

ARCTIC OCEAN SCIENCE FROM SUBMARINES

A Report Based on the SCICEX 2000 Workshop

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**ARCTIC OCEAN SCIENCE FROM SUBMARINES —
A REPORT BASED ON THE SCICEX 2000 WORKSHOP**

Warrenton, Virginia
5 - 9 October 1998

By the
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EXECUTIVE SUMMARY

The Scientific Ice Expeditions (SCICEX) program has demonstrated the benefits of using submarines to study arctic marine science. The submarine is an extraordinary platform for this purpose, able to cross the Arctic Ocean in days, complete a synoptic ocean survey in a month, and cruise beneath the worst ice conditions. The five cruises to date have provided valuable insights into the circulation within the Arctic Ocean, the recent state and dynamics of the sea ice cover, the sources and movement of carbon within the ocean system, and the structure and origin of bathymetric features. The scientific results presented at the SCICEX 2000 Workshop and summarized in the Appendices D and E of this report are just the beginning of the scientific payoff. The program has proved to be a worthy collaboration of many military and civilian participants.

This report makes the case for continuing to use submarines for scientific work in the Arctic Ocean. There are important scientific problems in physical, chemical, and biological oceanography, sea ice geophysics, and marine geology and geophysics that can be studied effectively only from submarines. Because of declining numbers and changing classes of submarines, this valuable resource for science will be quite limited over the next several years. We emphasize that extremely valuable scientific research can be accomplished with little or no impact on submarine operations or cruise plans. We describe the scientific work that could be done on three types of missions: (1) *Baseline Data Missions (BDMs)*, which would have no impact on the submarine's primary military mission; (2) *Science Accommodation Missions (SAMs)*, which would have only a small impact; and (3) longer-term *Dedicated Science Missions (DSMs)* in the mold of SCICEX. Each has a unique scientific payoff.

We cannot overstate the significance of routinely acquiring a few basic Arctic Ocean data in *BDMs*, which would have no impact on submarine operations. As a starting point for expanding our knowledge of ocean bathymetry and of the state and variability of the ocean and sea ice, these missions are crucial. Uncertainty about arctic climate change, whether cyclical transients or trends that will continue into the future, is rooted in the lack of a historical record of oceanographic and climatological observations. Continual observations of a few fundamental variables are needed. The strength of these observations would grow as they accumulate over many years, adding to the SCICEX and historical submarine records.

Since these *BDMs* represent the biggest change from the SCICEX program, they may well require the most effort to institute properly. We recommend that the Science Steering Committee (SSC) and the U.S. Submarine Force develop a mechanism to assess the scientific potential of upcoming arctic missions of suitable security classification. Candidate cruises for *BDMs* would require little or no input from the scientific community in advance, whereas *SAMs* would require some notification and planning. The SSC should work with the Submarine Force to minimize the uncertainty about future science opportunities—e.g., by estimating the number of science cruise days for the upcoming year. The funding agencies must identify an appropriate and possibly nontraditional way of funding this type of science. A body of scientific investigators, built on the Science Working Group (SWG), should develop science plans and examine the technical issues associated with implementing *BDMs* on Los Angeles- and Seawolf-class submarines. Quick release, processing, and public archiving of these baseline data are imperative.

Science Accommodation Missions would take advantage of a few days out of a longer military mission when the submarine would be used for science. With some additional impact, especially improved water sampling, and some selectability of portions of cruise tracks, the scientific opportunities would become more broad, in particular, opening the door to biogeochemical sampling. Planning for these *SAMs* would involve a more active process coordinated by the Science Working Group with expanded community involvement.

Dedicated Science Missions in which the entire cruise plan is developed in the mold of SCICEX to address scientific rather than military objectives can address important additional scientific goals. The inclusion of civilian scientists as riders enables onboard biological and chemical analyses of water samples crucial to understanding how the biological and chemical state is maintained. Geological studies with bathymetric swath mapping can be pursued. Selection of the cruise track opens a range of possibilities: to observe particular locations, to study particular processes, to coordinate with field exercises, and to validate satellite observations.

There are four technological needs for maximizing the scientific payoff. For all mission scenarios, time and location tagging of data should be improved, and the quality of salinity and depth measurements should be improved. For *SAMs* and *DSMs*, water sampling capabilities need to be extended by means of a flow-through manifold. For *DSMs*, the most demanding extension of present capabilities would be a means of sampling water outside the SCICEX submarine operating depths—above a depth of 50 m and beneath a depth of 243 m (800 ft).

The organizational components are in place but need to be reoriented to comply with these new missions. The SSC should reexamine the Memorandum of Agreement (MOA) and determine how their operating procedures should accommodate the new requirements for more pre-planning, faster response times, new data protocols, and international coordination. The SWG also has different demands on it, since the environment is less driven by individual investigators and more crafted by panels and consensus. The SWG will need to specify preferred cruise tracks and define instrument packages. The submarine science program of the next decade will succeed only with more thorough up-front planning that fully prepares for observational opportunities with short lead time.

1. Purpose of the SCICEX 2000 Workshop Report

A workshop was held in Warrenton Virginia in October of 1998 to discuss science accomplished during five cruises that had been completed under the Scientific Ice Expeditions (SCICEX) program, and to consider what might possibly supersede SCICEX. There were participants from the civilian scientific community, funding agencies, the U.S. Navy, and several international colleagues.

This report summarizes the workshop and provides a basis for an arctic scientific program that takes advantage of the unique capabilities of U.S. Navy submarines. Specifically, we

- Summarize SCICEX results.
- Outline the scientific objectives for possible submarine cruises beyond the original SCICEX program.
- Communicate funding agency assessments of a continuing SCICEX program, with stable funding and the requisite sensor capabilities. These were given for NSF by Dr. Bordogna and for ONR by RADM Gaffney; Dr. Bordogna's remarks appear in Appendix C.
- Communicate a U.S. Navy assessment of the likely submarine resources available for scientific observations. This assessment was given by RADM Ellis, speaking for VADM Giambastiani, COMSUB-

LANT, and appears in Appendix C.

- Recommend a management strategy for a future program. In this area, the Organizing Committee has tried to go beyond what was discussed at the workshop.
- Identify needed sensor development.

This report represents the opinions of the workshop Organizing Committee. All attendees were invited to comment on the draft report, and many did, so it may be said to represent a consensus of the workshop. This report does not purport to represent the views of the U.S. Navy.

2. The Legacy of SCICEX

2.1 Elements of the SCICEX Program

In 1993 scientists from various academic institutions were invited to participate in a submarine cruise under the arctic sea ice aboard USS *Pargo* to explore using a submarine as a platform for scientific observations. The first mission was so successful that it was expanded into a program called SCICEX, Scientific Ice Expeditions. As a part of this program, five arctic cruises have been completed so far (Table 1), and a cruise is scheduled in the spring of 1999.

For 3 to 6 weeks, each of these cruises collected data throughout much of the Arctic Ocean in a Data Release Area referred to as the SCICEX box (Figure 1) in which the Navy approved declassification and release of data. This region includes international

Table 1. SCICEX cruises.

<i>Dates in Data Release Area</i>	<i>Submarine</i>	<i>Commanding Officer / Chief Scientist</i>
23 August—13 September 1993	USS <i>Pargo</i>	CDR Brian Wegner / T. DeLaca
26 March—8 May 1995	USS <i>Cavalla</i>	CDR Joe Leidig / T. DeLaca
13 September—28 October 1996	USS <i>Pogy</i>	CDR Jim Reilly / R. Sambrotto
3 September—2 October 1997	USS <i>Archerfish</i>	CDR Steve Kremer / T. Whittedge
1 August—2 September 1998	USS <i>Hawkbill</i>	CDR R. Perry / R. Muench
April—May, 1999	USS <i>Hawkbill</i>	CDR R. Perry / M. Edwards

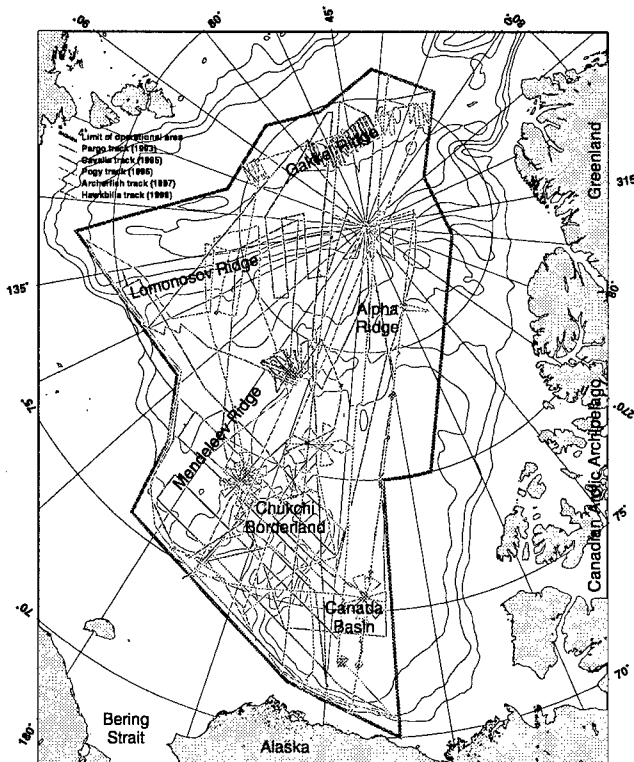


Fig. 1. The data release area (solid black line) and tracks for five SCICEX cruises in the years 1993 through 1998. (Courtesy of B. Coakley)

waters and waters in the United States Exclusive Economic Zone (EEZ). Data were collected from a large portion of the box on every cruise; the cumulative coverage of the first five cruises is shown in **Figure 1**.

Each cruise had several civilian science "riders." Investigators were selected from proposals submitted in response to Broad Agency Announcements issued by the Office of Naval Research and the National Science Foundation. The scientific objectives for each mission were developed by the selected investigators. The staff of the U.S. Navy's Arctic Submarine Laboratory was responsible for planning the mission and providing support to the scientific investigators. The general guidelines for the participation of the agencies and the U.S. Submarine Force in SCICEX were agreed to in August 1994 in a Memorandum of Agreement (MOA).

2.2 Scientific results from SCICEX

The scientific insights being gained from these unique data are substantial. Hydro-

graphic data show a warming of the Atlantic water that circulates counterclockwise around the Arctic Ocean at several hundred meters depth; this indicates a strengthened inflow of warm water into the Arctic Ocean that could affect the ice cover. Chemical tracers provide a detailed picture of the circulation within the Arctic Ocean at all depths, in particular, how strongly circulation is tied to bathymetric features. Sea ice draft data show how thin the ice cover has become in the 1990s, especially in the eastern longitudes of the Arctic Ocean; this may prove to be one sign of the Arctic's response to global warming. Biological and chemical data show the regions where organic matter and carbon dioxide are entering the Arctic Ocean and indicate that the Canada Basin is a large repository for carbon from rivers, the atmosphere, and other areas of the Arctic Ocean. Gravity and bathymetry data suggest that the Earth's crust is thin or nonexistent at the slow-spreading Gakkel Ridge; this confirms some model predictions of magma production at the terminus of a mid-ocean ridge and extends our understanding of entire ridge systems.

More detailed discussions about specific scientific disciplines appear in Section 3 and in the scientific abstracts in Appendices D and E. A bibliography of preliminary results from conferences and of reviewed publications is available in Appendix G and on the SCICEX web site (<http://www.ldeo.columbia.edu/SCICEX/>).

2.3 Observational lessons

Alone among the ships operating in the Arctic, the submarine can operate freely beneath the shifting pack ice. It is also stable and quiet. These attributes make it an ideal platform for underway observations. The great strength of the submarine in the Arctic Ocean is in making repeated basin-wide surveys as well as more localized and detailed surveys and in geophysical mapping. This unique ability argues that submarines should

be exploited for scientific observations primarily in these modes.

Depths of 50 m to 243 m are readily sampled by the submarine itself. Having the submarine spiral down through this depth range provides "vertical" profiles of water properties over these depths, but time lags in the pressure sensor, probably caused by submarine hydrodynamics, make this a poor way to try to resolve hydrographic structure. Expendable probes are presently the best means of sampling above and beneath the submarine between depths of about 25 and 800 m, but only for temperature and salinity. The oceanic mixed layer (above 50 m) is difficult to sample. The submarine avoids maneuvers in this zone close to the sea ice. A series of extremely useful deep casts was made on some SCICEX cruises by surfacing and operating a winch from the ice beside the submarine. However, this procedure is costly of cruise time, and on the autumn cruise of 1997 surfacing in sea ice was not permitted by the U.S. Navy for concern that ice overriding the hull could endanger personnel or damage the boat. Such measurements are more suitable to surface vessels in regions they can reach, but some regions can be reached only by submarines.

Submarine operations and the arctic environment impose severe requirements on the design, fabrication, installation, testing, and operation of scientific instruments. Addressing cutting-edge scientific issues requires instrumentation of the highest possible accuracy and a program of careful calibration and operation. Specially built instruments, designed for the Arctic and appropriately adapted for the submarine, are required to make the most of the unique opportunity offered by the Navy to use submarines for scientific research. Well in advance of any installation, the U.S. Navy requires submission of extensive engineering documentation that describes in minute detail every aspect of any proposed modifi-

cation to the ship. This process requires making a "temporary alteration," or "TEMPALT," to the submarine. The Navy is extremely careful in how it manages TEMPALTs. The detailed process of design and review for a complex TEMPALT can take months and in some cases years, substantially complicating the development and installation of any instrumentation. A scientific program must plan for this process.

3. Scientific Thrust of Future Submarine Observations

3.1 Upper ocean structure and circulation

The upper Arctic Ocean is fed by waters from the Atlantic Ocean that enter through Fram Strait and the Barents Sea, by waters from the Pacific Ocean that enter through Bering Strait, and by rivers that drain North America and Eurasia. Ice formation and melting also contribute to the water mass structure. Prior to 1990, the boundary between the upper water layers dominated by the Atlantic and Pacific regimes was located along the Lomonosov Ridge, but it has since shifted to the Alpha and Mendeleev ridges. Also, the temperature of the underlying layer of Atlantic water (ca. 200—800 m) has warmed by as much as 1°C in some locations, and the water overlying the Atlantic layer in the Eurasian Basin has become more salty (and less stably stratified) during this time. Some of the earliest and most dramatic evidence of this change (Morison et al., 1998) came from the 1993 cruise of USS *Pargo*, which was able to penetrate interior regions of the Makarov and Canada basins that icebreakers had not been able to reach. The recent warming of the Atlantic layer is clearly seen in the temperature difference between the *Pargo* observations and the climatological mean based on data collected prior to the 1990s (Figure 2). Further evidence was obtained on the SCICEX cruises conducted between 1995 and 1998 (Steele

and Boyd, 1998; Smith et al., 1998; Mikhalovsky and Moustafa, 1999). The boundary between the Pacific and Atlantic regimes in the halocline is particularly clear in the distribution of the isotope ^{129}I which originates from European nuclear-fuel reprocessing plants and enters the Arctic from the Atlantic side (Figure 3). The expansion of the Atlantic regime in the upper layer, the increase in the temperature of the Atlantic layer, and the decrease in the salinity stratification separating the Atlantic layer from the ice-covered surface all have the potential to bring about significant changes in the Arctic's contribution to global climate and could even lead to the reduction or removal of the perennial arctic ice cover. It is not known whether the expansion and warming of Atlantic components will continue, reverse, or are part of cyclic behavior.

SCICEX and other recent cruises have shown a strong relationship between the circulation and bathymetry of the Arctic Ocean. Stratification (and thus geostrophic shear) below about 300-m depth is weak, so much of the water column "feels" the bottom. The result is strong bathymetric steering of intermediate and deep water masses. An example is the layer of warm and salty Atlantic Water

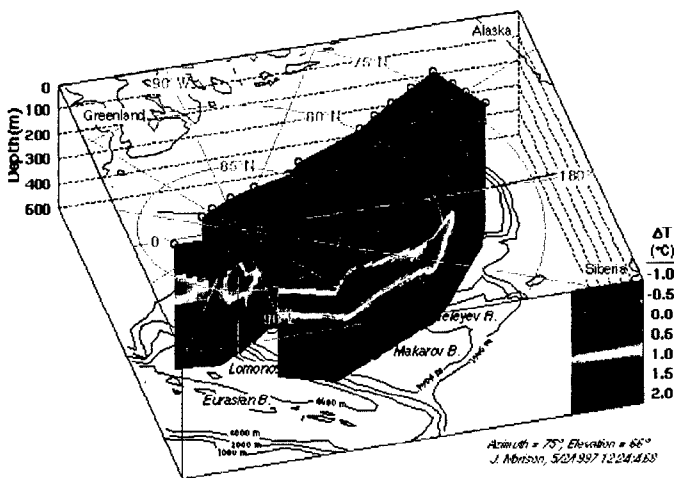


Fig. 2. Temperature difference in the upper 500 m of the Arctic Ocean between the USS *Pargo* observations taken in 1993 and the climatological average. (Courtesy of J. Morison)

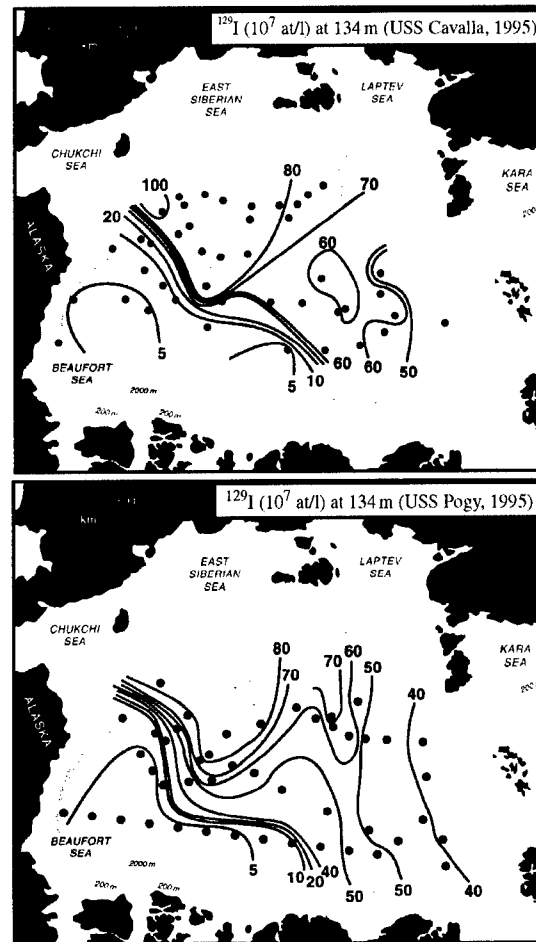


Fig. 3. Maps of ^{129}I distribution at 134 m depth taken on the 1995 and 1996 SCICEX cruises (Smith et al., 1998). Water of Atlantic origin has a high ^{129}I concentration, and water of Pacific origin has a low concentration. (Courtesy of J. Smith)

centered at 200–800 m depth, which flows along continental slopes and ridges. Of course, in some locations ridges intersect slopes, which should create bifurcation points for these flows. These features are for the most part still poorly mapped. Also poorly understood is the variation in the minimum height along most arctic ridges, which is important for determining the evolution of deep-basin water masses. Finally, the shallow continental shelves are another poorly mapped region, where isolated rises and valleys can produce Taylor columns, outflows of dense water, and strong mixing. These all play important roles in the thermohaline structure of the Arctic Ocean. A submarine equipped with Seafloor Characterization and

Mapping Pods (SCAMP) is by far the best tool for accurately mapping bathymetry to aid in understanding circulation issues.

Some regions of the Arctic Ocean, particularly in the Canadian Basin, are difficult or impossible to reach by icebreaker, and thus have had no hydrographic or tracer observations. Recent observations in the Canadian Basin during SCICEX '96 provided high quality data to 1600 m that reveal renewal of the intermediate waters on a decadal time scale (Smethie et al., 1999). The arctic marginal seas of Canada and Greenland remain nearly unsampled, yet are of critical interest to arctic oceanographers. Submarines provide access to these regions far superior to that from ice camps, the only other viable means of access. Submarine observations could also assist in understanding processes important to Arctic Ocean circulation and structure, by providing direct measurements of heat, salinity, and momentum fluxes, and data on the flow of dense water from shelf regions to the interior, the role of eddies in the horizontal transport of water and properties, and small scale circulation and mixing in frontal regions.

Upper Ocean Science Objectives

- Document changes of water properties in the upper ocean, including movement of the boundary between Atlantic and Pacific dominated waters.
- Extend hydrographic observations to poorly sampled regions.
- Improve our understanding of the effect of bathymetry on circulation and of the deep thermohaline structure in the Arctic Ocean.

3.2 Biology and chemistry

The Arctic Ocean is far from the sterile environment its frozen surface suggests. Recent sampling indicates that significantly more biological production occurs in arctic

basins than had been assumed, much in the form of dissolved organic material (Gosselin et al., 1997; Wheeler et al., 1997). Shelf regions are extremely productive and, together with the characteristically short arctic food chains, maintain large populations of marine mammals and other top predators (Codispoti and Richards, 1971; Cota et al., 1996; Rao and Platt, 1984; Grebmeier and Barry, 1991). The biological gradients between shelves and deeper waters have a profound influence on the chemical fields in the Arctic Ocean. The SCICEX program has provided some of the first detailed information on the pathways by which organic matter from shelves is transported to the ocean interior (**Figure 4**). Submarines provide a unique platform from which to chart these pathways and quickly focus on important regions. Arctic rivers, for example, can be significant sources of dissolved organic matter (Guay and Faulkner, 1997). SCICEX data are being used to help sort out the contribution from rivers compared to contributions from the ocean water column and ice algae. Because submarines can extend sampling into winter, they provide the first quantitative basis for assessing seasonal changes in biological fluxes.

Many important biological and chemical signals characterizing arctic processes are within the 243 m depth range that includes surface water and the upper halocline. Submarine sampling, for example, has helped to clarify the size of the carbon reservoir in the upper halocline (**Figure 5**). This is an important water mass that receives biological material produced both locally and on the surrounding shelf regions; chemical signals measured here can be used to infer regional biological production (MacDonald and Carmack, 1991; Wallace et al., 1987; Zheng et al., 1997). The SCICEX program has characterized this layer in parts of the Canada Basin for the first time.

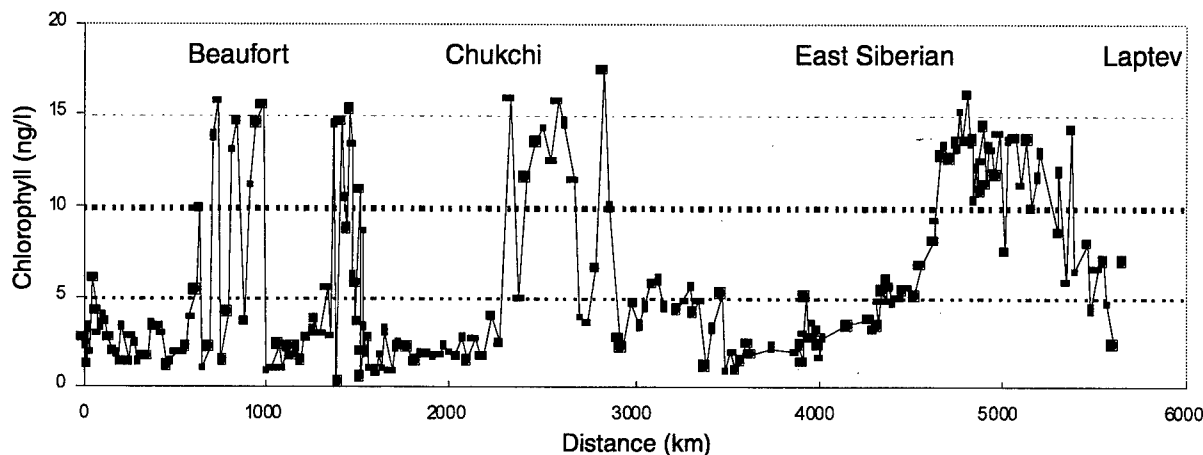


Fig. 4. Chlorophyll concentrations along the shelf edge from Beaufort, Chukchi, E. Siberian, and Laptev seas showing the export of particulate organic matter from the shelves at four locations during SCICEX in April 1995. This track follows the shelf break along the U.S. and Russian sides of the data release area shown in **Figure 1**, 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 which appear to be related to canyons or other depressions in the shelf topography. The left two peaks are probably from Beaufort Canyon. The central peak is probably from Herald Canyon in the Chukchi Sea. The broad peak is probably from the Russian shelf and mostly from the East Siberian Sea. (Courtesy of T. Whitledge)

The Arctic Ocean has received significant inputs of pollutants during the industrial age (Carmack et al., 1997), and the susceptibility of arctic food webs to pollutants is closely associated with the fate of the organic matter described above. Because the movement of most pollutants depends on biological transformations, it is critical to understand how specific populations are linked to microbial productivity. Sampling from submarines can be used to focus on hot spots where such organic matter and pollutant transfers are particularly important, so that the storage and dispersal of pollutants in the Arctic can be assessed and predicted.

A continuation of the SCICEX program would contribute to a time series that can help determine whether there are trends in the biogeochemical cycles in the Arctic. Existing data are too sparse to tell whether physically forced decadal oscillations give rise to specific chemical or biological responses. The situation is even less clear for longer time-scale changes associated with potential climate warming in the Arctic. Such changes may alter the role of the Arctic in the global carbon cycle (Anderson et al.,

1990; Anderson et al., 1998) in addition to changing the biological communities that the Arctic now supports.

Thus, despite the critical role the Arctic plays in the global environment (Aagaard and Carmack, 1994) and despite the climatic changes that may be occurring in the near future, there are few data with which to address many of the first-order questions about the biology and chemistry of the high Arctic. The SCICEX program has demonstrated that submarines can ameliorate many of the logistical limitations imposed on other platforms in ice covered regions and can significantly improve the sampling of transient or spatially variable biogeochemical signals. Future submarine sampling can be coordinated with planned programs in arctic biogeochemistry. For example, submarine cruises could be coordinated with sampling in the Alaskan shelf region during the upcoming Shelf-Basin Interaction project (Grebmeier et al., 1998). Such interaction between SCICEX and other research programs greatly leverages the impact of the scientific sampling, as has been evidenced by the SCICEX work with the Surface Heat

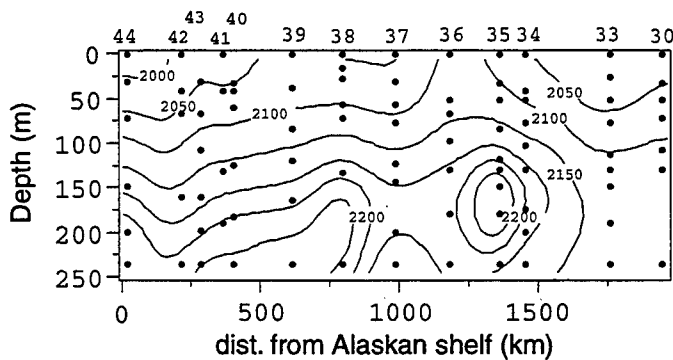


Fig. 5. Section of dissolved inorganic carbon (DIC) concentrations, in $\mu\text{mol kg}^{-1}$, in the Canada Basin collected during Phase 2 of the SCICEX '96 cruise. The north coast of Alaska is on the left, and the Lomonosov Ridge is on the right. Elevated concentrations were found at depths from 100 to 243 m in the region of the upper halocline layer, and most of this carbon likely has come from shelf regions and rivers. (Courtesy of R. Sambrotto)

Budget of the Arctic (SHEBA) station. The interaction among programs also provides the Navy access to a broad range of additional scientific expertise in ocean science.

Biogeochemistry Science Objectives

- Understand the production and cycling of carbon in the Arctic Ocean.
- Determine the fluxes and storage of chemical tracers and pollutants.
- Establish the food chain from microbes to large mammals.

3.3 Sea ice

The first things we want to know about sea ice are its extent and its thickness. Such knowledge has applications in understanding physical, chemical, and biological systems in the Arctic, in a broad range of engineering problems related to operations in the Arctic, and in studies of environmental change. Satellite remote sensing has proved to be an excellent way to monitor ice extent. As a result, good data sets extending over two decades have revealed the seasonal and inter-annual variations in ice extent (Cavalieri et al., 1997). On the other hand, our understanding of ice thickness is rather crude. We cannot, for example, state the mean thickness

to a precision of better than about 20%, and we cannot say whether the mean has increased or decreased over any period of several years. We have theories for how the ice thickness distribution—the local mixture of ice of different thicknesses—may evolve in time (Thorndike et al., 1975) and routinely use these theories in sea ice models (Hibler, 1980), but have only begun to test these ideas. Models that include interactions between the ice cover, the ocean, and the atmosphere are used to predict how ice thickness may have changed in the recent past and may change in the future, but, again, our observational base is not adequate to test these predictions. At present, the claim that sea ice thickness may be a sensitive indicator of change in the Arctic remains to be demonstrated. We don't have adequate systems in place to observe changes in ice thickness, and we don't know how ice thickness is related to other climate processes that may also be changing.

Nevertheless, there are reasons to expect progress. First, there is a large backlog of ice thickness data, some from SCICEX and many other earlier submarine cruises, and some from moored upward-looking sonars. We can expect analysis of these data over the next few years to improve our historical data base. Second, as a result of SCICEX cruises, we have a better understanding of the statistical properties of the ice thickness and can design more appropriate sampling and data processing strategies. Third, current sea ice models are capable of resolving time and space variations in thickness distribution (e.g., Flato, 1995). So while these variations make it harder to measure the mean thickness, they nevertheless present a modeling opportunity. In effect, every measurement of thickness distribution, no matter where or when, becomes a validation point for a model, as illustrated in Figure 6. Fourth, there is a lively interest in examining other measurement techniques that may place

independent constraints on the ice thickness. These techniques include acoustic tomography, satellite altimetry, and analysis of wave propagation in the ice pack. The final reason supporting an optimistic view is the prospect of continuing observations from submarines and moored instruments.

The thickness distribution displays the relative abundance of ice of different thicknesses. The distribution evolves in response to ice transport, deformation (ridging and lead formation), and thermodynamic growth and melt. According to various estimates (e.g., Flato, 1995), ridged ice accounts for about half of the total volume of arctic ice,

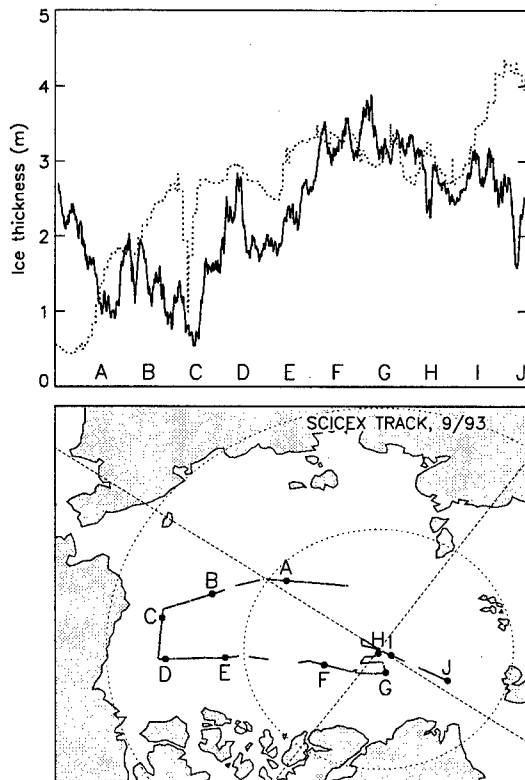


Fig. 6. (upper) Comparison of modeled mean ice thickness (dotted line) and mean ice thickness measured during SCICEX '93 along the transect of USS *Pargo* (solid line). (lower) Map of cruise track showing locations. Because the model captures the major change in thickness from about B to H, the correlation between the model and the observations is fairly strong, 0.5. However, there are still many locations where the model and observations differ by over a meter, leaving a need for model improvement. (Courtesy of D. Rothrock, Y. Yu, and J. Zhang)

and thus it is an important component of the ice mass balance and its long-term variability. However, the processes that form ridged ice are represented inadequately in present models. Repeat surveys of ice thickness that follow a particular patch of ice provide direct observations of the changing thickness distribution, allowing quantitative evaluation of model results and insight into the dynamic and thermodynamic processes involved. Initial experiments in SCICEX '96 show changes in distributions over a 40-day interval that are big enough to test models (see Babko and Rothrock in Appendix E). More such case studies are needed.

The orientation, shape, and spacing of features such as ridges, leads, and floes are not represented at all in present models, although this is an area of active research (e.g., Hibler, 1997). Practical applications of these geometric observations include ship routing and selection of surfacing opportunities for submarines. Scientific applications are based on the idea that the ice pack may have anisotropic mechanical properties and that this anisotropy can be understood in relation to the orientation of these observable features. Progress in this area would benefit from areal, as opposed to linear, observations of the variation of ice thickness.

On larger scales, the time-varying spatial patterns of mean thickness and other thickness and feature statistics reflect the response of the ice cover to changes in atmospheric and oceanic forcing. Recent satellite observations indicate a statistically significant reduction in the area covered by arctic ice over the past two decades (Cavalieri et al., 1997), while other observations indicate variations in ice circulation and outflow to the North Atlantic. Analyses of the regional and basin-scale variations in ice mass balance, estimates of natural variability, and tests of the variability seen in models (**Figure 7**) require long time series and broad coverage. Continued processing and release

of archived data obtained from upward-looking sonars on submarines are the sole source of historical information for such studies. Continuation of submarine data collection will provide the raw material vital for future studies.

Observations from submarines can also be used to study optical and acoustic properties of the sea ice. This received little discussion at the workshop, but should not be overlooked. The light that penetrates the ice pack regulates biological growth and heats the upper ocean. Furthermore, light carries information about the condition of the ice above that can be interpreted in terms of ice thickness, snow depth, melt ponds, etc. Submarines operate in an acoustic environment that is affected by the ice pack. The ice

Sea Ice Science Objectives

- Determine basin-scale variations in the ice thickness distribution.
- Observe year-to-year changes in the thickness distribution.
- Provide data to test ideas about how the thickness distribution evolves.
- Provide data to test theories relating anisotropic mechanical properties to the geometry of the ice cover.

affects the propagation of acoustic signals and is itself a source of acoustic noise.

3.4 Marine geology and geophysics

The Arctic Basin has evolved through time (Figure 8). Subsidence, uplift, and sea floor spreading (Srivastava and Tapscott, 1986) have expanded the basin since the mid-Mesozoic and regulated oceanic circulation patterns. Geological and geophysical studies of the Arctic Basin seek to improve our understanding of its tectonic evolution, which is crucial to understanding much of arctic history.

The two basins that make up the Arctic Ocean, the Eurasian and Amerasian, have distinctive plate tectonic histories. Very little is understood about the development of the Amerasian Basin and its inactive plate boundaries, which limits our understanding of the tectonic provinces of northern North America and Asia. Although the Eurasian Basin is much better understood in terms of plate tectonics, the ultra-slow seafloor spreading observed there provides an exceptional opportunity to test hypotheses formed at other, faster spreading ridges.

At its northern extremity, the Gakkel Ridge, the Mid-Ocean Ridge system of the Atlantic is characterized by spreading rates ranging between 0.6 and 1.3 cm/year. This is the slowest spreading observed anywhere on this ridge system. Spreading influences the rate of melt production in the mantle, the

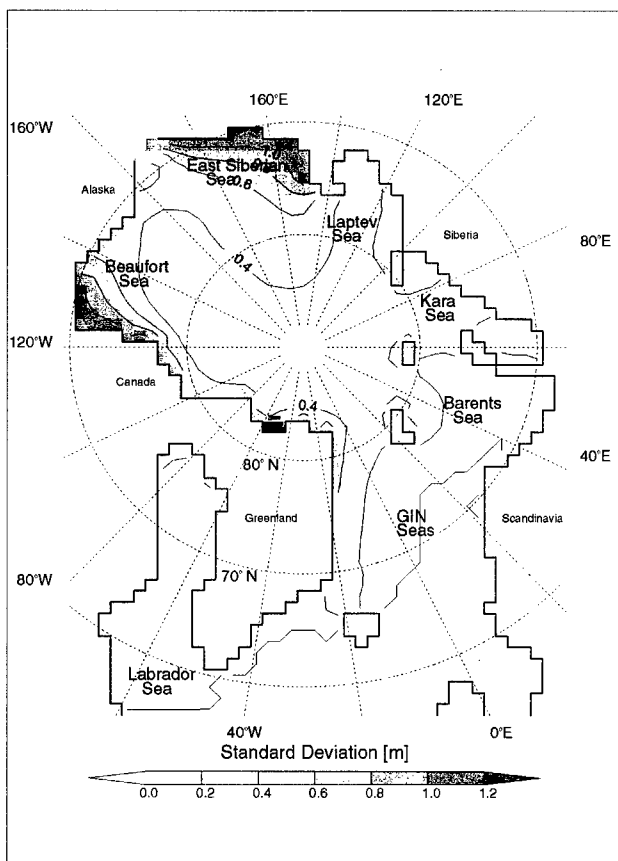


Fig. 7. Standard deviations of the annual means of simulated ice thickness for the period 1958—1997 in meters as a measure of the interannual variability. (Courtesy of M. Hilmer)

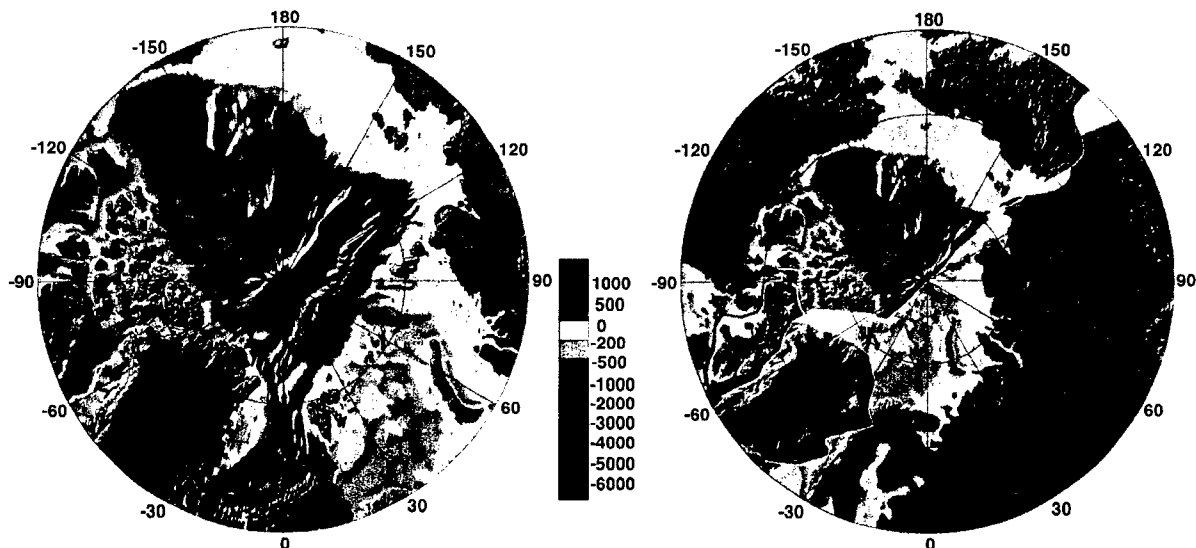


Fig. 8. (left) Present configuration of the Arctic Ocean and (right) reconstruction of its configuration 118 million years ago when it was about half its present size. Topography is shown in meters. (Courtesy of S. Srivastava)

thickness of the crust, and the tectonic features associated with the ridge (Reid and Jackson, 1981). SCICEX data gathered from USS *Pogy* in 1996 indicate that the oceanic crust may be very thin or nonexistent (Coakley and Cochran, 1998), providing an exceptional opportunity to examine the seafloor spreading process in some detail. SCAMP data collected along the Gakkel Ridge in 1998 will be augmented by additional data acquired during 1999 to complete a map of the faster spreading portions of the ridge out to 50 km on either side of its axis. These data will provide very useful support for future cruises to sample the seafloor or conduct other geophysical experiments.

