PAPER

SCICEX-93: Arctic Cruise of the U.S. Navy Nuclear Powered Submarine *USS Pargo*

Marcus Langseth
Lamont-Doherty Earth Observatory
Palisades, New York

Theodore Delaca
University of Alaska
Fairbanks, Alaska

George Newton
System Planning Corporation
Arlington, Virginia

Bernard Coakley
Lamont-Doherty Earth Observatory
Palisades, New York

Roger Colony
Polar Science Center
Applied Physics Laboratory
University of Washington
Seattle, Washington

Jeff Gossett
Arctic Submarine Laboratory
San Diego, California

Christopher May
Polar Science Center
Applied Physics Laboratory
University of Washington
Seattle, Washington

Peter McRoy
University of Alaska
Fairbanks, Alaska

James Morison
Polar Science Center
Applied Physics Laboratory
University of Washington
Seattle, Washington

William Smethie
Lamont-Doherty Earth Observatory
Palisades, New York

Daniel Steele
Arctic Submarine Laboratory
San Diego, California

Walter Tucker
Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

ABSTRACT

A nuclear powered submarine, USS Pargo, made a scientific cruise to the Arctic Ocean during the late summer of 1993. This was the first cruise of a nuclear submarine to the arctic in which the U.S. oceanographic community was openly invited to participate in the planning and implementation of the cruise. The data from the cruise will be placed in the public domain and results published in the open literature. During the cruise, called SCICEX-93, 9,080 km (4,900 nm) of underway data (bathymetry, gravity anomaly, temperature, salinity, ice draft, and images of the underside of the ice) were collected in the deep Arctic Ocean below the ice pack. Surface stations were occupied at 20 locations along the track. At these stations 35 CTD (conductivity, temperature, depth) casts were made in the shallow water of the Arctic Ocean (400-600 m), and 31 vertical current profiles were made using an expendable free-fall device. Bottle casts collected 1,500 water samples for chemical and biological analysis. While submerged, 31 submarine-launched, expendable CTDs were deployed and 46 water samples were drawn through the submarine's seawater system. Four buoys were deployed in the ice: two were used for meteorological observations and two polar oceanographic profiling buoys were used to make long-term time-series measurements of temperature and salinity at six different depths in the shallow water of the Arctic Ocean. The SCICEX-93 cruise demonstrated the remarkable potential of nuclear powered submarines for oceanographic and geophysical studies of ice covered regions of the ocean.

INTRODUCTION

It has been 35 years since the U.S. Navy nuclear submarine *Nautilus* transited from the Bering Strait to the Norwegian Sea via the North Pole under the arctic ice. Closely following the much heralded exploits of the *Nautilus*, the *USS Skate* made cruises to the Arctic Ocean to test further the feasibility of operating nuclear submarines during summer and winter conditions. The *Skate*'s cruises included many successful surfacings of the submarine in leads or polynya where there was open water or thin newly frozen ice. These early probings under the arctic ice by *Nautilus* and *Skate* not only showed that nuclear submarines could operate and navigate safely in the Arctic Ocean year round but also emphatically demonstrated the unique capabilities of nuclear powered submarines. Of principal concern to the Navy was the military importance of being able to operate in the only ocean that is shared by the United States and Russia, but it was also clear that nuclear submarines have the potential to be extraordinarily powerful oceanographic platforms that could collect data and make observations in areas that are virtually inaccessible by any other means.

The *Nautilus* and *Skate* collected scientific data on ice cover and ice dynamics in the arctic using instrumentation specially developed and adapted to submarines (Lyon, 1963). Bathymetric profiles that were among the first soundings to show the seafloor topography in Arctic Ocean basins were also collected (Beal, 1969). Subsequent cruises continued to collect data, most of it relevant to operational and military concerns and nearly all of it classified. Recently, some of these data on ice distribution collected by U.S. Navy submarines have been published (McLaren, 1989). The efforts of the office of then U.S. Senator Gore have further stimulated the release of these data. Although bathymetric data have been systematically collected during nuclear submarine cruises in the Arctic Ocean, the findings remain classified. Consequently, most of the public knowledge of the hydrography of the arctic waters and the morphology and structure of the floors of the central Arctic Ocean basins was obtained from ice breakers, ice camps, and ice island stations.

This year the prospects for using nuclear submarines as research platforms improved markedly. In January, the U.S. Navy announced that a nuclear submarine cruise to the Arctic Ocean would take place during the late summer of 1993 and that the U.S. oceanographic community was invited to plan and participate in the cruise. Furthermore, the data collected on the cruise would be made available to scientists who participated in the cruise or enlisted as shore-based investigators. The results could be published in the open scientific literature, and all raw data would be placed in the public domain.

