The SCICEX Program

Arctic Ocean Investigations from a U.S. Navy Nuclear-Powered Submarine

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The SCience ICe EXercise (SCICEX), an unprecedented collaboration between the U.S. Navy and the marine research community, was designed to use nuclear-powered submarines to map and sample the ice canopy; the physical, chemical, and biological water properties; the seafloor topography; and the shallow subsurface of the Arctic Ocean. Data acquired during eight submarine cruises vastly improved our understanding of the Arctic Ocean and demonstrated the inextricable linkages between organisms, atmosphere, ice, water, and rock. This paper summarizes SCICEX results to demonstrate the important contribution of this program to Arctic science.

Brief History of the SCICEX Program

The SCICEX program began in January 1993, when the U.S. Navy announced that a nuclear-powered submarine would survey the Arctic Ocean that summer; the Navy invited the U.S. academic community to help plan the mission and participate in the cruise. In contrast to standard procedures, the Navy agreed to allow data collected during SCICEX-93 to be publicly disseminated. In August and September 1993 the USS *Pargo* carried out the joint naval and academic proof-of-concept field program. Based on the success of this program, the U.S. Navy and the National Science Foundation (NSF) signed a Memorandum of Agreement to undertake more joint submarine deployments to the Arctic Ocean. Five dedicated science programs took place annually from 1995 to 1999, with each including science-driven planning and civilian science riders. SCICEX-95 was a 43-day mission that took place during the spring of that year aboard the USS *Cavalla*. SCICEX-96 was a September–October program on the USS *Pogy* that lasted for 45 operational days. SCICEX-97 was a 30-day deployment aboard the USS *Archerfish* in the fall of 1997. The USS *Hawkbill* was the only Sturgeon-class submarine to repeat its participation in SCICEX, spending 31 operational days in the Arctic Ocean in August–September 1998 and another 42 days during April and May 1999 as part of the final dedicated-science SCICEX mission.

In October 1998 the U.S. Navy informed NSF that it would no longer be able to conduct dedicated Arctic Ocean science surveys, primarily because the nuclear submarine force was being reduced drastically. As an alternative to terminating the collaboration, the U.S. Navy and NSF agreed to “accommodation missions” that set aside time for acquiring unclassified data during otherwise classified submarine exercises. Results of two accommodation missions conducted in 2000 and 2001 are included in this paper.

SCICEX Results

SCICEX publications have contributed to most every field of science, providing novel observations, testable hypotheses for future work, and an increased understanding of both Arctic and global processes. SCICEX scientists were among the first to report on the pronounced changes in Arctic Ocean water temperature during the 1990s, to document the thinning of the Arctic ice canopy, to produce a detailed description of an oceanographic eddy in the Arctic Basin, to present evidence for a kilometer-thick ice shelf covering parts or the entirety of the Arctic Ocean during ice ages, and to show that recent volcanic eruptions have occurred along Gakkel Ridge. In some instances SCICEX data have supported widely held hypotheses, while in other cases SCICEX data demonstrate that existing models and theories need to be re-evaluated. In a 2003 paper, we presented a comprehensive overview of SCICEX accomplishments; this paper summarizes many of the major program results.

Preparations for surfacing of the U.S. Navy nuclear-powered submarine USS Hawkbill *at an ice camp 150 miles north of Barrow, Alaska, as part of the 1999 SCICEX program. The camp was named after the man who led the development of Arctic submarines, Dr. Waldo Lyon. An "X" shoveled across the ice pack at Ice Camp Lyon was visible on the upward-looking camera mounted on the sail of the USS* Hawkbill *and indicated to the sub's crew where they should surface. The arrow at one end of the "X" shows the suggested direction for the long axis of the submarine. A beacon and microphone were also lowered through the ice to communicate with the Hawkbill.*