The origin of the Alpha Ridge is an enigma. Some evidence supports a magmatic origin. This interpretation is consistent with the massive outpourings of lava that are recorded onshore on the Canadian Arctic islands. If so, these features represent a large igneous province formed when the mantle circulation was more vigorous than it is today. The geological development of the entire Amerasian Basin cannot be determined without better information on the structure, composition, and age of the Alpha Ridge.

The Lomonosov Ridge has a very different origin. It appears to be a sliver of Eurasia

that was rifted from the edge of the Barents and Kara seas by propagation of the Gakkel Ridge across the basin. Better definition of tectonic features such as boundary faults, transverse faults, and segmenting along these ridges will help to clarify their origin, development, and relationship to the Gakkel Ridge. Data collected so far during SCICEX have relocated the Lomonosov Ridge east of its previously mapped location and shown an extensive area of extended continental crust on the Amerasian margin of the ridge. Investigation of this extension is one of the primary goals of SCICEX '99.

The sedimentary record in the Arctic Ocean holds the story of past climates. Understanding that story will give us perspective on changes occurring now in the Arctic and in the global climate system. The relatively shallow mid-ocean ridges are likely targets for coring. The sedimentation rates there are slow, and the geological environment is peaceful, leaving the record undisturbed. Cores should reach back millions of years (Grantz et al., 1998). On the other hand, cores from the shallow continental shelves, where sedimentation rates are high, can provide detailed information about glacial-interglacial cycles on scales from submillennial to tens of thousands of years.

Evidence of glacial erosion and iceberg

scouring is found on the shelves and on shallow mid-ocean plateaus and ridges, as evidenced in **Figure 9**. These glacial bedforms provide crucial information on Pleistocene glaciations in the Arctic and related paleoclimatic changes.

The arctic continental shelves also sequester methane hydrates. There is evidence that massive slides have occurred along the shelf breaks. It is likely that these slides released methane gas to the atmosphere, where it would affect the longwave radiation balance.

Progress on these two fronts—tectonics and paleoclimate—will require a variety of geophysical measurements. Some, such as extracting sediment cores, may be some years away and will require surface ships. But the point to be emphasized here is that all geophysical studies of the ocean require good bathymetric data, and the submarine is an excellent platform for mapping the sea floor. SCAMP, designed and fabricated for use in the Arctic on submarines, was tested and proven during SCICEX '98. It consists of a SeaMARC-type sidescan sonar, a chirp

subbottom profiler, and a data acquisition and quality control computer system. The sidescan sonar collects data along a swath that can be processed to create images of bathymetry and backscatter representing the geometry and texture of the seafloor. The subbottom profiler can image shallow strata down to 100 to 200 m. **Figure 9** is an example of the kind of detailed mapping SCAMP can produce. It is common to find errors in arctic charts. We simply do not know the bathymetry. Two strategies are suggested: first, to equip all submarines with SCAMP or equivalent technology, so that new bathymetric data can accumulate from all cruises; second, to design missions to map regions of special interest. Mapping of candidate coring sites, for example, is absolutely required before final site selection and actual coring from surface ships can begin. There are other measurements that can and should be made—gravimetry is an example—but the important point is that the geophysical community needs better bathymetric data and high resolution seismic data, and a SCAMP equipped submarine is a superb way and in

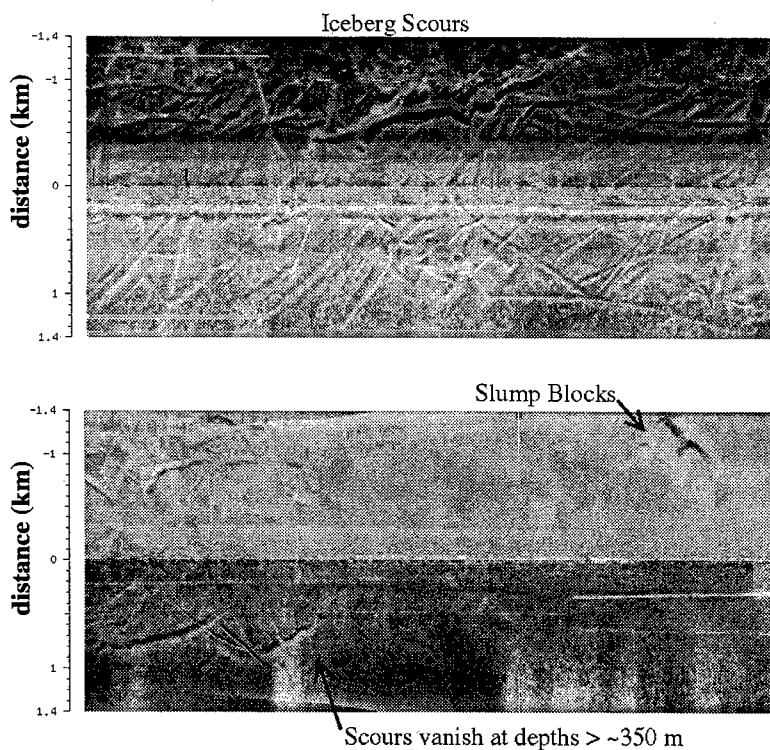


Fig. 9. Two sections of SCAMP sidescan sonar data for the Chukchi/Alaskan margin acquired aboard USS *Hawkbill* during SCICEX '98. (upper) Data acquired in water depths less than 300 m exhibit pronounced iceberg scouring. (lower) Depth increases from under 350 m at the left side of the image to 450 m at the right. High acoustic returns are white; low returns and acoustic shadows are black. Swath width, which is just under ten times the water depth, is shown on the left of each image. (Courtesy of M. Edwards)

many areas the only way to get them.

Understanding the tectonic history of the Arctic Basin will place paleoclimate studies in context, constraining the timing of the various fluid fluxes that are an essential control on ocean circulation in the northern hemisphere. It will also allow proper planning for ocean drilling programs to recover paleoclimatic records from condensed sections on high ridges in the basin. By using submarines to explore the basin, we can lay the groundwork that allows subsequent surface cruises to accomplish several different goals; for example, making deep water hydrocasts, coring or drilling the seafloor, and acquiring multichannel seismic data.

Geology and Geophysics Science Objectives

- Improve bathymetric data to support studies of tectonic development, ocean circulation, and paleoclimate.
- Identify sites for subsequent sampling by coring, drilling, and dredging.
- Map glacial erosion, iceberg scours, and other ice-formed features on the shelves and high plateaus and ridges in the basin.
- Characterize the ultra-slow spreading Gakkel Ridge to answer questions about seafloor spreading that can be addressed only in the Arctic.
- Search for the plate boundaries that must exist in the Amerasian Basin.
- Map sedimentary features, such as deep-sea channels and mass wasting deposits, to characterize sediment fluxes into the deep Arctic Ocean.

4. Future Submarine Science Missions

4.1 Three mission scenarios

The workhorse of the Arctic has been the 637 *Sturgeon* class submarine. It is fully ice capable. All SCICEX cruises have been car-

ried out on this class of vessel. This class is being retired; the last *Sturgeon* class submarine is scheduled to be decommissioned by the year 2001. The future of arctic operations lies with the *Seawolf*- and the 688 *Los Angeles* class. The early versions of these vessels are not fully ice capable; the later 688-Improved class vessels are considerably more ice capable. Tests are presently being carried out to confirm the under-ice operational capabilities of both the 688s and 688-Is. By the year 2000, the number of attack submarines in the fleet will be reduced to about half of what it was in 1993 when USS *Pargo* conducted the proof-of-concept cruise as a precursor to SCICEX.

In his workshop address (reproduced in Appendix C), Admiral Ellis gave the first public statement from the U.S. Navy Submarine Force about the possible shape of a future submarine-based science program. The bottom line is that cruises dedicated to science in the mold of SCICEX may recommence at some point, but that there will be a period of some years when the science opportunities on submarine cruises will be limited.

Excellent scientific research can be achieved with the access to submarine cruises that Admiral Ellis outlined. Below we describe the scientific components for three future cruise scenarios: Baseline Data Missions, Science Accommodation Missions, and Dedicated Science Missions.

4.2 Baseline Data Missions (BDM)

For arctic marine science, it is highly desirable that the Submarine Force, with the assistance of ASL, make some nonclassified scientific observations as a routine part of all arctic submarine missions with a suitable security classification. This concept of "automatic" science operations could be expanded as far as the Navy can allow. These cruises might be called Baseline Data Missions (BDMs).

Baseline Data Mission characteristics

- No influence on cruise track.
- Minimal impact on submarine's crew.
- Minimal training of submarine's crew for science tasks.
- No civilian science riders.
- Data from within the "SCICEX box" released by prior agreement.

Observations

- Digital recording of time, position, depth, and other scientific data.
- Log book.
- Ice draft profile data.
- SSXCTD data instead of SSXBT.
- Sail CTD data.
- Gravity data.
- Bathymetric profile data from operational systems.
- Calibration samples for underway sensors.
- No other water samples.

We assume that on all arctic missions there would be riders from the Arctic Submarine Laboratory who would perform scientific tasks. When we speak of minimizing any impact on the crew, we are speaking of the submarine crew.

For upper ocean studies, we recommend that during the daily housekeeping an SSXCTD be released instead of an SSXBT and that temperature and salinity data be continuously collected with the sail CTD. As discussed in Section 5.2, this step would improve salinity and depth accuracies. For sea ice, narrowbeam, upward-looking sonar profiles of ice draft at least as good as those available from 637 class submarines are essential for scientifically useful data. The overriding motivation for conducting physical oceanography and sea ice measurements in BDMs is to identify the cyclical or secular nature of changes in the upper ocean circulation, temperature, and salinity structure and of changes in the ice cover. For biogeochem-

istry studies, the sail system can collect fluorescence, oxygen, and beam transmission data. Periodic calibration samples must be collected for any sensor operating on a cruise. For geology and geophysics, navigation information, high-density narrowbeam bathymetry data, and gravity data should be acquired along all tracks. For biology and geology, the driving goal in BDMs is to extend basic surveys of the Arctic Ocean. We recommend that such data be recorded on all arctic cruises and promptly processed, declassified, and released by ASL for the approved data release area.

Location and time are critical aspects of the data. For the SCICEX data, the declassification guidelines allow exact time and position information (within the SCICEX data release area) to accompany the data. The SCICEX position and time accuracies are quite sufficient for scientific purposes. It is recommended that data releases from BDMs, SAMs, and DSMs follow the SCICEX declassification guidelines and not the more stringent criteria associated with classified ICEX missions, for which exact time and position are not released and for which the data release area (the "Gore Box") is roughly half the size of the SCICEX box. Clearly, however, data released under the more severe ICEX restrictions are better than none. For underway data recording, a system similar to the Submarine Data Recording System (SDRS) used in SCICEX is essential.

4.3 Science Accommodation Missions (SAM)

In addition to BDMs, the opportunity to carry out occasional preferred transects is of huge interest to the scientific community. Blocks of a few days dedicated to science projects would permit the sampling of regions determined from SCICEX and other cruises to be of particular importance. Impacts on submarine operations would include additional time for higher density

SSXCTD sampling, time for collecting and space for storing water samples, and somewhat more sophisticated instrumentation. At some point, a mutually agreed upon science plan for the mission becomes necessary. Altogether, this fits well within possible submarine arctic transects and would provide outstanding scientific information.

A SAM has all of the BDM characteristics with these changes:

Science Accommodation Mission characteristics

- Some impact on cruise track.
- Some impact on crew for data collection requiring some training.
- Manifold for water sampling, tap or flow-through.
- Other modest TEMPALTs.

Observations as in BDMs, plus

- Water samples.
- A sampling manifold to obtain conductivity, temperature, fluorescence, and oxygen measurements, in addition to the sail CTD.

A possible scheme for water property observations utilizes the four sampling corridors shown in **Figure 10**. Each corridor is about 100 km wide; data would be collected along lines run through these corridors. The corridor sampled on any given mission would be chosen based on the time available for science projects and the operational area of the submarine. It is hoped that corridor 1 would be sampled about once a year and the other corridors once every 2 years. Sampling along each line would consist of SSXCTD drops and CTD measurements from the flow-through manifold with vertical water sampling at eight depths between 40 and 240 m. These measurements would be taken every 20 km for corridor 1 and every 40 km for the other corridors. The manifold sampling can be done either in a spiral pattern or as the submarine moves slowly along the track.

Water samples from the manifold would be collected to determine salinity, ^{18}O , barium, tritium, ^3He , ^{129}I , ^{137}Cs , CFCs, oxygen, nutrients, and carbon system variables. Temperature and salinity measurements from the manifold CTD would be obtained continuously along the cruise track at a single depth with once or twice daily salinity calibration samples. Retention of the sail-mounted CTD would provide redundancy, establish that the manifold mounted system was working correctly, and, with adequate calibration and synchronization, allow the possibility of observing vertical gradients over the roughly 13 m between the sail and manifold intake.

SAMs require several modest class TEMPALTs, including one for SSXCTD launches and one for a flow-through manifold with temperature and conductivity sensors. The SSXCTD launches require data logging (included with the device electronics) and maintenance of a launch log sheet. Underway CTD sampling requires accurate recording of time and position along with the CTD data. The water samples require storage space and maintenance of a log sheet. For continued high quality ice draft data, the ice profiling and recording system on the 688-I class submarines would require a class upgrade as discussed in Section 5.2.

4.4 Dedicated Science Missions (DSM)

A Dedicated Science Mission would be similar in format to SCICEX cruises and would include the features of a SAM with some crucial additions.

Dedicated Science Mission characteristics

- Control of cruise track for tens of days.
- Civilian science riders.
- More elaborate TEMPALTs.

Control of the cruise track permits intensive surveys of oceanic or ice features and processes. It is crucial for surveys of geolog-

ical features of special interest. Coordinating submarine cruises with icebreaker missions is desirable so that complementary data such as geological samples and deep-penetrating seismic reflection and refraction profiles can be acquired. Control of the track allows coordination with other science programs, as was done during SCICEX '97 and '98 with the SHEBA program. It permits synchronizing with satellite overpasses, for example, to test satellite altimetric estimates of ice thickness.

The inclusion of civilian science riders opens possibilities for onboard analysis of water samples to determine biological variables, rates of biological processes, and trace chemical concentrations. These are crucial tests for understanding how the biological and chemical state is maintained rather than just observing the state itself as in the other mission scenarios. The geological program also benefits by having on board scientific staff with expertise in specialized computing systems.

The acceptance of more complicated TEMPALTs opens the program to a wider

range of observations, such as measurements by Acoustic Doppler Current Profilers (ADCP), a sea ice swath mapper, and SCAMP, and to new techniques for sampling outside the SCICEX range depth of 50 to 243 m. Instrumentation is discussed in the next section.

These additions enable DSMs to address important scientific questions beyond the scope of BDMs and SAMs. As with SCICEX to some extent, each cruise might have a top priority theme. We list some examples of objectives for dedicated missions.

- 1) Gather critical data for validating the next generation of the Navy's operational Polar Ice Prediction System (PIPS 3.0) ice-ocean model. These data would include the temporal and spatial variability of sea ice thickness and water column structure, orientation of leads, deductions from chemical tracers of the large-scale current structure, and near-surface current measurements with ADCPs. Regions with little existing data, including those outside or at the periphery of

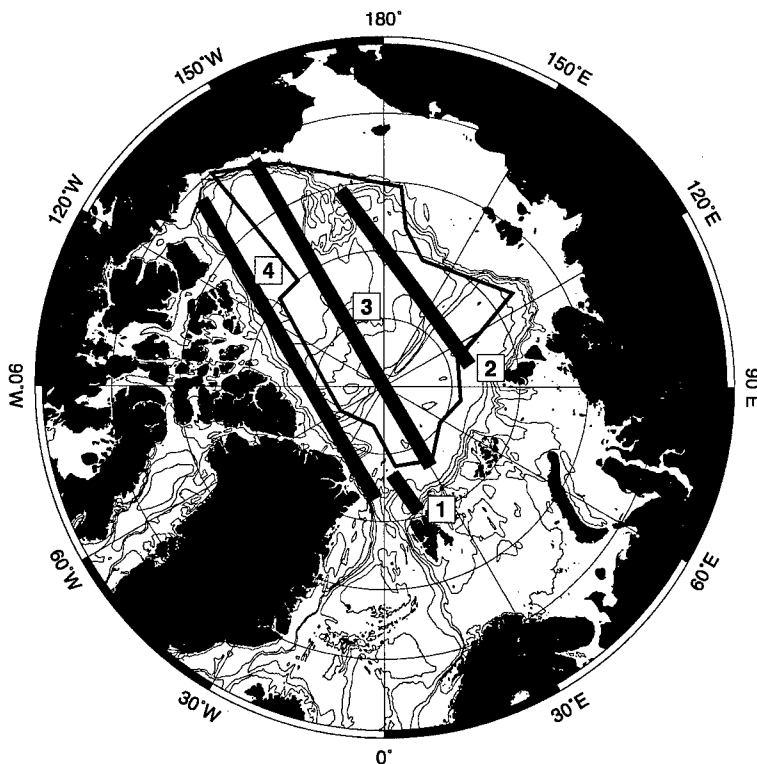


Fig. 10. Sampling corridors proposed for oceanographic observations during SAM operations. Corridor 1 is located just north of Svalbard and crosses the inflow of Atlantic Water through Fram Strait. Corridors 2 and 3 cross at right angles to the Lomonosov and the Alpha-Mendeleev Ridges—and hence to the associated boundary currents and to the Atlantic/Pacific boundary. Corridor 4 parallels the Canadian/Greenland margin in a region where oceanographic observations are sparse and the need for ocean and ice information is particularly crucial for developing and verifying ice-ocean models. Corridor 4 is within Canadian and Danish waters; the science communities within both countries have indicated a desire for scientific submarine cruises to be conducted in these regions. The corridor can be shifted to outside their territorial waters if needed, although in this case the corridor would be split into two segments; the segment south of 80°N would overlap corridor 3, and the northern segment would lie along the edge of the box.

the SCICEX data release area, would be of special interest.

- 2) Study specific instances of changing ice thickness distributions. This would include repeat surveys of a patch of ice separated by a period of a month or longer but within a single season of growth or of melt. Tests should include seasonal ice in the Beaufort Sea.
- 3) Observe bathymetric features of special geological interest, such as the slowly spreading Arctic Mid-Ocean Ridge and the junction of the Alpha and Mendeleev Ridges, which holds secrets about the evolution of the Amerasian Basin. Observe candidate sites for subsequent coring from surface ships; examples are the Lomonosov Ridge, the "Canadian end" of the Alpha Ridge, and the Morris Jessup Rise north of Greenland. Also observe features that strongly affect ocean water masses and circulation, such as the height along the Alpha, Mendeleev, Lomonosov, and Nansen-Gakkkel Ridges, the intersections of ridges with continental slopes, which steer currents, and valleys that cut through continental shelves and drain shelf waters into deeper waters.
- 4) Collaborate with the Shelf-Basin Interaction (SBI) program, the Study of Environmental Arctic Change (SEARCH) program, and the Nansen Arctic Drilling program, to name several examples.
- 5) Take advantage of future invitations for U.S. submarines to collect data in arctic exclusive economic zones and territorial waters of other countries. All disciplines would benefit from data from the data-poor regions in the Canadian, Greenland, and Norwegian exclusive economic zones; in many cases, the submarine is the only viable scientific platform.

5. Observational Capabilities of Submarines

Some SCICEX observational methods should be improved in accuracy, calibration, or reliability. Other advances are well within reach using new instrumentation or technology. We review both issues here. We do not try to include all possible new sensors or measurements.

5.1 Ship's own data

Measured quantities lose all value without position and time tags. During SCICEX cruises on 637-class submarines, position and time were recorded by a SDRS. The SDRS captures the submarine's own data, which include position, heading, speed, depth below the surface, and height above the bottom. The SDRS is interfaced to the Data Acquisition and Quality Control System (DAQCS), which is part of SCAMP. DAQCS records the binary data stream and provides software tools for decoding and displaying the data. The position data obtained from the SDRS are the only way to geo-reference the underway data that are crucial to the SCICEX cruises, for example, data from the sail mounted CTD, ice profiler, gravimeter, swath mapper, subbottom profiler, ADCP, and Zero Angle Photon Sensor.

Post-cruise data processing requires significant effort to reduce spurious outliers in the raw navigation data and produce reliable cruise tracks. Data quality is not as good as the research community is used to on surface ships, where use of P-code and/or differential GPS is a common practice. The precision of the SCICEX navigation data needs to be matched to the accuracy requirement(s) of the specific scientific mission. Continuous availability of navigation data requires a robust and redundant data acquisition system. To this end, a Ring Laser Gyro (RLG) is being carried on SCICEX '99.

Future scientific cruises will require access to the ship's own data stream similar to that in SCICEX. Depending on the existing data infrastructure, it may be necessary to install an SDRS-like TEMPALT or to develop an alternate interface between DAQCS and the boat's own data.

5.2 Scientific instrumentation

Upper ocean — physical, chemical, and biological

The observational requirements for the upper ocean are presented in **Table 2** grouped by mission type. For the upper ocean, the most important short-term improvements are

- to obtain more accurate salinity and depth data from XCTDs for observing vertical profiles of temperature and salinity. Below about 200 m, the change in salinity is presently lost in instrumental noise. Better accuracy of ± 0.003 psu is needed.
- to improve water sampling with a flow-through manifold.
- to obtain currents throughout the vertical range from about 200 m above to 200 m beneath the boat by means of upward and downward looking ADCPs.

Biogeochemistry would benefit from underway sampling packages on a flow-through manifold with smaller instruments that require a smaller sample size, provide better precision, and a more rapid sampling rate. Such a system should be tested on a non-arctic mission before being deployed on an arctic science mission. For BDMs and SAMs, the data logging systems must be robust and reliable in "hands off" operation. Based on system upkeep requirements during SCICEX, this may require additional development.

For longer range development, possibly for use in DSMs, the focus for upper ocean research is to extend the vertical sampling range above 50 m and below 243 m. This

has been done previously by surfacing and taking deep casts from winches placed on the sea ice cover. Some possible technologies for accomplishing this goal without surfacing are

- An upward profiling SSXCTD to measure temperature and salinity between the submarine and the surface. This would provide upper ocean information critical to ocean circulation studies and ice models. It could be launched from the present launcher. It might require a pressure sensor because the changing salinity would alter the rise rate. Once developed, it could be used on BDMs and SAMs.
- A yo-yo CTD system that could be mounted on the hull by a diver to provide high quality CTD measurements down to 1500 m. The present SSXCTD salinity is not sufficiently precise to capture salinity variations below about 200 m, and given the cost of SSXCTD probes it may be more cost effective to develop a new CTD system that would provide much better data.
- Autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) and a means to operate them from the submarine. This development would enable sampling over the full water column and benthic sampling. This technology is complex and may be beyond the financial means of an arctic submarine science program; however, it may be possible to adapt existing Navy hardware for use in the submarine science program.

Sea ice

The observational requirements are listed in **Table 3**. The essential observation for sea ice on all missions is ice draft profiles. During SCICEX cruises, the digital ice draft data from the ship's OD-161 topsounder were recorded on the Digital Ice Profiling System (DIPS), along with crucial ancillary data: ship's speed, depth, position, and heading.

Table 2. Observations required for the upper ocean.

Measurement	Done in SCICEX?	Comments
Observations for Baseline Data Missions		
SSXCTD: temperature, salinity, pressure (depth)	Routinely	Need better sensor precision (± 0.003 psu) and calibration for water beneath halocline. Need a pressure sensor to calibrate or replace fall rate.
Sail CTD: conductivity, temperature, fluorescence, beam transmission	Routinely	Pre- and post-cruise calibration are necessary.
Water sample port	Routinely	
Flow-thru CTD and water sampling manifold	No	Designed for <i>Sturgeon</i> class but not tried. It could probably replace the sail CTD and the water sample port. Its advantage over the sail CTD is that sensors can be replaced and repaired without surfacing and water samples can be collected easily.
Autosal salinity	Routinely	Need two samples per day to calibrate the sail or flow-thru CTD. Calibration can be made with an Autosal operated on board, or samples can be stored and analyzed on shore.
Observations for Science Accommodation Missions, in addition to those above		
Tracers: Barium, tritium, ^3He , ^{18}O , ^{129}I , ^{137}Cs	Routinely	Water samples must be stored (unfrozen).
CFCs	Routinely	High CFC concentrations in submarine air cause contamination of samples collected on board, but surface stations provide clean samples. A new sampling method is being tried in SCICEX '99.
Nutrients: NO_3 , NO_2 , PO_4 , SiO_3 , NH_4	Routinely	Water samples must be stored (frozen).
Dissolved inorganic carbon	Routinely	Water samples must be stored (unfrozen).
Dissolved oxygen	Routinely	Water samples must be analyzed on board.
Oxygen sensor	Routinely	Can be installed on sail CTD or flow-thru CTD. Must be calibrated by measuring dissolved oxygen in on-board water samples.
Particles	Routinely	Filtered samples must be stored (frozen).
Beam transmission	Routinely	Requires occasional calibration.
Observations for Dedicated Science Missions, in addition to those above		
Horizontal currents: upward- and downward-looking ADCP	Upward-looking ADCP used routinely	Requires installation at pier.
Horizontal currents: XCP	No	Requires electronic modifications. Would be launched in a manner similar to the SSXCTD.
Fluorescence (ZAPS)	Routinely	Requires hull installation at pier.
Bacterial growth, genetic analyses, viruses	Yes	Requires complex onboard processing and storage space.

On 637 class submarines, those ancillary inputs come from either the BQS-14A sonar or the SDRS. The first flight 688's have an identical topsounder in the BQS-15 sonar system. To record the ancillary data, however, either an SDRS must be installed or a new interface must be built between the DIPS and the synchronization signal sources. Ice draft data from the BSY-1 sonar on 688-I class submarines, are less accurate than are from the OD-161 and are not recorded.

We recommend that OD-161 and DIPS or an ice swath mapper be installed as class TEMPALTs for all 688 and 688-I DSM missions to the Arctic.

Further, to prevent the loss of ice draft data, *we recommend that a backup DIPS recorder be installed, or a rigorous protocol be developed for recording ice draft data, or both.*

There are two primary sources of error in estimating ice draft. One is uncertainty about the vertical sound speed profile. The use of XCTD data could reduce this error if the sampling rate were sufficient to track changing water properties and structure. A more continuous estimate of sound speed could, in principle, be obtained by installing multiple transducers along the hull, but this method remains untested. The second source of error is uncertainty about the depth of the

sonar transducer. When the pressure sensor on the submarine fails or works intermittently, depth is estimated during data post-processing by identifying patches of open water and interpolating between them. A more robust pressure sensor, and synchronization with the sail-mounted CTD to provide a redundant pressure signal, would reduce the error associated with sensor failure. Independent barometric pressure data could also be introduced into the processing stream; every millibar of uncertainty in surface pressure translates to a centimeter of uncertainty in submarine depth and hence in ice draft. Finally, improvements in the data acquisition system (notably reduced reliance on operator settings of threshold and gain) would reduce uncertainties in the digital data produced by DIPS.

An ice swath mapper is similar to the sea-bottom mapper SCAMP in concept but requires more modest alteration to the submarine. An instrument is currently available (see white papers by Goff et al. and Tucker and Anderson in Appendix F), and *we recommend that it be tested as soon as possible.* Processing of data from such a system is more demanding than that for single-beam system. For consistency with historical data, *we recommend that if an ice-swath mapper is installed, the overhead nar-*

Table 3. Observations required for sea ice.

<i>Measurement</i>	<i>Done in SCICEX?</i>	<i>Comments</i>
Ice draft profiles from upward-looking narrowbeam sonar	Yes	Has been a standard observation on all arctic cruises for decades. Digital data should be acquired on every mission.
Sonar depth from pressure sensor	Yes	More reliability needed.
Sound speed correction	Yes	Reduce draft error.
Ice draft topography with ice swath mapper	No	System is proposed, accepted and ready to test.
Light transmission	No	Calibrated broadband photometer.

row beam profile data be recorded as an independent and redundant data stream.

Such a system could also provide a real-time, three-dimensional display of the ice canopy for operational use by the submarine crew. This system could replace the side-scan sonar, which is currently used operationally to aid in surfacing but has not been utilized scientifically.

The light penetrating the ice cover controls biological production. If observed at the top of the operating range of the submarine, 50 m, it can tell us a great deal about the biological environment. It also has information about the optical properties of the ice cover.

We recommend development of an upward looking, recording, spectral photometer to measure light transmitted through the ice.

The specifications for such an instrument will represent a compromise between what is desirable and what is practical, but even a minimal instrument—a single, broadband radiometer—would be valuable.

Geology and geophysics

Five observations required for collecting geology and geophysics data are listed in Table 4. All five have been acquired from submarines previously, so the primary need

is to make these observations on as many cruises as possible.

The swath bathymetry mapper requires a substantial effort to mount but was successfully used on SCICEX '98. The current SCAMP design requires that mounting points be welded to the hull and some cables run while the boat is in drydock. Later, the pods can be installed and removed dockside by divers. This two step installation is complex and expensive. When SCICEX TEMPALTs are re-worked for SCAMP installations on newer submarines, a cost benefit analysis should be made of mounting a redesigned SCAMP on 688s by divers and without a drydock. It is possible that the SCAMP's High Resolution Subbottom Profiler (HRSP) could be mounted inside the bow dome and thus could be installed dockside with no need even for divers. This possibility should be thoroughly explored.

An operational equivalent of a seismic refraction array is towed by the submarine. A TEMPALT has been developed for its scientific use, and a technique has been developed for reviewing the data for scientific release. However, the process and permissions are difficult, and the entire evolution, from data collection through data release, has yet to be evaluated. Such a test is needed and is contemplated in the near future.

Table 4. Observations required for geology and geophysics.

<i>Measurement</i>	<i>Done in SCICEX?</i>	<i>Comments</i>
Swath bathymetry and backscatter mapping from SCAMP	Yes	Capitalize on investment. Consider water-borne installation.
Seismic reflection from subbottom profiler (component of SCAMP)	Yes	Consider bow dome installation.
Seismic refraction from towed hydrophone array	No	Needs coordination and test evaluation.
Gravity field from gravimeter	Yes	Moderately important but easy.
Magnetic field from magnetometer	No	Moderately important and moderately difficult.

For a long-term development, we note that the HRSP that is part of SCAMP produces very good penetration (up to 200 m) with good resolution. This is adequate for many applications, including site surveys for conventional and long piston coring. However, deeper seismic records will be crucial for selecting drilling sites aimed at recovering the paleoclimatic record in the arctic basins.

We recommend a conceptual design study to evaluate a seismic profiling system capable of imaging the upper 1000 m while under way.

Possible sound sources might utilize "boomer" or "sparker" technologies. If a solid conceptual design emerges, a development effort should be considered.

6. Future Program Organization

6.1 Science organization

We take it as given that SCICEX will not continue in its present form, at least for several years. We also believe that there may be opportunities to do scientific work from submarines during the next decade. We know that there is good scientific work that could be done, contingent on the availability of a submarine. We also know that it may be necessary to change the ways we work to accomplish our scientific objectives. In particular, we may need to trust others to make observations for us, we may need to trust others to make decisions that affect our measurements, we may need to work without funding, and we may need to give up some of our prerogatives as principal investigators.

Although BDMs will not interfere with submarine operations, scientific investigators should participate in decisions about sensor types and data calibration, quality, and processing. These investigators could be funded principal investigators for each data type (e.g., ice draft, salinity and temperature, bathymetry) or an advisory group. In either

case, they would act as community representatives with responsibility for data quality, for communicating data status and changes in sensors or methods to the community, and for making data publicly available after quality-control checks. Some protocols would be needed for notifying the community and releasing the data. Some funding mechanism would be needed to cover costs of expendable instruments. The usual funding paths would be followed for subsequent scientific interpretation of the data.

The main difficulty we anticipate with the SAMs is short lead time. The conventional way of doing scientific work in the Arctic requires about 2 years from the announcement of opportunity to the cruise. But, as we understand it, there may be opportunities in the future with lead times of a few months, leaving little time for meetings, proposals, reviews, or instrument development.

To respond to such opportunities, we envision an organization somewhat as follows. We would establish informal disciplinary teams under the Science Working Group; a geodesy team, a physical oceanography team, etc. Team membership would be open to anyone with an interest. Each team would designate a spokesperson, who could speak for the team with as much or as little consultation as situations allow. Teams would develop several mission scripts appropriate for different cruise plans. There are models for this sort of scientific organization in the Ocean Drilling Project and the University-National Oceanographic Laboratory System (UNOLS) Council. An appropriate umbrella might be the National Ocean Partnership Program.

When a cruise opportunity arises, a real or virtual meeting would be called that included representatives of the Navy, the team spokespersons, and the funding agencies. Here some horse trading could occur to resolve what scientific research could be

accomplished within the operational constraints. Experience in SCICEX has been that this horse trading, effectively mediated by the Science Steering Committee, has resulted in cruise plans that maximize the scientific use of the submarine.

It would help the scientific community to prepare for SAMs to have even rough estimates of the upcoming opportunities. To this end,

we recommend that the Science Steering Committee work with the Submarine Force to provide estimates of the number and timing of cruises and the number of science days that might be available, with as much lead time as possible.

Even such guidelines as "no SAM next year," or "one springtime SAM with 5 days science time" would help. The greater the lead time, the more effectively the science mission can be planned. An addendum to the MOA would facilitate this process.

We anticipate that the traditional funding paths will be appropriate for DSMs.

6.2 Expanding submarine science opportunities

Since 1993, the submarine science program has included civilian riders to provide state-of-the-art scientific sampling and has provided wide coverage in extreme, ice-covered arctic regions. Incorporation of multiple scientific disciplines, specifically hydrography, geology and geophysics, ice dynamics, and marine biology and chemistry has provided previously unobtainable insights into the arctic system. Collaboration between the Navy, funding agencies, and scientific personnel has effectively streamlined the process for declassifying arctic data sets. The fact that a data-release area had been agreed to *in advance* of the cruises was important for a successful program with immediate scientific benefits.

In order to expand submarine opportunities in the future, three on-going topics require focused efforts.

Opportunities for women

The agencies involved in the SCICEX MOA should work toward equalizing opportunities for all members of the civilian scientific community. We understand that the design of submarines and the Navy's traditional way of operating them does not easily accommodate women on submerged cruises longer than a week. The National Science Foundation's mandate is to support science programs with equal opportunity. Women scientists have the same wish as men to participate directly if they feel their presence is necessary to ensure the highest quality data or sampling or quick sample analysis. Indeed, women have fully participated in developing the scientific agenda of the SCICEX cruises and have made significant contributions to the scientific output of these cruises. A milestone will be accomplished on the SCICEX '99 cruise, which has a woman as chief scientist. BDMs and SAMs will have no civilian riders, so this issue may subside only to resurface in the future.

The program is so scientifically valuable that it behooves all parties to continue to find ways to plan creatively, modify expectations, and cooperate in the future.

International collaboration

There is motivation for continuing and expanding international collaboration in several areas. First, data from regions outside the SCICEX data release area are eagerly sought by the scientific community. Second, U.S. agencies can be spared some of the cost of the program if non-U.S. scientists can offer instrumentation to share. Third, pursuing common aims jointly with international partners could enhance the U.S. submarine program. Coordination with British submarine cruise plans is one example. Another is sampling the highly variable ice cover of the East Siberian Sea, which would require some

cooperative scheme with Russian scientists. Cooperative experiments that involve non-U.S. scientists can result in invitations for U.S. submarines to execute specific missions within foreign Exclusive Economic Zones, as shown in **Figure 11**. An exciting breakthrough in this area is the cruise segment planned in SCICEX '99 in Norwegian waters north of Svalbard. Sampling corridor 4 (**Figure 10**) would require such a cooperative effort with the Canadians. There is interest in collaboration with the Danish/Greenlandic project, Greenland Arctic Shelf Project (GRASP), to study the Morris Jessup Rise.