The University National Oceanographic Laboratories (UNOLS) in coordination with the Arctic Research Commission and the Naval Undersea Warfare Center, Arctic Submarine Laboratory undertook the planning and preparation for the cruise. A meeting held at the Scripps Institution of Oceanography in February 1993 brought together a large group of scientists who are interested in arctic research and/or interested in the scientific potential of nuclear submarines. At this meeting scientific objectives that could be pursued during the cruise were discussed and the constraints and ground rules for submarine operations in the arctic were presented by the Arctic Submarine Laboratory personnel. An outline of a science plan for the cruise was developed and an ad hoc steering committee was established to refine the science plan and help with scientific preparations for the cruise. Members of the steering committee are listed in Table 1.

TABLE 1. Organizers of SCICEX-93.

Members of the ad hoc steering committee:		
Marcus Langseth (chair)	Lamont-Doherty Earth Obs.	Marine Geophysics
Ted Delaca	University of Alaska	Marine Biology
Walter Tucker	Cold Regions Res. & Eng. Lab	Ice Dynamics
James Morison	University of Washington	Hydrography
William Smethie	Lamont-Doherty Earth Obs.	Ocean Chemistry
Cruise participants from academic institutions:		
Ted Delaca (lead scientist)	University of Alaska	Marine Biology
Bernard Coakley	Lamont-Doherty Earth Obs.	Geophysicist
Roger Colony	University of Washington	Ice Dynamics
Peter McRoy	University of Alaska	Marine Biology
James Morison	University of Washington	Hydrology

SCICEX-93

The cruise was conducted on board the *USS Pargo*, a Sturgeon class nuclear submarine (Figure 1). The cruise, officially known as Scientific Ice Expedition-93 (SCICEX-93) began August 11 from Groton, Connecticut, and ended September 18 in Bergen, Norway. The submarine spent 23 days of the 38-day cruise operating in the ice-covered waters of the Arctic Ocean. On board the *Pargo* was a scientific staff of seven that included two scientists from the Arctic Submarine Laboratory and five academic scientists (see Table 1). In addition to those who participated in the cruise, 39 shorebased scientists are participating in analysis of samples and data taken during the cruise.

The *USS Pargo* is a nuclear attack submarine that is well suited for cruises under the arctic ice since her hardened sail and rudder structure allows her to surface safely through thin ice cover. However, the ship operates as a fully armed component of the U.S. Navy's submarine fleet and consequently requires a full operating crew. Strict security of some aspects of the cruise and the ship was maintained, thus for the SCICEX-93 cruise there were definite limitations to the science that could be conducted. Despite these constraints, a remarkable variety and quantity of data were collected for disciplines ranging from atmospheric science to submarine geology.

There were only six months between the meeting at Scripps and the departure date to plan and prepare for the SCICEX-93 cruise. Consequently, the instruments and equipment were limited to those instruments that were

FIGURE 1. A Sturgeon class nuclear powered submarine (*USS Queenfish*, SSN 651) at the North Pole.

already installed on the ship, instrumentation that had been previously installed aboard a Sturgeon class submarine, or equipment that could be installed with no modification to the ship's existing instrument systems or structure.

OBJECTIVES AND RESULTS OF SCICEX-93

General

The cruise of the *USS Pargo* was a combination of reconnaissance surveying, sampling traverses, and one detailed local survey (Figure 2). The submarine covered 9,080 km under the ice, including two long traverses that ran from the vicinity of the North Pole to the Alaskan margin. The long tracks were complemented by two shorter traverses that extended across the Lomonosov and Alpha/Mendeleyev Ridges. The submarine acquired data for geological, cryological, hydrological, chemical, biological, and meteorological science. Table 2 provides a summary of the measurements made and the samples taken during SCICEX-93.

TABLE 2. Summary of data collected on SCICEX-93.

9,080 km (4,900 nm) of underway data:	
	Bathymetry and gravity
	Salinity and temperature at cruise depth
	Ice draft*, uplooking side-scan sonar and video
Samples and measurements from the submerged submarine:	
	31 XCTDs (0-1,000 m)
	46 water samples drawn internally
20 surface stations:	
	35 CTD casts
	31 expendable current shear profilers
	1,500 water samples from bottle casts
4 buoy deployments with ARGOS telemetry:	
	2 University of Washington POP buoys with 6 CTD sensors
	2 meteorological buoys

*The digital ice profiler was not operational for approximately the first third of the cruise.

Marine Geological and Geophysical Observations

Observations made by the *USS Pargo* that are pertinent to the geology of the Arctic Ocean basin were bathymetry using a narrow beam, high frequency echo sounder, and gravity using a BGM-3 gravimeter provided by Lamont-Doherty Earth Observatory. The submarine proved to be a remarkably stable platform for gravity observations (Figure 3).