Young Volcanoes in the Arctic Basin

Gakkel Ridge is part of the global Mid-Ocean Ridge (MOR), a long, linear volcanic chain where the earth's new crust is created. Gakkel Ridge extends 1800 km across the Arctic Basin, from the northeastern tip of Greenland to the continental margin of Siberia. It is categorized as an ultra-slow-spreading MOR, where new crustal material is created at a rate of less than 1.3 cm/yr. Because of the extremely slow crustal accretion, the contribution of volcanism to Gakkel Ridge topography remained controversial until the SCICEX surveys. SCICEX-98 and SCICEX-99 imaged two young volcanoes covering approximately 20% of a 3750-km^2 region on Gakkel Ridge (Edwards et al. 2001). One of these volcanoes is located near the locus of a 1999 earthquake swarm where 252 events were recorded over seven months (Müller and Jokat 2000, Tolstoy et al. 2001). Since this is the only earthquake swarm detected on Gakkel Ridge in about 100 years, Edwards et al. (2001) theorized that the SCICEX program imaged an eruption shortly after its occurrence. The subsequent discovery of hydrothermal venting along the ridge axis (Edmonds et al. 2003) in association with fresh-looking lava (Michael et al. 2003) confirm that Gakkel Ridge experienced a recent volcanic eruption.

Evidence for Thick Ice Shelves Extending into the Arctic Ocean

It has been hypothesized that during ice ages, glaciers extended from continents into the Arctic Ocean as thick ice shelves (Mercer 1970, Grosswald and Hughes 1999). This theory contrasts with a more conventional view that in the past the Arctic ice canopy was similar to its modern counterpart: a few-meters-thick layer of perennial sea ice with scattered icebergs (Clark 1982, Phillips and Grantz 1997, Spielhagen et al. 1997). SCICEX data resolved the debate by depicting a variety of glacigenic bedforms, including submarine flutes and moraines as well as iceberg-generated scour marks, in all shallow regions mapped. These bedforms extend to depths of more than 700 m on the Alaska margin and Chukchi Borderland, a topographic rise north of Bering Strait. On the central portion of Lomonosov Ridge, which extends from Siberia to Canada via the North Pole, there is evidence of thick ice to depths of almost 1000 m. Based on the SCICEX findings, Polyak et al. (2001) suggested 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. Kristoffersen et al. (2004) presented an alternative model in which armadas of large icebergs entrained in sea ice modify 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, the discovery of glacigenic bedforms in the central Arctic Ocean will lead to the revision of models describing the earth's major glaciations and related paleoclimate.

Thinning of the Present-Day Arctic Ice Canopy

Near the initiation of SCICEX, a number of studies reported that the Arctic ice canopy was thinning (McLaren 1989, Wadhams 1990, McLaren et al. 1994, Wadhams 1994). These studies were based on declassified ice draft data collected by nuclear-powered submarines beginning in 1958. Although thinning of the ice pack ice is consistent with the observed decrease in areal extent of the ice canopy (Maslanik et al. 1996, Parkinson et al. 1999), ambiguities introduced by the historical data sets, combined with the dynamic character of the moving, deforming ice pack, obfuscated the spatial and temporal scales of the effect. The SCICEX program improved on historical records by acquiring data for a larger cross section of the Arctic Ocean.

The initial analysis of the SCICEX data produced a disturbing result: between the 1970s and the 1990s the mean ice draft decreased by 1.3 m in the deep water regions of the Arctic Ocean (Rothrock et al. 1999). Suggested causes included enhanced export of ice through Fram Strait, a change in ice circulation and thus deformation within the Arctic, and more open water during the Arctic summer allowing increased absorption of solar radiation. Tucker et al. (2001) and Winsor (2001) countered that while some parts of the Arctic ice canopy were thinning rapidly, others (such as near the North Pole) were remaining essentially unchanged. To resolve the debate, 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 at the North Pole, and the entire SCICEX data set. They concluded that the general trend is an approximate decrease in ice draft of 0.1 m/yr except at the North Pole, where little change is observed.