Continued declassification of historical submarine cruise data

Along with the need for contemporary data, a submarine science program should not ignore the wealth of scientific insight that the historical record can provide. Submarines have operated under arctic ice for over

four decades and have collected many data that can benefit scientific research, especially in the quest to establish a multidecadal arctic climate record. Dollar for dollar, the most efficient way to investigate arctic climate change is to make these historical data public and place them in a national archive. The primary data set at issue is ice draft data. The corporate knowledge of how these data were taken and what issues must be dealt with in resurrecting them is at risk of being lost as staff members at the Arctic Submarine Laboratory turn over. The data should be made public in as elementary a form as possible, that is, ice draft profiles with as much spatial and temporal information attached as security permits. Efforts to pursue this goal are under way but reach back only to 1986 and cover only the Gore box. Earlier data and the broader geographical coverage of the SCICEX box are desirable.

Similarly, there are bathymetric data that have been collected over the years of submarine cruises that would fill in our map of the Arctic and would help us in deciding which area to map in the future. The geology and geophysics community is awaiting these data. Data from 1975 to 1982 have been digitized and declassified and placed on a CDROM. They will be available from the National Geological Data Center in Boulder, Colorado, in early July 1999. Data for years after 1982 will be available pending funding to digitize, process, and declassify the raw data.

A primary need is for adequate funding. *We recommend that the science agencies actively support these data rescue operations.*

7. Recommendations

7.1 Management issues

Several science management issues ought to be addressed by the Science Steering Committee. The membership of this

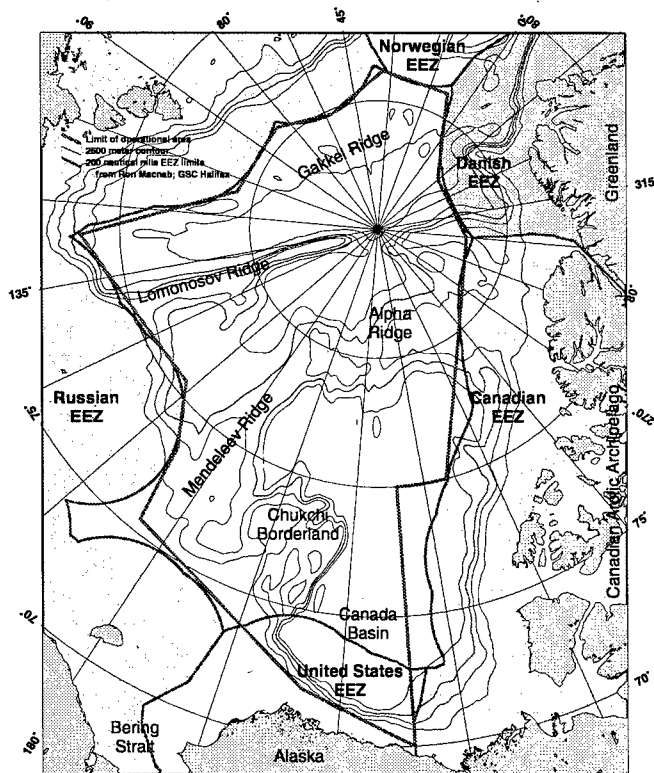


Fig. 11. The SCICEX data release area (or “box”), showing the surrounding Exclusive Economic Zones, which reach 200 miles from coastlines. (Courtesy of B. Coakley)

committee is established by the Memorandum of Agreement between the Navy and government science agencies. It includes representatives from NSF, ONR, NOAA, USGS, and the science community and a Navy liaison member.

We recommend:

- 1) That the membership of the SSC be reviewed; that civilian science representatives be added as described in the MOA; that operational Navy membership be expanded; that the chair and membership of the SSC be published on the SCICEX web site; and that the results of their deliberations be communicated broadly.
- 2) That the SSC review the MOA in light of the new mission scenarios suggested in this report. We feel that the current MOA does not require changing. Perhaps some less formal mechanism can be developed to cover situations not addressed by the MOA.
- 3) That a procedure be established for examining all arctic submarine missions with suitable security classification to estimate their potential contribution to science. To establish the procedure, a liaison should be formed between the Submarine Forces, the Arctic Submarine Laboratory, and the SSC. Appropriate security clearances would facilitate this interaction. The Submarine Forces would define the opportunities, the SSC would decide how the opportunities could be exploited, and ASL would help implement them. For arctic baseline science, the Arctic Submarine Laboratory, in conjunction with scientific investigators, would carry out operations after an initial period of protocol development and testing and with annual reviews.
- 4) That the SSC work with the Navy to establish the probable availability of future submarine science opportunities. While there is no assurance of developing a long-term schedule of science cruises, some estimate of the number of data-collection days likely to be available each year on otherwise classified cruises would help the agencies decide how to administer and fund their programs.
- 5) That the SSC develop a fast, flexible, response strategy, so that the funding agencies and scientific community can react quickly to opportunities. The strategy needs to support arctic baseline science, to provide mechanisms for alerting the scientific community to up-coming opportunities, to develop for each mission a scientific plan that fits within constraints set by the Navy, and to put in place necessary funding (see items 10 and 11 in Section 7.2).
- 6) That the agencies develop a suitable funding model for support of baseline and opportunistic science activities from arctic submarine programs. Arctic baseline science could potentially be made part of a U.S. contribution to global ocean observing systems and be supported as a routine activity under that aegis. Competitive proposals to carry out sampling programs for a period of 3 to 5 years, based on a public, nonbinding annual average estimate of opportunity by the Navy, could provide support for science programs above the baseline level.
- 7) That the SSC work with the Navy to develop a protocol for degrading the sensitive time and location labels that accompany most scientific data, so that data from BDMs and SAMs, which will be classified, can be promptly released to the science community. The data release area should be the SCICEX box or larger when the cruise is invited by another country.

- 8) That the SSC, the U.S. Navy, the Arctic Research Commission, and the National Science Foundation continue to work with international scientists and their governments to expand the territory available for science missions by U.S. Navy submarines.

7.2 Scientific and technical issues

The Science Working Group consists of SCICEX principal investigators representing the range of scientific interest in the Arctic Ocean. We recommend

- 9) That the program broaden its outreach to the community by defining an appropriate body of interested scientists. This scientific body might build on the present SWG. Community involvement can be increased by more successfully and more rapidly placing data into public archives.
- 10) That this body of scientists develop a number of science plans that would be appropriate for a range of BDMs and SAMs. These plans would serve as starting points to develop a plan for any actual mission. The SSC should be given these plans.
- 11) That this body form a small panel of experts to examine technical issues associated with making and recording certain standard scientific observations from 688, 688-I, and *Seawolf* class submarines with no impact on the submarine's primary mission. Representatives from the Arctic Submarine Laboratory should serve on this panel together with civilian scientists and engineers. Some of our remaining recommendations contain issues this panel should address.
- 12) That this body give immediate attention to developing the technical requirements for launching expendable CTDs or equivalent instrument packages from 688, 688-I, and *Seawolf* class submarines and for recording the data. These requirements should be communicated to the SSC.
- 13) That a process be devised to allow for training and gaining proficiency in underway sampling programs and that scientists define procedures and design experiments so that they can be performed in the absence of the PI. The new body of scientists should oversee this process.
- 14) That a plan be developed and implemented to achieve better vertical sampling for water shallower than 50 m and deeper than 243 m. This development would enable full water column and benthic sampling.
- 15) That a flow-through manifold, with a spigot for drawing water samples, be developed to provide continuous measurement of water properties along with a sensor that can be maintained and repaired while under way.
- 16) That advanced data processing be developed to provide redundancy and improve submarine navigational accuracy without modification to ships' systems.
- 17) That a data logging protocol and system be developed so that all data are stamped with the time and location.
- 18) That proposals for improving and extending scientific observational capabilities from submarines be invited by agencies.

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9. Glossary

ADCP	Acoustic Doppler Current Profiler
ASL	Arctic Submarine Laboratory
BDM	Baseline Data Mission
DIPS	Digital Ice Profiling System
DSM	Dedicated Science Mission
EEZ	Exclusive Economic Zone
HRSP	High Resolution Subbottom Profiler
MOA	Memorandum of Agreement
SAM	Science Accommodation Mission
SCAMP	Seafloor Characterization and Mapping Pods
SCICEX	Scientific Ice Expeditions
SDRS	Submarine Data Recording System
SHEBA	Surface Heat Budget of the Arctic
SSC	Science Steering Committee
SSXBT	submarine expendable bathythermograph
SSXCTD	submarine expendable conductivity temperature depth (probe)
TEMPALT	temporary alteration (to a submarine)
UNOLS	University-National Oceanographic Laboratory System
XCP	expendable current profiler
ZAPS	Zero Angle Photon Sensor

APPENDIX A. AGENDA

Day 1 (Tuesday, 6 October)

- 8:15-8:30 Welcome and Introduction (Rothrock/Maslowski)
8:30-8:45 A Perspective on the Evolution of SCICEX - George B. Newton, ARC.
8:45-9:15 Ocean structure changes and climate implications - Mike Steele, UW.
9:15-9:45 Ocean circulation from tracer chemistry - Bill Smethie, LDEO.
9:45-10:15 Arctic Biology: Recent Results and Future Directions - Terry Whitlege, UAF.
10:15-10:30 Discussion
10:30-11:00 Break
11:00-11:30 What SCICEX Data Are Telling Us About Sea Ice Changes - Drew Rothrock, UW.
11:30-12:00 Underway Geophysical Data Collected from US Navy Submarines During SCICEX; Achievements and Future Prospects - Bernie Coakley, LDEO.
12:00-12:15 Discussion
12:15-13:15 Lunch
13:15-14:30 Poster presentations
14:30-15:00 NSF Strategic Plan for Arctic Marine Science - Knut Aagaard, UW.
15:00-15:15 The Navy's Needs for Basic Arctic Science - John Schuster, Office of the Chief of Naval Operations.
15:15-15:45 Break
15:45-16:00 Operational constraints of working from a submarine - Robert Anderson, ASL.
16:00-16:15 Tempalts: The Process of Approving Alterations to a Submarine - Mike Hacking, ASL.
16:15-17:00 White Paper Presentations
17:00-18:30 Poster Session

Day 2 (Wednesday, 7 October)

- 8:15-8:30 Welcome (Rothrock/Maslowski)
8:30-9:00 Challenges of SCICEX - RADM Winford G. Ellis, USN.
9:00-9:30 Scientific Rationale for SCICEX - RADM Paul G. Gaffney, II, USN.
9:30-9:45 NSF's Perspective on SCICEX as a Future Science Program - Dr. Joseph Bordogna, NSF.
9:45-10:15 Questions on policy talks.
10:15-10:45 Break
10:45-11:00 Insights from SCICEX '98 - Robin Muench, ESR
11:00-11:15 Norwegian research interests relevant to SCICEX - Stein Sandven/Yngve Kristoffersen, Univ. of Bergen.
11:15-12:00 White Paper Presentations
12:00-13:00 Lunch
13:00-13:30 White Paper Presentations
13:30-15:30 Each of 4 science Working Groups discusses relevant white papers
Upper ocean structure and circulation
Sea ice
Biology and chemistry
Geology and geophysics
14:30-15:30 Members of the Working Group on Operations and instrument development meet separately
15:30-15:45 Break
15:45-18:00 Plenary Session
15:45-16:10 Report/recommendations from leaders of WG#1

16:10-16:35	"	"	"	WG#2
16:35-17:05	Break			
17:05-17:30	"	"	"	WG#3
17:30-17:55	"	"	"	WG#4

Day 3 (Thursday, 8 October)

8:30-10:00 Plenary Session (Discussion lead by chairs of the Working Group on Operations and instrument development)

10:00-10:30 Break

10:30-12:00 Plenary Session (Working Group recommendations / synthesis / wrap up)

12:00 Workshop Officially Adjourns

12:00-13:00 Lunch

13:00-18:00 Organizing Committee continues to work on report draft

Day 4 (Friday, 9 October)

8:30-12:00 Organizing Committee continues to work on report draft

12:00 Lunch

13:00 Adjourn

APPENDIX B. ATTENDEES

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APPENDIX C. INVITED POLICY TALKS

ADMIRAL ELLIS' REMARKS

Challenges of SCICEX

Ladies and Gentleman – Good Morning!

I'd like to thank the workshop organizers for the opportunity to speak at these discussions. VADM Giambastiani, COMSUBLANT, originally planned to speak this morning but his schedule would not permit him to attend, so he asked me to do it for him. The comments I will be making have been approved by him.

My own involvement in SCICEX dates back a few years. When I first relieved as Pacific Submarine Force Commander, USS CAVALLA had just finished SCICEX-95 and their cruise was one of the highlights of the previous few months. During my tenure at SUBPAC other Pacific submarines were also involved. POGY conducted SCICEX-96 and HAWKBILL geared up for SCICEX-98 which was just completed last month.

For all of these cruises, I was impressed with the excellent cooperation between the scientific community and the submarine force. Preparing a submarine for and carrying out any lengthy mission is difficult. This is especially true if that mission takes the submarine to the Arctic where the remoteness and hostile environment make every-day operations a special challenge. Doing this in conjunction with a diverse group of researchers from outside the submarine force was an immense undertaking. The success of these cruises is a real credit, not only to the crews involved but also to the Navy and civilian scientists who pulled the whole thing together. Things are different now. New challenges lie ahead and this workshop is needed to address them.

I see the stated objectives of this workshop as twofold.

The first is "to assess accomplishments of the past missions". Having been involved directly at the submarine end of these cruises and in my current job as Oceanographer of the Navy, I am very interested in what you have learned.

The second objective is to "form a vision of what could be tackled and achieved by a more coordinated program with stable funding, should it be continued into the next decade". In other words, developing an overarching program plan which applies all the lessons we've learned so far in order to focus on matching scientific needs with the real capabilities of the submarines.

There is also a big "if" in the objectives, namely "if" the program will be continued beyond 1999. When the Memorandum of Agreement creating the SCICEX program was signed in 1994, the Navy committed to five cruises through 1999. At the time, it appeared that this was about the length of time that we would have sufficient submarines to support SCICEX cruises. This prediction turns out to be pretty accurate.

By the year 2000, we will have only about half the number of attack submarines as we had when PARGO made the first proof-of-concept SCICEX cruise in 1993. At the same time, we've seen the number of unstable or hostile regions requiring submarine presence increase dramatically. Recent news stories from Bosnia, the Persian Gulf, Korea, India, Pakistan, and East Africa are reminders that, though the Cold War is over, we do not live in a peaceful world. As a world leader, the United States, often in the form of the submarine force, must maintain its readiness to assert its influence in many different regions of the world.

With more missions and fewer submarines, the Navy must carefully examine the priorities of all of its activities in terms of their contribution to our overall national defense mission. We are no longer a requirements driven force but an assets limited or budget driven force, as much as we might like to continue the SCICEX program, it should be recognized that, in the full picture of submarine force obligations, there are other, higher priorities.

Exacerbating this problem of a greatly reduced submarine force is the fact that, by the year 2000, we will have decommissioned all of our STURGEON (or 637) class submarines. Since their introduction over 30 years ago, the 637s have been our Arctic workhorse, including all of the SCICEX missions. Newer classes have been introduced since the 637 with varying degrees of Arctic capability. We have not yet had the opportunity to determine how capable these classes are of carrying out lengthy deployments to the deep Arctic. It takes several deployments to ensure that these newer ships have the right systems and procedures before we commit them to something like a SCICEX.

So here is our paradox. Because the 637s were so good at Arctic operations, we have never used one of our newer ships for any extended under-ice operation. In recent years, when there was an increasing need to do so, we found the majority of our submarine time, money, and personnel allocated to supporting Arctic operations were tied up in SCICEX. In essence, with the 637s disappearing, it looks like we must stop SCICEX so that we might at some later date continue SCICEX.

So this forms the boundaries of the "vision" this workshop is here to develop.

First, if we were able, a few years from now, to resume a regular SCICEX program, how would you make best use of a very valuable submarine asset?

Secondly, we may have opportunities in the interim, at little or no notice, for submarine crews to collect environmental data which could be fed back to the scientific community. With no added TEMPALTs, no lengthy planning process, and no embarked scientists, what data would be most worth collecting and how would the scientific community communicate these priorities to the submarine force?

This is your challenge for creating a vision for the future. VADM Giambastiani (COMSUBLANT), RADM Konetzni (COMSUBPAC), RADM Fages (N87), and I are very interested in what you develop.

Good luck and God bless. Thank you.

DR. JOSEPH BORDOGNA'S REMARKS

Thank you. I'm very pleased to be able to give NSF's ringing endorsement for this productive partnership with the Navy and ONR in the SCICEX program.

SCICEX has been a shining example of "dual use" of military assets. In tandem with national security objectives, it has given us access to the Arctic Ocean for research and education. This region's scientific secrets have remained locked away in ice long after our other oceans were being opened to exploration. Although smallest of the world's oceans, the Arctic still holds more than its share of mysteries, and the SCICEX submarines are helping us to plumb these depths.

Let me take a moment to underscore the importance NSF places on Arctic research. As my friends in the Arctic science field often remind me, the region is crucial to deciphering global change. We know that its snow, ice, and biota are sensitive bellwethers of the past and future. The permafrost, the ice, the lakes and the sea-all harbor histories of climate. And of course, many think that the Arctic exerts a strong influence on global climate. Tracing climate change, oceanic circulation, transport of contaminants-the Arctic Ocean is at the heart of these global questions.

Over the past few years, NSF has augmented its leadership role in Arctic science across the disciplines, and we expect to do much more in this critical region.

The scientific harvest being reaped by SCICEX has helped to make this progress happen. The submarines give us access to permanently ice-covered areas. They provide a stable and quiet platform for research. They let us gather data continually. We can sample the physical and chemical characteristics of the water while the ship is underway.

While icebreakers offer us a lot, they simply cannot provide the same kind of stable and super-quiet platform for research, and furnish the same clarity of acoustic data. In fact, the SCICEX data provides the U.S.'s primary time series-a series of scientific snapshots-of the Arctic Ocean.

As my Arctic science colleagues have explained to me, SCICEX has found dramatic changes in temperature, ocean currents, and how water coming in from the Pacific and Atlantic moves around the Arctic Ocean. And we have indicators that the sea ice covering the Arctic Ocean is thinning.

This all adds up, I am told, to an emerging picture of how the Arctic Ocean circulation works.

SCICEX has also opened up new vistas for us in geology and geophysics. This is the realm where the Mid-Atlantic Ridge continues up into the Arctic. With the submarines as platforms, we've been able to inaugurate the first use of modern mapping methods in the Arctic Ocean. The submarine data, I am told, could transform our understanding of the structure and history of the Arctic Ocean basin.

All of this fantastic science is happening at a bargain price, thanks to our partnership with the Navy. In essence, we're getting a logistics capability in the Arctic Ocean that we could never afford otherwise.

This unique partnership between the federal science and engineering agencies, the Navy, and the research community stands now at a new threshold. Of course, that's why we're here: not just to take stock of where we are but to consider what might come next.

As the Sturgeon class of submarines is exhausted for scientific use, we certainly want to explore new possibilities. On NSF's part, we are interested in new classes of subs that might become available for science.

Even with our new Arctic research vessel, the Healy, coming on line, the submarines offer unique and complementary capabilities for science. At the same time, we know the Navy is being asked to carry out more submarine missions with fewer vessels.

Let's keep talking in the interest of fashioning a mutually beneficial solution. If we're fortunate to continue this partnership using other ice-capable submarines, we know that annual cruises may no longer be possible. We actually see that as another kind of opportunity.

More time between cruises-something that may fit well with the Navy's requirements-could give us the opportunity to digest the data already gathered and hence target science on a future cruise in a more refined way. A cushion of time between cruises also gives a chance to develop and test new scientific instrumentation in a way researchers haven't been able to do with the current schedule.

In any case, as we continue discussing the future of submarine-based science, you should remain assured of NSF's strong support for Arctic research. We enthusiastically endorse this productive partnership, in keeping with the Navy's mission responsibilities.

Our consistent support over the past few years shows, I think, how much we value this type of program. Now that we've learned to coordinate the science more efficiently and how vital it is to have a plan with priorities, let's look at what we may be able to do next-together.

Thank you.

GEORGE B. NEWTON'S PRESENTATION

A Perspective on the Evolution of SCICEX

Submarine Arctic Science ("SCICEX") Program

Viewgraph 1- A Perspective on the Evolution of SCICEX

- George B. Newton, Chair
- U.S. Arctic Research Commission
- October 1998

Viewgraph 2 - A Fairy Tale

- "Once a upon a time..."

Viewgraph 3 The Motivation

- The Cold War Wound Down

- “Dual Use” of Military Resources
- Submarine Arctic Experience Perishable
- Knowledge Deficiencies of Arctic (Ocean)
- Some Aspects of Security Were Softening (The Original “Gore Box”)

Viewgraph 4 The First Steps

- Planning in 1988
- First Experiment Conducted During ICEX 1-89
 - Spring Deployment
- Water Samples
 - Frozen...for awhile
- Exxon Valdez Interruption

Viewgraph 5 A Bigger Idea -> A Dedicated Cruise

- In 1990-91-92
- Initially Resistance, then
- Discussion, Followed by...
- Brief: ARC NSF ARCUS

Naval Submarine League

- Develop the Concept
 - The New “SCICEX” Area

Viewgraph 6 “A Blind Date”

- January 1993 in San Diego
- Science Presentations of the Navy
- UNOLS Planning
- USS Pargo Cruise in Fall ‘93

Viewgraph 7 Creating the SCICEX Program

- MOU Prepared in 1994
 - Signed by all in August
- ARC Brokered
- To Start in 1995
- Navy Relaxed Security Limits on SSN Submerged Performance

Viewgraph 8 the Submarine’s Unique Capabilities for Arctic Data Collection

- Speed
- Stability
- Endurance
- Reliability
 - The platform itself getting here, saying here
 - going where science wants...exactly
- Mobility in Deep Ice Covered Waters
- Continuous Data Collections Submerged
 - flexibility to adapt to new requirements
- Only Source of Ice Profile Data

Viewgraph 9 - SCICEX Statistics

- The Science Opportunity So Far

		DAYS	RESEARCH MILES STEAMED IN AREA
USS PARGO	'93	17	4,900
USS CAVALLA	'95	44	10,800
USS POGY	'96	45	12,500
USS ARCHERFISH	'97	30	7,600
USS HAWKBILL	'98	32	9,000
5 CRUISES		168	44,800 NM

- for every hour in the SCICEX area, the SSN collected data over 11+ nautical miles

Viewgraph 10 - Cast of Characters (in order of appearance)

- The U.S. Navy (Bob Perry & Sam Blackadar)
- Peter McRoy
- Ted DeLaca
- Garry Brass
- Jeff Gossett
- Mark Langseth
- RADM Tom Ryan
- ...Plus many "extras"
- (if you are in this room today: You Count)

Viewgraph 11 - The purpose of SCICEX 2000:

- Look Back
- Summarize and Integrate Results
- Create a Proper Scientific Focus for the Year 2000 and Beyond

JOHN SCHUSTER'S PRESENTATION

Arctic Science and Navy Needs

Vugraph 1 - Summary

- Current and planned submarines meet the Navy Arctic requirements
- The Navy has a continuing interest in Arctic scientific data
- Reduced numbers of submarines coupled with fleet demands for submarine services, complicate discussion of possible SCICEX opportunities

Vugraph 2 - Environment Needs

- Techniques for remote measurement of surface weather conditions
- Techniques for accurate measurements near the ice interface
- Prediction and sensing of fronts, eddies and currents

Vugraph 3 - Environment Issues

- Prediction/measurement of surface weather important for surfaced operations
- Knowledge of conditions near the water-ice interface is important for
- Submerged operations (ice keels, water density)
- Arctic fronts and eddies are important especially for acoustics

Vugraph 4 - Communications Needs

- Antennas for low angle transmission/reception
- Concepts for submerged, under ice communications

- Multipath robust acoustic communications

Vugraph 5 - Communications Issues

- Ice cover and high latitudes make communications more difficult in the Arctic
- Acoustic communications are impacted by Arctic propagation

Vugraph 6 - Navigation/Bathymetry Needs

- Development of robust submerged navigation techniques
- Measurement of Arctic bathymetry
- Measurement of acoustic bottom properties

Vugraph 7 - Navigation/Bathymetry Issues

- Navigational checks are difficult while under the ice
- knowledge of the bottom characteristics could aid in navigation as well as in acoustic propagation
- Arctic bottom types and water depths vary widely

Vugraph 8 - Acoustics Needs

- Continuing measurements of Arctic propagation
- Measurements of high frequency scattering
- Seasonal measurements of noise levels

Vugraph 9 - Acoustics Issues

- Acoustic propagation in the Arctic is unique
- Scattering from the ice surface disrupts high frequency propagation
- The noise environment under the ice can pose special problems

Vugraph 10 - Ice Cover Needs

- Prediction/measurement of ice cover extent and ice thickness
- Method for non-hardened submarine to surface
- Techniques for ice penetration

Vugraph 11 - Ice Cover Issues

- The submarine is an ideal platform for arctic operations
- Surfacing poses many more problems than in the open ocean
- Deployment of sensors through the ice is difficult

Vugraph 12 - Arctic Science

- Ice Cover
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APPENDIX D. INVITED SCIENCE OVERVIEW TALKS

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Underway Geophysical Data Collected from US Navy Submarines During SCICEX; Achievements and Future Prospects

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All Arctic science suffers from a lack of knowledge about the seafloor of the Arctic Ocean and the sediments beneath it. During each SCICEX cruise we have had an unparalleled opportunity to collect under-way data and observe the seafloor. The data collected so far with the ship's own narrow-beam bottom sounder and a gravimeter on loan from NAVOCEANO has improved our understanding of the form and development of the major seafloor plateau and ridges in the Arctic Ocean basin. The data that were collected with SCAMP in 1998 as well as the data that will be collected in 1999, will dramatically change our view of the Arctic Ocean, expanding the impact of SCICEX on Arctic Science and helping to develop other programs of seafloor exploration and sampling.

1.0 The Arctic Ocean Basin

The Arctic Ocean can be divided into two distinct basins, separated by the Lomonosov Ridge, of contrasting form, history and age. Our understanding of the development of the Eurasian and Amerasian Basins, and the continents that ring them has developed slowly over time. SCICEX has already made substantial contributions to what we know.

1.1 Geology of the Eurasian Basin

The Eurasian Basin lies north of Europe, extending from the Barents shelf to the Lomonosov Ridge. It includes the Gakkel Ridge (Arctic Mid-Ocean Ridge), the slowest spreading ridge in the world ocean. Of the two major ocean basins which make up the Arctic Ocean, the tectonic development of the Eurasian basin is much better understood.

1.1.1 Gakkel Ridge (Arctic Mid-Ocean Ridge)

Although the development of the Eurasian basin is well-understood in the context of global plate tectonics, we know very little about the morphology, structure, petrology or distribution of sediments on the Gakkel Ridge. Aeromagnetic surveys over the basin by Russian, Canadian and American scientists revealed it to have been formed by nearly symmetric seafloor spreading that began at about 55 Ma. Around this time, propagation of the Gakkel Ridge across the Arctic separated the Lomonosov Ridge from the Barents shelf. The Gakkel Ridge terminates at the eastern end of the Eurasian Basin at the Laptev Sea shelf.

The morphology of mid-ocean ridges is, to first order, a function of the spreading rate. The Gakkel Ridge is the slowest spreading ridge in the world ocean, a limiting case that can expand our understanding of seafloor spreading processes. Four "patch surveys" were collected over the ridge axis from the USS Pogy during SCICEX-96 to examine the variation in axial morphology at ultra-slow spreading rates. The combined gravity and bathymetry data were used to constrain the crustal thickness and density, yielding a pair of values that best reproduce the observed gravity anomaly.

Conclusions from this work to date;

- A continuous rift zone was observed, even at spreading rates less than 1.0 cm/yr.
- The morphology of the Gakkel Ridge is distinctively blocky and the axis is deeper than other mid-ocean ridges (MORs).
- Ridge segmentation and inner-corner highs were observed.
- Peak to trough Free Air gravity anomalies ranged between 80-120 mGals, as much as twice the amplitude seen on other MORs.
- The combined gravity anomaly and bathymetry data require thin, normal density crust or thick, high density crust.
- These results suggest that magmatic production at the Gakkel Ridge may be suppressed by the exceptionally slow spreading rates.

A critical step in further studies of the Gakkel Ridge is to map the 3-D morphology and image the sea floor texture of critical sections of the Ridge at a scale that will reveal the fabric and interrelationships of volcanism and faulting, the ideal locations for obtaining representative samples for petrologists, possible sites of recent magmatic activity and hydrothermal vent sites. Approximately 3300 km of swath data collected with SCAMP during SCICEX-1998 from USS Hawkbill fill in the gaps between the 1996 patch surveys collected from the USS Pogy, providing the first ever 3-D characterization of segments of the ridge axis as well as complete coarse bathymetry and gravity anomaly data for the ridge at an approximately 10 km spacing, covering the range in spreading rates between 1.25 cm/year and 1.0 cm/year full rate.

1.1.2 Lomonosov Ridge

The Lomonosov Ridge is a long sliver of continental crust, perhaps analogous to Baja California, that was rifted off the Barents Shelf by the propagation of the Gakkel Ridge across the Arctic. Data collected so far during SCICEX show a sinuous, continuous ridge that spans the basin, dividing the Eurasian from the Amerasian Basin. The combined gravity and bathymetry data have been used to identify the location of a series of half-grabens that segment the ridge into a series of high-standing en echelon blocks. The variable morphology and internal structure of this ridge may be inherited from the initial rifting of the Barents Shelf and propagation of the Gakkel Ridge across the basin.

1.2 Geology of the Amerasian Basin

The plate tectonic history of this large Mesozoic ocean basin and the continents that ring it is unresolved. Break-up unconformities on the Alaskan and Canadian margins, heat flow and basement depth and a few cores on the Alpha Ridge constrain the initiation of the opening of the Canada Basin to about 130 Ma. No plate boundaries have been recognized in the entire basin. There is growing evidence that sub-basins of the Amerasian Basin may have different opening histories. The origins of major tectonic elements in the basin, the Alpha-Mendeleev Ridge, Chukchi Borderland and Makarov Basin are not well understood.

The bathymetry data collected with SCAMP will, with the gravity data SCICEX will continue to collect, provide the opportunity to quantitatively test hypotheses about plate boundary location, complementing the more densely sample, lower resolution aerogravity data and ERS-1 satellite data [below 810 N]. Positively identifying these boundaries will improve our understanding of the history of the adjacent continents, providing regional context for the Brooks Range and other Cretaceous age tectonic provinces in North America and Eurasia.

1.2.1 Chukchi Borderland Complex

This Complex consists of two high standing ridges of continental crust which project outward from the East Siberian shelf into the Amerasian Basin; the Northwind Ridge and Chukchi Rise. It is possible that the Arlis Plateau and Mendeleev Ridge form a third ridge in this complex. The ridges are separated by thickly sedimented extensional basins which may, in part, be floored by oceanic crust. Recently Grantz recovered Permian redbeds from the Northwind Ridge, confirming the continental character of this feature.

Bathymetry data collected during the 1995 and 1997 SCICEX cruises have helped to improve our understanding of the morphology of the Chukchi region and begun to raise questions that can be uniquely answered by swath mapping. In the narrow-beam data collected in profiles crossing the Northwind escarpment, a set of narrow, high ridges trending oblique to the trend of the escarpment can be seen. The gravity data suggests that these are ridges, trending nearly perpendicular to the profile line, not isolated seamounts.

The successive profiles collected across the Chukchi on previous SCICEX cruise are like a set of serial sections perpendicular to the Northwind escarpment. On these sections, behind the Northwind Ridge, there is a large extensional basin that can be tracked from a slight depression near the Siberian continental margin to the floor of the Canada basin. The steep slopes that bound this basin appear to continue north of what has been commonly believed to be the edge of the Chukchi, into what has been believed to be oceanic crust, across a proposed plate boundary. There are two high scarps (one nearly 500 meters) which appear to be continuations of the structure that flank this deep basin. Mapping the 3-D morphology

of these structures is an important test of the relationship between the Chukchi and the surrounding ocean crust.

2.0 Data Infra-structure in support of other scientific programs

As detailed above, the primary use for the data that will be collected with SCAMP will be to address geophysical problems related to particular features collected during dedicated surveys. These data, and the data collected during transits and oceanographic work, will also help build our knowledge of the Arctic across a variety of disciplines, supporting paleo-climate, glaciological and oceanographic research.

2.1 Nansen Arctic Drilling

The high ridges and plateau of the Arctic Ocean are mantled by slowly deposited sediments, condensed sections which contain the oceanographic history of the basin. The history of bottom sampling in the Arctic is rather bleak. Only short, opportunistically located cores have been collected so far. Any cruise dedicated to Arctic seafloor sampling, either by giant piston corer or drilling, will be extremely expensive. Acquisition of seismic reflection data from ice breakers is difficult. While no mechanism exists to utilize SCICEX for site survey work, data collected with SCAMP will help identify the best sites for sampling and assist in the development of offset coring strategies that would exploit seafloor erosion to construct complete, composite records from separate shorter cores.

2.2 Sedimentary Processes and Peri-glacial features

The backscatter data that will be collected with SCAMP maps out textural variations in the shallow sedimentary column. This data and the sub-bottom profiler data will be useful for mapping debris flows, deep sea channels, peri-glacial features on the high plateau and deep shelves and other bottom features like the sediment waves observed from ice island T-3 on Alpha Ridge. This data will provide a wealth of information on bottom processes, mass fluxes into the basin and the Pleistocene glacial history of the High Arctic.

2.3 Constraints for Ocean Modeling/Contaminant Transport

It is well known that currents and eddies in the Arctic are localized by the ridges and plateau in the basin, which also act as sills, separating deep water masses. Bathymetric mapping is crucial to understanding the evolving ocean circulation system, which may be in the midst of dramatic change, and predicting the trajectory of contaminants that enter the Arctic Ocean from the rivers and oceans connected to it.

2.4 A New Arctic Bathymetric Map

An international group, comprised of representatives of the Arctic Coastal States plus Iceland, Germany and Sweden, has begun the work of compiling a new digital bathymetric data base for the world north of 64° N. The International Oceanographic Commission has accepted this group, originally formed as an IASC project group, as an editorial board for its GEBCO chart series. Data collected during SCICEX combined with newly declassified US submarine data collected between 1957 and 1982 are the largest new addition to the public data set. SCAMP data will substantially expand this effort, which will focus on release of documented digital bathymetric datasets and grids.

What SCICEX Data Are Telling Us About Sea Ice

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What do we want to know about sea ice?

The sea ice cover is not static. It grows thermodynamically, is pushed all around the whole Arctic Ocean by winds and currents, breaks and pulls apart in leads and polynyas where ice grows particularly fast, piles itself into ridges, and melts some in summer, or is carried out of the ocean between Greenland and Spitzbergen. Being able to represent these processes realistically in predictive and retrospective mod-

els allows us to help operations in the arctic and to understand the role of sea ice in the global ocean-atmosphere climate system.

In spite of the fact that the ice cover is in a continual state of change, one wants to answer such simplified but basic questions as "How much ice mass is in the ocean?" and "What regions of the ocean tend to be ice sources and which are regions where ice tends to melt?" The long record of observation from submarines is our only hope of answering these questions, and of determining whether ice mass is declining? Satellites can tell us if ice extent is shrinking but cannot tell us much about ice mass.

Ice plays an important role in the heat balance of high latitudes by insulating the warm (-2°C) ocean from the cold (-30°C) atmosphere. The thin places in the ice cover (leads) are intense localized sources of heat for the atmosphere; a submarine can measure their abundance. The ice growth and melt are the critical surface control on ocean buoyancy, determining where the ocean is stable and where the ocean can convect deeply, replenishing deep ocean water masses in the global ocean circulation.

How accurately can we measure ice thickness?

A crucial aspect of answering questions about ice and changes in the ice cover is quantifying how well submarine profiles can pin down ice draft, or, put differently, how long a profile is needed to reduce sampling errors to a sufficiently small level. By densely surveying a patch of sea ice during SCICEX '96, we find that it seems quite possible to reduce the sampling error in mean thickness to under 10 cm. Surveys with perpendicular legs are more effective than single long legs at reducing this error. These tests pinned down only sampling errors; other sources of error remain, such as sound speed and the depth of the transducer.

Is sea ice getting thinner?

The big climate question in the arctic is whether sea ice is getting thinner. Global climate models suggest that with rising CO_2 , the arctic atmosphere should warm faster than, say, northern mid-latitudes, and one would expect this to show up as a thinning ice cover. The SCICEX data from the '93, '96 and '97 cruises show a weak signal that the ice cover is thinning during these four years. The Beaufort Sea and Eastern Arctic are thinner in 1997 than in the previous years, but the ice around the North Pole is thicker. It seems that thickness is responding to changing winds that force a changing ice circulation rather than to a general warming. The small increases in air temperatures seen in the Arctic are not sufficient to reduce ice thickness measurably.

How well can we model ice thickness distribution?