The *Pargo* made six crossings of the linear and narrow Lomonosov Ridge, which is believed to be a fragment of the western Siberian continental margin that was rifted away when the Eurasia Basin began to open in the early Tertiary. The long traverses of the *Pargo* from the Lomonosov Ridge to the Alaskan Margin were designed to pass over major sub-basins and ridges in the Amerasia Basin. The origin and evolution of this basin, which is the largest in the Arctic Ocean, remain enigmatic. In addition to the long traverses, the *Pargo* carried out a detailed survey of gravity and bathymetry near the junction between the Alpha Ridge and the Mendeleyev Ridge. Few features in the world oceans have been honored with more hypotheses as to their origin than the Alpha/Mendeleyev Ridge complex. Within the 100 × 100 km area surveyed by *Pargo*, observations were made along parallel tracks that were spaced 25 km apart. This detailed survey should provide the first indication of topographic trends in the Alpha/Mendeleyev Ridge complex at a scale of 25 km.

One of the long traverses runs down the axis of the Canada Basin. This basin, which lies south of the Alpha/Mendeleyev Ridge and adjacent to the northern margins of Alaska and Canada, is believed to have been formed during the Cretaceous by a counterclockwise rotation of Alaska away from the Canadian Archipelago

FIGURE 2. The cruise track of SCICEX-93. Locations of surface stations are shown as open circles. The segment of the track shown in Figure 3 is indicated by a bold line.

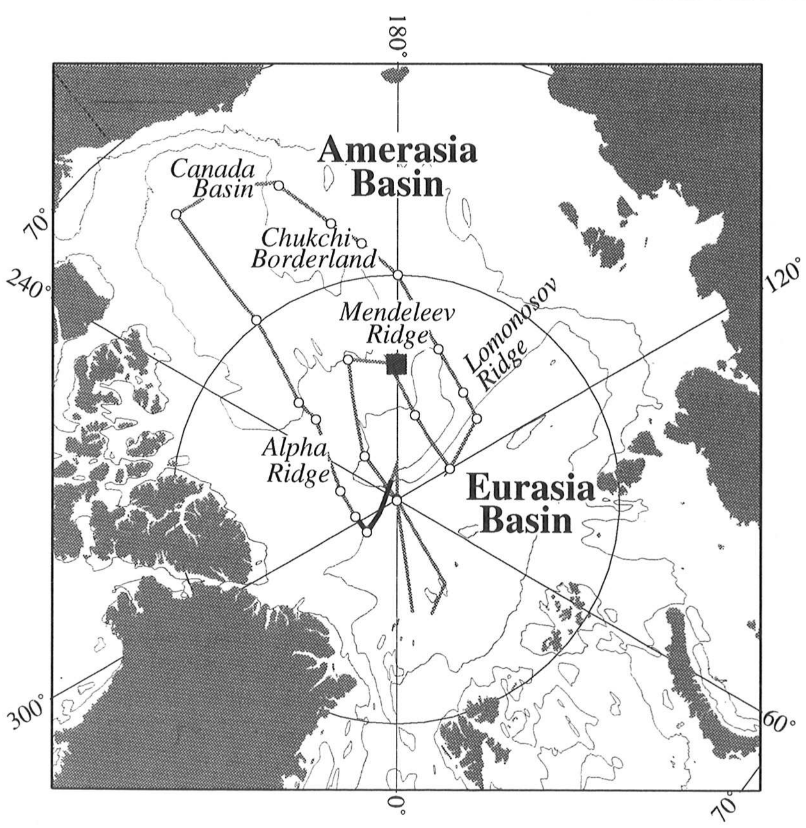
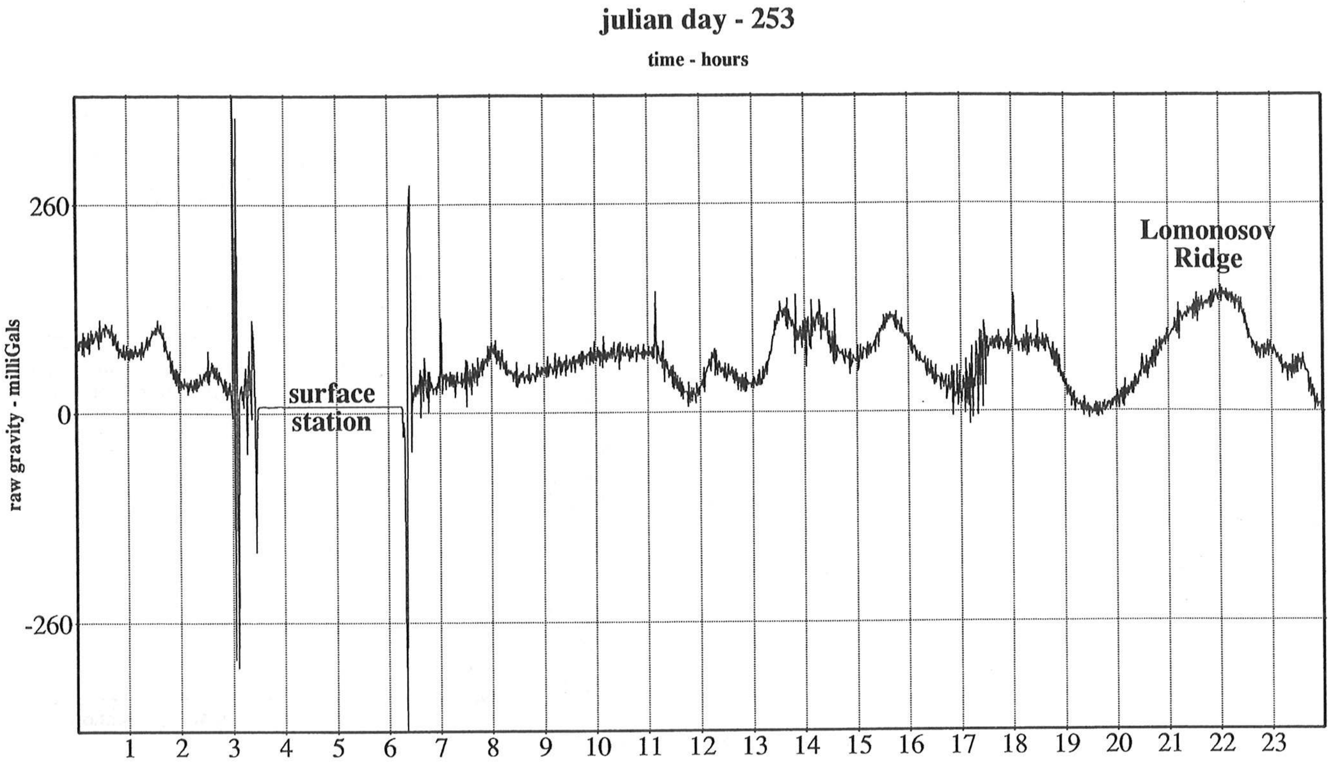


