SBE 25 with a scan rate of 8 Hz was deployed from the surface. Sea-Bird specifies the accuracy of the SBE-19 is 0.01 °C in temperature, 0.001 mmho/cm in conductivity, and 0.25% in depth. Comparisons of pre- and post-cruise calibrations for the primary unit deployed during SCICEX-93 surface stations showed agreement of 0.006 mmho/cm in conductivity and 0.002 °C in temperature (Morison et al. 1998).

The second type of CTD was mounted in the sail of SCICEX submarines to collect continuous underway measurements. Instruments ranged from the Sea-Bird SBE-16 during SCICEX-93 (Morison et al. 1998) to the more advanced Sea-Bird SBE-19 during the *USS Archerfish*, *USS Hawkbill* and *USS L Mendels Rivers* deployments (Muench et al. 1998; Edwards et al. 1999; Gossett 2000). These underway CTDs received water from the top of the sail via a pump. Various intake arrangements were used for different installations to bring water into the sail. Comparison of the sail-mounted readings with surface-lowered CTD measurements for SCICEX-93 demonstrated that water sampled by the sail CTD actually came from a position a few meters below the sensor because of submarine movement (Morison et al. 1998). After accounting for the depth shift, the agreement between the surface-lowered and sail-mounted CTDs was 0.03 in salinity and 0.02 °C in temperature. During several SCICEX deployments the sail-mounted CTDs were upgraded to measure one or all of the following: dissolved oxygen concentrations, fluorescence and light transmission.

The final type of CTD was fairly new at the time of its first SCICEX deployment during the 1993 *USS Pargo* program. Developed by Sippican, an under-ice submarine ship-launched expendable CTD (SSXCTD) was launched in a canister toward the ocean surface from a submerged submarine (Hopkins et al. 1998; Morison et al. 1998). This was a modification of more standard submarine-launched expendable CTDs that go into free fall upon reaching the ocean surface. To avoid contact with, and possible damage from, the ice canopy, when an

SSXCTD canister reached a depth of ~ 15 m a pressure switch activated causing the probe to release from its housing and free-fall to depth. Flooding of the probe housing activates another switch that caused the probes batteries to power up, allowing data collection to commence (Hopkins et al. 1998). The probe is attached to the submarine by a signal wire that relays temperature and conductivity measurements to the ship. Depth is estimated from elapsed time and predicted fall rate (Morison et al. 1998). Sampling rate is 0.25 seconds.

Several types of errors were associated with the SSXCTD probes. Some probes did not function after deployment; the percentage of properly functioning probes increased from 70% during SCICEX-93 to >90% during SCICEX-98 through SCICEX-2000. The movement of the probes through launch, activation and free-fall was not well understood (Hopkins et al. 1998) and derivation of depth from elapsed time produced systematic errors as a result. Depth errors were corrected by matching SSXCTD profiles with surface-launched CTD profiles (Morison et al. 1998). Comparison of surface-cast CTDs and SSXCTDs also demonstrated residual conductivity and temperature biases that were systematically removed from all of the SSXCTD profiles (Morison et al. 1998).

Through-hull Water Sampling

For SCICEX-93, SCICEX-95 and SCICEX-96, through-hull water samples were obtained by ASL personnel from an aft compartment of the submarine and brought to the torpedo room for storage. Beginning with SCICEX-97 and continuing through the rest of the deployments, water samples were collected inside the torpedo room via a sampling line supplied by an intake valve located above the keel (Guay et al. 1999; Figure A2-4). Some underway analyses of water samples were performed. For example, during SCICEX-98, salinity was determined for through-hull water samples once the samples had reached thermal equilibrium with the torpedo room environment (22–24 °C). A Guildline model 8410 salinometer was maintained at 24 °C for analyses, with calibrations performed before and following each run using a freshwater standard (Muench et al. 1998). Dual analyses run for each sample showed agreements typically on the order of 0.01 to 0.001 PSU. Similarly, onboard analyses of dissolved oxygen concentrations were accomplished by performing titrations while underway (Muench et al. 1998).

Fig. A2-3. The science laboratory (a.k.a. the torpedo room) on the *USS Hawkbill* during SCICEX-99. Equipment, computers and displays were mounted on top of a skid plate; storage containers for water samples were tucked underneath. Photo: ASL.

Fig. A2-4. Oceanographer Steve Okkonen (UAF) collecting through-hull water samples in the forward part of the torpedo room during SCICEX-99. Okkonen stands on a grate that drains spilled water to the submarine's bilges. The blue curtains to Okkonen's right cover bunks belonging to two *USS Hawkbill* sailors. In addition to serving as the science center, the torpedo room provided bunk space for ~ 30 sailors. Photo: Mark Rognstad.