This question can be answered in different ways. One approach is to survey a patch of ice once, go away and let it evolve as described in the first paragraph, and return later and resurvey it to see how the thickness distribution has changed and if our models can describe the change. This approach is described in this appendix by Babko and Rothrock. The second approach is to compare observed to modeled ice thickness whenever and wherever there are data. We have done this with the '93, '96 and '97 SCICEX draft data along all tracks. These are comparisons of values on a particular day of a particular year within the model's 40-km cells, not comparisons of long-term or basin scale averages. The modeled ice is about 40 cm thicker than observed in each year. The modeled spatial variability is similar to that observed; the standard deviation in 40-km mean thicknesses is about 1 m in both the model and the real ice. But the model does not always put the thicker regions where nature did. These along-track thickness variations have a mean squared correlation of about 0.5 in two of the years but are negatively correlated by -0.5 in the third year. There is room for improvement in the model! And now we have some wonderful data for this purpose.

Can we observe preferred lead directions?

We wanted to see whether the SCICEX intensive ice draft surveys could show preferred orientation of leads. They can. One survey consisted of ten legs, each through the center of a circle of about 160 km diameter, arranged like spokes with headings at 18° intervals. On each leg we computed the probable distance to the nearest lead (ice no thicker than 1 m). On a polar plot, this distance varied smoothly with heading. The clear winner was the north-south direction for which the nearest lead was about 200 m away. In a roughly perpendicular direction, it was 800 m to a lead. This technique could help validate model forecasts or satellite estimates of preferred lead directions.

What could future SCICEX ice draft observations provide?

Future missions should continue to make broad surveys over the entire SCICEX data release area, and outside it by foreign invitation, to document the ice thickness year by year as broadly as possible. This is the only way to document the mean state and the annual cycle, and to identify interannual change. Observational targets should include regions of greatest variability (E. Siberian Sea, Amerasian basin), regions of the thickest ice (off the Canadian archipelago), and regions of sparsest data. More repeated surveys of Lagrangian regions should be made to provide more test cases of changing thickness distribution. Satellite estimates of ice thickness should be tested with submarine draft data.

A most important complement to SCICEX is to release historical ice draft profile data to public archives where it can be applied by the community to ice and climate issues. Every effort should be made, as security can allow, to declassify draft data from future classified missions.

Draft data are too valuable to be missed by simple equipment malfunctions. Backup DIPS recorders and depth gauges are called for. Techniques to reduce the sound speed uncertainty should be explored.

Studies of Ocean Circulation from Tracer Chemistry: Highlights from the SCICEX Program

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Tracers provide information on water mass formation and composition, circulation pathways and circulation timescales. There are two classes of tracers, steady-state and transient. Steady-state tracers measured during the SCICEX program include oxygen-18, barium, oxygen, nutrients and dissolved organic carbon (DOC). Oxygen-18 is used to distinguish between river runoff and sea-ice meltwater and can also be used to estimate the amount of sea-ice formed at a location. Barium is more enriched in river water than seawater and is about 5 times more concentrated in the Mackenzie River than in Eurasian rivers and thus can be used to distinguish between Eurasian Basin and Canadian Basin river runoff. Nutrients (silicate, nitrate and phosphate) are useful in distinguishing between Pacific and Atlantic waters, although their non-conservative behavior make them difficult to use quantitatively. Nutrients and oxygen can be combined using Redfield ratios to produce quasi-conservative tracers such as NO, PO and PO₄*. DOC is highly enriched in river water and appears to have higher concentrations in Eurasian rivers than Canadian rivers. Transient tracers measured during the SCICEX program are tritium, helium-3, chlorofluorocarbons (CFCs), iodine-129 and cesium-137. The concentrations of these substances are continually changing with time either due to a changing input function or radioactive decay. Knowledge of the changing source function or radioactive decay rate allow a time scale to be placed on circulation. Iodine-129 and cesium-137 enter the Atlantic Ocean from European nuclear fuel reprocessing plants and are transported to the Arctic Ocean in the Norwegian Current, providing a unique tag for Atlantic water. CFCs enter the ocean at the surface and provide information on how long a water parcel has been isolated from the surface. Tritium

enters the Arctic mainly with river runoff in which it is highly concentrated relative to seawater. It decays to helium-3 and the ratio of tritium/helium-3 provides a clock for the isolation time of a water parcel from the atmosphere.

The oxygen-18 data collected from SCICEX cruises revealed a high concentration of river water in the central and southern Canadian Basin and the barium observations suggested that the Mackenzie River was a major source of this runoff. Much lower amounts of river water were observed in the northern Canadian Basin and Makarov Basin. The oxygen-18 data also revealed that ice formation exceeded ice melting in the central Canadian Basin. The iodine-129 observations clearly showed the boundary between Atlantic and Pacific water in the upper water and the underlying halocline. This boundary remained roughly along the Alpha/Mendeleyev Ridge between 1995 and 1997. Transit times of Atlantic water from the Norwegian Current estimated from the iodine-129/cesium-137 ratio ranged from 4-5 years in the Barents and Kara shelf regions to 8-9 years in the Makarov Basin, suggesting a 4-5 year transit time from the Barents and Kara shelf regions to the Makarov Basin. Tritium/helium-3 ages for the upper water in the Makarov and central Canadian basins were 4-5 years, in agreement with the transit times estimated from the iodine-129/cesium-137 ratios. Below the halocline, the temperature, salinity and transient tracer data collected along the SCICEX-96 transect through the central Canadian Basin reveal that water of Atlantic origin flows along the East Siberian slope and enters the central Canadian Basin in the vicinity of the Chukchi Borderland. The intermediate water with the slowest renewal rate relative to Atlantic water inflow is located at the northern end of the Canadian Basin over the southern flank of the Alpha Ridge. The transit time, based on tritium/helium-3 ages, for intermediate water to be transported from the eastern Eurasian Basin to the central Canadian Basin is about a decade.

Ocean Structure Changes & Climate Implications

Michael Steele

PSC/APL/UW

The Arctic Ocean sits at the top of the world, representing a meeting place for waters from the North Pacific and North Atlantic Oceans. North Pacific waters are relatively fresh (around 32 ppt) and cool (-1 degC, just above the freezing point). North Atlantic waters are much saltier (just below 35 ppt) and much warmer (2-3 degC). Recent cruises and new data bases show that there exists a "front" between these source waters that lies within the Arctic Ocean, and that the location of this front has shifted in recent years. Evidence for this front comes from hydrographic and chemical tracer data obtained by surface and submarine ships in the late 1980's and the 1990's. We stress, however, that the Arctic Ocean is itself a unique sea that exhibits distinctive properties (e.g., it is the freshest major ocean in the world).

Why does a climatologist care about the Arctic Ocean? Several answers come to mind. First, it represents a crucial link in the global freshwater balance. Evaporation in the North Atlantic is much stronger than in the North Pacific, representing an atmospheric transfer of water vapor from the Atlantic to the Pacific. The loop is closed by the oceanic circulation of freshwater from the Pacific to the Atlantic through the Arctic. The world would be a very different place without this transfer circuit.

The freshwater that flows out of the Arctic Ocean is relatively light. It flows into the Greenland Sea, perilously close to the location where waters tend to get heavy enough (via air cooling) to sink to great depths. It has been proposed that increases in the Arctic freshwater outflow might tend to suppress this sinking, which would affect the global oceanic circulation as happens during ice ages.

The relatively warm Atlantic Water flows into the Arctic Ocean and subducts to several hundred meters depth, cooling and freshening as it transits around the basins and eventually exits through Fram Strait. Ice-breaker cruises in summer 1990 and summer 1993 supplied intriguing evidence that this water had warmed relative to previous years. Yet the data were spotty in time and space. Also in summer 1993, the first ("pilot") SCICEX cruise took place on the USS Pargo. The data (Morison et al., DSR, 1998) showed dramatically how the Atlantic/Pacific front had shifted over 30 degrees of longitude so that Atlantic influence in the Arctic had increased in volume by about 20%. Warming of over 2 degC relative to climatology was

observed, and also changes in the surface salinity. Clearly, changes were occurring at different depths and locations for different variables.

Hydrographic data have been collected by SCICEX submarines in 4 ways. First, a conductivity-temperature-depth (CTD) instrument is mounted in the sail, continuously measuring temperature, salinity, and depth as the ship cruises through the Arctic. Second, an expendable CTD (SSXCTD) was developed for SCICEX that takes a profile from about 30 m to 800 m. It is launched through the torpedo tubes. Third, traditional CTD casts may be taken when the submarine surfaces, if conditions allow. Finally, bottle samples are collected during surface stations and also via the ship's intake.

The next SCICEX cruise occurred in late winter, 1995, aboard the USS Cavalla. Data were collected in a variety of locations, including the first Trans-Arctic Propagation (TAP) section from near Barrow, Alaska, towards Franz Josef Land within the Nansen Basin. Part of this track overlapped an icebreaker cruise track from 1991, allowing a good comparison of change over those 4 years. The result showed how water masses have changed over the 1990's. In particular, we found that the insulating layer that lies above the warm Atlantic Water has vanished within the Amundsen Basin, exposing the surface mixed layer (and the overlying sea ice cover) to potentially large upward heat fluxes (Steele and Boyd, JGR, 1998).

What is causing these changes? The answer is almost certainly tied to changes in the atmospheric circulation at high latitudes. The North Atlantic Oscillation (NAO) describes two patterns of atmospheric circulation. One becomes dominant for a number of years, and then switches to the other. These patterns influence the amount of warm, wet air carried into the Arctic regions, which influences the heat and freshwater inputs. Our understanding of this phenomenon is rapidly evolving.

These studies would have been difficult or perhaps impossible without the use of a submarine. Submarines can go where and when the scientist wants them to go. They cover large areas in a short amount of time. Their main drawback is that the instrumentation is still evolving, and lags the quality and depth coverage obtainable by icebreakers. But of course this could change with sufficient opportunity.

I closed my talk with some recommendations. Studies indicate that Arctic changes are occurring on a roughly 8 year time scale. Thus, annual cruises are perhaps not necessary to capture these changes, but waiting more than 3 years or so is also not wise. It is always desirable to perform repeat sections, but also to go into data-poor regions. It would be advantageous to extend the data-release area to include the waters near Greenland and Canada, where freshwater flows are important and poorly understood. Finally, I recommended that effort be made to improve the range and precision of SSXCTD's, the instruments that we have heavily relied on in the SCICEX program to provide near-three dimensional snapshots of these exciting changes in the Arctic Ocean.

Arctic Biology: Recent Results and Future Directions

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Many of the current biological questions in the Arctic are driven by the lack of data. Since many biological measurements cannot take advantage of time series from moored instruments and the various experimental approaches are not easily performed in ice camps and/or aircraft there have been few biological measurements collected. Not the least of the problems encountered has been the lack of available platforms to support an integrated set of biological experiments to determine standing stocks and biological process rate measurements at a variety of spatial and temporal scales.

Fortunately, the SCICEX program was developed at a time when many questions were being raised about the biological effects of global change in the Arctic. The combination of available submarines and the need for new biological measurements arose simultaneously to allow new and widespread measurements to be collected over the Arctic Basin. In general, most biomass and biological rate measurements are enhanced near the boundaries so an attempt was made to collect as many measurements as possible 1) along the edge of the continental shelf where materials exit the continental shelf to the deep basin; 2)

across fronts and other hydrographic features such as eddies; and 3) vertically in the water column to observe changes that result from changing profiles of light, nutrients, sinking organic matter or microorganisms.

The basis of the biological populations in the ocean begins with nutrients utilized in primary production processes. The introduction of nutrients into the Arctic ecosystems through physical processes such as advection and mixing including terrestrial runoff will not be described here but are important aspects to understand the inputs and transport through the ecosystem(s). The inputs and fluxes occur at many scales throughout the Arctic Basin and the resultant biological response(s) are probably related to the scales of the inputs. It has been postulated that the relatively large nutrient concentrations combined with water fluxes through Bering Strait in the western Arctic stimulates a large response in total production and may also produce a large percentage of production exported off the shelf to the deep basin (SBI/OAII Science Plan, 1998). Much of the dissolved and particulate fluxes of nutrient materials have been observed to reside in the Pacific halocline in the upper 100-300 m.

The locations and size of the Pacific-origin streams of water exported from the shelf were examined in an alongshelf transect along the edge of the data release box for the Beaufort, Chukchi and East Siberian shelves. Hourly samples were collected at 55 m which showed the presence of several high nutrient/high phytoplankton pigment leaks near canyons and depressions in the shelf. The signals of nitrate, silicate, phosphate and chlorophyll showed a Pacific origin of the plumes compared to the low nutrient upper halocline water. In addition, relatively high concentrations of ammonium indicated that substantial amounts of regeneration had also occurred in the shelf waters. There were four primary regions that displayed relatively high nutrient/pigment concentrations along the edges of the Beaufort and Chukchi shelves. It was particularly useful to observe the relative changes of chlorophyll:phaeopigments which indicated three regions where relic pigments and one region where recent phytoplankton pigments were leaving the western Arctic shelf. This information will now make it possible to return to those specific areas to collect additional samples that will provide a much improved knowledge of biological processes occurring within those highly dynamic areas.

Other recent biological samplings on the trans-Arctic section investigated the relationship of ice and snow cover, underwater light, nutrients, chlorophyll, bacterial abundance, primary production and phytoplankton species (Booth and Horner, 1997; Rich et al, 1997). Although there were relatively few stations in the transect, the new information offered many new insights into Arctic biological processes. There has also been an increased awareness that the organic production and decomposition cycles including the carbon cycle is much more dynamic than previously described. Higher rates of primary production, elevated amounts of particulate and dissolved organic matter, larger quantities of microbial biomass and activity promote the idea that the Arctic has much more interesting and important biological processes than previously thought. This includes upper consumer trophic levels which dependent on the primary levels. The zooplankton, fish and mammal populations continue to show a greater degree of flexibility than before but also there is a widespread concern that the populations are in jeopardy from over harvest and global change.

The importance of the SCICEX program and the availability of submarines to carry out research in the Arctic cannot be overstated. The SCICEX program represents an unparalleled opportunity to collect biological measurements over a wide area in the Arctic that could not be accomplished any other way. The future biological research carried out on submarines in the Arctic should focus on new techniques and sensors that can broaden the types of measurements collected and would maximize the productivity of the studies. A few examples of new or extended capabilities in biological measurements are:

- Nutrient and Organic Matter Budgets distributions and temporal trends
- Phytoplankton Species
 - dominant species, seasonal cycles, trends
 - ice algae versus water column productivity
 - light effects and limitations
- Microbial Activity

DECOMPOSITION AND TRANSFORMATION RATE PROCESSES

- Zooplankton
dynamics of micro and net zooplankton
- Fish
- Whales
Bow Head populations and migrations.

Most of the above tasks in this abbreviated list can be accomplished with new automated sensors that would collect data continuously and unattended. Calibrations before deployment may be practical for some measurements but in situ calibrations may be necessary too for some measurements.

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Modeling Changes in Ice Thickness Distribution Seen in SCICEX '96

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During SCICEX '96 submarine experiment very dense ice draft measurements were collected for a Lagrangian area 200 km across. The first survey was accomplished during September 14-18 with the center at 79.23N, 170.72W. The fact that the area was marked with a drifting buoy allowed it to be re-surveyed 40 days later on Oct.24-28 when the center had moved to 78.74N, 171.08W.

The ice draft profile data were analyzed and probability density functions with 0.1 m resolution were calculated for each survey. Figure 1 shows plots of ice thickness area and volume distributions for both surveys and also plots of differences in these distributions. Some changes were as expected. The reduction of open water in favor of more thin ice is normal for autumn freeze-up. The appearance of new thick ice (in the 3.5 to 8 meter range) is compatible with ridging of much of the newly grown thin ice. Rather surprisingly, though, the peak in ice thickness distribution at about 1.8 m appears to have moved towards the left about 0.2 m in October.

Three hypotheses were considered to explain this last, peculiar observation:

- (1) There is a bias in draft measurements between the two surveys.
- (2) At the beginning of freezing period there may have been a very strong oceanic heat flux which was able to melt over the 40 days about 0.2 m of the ice thicker than a meter while still allowing thinner ice to grow by virtue of cold air temperature and a steep temperature gradient through thin ice.
- (3) The ridging process as modeled by a "redistribution function" is more complicated than represented in most ice models.

We are exploring the first possibility with the staff of the Arctic Submarine Laboratory, but do not believe that such a large bias exists.

To investigate the second hypothesis we analyzed oceanographic data—XCTD profiles of temperature and salinity—from SCICEX '96 for the same time and location. Estimates of the flux turn out to be about 2 to 4 $W m^{-2}$ which is nearly an order of magnitude less than the flux necessary to have to support the second hypothesis, that 2-meter-thick ice melts 0.2 m in 40 days in autumn.

According to the ice thickness distribution theory [Thorndike et al., 1975] the redistribution function is assumed to have the simplest possible shape: just one negative portion for thin ice annihilated by ridging and one positive portion for thick ridged ice. This analysis shows two positive and two negative peaks for the redistribution function, even after removing the contribution of thermodynamics from the lower panels in Figure 1. It looks as there is a positive peak due to rafting of ice. Melling and Riedel [1995] have noted that a noticeable contribution of ice as thick as 2 to 3 meters can be made by rafting. Coon and Echert [personal communication, 1995] concluded from SCICEX '95 observations that "rafting may be a significant contributor to open water generation through ice redistribution". Melling et al. [1993] noted that "extensive areas of rafted ice are observed within deformational features in thick first-year ice."

The negative peak in redistribution for ice about 2 m thick (lower left panel of Figure 1) can be explained as "the lateral spreading of the rubble accumulation" [Hopkins, 1996]. As thin ice ridges, it piles on top of and beneath the populous 2-m ice that is surrounding and crushing it, causing some of this 2-m ice to be converted to greater thicknesses. Our analysis of ice draft data from moored sonars in Beaufort Sea [Melling and Riedel, 1996] shows a similar phenomenon in the redistribution function.

Acknowledgments. We are grateful to Diane Bentley and Burt Markham of the Arctic Submarine Laboratory for preprocessing the ice draft data and to Yanling Yu of the Polar Science Center for further preprocessing and creating the pdf's of ice thickness that we analyzed here.

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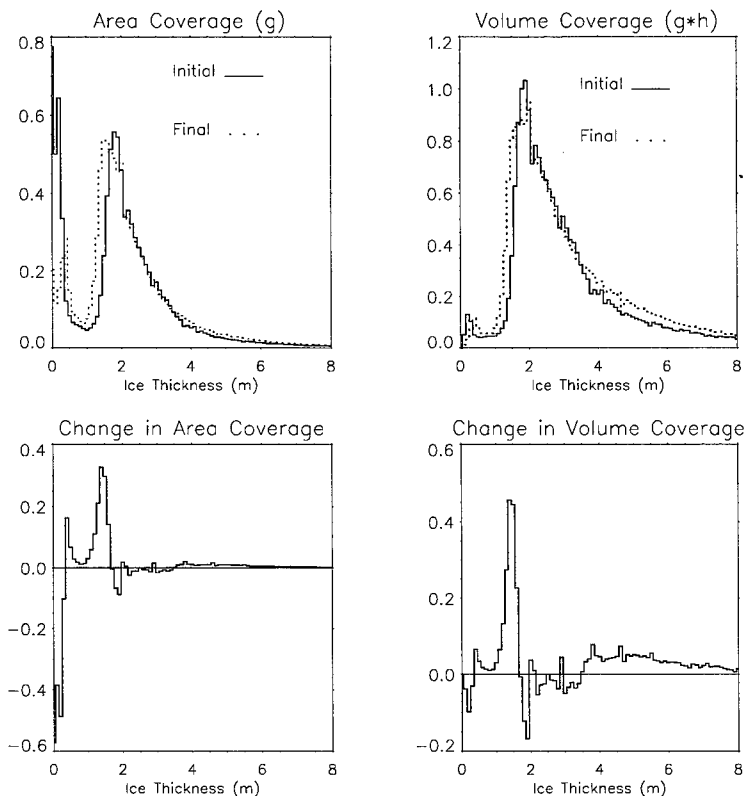


Figure 1. Probability density functions of ice thickness h by area $g(h)$ (left) and by volume $h*g(h)$ (right) for two ice surveys, the initial one in September 1996 and the final one, 40 days later, in October 1996. The lower panels show the changes from initial to final distributions. The area pdf $g(h)$ with units of m^{-1} shows the fraction of area covered by ice in the range $(h, h+\Delta h)$. The volume pdf (dimensionless) is simply $h*g(h)$ and shows the fraction of volume in the range $(h, h+\Delta h)$. We have used a thickness resolution of $\Delta h = 0.1$ m.

Swath Mapping the Arctic Ocean from US Navy Submarines; Installation and Performance Analysis of SCAMP Operation During SCICEX 1998

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The 1998 SCICEX cruise aboard the USS Hawkbill spent the month of August conducting oceanographic and geophysical surveys in the Arctic Ocean. This cruise was the first deployment of the SCAMP (Seafloor Characterization And Mapping Pods) sonars which enabled us to conduct swath surveys and col-

lect sub-bottom profiler data throughout the Arctic basin. The gravity, sidescan, swath bathymetry, and chirp sub-bottom data that were collected along approximately 17,000 km of track will be used to study and better define the geology of the Arctic basin.

SCAMP is one of the most complicated civilian instruments ever installed on a U.S. Navy submarine. Its installation required the coordinated efforts of personnel from LDEO, Johns Hopkins Applied Physics Lab, Electric Boat, HMRG and Norfolk Naval Shipyard Divers and the unfailing cooperation of the Navy personnel of USS Hawkbill, Submarine Squadron One, and COMSUBPAC. Fabrication, installation and testing of the SeaMARC-type swath system and data logging computers and testing and installation of the sub-bottom profiler were funded entirely by the NSF Arctic Program. Additional support from the Geological Survey of Canada and the Palisades Geophysical Institute funded acquisition of the sub-bottom profiler and some engineering work. The Norwegian Petroleum Directorate is assisting with support for data acquisition and processing.

While the geophysical objectives of the cruise were focused on the ultra-slow spreading Gakkel Ridge, data were collected continuously during all phases of the program, including along the cross-Arctic transit, and over portions of the Alpha-Mendeleyev Ridge, the Lomonosov Ridge, and the Chukchi Cap. These data sets provide the first 3-D characterization of these features, significantly increasing the geologic database for the Arctic Basin. The data collected by SCAMP while crossing the Arctic Ocean provides a geophysical cross-section from the North American continent to the Nansen Basin. The five day survey of the Gakkel mid-ocean ridge, the slowest spreading center on the planet, has produced swath bathymetry, sidescan, sub-bottom, and gravity data for 100km across-axis and 280km along-axis from 86°N 30°W to 86.5°N 75°W. The Atlantic-Pacific frontal survey over the Alpha-Mendeleyev Ridge has provided multiple crossings of the ridge crest along the eastern portion of the ridge. The two phase SHEBA ice survey and the final exit from the Arctic covered the northern edge and western edges of the Chukchi Cap.

Structure of the Lomonosov Ridge and the Development of the Amerasian Basin from SCICEX data

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The Lomonosov Ridge divides the Arctic Ocean into two distinctive basins of differing age and tectonic history, the Amerasian Basin on the Pacific side and the Eurasian Basin on the Atlantic side. This long sliver of continental crust, perhaps analogous to Baja California, was rifted off the Barents Shelf by the propagation of the Gakkel Ridge across the Arctic. The history of the early development of the Amerasian basin, surrounded by continental crust, is preserved in the internal structure of the Lomonosov Ridge.

Data from the Amerasian Basin can be used to support radically different models for its opening. Aeromagnetic anomalies lack a clear pattern of seafloor spreading anomalies. No relict plate boundaries or abyssal hill fabric has been identified. The two major classes of models each predict a very different structure for the Amerasian flank of the Lomonosov Ridge. According to the "rotational" model, the Lomonosov Ridge is a transform margin, while in the "Arctic Islands transform" model it is a rifted continental margin. Each model predicts very different structures on the continental margin. By determining the structure of the Lomonosov continental margin of the Amerasian Basin and characterizing the nature of the ocean-continent boundary, we can place constraints on acceptable models for the development of the Amerasian Basin.

During the SCICEX cruises data were collected along 25 new crossings of the Lomonosov Ridge. The gravity anomaly and narrow-beam bathymetry data can be used to divide the ridge into segments of distinctive form and structure which may have distinctive tectonic histories. Near Greenland, the Lomonosov Ridge is less than 100 km wide and divided by coincident gravity and magnetic lows. The central ridge, near the North Pole is a single, narrow monolithic block. As the Siberian margin is approached, south of 88°N, the character of the Lomonosov Ridge changes. The ridge is much broader, averaging close to 200 km in width. South of 85°N, it also becomes much less blocky, taking the appearance of a broad rise rather than an abrupt, steep-sided ridge, although the gravity anomalies still suggest that the ridge consists of a number of large fault blocks.

Aeromagnetic data over the Lomonosov Ridge also show a change in the pattern of anomalies at about 88°N. From there past the pole toward Greenland, a positive magnetic anomaly roughly follows the trend of the Lomonosov Ridge. South of 88°N, toward Siberia, the aeromagnetics data show an en echelon series of broad anomalies trending at roughly 35° to the overall north-south trend of the Lomonosov Ridge. The available bathymetric data also suggests that this portion of the Lomonosov Ridge may consist of a series of oblique blocks oriented at an angle of 30°-40° to the trend of the ridge.

The Lomonosov Ridge is flanked by a gravity low on the Amerasian side. Away from the Lomonosov Ridge, this gravity low is bounded by Marvin Spur, which is also observable as a gravity feature, suggesting the presence of a buried basement ridge beneath the Makarov Basin sediments. This portion of the Lomonosov Ridge is flanked on both sides by gravity lows and basement features which may mark the boundary between the oceanic crust in the basins and the continental crust of the ridge.

Based on the gravity and bathymetry collected so far from US Navy submarines in the Arctic, our working hypothesis is that the Greenland end of the Lomonosov Ridge is a transform margin and that the Siberian portion of the Lomonosov Ridge is an oblique sheared margin. This hypothesis is compatible with the "rotational" model for the opening of the Amerasian Basin.

Morphology and Segmentation of the Gakkel Ridge from SCICEX data

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Gakkel Ridge, the active spreading center in the Arctic Ocean, is the slowest spreading portion of the global mid-ocean ridge system. A thorough bathymetric and gravity survey of the western portion of the Gakkel Ridge axis, from 0°E to 60°E was carried out by U.S. Navy submarines during SCICEX cruises in 1996 and 1998 with some additional lines run to the east of 60°E. Swath bathymetry and backscatter data were collected during the 1998 cruise to complement narrow-beam data collected in 1996. Spreading rates on the surveyed portion of the Gakkel Ridge vary from 1.28 cm/yr to 1.10 cm/yr.

Gravity studies [Coakley and Cochran, 1998; EPSL in press] indicate that thin (< 4 km) crust is characteristic of the western Gakkel Ridge. While the volcanic crust may be poorly developed or thin, the seafloor spreading process appears to be orderly across the basin, with a clearly-defined spreading axis, lineated aeromagnetic anomalies, and a well-developed axis-parallel abyssal hill fabric on the ridge flanks.

The ridge axis, located within a 20 km-wide, 1500-1800 m deep rift valley, is very deep (4600-5200 m) compared with the Mid-Atlantic Ridge. The abyssal hills are large and blocky reflecting the importance of tectonic extensional processes. Large scarps of 500 -1500 m relief are common on the ridge flanks and deep axis-parallel, fault-bounded troughs with up to 1000 m relief are found throughout the survey area.

The ridge axis is segmented at 50-100 km intervals by non-transform discontinuities of less than about 30 km offset. The rift valley morphology is very asymmetric within segments. Inside corner highs are well developed with steep slopes and up to 3 km relief. Outside corners are deep with low slopes and do not get much shallower than 3600 m. Exposures of mantle rocks at the seafloor may be widespread along the western Gakkel ridge.

The ridge crest is about 600 m deeper to the east of a 150-km right stepping oblique offset of the axis near 60°E. This offset tracks back along flow lines to an offset of the Lomonosov Ridge near the pole and to the Santa Anna Trough on the Eurasian shelf and may be inherited from the original geometry of continental rifting. The great difference in the depth of the eastern and western Gakkel Ridge suggests that a fundamental change in the spreading process and in crustal generation may occur at a total spreading rate of about 1 cm/yr.

High-resolution mapping of dissolved organic carbon in the Arctic Ocean from a nuclear submarine

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The most extensive survey of dissolved organic carbon (DOC) in the Arctic Ocean was achieved by means of a high-resolution in-situ UV fluorometer deployed on a nuclear submarine. The SCICEX-97 mission aboard the USS Archerfish presented a unique opportunity to directly access the ice-covered interior of the Arctic Ocean and allowed quasi-synoptic data to be collected on an unprecedented scale and degree of resolution. The data reported in this paper were obtained while the submarine maintained a keel depth of 58 m along an approximately 2900 km-long transect north of the Beaufort, Chukchi, East Siberian and Laptev seas.

Distributions of salinity, temperature, Ba, TOC and DOCZAPS at a depth of 58 m along the transect are consonant with known hydrographic features of the Arctic Ocean (Fig. 1). The hydrographic front separating waters of Pacific and Atlantic character (points C-D) was observed over the Arlis Plateau, consistent with other studies indicating a recent (late 1980's) shift from its historical position over the Lomonosov Ridge to a position aligned along the Alpha and Mendeleev ridges¹. The transect was punctuated by warm (temperature > 0°C), relatively fresh (salinity < 32) waters over the slope north of Alaska. These features are associated with the Beaufort Undercurrent, a strong ($\approx 10 \text{ cm yr}^{-1}$), bathymetrically-steered mean eastward flow that typically extends from near-surface to the bottom between the 50-m and 2500-m isobaths over the shelf and slope in the southern Beaufort Sea². Local minima in salinity coincident with local maxima in Ba, DOCZAPS and TOC (points A, E-H) indicate points along the transect strongly influenced by fluvial discharge and identify areas where river waters cross the shelves and enter the Arctic interior. The high Ba associated with the feature observed at point A and its location in the southern Beaufort Sea suggest that it is part of the Mackenzie River plume, while the high DOCZAPS associated with the features observed at points E-H and their locations over the Makarov Basin and the flanks of the Mendeleev and Lomonosov ridges suggest that they are associated with discharge from Eurasian Arctic rivers^{3,4}. These data demonstrate the utility of combined physical and chemical tracer measurements for mapping distributions of fluvial discharge in the Arctic Ocean; in particular, they suggest that DOC and Ba may serve as complementary tracers for distinguishing between contributions from North American and Eurasian rivers.

The DOCZAPS measurements, combined with data for other physical and chemical tracers, indicated that over half of the total DOC in areas of the upper Arctic Ocean can be accounted for by fluvial contributions and identified areas where river waters crossed the shelves and entered the Arctic interior. Because the large amount of fluvial discharge to the Arctic Ocean influences the formation of sea-ice in the region⁵ and affects water column stability in areas of deep water formation in the North Atlantic⁶, an ability to track river waters is needed to assess the links between the Arctic and global oceanic circulation and climate. Knowledge of the mixing pathways of fluvial discharge within the Arctic also provides information about the transport and fate of riverborne contaminants in the region.

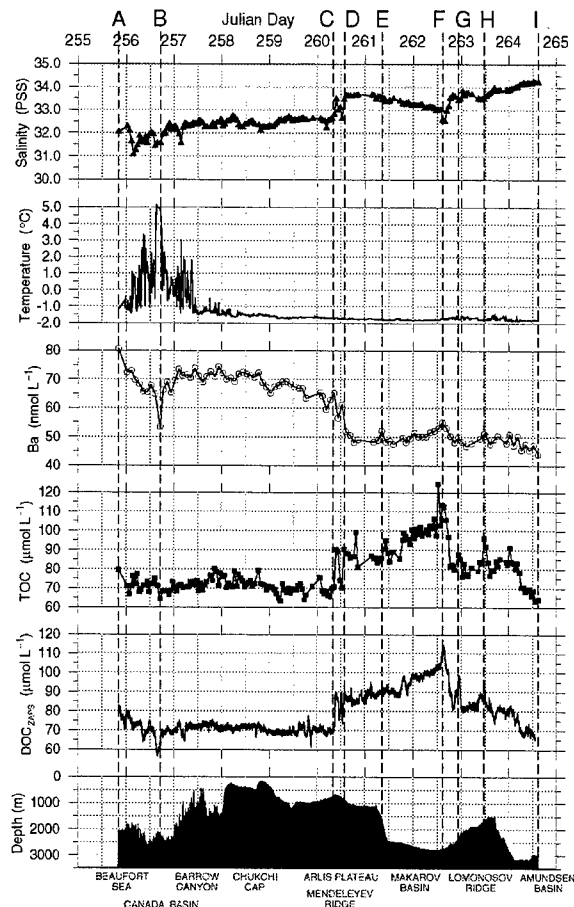


Figure 1. Distributions of salinity, temperature, Ba, TOC and DOCZAPS along the transect at a keel depth of 58m. The DOCZAPS parameter indicates concentrations of DOC determined from UV-fluorescence measurements obtained by a zero angle photon spectrometer (ZAPS). Letters A-I indicate points of reference discussed in the text.

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Tidal Currents along the Beaufort Slope

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1 Submarine Set and Drift

The basic assumption in calculating ocean currents by set and drift is that the vector sum of the relative velocity through the water and the ocean current is equal to the absolute velocity or inertial velocity relative to the earth. In a submarine the electromagnetic (EM) speed log gives the speed through the water, and the relative velocity is computed from this speed and the ship's heading. The submarine inertial navigation system supplies the absolute velocity and ship's position. Depth is also used to aid in the interpretation of the data. In practice, ship's systems produce estimates of these quantities at various sampling rates from once per second to once per minute. Intuitively, the current estimates from closely spaced samples will not be independent, which suggests that averaging is appropriate. In fact, the response of the submarine to a change in current may be computed from a simple dynamic analysis. The analysis shows that the response of the submarine to currents takes the form of a low-pass filter with a characteristic length scale 3 to 10 times the length of the submarine. This suggests that the averaging should be specified in terms of distance rather than time. In practice, the averaging length of 1 kilometer, corresponding to about 10 ship lengths, is often used, but a longer averaging length of 10 kilometers is used for the SCICEX to conform to classification guidelines on maximum absolute position accuracy. One restriction on the accuracy of set and drift measurements arises when the ship is executing a turn or change of course. When this happens the ship's velocity vector is no longer parallel to the heading as it "side slips" through the turn. For this reason, current estimates during course changes are potentially inaccurate and are usually edited from the data set.

Data for the drift current calculations for SCICEX are recorded on Submarine Data Recording System (SDRS), where time, position (latitude and longitude), EM log speed, heading, submarine keel depth, and water depth are recorded once per second. The INS measures inertial velocities, as well as positions, but they were not recorded by the SDRS on Cavalla. In practice these velocities must be calculated by differentiating the latitude and longitude.

2 Current Time Series

The data set for this study consists of a single transit along the shelf break beginning in the Chukchi Sea east of Herald Canyon on Julian Day 85, 1995 and ending in the Beaufort Sea near Barter Island on Julian Day 91. The submarine track roughly followed shelf break maintaining a speed of approximately 2.8 m/s at a keel depth of 58 m. During this period, the submarine made 4 stations where the submarine slowed and dove to a deeper depth before returning to its transit at 2.8 m/s and 58 m. These maneuvers took 1-4 hours, during which time the current measurements are unreliable because of the submarine's accelerations. Water depth varied between 200 and 1000 m during the first part of the section, where the submarine crossed the complex terrain south of the Chukchi Cap and the Northwind Ridge. Near the end of Julian Day 87, the submarine track moved down the slope to deeper water where the depth was 1500 to 2500 m. The total length of the section is approximately 1300 km.

Figure 1 shows the north current, east current, magnitude, and phase time series for the section. Each point represents the current averaged over 10 km along the submarine track. There are 4 time periods when the submarine slowed and made a depth excursion, which have been edited from the data set. Both components are clearly periodic with a frequency of approximately 1 cycle/day with 5 complete cycles in the 5 days covered by the section. The mean current is relatively weak. Both components have comparable amplitudes with the peak values of the north current leading the peak in the east current by about 6 hours. This indicates a clockwise or anticyclonic polarization, which is confirmed by the linear increase in the phase plot throughout the period. Careful examination of the traces shows that the amplitude of the east component is smaller in the early part of the record but increases in strength near the beginning of Day 88. This increase in strength can also be seen the magnitude plot. The geographic position where the transition to stronger currents occurs is north of Point Barrow where the width of the shelf narrows significantly. This time also coincides with the shift of the submarine track to deeper water.

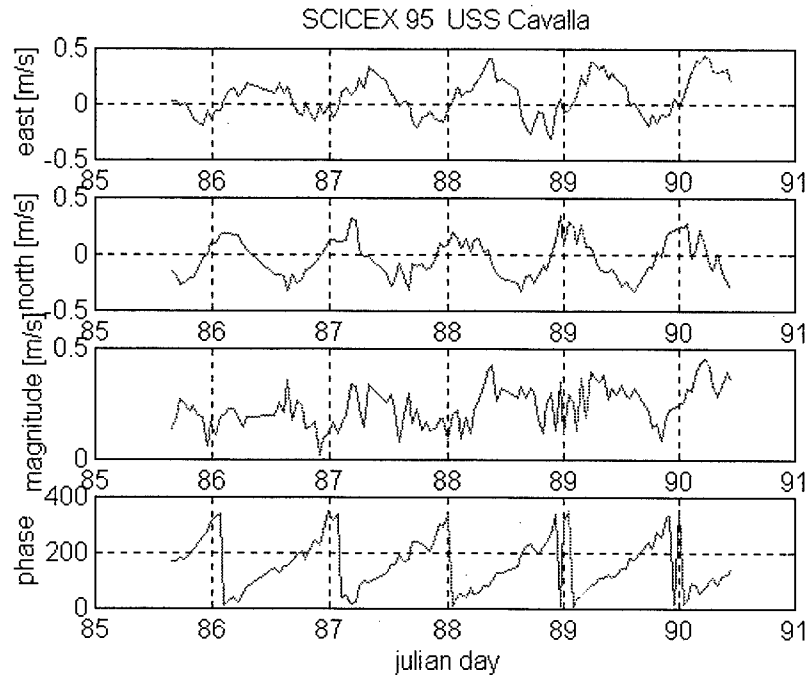


Figure 1. Time series of currents measured by set and drift of USS Cavalla during SCICEX 95.