FIGURE 3. One day of gravity data taken by the *Pargo* in the vicinity of the Lomonosov Ridge.



(Halgedahl and Jarrard, 1987). However, both the age and proposed mode of formation are based on sparse and ambiguous observations (Lawver and Scotese, 1990).

The long track that runs roughly parallel to the Siberian margin was positioned to cross the Chukchi Borderland, a complex of spur-like ridges that extend northeastward from the Chukchi shelf out into the Amerasia Basin. Like most of the features in the Amerasia Basin the tectonic development of these ridges is not understood.

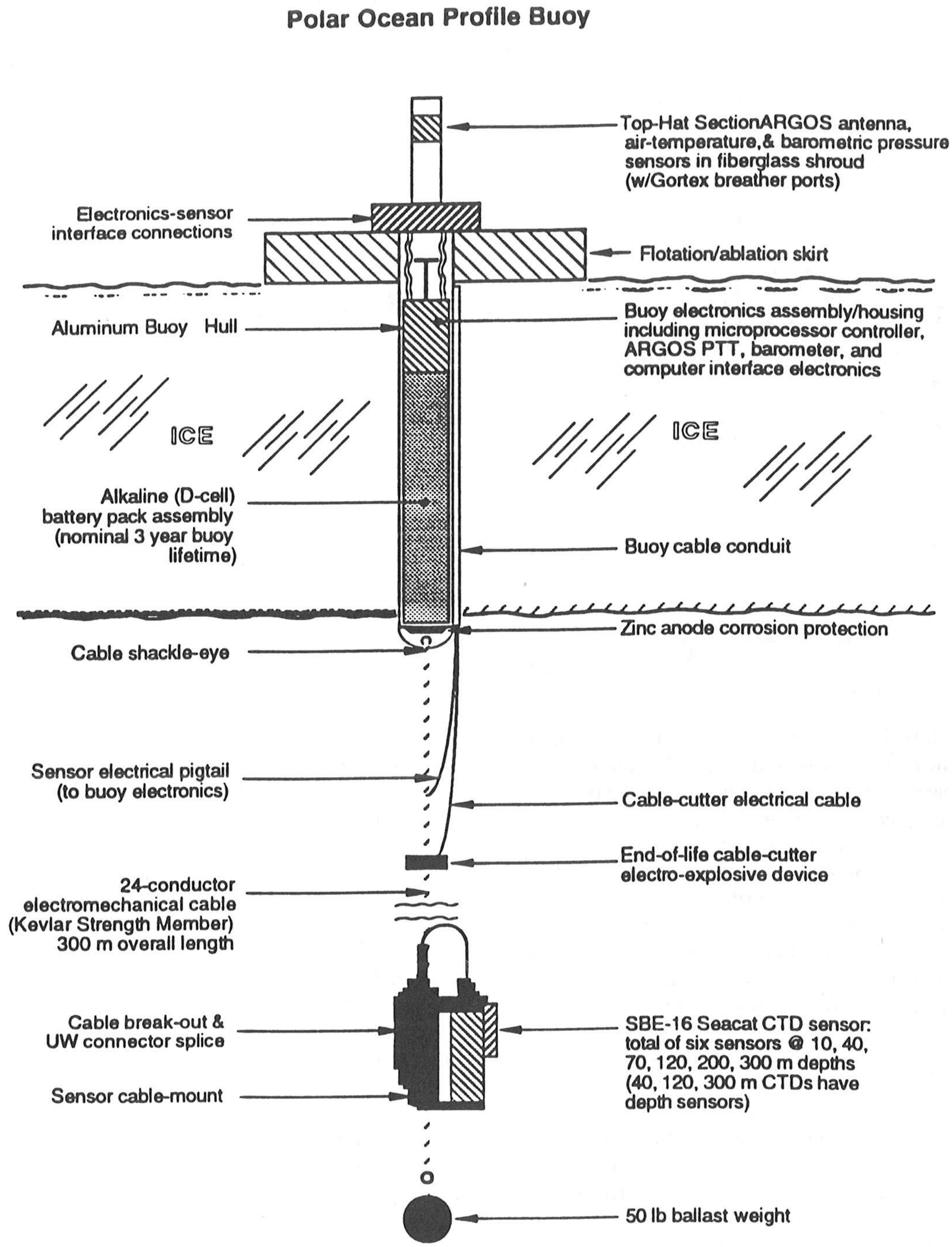
Studies of the Arctic Ice Pack

Since the cruise of the *Nautilus*, the Arctic Submarine Laboratory has operated ice detection and imaging systems from nuclear submarines in the arctic. These instruments include a digital ice profiler system (DIPS), an upward-looking side-scan sonar that produces reflectivity images of the under surface of the ice, and an externally-mounted upward-looking video camera. During the SCICEX-93 cruise the DIPS instrument was used to trace the draft of the ice, which is believed by some to be a good proxy for thickness. Simultaneously, the upward-looking side-scan sonar and video camera recorded images that indicate the type of ice and the extent and orientation of leads and ridges. The ice pack thickness can vary greatly but averages between 2 and 3 m. Climatologists have a great interest in monitoring the extent and volume of the ice pack over periods of years and decades because significant changes in total ice volume may be one of the most sensitive and reliable indicators of global climate change at decadal time scales.

The detailed survey within the 100 × 100 km area conducted by the *Pargo* for bathymetry and gravity also mapped the bottom of the ice cover. This survey provided a two-dimensional map of ice draft, which among other things, provides a test of how well ice profiles along a single line represent the two-dimensional variation of ice thickness.