Fig. A2-5. Tent set up adjacent to the *USS Hawkbill* during SCICEX-99. Although no surface sampling was performed during SCICEX-99, a film crew from the National Geographic Society, in collaboration with Dr. Tom Lehman (LDEO), lowered cameras through a hole in the ice next to the submarine to photograph its descent. Photo: Mark Rognstad.

Fig. A2-6. SCAMP pod (rounded housing at right) for the high-resolution subbottom profiler (HRSP) mounted on the underhull of the *USS Hawkbill*. Photo: Dale Chayes.



Other water samples were stored shortly after being drawn from the through-hull sampling line according to protocols defined by various SCICEX principal investigators. Stored samples were sealed into a variety of containers and typically either frozen or refrigerated for subsequent analysis. Samples were labeled and logged before stowage with detailed log sheets being maintained by scientific personnel onboard. The measurements made on water samples collected during SCICEX cruises are listed in Table 1.

Table 1. Measurements taken on water samples collected during SCICEX cruises.

Salinity*	Dissolved Oxygen*
Nitrate*	Silicate*
Phosphate*	Ammonium*
Nitrite*	Dissolved Organic Carbon
Dissolved Organic Nitrogen	Chlorophyll a
Phaeopigments	HPLC pigments
¹⁸ Oxygen	Barium
Tritium	Helium
Particulate Carbon	Particulate Nitrogen
¹²⁹ Iodine	¹³⁷ Cesium
CFCs	Lignin
Virus	Bacteria
Protozoa	DNA
MicroGrazing	MicroRespiration

*analyzed on all water samples

Surface Stations

Surface sampling was carried out for all SCICEX programs except SCICEX-97, SCICEX-99, SCICEX-2000 and SCICEX-2001. It involved either installing a combined winch and gantry system (provided by the UW's Polar Science Center in 1993 and ASL for every subsequent deployment) on the deck of a SCICEX submarine and deploying equipment through open water (Figure A2-1) or setting up a temporary ice camp with a tent to house equipment (Smethie et al. 2000) and cutting a hole through the ice canopy to deploy various sensors (Figure A2-5). Instruments lowered from surface stations included CTDs, Niskin bottles for collecting water samples, biology boxes for collecting fauna such as amphipods, and acoustic Doppler current profilers. Expendable instruments deployed at surface stations included SSXCTDs, bathythermographs and current profilers (Langseth et al. 1993).

During SCICEX-93 two Polar Oceanographic Profiler (POP) and two "MET" buoys were installed in arctic pack ice (Langseth et al. 1993). The POP buoys measured air temperature and pressure above the ice canopy as well as water temperature and salinity below the ice using six CTD sensors hanging beneath the buoy at depths of 10, 40, 70, 120, 200 and 300 m. The data were telemetered back to UW's Polar Science Center via the ARGOS satellites. The "MET" buoys measured air temperature and pressure at a height of 2 m above the ice pack.

These sensors were deployed in the central Arctic Ocean to fill gaps in the International Arctic Buoy Program's (IABPs) network of drifting buoys. IABP uses data collected by its drifting buoys to support the World Climate Research and World Weather Watch Programs. Additional "MET" buoys were deployed during SCICEX-96 and SCICEX-2000 (J. Gossett, pers. comm.).

During SCICEX-93 a small remotely-operated vehicle (ROV) was also tested at the surface and used to launch expendable probes to measure horizontal current shear (Langseth et al. 1993). The 1993 program was the only time ROV operations occurred during a SCICEX.

Surface conditions often negatively affected data acquisition from surface stations. For example, during SCICEX-96 unstable ice forced *USS Pogy* personnel to abandon two surface stations, one time resulting in a significant loss of equipment (J. Gossett, pers. comm.). During SCICEX-98 high wind speeds caused the *USS Hawkbill* to drift over the hydrowire resulting in large wire angles that limited the depth from which samples could be obtained (Muench et al. 1998).

Acoustic Doppler Current Profiler (ADCP)

An RDI Instruments 150 kHz ADCP was used during SCICEX deployments from 1997–1999 to measure continuous current profiles above the *USS Archerfish* and *USS Hawkbill* to ranges of about 200 m (R. Muench, pers. comm.; Muench et al. 1998; Edwards et al. 1999). Due to installation requirements the ADCP was mounted with a slight forward and starboard tilt. The system was run continuously throughout these three cruises.