3 Analysis

Although direct measurements of currents in the Arctic Ocean are sparse, there are reports of strong tidal currents associated with topographic features (Padman et al., 1992). In the present observations, the track of the submarine is roughly over the midslope region. In the western part of the track (Day 85.5-88), the bottom topography is irregular and highly variable with maximum depths on the order of 2000 and submarine ridges as shallow as 200 m. In the eastern part (Day 88-90.5), the shelf is shallower and narrower, the slope is steeper and the deep water is approximately 3000 m. Current ellipses are close to circular throughout, but they become slightly elongated in the eastern part with the major axis in the north-northeast direction, which is nearly in the cross-slope direction. In the western section the Chukchi Sea forms a broad shelf hundreds of kilometers wide and 20-50 m deep, but in the east, the shelf is very shallow (~20 m). Here, the ratio of the deep-water depth to the width of the combined shelf and slope is approximately $H/L=3\text{km}/30\text{km}=0.1$, making this a strong slope for topographic effects. Several expendable CTD probes were deployed along the section (T. Boyd, personal communication), and they show that the maximum buoyancy frequency is typically $1.5 \times 10^{-2} \text{ s}^{-1}$ at 200 m depth. This compares to the local inertial frequency, $f=1.4 \times 10^{-4} \text{ s}^{-1}$. Chapman (1983) has shown that the ratio $S = NH/fL$ determines the relative importance of the stratification and the slope in subinertial coastally trapped waves. In these observations $S \sim 10$, suggesting that stratification effects are very important.

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SCICEX and Acoustic Monitoring in the Arctic

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1 Introduction

It is now widely accepted that the Arctic Ocean is undergoing significant change. First observed in 1993 by the inaugural SCICEX cruise of the USS Pargo (Morison et al., 1998a) and the CCGS Henry Larsen (Carmack et al., 1995; McLaughlin et al., 1996), warmer water of Atlantic origin was found in the Makarov Basin, the eastern Arctic Ocean and into the western Arctic across the Lomonosov Ridge. In the spring of 1994 phase coherent acoustic signals were transmitted across the Arctic Ocean for the first time from a source located north of Svalbard, 2600 km to an ice camp in the Beaufort Sea. These signals, designed for accurate travel time measurements, detected average warming of the Atlantic Intermediate Water (AIW) of .4°C (Mikhalevsky et al., 1995; Mikhalevsky et al., 1998) as compared to historical climatology from the U.S. Navy GDEM data base and the Russian POLEX data recently incorporated into the Joint U.S.-Russian Atlas of the Arctic Ocean (EWG, 1997). This acoustic experiment, known as the Transarctic Acoustic Propagation (TAP) experiment demonstrated the feasibility of using Ocean Acoustic Thermometry in the Arctic Ocean and was the first indication of the warming of the AIW in the Eurasian Basin of the Eastern Arctic Ocean.

Every SCICEX cruise since the 1995 cruise of the USS Cavalla has included an Arctic transect similar to the TAP propagation track. These data have been used to model the response of an acoustic monitoring system and show that these changes when compared to the historical climatology are easily observed.

2 Climate Monitoring in the Arctic

A full understanding of the changes that are occurring now in the Arctic Ocean is limited by the inadequate observational data base that currently exists as well as the lack of capability to make synoptic observations in the Arctic Ocean. Satellite observations can monitor the extent and type of sea ice, but have no visibility into the Arctic Ocean. The SCICEX program, should it continue beyond 1999, could provide annual observations of selected sections of the Arctic Ocean. Ice camps and ice breakers can also provide selected sections and point measurements, but do not have unlimited access to all parts of the Arctic Ocean year-round. Acoustic monitoring using fixed and buoyed sources and receivers could provide real-time synoptic monitoring of the Arctic Ocean. Acoustic Thermometry in the Arctic will be able to monitor Arctic Ocean temperature, an important tracer (Morison, et al., 1998b). Acoustic intensity depends upon ice thickness and roughness and initial modeling results as well as measurements from the TAP experiment show that it is feasible to monitor average ice thickness by monitoring the changes in acoustic intensity over the propagation path (Mikhalevsky et al., 1998; Gavrilov and Mikhalevsky, 1995). This technique can provide estimates of sea ice mass, critical for climate modeling currently unavailable. Finally, monitoring of the thickness of the upper mixed layer in the Arctic Ocean can be accomplished by observing the attenuation of selected acoustic modes that are trapped above the thermocline. This upper layer of cold fresh water insulates the sea ice from the warmer more saline Atlantic water. Weakening and thinning of this layer, indicated from SCICEX 1995 (Steele and Boyd, 1998), could portend an ice-free state, predicted by some climate models.

The need for real-time synoptic monitoring in the Arctic Ocean is evident. Acoustic monitoring with multiple source receiver pairs could feasibly provide real-time year-round observations of the Arctic Ocean temperature, sea ice thickness, and mixed layer thickness on spatial scales of 100 km by 100 km in the next 5 years. Basin scale resolution is the goal of an on going program known as the Arctic Climate Observations using Underwater Sound (ACOUS, from the Greek meaning listen!). The acoustic measurements can be used for detection of changes and help direct submarine, ice breaker and ice camp deployments for higher spatial and temporal measurements using conventional means. In the fall of 1998 the first of two acoustic sources planned for the ACOUS program will be installed off Franz Josef Land. The signals will be monitored by an autonomous receive array in the Lincoln Sea. A cabled array in the Beaufort Sea is

planned for installation in the spring of 2000, along with a second source to be deployed in the central Arctic on the Lomonosov Ridge.

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Recent Hydrographic Variability of the Upper Arctic Ocean

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1. Recent Hydrographic Measurements

Recent hydrographic measurements collected from SCICEX submarine and icebreaker cruises in the Arctic since 1993 have captured a five-year snapshot of recent variability in the upper water column of the central Arctic basins. Our data collection accounted for over 525 CTD measurements including three synoptic transarctic transects. These three SCICEX transects parallel each other and are separated by a distance of approximately 150 km. The SCICEX-95 and -97 transects are approximately 2500-km long and extended from just north of Franz Josef Land in the Barents Sea to the Beaufort Sea just off the northeast coast of Alaska near Barrow. The SCICEX-95 transect lies closest to the Siberian boundary, while the SCICEX-97 transect lies just to the west, bisecting the pole. The SCICEX-96 transect is located nearest to the western boundary, extending over 2100 km from its origin at the Lomonosov Ridge.

The goals of these annual transarctic measurements are to (1) collect recent data to solidify our understanding of temperature and salinity variability in the central Arctic basins, and 2) combine these measurements with long-range, low-frequency acoustics to continuously monitor Arctic Ocean temperature changes and sea ice thickness and roughness. Sippican's 1000 m, under-ice submarine-launched expendable CTD probes (SSXCTD), specifically designed for under ice operations, were deployed approximately every 45 km along these transects. During other phases of the SCICEX cruises, SSXCTD probes were deployed at approximately a diurnal rate. Self-recording Sea-Bird CTDs taken from surface stations supplemented the SSXCTD probes during SCICEX-95 and -96. This sampling strategy intended to provide accurate vertical casts of the water-mass distributions and concurrent data needed to calibrate the SSXCTD casts.

2. SCICEX Transarctic CTD Transects

Over the five years of the SCICEX program, these hydrographic measurements consistently showed the effects of warmer Atlantic Water, mid-depth eddies, topographic features, and shelf driven circulation on the temperature and salinity structure in the central Arctic basin. Vertical temperature, salinity, and density cross-sections along the SCICEX-95, -96, and -97 transects of the upper water column were generated to determine the water-mass structures and compare these observations with historical climatologies. These vertical cross-sections were compared with US Navy gridded seasonal climatological data derived from all available historical T/S measurements (GDEM) and with Russian climatological data from the 1970's (POLEX). Measured data were subtracted from the climatology for that season and a difference plot was created along each vertical section.

These results indicated that the most dramatic temperature increase in recent data was present in distinct warm water cores in the Atlantic layer over the southern flank of the Nansen-Gakkel Ridge, closest to Atlantic source water flowing through the Fram Strait and Barents Sea. Data collected during the SCICEX-95 and -97 transects showed that temperatures in the Atlantic layer were over 2.0°C warmer than found in gridded climatology. The leading edge of these warm cores exhibited a downwelling of colder halocline water into the Atlantic layer following a topographic depression in the Nansen-Gakkel Ridge. Additional warm cores were noted near the Lomonosov Ridge in the SCICEX-95, -96, and -97 transects, and over the Mendeleev Ridge in the SCICEX-95 transect. Atlantic water temperatures in the Eurasian and Canadian Basins were more than 1.0°C warmer than climatologies. Recent data suggests that warmer Atlantic waters may have cooled very little during their transit through the Norwegian Sea.

3. Spatial Variability in the Central Basins

As a result of the SCICEX cruises we had sufficient coverage of water column measurements in the central Arctic basins to evaluate the spatial variability and map measured profiles based upon similarities in their upper water-mass structure. Cluster analysis techniques, applied to potential density measurements and derived from T/S profiles of the upper 600-m, resulted in several geographically and structurally distinct provinces (water assemblies). Identified provinces, containing profiles of similar T/S characteristics, appear bounded by bathymetric features. Our province results indicated that Atlantic water in the eastern basin occupies an increasingly larger area. We have mapped the shift in the frontal boundary, separating Atlantic/Pacific water, from the Lomonosov Ridge westward into the Makarov Basin. Also identified was a province that appears to be controlled by the circulation in the Canadian Basin. These T/S profiles contained colder less saline water in the halocline and upper Atlantic layer than measured in the surrounding water; probably originating from a cold, low-salinity shelf source influenced by water from the Bearing Sea.

In comparison with US and Russian Climatologies, the extensive coverage of recent synoptic measurements in the central Arctic basins concurs that significant warming has occurred in the Atlantic layer, signaling a shift in the Arctic Ocean circulation, and a large scale warming of the Arctic Ocean. Thus far, our analysis suggests that the Atlantic layer warming is most likely due to temperature fluctuations in the source water-masses. Our results also indicate that more than one mechanism may be responsible for the recent warming of the Atlantic Water. Continued analysis of existing SCICEX measurements along with future data collection will further clarify variations in the extent, path, and rate of spreading of recent warm anomalies and the shifting of water-mass boundaries in the upper water column.

The Atlantic Water in the Arctic Basin: Distribution and Variability

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1. The Atlantic Water provides the majority of heat, mass and salt flux into the Arctic Ocean. These fluxes determine not only general features of spacial thermohaline structure of the Arctic Ocean, but also its climatic variability.

The Atlantic Water in the Nordic Seas occupy the surface layer and are characterized by temperatures above 0°C and salinity above 34.4 ppt. The Atlantic Water entering the Arctic Basin through the Fram Strait, submerges under the more light surface waters and fills the Arctic Basin as a continuous layer. As this water streams out, it loses heat and slightly freshen itself. Depth of this layer increase, as a result of this process, and it reaches maximum values in the Canadian Sub-basin.

2. Spatial distribution and variability of the Atlantic Water in the Arctic Ocean are represented by their maximum temperature distribution for the decades 1950-59, 1960-69, 1970-79, 1980-89. These distribution maps were drawn using data of the Arctic Ocean Atlas (1997, 1998). The most maximum temperature values observed in specific years of each decade are given in these maps. It is emphasized that well-known dramatic warming of the Atlantic Water in the beginning of 90's is not an exceptional event. Analogous positive anomaly was observed in 1953-56. Very few measurements available for the year 1939 also show the signatures of the presence of the positive temperature anomaly in this time period.

We analyzed observation data and revealed the fact that this temperature anomaly had been registered at in Square 1 in May, 1990, when the maximum temperature had been as high as +9.4°C. later on, in May, 1990, when the maximum anomaly in kernel of the Atlantic waters (+3.36°C) was registered in Square 3. In May, 1993 the abnormal temperature value (+2.35°C) was registered in Square 4.

Analysis of historical data revealed the fact that entrance of the abnormally warm Atlantic water in the Norwegian Sea and streaming out of this plume in the Arctic Ocean had been previously observed too. For example, maximum temperature value (+10.10°C) was registered in Square 1 in May, 1954. Later on (in May, 1955), the maximum temperature value in Square 3 was +3.10°C, and it was equal to +2.36°C in Square 4 in May 1957. Estimation of the Atlantic Water spreading velocity is based on the analysis of location of these anomalies. The well-known circulation schemes (Nikiforov, Rudels, Poliakov) are compared with the observed temperature distribution for the Atlantic Water.

3. A combined database gives the opportunity to estimate interannual variability of the Atlantic Water in specific regions. Seven squares were chosen for illustration of interannual variations of features of the Atlantic Water layer. Mean and maximum temperature values for these regions were obtained separately for winter (March-May) and summer (July-September) Periods.

First of all, the attention should be paid on the fact that character of the interdecadal variations of the mean temperatures in small squares differ from their variability in the chosen relatively big regions, which include these small ones.

The Magnitude of the interdecadal temperature variations in the squares in higher than magnitude of the mean temperature variations of the Atlantic Water in the regions. It testifies that spatial irregularity of the Atlantic Water layer is significant.

The magnitude of the interannual variations of the mean and maximum temperatures in the squares is 2-5 times higher than the magnitude of the interdecadal variations. This fact should be taken into account while making estimation of climatic trends using single transections.

4. The interannual variations of the Atlantic Water are studied using fields of their upper boundary in the Arctic Basin at the end of the winter period (March-May). Fields of the upper boundary depth of the Atlantic Water for the winter period of 1950-1993 were constructed using the combined database. The interannual variability of the depth of the upper boundary of the Atlantic Water in the Arctic ocean may be well represented by first three significant EOF modes of those.

The analysis of the temporal variability of principal components mentioned above first three EOF modes have shown the dominance of the periods 6-8 and 11-12 years.

5. Interdecadal variations of volume, thickness, mean temperature and salinity of the Atlantic Water are given for the Arctic Sub-basins and Nordic Seas. Analysis results of conjugation of the decadal variations of different integral characteristics of the Atlantic Waters are presented. Variability of the Atlantic Water conditions and mean annual air temperatures in the North Polar region are compared.

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Decadal and interannual variability of surface water and surface circulation in the central Arctic Ocean

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1. We concern the class of surface water so called <<Polar Water>> or "Upper Layer Water" with temperature below 0 C and salinity below 34.4 ppt. Polar Water occupies not more than 2% of the water column in the ocean. However, their role in climate variability of the Arctic Ocean is of great importance. Location of the upper halocline is often correlated not only with geographic distribution of sea ice cover, but also with its stability.

The processes of salt release in winter and freshening through ice melt and river run-off in summer play main role in variability of the surface layer structure. The mean salinity distribution, standard deviation of salinity at 5 m depth in the Arctic Ocean and fresh water inflow for winter and summer periods are calculated (Arctic Ocean Atlas, EWG, 1997, 1998).

There are three remarkable regions with lower water salinity. Those are: Kara -, Laptev-, East Siberian- and Beaufort Seas both for summer and winter periods. In central part of the Arctic Ocean there are two low salinity areas in winter. The first is in the Beaufort gyre and the second area inclines to the line: New Siberian Islands - North Pole. These are regions of high values of standard deviation of water salinity. Processes in these regions play a key role in surface circulation and climate variability of the upper layer.

Maps of mean salinity distributions at 5 m depth in the Arctic Ocean give a good indication the range of spatial variability. These maps are drawn for the decades (50-s, 60-s, 70-s, 80-s) for the winter period (March-May) and for the summer period (July-September). Salinity contours allow us to gain idea of trajectories of freshened water spreading in the Arctic Ocean.

2. To show decadal variability of upper layer parameters the following parameters are calculated for 4 regions of the Arctic Ocean: volume of Upper Layer Water, total heat capacity; mean layer thickness, volume averaged temperature, salinity and heat capacity for each region from surface to depth of upper layer. Decadal variability of calculated parameters is shown on pictures.

Ranges of decadal and seasonal variability of integral parameters of surface layer are estimated. Estimated climatic trends demonstrate freshening the upper layer in the Arctic Ocean.

3. To show the interannual variability some parameters of upper layer are calculated for years those are covered a lot of observations. One can see the amplitude of interannual variability is five-ten times more than decadal one (Morison et al., 1998).

4. Dynamic height is a classical oceanographic variable often used to relate the spatial distribution of sea water density to large scale horizontal currents and to broadly characterize water masses. It should be mentioned that dynamic heights calculated in reference to the 200 db surface are an integral index of thermohaline and dynamic conditions of this layer and that's why can be used as an index of surface ocean circulation. Current velocities being averaged for 3 months are in a good agreement with velocities of geostrophic currents.

Dynamic height fields are used as an index of ice and upper layer ocean circulation in the Arctic Ocean. Late winter hydrographic measurements from the Arctic Basin are used to construct annual fields of dynamic height (surface to 200 db) for the years 1950, 1956, and 1973 through 1978. The method of field reconstruction (EWG, 1997) using three statistically significant EOF was used in order to obtain

fields completely covering the Arctic Basin. These three EOF characterize 76% of variance. A series of dynamic height fields was prepared for the years 1954-1993 (Koltyshev et al. 1997).

5. The first three EOF have a rather clear physical interpretation. We did an artificial simulation of dynamic heights field which approach helped us to reveal the physical sense of EOFs. Using the mean multiannual field as a basis we simulated its extreme distortions under the influence of each EOF separately. Each mode consists of EOF (which represents spatial structure) and principal component (which represent temporal variations). So, possible maximum and minimum values of the principal component for the considered EOF were taken for that purpose on condition that principal components of other numbers equal zero. Using next inverse transformation of the EOF method we restored the initial mean fields and obtained model examples of interest to study influence of the first, second and third EOF taken separately.

6. Classification of circulation of Arctic Basin was done. Three main types were revealed and also up to 7 subtypes. Analysis of temporal variability of dynamic heights was done. Possibilities of some oscillations were revealed, dominating are 6, 11, 17 years. Also some possible oscillations were revealed in time series of principal components of dynamic heights. Some high frequency oscillations seems to be possible' but most important are rather clear sights of low frequency oscillations of period 32 - 34 years both in time series of 1st and 2nd principal components. In time series of 3rd principal component we can see trend and anomalous condition of variability during 1989 - 1993, which can be linked to Atlantic waters anomaly or rivers runoff anomaly.

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Chemical signatures of production and respiration in the Canadian and eastern Makarov Basins of the Arctic Ocean

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1.0 Introduction

The permanent Arctic ice cover profoundly alters biological and chemical conditions in the deeper basins. The ice restricts the light available for the synthesis of organic matter, while peripheral ice free regions support large rates of primary production in the summer months. Thus, an unusually steep gradient exists between the rates of organic matter production in shelf and basin regions of the Arctic. Also, these regions are linked physically by the flux of ca. $2.5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ of cold shelf water to the upper halocline of adjoining basin regions (Aagaard, Coachman and Carmack, 1981). Sampling from submarines during the Scicex project afforded the opportunity to examine the distribution of variables in the inorganic carbon system (e.g. dissolved inorganic carbon (DIC) and alkalinity), oxygen, and dissolved and particulate organic carbon (TOC and POC).

Samples taken during the Scicex 93 and 96 cruises have added much detail to the known distribution of these parameters down to 1600 m in the Canadian and eastern Makarov Basins of the Arctic from that based on a small number of samples available previously. These data permit an analysis of the production signals in the chemical fields of the upper water as well as the respiration associated with the upper halocline and mid-water depths of the Canada Basin. Throughout most of the central Arctic, a layer of cold, more saline water can be found underlying the fresher, more alkaline, surface layer and is a dominant fea-

ture of the Arctic Ocean that varies between 50 and 200m in various basins (Jones, Nelson and Treguer, 1990). The halocline has also been found to be a nutrient maximum layer across the Arctic Ocean in all but the Nansen Basin. Other features relevant to the present discussion include the effect of bathymetric isolation among basins, that results in the Canada Basin being warmer and saltier than the Eurasian and also having higher silicate concentrations due to inputs from the Bering Strait and Siberian rivers (Aagaard, Swift and Carmack, 1985).

2.0 Results

In the eastern Canadian Basin, the upper halocline (~33 psu; 100-150 m) waters off the Chukchi and East Siberian Seas, a layer with a greatly elevated DIC indicative of respiration was found that dissipated away from the shelf (Fig. 1).

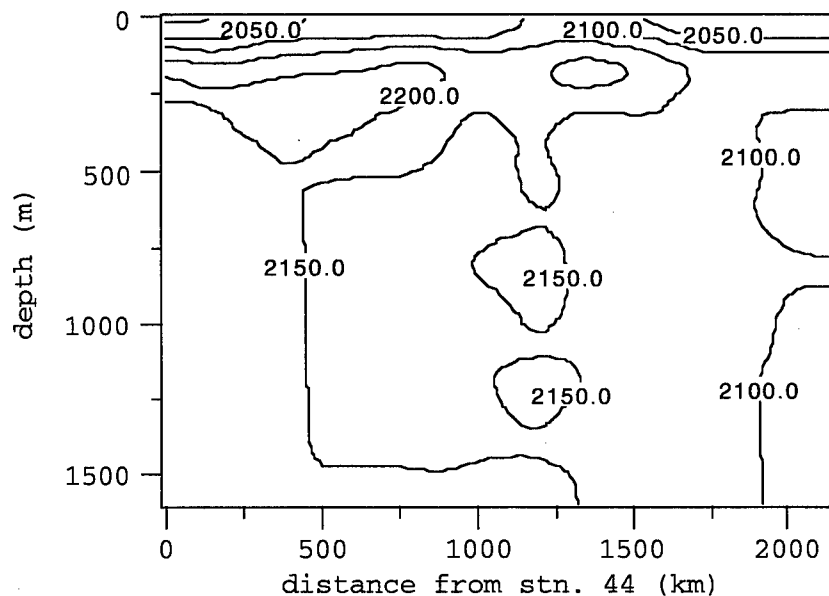


Fig. 1. Section of total dissolved inorganic carbon (DIC; $\mu\text{moles/kg}$) along the eastern side of the Canada Basin from the Scicex 96 cruise. The section runs from the Alaskan coast in the Beaufort Sea on the left to near the North pole on the right (Sambrotto, Langdon and Peltzer, submitted).

During Scicex 96, an extensive set of dissolved organic matter samples from the Amerasian basin was collected. These data indicate that surface and upper halocline concentrations of DOC (analyzed as total organic carbon, TOC, without filtering) are relatively large.

3.0 Conclusions

Based on these and additional parameters measured during the Scicex cruises, we conclude the following:

- 1) The respiration signal of elevated DIC and apparent oxygen utilization (AOU) varies geographically. On this basis it is possible to separate Amerasian waters into those that reflect mainly autochthonous production (from organic matter produced locally), from those that reflect significant allochthonous inputs (from organic matter produced elsewhere and mixed into the region). The carbon inputs in the Amerasian basin are much more influenced by allochthonous fluxes than are those in the Eurasian basins studied thus far.

- 2) There are significant frontal features at intermediate (~1000 m) depths just south of the Alpha Ridge. We suspect this is due to the winding of the shelf influenced water along the topography in this region. This mechanism may also play a role in pulling water we are tentatively calling lower halocline water into deeper depths near Alpha Ridge. This identification is based on the distribution of AOU and computed geochemical tracers such as NO and PO.

3) Elevated levels of dissolved organic matter (DOC) are found in surface waters that are not obviously influenced by river discharge. We suggest that DOC is produced locally in central basin regions, perhaps in association with the growth of ice algae.

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SCICEX-96: Hydrographic and Tracer Evidence of Intermediate Water Circulation and Renewal in the Canadian Basin

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During the summer of 1996 a line of 8 stations extending through the center of the Canadian Basin were occupied from the nuclear submarine, USS Pogy. CTD/Niskin bottle casts extending to about 1600 m at each station provided the first high quality temperature, salinity, CFC, tritium and ³He data from this region. These data revealed the presence of well ventilated intermediate water beneath the halocline in the center of the Canadian Basin suggesting renewal times of the order of 1-2 decades. The poorest ventilated intermediate water was found above the southern flank of the Alpha Ridge at the northern end of the Canadian Basin. Atlantic water enters the Arctic Ocean through Fram Strait and the Barents Sea and forms intermediate water that is observed throughout the Arctic Ocean. It flows around the Arctic basins in boundary currents and splits in the eastern Amundsen Basin with one branch crossing the Lomonosov Ridge and flowing along the East Siberian continental slope and the other flowing along the Eurasian flank of the Lomonosov Ridge. The SCICEX-96 data suggests that intermediate water transported in the East Siberian continental slope branch enters the central Canadian Basin in the vicinity of the Chukchi Rise and also is transported along the boundary to the southern end of the Canadian Basin. Along this flow path intermediate water derived from the Fram Strait inflow of Atlantic water mixes extensively with waters from the Canadian Basin, being diluted by a factor of about 5 between the eastern end of the Nansen Basin and the central Canadian Basin. However, intermediate water derived from the Barents Sea inflow does not undergo as extensive mixing and is diluted by only a factor of about 2.

Comparison of CTD and XCTD Data from the SCICEX-96 Cruise

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During the SCICEX-96 cruise, a line of CTD and XCTD stations through the center of the Canadian Basin were taken and provide an excellent opportunity for comparison of the two techniques for measuring temperature and salinity. The CTD data were collected using an internally recording Seabird (SBE-19). The XCTDs were manufactured by Sippicon and specially designed for submarine launch. A direct comparison by plotting CTD temperature vs. XCTD temperature and CTD salinity vs. XCTD salinity is difficult because uncertainties in the depth of the XCTD data (due to uncertainties in the fall rate of the XCTD probe) can cause a mismatch in the comparison as shown by Boyd et al. (1997). Also movement of density

surfaces by internal waves between CTD and XCTD casts can cause a mismatch. However, a comparison of potential temperature/ salinity plots avoids this mismatch and this approach is used here.

The CTD and XCTD data from overlapping and adjacent stations were compared in three ways using potential temperature/salinity plots: 1) the scatter in the plots, 2) the trends in the plots at each station which result from the vertical distribution of temperature and salinity, and 3) the trends in the lateral variability of the potential temperature/salinity plots.

Scatter in the potential temperature/salinity plots can be caused by variability in both temperature and salinity. However temperature sensors can resolve much smaller relative differences than conductivity sensors used for salinity determinations. For CTDs, the temperature resolution is generally a few millidegrees (1-2) and for XCTDs, 10-20 millidegrees. The scatter observed in the potential temperature/salinity plots is mainly the result of scatter in salinity. For the CTD data this scatter is 0.001-0.002 psu. For the XCTD data the scatter ranged from 0.006 to 0.02 psu.

The general trends at each station were the same for CTD and XCTD data and the halocline and the temperature maximum that marks water of Atlantic origin were readily apparent for both data sets. However, there was a systematic offset in salinity between the CTD and XCTD data that varied from station pair to station pair. The XCTD data always was higher in salinity and the offset ranged from 0.012 to 0.045 psu.

For water beneath the halocline (about 150 m depth) there was a clear trend in the CTD data. Salinity increased monotonically from the central Canadian Basin to a maximum at the southern flank of the Alpha Ridge and then decreased monotonically to the Lomonosov Ridge. This trend was not observed in the XCTD data due to a combination of the scatter in the XCTD salinity data and the variable offset in salinity between the XCTD and CTD data.

The conclusion of this comparison is that the salinity data obtained with the current generation of XCTDs is not of sufficient quality to be useful below the halocline in the Arctic Ocean which extends to about 150 m depth. Investigations of circulation of the Atlantic water, which is found beneath the halocline, should not rely on XCTD salinity data.

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O-18, Tritium, and He-3 Data Collected in the Canadian Basin During SCICEX 96: Implications for the Freshwater Balance and Mean Residence Times of the Upper Waters

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We present O-18, tritium, and helium isotope data collected from surface stations occupied during the SCICEX 96 cruise (USS POGY) in the central Canadian Basin. The stations fall along a section extending from about 88°N, 44°W (Lomonosov Ridge) to about 78°N, 144°W (middle of the Canadian Basin). The data are compared to sections collected during the Arctic 91 Expedition and discussed in terms of (i) their information on circulation patterns of freshwater, (ii) the relative proportions of river runoff, sea ice meltwater, Atlantic Water, and Pacific Water.

APPENDIX F. WHITE PAPERS

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A Submarine-Launched Expendable Current Profiler

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1. Measurements of Water Velocity from Submarines

An upward-looking ADCP installed for SCICEX-96, -97, & -98 provided continuous time series of horizontal currents from the depth of the submarine to the surface - providing coverage of at most the upper 200 m of the water column with 8 m vertical bins, 1-5 cm/s accuracy, and 1-5 km horizontal resolution, depending on the levels of navigational and instrumental noise. In principle, a downward-looking ADCP could also provide time series of currents to 450 m below the vessel (to a total depth of 650 m).

In SCICEX-98, a wire-lowered profiling ADCP was used to obtain station profiles of horizontal currents with 4 m bins and 0.5 cm/s accuracy. In principle, there is no limitation on the depth to which the profile can be obtained, but the unit used in SCICEX-98 could only sample to 600 m.

The straightforward adaptation of a successful, commercially available expendable velocity profiler for deployment from the submerged submarine is discussed below. It is intended that these current profilers will be launched closely in space and time to the SSXCTDs, allowing estimates of the Richardson number and vertical heat flux throughout the halocline and the Atlantic Layer of the Arctic Ocean.

2. The XCP: Principles of Operation

The Sippican Expendable Current Profiler (XCP) provides a vertical profile of relative horizontal velocity and temperature as it falls through the water column. The water velocity is inferred from the weak electric current that results when the electrically conductive seawater moves through the earth's magnetic field. The electric current generated is a function of the velocity of the conductive seawater, the conductivity of the water, and the strength of the earth's magnetic field (Sanford et al., 1982). The standard model is launched by hand from a surface vessel that is underway. After entering the water, a flotation bladder inflates, keeping the probe at the surface and providing a platform for a radio transmitter and antenna. After a short delay, during which the vessel has moved far enough away (> two shiplengths) such that its electromagnetic field does not contaminate the geophysical signal, the surface buoy releases the XCP probe which falls at about 4.5 m/sec, rotating at about 16 cycles/sec, to a depth of 1500 m (Sanford et al., 1991). The velocity signal is derived from the measurement of voltage between horizontally separated electrodes on the XCP probe. This signal is sent up a pair of wires to the surface float and then transmitted to a radio receiver on the surface vessel.

3. Historical use of XCPs in the Arctic Ocean

XCPs have been successfully used to sample currents throughout much of the world's oceans (see Sanford et al., 1993, for a bibliography of XCP references). Performance of the XCP will be degraded within 1-2° of the geomagnetic equator due to disappearance of the vertical component of the magnetic field and within a few degrees of the geomagnetic poles due to disappearance of the horizontal component of the magnetic field. The error near the magnetic poles is inherent in any compass and leads to greater uncertainty in the direction of the velocity. In the northern hemisphere, this should preclude XCP measurements only within the Canadian Arctic Archipelago. XCPs have been used successfully to determine vertical and horizontal distributions of horizontal velocity in the Arctic Ocean and adjacent seas in AIWEX '85 (D'Asaro and Moorehead, 1991), MIZEX '83 and Polarstern '87 (D'Asaro and Morison, 1992), and CEAREX '89 (Boyd and D'Asaro, 1994).

4. XCP modifications required for launch from a submerged submarine

The submarine-launched XCP will be deployed from the submarine's aft signal ejector in a similar fashion to the SSXCTDs that have been used successfully in SCICEX-93, -95, -96, -97, and -98. It will rise to a depth of 40 feet in a buoyant capsule, where a pressure trigger will cause the package to flood, and the XCP probe to invert and begin its descent. Transmission of the signal will be through wire back to the deck unit in the submarine. This does not represent untested technology. An early version of the XCP,

denoted Mod 6 by Sippican, transmitted the signal via wire the full distance from the probe to the deck unit on the surface vessel (Sanford et al., 1993). Since the transmission wire has a breaking strength of about 1 lb, wire must be continuously laid out between the surface vessel and the XCP float as the ship moves away from the float. For this reason, the Mod 6 XCPs only sampled to 850 m. Transmission losses may preclude increasing the amount of wire that can be spooled out during deployment from the submarine. In this case, the length of wire for the probe descent will depend on the distance the submarine moves away from the probe as it falls. Prior to manufacture of the XCPs, it will be necessary to determine a launch sequence for the XCP that allows for maximum profile depths consistent with the required margins of safety for under-ice submarine operation. This will determine the distribution of wire between vessel-to-buoyant capsule and buoyant capsule-to-probe spools within the XCP. The profile maximum depth will probably be in the range of 850 m to 1000 m. This is similar to the profile maximum depth for the SSX-CTDs deployed in SCICEX-95 (Boyd et al., 1997).

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SCICEX; an Opportunity to Complete Arctic Exploration

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1 SCICEX history

SCICEX has developed from an ad hoc collection of experiments that sailed on the USS Pargo in 1993 into a sophisticated science cruise which utilizes purpose-built data acquisition systems to observe the Arctic Ocean. Each SCICEX cruise brings two unique resources to the Arctic; mobility and instrumentation. These resources are not available from any other Arctic research platform. Each Arctic cruise should be structured to make the most of these resources for systematic exploration of the Arctic Ocean basin.

2 Science Access to the Arctic Ocean

There are a number of means to access the deep Arctic Ocean. Planes, satellites, ice breakers, ice camps and submarines have differing potential as science support platforms. To make the most of these limited resources, appropriate use of the complementary capabilities of each research platform should be defined by what it can do most effectively.

Icebreakers and ice islands are restricted by the drifting ice pack, but because of their ability to support heavy winches and other equipment, can be readily equipped for over the side work such as deep hydrocasts. Satellites and airplanes cover wide areas with a variety of sensors, but cannot directly image the seafloor or simply sample the water column. The wide areal coverage that can be obtained from air-

planes and satellites, while not as high resolution as similar data sets obtained from submarines, provides an excellent map view of gravity and magnetic anomalies that can be investigated in greater detail from a submarine.

2.1 SCICEX; Mobility and Instrumentation

Each SCICEX cruise brings two unique opportunities to the Arctic Ocean; the first is the mobility of the submarine, the second is the set of purpose built instruments installed for each cruise. In contrast to other Arctic platforms, a nuclear-powered submarine can move both vertically and horizontally in the ocean. Unrestricted below the ice pack, it can operate at speeds up to 25 knots, down to 800 feet, collecting water samples, underway geophysical and oceanographic data and using expendable probes to observe the water column, down to as much as a kilometer. No other science platform can simultaneously map the seafloor, image the underside of the ice, do near-synoptic three-dimensional mapping of the upper ocean or image the sediments beneath the seafloor.

Mobility and instrumentation should define appropriate use for US Navy submarines on SCICEX cruises. Much data has been collected in the Arctic over the last few decades, but it is not evenly distributed across the basin. Some areas have been visited repeatedly and are relatively well known (e.g. the North Pole, northern Alaska), others have rarely or never been sampled. Only a very few regions have been swath mapped, mostly those visited by the USS *Hawkbill* during SCICEX 1998. The present oceanographic and bathymetric data set, mostly collected from the surface, is restricted by the limited mobility of ice breakers and ice islands. The surface circulation concentrates ice in certain areas, practically eliminating access to the water column from above. In these regions the submarine offers its greatest potential yield. This yield will be dramatically amplified if the EEZs of Canada, Norway and Greenland are opened to SCICEX.

3.0 Systematic Mapping of the Ocean and Seafloor

While much of what we have learned during SCICEX has been built on hypothesis-driven research, there is still much we do not know about the Arctic Ocean that we might learn through a program of systematic mapping. Using the ability of the submarine to go places no one else has or could, with tools that can only be efficiently used from a submarine, we could thoroughly examine the water column, the seafloor and the shallow sedimentary record. SCICEX would become a program dedicated to synoptic oceanography of the upper ocean, systematic seafloor mapping and real time environmental monitoring of global change.

White Paper on Research Related to Submarine Methane Hydrates in the Arctic

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Methane hydrate (also known as methane clathrate) is an icelike material consisting of methane molecules engaged by a spherical hydrogen-bonded cluster of water molecules. Hydrates form from natural gas and water in sediments and permafrost, where temperatures are low (<20 deg C) and pressures are high (typically 20 bar or more). Natural hydrates often contain small amounts of other gases in addition to methane such as ethane, carbon dioxide or hydrogen sulfide. They are generally found beneath the ocean floor along continental margins and in regions north of the Arctic circle. It has been estimated that the organic carbon stored in the form of gas hydrates (about 1×10^4 GT) exceeds that held in all other known fossil fuel reserves (Gornitz and Fung, 1994; Kvenvolden, 1988; MacDonald, 1990). Growing interest in methane hydrates is based upon 1) their role in the global carbon budget 2) their impact on past and future climate 3) their capacity to become geologic hazards and 4) their potential as a energy resource.

Methane is a greenhouse gas that absorbs infrared radiation in wavelengths bands (3-8 μm) that are distinct from those of the more abundant greenhouse gases — H_2O and CO_2 (Blake, 1992). Methane resides in the troposphere on the order of a decade before eventually being converted predominantly by chemical oxidation with hydroxyl radical to CO_2 (Khalil and Rasmussen, 1983). Water vapor produced as a methane oxidation product magnifies the effect of methane transport into the stratosphere. Stratospheric water vapor not only produces a greenhouse affect but contributes to formation of the stratospheric clouds

that are implicated in dramatic ozone losses over Antarctica (Hamill and Toon, 1991). At present, approximate equal amount of water are delivered to the stratosphere by direct upward vapor transport and methane oxidation (Blake, 1992). Thus, there are multiple links between methane and the radiative budget of the Earth.