Polar oceanographic profiler (POP) buoys (Figure 4) were installed at two locations in the ice. A string of six Seacat CTD sensors, which hang below the POP buoy, record water temperatures and salinities at six depths (10, 40, 70, 120, 200, and 300 m). These buoys also measure air temperature and pressure and transmit the data back to the Polar Science Center via ARGOS satellites. The POP buoys will provide a long-term record (up to three years) of temperature and salinity in two areas of the arctic where few measurements currently exist. These results will provide histories of heat flux through the ice as well as records of seasonal freezing and melting at the base of the ice. Tracking the location of these buoys over the next three years will provide information on the motion of the ice as

FIGURE 4. Schematic of the polar ocean profiler (POP) buoy developed at the Polar Science Center, Applied Physics Lab, University of Washington.



it is driven by Arctic Ocean surface currents and wind. The two POP buoys that were installed during SCICEX-93 are currently transmitting data to the Polar Science Center.

Hydrography and Circulation of Shallow Waters of the Arctic Ocean

A wide variety of measurements were made and samples taken from the *Pargo* to define the near surface water hydrography of the Arctic Ocean better. The upper waters of the Arctic Ocean are composed of water entering from the Atlantic Ocean through the Fram Strait, water from the Pacific Ocean entering through the Bering Strait, and water over a wide density range entering from the extensive continental shelf regions. The water from the shelf regions consists of fresh, low density water from river runoff and sea-ice melt in the seasonal ice covered areas, denser waters formed by brine rejection during sea ice formation, and mixtures of intermediate density.