Arctic Oceanography

The important contributions of SCICEX to volcanology, paleoclimatology, and climatology are mirrored in the field of oceanography. SCICEX

The USS Hawkbill *after it broke through the Arctic ice canopy in April 1999, greeted by distinguished visitors from the U.S. Cabinet and Congress, the U.S. Navy, and the National Science Foundation. Reporters from the National Geographic Society, CNN, PBS, and the Christian Science Monitor filmed and photographed scenes from the final year of the historic collaboration, documenting how the dedicated-science missions of nuclear-powered submarines significantly contributed to our understanding of the Arctic Ocean and global climate change.*

data provide new three-dimensional perspectives of the Arctic Ocean and, because of repeated surveys along the same tracks, yield time-series data that depict how the ocean is changing.

Warming Intermediate Water. During the first half of the 1990s, several Arctic field programs, including SCICEX, reported widespread changes in the Arctic Ocean's upper water column (Morison et al. 1998). The Atlantic Layer (AL; approximately 200–800 m deep) was observed to be extending farther from the Fram Strait into the Arctic Basin and becoming warmer; the front between the eastern AL (characterized by a temperature of 2–3°C) and the western AL (0.5°C) shifted from Lomonosov Ridge westward to Alpha-Mendeleev Ridge, which runs from Siberia to Canada on the Pacific side of Lomonosov Ridge. The AL also shoaled by approximately 40 m between 1991 and 1995 (Steele and Boyd 1998). To monitor changing water properties, various SCICEX submarines conducted repeated transects from the Alaska margin to the Barents Sea, collecting oceanographic data. Mean and maximum temperatures observed on the transects show that warming continued from 1995 until 1998, followed by a slight cooling during 1998-1999, with renewed warming between 1999 and 2000 (Gunn and Muench 2001, Mikhalevsky et al. 2001). Gunn and Muench (2001) showed that temperature changes as a function of location, leading them to propose that northward currents flowing along the flanks of the Arctic ridges move warm water from the continental margins into the central Arctic Ocean.

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. The halocline, where salinity changes rapidly, suppresses vertical mixing, isolating the upper ocean and ice cover from the underlying warm Atlantic water (Aagaard et al. 1981, Rudels et al. 1996). The central Arctic Ocean exhibits a cold halocline layer (CHL), characterized by an approximately constant, near-freezing temperature and strong vertical stratification in salinity. 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.

Using SCICEX data, Steele and Boyd (1998) showed that the extent of the CHL decreased during the early 1990s. They inferred that between Barents Shelf and Lomonosov Ridge, much of the upper mixed layer was in direct contact with the AL, yielding higher heat fluxes and reduced ice formation during the winter. Boyd et al. (2002) used SCICEX to demonstrate that the CHL began to recover in 1998, with the recovery continuing into 2000. Was the CHL sufficiently weakened to account for the observed reduction in sea ice during the 1990s (Rothrock et al. 1999, 2003)? Estimating upward heat flux, Boyd et al. (2002) concluded that the weakened CHL did not unilaterally cause the decrease in sea ice thickness. Björk et al. (2002) suggested that the recent return of the CHL could increase the mass balance of sea ice; their model predicts 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 Arctic Ocean circulation is necessary to understanding global climate. A number of Arctic expeditions, including SCICEX, systematically sampled the Arctic water column to this end, lowering bottles from the ice canopy to depths reaching 1600 m. SCICEX water samples were analyzed for temperature, salinity, oxygen, nutrients, and chemical tracers. Smethie et al. (2000) used these data to develop a time scale describing the transport of intermediate water into the Arctic Basin. Their results show that, in contrast with the prevailing model of Arctic circulation (Rudels et al. 1994), intermediate water moves rapidly into the interior of the Canada Basin near Chukchi Rise. Smethie et al. (2000) found the oldest intermediate water near Lomonosov Ridge and suggested that its location is the result of either a small gyre isolating this part of the ocean or the observed influx of AL water into the Arctic Ocean. Using radionuclides in SCICEX samples, Smith et al. (1999) estimated that it takes 6.5–7 years (±0.5 years) for the transport of upper AL water from the Norwegian Coastal Current to the Siberian continental slope, with transport into the interior Arctic Basin having a lower limit of eight years. Transit times for the halocline at water depths of 59 and 134 m are, on average, 0.5 years lower than those for AL water at 240 m deep (Smith et al. 1999).