Zero Angle Photo Spectrometer (ZAPS)

SCICEX-97 personnel measured DOC by fluorescence using a ZAPS probe (Klinkhammer et al. 1997) installed on the *USS Archerfish* in a foredeck compartment located between the skin and the pressure hull of the submarine ~8 m above the keel (Guay et al. 1999). Sampling rate of the probe was 1.7 Hz. Although water residence time in the compartment and submarine operations such as station keeping had the potential to affect the ZAPS probe, DOC measured by ZAPS was strongly correlated with results obtained using high-temperature combustion analysis of 186 through-hull water samples. Although it operated flawlessly in 1997, the ZAPS sensor was not used during any of the later SCICEX deployments.

Seafloor Characterization and Mapping Pods (SCAMP)

During the 1998 and 1999 SCICEX deployments, a purpose-built geophysical system called the Seafloor Characterization and Mapping Pods (SCAMP) was mounted on the hull of the *USS Hawkbill* (Chayes et al. 1996; 1998; 1999; Figure A2-6). SCAMP was designed to map seafloor topography in three dimensions. Components of the SCAMP system include a Swath Bathymetric Sidescan Sonar, a swept frequency High-Resolution Subbottom Profiler, and the Data Acquisition and Quality Control System. The Bell BGM-3 gravimeter used during all of the previous SCICEX missions was also incorporated into the SCAMP system.

- Data Acquisition and Quality Control System (DAQCS)

The Data Acquisition and Quality Control System (DAQCS) is a Unix-based multi-processor data system based on the similar systems built, installed and operated by LDEO. The primary role of the DAQCS is to provide the real-time data logging and routine data quality checking for the SCAMP instruments. For the 1998 and 1999 SCICEX deployments, DAQCS logged data from the Sidescan Swath Bathymetric Sonar (SSBS), the High Resolution Subbottom Profiler (HRSP), the SDRS, the #2 sail-mounted CTD, the gravimeter, and an electrostatic pitch and roll sensor. In addition, DAQCS provided resources for software development and data analysis during SCICEX-98 and SCICEX-99.

- Sidescan Swath Bathymetric Sonar (SSBS)

The SSBS is a 12 kHz continuous-wave interferometric sonar capable of emitting pulses between 83 μ s and 10 ms in length. Four SSBS transducer rows per side of the submarine are electronically summed to minimize returns from the sea or ice surface by steering the outgoing sound toward the seafloor. Ping rate is operator controlled, varying as a function of submarine altitude from 4 second intervals in shallow water to 16 second intervals in deep water. In deep water sidescan swath widths were $\leq 160^\circ$ while bathymetric swath widths were limited by the occurrence of the first multiple return to 120° . In shallow regions bathymetry swath widths occasionally reached 140° . The spatial resolution of the SCAMP system varies as a function of altitude off-bottom, survey speed, and sample position relative to the submarine's nadir as well as sound speed along the transmission and return paths, which causes refraction of the acoustic signals. Bathymetry data are processed (Davis et al. 2001) using cell sizes 1–2% of the total water depth. Sidescan cell size was typically set to 5 m where total water depth was < 1000 m and 10 m everywhere else. For charting purposes bathymetric and sidescan data were gridded with 16–100 m² grid cells depending on total water depth.

Although it was designed to minimize acoustic returns from the sea surface and ice canopy, the SSBS inadvertently functioned as an upward-looking ice mapping system, collecting sidescan data that provide a wider perspective of the base of the Arctic ice canopy than higher frequency upward-looking Klein sonars (Edwards et al. 2003). At an operating depth of 100 m, a 10 ms pulse length from the SSBS has a beam with that is similar to the OD-161; however, at ping repetition rates between 4 and 16 seconds, the along-track sampling of the ice canopy is significantly less for the SSBS than for the OD-161. Because the SSBS was not intended as an upward-looking system, no effort was made to use the system to map the underside of sea ice during SCICEX-98 and SCICEX-99. Nevertheless, the serendipitous success of the technique suggests an approach that will hopefully guide instrument development for future ice canopy mapping programs.

- High-Resolution Subbottom Profiler (HRSP)

The HRSP is a modified Bathy-2000P developed by Ocean Data Equipment Corporation in collaboration with SCICEX scientists. The HRSP transmits a frequency-modulated chirp from an array of nine elements mounted in a pod on the ship's keel. During SCICEX-98 and SCICEX-99 a 50-millisecond linear swept pulse ranging in frequency from 2.75 to 6.75 kHz was used with power set to the maximum 2 kilowatts.