Two CTDs mounted in the sail of the submarine continuously recorded conductivity, temperature, and depth all along the track. Expendable devices were launched from the submarine while submerged to measure temperature and salinity profiles. After launch, these devices first float upward to a depth just below the bottom of the ice and then free fall through the water making measurements to about 1,000 m. Thirty-two XCTDs (expendable conductivity, temperature, and depth devices) were launched along the traverses through the Arctic Basin; the data they collected will provide a crude snapshot of hydrographic conditions during the summer of 1993. Especially important are the observations along the traverse that runs parallel to the Siberian Margin. The hydrography between the eastern end of the Lomonosov Ridge in the Laptev Sea and the Chukchi Borderland is virtually unknown.

The *Pargo* surfaced in open water or thin ice (typically 8-13 cm thick) to make surface stations. CTD and bottle casts were made at these stations using a small winch and gantry assembly developed at the University of Washington Polar Science Center, which was installed on the deck of the surfaced submarine for each station. This system allowed CTD and bottle casts to be taken to a depth of about 400 m. Twenty surface stations that were well distributed along the cruise track were occupied during the 20 days in the data collection area (Figure 2).

Another objective of SCICEX-93 was to determine whether and where enhanced mixing occurs over topographic features in the arctic. Previous measurements of vertical current shear in the Arctic Ocean indicate vertical mixing is very low over the deep water portions of the Nansen Basin; however, significant vertical mixing has been found in shallow waters around the Yermak Plateau and to a lesser extent over the Arctic Mid-Ocean Ridge. Extrapolation of these observations to the entire Arctic Basin suggests that internal wave mixing can support only a small fraction of the heat flux required to cool the Atlantic water in the Arctic Ocean. Measurements of horizontal current shear in the water column were made on SCICEX-93 using expendable current profilers (XCP). Thirty-one of these devices were deployed from a remotely operated vehicle operated from the deck of the surfaced submarine. This device carried the XCPs away from the influence of the submarine before releasing them. During descent an XCP measures relative velocity and temperature from 5 to 1,500 m with a spatial resolution of 5-10 m and an accuracy of about 1 cm/s.

The continuous records of temperature and salinity measured by the CTD mounted in the sail should detect fronts and eddies in the shallow waters of the Arctic Ocean through which the submarine passed. In the central Arctic Basin eddies of anomalous water have been identified and tracked from observations taken at manned ice camps in the Beaufort Sea (Manley and Hunkins, 1985). These eddies are 10 to 20 km in diameter and exist between 50 and 300 m depth. The eddies are scientifically important since they transport packets of water and vorticity around the basins. The continuous temperature and salinity records collected by *USS Pargo* will be examined for these features. Additionally, the submarine's set and drift, estimated from the vector differences between dead reckoned and inertial navigation velocities, may be suitable for detecting currents and large velocity perturbations due to fronts and eddies.

Ocean Chemistry and Biology

Two of the objectives of SCICEX-93 were to determine the distribution of the various water types that comprise the upper 600 m of the Arctic Ocean and to estimate the transit times from their source regions. The various sources of upper Arctic Ocean water are tagged in different ways with natural and anthropogenic substances, which can be used to identify the sources and estimate how long it has taken for the source waters to be transported to the interior of the Arctic Ocean. Biological studies also provide a means for water mass identification, as well as proxy data for dynamics of biochemical processes in the central Arctic Ocean.

To meet these objectives water samples for chemical and biological analysis were collected in two ways. First, over 1,500 water samples were collected by bottle casts from the surfaced submarine using the Polar Science Center's winch and gantry system at locations shown in Figure 2. Bottle casts were made to 600 m at each surface station. Second, forty-six water samples were drawn through the seawater system of the submarine while it was submerged. These samples were returned to shore-based labs for analysis.

Samples taken during the SCICEX-93 cruise will be analyzed for tritium, helium-3, oxygen isotopes, and trace elements. The surface mixed layer contains fresh water derived from river input and sea ice melt. These two sources can be distinguished using a combination of salinity, tritium, and $^{18}O/^{16}O$ measurements (Schlosser et al., in press). Certain trace elements (Rb, Cs, Ba, Sr, Li, B, F, I, and transition metals) can also be used to identify river water and possibly the input from specific rivers. The residence time of water on the shelf and the time required for the water to be transported from the shelf regions to the interior can be determined from tritium and helium-3 measurements.

Biological and chemical analysis of samples will also provide clues to oceanic sources of near surface waters in the Arctic Ocean. The Arctic Ocean mixed layer consists of upper and lower layers separated by a halocline. The halocline is identified as a nutrient maximum and is of Pacific origin. A second deeper halocline separates the mixed layer water from Atlantic water, which can be identified by its oxygen and nitrate characteristics. Both types of water form over the continental shelf regions where extensive air-sea interaction occurs and where they become tagged with anthropogenic substances. These substances include chlorofluorocarbons (CFCs), tritium, and helium-3. All of these can be used to estimate the time for the water to be transported to the interior.