Bacteria can produce methane by anaerobic fermentation under wet, low oxygen conditions such as occur in wetlands, paddies, and the intestinal tracts of insects and animals. Methane can also be produced as buried organic matter is heated geothermally. Methane is introduced to the atmosphere by such a wide range of bacterial and other sources (ruminant animals, organic rich sediments, rice paddies, biomass burning, fossil fuel leakage, methane hydrate decomposition, etc.) that its cycle is difficult to quantify with certainty. We do know that the northern hemisphere sustains somewhat larger concentrations (about 7%) of methane than the southern and levels increase with latitude in the north suggesting strong northern sources in the face of relatively rapid inter-hemispheric mixing times (Khalil and Rasmussen, 1983; Steele et al., 1987). It is also clear that tropospheric methane levels are rising on the order of 1% per year due to anthropogenic disturbance of its cycle (Blake, 1992; Rasmussen and Khalil, 1981; Rinsland et al., 1985). While aspects of its cycling remain unclear, it appears that present-day sources for atmospheric methane are on the rise while its dominant sink may be decreasing somewhat as rising carbon monoxide concentrations compete for atmospheric hydroxyl (Blake, 1992). Ice core records show that methane concentrations have doubled since pre-industrial times (Craig and Chou, 1982). These data also reveal ice age time scale fluctuations in methane that are coherent with other indicators of climate variability (Chappellaz et al., 1990).

Stable carbon isotopes and radiocarbon measurements suggest that up to 30% of the present atmospheric methane burden (about 5 Gt carbon) results from fossilized carbon sources (Lowe et al., 1988). Normally, the bulk of this signal is attributed to the use of fossil fuels though the amount of methane being released to the atmosphere from hydrates remains unclear. However, only a small fraction of the estimated reserves of hydrate methane would need to be released to more than double the present atmospheric inventory. There is speculation that such releases may have been responsible for abrupt climate shifts in the past (MacDonald, 1990; Nisbet, 1990), may limit the extent of glaciation (Paull and Ussler, 1991) and may contribute to enhanced greenhouse warming (Bell, 1982; Gornitz and Fung, 1994; Revelle, 1983). This potential for destabilization of methane hydrate appears to be greatest in the Arctic region where seawater flooding at the edge of heavy ice sheets could trigger very rapid releases of surface to near-surface hydrates. Following the climax of the last glacial period, subaerial permafrost settings along the Arctic coast became inundated with seawater as sea level rose and glaciers retreated. Heat penetration from the overlying seawater can destabilize permafrost hydrates on 100-1000's of year time scales (MacDonald, 1990). Gas seeps and pockmarks observed in the Mackenzie Delta area of the Beaufort Sea have been attributed to this phenomenon (Judge and Majorowicz, 1992). This may explain very high (up to 30 times atmospheric equilibrium) concentrations of methane observed in ice-covered coastal waters north of Alaska (Kvenvolden, 1993) and may contribute to the fact that highest observed atmospheric concentrations occur at the most northerly time series observing station at Barrow, Alaska (Khalil and Rasmussen, 1983).

Destabilization of continental slope hydrates can also come about by tectonically driven decreases in pressure such as have been demonstrated for the Oregon margin or changes in overlying and underlying thermal gradients. Basic information regarding the present rate of such releases from the seafloor in general is lacking. Nor is it known what fraction of such methane survives transit through the water column to the atmosphere. From both basic and applied research perspectives, this lack of information represents a major gap in our understanding of the global methane cycle. It is necessary that such baseline information be gathered now to allow projection as well as future evaluation of environmental impacts since international plans are projecting exploitation of hydrates as a fuel source within a few decades (http://www.fe.doe.gov/remarks/hydrate_052198.html). Given its large shelf area (25% of global shelf area), the occurrence of marine permafrost as well as deeper continental margin hydrates and the particular susceptibility of high latitude systems to projected global warming, this is particularly true for the Arctic Ocean.

A widescale multi-seasonal survey of upper Arctic ocean methane distributions would be a first order contribution to the assessment of the magnitude of the present Arctic methane source. Eventually

these results could be used to develop a rationale for geophysical studies and a lower frequency sampling plan to obtain more chemically diagnostic information, including the carbon isotopic composition of the methane and finer scale gradient definition for sediment water and air-sea flux estimates. Such a widescale survey program would be best accomplished with a continuous in-situ sensor approach combined with some shipboard or laboratory based analyses for calibration and cross-check. The time for such an approach is ripe as such sensors are just becoming commercially available. For example, GEOMAR (Kiel, Germany) has partnered with GKSS Research Center in Geestacht for the development of an in-situ methane sensor for deep sea deployment. The GKSS device is called the METS Sensor which relies on the diffusion of dissolved methane through an asymmetric silicone membrane (GKSS product) and it is commercially marketed by ASD Sensortechnik of Warnau. Measurements of methane behind the membrane are made with a SnO₂ semiconductor (patent pending). The sensitivity of the device is better than 10 nM. The current sensor has a 1000 m depth rating which exceeds the requirements of Arctic shelf and margin studies. Moreover, this sensor has recently been successfully tested on the MIR submersibles at a massive hydrate/mud volcano on the seafloor off of Norway.

Adaptation of such a sensor for deployment on the hull of a nuclear submarine should be straightforward and analogous to the operation of other sensors that have been successfully modified for SCICEX deployment. Flame sealed samples for calibration purposes could be taken through the intake or via surface based hydrocasts and run back in the laboratory. The primary advantage of the nuclear submarine platform would be widescale multi-seasonal surveying of the ice-covered Arctic interior as a complement to work conducted over the shelves from other platforms. It would be of great interest for survey purposes to sample as near to the surface as possible without conflicting with safe operation of the vessel. The project would also benefit from plans under discussion to extend the boundaries of the present SCICEX operation area to accessible Arctic shelves.

Development of widescale methane distributions for the Arctic would be complementary to work conducted over marine shelves from other platforms. TECFLUX (tectonically controlled flux) is an international and interdisciplinary research program just getting underway with US investigators funded by NSF and NOAA. This program will study the geotectonics and geochemistry of hydrate deposits associated with the subduction zone in the Cascadia Basin. Another relevant NSF program in the early stages of funding is the Arctic Western Shelf Basin Interactions Initiative being sponsored by the Office of Polar Programs. It could provide platforms for complementary process oriented studies. At the national level, the US Senate has recently passed a "Methane Hydrate Research and Development Act of 1997" (S.1418) which is presently under consideration by the House. This is a bill to promote a decade of research, identification, assessment, exploration, and development of methane hydrate resources which will certainly increase US interest and scientific activity in this domain (http://www.fe.doe.gov/oil_gas/methanehydrates/hydrateplan.html). The technology and methodology developed for these programs will enhance the value of methane research through SCICEX.

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Greenlandic/Danish research initiative in the Arctic Ocean region north of Greenland

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1. Background

The continental shelf and adjacent Arctic ocean region north of Greenland is one of the least investigated regions of the Arctic. Even the most basic data on bathymetry are only known very rudimentally from historical expeditions, a few icefloe and ice breaker traverses, and from a few US and Russian map compilations, which might be based on additional (classified) data. Official Danish nautical charts of the region are extremely coarse, and even the coastline was only in recent years mapped to a modern precision, being more than 20 km off in many international charts based on the older mapping material from Greenland.

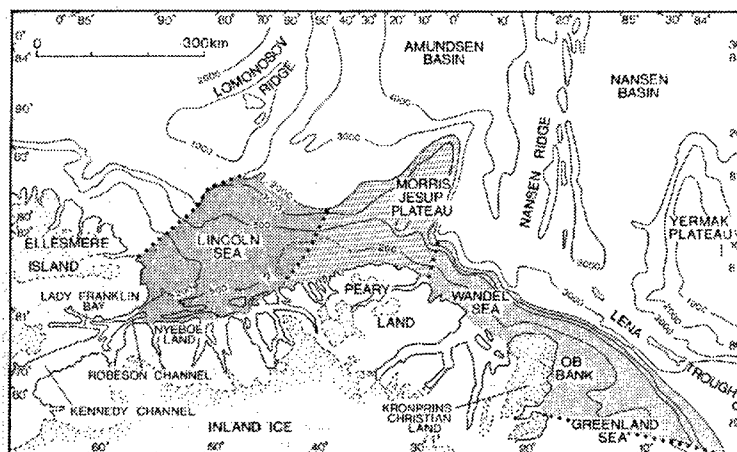


Figure 1. North Greenland shelf region with main physiographic regions shown in different shading

(from Dawes: "The North Greenland Continental Margin", DNAG vol. L, Geological Society of America, 1990)

Danish research activities in the Arctic Ocean north of Greenland have up to now been very limited, consisting mainly in participation in a few international ice floe or ice breaker expeditions (e.g., "Polarstern" and "Odin" cruises, and e.g. the "FRAM" ice camps). Danish/Greenlandic activity has been larger on the NE-Greenland shelf, where e.g. extensive commercial seismic surveys in recent years have been carried out up to latitude 78° by an ice-strengthened Danish naval vessel.

A recent emphasis on airborne geophysics has resulted in increased Arctic Ocean survey activities, where Denmark has supported Canadian-German magnetic measurements in the Lincoln Sea region (PMAP project), as well as initiated own airborne gravity measurements over the continental shelf (fig. 2) in a cooperation with the US National Imagery and Mapping Agency (NIMA), in continuation of earlier land-based activities. However, airborne measurements can only address a limited amount of scientific problems, and there is a need for a broader research effort.

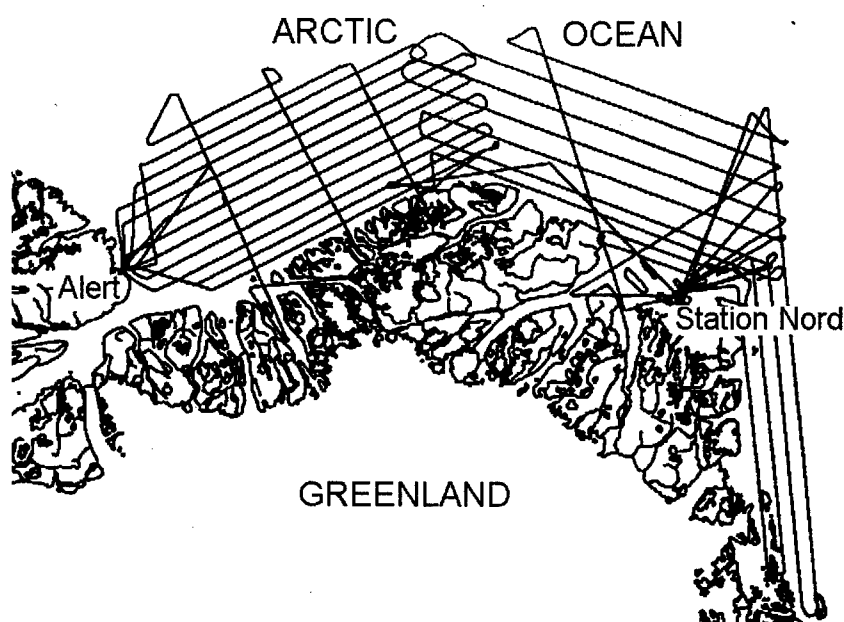


Figure. 2. Survey tracks of the 1998 KMS aerogravity survey of the North Greenland shelf

Recently the Commission for Scientific Research in Greenland has taken an initiative to bring relevant Danish scientific groups together with the aim of focussing on a multi-disciplinary research activity in the North Greenland shelf area and adjacent ocean regions. As part of this initiative, a national science plan for such research will be worked out.

The need for an increased research activity is both due to the basic scientific wish to study a virtually unknown region, and to obtain basic data in support of national bathymetric and geophysical mapping, including basic geophysical data relating to basic sedimentary structures and thus potential for hydrocarbons. A basic active participation in scientific investigations of the continental shelf, and especially a detailed knowledge of shelf bathymetry and sedimentary cover, is also very important in view of a future declaration of a Greenland exclusive economic zone (EEZ), in accordance with the basic rules of the United Nations' "Law of the Seas" convention.

It should be pointed out, however, that the proposals outlined here have not yet been funded, and may thus at present be viewed as ideas only. Denmark/Greenland would welcome and encourage broad international cooperation in the study of the region, in accordance with the general Danish science policy to encourage international cooperation to the maximal degree in research projects.

2. The North Greenland shelf and adjacent ocean areas - features and science possibilities

The main physiographic features of interest in the region include the Lincoln Sea shelf, representing a little known sedimentary basin, the Morris Jessup Rise, a bathymetric feature of probably mixed oceanic and continental origin, the unusually narrow continental shelf west of Cape Morris Jessup, the wide continental shelf off NE-Greenland, and the deeper ocean north and north-east of this. In the deep ocean features of specific Greenland geophysical interest (due a.o. to its proximity) would be the Gakkel (Nansen) ridge and the Spitsbergen Fracture Zone linking it to the mid-ocean ridge of the Greenland Sea.

The main scientific areas where Danish and Greenlandic researchers have interests include a.o.:

Oceanography and related fields:

- Basic bathymetric data, preferably acquired as multi-beam or side-scan sonar in a "move-the-lawn" fashion. Obviously a submarine would be the most useful vehicle for such surveys due to the freedom of navigation in icecovered regions, and the proven capability of such vehicles to collect these data.

- Basic oceanographic data: Salinity, temperature, currents etc., giving contributions to the identification and study of dynamics of the arctic water bodies and the exchange of water through the Fram and Nares Straits.

- Hydraulic and environmental data relating to the polar ocean ice cover, environmental information from shallow ocean bottom cores etc.

Geodesy:

- Gravity surveys and airborne altimetry to support geoid determination and upcoming gravity field satellite missions (CHAMPS, GRACE, and GOCE), which due to orbit restrictions will not provide data over polar regions.

Geophysics/geology:

- High resolution gravity and magnetic surveys to aid in understanding geological settings and obtain data on sedimentary basins.

- Seismic experiments: reflection seismology for understanding sedimentary basins and define extent of continental shelf sediments, refraction seismology, and travel time anomaly studies of natural earthquakes for investigating large-scale crustal structures.

- Shallow coring and dredging for geological sampling.

Biology:

- Acquiring a basic knowledge of the deep-ocean fauna, and acquire data relating to the natural living resources and mammals of the region.

The above list is in no way exhaustive, but represents some areas where Danish and Greenlandic scientists have active interests, the listed topics are obviously similar to earlier identified science needs both nationally and internationally. An earlier science report - "Eastern Arctic Science" (published 1980 by the Commission for Scientific Research in Greenland) outlines in detail a number of research objectives for the region, most of which are still most relevant and unanswered to this day.

3. The proposed logistical and cooperation possibilities

In fulfilling the scientific needs Denmark and Greenland welcome international cooperation, and through such cooperation also hope to get access to logistical platforms and data from other Arctic research programmes.

Obviously, bathymetry data are most efficiently collected by submarines, as is the measurement of precise gravity profiles, to be used to evaluate and supplement airborne surveys. Greenlandic and Danish scientific groups would welcome and invite possible future SCICEX or other submarine cruises into Greenland Arctic Ocean waters as a means of obtaining such data.

Other scientific studies, especially related to seismic surveys, shallow bottom coring, dredging and marine fauna sampling could with advantage be done from icebreakers. Denmark has no suitable vessels

for this purpose, but a cooperative programme with the German icebreaker "Polarstern" would be a good possibility, since Polarstern in recent years has operated several times in the area, especially in and around the Fram Strait. Germany has recently issued an invitation to cooperative work involving Polarstern.

A national Danish effort should be based on temporary ice floe camps, open for international cooperation, and especially focussed on the Lincoln Sea and the Morris Jessup Rise region. Ice camps could support a broad range of scientific objectives in a cost-effective manner, and be especially suited as bases for seismic profiling, mixed gravity/bathymetry surveys, and hydraulic/biological projects. A logistical setup would call for "light-weight" logistics, deploying smaller Twin-Otter and helicopter supported spring time camps, launched from Station Nord or Alert (pending agreement with Canada). The Greenland village of Qaanaaq could serve as an additional entry and supply point for such activities, taking advantage of a new airport to be constructed. Ice camps could be launched in alternate years at suitable positions in the Lincoln Sea, and with a little luck be able during a 1-2 month season to sample the outer parts of the Lincoln Sea shelf and drift across the Morris Jessup rise.

4. Conclusion

There is a wish among Danish and Greenlandic scientific institutions and administrative bodies to see an increased research activity in the Arctic Ocean, especially in the Lincoln Sea, Morris Jessup Rise, and the NE-Greenland shelf region. An open and free international cooperation in this field is most welcome and encouraged by Danish and Greenlandic authorities.

Submarine Installation Preparations

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1.0 Submarine Installation Preparations Overview

Installation of SCICEX equipment on submarines are characterized as temporary alterations for mission critical research, development, and test/evaluation purposes. The installation period is finite and generally less than a year. Preparation for a submarine equipment installation is a complex process involving several organizations and requiring thorough documentation. A typical process includes:

- Sensor housing and mounting design
- Electronics packaging
- Preparation of draft of Temporary Alteration Package
- Ship identification
- Shipcheck
- Completion of Submarine Temporary Alteration Package
- Fabrication of ship specific components
- Review and approval of Temporary Alteration Package
- Equipment Installation

Equipment and system designs should be complete and documented prior to requesting a ship. A draft temporary alteration package (TEMPALT), containing all relevant mechanical and electrical system information, is prepared at this time. After a ship has been identified, it is visited to identify equipment locations, cable paths, power sources, and ship-specific brackets. Next, the TEMPALT is updated to reflect the information determined during the shipcheck, and it is submitted to the Naval Sea Systems Command (NAVSEA) for review and approval. NAVSEA review usually requires 60 days and can be longer or shorter depending on priority. Following NAVSEA approval, the TEMPALT is submitted to the Type Commander (TYCOM) for review and approval. Type Commander approval can be given immediately after NAVSEA approval or can take as long as 60 days after NAVSEA approval. Installation activities can begin after NAVSEA and TYCOM approval.

1.1 Organizations Involved in Submarine Installation Preparation Sequence

An installation process involves several organizations including the sponsor, Type Commander, squadron, ship, NAVSEA, installing activity, and associated subcontractors. The sponsor provides funding, and the Type Commander (such as Commander Submarine Force, U. S. Atlantic Fleet) provides the ship. Submarines are grouped in squadrons, and squadron organizations provide much of the day-to-day oversight. NAVSEA provides guidance for developing installation designs and related documentation, and reviews and approves the TEMPALT to assure optimum ship/system performance and personnel safety. The installing activity is responsible for installing all equipment according to the guidance provided by NAVSEA. Subcontractors are involved to provide specialized services. After mission completion, the equipment must be removed and the ship restored to its pre-installation configuration. It is the responsibility of the sponsor to fund this effort as well.

Memorandums of agreement (MOA) are generated by the installing activity for the shipcheck and installation. An MOA identifies the responsibilities of each organization for the work to be done. A pre-installation meeting is arranged to review the MOA with all organizations and make any necessary revisions.

1.2 Submarine Installation TEMPALT Package

The TEMPALT package documents the temporary submarine installation. It contains an installation overview, internal- and external-to-the-hull equipment arrangement drawings, wiring block diagrams, cable running sheets, stress calculations, weights and moments, and electrical hull penetrator information. A TEMPALT does not typically include installation procedures; these are provided by the installation activity. Also, any impacts on ship dynamics, maneuverability, habitability, safety, and systems are described. The package should provide an overview of equipment function and purpose, and reference a test plan.

1.3 Submarine Installation Preparation Sequence Recommendations

The installation preparation sequence is complex. The following recommendations are provided:

- Review the Guidance Manual for Temporary Submarine Alterations before initiating installation preparations
- Maintain effective communications with all involved organizations
- Exchange status information often
- Thoroughly test all equipment – individually and integrated – prior to shipment to the installation site
- Fitchek assemblies
- Generate thorough MOAs
- Develop a shipcheck checklist
- Be aware of and adhere to Navy procedures
- Be aware of ship schedule
- Be thorough, accurate, and consistent when generating the TEMPALT package

Submarine Installation Design Considerations

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1.0 Submarine Installation Design Considerations Overview

Submarine installations must be designed to assure optimum system performance, maintain ship performance, and assure personnel safety. A critical element of this design effort involves identification of

external equipment location(s), because hull attachment, cabling, and serviceability pose the biggest challenges. Specific considerations include:

- System performance requirements
- System survivability
- Proximity to ship's systems
- Hull structure foundation
- Welding and cutting
- Special Hull Treatments
- Ballast removal
- Pod Shape
- Electrical hull penetrators
- Dry-docking
- Maintenance

1.1 Submarine Installation Position Considerations

System performance is optimized by selecting the best operating position on the hull, maintaining appropriate separation from ship's systems, and properly orienting sensors. For example, for bottom-mapping systems, keel-mounted sensors are recommended to minimize hull interference and maximize sensor performance. Sensor orientation would be symmetrical. Also, attachment is simplified because roll is zero and pitch is small, and no anechoic tiling has to be removed. For symmetric acoustic arrays that require large horizontal separation, the port and starboard arrays may be mounted in separate pods, each further up the hull from the keel. Anechoic tiles would have to be removed and cable enclosures would be required. Forward and upward-looking sensors can be mounted on the deck or in the sail thereby avoiding tile and below-the-waterline related complexities. Deck or sail mounted materials may, however, be damaged during an ice penetration.

1.2 Hull Attachment Considerations for Submarine Installations

Typical hull-mounted structures consist of a foundation and pod. The foundation provides a flat surface to attach the pod while accounting for hull curvature and ship frame locations. Attachment points must be located at frame locations to avoid possible hull distortion. A typical attachment technique involves welding cylindrical mounting pads to the hull. Each pad has a tapped hole which results in a hull attachment point significantly stronger than simply welding a stud to the hull. The number of pads and size of hardware depend upon the size of the pod and number of frames in the pod location. Below-the-waterline welding and anechoic tile removal and restoration requires dry-docking the submarine because of the precision required. A skirt, which is fitted during the installation, is attached to the foundation to ensure no gaps between the foundation and hull exist. These gaps could cause hydrodynamic noise. Hull structures, such as range pingers, can also be mounted directly to a submarine's main ballast tank (MBT) grates. These structures are simply clamped to the grates. Care must be taken to minimize the size of grate-mounted structures that would block the free exchange of water in/out of the MBT. Dry-docking would not be required for simply clamping structures to MBT grates.

Criteria for attaching hull-mounted structures is defined by Naval Sea Systems Command in Washington, DC. Structures mounted on the deck or sail may have to be designed to withstand ice loading depending on mission requirements. All hull structures must be designed to withstand wave slap with a minimum factor of safety of 2. Depending on the weight and location of the hull attachment(s), ship's ballast may have to be removed. Removing ship's ballast may or may not require dry-docking the submarine.

1.3 Pod Shape Considerations

The pod houses the sensor(s) in a hydrodynamic shape which may be readily removed from the foundation. Typically pods are designed to have NACA (National Advisory Council on Aeronautics) or "tear drop" shape where the length is at least 4 – 5 times the pod's width to minimize hydrodynamic noise. An

example of a NACA shape is the submarine's sail. The surface of the pod opposite the foundation is typically domed.

1.4 Cabling Installation Considerations

If the pod is located near the forward MBTs, cable routing is simplified. The pod is typically not located near the aft MBTs because of the complexity associated with routing cables internal to the hull from the engine compartment forward where operators and equipment are located. MBTs, as well as free flood areas, typically have wireways, electrical hull penetrators, and tank penetrators located within them servicing various ship systems. Electrical penetrators are electrical connections which penetrate the pressure hull of a submarine, and tank fitting penetrators are conduits which pass cables between ballast tanks and between ballast tanks and free flood areas such as the sail and torpedo tube launchways. Cables can be routed in to MBTs either through MBT grates or by cutting holes in the non-pressure hull near the grates as long as the hole is not above the level of the grate. Identifying and utilizing available space in existing electrical hull penetrators and tank penetrators is preferred. Replacing existing electrical hull penetrators and/or tank penetrators with new penetrators which accommodate both existing cables and new cables can be complex and expensive. Replacing electrical hull penetrators located below-the-waterline requires dry-docking the submarine.

1.5 Installation Dry-docking Versus Pierside Considerations

There are many pros and cons associated with dry-docking a submarine. Dry-docking is difficult to schedule, expensive, and creates a risk to the submarine. It also may require unique support blocking specifications. However, working in a dry environment provides many advantages. Working with divers pierside is typically much more complex. Divers may not be as familiar with equipment as the designers and they may require more time to complete a task. Problem identification and resolution is more difficult, rigging is more complex, and QA is more difficult to implement.

Submarine Installation

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1.0 Submarine Installation Overview

Submarine installations are typically very complex and critical evolutions. Preparation is crucial to ensuring that an installation is conducted efficiently and smoothly. Subcontractors as well as Navy activities are involved; therefore, responsibilities must be clearly defined. The installation itself follows a typical sequence beginning with equipment staging through testing and wrap-up.

1.1 Submarine Installation Preparation

Preparation for a submarine installation includes:

- Proper safety reviews
- Thorough fitchecking, testing and integration
- Careful inventorying and packing of equipment, tools, and expendables
- Obtaining copies of Naval Sea Systems Command and Type Commander Approvals
- Developing detailed shipping plans
- Developing a memorandum of agreement detailing the responsibilities of all activities involved
- Arranging a pre-installation meeting to review this memorandum of agreement and make any necessary revisions
- Preparing a QA process

1.2 Submarine Installation Sequence

A typical installation sequence follows:

- Staging and organizing equipment
- Opening and gas freeing ballast tanks
- Laying out equipment locations
- Welding, cutting, and grinding
- Cleaning and weld inspection
- Painting
- Assembling system equipment
- Assembling handling equipment
- Routing and connecting cables
- Checking end-to-end signal and power path continuity
- Positioning equipment for testing
- Testing system equipment
- Testing ship's equipment affected by installation
- Completing installation of equipment
- Dressing cables
- Inspecting and closing ballast tanks

This list assumes a dry-dock installation. For a pierside installation, welding may not be required. However, diver services are required thereby adding to the complexity of the effort. Divers must be Navy nuclear-qualified and be familiar with Navy procedures and organizations, especially Navy Intermediate Maintenance Activities, which provide much of the submarine maintenance and repair services. Also, the divers must be experienced working in and around main ballast tanks. During installations the following diver-related actions are recommended:

- Detailed explanations of the work to be accomplished prior to each dive
- Thorough explanation of associated QA procedures
- Close monitoring of dives to address questions as they arise
- Maintaining accurate inventory of all tools and parts provided to divers (loose parts or tools can not be left in ballast tanks)
- Accurate record keeping of work done by each diver for reference if questions arise and for maintaining an experience record
- Underwater video taping as required to observe work and provide input (also, for future reference)

1.3 Submarine Installation Recommendations

Lastly, the following advice is also provided when conducting an installation:

- Have daily meetings with all involved organizations to review status and requests, and resolve problems
- Provide QA procedures especially in the areas of underwater cable connections, cable inspection, equipment installation procedures, and configuration management
- Provide a good communication system during equipment testing
- Be aware of ship procedures and routines
- Have flexibility in the schedule sequence especially if other unrelated activities are ongoing
- Add one to two days in the schedule to account for unplanned work interruptions.

High Resolution, Upward-Looking Swath Sonar Investigation of the Underside of Sea Ice

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The thickness distribution of sea ice is a critical defining parameter for the air-sea heat exchange as well as for a variety of mechanical and acoustic problems. Developing models to describe the thickness distribution is currently an active area of research with a number of different research groups carrying out numerical and observational research along these lines. In addition, recent work both in ice forecasting and ice mechanics has focused on the development of anisotropic ice mechanics sea ice models whose goal is largely to be able to predict oriented leads and ridges. As a consequence, observational information on the oriented character of ice thickness characteristics as well as oriented leads is becoming a crucial piece of information limiting further progress in this field.

Under-ice sonar observations have typically been in the form of single tracks and, within limited circumstances, intersecting tracks. While valuable, attempts to use these intersecting tracks to characterize the anisotropy has led to only limited success. Cases where this has been successful have involved local two dimensional surveys of the under ice roughness, utilizing upward swath sonar studies from remotely controlled submersibles. These successes, in turn, have motivated efforts to include upward looking swath sonar topography devices on submarine cruises. However, due to past expense and logistics problems, this capability has only become available recently. This has been due to a number of factors, not the least of which is the recent development of more compact versions of this equipment over the last few years together with improved and more compact data acquisition capabilities that were unavailable several years earlier.

The purpose of this white paper is to propose permanent installation of a high resolution, upward-looking swath sonar system (both backscatter and topography) aboard SCICEX submarine platforms. Prior to now, data on the underside of sea ice have been confined primarily to swath sidescan images and profile topography. Furthermore, the upward-looking swath sonar technology currently available aboard US submarines is rudimentary by current standards; the systems are intended primarily for submarine operations, and the data produced are in a format that is not amenable to processing and quantitative interpretation. Installation of a compact, high resolution swath sonar system will vastly increase measurement capabilities by acquiring swath topography as well as sidescan in a format readily accessible to available processing software packages. Such data will enable researchers to confidently image and quantify under ice morphology in three dimensions. A permanent installation of such a system will substantially expand the capabilities of current underice observations of sea ice. Furthermore, the new systems, with easy-to-use interactive graphic displays, can substantially enhance submarine operations under the ice.

Much of what we know regarding the thickness distribution of sea ice has been based on submarine sonar observations of the underside of the ice cover. Analysis of both the spectral distribution and discrete roughness of this data has been an active area of the authors of this white paper over a long time interval. Moreover there is currently a focused effort to compile and compare historical data sets of upward looking sonar data to provide some historical information on the climatological variability of the Arctic ice pack as well as to supply an invaluable data set for comparison to models.

A major impediment to characterizing the sea ice pack in climate models, as well as in more applied acoustic and forecasting applications, has been the ability to characterize the fraction of ice in ridges versus thin ice in leads and the characteristic thicknesses of undeformed multi-year floes. Modeling (Flato and Hibler, 1995) and profile track estimates (Wadhams, 1989; McLaren, 1989) have suggested that ridged ice volume accounts for over 50% of the volume of the ice pack. Estimates of the areal extent of ridged ice are less certain with profile tracks, and generally are much larger than derived from variable thickness model estimates (e.g., Flato and Hibler, 1995). Another impediment is accurate estimation of the distribution of lead and thin ice widths and the scales over which these occur. Satellite observations, for example,

seem to suggest that the amount of slip lines and leads are relatively few, while experience in ice camps suggests that there are many more leads than can be detected with satellite imagery. These features are important, since they affect the way in which ridging is modeled in variable thickness models currently being developed for use in numerical investigations of climate (Flato, 1995; Holland et al., 1998). The critical factor in all these issues is anisotropy; previous studies have not adequately characterized the anisotropic nature of sea ice, which is likely an important determinant for the mechanical characteristics of sea ice (Coon, et al., 1992; Hibler and Schulson, 1997) and for air-sea heat exchanges.

The root cause of these problems in characterizing sea ice is imprecise data and the inability to adequately characterize quantitatively the morphology of the ice pack from a single sonar profile. For example, volume of ridged ice is usually judged by a slope criterion (McLaren, 1989; Wadhams, 1992) which depends on the angle at which a pressure ridge is being crossed. Consequently, determining the area of deformed ice and, indeed, deciding on the existence of pressure ridges becomes difficult from single line tracks. We also currently depend largely on field observations (e.g., Tucker and Govoni, 1981; Tucker et al., 1984) of individual ridges for typical slope angles of ridges, whereas with a profile and knowledge of the ridge orientation average slope angles from submarine profiles may be deduced.

The acquisition of swaths of ice topography over a large portion of the Arctic basin should provide a quantum leap in available information on sea ice morphology over what is possible from single profiles, and solve all the observational difficulties detailed above. Moreover, swath topography will provide information on the spatial shape of floes and floe size distribution, which heretofore has been lacking. Oriented floe information is particularly relevant to small scale discrete element modeling of pack ice (Hopkins and Hibler, 1991; Hopkins, 1994). Such data, gathered at the end of the growth season and into the melt season, would offer the opportunity to obtain precise statistics on the fractions of open water versus melt pond, a distinction that is difficult to ascertain from satellite imagery. Consequently swath sonar data could form an important "ground truth" for subsequent comparison to satellite based observations.

From a cruising depth of ~200 m, topographic swath widths of ~750 m can be obtained. Statistical characterization of this data would allow compilation of a more complete summary of the quantities mentioned above: volume and area of ridged ice, distribution of thin ice in leads and lead widths, information on floe size distributions, typical average multi-year ice thicknesses and areal extent, and characteristic ridge heights, widths and orientations (e.g., Goff, 1995, Goff et al., 1995).

Another problem is that past upward-looking sonar studies have not succeeded in obtaining ice thickness distribution over the whole Arctic basin during the same year and month. Such information could be critical. For example, high interannual variability in ridging in certain regions (e.g., Hibler et al., 1974a,b) is substantial enough that year to year sampling variations may bias spatial variability estimates (Bourke and Garrett, 1987)

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Biogeochemical Processes within SCICEX

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The development of the Submarine Science Experiment (SCICEX) program has provided extremely valuable scientific data to the Arctic marine science community. The performance characteristics of nuclear submarines permit the rapid collection of large scale physical, chemical and biological observations. These observations have in conjunction with results from other programs such as the Arctic Ocean Section (AOS; Wheeler, 1997) helped significantly in identifying major stratification and circulation changes, and potential ecosystem changes in the Arctic Basin in recent years (Morison et. al, 1998a). More recently, SCICEX operations have been effectively integrated with the Surface Heat Budget of the Arctic Ocean (SHEBA) program of research. It is also generally appreciated that with feasible and appropriate equipment, nuclear submarines would have many advantages over surface vessels as a geophysical research platform in ice-covered waters. In this white paper, we discuss issues surrounding the use of SCICEX platforms for studies of biogeochemical cycling in the Arctic.

With respect to biogeochemical studies, a major issue is that only limited sampling has, so far, been possible over continental shelves and upper slopes. [We recognize that much of the arctic shelf region is not accessible for safety reasons, but some critical portions are.] This is a significant drawback because shelf/upper slope processes are crucial in influencing Arctic biogeochemical cycles and in ventilating subsurface layers of the interior basin. Outflows arising from physical processes coupled with enhanced biological activity effectively transfer biogeochemical products from the shelves into the subsurface layers of the Arctic Basin (Björk, 1989). We currently lack the information necessary to quantify these exchanges, assess their seasonal and interannual variability, and predict their susceptibility to global change. Within the Arctic halocline, some of the clearest physical and biogeochemical signals are caused by Pacific Ocean waters that are modified on the western Arctic continental shelves (Bering, Chukchi, Eastern Siberian and Beaufort seas) before passing into the interior ocean. The Pacific Ocean is an important source of nutrient-rich, low-salinity water that flows northward through Bering Strait into the Arctic Ocean, ultimately influencing the nutrient maximum in the upper halocline (Cooper et al., 1997 and references therein). The large continental shelves of the Arctic have been hypothesized to be important for transporting atmospheric CO₂

to deeper regions of the ocean (Anderson, 1995) and arctic shelf regions may also have their CO₂ exchange modified by seasonal ice cover in a way that promotes sequestering atmospheric CO₂, the role of high latitude processes requires increased attention (Sarmiento et al., 1989).

Major biogeochemical topics relevant to global change scenarios include understanding the transport, transformation, and fate of carbon and nitrogen among the outer shelf, slope and interior Arctic Ocean regions. Data collected during the National Science Foundation's (NSF) Arctic System Science (ARCSS) Ocean-Atmosphere-Ice Interactions (OAI) program, specifically the AOS and NSF/Office of Naval Research (ONR) SCICEX cruises, indicate the transfer of western Arctic shelf-derived carbon into the Canada Basin (Sambrotto, 1996). High total CO₂ water was observed to extend from the shelf edge and enter the upper halocline at about 100 m, suggesting that the Canada as in could be an important reservoir for oceanic carbon. Subsequent submarine analyses support an offshore exchange of both particulate and dissolved organic carbon from shelf to basin regimes. The role of riverine input versus marine production on the balance of particulate organic carbon and dissolved organic carbon in the Arctic is also unknown and could be investigated through submarine collections of surface and subsurface water emanating from the shelves. In addition, portions of the Arctic shelf/slope region have extremely high biological productivity and are rich in living resources. Despite this ecological importance, the outer shelves and slopes of the Arctic remain one of the most under-sampled environments in the global ocean. We believe that if given the freedom to comprehensively sample the upper slope region, SCICEX platforms could make an enormous contribution to furthering our understanding of the above-mentioned topics.

Variables controlling biological production in the Arctic that can be measured by a submarine and benefit from the large spatial/temporal capabilities of this platform include ice coverage, seasonal irradiance, and nutrient distributions. Recent studies of chemical water mass tracers (i.g., nutrients, stable and radioactive isotopes), undertaken by both submarine and ship-based studies, have provided key information on water mass circulation in the Arctic basin. Specific water column biological studies that have proven practical for submarine-based studies include bacterial and phytoplankton population studies via the underway sampling port. Particulate and dissolved organic carbon, and inorganic carbon measurements also appear to have been successfully obtained from SCICEX platforms.

Future studies might include HPLC analyses for various pigment types related to phytoplankton species composition over a wide spatial grid as well as primary production determinations using stable isotopes. Arctic waters can also be a significant source of trace gases such as dimethyl sulfide (DMS) and bromoform, which affect the radiative properties of the Arctic atmosphere. It may be feasible to obtain data on these gases with samples collected using the existing SCICEX water sampling techniques.

Many SCICEX studies have, to date, been inhibited by the difficulty of sampling multiple depths, but we do not believe that this is an insoluble problem. Modest technology development and increased surfacing opportunities would improve SCICEX biogeochemical programs by permitting sampling over the entire water column.