A noticeable problem in SCAMP performance is acoustic crosstalk in the SSBS data caused by the HRSP. The crosstalk signature from the HRSP that appears in the SSBS data consists of small peaks when the HRSP sweep passes through frequencies 3 kHz, 4 kHz and 6

kHz, which are sub-harmonics of the SSBS receive frequency 12 kHz. This problem has been rectified in post-cruise data processing (Davis et al. 2001).

Gravimeter

On all of the dedicated-science SCICEX cruises, a Bell Aerospace BGM-3 gravimeter was installed on skid plates in the Torpedo room to collect underway gravity measurements. For SCICEX-98 and SCICEX-99 the gravimeter was incorporated into the SCAMP system, allowing an interface to convert gravimeter output to serial data that was time-stamped and logged by DAQCS. The Bell BGM-3, developed by Bell Aerospace (now owned by Lockheed-Martin), is the standard underway marine gravimeter used by the U.S. Navy's Naval Oceanographic Office (NAVOCEANO) and the academic research fleet (Bell and Watts 1986). Except for the first cruise in 1993, BGM-3 gravimeters used during SCICEX deployments were obtained on loan from NAVOCEANO. For the first SCICEX program the BGM-3 gravimeter was borrowed from LDEO's *R/V Ewing*.

The exceptional stability of U.S. Navy Sturgeon-class submarines makes them effective platforms for the acquisition of gravity data. Underway at ~30 km/hr (16 knots), SCICEX submarines "porpoised" about 1 meter with a period of three to five minutes. Vertical platform accelerations were estimated by double-differencing the ship's keel depth. Keel depth data recorded at a sampling rate of 1 Hz throughout the cruise were synchronized to the BGM-3 output to within ± 2 seconds to ensure proper noise cancellation. In addition to explicit removal of platform vertical accelerations, typical corrections for latitude, elevation and ship's horizontal motions (Eotvos) were applied (Tsuboi 1979). The data were referenced to sea level by accounting both for the elevation of the ship (free-air correction) and the mass of overlying water (free-water correction; Cochran et al. 1999). This results in high quality data as compared to co-registered satellite and airborne profiles (Childers et al. 2001).

Ship's Fathometer (AN/BQN-17)

Each of the SCICEX submarines was equipped with a narrow-beam high-resolution fathometer that collected bathymetric data (Gossett 1996). For the dedicated-science cruises, the underway bathymetry data were recorded continuously. In the case of accommodation missions soundings were recorded approximately every 30 minutes. The fathometer uses a sound speed velocity of 4800 fathoms per second to determine depth beneath the submarine's keel (Gossett 2000).

Navigation

The Ship's Inertial Navigation System (Mark 3 Mod 6 SINS), or variants of that system, provided navigation data for all of the dedicated-science SCICEX cruises except the *USS Cavalla* deployment in 1995, which used Electronically Suspended Gyro Navigation (ESGN). Navigation data were acquired through the SDRS at one-second intervals. Data fields included longitude, latitude, heading, and velocity that were linked to time references from the submarine's master clock. When the submarine surfaced one-minute fixes from the Global Positioning Satellites (GPS) were used to update position.

Quality of navigation data was evaluated using crossover analyses. The Office of Naval Research evaluated crossover differences for declassified bathymetric profiles collected by

U.S. Navy nuclear submarines including profiles acquired during the SCICEX dedicated-science cruises that had been sampled at one-minute intervals (Jung et al. 2002). Jung et al. (2002) examined these data for three different types of error:

- 1) bad sounding, good position;
- 2) good sounding, bad position; and
- 3) errors caused by poor interpolation between soundings.

Based on the predominance of errors associated with steep slopes, they concluded that type 2 errors are common while type 1 and type 3 errors are rare. For the SCICEX bathymetric profiles Jung et al. (2002) cite vertical errors in the range of meters to tens of meters.

CAMP swath bathymetry data collected during SCICEX-98 and SCICEX-99 provided the first opportunity to perform much higher resolution crossover analyses using both sidescan and bathymetry data. Since SCAMP grid cell size varied as a function of water depth, the highest resolution SCAMP comparisons corresponded to the shallowest regions with overlapping swaths of data. These found relative positional accuracy to be good to within ~2 km with navigational ambiguity increasing as a function of time since the last GPS fix. A comparison of a GPS-navigated Seabeam-2112 bathymetry for a portion of Gakkel Ridge collected by the icebreaker USCGC Healy with SCAMP data for the same region showed a range of offsets between the datasets of one cell (250 m) to ~3 km (Kurras et al. 2001).