The Atlantic water is identified by a temperature maximum. At its entrance to the Arctic Ocean in the Fram Strait, the Atlantic layer has a high anthropogenic tracer content. CFCs and the tritium/helium-3 pair can be used to estimate transit times to the interior as for the shallower water masses. Atlantic water entering both the halocline and the lower Atlantic layer has another unique tag, cesium-137. This enters Atlantic water from the Sellafield nuclear fuel reprocessing plant located on the Irish Sea and is transported northward in the Norwegian current. Cesium-137 measurements can be used both to identify and to estimate transit times of water of Atlantic origin in the Arctic Ocean.

It has recently been observed that the shelf waters over the Alaska shelf acquire large methane concentrations (Kvenvolden et al., 1992). The methane apparently comes from dissociation of gas hydrates in the shelf sediments during winter when the shelf is ice covered. This could be an important source for the global atmospheric methane budget and may provide another means to trace the flow of shelf water into the interior. Water samples for methane measurements were obtained during SCICEX-93 to make a better assessment of methane production by gas hydrate dissociation in Arctic shelf sediments and of its impact on the global atmospheric inventory of methane, which is increasing at about 1 percent per year.

Meteorological Observations

During the SCICEX-93 cruise two "MET" buoys, which measure temperature and pressure at a height of 2 m above the ice surface, were installed. The temperature and pressure measurements on a 2 m mast are far superior to the buoy hull temperature measurement of air-dropped buoys, the only other technique for installing buoys in this otherwise inaccessible region. The International Arctic Buoy Program (IABP), in which the United States is participating, is establishing and maintaining a network of drifting buoys in the Arctic Ocean to provide data for meteorology and oceanography and for real-time operational information for research expeditions to the arctic. The data gathered by the IABP supports the World Climate Research Program and the World Weather Watch Program. The buoys installed by the *USS Pargo* in the central Arctic Ocean are at locations that help fill gaps in the existing array.

CONCLUSION

Perhaps the most important objective of *Pargo*'s cruise to the Arctic Ocean this summer was to test the feasibility of a nuclear submarine as an oceanographic platform and, further, to test the partnership between civilian scientists and the U.S. Navy submarine command. The initial results of this test were highly successful on all counts. The submarine provided easy access to the central Arctic Ocean. It demonstrated the capability to make a wide variety of measurements and to collect samples while on the surface and while submerged. It provided an acoustically quiet, stable, and fast moving vehicle for underway geophysical and hydrographical observations both above and below the submarine. Most encouraging for the scientists was the competence and enthusiastic support of the officers and crew of the *USS Pargo* for the scientific mission.

The principal advantages that a nuclear submarine has over other vehicles for selected oceanographic problems have been stressed by a number of earlier authors (McLaren, 1990; Keigwin and Johnson, 1992). Foremost are accessibility and range. Nuclear submarines allow scientists to work not only in areas of permanent ice cover in the arctic and antarctic but also in regions where the weather and sea state obviate measurements from surface ships. For example, hydrographers would be able to cruise below full-blown hurricanes or monsoonal storms of the Northwestern Indian Ocean and measure a storm's impact on the dynamics and structure of the upper water. For the marine geologist the submarine offers a uniquely quiet and stable platform for underway geophysical observations and the potential for high resolution acoustical imaging of the seafloor. For biological oceanographers a submarine provides new tools and a three-dimensional perspective for in situ assessment of biological populations and processes.

Currently, plans are being made for additional scientific cruises to the Arctic Ocean aboard nuclear submarines beginning in 1995. These expeditions will be made in Sturgeon class submarines with approximately the same constraints as SCICEX-93. However, with the longer lead time it is anticipated that additional measurements and sampling capability can be added and improvements made in the handling and stowage of equipment. Table 3 lists some possible types of instruments or instrument systems that could be added to a submarine to enhance productivity. It is also important to evolve from the ad hoc science planning mode of SCICEX-93 to a mode more consistent with established practices of funding and peer review.

Projecting further into the future, oceanographers envision a nuclear research submarine that is dedicated to science. If some weapons were removed from an attack submarine and its mission changed to a purely scientific one, much more "lab space" would become available for scientific instruments and sample analysis. It might also be possible to mount additional types of sensors and instruments on the submarine. In short, a submarine such as the *USS Pargo*, if converted for scientific use, would become an even more potent oceanographic vessel. If a nuclear powered submarine dedicated to research is to become a reality, it is urgent that action be taken now because the last of the Sturgeon class submarines, which are ice-strengthened for arctic operations, will be decommissioned soon