Although many water column biogeochemical measurements are feasible from the submarine, this platform has not proven practical yet for benthic sampling with grab and coring devices, which are critical for determining biogeochemical source and sink terms that are primarily sediment-based. These processes that can only be inadequately approached using current submarine capabilities include denitrification and carbon transformations, along with paleorecord determinations, which are of course important for understanding past global change. Denitrification, to expand upon one example, is enhanced primarily in shelf and slope sediments. This process is a major marine sink for fixed nitrogen (Christensen et al., 1987). Present estimates suggest that Arctic-shelf denitrification accounts for about 12% of the total oceanic rate, but small redistribution of organic materials (whether in water or sediments) could cause significant changes in the capability of the world ocean to assimilate increased atmospheric carbon dioxide (Codispoti, 1989). We think that modest effort could significantly increase the ability of SCICEX platforms to conduct benthic studies.

Various OAI science projects, such as the SHEBA project, are benefiting greatly from the unique under-ice surveying and hydrographic capabilities of the submarine. We envision submarine-based sam-

pling as part of the newly initiated OAII Western Arctic Shelf-Basin Interactions (SBI) project (Grebmeier et al., 1998), which will be a 7-10 year global change program that will include both field and modeling studies directed at elucidating the underlying physical and biological shelf and slope processes that influence the structure and functioning of the Arctic Ocean. Major goals for SBI include studies of: 1) the interactions of physical mechanisms (including ice) on advective processes and shelf-basin exchange, including the timing of physical movement relative to biological rate processes, 2) the fate of fixed carbon as it is advected, consumed (by pelagic and benthic consumers), or transformed, with particular emphasis on the relative importance of different types of primary producers to total annual production, and 3) the overall effects of global change on various taxa and trophic structure. A retrospective, opportunistic field sampling, and modeling phase will initiate in January 1999. The core seasonal field program is planned to begin in 2001/2002 and will encompass a variety of scientific sampling platforms. Although laboratory and berthing space on a submarine are too limited for some process oriented experiments that are likely to be conducted under the SBI aegis, the SCICEX platform's ability to rapidly sample the under slope could provide important information, particularly if surfacing opportunities could be included in the program. The scientific strength of the SCICEX program could also be greatly enhanced by sampling over shelves and slopes in U.S. territorial waters (e.g., Chukchi Sea continental shelf) during transit to the Arctic Ocean including variable depth sampling at the shelf break.

Other OAII programs in formative stages could also be well-served by a submarine platform, in particular the Study of Arctic Change program (SAC, Morison et al., 1998b) which will focus primarily on physical and ice dynamics studies related to observed warming and shallowing of the Atlantic layer in the Arctic Ocean. In many ways, this initiative was stimulated by the results of the Pargo expedition and the value of SCICEX operations to such programs are, therefore obvious. We would suggest, however, that increasing the ability of SCICEX operations to collect data relevant to biogeochemical cycles would also be important within the context of a Study of Arctic Change since these changes are likely to include changes in the ecosystem.

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Marine Geology/Geophysics Opportunities from a Submarine Platform

Leonard Johnson

Outside the Arctic, many paleoenvironmental and geologic questions related to the world ocean have been resolved by deep-sea drilling. By obtaining and dating basement rocks and sediment cores hundreds of meters long, geologists have deciphered the history of basin development throughout the world. Data from the Arctic, by contrast, is non-existing or is scarce at best. Scientists have only six samples of Arctic deep-sea sediment from during the Late Mesozoic and Paleogene, and these indicate a temperate climate regime without an Arctic ice cover. Only one dredge sample has been recovered from Alpha Ridge: an alkaline weathered basalt.

The tectonic development of the Arctic basin is not just a regional problem. It is intimately linked to the evolution of the adjacent ocean basins and continents. An understanding of past and present plate movements in the Arctic will be required before a complete model of late Mesozoic and Cenozoic northern hemisphere plate motions can be achieved. These motions and the composition, paleobiology, and paleoenvironment of the sedimentary rock sequences of the circum-polar regions are highly relevant to the exploration of hydrocarbons.

SCIENCE ISSUES

The kinematics and history of the opening of the Arctic Ocean Basin within the margin of the supercontinent of Laurasia, the history and kinematics of the interaction in the Arctic with the North Atlantic rifting and the highly mobile and complex Pacific Basin convergence are first order scientific problems. Our knowledge of the geologic framework of the ridges and subbasins of the Arctic Ocean, and of the age of its large areas of oceanic crust is insufficient for solving these problems. However, this knowledge does provide some guidance in identifying the most productive regions for focusing our efforts. The Cenozoic history of the Eurasia Basin is well understood because it involves the Eurasia and North America plates and is therefore constrained by data from southerly regions and it contains a more readily decipherable magnetic pattern. It is widely accepted that the origin of smaller, structurally and morphologically simpler Eurasia Basin is by sea floor spreading along the Arctic Mid-Ocean Ridge beginning between chrons 29 and 25 (65 to 59 million years) on the geomagnetic polarity time scale. The key to understanding the tectonic history of the older Arctic lies in learning the geologic framework and tectonic history of the bathymetrically complex Amerasia Basin, one of the most inaccessible and poorly known areas on Earth. There are many quite divergent hypotheses but no general agreement as to its origin and age. The most popular explanation for the origin of the Amerasia Basin is a scissor-like opening with the pivot point near the Mackenzie River delta. The actual composition of the structural elements and their drift paths are open to question and many hypotheses have been proposed.

SCIENTIFIC FOCUS

One key to the western Arctic problem is the origin and nature of the Alpha- Mendeleev Ridge, which is the largest single submarine feature in the Arctic Ocean. In areal extent it exceeds the Alps, and, in addition to the massive exposed structure, large portions are buried beneath the Canada Abyssal Plain. Three basic models have been proposed: 1.) creation of the basin by sea floor spreading, with possible modification by "hot spot" activity; 2.) entrapment of continental crust with subsequent crustal thinning; and 3.) a former region of subduction or compression. It is thus proposed that rock samples be collected by submarine from the Alpha- Mendeleev Ridge to constrain the hypotheses. The Nansen-Gakkel spreading ridge is an unique structure in that this ridge is characterized by the lowest spreading rates (0.2-0.3 cm/yr) and thus is an end member for the system. It has been hypothesized based on limited seismic refraction and submarine gravity data that the ridge is characterized by outcropping mantle rocks. This would be truly unique and yield insight into lithospheric processes not exposed to the surface elsewhere.

APPROACH

To overcome the lack of sea bed samples from the Arctic Ridges it is suggested that a Remote Operated Vehicle be developed under the SCICEX program which is compatible with a submarine torpedo tube. This vehicle would operated in a mode similar to wire guided torpedoes with operator guidance. In this way it is similar to the Argo-Jason System. The approach would be that using the SCAMP system sites would be selected for potential talus slopes and then the vehicle launched with operator guidance to collect rock samples. Several kilometers of fiber optic cable would be required for the ROV to reach its targets and only relatively shallow targets near the ridge crests would be targeted. Manipulators and attendant light source would be required and a collection basket as has been done aboard NR-1.

NAVY RELEVANCE/COORDINATION

The ability for a submarine launched ROV to inspect and collect objects from the sea floor is a technology of interest to the Navy. Present Navy programs are focused on clandestine mine reconnaissance.

The Impact of High Quality Bathymetric Data on Geoscientific and Paleoenvironmental Research in the High Arctic

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General Remarks

The Arctic Ocean is an area of extreme environmental conditions compared with the world's other oceans because of its perennial ice cover. In the recent discussions on global warming both polar regions play an important role as it is believed that they are the most sensitive to any major changes of climatological factors. Furthermore, melting of the Antarctic and Greenland ice caps would cause a significant sea level rise with dramatic consequences for most of the world's population living in coastal areas. It is, therefore, important to understand the processes controlling the size of the polar caps from past to present.

Research on ice cores recovered from Greenland and Antarctica reveal the climate variations for the last 15,000 to 300,000 years. To look further back in time sediment cores from submarine ridges, seamounts and shelf areas have to be analyzed. Studies of such cores suggest that the frequency and/or duration of glacial ice influx into the Arctic Ocean has increased during the past several million years. Furthermore, geological data suggest that the Arctic Ocean was not continuously ice covered during the last 100 Myr (Cretaceous times). What has caused the formation of the sea ice cover and of the continental ice caps? The transition from an ice-free Earth of the warmer Cretaceous to the present bipolar ice condition is presently explained in the context of palaeogeography and Earth orbital forcing. The distribution and size of continents and ocean basins influence ocean and atmospheric circulation. Particularly, the crustal plate motions towards the present poles changed the ocean circulation system by opening and closing seaways. At least, this is our current knowledge and interpretation of the processes involved. These hypotheses have to be verified and most likely modified by new geoscientific data from both polar regions.

For a better understanding of the long term environmental changes, high quality geophysical, bathymetric and geological information from the Central Arctic are needed. Several hundred sediment cores taken from ice island and recent icebreaker experiments contain information on the Quaternary of the Arctic Ocean but less than 10 cores provide information on the older geological history. The reasons for this incomplete information are easy to explain:

- So far, the perennial pack ice in the high Arctic has prevented systematic research. The random drift of the ice stations precluded site specific coring. Ice breaker expeditions were carried out since 1987; however, due to the logistic difficulties and the large costs of these expeditions only a few were undertaken. Most of the expeditions were reconnaissance surveys and the available information is unevenly distributed. Furthermore, no complete geophysical data sets; e.g. bathymetry and seismic, were available to optimize these cruises.
- Target areas were chosen on the base of the available GEBSCO bathymetry, which often was inaccurate.

Based on the available bathymetry it was not possible to select detailed cruise tracks. Swath bathymetry along the Lomonosov, Alpha and Mendeleev ridges would provide significant new information for focusing expensive surface ship expeditions for acquiring the geophysical and geological data needed for solving scientific problems.

- Furthermore, surface ships will always be limited in their ability to do systematic surveys in the Arctic Ocean due to the ice cover.

Pertinent questions

In the scientific community there is a consensus that the presence/absence of the Arctic Ocean ice cover during geological times affected sedimentation pattern and biologic evolution plus the Earth's climate. Different theories are available to account for the time of initiation, size and style, and stability of the Arctic ice cover, but the current geoscientific data base is inadequate to decide which one is realistic. For further advances in the understanding of the Earth's climate during the last 100 Myr (transition from a 'hot' to a 'cold' house), it is important to collect systematic bathymetry and geophysical data in the High Arctic to locate coring sites, where material of different geological epochs can be collected. Such a data set will provide the first reliable information on the geodynamic history of the pre-Quaternary Arctic, which is critical for any plate and environmental reconstructions. Critical information on the palaeogeography, the geodynamic history and the environment of the Arctic Ocean during different intervals can then be used as boundary conditions for a more sophisticated long term global climate modeling. Again, the detailed knowledge of the bathymetry of the Central Arctic Ocean is the key for any progress in acquiring new data. Such information combined with other geophysical and geological data can address the following scientific problems:

When did the Canada, Makarov, Nansen and Amundsen basins open? Bathymetric information showing locations of steep escarpments and/or canyons would allow sampling of basement rocks by icebreakers or submarines. After dating of these samples existing geodynamic interpretations based on aeromagnetic data or plate reconstructions can be tested.

- What are the origin and nature of the Alpha-Mendeleev ridges and how did the submarine mountain chain influence the Arctic environment in the past? Again carefully chosen coring locations are needed to retrieve old samples and/or to drill a complete sedimentary section. Key information for the finding these sites are bathymetric and seismic data.
- When did the Lomonosov Ridge subside below sea-level? When did seaways open to the newly formed Eurasian Basin? Did the whole 1800 km long Lomonosov Ridge subside as a rigid block or did local seaways along the ridge make gateways to the Eurasian Basin? The presence/absence of such seaways would create a totally different paleoceanographic scenario. Again a comprehensive bathymetric data set would strongly support a regional interpretation of seismic, gravity and magnetic data along the ridge.
- Finally, when and why did the sea ice cover form in the Arctic? Is the present day situation of an ice-covered Arctic Ocean an exception in geological history or did it occur in the past? Carefully selected core/drilling sites are needed to retrieve such information from the sedimentary record.

In general, high quality bathymetric and geophysical information are urgently needed to justify any major effort for deep drilling in the Arctic as promoted by the Nansen Arctic Drilling/Ocean Drilling programs (NAD/ODP). Arctic research has to compete against scientific proposals from all regions of the world, where the above mentioned data sets are easily collected. Therefore, major progress in Arctic geoscientific research can only be achieved by increasing our bathymetric knowledge to a level that is standard in other ice free regions. Finally, high quality bathymetric data along the large ridge systems will provide information for planning future geoscientific cruises and will guide scientific surface ship/ice breaker expeditions.

Studying Climate Change in the Arctic with Fiber Optic Spectrometers: Detailed Mapping of Dissolved Organic Carbon using Nuclear Submarine Patrols

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1 Dissolved Organic Carbon in the Arctic Ocean

Both models and recent observations suggest that the Arctic is highly perturbable and thus can act as a harbinger of global change. Despite large natural variability, several recent investigations have documented significant trends in atmospheric and oceanic conditions over the last few decades (Carmack et al., 1995, Morison et al., 1998, Steele & Boyd, 1998, Thompson & Wallace, 1998). Research must be accelerated to determine the forcing behind these changes and the extent to which they are anthropogenically driven as well as their impacts on the global system. The Arctic Ocean is relatively small, with disproportionately wide shelves and is nearly enclosed by land masses. Input of 10% of the world's river waters to its relatively small basin amplifies the chemical impact of biogeospherical processes relative to other oceans. Arctic rivers drain unstable permafrost terrains, tundra and taiga forest which are vulnerable to warming (Oechel et al., 1993). In addition, these drainage basins have been exposed to contaminants of every conceivable description, much of which ends up in the Arctic (Macdonald & Bowers, 1996).

One parameter in the Arctic Ocean that should be especially sensitive to global change is the amount of dissolved organic carbon (DOC) delivered by rivers. Arctic rivers, particularly the Eurasian rivers, contain large amounts of DOC ($548 \pm 118 \mu\text{M}$; Gordeev et al., 1996). Wheeler et al. (1997) estimated that river run-off supplies 25% of the DOC inventory of the entire Arctic and is the major source of organic carbonaceous material in surface waters. The dominance of terrestrial DOC in the surface waters of the Arctic has important implications. Firstly, since most DOC in the Eurasian Arctic originates in rivers, this parameter can be used to trace cross-shelf transport. Secondly, since Arctic rivers drain tundra terrains, the chemical composition of their discharge may serve as a sensitive integrative measure of change at the drainage basin-scales (Syvitski and Alcott, 1995). Thirdly, humic materials that make up most of the terrestrial DOC are known to be strong chelators of anthropogenic compounds and heavy metals (Patterson et al., 1996) and so tend to keep these materials in solution. Thus we would understand considerably more about the fate of pollutants by following the dispersal of terrestrial DOC. Fourthly, there is a growing body of evidence to suggest that terrestrial DOC is not conservative in the oceans but is degraded by photooxidation and microbial activity thus fertilizing coastal surface waters. Rapid recycling of terrigenous DOC could contribute to high rates of primary production in coastal waters (Opsahl and Benner, 1997). Considering this evidence, remineralization of terrestrial DOC could be especially important in the Arctic where productivity is relatively low and DOC is strongly influenced by fluvial input.

2 ZAPS Technology and SCICEX

As past participants in the SCICEX Program we were given the opportunity to develop an underway fiber optic sensor system for submarines (ZAPS: zero angle photon spectrometer) which has been deployed on two Arctic patrols (Pogy 1996 & Archerfish 1997). We found that continuous output (25 Hz) from a ZAPS instrument correlates remarkably well with the DOC content of discrete water samples collected through the hull of the submarine. DOC for this project was measured in the laboratory of R. Benner at the University of Texas Marine Science Institute by high temperature combustion (HTC). The correlation between HTC and optical fluorescence is striking and serves as a validation of both techniques. These data sets clearly show that rivers increase DOC levels in the Eurasian basin by as much as 40% over those in the Canada Basin, even at the transit depth of 58 meters. The effect of this distribution on contaminants that become attracted to natural organic matter is unknown, although current wisdom would predict that this "complexation" effect would be substantial. Likewise the impact of this influx on marine productivity is unknown although remineralization of terrestrial carbon by photooxidation and microbial degradation is well-documented. We do know that such processes release nutrients and metals and thus have the potential of fertilizing surface waters.

3 SCICEX and Future Monitoring Needs

Based on our SCICEX results it seems certain that fiber optic spectrometers could be used to couple oceanic and land-based efforts to evaluate the effects of climate change. A scheme could be devised wherein the DOC content of the Lena, Yenisei, Ob, and MacKenzie Rivers would be monitored continuously with time. This data base could be combined with seasonal mapping of DOC in the Arctic. This integrated study would allow us to directly relate river input to climate fluctuations and their effect on the ocean. The impact of this input is bound to be seasonal so such studies could only be accomplished with a submarine. Such a monitoring scheme would benefit from plans under discussion to extend the boundaries of the present SCICEX operation area to accessible Arctic shelves. This information collected over several years would allow us to evaluate the net effect of global change on the organic carbon cycle. It would also reveal links between climate change and continental weathering rates. Both of these topics are complex problems that require multi-seasonal access to remote areas—a requirement uniquely satisfied by submarine patrols.

This research would be highly complementary to a number of existing and developing international research programs. One example is the Shelf-Basin Interaction (SBI) Program just getting underway in the US and sponsored by the Office of Polar programs at NSF. The goal of SBI is to study cross-shelf transport and relate variability in this phenomenon to the effects of global change on biogeochemical cycling in the Arctic Ocean. Continuation of the SCICEX Program would enhance the scientific return from SBI and other programs by generating data sets not obtainable in any other way. The underway approach of ZAPS maximizes the advantages of the submarine platform and minimizes problems with safety and time overhead associated with surfacing. Multi-seasonal coverage is highly desirable for the proposed research as is expansion of the work area to cover as much of the shelves as is feasible. In order to achieve the greatest scientific return, SCICEX science should be better integrated into programs like SBI as well as land-based, and ice-based monitoring efforts. Multiple patrols from the same submarine would help to minimize cost and maximize data quality.

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Validation of satellite radar altimeter estimates of ice freeboard as part of SCICEX 2000

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1 Introduction

A new technique to directly measure ice freeboard from spaceborne altimetry has recently been developed at UCL [Peacock et al., 1998]. This technique offers the potential to provide up to 250,000 estimates of ice thickness per month over a large fraction of the Arctic Ocean. There is a critical need to calibrate and validate these estimates prior to the widespread use of this data. This paper discusses the use of data gathered under SCICEX to validate these measurements. Particular attention is paid to the spatial and temporal coverage of the altimeter estimates which will affect the usefulness of SCICEX measurements obtained in a given location and season.

2 Altimeter measurements of ice freeboard

Although the technique for determining ice freeboard, and hence thickness, from spaceborne altimetry is at an early stage the results are already promising. Comparisons with Upward Looking Sonar mooring in the Fram Strait show agreement to within 0.5 m in thickness. Nevertheless uncertainties remain concerning the possible effects of ridging and snow cover on the altimeter estimates. Validation of these data by in situ measurements are essential in better understanding and correcting for these effects.

Altimeter estimates are available only over areas of consolidated (100% concentration) ice cover resulting in a strong seasonal and regional variation in the density of measurements. Additionally the convergence of ground tracks results in the greatest density of measurements near the latitudinal limit (81.5N). Figure 1 shows how the density of measurements varied during 1996.

The current technique for measurement of ice freeboard by spaceborne altimeter has been developed using data from ERS-2, launched in April 1995. The RA-2 altimeter, planned for launch in May 2000 onboard ESA's 5 year Envisat mission, will provide enhanced measurements due to better echo sampling, an improved tracking system and dual frequency operation. Operation of ERS-2 is planned to continue through the first year of the Envisat mission. Acquisition of validation data during this period (May 2000-May 2001) will enhance efforts to cross-calibrate measurements from the two instruments.

3 SCICEX data for validation of altimeter ice freeboard estimates

Under a recently funded program UCL plans to carry out theoretical and modelling studies to better understand altimeter measurements of sea ice freeboard. A key part of this study is the use of co-incident measurements of ice draft distribution. The use of ULS data from moorings in the Fram Strait is already planned as part of this effort. There is a requirement for validation data in other regions, in particular the Canada Basin where the greatest density of measurements occur (Fig. 1).

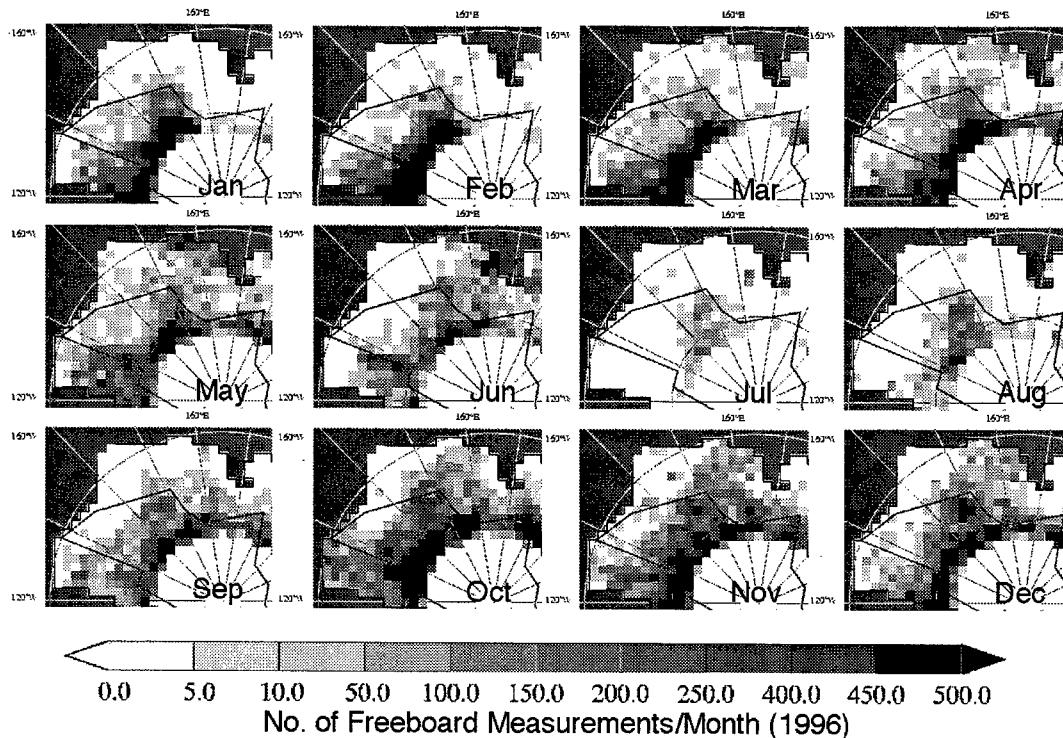


Figure 1. Density of ERS-2 altimeter freeboard estimates during 1996. The SCICEX box polygon is also shown. This figure shows that the highest density of altimeter measurements are available during the winter months. Note that there is a strong inter-annual variability in data density and that, during the months of July and August, virtually no data was acquired in the SCICEX region during 1995 and 1997.

Validation of ERS-2 estimates is planned using data acquired during previous SCICEX cruises since 1995. However validation of Envisat estimates will require SCICEX data in the 2000-5 time frame. These are particularly important given the improved potential offered by the RA-2 instrument, in particular it's greater sensitivity to sea ice ridging. Future SCICEX cruises offer the potential to concentrate ice draft measurements in areas where the altimeter estimates are particularly dense. Clearly there is a significant advantage in SCICEX data obtained during the winter months. However measurements obtained during early spring/late summer would also be of considerable value.

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Measuring Ice-Ocean Heat and Mass Flux by Submarine

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Background

Direct measurements of the turbulent fluxes of momentum, heat, and salt in the boundary layer under drifting pack ice during a series of recent ice-drift experiments have significantly improved our understanding of turbulence dynamics in the ocean boundary layer. As a result, we now have a much broader appreciation of how ocean heat flux affects the heat and mass balance of sea-ice covers. A sampling of recent papers and observations illustrates this:

- Maykut and McPhee (1995) used a simple parameterization based on direct flux measurements (McPhee, 1992) to estimate ocean heat flux at four manned stations during the 1975-1976 AIDJEX

project in the Beaufort Gyre of the Arctic Ocean. We found that the ocean heat contribution was much larger than previously thought during the summer (averaging $> 10 \text{ W m}^{-2}$), was highly dependent on the amount of open water, and that the upper ocean was capable of storing a considerable amount of heat for extended periods, even when high concentrations of ice were present. During the AIDJEX year, virtually all of the ocean heat flux originated from solar heating of the mixed layer.

- In seasonal ice of the Weddell Sea (Antarctic), we measured extreme values of ocean heat flux (hundreds of watts per square meter) during midwinter storms, and showed that growth of the ice cover in the Weddell is severely limited by ocean heat flux originating from below the mixed layer (McPhee et al., 1996; 1998a).
- At the outset of the SHEBA drift last fall, we found strong circumstantial evidence (McPhee et al., 1998b) that ocean heat flux and basal melting had been much more intense during the 1997 summer than in the same region during 1975 (AIDJEX)—enough to trigger concern for the long term viability of the perennial pack in the Beaufort Gyre. Yet when we arrived in October, 1997, the mixed layer was close to freezing, and ocean heat flux was effectively curtailed by a strong halocline formed from the summer melting
- Later on during SHEBA, after the ship had drifted out of the Canada Basin into substantially reduced upper ocean stratification over Chukchi Rise, we observed mixed layer warming and ocean heat flux (as high as 30 W m^{-2} [T. Stanton, pers. comm., 1998]). This was in mid- to late winter when solar heating was negligible.

These and other observations suggest a picture of ocean heat flux under sea ice that differs markedly from the steady, diffusive upward flux of 2 W m^{-2} (from Maykut and Untersteiner, 1971) commonly prescribed for sea-ice models prior to the 90's. We are finding that ocean heat flux varies greatly with season and location, and is highly sensitive to ice concentration and ocean stratification. It is also becoming clear that it sometimes exerts a controlling influence on the heat and mass balance of the ice cover.

The SCICEX experiments have demonstrated convincingly that a submarine can provide a stable platform with unmatched mobility for oceanographic measurements, and have been instrumental in documenting a significant shift in the upper ocean thermal regime in the Arctic (Morison et al., 1998). It is natural to ask whether a submarine could provide routine observations of momentum, heat, and salinity (buoyancy) flux in the Arctic mixed layer. This is clearly a difficult task, which, in my estimation, involves answering three critical questions: (1) Can we deploy instruments capable of measuring turbulent fluctuations in the boundary layer, yet rugged enough to survive the rigors imposed by a SCICEX cruise? (2) Can we relate measurements made at a particular level in the mixed layer (typically far beyond the "constant flux" surface layer where Monin-Obukhov similarity holds) to fluxes at the ice-ocean interface? (3) Is it operationally feasible to make routine measurements in the mixed layer?

The rest of this document will consider questions 1 and 2, and suggest that they can be answered affirmatively. Question 3 is the crux. The problem is that the Arctic mixed layer is often quite shallow, and the presence of pressure ridge keels makes it very difficult to safely operate the submarine with its sail in the mixed layer for extended periods. ***If a means of safely making routine measurements in the ocean boundary layer from an underway submarine can be developed, SCICEX will greatly enhance our understanding of the heat and mass balance of the ice pack, and its response to major changes in large scale forcing now occurring.***

The Inertial Dissipation Method

Direct measurement of turbulent fluxes requires measuring covariances of collocated fluctuations in the three-dimensional current, temperature, and salinity (e.g., $\langle u'w' \rangle$, $\langle w'T' \rangle$, $\langle w'S' \rangle$) to high enough wavenumbers (small enough scales) to be comfortably into the inertial subranges of the turbulent spectra of velocity, temperature, and salinity variances, respectively. In the turbulent boundary layer under sea ice, these scales are typically of the order of a meter or less. (In the stratified pycnocline below the mixed layer, scales are much smaller and microstructure measurement techniques, which infer turbulence properties from the high end of the turbulence spectrum, are commonly used.) The technology for direct flux mea-

surement is readily available, and has been used repeatedly under sea ice (e.g., McPhee, 1994) and occasionally from research submarine (Yamazaki et al., 1990), but the instrumentation is often relatively delicate and ill-suited for long, unattended operation.

A different approach to inferring vertical fluxes in the turbulent boundary layer is the *inertial-dissipation method* (IDM). It requires measuring variance spectral levels of vertical velocity, temperature, and salinity in the inertial subrange, which is often a much less stringent requirement than measuring covariances. In principle, the measurements could be made with a one- or two-axis acoustic or electromagnetic current meter, and reasonably fast response thermistor and conductivity sensors. The method is also less susceptible to low frequency platform motion than direct covariance measurements.

Briefly, IDM (a) relates the dissipation of turbulent kinetic energy (TKE) to spectral levels in the inertial subrange, then (b) solves a simplified version of the TKE conservation equation for the local turbulent stress. A similar technique relates spectral levels of temperature or salinity variance to local vertical fluxes. A major stumbling block in applying the method in the ocean mixed layer has been determining either local vertical gradients (which by definition are very small in the mixed layer), or the local mixing length (eddy diffusivity). A viable approach to the latter is relating the turbulent mixing length to the inverse of the wavenumber at the peak in the weighted vertical velocity spectrum (McPhee and Martinson, 1994). The great advantage is that all the information needed to calculate, e.g., the magnitude of local turbulent stress is contained in the wavenumber spectrum of vertical velocity—which should be relatively easy to measure via submarine. Similarly, if wavenumber spectra of temperature and salinity are measured, estimates of their respective flux magnitudes may be made, without having to measure the local vertical gradients.

Friction velocity ($u_* = (\langle u'w' \rangle^2 + \langle v'w' \rangle^2)^{1/4}$) and turbulent heat flux ($\rho c_p \langle w'T' \rangle$) measured directly are compared with values calculated via the IDM in Figure 1. The data are from a drifting ice station in the Weddell Sea during austral winter, 1994. The IDM estimates (red pentagrams) were made exclusively from the vertical velocity and temperature variance spectra at the one level (21 m below the ice). The turbulent length scale was obtained from the wavenumber at the peak in the weighted w spectrum.

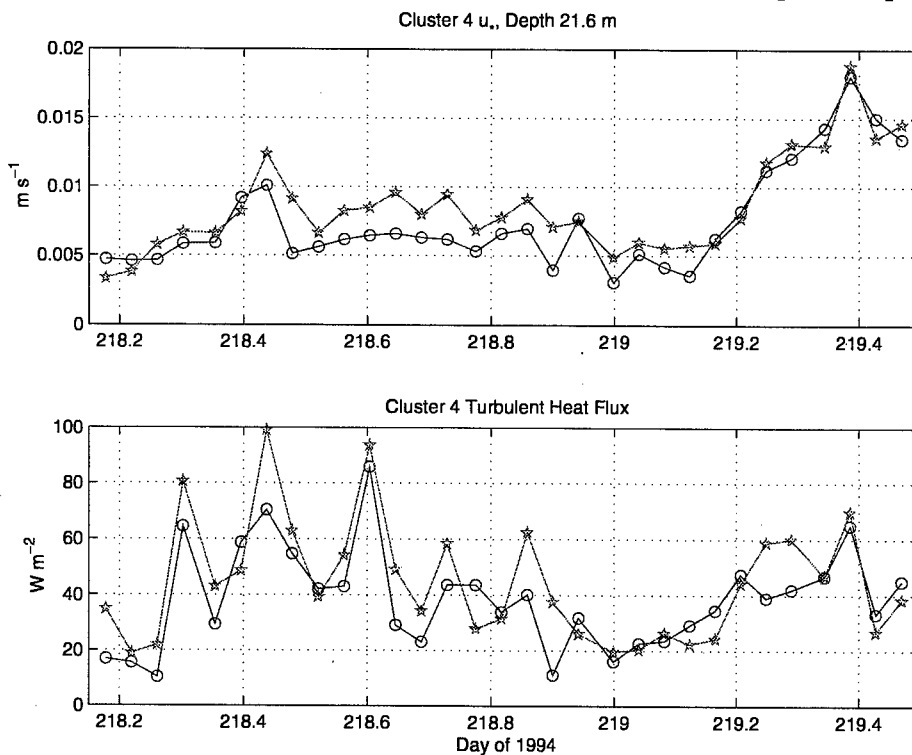


Fig. 1. Comparison of turbulent friction velocity and vertical heat flux measured by the direct covariance method (blue circles) and inertial dissipation method (red pentagrams) with instruments suspended beneath the ice during the 1994 ANZFLUX project in the Weddell Sea. The mixed layer was about 100 m thick.

Surface (Interface) Fluxes from Measurements in the Outer Boundary Layer

The second critical question is how flux measurements made at a particular level in the ocean boundary layer are related to heat, mass, and momentum exchange at the ice/ocean interface. In the atmosphere, it is usually assumed that fluxes measured within a few tens of meters of the surface are representative of surface values. In the ocean, this assumption is invalid, because the boundary layer scales are much smaller—usually by about the square root of the air-water density ratio. Thus measurements at 20 m in the ocean boundary layer are equivalent to measurements at about 600 m in the atmosphere, a sizable fraction of the entire boundary layer thickness.

The problem may be approached by considering an extension of Monin-Obukhov similarity theory with additional imposed scales in the boundary layer, namely the rotational scale, u_{*0}/f where f is the Coriolis parameter, and the depth of the mixed layer. Using a similarity approach, I developed an algorithm for calculating mixing length in the ocean boundary layer (McPhee, 1994), which may be used via an iterative technique to infer surface flux values from measurements made relatively deep in the mixed layer. During times when the mixed layer depth is appreciably smaller than the rotational scale, stratification in the upper part of the pycnocline must also be considered. Development and application of the technique are described by MCPhee (1998) and MCPhee et al. (1998a), and based on results from several recent projects, it appears to work quite well. In terms of submarine operations, the mean profile data would be readily obtained with underway expendable CTD probes.

Summary

In my estimation, a compelling case may be made for measuring ocean heat, salinity, and momentum flux over large areas of the Arctic Basin, especially in the quasi-synoptic mode offered only by dedicated submarine. As a result of several field projects, we now have the tools to relate spectral measurements (specifically, variance spectra of vertical velocity, temperature, and salinity to wavenumbers in the inertial sub-range) made at some reasonable level within the under-ice mixed layer to surface flux values.

While cognizant of the safety and other issues associated with current SCICEX shallow operations, I recommend that serious consideration be given to engineering developments (a tethered, buoyant drogue?) for future SCICEX submarines that would make mixed layer measurements routine.

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Sea Ice Surface Thermal States in Polar Regions

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1 Objectives

This paper discusses the role of submarine as a research platform in conjunction with surface measurements and spaceborne sensing to study sea ice surface thermal states. It is necessary to determine sea ice thermal states to evaluate the overall effects of climatic feedback processes in polar regions under various snow and cloud cover conditions. Such processes need to be investigated at local, aggregate, regional, and global scales with frequent observations.

2 Scientific Issues

Changes in sea ice surface thermal states modify surface albedo, which induces further changes in surface heat balance and subsequent changes in ice surface temperature. These changes are results of complex interactions due to feedback mechanisms under different snow and cloud cover conditions over sea ice of different types and thicknesses. An amplification effect in the ice-albedo feedback process has been long recognized [Croll, 1875] and various simulations of global warming have indicated the importance of the ice-albedo feedback [Ingram et al., 1989].

In the feedback process, cloud cover interferes with the distribution of shortwave and longwave radiations, and thus strongly affects the surface energy balance. Yet is currently uncertain whether the net cloud feedback is positive or negative because of the complexity of ice-albedo cloud feedback mechanisms in the atmosphere-ice-ocean system [Moritz et al., 1993].

Depending on geographical locations and seasonal conditions, effects of clouds on the total surface heat budget can be very different due to the warming 'blanket effect' or the cooling 'umbrella effect'. However, the resultant temperature changes should represent the overall effects on sea ice thermal states. Temperature is considered as a leading climatic factor and temperature changes characterize climatic changes.

In the above respects, it is necessary to observe sea ice surface thermal states at various scales, over large areas, and with a frequent coverage. The intensive field experiment of the SHEBA program (Surface Heat Budget of the Arctic Ocean) and the extensive field experiments of the Canadian C-ICE program (Collaborative-Interdisciplinary Cryospheric Experiments) address the scientific issues at the local scale over the experimental sites. For the aggregation scale (10-100 km) to the regional and global scales, extensive coverages of coordinated submarine, surface ship, and spaceborne remote sensing measurements are required.

3 Navy Submarine Role

Ice thickness regulates sea ice surface temperature and the temperature change under thermal forcing. Using a heat transport model combined with climatology and radiation data in the central Arctic, Maykut [1978] shows large variations in sea ice surface temperatures over various thickness categories of ice from 0.05 m (thin new ice) to 3 m (very thick ice) during a sea ice season from September to May. The magnitude of ice surface temperature change and net surface heat budget balance for a given atmospheric thermal forcing strongly depend on ice thickness categories [Maykut, 1978]. Furthermore, ice thickness is a good indicator of ice age and snow cover depth.

Submarine sonar data is the richest source of in-situ ice thickness measurements that have been collected over several years for unclassified scientific studies under the SCICEX program [Gossett, 1996]. The area of submarine sampling defined by the Chief of Naval Operations covers a large part of the Arctic region. Submarine sonar data have been taken extensively along submarine cruise tracks over thousands of kilometer under Arctic sea ice. See <http://www.ldeo.columbia.edu/SCICEX/> for composite SCICEX tracks

from 1993 to 1997. Another submarine cruise is planned for 1999. Such massive submarine data are crucial and most effectively used to determine ice thickness.