Guay et al. (1999) analyzed SCICEX samples collected along the Beaufort, Chukchi, East Siberian, and Laptev shelves to identify where river waters cross the shelves and join the circulation of the upper Arctic Ocean water column. Their data sets include temperature, salinity, chlorophyll, barium (Ba), total organic carbon (TOC), and dissolved organic carbon (DOC). Regions where river waters cross the shelves and enter the interior Arctic Ocean are identified by the coincidence of salinity minima with maxima in Ba, DOC and TOC. Guay et al. (1999) found three major regimes along the shelf transect: the Canada Basin and Chukchi Cap regime that is dominated by mixing between Pacific inflow, discharge from the Mackenzie River, and ice melting; a transition zone centered over the Siberian end of Alpha-Mendeleev Ridge that corresponds to the front between Pacific and Atlantic waters; and a Makarov and Amundsen Basin regime that is 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 1970s (Newton et al. 1974). These nearly ubiquitous features of the western Arctic Ocean provide important roles in ocean circulation and mixing and can persist for years. During SCICEX-97, embarked researchers seized an unprecedented opportunity to map a cold core eddy both horizontally and vertically. Muench et al. (2000) detailed the shape of the eddy and used chemical tracers to examine its age and source region. The eddy they encountered was approximately 20 km in diameter, extending from 40 to 400 m deep. Core temperatures in the eddy were cooler than in the surrounding water, with the greatest difference occurring at approximately 230 m deep. The eddy core contained less salt than the surrounding water from the top of the eddy to depths of about 185 m; deeper than that, the salinity was less than ambient values. The maximum current speeds recorded in the eddy were 20 cm/s. Muench et al. (2000) suggested that the likely source of the eddy was a polynya along the Alaskan Chukchi coast; chemical tracers placed an upper limit of two years on the age of the eddy core. Muench et al. (2000) estimated that if the eddy formed along the Alaskan Chukchi coast during the winter prior to its encounter, it migrated northward at a rate of approximately 1 cm/s, transporting 2000 m^3 of shelf water per second. If eddies are the sole mechanism for venting water from the shelves into the deep Arctic Ocean, volume considerations imply that approximately 250 eddies form and migrate annually.

Steve Okkonen and Dean Stockwell from the University of Alaska Fairbanks store water samples in copper tubing for post-cruise analysis by oceanographers at Lamont-Doherty Earth Observatory.

Biogeography of Bacterioplankton. The Arctic Ocean receives organic matter from several sources, including riverine inflow from continents, phytoplankton production, and ice-algal production (Ferrari and Hollibaugh 1999). SCICEX water samples presented an unprecedented opportunity for biologists to study organic matter on a basin-wide scale and in different parts of the water column. Bano and Hollibaugh (2000) examined the distribution of ammonia-oxidizing bacteria in the Arctic Ocean and found that these oxidizers are more prevalent in halocline waters than in shallower and deeper waters. They suggested that this is the result of organic matter accumulating at the boundary layer (where water density changes rapidly) and decomposing to release ammonium. Bano and Hollibaugh (2002) also addressed 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 species. They found that the diversity of the Arctic assemblage is comparable to temperate oceans and that the Arctic community is composed of a mixture of uniquely polar and cosmopolitan types.

The Future of SCICEX

Because 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 been discontinued. While the international science community would welcome further dedicated cruises, the decommissioning of Sturgeon-class submarines has limited the ability of the U.S. Navy to support scientific missions. Alternative approaches for SCICEX-like investigations involve using autonomous underwater vehicles or nuclear-powered submarines from other nations; 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.

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