There are some serious hurdles that must be cleared to make the dream of a nuclear research submarine reality. The highest of which is the cost. The annual costs of a research program pursuing the goals outlined above would be comparable to other large National Science Foundation sponsored programs ($15 to $20 million) and thus would be out of the reach of current budgets for academic ocean or arctic science. The funds to meet these costs could be generated only through development of a fixed-term science program that utilizes the unique capabilities of the nuclear submarine to the fullest. Placing the scientific use of a nuclear submarine into the context of an inclusive, multi-year program has many advantages:

1. The program planning process makes sure that the scientific efficacy and cost effectiveness issues are addressed at the outset and that the oceanographic community's voice is heard.
2. A program ensures the broad and equitable participation by the U.S. oceanographic community, including academic, agency, and defense department scientists. It is conceivable that such a program could include classified research cruises for the Department of Defense as long as they were scheduled within the context of the program.
3. An effective program requires an advisory structure that provides broadly based counsel to the program's managers as it progresses and that guards against domination of the program by any one group or institution.

Such a program would require a new type of partnership between the Navy's submarine command and academic and agency scientists. Obviously only the Navy has the infrastructure and personnel to operate a nuclear research submarine. To be successful, however, a program making use of a nuclear powered submarine must exploit the collective interest and expertise of the U.S. scientific community.

TABLE 3. Potential future enhancements to a nuclear powered submarine for arctic research.

- Integrated digital data management system for logging navigation and digitally recorded scientific data versus time
- Installation of an acoustic Doppler current profiler (ADCP) that can look both up and down to detect and record current shear relative to the submarine
- Deck fixtures to provide a flat and safe open working area
- Low frequency depth sounder and multibeam bathymetric mapping system
- A towed magnetometer and hydrophone streamer
- Provision for attachment of "science pods" that could carry instrument systems that cannot be installed in or attached directly to the submarine

ACKNOWLEDGMENTS

Many people and organizations worked together to make SCICEX-93 a success. The Arctic Submarine Laboratory, San Diego, was responsible for the coordination of the science operations on the cruise. Marshall Mosher and Michael Hacking were extremely helpful with preparations for the cruise. Thomas Nutter and Thomas Lewis at COMSUBLANT in Norfolk played key roles in converting the ambitions of the scientists into an operational plan. Cmdr. Brian J. Wegner, the commanding officer of the *Pargo*, and his crew were responsive to and patient with the requirements of the science plan and requests of the scientific party. The operations at the surface stations, such as moving equipment up from below decks through the hatch, installing buoys and taking hydrocasts, would have been impossible without the able assistance of the crew. Short-term grants from the National Science Foundation's Office of Polar Programs (OPP 93-17712) and the National Oceanic and Atmospheric Administration (NA36RU0463) provided support planning, acquisition, and logistical costs. A significant part of the science effort was supported by institutional funds from the University of Alaska, Applied Physics Laboratory's Polar Science Center of the University of Washington, and Lamont-Doherty Earth Observatory of Columbia University.

REFERENCES

Beal, M.A. 1969. Bathymetry and structure of the Arctic Ocean. Ph.D. Thesis, Oregon State University, Corvallis, OR. 205 p.

Halgedahl, S. and Jarrard, R. 1987. Paleomagnetism of the Kuparuk River Formation from oriented drill cores: Evidence for rotation of the North Slope Block. In: *Alaskan North Slope Geology*, Tailleur, I.L. and Weimer, P., eds. Society of Economic Paleontologists and Mineralogists, Pacific Section, Special Publ. 50, pp. 581–620.

Keigwin, L.D. and Johnson, G.L. 1992. A plan of action for utilization of a nuclear submarine for arctic research. *EOS* 73:203.

Kvenvolden, K.A., Lorenson, T.D. and Lilley, M.D. 1992. Methane in the Beaufort Sea on the Continental Shelf of Alaska. *EOS*, 73:309.

Lawver, L.A. and Scotese, C.R. 1990. A review of tectonic models for the evolution of the canada basin. In: *Geology of North America, vol. I, The Arctic Ocean Region*. Grantz, A., Johnson, G.L., and Sweeney, J., eds. Geol. Soc. of Amer., pp. 593–618.

Lyon, W. 1963. The submarine and the Arctic Ocean. *The Polar Record*, Vol. 11, No. 75, pp. 699–705.

Manley and Hunkins. 1985. Mesoscale eddies of the Arctic Ocean. *J. Geophys. Res.*, Vol. 90, No. C3, pp. 4911–4930.

McLaren, A.S. 1989. The under ice thickness distribution in the Arctic Basin as recorded in 1958 and 1970. *J. Geophys. Res.*, 94 C4 , pp. 4971–4983.

McLaren, A.S. 1990. Nobody asked me, but..., *Proceedings of the U.S. Naval Institute*, p. 108.

Schlosser, P., Bauch, D.G., Fairbanks, R. and Bönisch, G. In press. *Deep Sea Research*.