Ice thickness from submarine measurements is therefore essential in the development, evaluation, and validation of observation techniques and algorithms using remote sensing data to address the scientific issues. Thus, an important requirement for submarine measurements is the coordination with concurrent satellite sensors. This is particularly relevant to infrared-visible passive sensors used to detect clouds because of cloud dynamics. Microwave radars can see through clouds to detect sea ice surface thermal conditions. The magnitude of radar backscatter change is dependent on ice thickness categories. Because of ice motion, the data coordination is necessary.

Submarine data acquired in the past can be used with remote sensors operated during that time frame. However, future remote sensors, both active and passive, are more advanced with polarization diversity, higher resolutions, larger coverages, and more frequent observations. Furthermore, we have proposed the concept of formation flights of spacecrafts carrying different active and passive sensors to utilize the strengths of both with data from different sensors collocated in time and space to deal with the dynamics of sea ice, clouds, and climate systems. New algorithms need to be developed and coordinated concurrent submarine data are required for the future missions.

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High Resolution Arctic Oceanography

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One of the more significant findings of the first phase of SCICEX is the importance of frontal features in the overall structure of the Arctic Ocean. Large-scale fronts bound distinct water types. The position of these fronts is an index of the relative volume of the different water masses in the Arctic. Smaller scale frontal activity is associated with shelf-slope interaction, river outflow and other phenomena that, at present, are not known. The basic geography of Arctic frontal structures is still being determined. Significant refinement of the present understanding can be expected.

Fronts both define the boundaries between different water masses and strongly affect the diffusive processes which cause these boundaries to blur. Frontal structures can transport fluid laterally (parallel to the front) great distances and might serve as conduits for the transport of pollutants or nutrients from coastal waters to the deep sea. There is strong evidence (primarily from ice camp observations) that these features modulate the oceanic internal wavefield significantly. Both the enhancement and reduction of near inertial waves have been reported in the proximity of mesoscale features. Theoretical models exist which relate the expected enhancement to spatial patterns in mesoscale vorticity. Such patterns are difficult to map from surface based observations. Since internal waves are responsible for most of the shear in the Arctic Ocean, and the shear also plays a role in the lateral dispersion of properties, these patterns must be understood. This issue is particularly relevant to the environmental prediction problem. If most of the dispersion in the Arctic is caused by mesoscale and sub-mesoscale features, and predictions of dispersion are expected from numerical models which are unable to resolve these features, the potential for error is high.

To advance the contribution of SCICEX to the next level, we must develop the ability to survey ocean structures at depths above and below the operating depth of the submarine. To date, this has been accomplished by using expendable temperature and CTD probes and the single upward-looking ADCP which we have supplied to the program. Much higher resolution sonar systems can be built, and indeed must be built if we are to exploit the full capability of the submarine.

The high operating speed of the submarine places a premium on rapid, precise estimation of velocity. With the platform moving 15 kts, a two-minute average velocity estimate has one kilometer along-track resolution. This is a minimum for mesoscale studies. The precision of the sonar must be such that the oceanic signal is greater than the uncertainty in the velocity estimate over these short averaging times. Narrow transducer beam widths are required to prevent "spectral broadening" associated with the forward motion of the submarine. Careful coding of the transmitted pulse is necessary to avoid the "aliasing" of the broadband return echo, given the large Doppler shifts associated with the forward motion of the submarine. Such specialized systems have been built for oceanographic research vessels, but these are not available commercially.

It is clearly necessary for a next-generation system to be able to look down into the sea, as well as upward from the submarine. Individual sonar transducers mounted on the submarine sail can provide this down-looking capability. Up-looking transducers, baffles that prevent ice echoes from contaminating near surface data, and armor that protects transducers from ice damage can be incorporated with the down looking transducers into compact modules.

The software and data processing of a next-generation system should extend present capability in several respects. The display of data must be user-friendly, providing sufficient information to direct a spatial survey program in real-time. Accurate, calibrated estimates of acoustic scattering strength should be available, in support of biological studies. Algorithms that detect and separate "hard hits" (fish?) from continuum scattering (plankton) should be implemented, such that these separate populations can be independently tracked. An algorithm that detects the ice surface hit can be implemented on the individual up-looking beams, such that the slope (cross-track and along-track on 100 m scales), as well as depth of the ice cover can be estimated.

The conduct of a frontal survey, based on real-time data, will require great cooperation between scientists and crew. Such surveys will be extremely opportunistic, with intense survey activity following the discovery of a front. This mode of operating will be difficult to integrate into the present, highly refined, SCICEX scheduling process. However, we are all challenged to use resources more effectively as the SCICEX program continues.

SCICEX/SCAMP Mapping of the Arctic Ocean Floor to Study the History of the Late Cenozoic Arctic Ice Sheets

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1 Rationale and Objectives

Very little is known about the extent of ice sheets around the Arctic Ocean perimeter during the Late Cenozoic glacial periods. Flowing off the exposed continental shelves, these sheets may have coalesced, capping portions of the deep Arctic basins with thick ice plates, similar to the Ross Ice Shelf in Antarctica (e.g., Grosswald & Hughes, 1995). Sediment-core studies of the Arctic Ocean floor cannot comprehensively address this problem, as they do not provide the means to distinguish abnormally thick sea ice from a floating ice shelf (e.g., Phillips and Grantz, 1997). Understanding the extent of ice sheets, floating and grounded, in the Arctic Ocean is crucial for developing a complete description of glaciation in the Northern Hemisphere, the history of global sea-level and circulation changes, and the evolution of Arctic Late Cenozoic sedimentation. We can test the existence and define the limits of the former Arctic ice sheets by survey-

ing the high ridges and plateaus and the outer shelves of the Arctic Ocean for peri-glacial bedforms and sedimentary environments.

Recognition of sea-floor features characteristic of direct glacial impact on the outer continental margins and sea-floor rises in the Arctic Ocean (e.g., glacial-sole markings, marginal morainic ridges, and glacial gravity flows) would provide direct evidence for the Late Cenozoic Arctic ice sheets and begin to document their history of fluctuations. In the absence of subglacial geomorphic features, the depth limits and prevailing orientation of iceberg plowmarks will provide useful constraint on the thickness and locations of ice-sheet termini. Mapping of iceberg drift trajectories will help to reconstruct Arctic oceanic and atmospheric circulation patterns.

To accomplish these goals, we propose to survey selected areas of the Arctic Ocean perimeter and oceanic ridges (to water depths of 1-2 km) to identify and map glacial sea-floor features using the Seafloor Characterization and Mapping Pod (SCAMP) (Pyle et al., 1997). The unique access provided by US Navy Sturgeon-class submarines combined with the Sidescan Swath Bathymetric Sonar and chirp-type High Resolution Subbottom Profiler, that are components of SCAMP, will enable a comprehensive study of peri-glacial features on the Arctic Ocean floor, focussing on:

- Bedforms resulting from a direct glacier impact, such as marginal morainic ridges and glacial-sole markings;
- Estimation of water depth range of iceberg plowmarks (buried and exposed);
- Mapping the orientation of plowmarks and other linear features;
- Identification of gravity flows on the slopes in association with glacial features.

The subbottom profiler will further elucidate the structure of landforms and the stratigraphy of these features as well as stratigraphic relations with the underlying deposits.

2 Target Areas

(1) Chukchi Borderland is the shallowest portion of the Amerasian Basin, in places as shallow as 300 meters. This area should have been very sensitive to the impact of a floating ice shelf and/or big icebergs during glacial periods. Moreover, Chukchi Borderland would have been directly affected by grounded glacier ice if an ice sheet existed over the Chukchi Sea shelf at some point during the Quaternary (Grosswald and Hughes, 1995).

(2) Lomonosov Ridge. Shallow portions of the Lomonosov Ridge may be capped by glacial landforms. The swath sidescan and profiler data from the ridge are crucial for understanding the regional pattern of the distribution of ice shelves and/or iceberg fields during glacial maxima.

(3) Canadian continental margin. Due to present-day thick ice pack, the Canadian margin cannot be easily accessed except from the ice surface. The sidescan and profiler investigation of the Canadian margin will shed light on its glacial history. Surveys should be concentrated on the outer parts of major troughs/channels of the Canadian Archipelago, which are potential outlets for ice-sheet tongues during glaciations.

(4) Morris-Jessup Rise and Voring Plateau. These extensions of the Greenland and Svalbard continental shelves "guard" the outlet from the Arctic Ocean to the Norwegian-Greenland Sea, and therefore should contain records of any significant movement of ice masses. Findings of the mega-iceberg scours at the Yermak Plateau illustrate the importance of this area for paleoglaciological studies (Vogt et al., 1994).

3 Expected Results and Linkages

The major scientific output of the surveying of glacial landforms in the Arctic Ocean will be the establishment of critical boundary conditions for the Late Cenozoic Arctic ice sheets. The basin-wide identification of depth limits for iceberg plowmarks will impose an efficient control on the maximum thickness of a floating ice shelf and/or glacial termini in the Arctic Ocean. Furthermore, the mapping of plowmark

orientation will trace the prevailing trajectories of iceberg drift during glacial periods, which could have differed significantly from the modern pattern (Bischof & Darby, 1997).

SCAMP sidescan and profiler images will provide information on the sea-floor morphology as well as seismostratigraphy of up to 100-m thick sedimentary strata. However, these data will lack chronostratigraphic control, which should be achieved in the future by the investigation of sediment cores collected from the survey sites. Current plans of using USCGC icebreakers for research purposes under ARCSS SBI initiative and establishing a Nansen Arctic Drilling Program give us good hope for obtaining sediment records that will provide time constraints for mapped landforms, and facilitate an in-depth understanding of glacial processes that have affected the Arctic Ocean.

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Monitoring of Bowhead Whale Distribution in the Eastern Beaufort Sea

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1. Background

The expansion of the oil and gas industry into the offshore Beaufort Sea has been the subject of intense environmental scrutiny. In addition to the obvious problems involved in cleaning up a spill in ice covered water, the best offshore prospects are located in the migratory route of bowhead whales, an endangered species. Bowhead whales spend the winter months in the marginal ice in the Bering Sea and migrate northwards in the spring. By working through the leads in the pack ice, the whales arrive in the polynyas west of Banks Island in June and after summering in the eastern Beaufort Sea, they move westward along the Alaskan shelf arriving in the Chukchi Sea in late September – early October. Although the westward migration in open water areas has been fairly well documented through the use of aerial surveys and the observations of Inupiat whalers, virtually nothing is known about the activities of the adult whales while in the eastern Beaufort Sea. The whales spend most of the time submerged, the ice cover may extend to the shoreline and low overcast and fog typify late summer. The importance of this environment as a feeding habitat for the whales or as a location for socialization and breeding activities will have direct bearing on assessing the sensitivity of the region to offshore oil industry development. Displacement by ship noise, seismic exploration, or drilling activities could have impacts on the habitat usage and the success of subsistence whalers. The U. S. Minerals Management Service has expressed strong interest in these problems and has conducted extensive (and expensive) research on the importance of the eastern Beaufort Sea as whale habitat to bowhead whales over the past 15 years. Nevertheless, the constraints imposed by ice cover and bad weather have severely impaired observational studies and have required continued expenditures of funds. The author of this paper has conducted indirect assessments of habitat importance through the use of isotopic techniques (Saupe et al., 1989; Schell et al. 1989) but the need for direct observational information is acute.

2. Proposed Study

The nuclear submarine offers all of the critical requirements to assess bowhead whale habitat usage in the eastern Beaufort Sea: the ability to move quietly under the ice, a powerful listening capability and the ability to remain on-station long enough to observe movements and activities. The whales vocalize frequently and tend to be in small groups that would be easy to track. The ability of the sonarman to range and assess travel velocity of individual whales would be extremely valuable in assessing feeding versus migratory movements. By installing 420kHz sonar on the submarine, it would also be possible to estimate zooplankton densities to determine the quality of feeding habitat. Although bowhead whales are often found on the continental shelf in shallow water, most of the population and especially the adult whales are observed near the shelf break and in deeper waters. In truth, very little is known of the onshelf vs. offshore distribution and a careful description of the whale movement patterns would be valuable in avoiding or ameliorating potential impacts of offshore oil and gas activity.

2.1. Goals and Objectives

The following objectives would contribute to the goal of understanding the habitat usage and migratory patterns of bowhead whales in the Eastern Beaufort Sea:

- a) Determine the distribution of the whales during the months of July-September in the Beaufort Sea;
- b) Determine the activity patterns of adult whales accessible from the boat using vocalization and movement patterns at given periods of the season, i.e., social activity, feeding, breeding,
- c) Assess habitat quality through sonar assessment of zooplankton densities and distribution in the areas that whales are found,
- d) Follow groups of whales for sufficient lengths of time to determine activities and duration in areas of high offshore oil industry potential for development.

3. Methods

Successful accomplishment of the above objectives would require close cooperation with sonarmen and a cruise track designed to optimize coincidence with migrating whales. Since the population spends much of the summer in the eastern Beaufort Sea, it would be necessary to have cooperation with the Canadian government and preferably joint operations with Canadian biologists if security allowed. Recordings of bowhead calls along with other marine mammals present are available for observer training and identification of targets. Population distribution would be described by counts along survey transects. Activities of individual animals would be assessed by on-station sonic observation and ranging of whales and by matching behavior patterns with known feeding and socialization activities. Since activities would undergo change over the summer season, observations would be conducted periodically between other project operations.

The major limitations to accomplishing the objectives are the need for boat time on station and the possibility that the whales might move into shallow water that would preclude following them. Acquired data on whale activities and movements would be synthesized to produce a description of natural history that could then be reviewed in context with oil industry scenarios for development.

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SCICEX 2000 White Paper: Improvement of Vertical Water Sampling Capabilities

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Submarines can readily obtain high quality water samples from about 25 m to 220 m of the Arctic Ocean by taking water through the hull. However, there are significant marine biological and physical oceanographic problems that require high quality temperature and salinity measurements and water samples in the surface mixed layer and from depths below 220 m. During the SCICEX cruises such samples have been obtained by surfacing the submarine either in a lead or through the ice and performing hydrocasts which have extended from the surface to approximately 1600 m depth. Considerable effort is required to carry out such sampling, but the few stations that have been taken during the SCICEX cruises in regions that have not been sampled by icebreakers have revealed new and valuable information on the circulation of the upper and intermediate waters in the Canadian Basin. Because of the submarines unique ability to reach remote regions of the Arctic easily and quickly, it is desirable to continue the collection of this type of data and samples. There are two basic approaches to obtaining vertical profiles of water samples and temperature and salinity measurements: 1) improve the surface station capability of the submarine and 2) develop a means to obtain vertical profiles from inside the submarine.

The ability to perform surface stations could be improved by developing equipment that is lightweight and easy to handle and assemble on the deck of the submarine or on the ice. This includes winches, sampling bottles, booms, tents, etc. It would also be very beneficial to improve the ability of the submarine to recognize and map regions of open water and ice of the appropriate thickness for surface stations.

In-board sampling has the advantage of not requiring the submarine to surface or if it does surface not requiring setting up the deck for hydrocasts. There are two possibilities for this. One is to lower a package of Niskin type bottles with a CTD from a torpedo tube or another through-hull device. The other is to lower a CTD at the end of a sampling tube to the desired depths and sample water pushed up into the submarine through the tube. The pressure differential between inside the submarine and outside would provide the force for the water to flow through the sampling tube and a pump would not be required. The tube could remain at the desired depth for as long as needed to take samples at that particular depth and there would be no volume limitation on the samples that could be obtained.

In considering these options a cost benefit analysis should be done for the amount of science that can be carried out over the coming decade. For example, improving the ability to perform surface stations could possibly be done quickly for a modest cost which would make surface stations somewhat less cumbersome, but would not provide the capability for doing a large number of such stations. To develop the capability to obtain vertical profiles of samples through the hull might require significant engineering costs and require half a decade to perfect, but would then provide a greater capability for obtaining vertical profiles. Overall, which would provide the greatest scientific productivity?

SCICEX 2000 White Paper: Hydrographic and Tracer Sampling from Submarines

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Submarines can travel rapidly beneath the ice of the Arctic Ocean and can reach remote and heavily ice covered regions that are difficult to reach by icebreaker. They are excellent platforms for oceanographic investigations in such regions and for obtaining repeat observations at specific locations. Here we propose two studies for the first decade of the next millennium.

During the mid to late 1990s, high quality hydrographic and tracer data have been obtained in the western and central Canadian and Makarov basins. However, there is very little data along the eastern margin of the Canadian Basin and in the Lincoln Sea located just north of Ellesmere Island and Greenland.

These regions are difficult to reach because of their remoteness and the ice thickness, particularly the Lincoln Sea region. Near surface and intermediate waters are postulated to flow along the eastern side of the Canadian Basin and to mix with waters from the Eurasian Basin in the Lincoln Sea before flowing towards Fram Strait. Some of the water flowing along the eastern side of the Canadian Basin may also flow through the Canadian Archipelago to Baffin Bay and then to the North Atlantic. We propose 4 sections of hydrographic/tracer stations normal to the continental slope to investigate this circulation: 1) from Banks Island to the basin interior, 2) from the center of the Queen Elizabeth Islands (about 80°N latitude) to the basin interior, 3) from the eastern end of Ellesmere Island to the interior parallel to the Lomonosov Ridge and 4) from the north slope of Greenland to the interior parallel to the Lomonosov Ridge. Each section would consist of 4-6 stations.

During the 1990s a dramatic shift in the distribution of waters of Atlantic and Pacific origin in the Arctic Ocean occurred with Atlantic waters penetrating further into the Canadian Basin than had been observed previously. This shift in water masses and the change in circulation that caused it may provide more heat to the Arctic Ocean, which could affect the ice cover and global climate. It is important to document this change and determine if the volume of Atlantic water in the Canadian Basin is expanding or contracting. The submarine with its ability to rapidly reach all regions of the Arctic can make a tremendous contribution to this. We propose to occupy 10 hydrographic/tracer stations every other year with sampling down to about 1600 m. The station locations are as follows: 1) the Alaskan slope at about 140°W, 2) the central Canadian Basin at about 78°N, 3) the center of the Alpha/Mendeleye Ridge, 4) the center of the Makarov Basin, 5) the Eurasian side of the Lomonosov Ridge at two locations, 6) one near the western end and one near the eastern end, 7) the slope of the East Siberian Sea, 8) the northwest corner of the Canadian Basin at about 82°N, 170°W, 9) over the continental slope off Banks Island and 10) over the continental slope off the Queen Elizabeth Islands. These stations provide coverage in both the boundary currents that transport Atlantic water and in the interior regions of the Canadian and Makarov basins.

Both of these projects would be coordinated with sampling surveys being carried out on other platforms as part of other projects. In particular documenting how the Atlantic water inflow varies will likely require more than 10 stations. There has been some discussion of using aircraft to perform hydrographic/tracer surveys. The submarine stations could provide the backbone of such a survey, providing deeper sampling than could be obtained from aircraft at key locations and sampling in regions where aircraft could not reach.

Adaptation of Laser Infrared Spectroscopy to a Nuclear Submarine to Measure Seawater Volatiles in Real-Time

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Oceanographers have long measured the distribution of physical properties and chemical species in the ocean in order to investigate the physical, chemical and biological processes which determine those distributions. Great determination and ingenuity have been shown in collecting and analyzing seawater samples and in interpreting the results of those analyses. Still, it is a truism in oceanography that this branch of science is 'measurement limited'. The questions which can be answered are limited by the quality and quantity of data which it is possible to collect. The collection of data, in turn, is limited by the availability of research platforms which can reach critical parts of the world ocean and measurement systems which can function reliably. Nowhere is this more true than in the Arctic.

To characterize the processes that occur in the Arctic Ocean we propose an innovative methodology of adapting a infrared tunable diode laser (TDL) spectrometer to measure multiple trace gas species (CO₂, CH₄, N₂O, CO, DMS) and pollutants (chlorofluorocarbons). We envision a measurement system which can quantify gases in seawater with a turnaround time on the order of ten minutes using gas phase laser infrared spectroscopy. The gases that can be analyzed are all related to the marine biological cycle and to its alteration by human activities. The goal is to develop a measurement system package which can be

deployed on a submarine and reliably obtain quantitative data using water samples pumped through the ship's hull and which are at no time in contact with the ship's atmosphere.

In addition, this methodology would introduce the use of gas phase tunable diode laser infrared spectroscopy to the measurement of volatiles in seawater. This measurement technology has been used extensively and successfully used for the quantification of atmospheric trace gases (Kolb et al. 1995). Although it has not yet been applied to gases in seawater, the potential advantages over the gas chromatographic methods widely used today are significant. A multi-laser optical system can obtain spectral data sufficient to determine concentrations of several gases on a time scale of seconds. The necessary gas samples can be obtained using gas-water equilibrators which are well suited to through-hull pumped systems. Since these measurements are absolute (i.e., not referenced to a calibration gas), computer based data reduction can provide near real-time results. If, as we expect, the turn-around time for these measurements is ten minutes or less, it should be possible to map seawater volatiles while the ship is underway. From a submarine, the possibilities for investigation of three dimensional distributions of these important seawater constituents and greenhouse gases are unprecedented.

Infrared tunable diode laser (TDL) spectrometers have been used for many years to detect and measure environmental pollutants in trace quantities (Zahniser et al. 1995; Kolb et al., 1995, 1996). TDL's provide a highly effective means of measuring trace concentrations, with either remote sensing or with advective sampling. Trace constituent concentrations in the sub-parts-per-billion range are readily achieved with 1 second measurement times. The concentrations may be derived from known spectroscopic parameters and thus are absolute, which minimizes the need for calibration gases.

Many seawater volatile gases can be easily detected by tunable diode laser spectroscopy. Nitrous oxide (N₂O), carbon dioxide (CO₂), methane (CH₄), and carbon monoxide (CO) have suitable mid-infrared transitions for monitoring with TDLs. The mixing ratios of these trace gases can vary with time, location and ocean depth. Information on these variations and identification of concentration trends provide insight on a number of physical, biological and chemical processes in the ocean-atmosphere system, including circulation of pollutants, general ocean circulation, and production and destruction of trace species in the ocean.

We propose a design for an instrument to measure in situ a combination of several trace gases while mounted in a submarine. Seawater must be introduced into the measurement system without exposure to the internal submarine atmosphere. The required detection limits for N₂O, CH₄, and CO are on the order of 1 nmol/liter in seawater; that of CO₂ is about 1 μmol/liter in seawater. If the seawater is in equilibrium with air, the corresponding gas phase mixing ratios, are in the range of 40 parts-per-billion (ppb) to 30 parts-per-million (ppm) depending on the gas. These mixing ratios can be easily detected by a TDL system (Kolb et al., 1995, 1996).

Tunable diode laser systems have a number of advantages over gas chromatography (GC), a technique which is often used in monitoring trace species in marine environments. TDLs are high sensitivity and high specificity instruments. The high resolution of the diode lasers allows one to monitor individual or groups of infrared transitions of specific molecules. Potential interferents are more easily identified and accounted for than with GC. A further advantage of optical techniques is the ability for real-time, continuous trace gas monitoring, as compared to discrete injections into a GC. TDL instruments can accomplish all of the above without calibration gases, compressed gases, or any other reagents. Although present TDLs use liquid nitrogen for cryogenic cooling of the lasers, we will incorporate a closed loop refrigeration system into the submarine instrument design and thus eliminate the need for liquid nitrogen. The lack of reagents or other gases makes the system safer and more suitable for the submarine environment.

As an example, we envision an application of the TDL instrument to measure the changes in Pacific water along its route through the Bering Sea, across the Chukchi Sea platform and into the Arctic Ocean (Coachman and Barnes 1961, 1962; McRoy and Delaca 1996). En route these waters acquire physical, chemical and biological characteristics due to processes on the broad, shallow shelves of the Bering and Chukchi seas that distinguish them from ambient waters in the Arctic (Kusunoki 1962, Kinney et al. 1970). This water forms a plume in the Arctic, with a core about 110 m deep that contributes to the layers of the

Upper Halocline in the Canada Basin. It can be traced by chemical signal from its entrance into the Arctic via Bering Strait to its exit through the Canadian Archipelago and around Greenland. Residence time of this water in the Arctic Basin is thought to be less than 10 years (Carmack and Swift 1990). The TDL instrument could provide a very fine scale resolution for the measurement of trace gases that would contribute to fundamental understanding of biogeochemical processes in the upper layers of the Arctic Ocean.

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SSN Geophysical Surveys of Arctic Continental Margin Slopes: An Opportunity.

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An important program of the Arctic Ocean Science Board is Arctic Paleo River Discharge (APARD) designed to investigate how various processes and pathways of sediment lead to the preservation of strata and the subsequent development of the margins of the Arctic Ocean. There is a strong desire of marine scientists to interpret the offshore sedimentary record on arctic (particularly Russian) continental margins, in the belief that proxy indicators would establish a history of paleo-discharge from arctic mega-rivers. This information would in turn provide a direct record of continental climate with the flux of river sediment providing the strong and integrative record of terrestrial climate dynamics. Arctic rivers, frozen for much of the year, are subjected to a continental-scale thaw over a very short period of time with a consequence of a sudden release of sediment, water, and river ice.

Downslope-transport of riverine material by turbidity currents controls much of the sedimentation in the deep basins. For example, major proportions of the Late Quaternary sedimentary columns in the Nansen and Amundsen Basins consist of turbidites. In the southeastern part of the Canada Abyssal Plain adjacent to the Canada polar margin or the Mackenzie cone, near the base of Northwind Ridge, 50 to 70 % of the cored sediments are turbidites. Fine-grained material might be transported from coastal areas into the central part of the Arctic Ocean by the major boundary currents and the downslope flow of shelf-brine.

During glacial conditions sea-level fall in conjunction with atmospheric cooling cause the propagation of the coast line to the shelf break. The wide shallow shelves surrounding the Arctic Ocean would progressively disappear, exposing ca. 35% of today's Arctic Ocean surface area. Rivers might then directly supply freshwater to the deep ocean basins or may have been diverted because of isostatic adjustments owing to the waxing and waning of ice sheets. Freshwater supply undoubtedly varied between glacial and nonglacial conditions because of regional differences in drainage, with catastrophic effects on the water column structure of the entire Arctic Ocean. The absence of any freshwater supply might trigger a weakening of the strongly developed halocline in the Arctic Ocean, probably leading to a reduced sea-ice cover or even an ice free Arctic Ocean. Brine formation on the shelves which is crucial for the modern deep water formation in the Arctic Ocean would have concomitantly been reduced.

In North America, the modern course of Mackenzie River is entirely the product of glacial diversion by the Late Wisconsin Laurentide Ice Sheet. In Siberia, the extension of mountain glaciers in main rivers basins resulted in a significant reduction in the discharge of these rivers during ice buildup and the glacial maximum. For example, in the Yana River basin it led to a 40% decrease in discharge. However, during deglaciation its discharge increased strongly affected by catastrophic floods.

Mapping of paleoriver systems and channels in shelf areas using sub-bottom acoustic profilers in the Laptev Sea area, for example, document refilled paleoriver channels in the uppermost sediments (1–13 m) of the Laptev Sea shelf, ranging in water depths between 25–94 m. Channels are incised into stratified sediments of probable Pleistocene age. The river channels must have been active during Weichselian time when the inferred sea level was up to 120 m below present sea level. Most likely the observed paleoriver channels are the result of rivers formed at the termination of Weichselian glaciations caused by melting of local ice sheets and/or glaciers on the Taymyr Peninsula and the New Siberian Islands.

At the glacial maximum (ca. 30–22 ka) most of the glacial ice on the Beaufort shelf did not extend beyond the inner shelf east of the Mackenzie Trough, even though the delta was covered by thick (1 km) ice from an ice tongue in the Mackenzie Trough. A regional basal hummocky reflector suggests this event was followed by a brief interval of postglacial flooding. The formation of large lakes (Tutsieta and Mackenzie lakes) from 13 to 10 ka would have reduced sediment discharge into the Arctic Ocean. In contrast, the outflow of water from glacial Lake Agassiz at 9.9 ka would have discharged 21,000 km³ of sediment-laden water to the Arctic Ocean, raising the global sea level by 6 cm.

Another important environment of surrounding the Arctic Ocean were the ice-sheet dominated margins where debris flow processes dominated over other forms of downslope sediment movement (e.g., turbidity currents) typical of the above fluviually-dominated margins. At present, 15% of the Earth's land surface is covered by glaciers. During the peak of the last glaciation only 18,000 years ago, glaciers covered 30% of the land surface. About 60% of the world's continental shelves have been impacted by glaciations. Hence, debris flows have probably been a dominant process in shaping the Quaternary morphology and stratigraphy of a significant portion of the world's continental slopes. Understanding the cause for their dominance will greatly advance our understanding of how glaciated margins evolve. On a more fundamental level, this knowledge will also advance our understanding of how continental margins evolve elsewhere in the world. This is because turbidity currents and debris flows are the dominant mass sediment transport processes along continental margins worldwide. Yet what determines whether sediment will be transported as a debris flow or as a turbidity current remains an outstanding question.

Detailed study of these two end-member types of arctic continental slope environments (i.e. where glacier-generated debris flows predominate versus where river-induced turbidity currents predominate) offers an important opportunity to compare and contrast these very different margins. We propose to use a SCICEX SSN submarine and its swath mapping and acoustic profiling capability to investigate the two end-member arctic margins. River-dominated slope possibilities include areas off of Beaufort Sea margin and/or the Eastern Siberian Sea margin (Kolmya, Yana, Indigirka, Lena River influenced). Glaciated continental margins with the preponderance of debris flows deposits have been clearly documented already and those off of Canada, Greenland, and Norway (however ideal areas lie just outside of the 200 nm block). Detailed mapping of these slope morphology and deposit geometries would be required to complete the study.

Should We Pursue Multibeam Mapping of Sea Ice?

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1. Background

Submarine upward-looking sonar ice profile data are one of the few sources of quantitative information on ice thickness in the Arctic Ocean. Current efforts are directed at processing and releasing a considerable amount of previously classified data. The SCICEX program is adding tens of thousands of kilometers of unclassified ice draft data to this data set.

Since the sonar measured ice draft is a reasonable proxy of thickness, the data are especially useful for examining the temporal and spatial variability of Arctic sea ice thickness. Most often, general statistics are calculated for specific length segments of ice drafts (commonly 50 km). The statistics of other characteristic features such as ridge keels, thin ice, deformed and undeformed ice segments are also generated.

Three-dimensional swath mapping of the ice cover might provide additional useful quantitative thickness information, particularly regarding the characterization of deformed ice and other morphological features. For instance, three-dimensional mapping will allow the documentation of the geometrical configuration of ridge keels. The depth, width, slope, and orientation of keels can be determined quite accurately. In addition to superior quantification of pressure ridge features, swath mapping can provide quantification of other features including thickness, length, width and orientation of thin ice areas and leads. Partitioning deformed and undeformed ice based on its bottomside signature should be straightforward, and it may be possible to distinguish first-year from multiyear ice. The swath mapper may be able to document the occurrence of "false bottoms", where fresh meltwater lenses contacting colder saline water freeze beneath floes during the summer. Three-dimensional mapping would also appear to be the ideal method for conducting site surveys of field experiments or locations of autonomous instrumentation.

2. The Opportunity

Whereas the SCAMP bottom mapping system has required considerable system development, an underice three-dimensional mapping system has been previously deployed on a Sturgeon class submarine during Navy ICEX experiments. That system was designed and fabricated by the Applied Research Laboratory of the University of Texas. Most of the system still exists, and components which have been removed can be easily rebuilt or procured.

The system is essentially a multibeam swath mapping system turned upside down to provide digital drafts of the ice cover. Operating at a frequency of 150 kHz, the system employs a projector which forms a fan-shaped beam that ensonifies a swath of ice to each side of the submarine. The hydrophone array is beamformed into 120 one-degree beams oriented orthogonally to the transmit beam, so the angular resolution is 1x1 degree, and the receive beams provide 120 soundings to the ice on each ping in an annulus from zenith to 60 degrees to each side. Typically, the beamwidth maps a swath of about 500 m width from a depth of 500 ft. The system has interfaces to the ship's synchros to measure depth, speed, course, and trim angle. The ship's data and sonar data were previously stored on a PC equipped with 90 MB Bernoulli disk drives.

The outboard installation included foundations for the projector and hydrophone on the bridge. The hydrophone was flush with the top of the sail and designed to withstand direct impact and forces by the ice during surfacing. The projector protruded a few centimeters above the top of the sail and was mounted on springs which allowed it to retract into the sail when loaded by ice. Future installations should consider simplification of the system by installing the transducers in a fixture on the deck. All inboard components could be mounted on two short racks on a torpedo skid plate. A remote display could also be mounted in the control room if desired.

The cost of rebuilding of the system and installing it with the suggested modifications is estimated to be about \$350K. The aim of this paper is to generate discussion on the issue of whether the swath mapping ice system is a worthwhile SCICEX endeavor.

APPENDIX G. SCICEX BIBLIOGRAPHY

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UNIVERSITY OF WASHINGTON

15 June 1999

Dear Colleague,

The enclosed report is based on the SCICEX 2000 Workshop held in October of 1998. It summarizes the state of pursuing arctic marine science from U.S. Navy submarines and contains abstracts and a bibliography of science accomplished in SCICEX and a wealth of scientific and technological ideas for a future program.

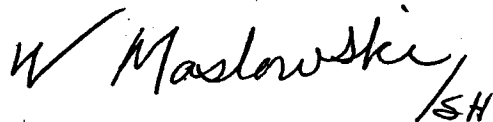
We hope the report and its recommendations facilitate a continuing program in Arctic Ocean observations from submarines.

To obtain more copies, use the address on the title page. The document will be posted on the SCICEX 2000 web site (<http://psc.apl.washington.edu/scicex/scicex2000.html>).

Sincerely,



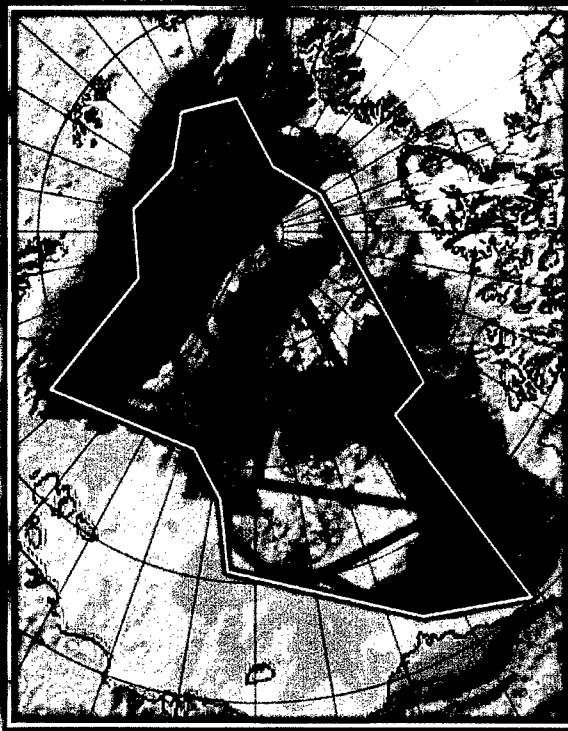
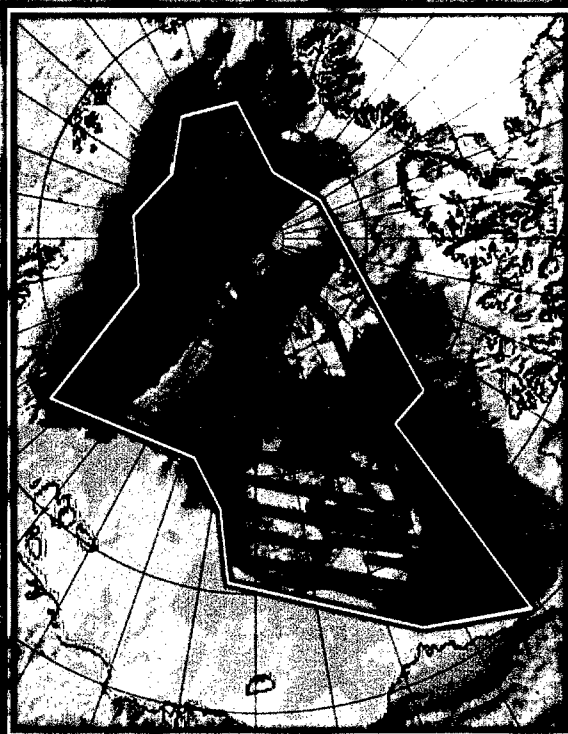
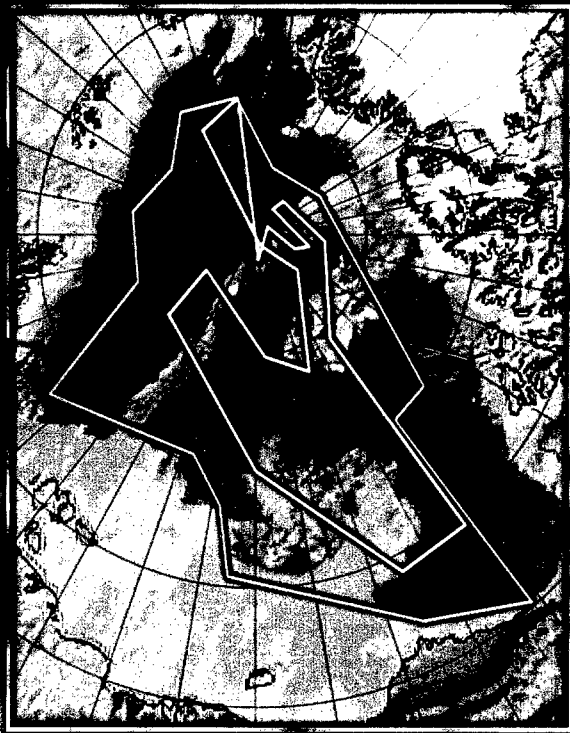
Drew Rothrock



Wieslaw Maslowski

for the SCICEX 2000 Organizing Committee

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