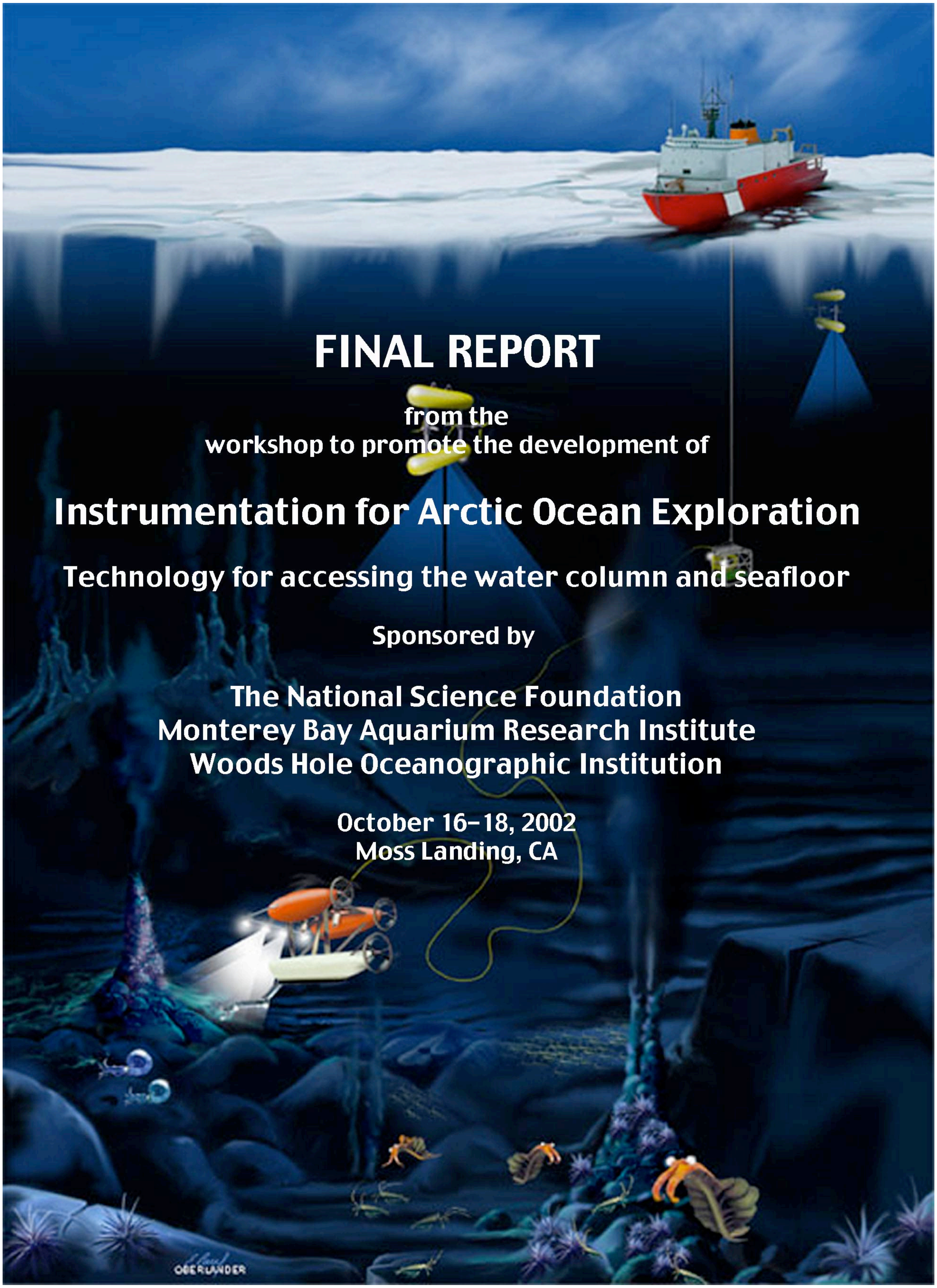

FINAL REPORT

from the
workshop to promote the development of

Instrumentation for Arctic Ocean Exploration

Technology for accessing the water column and seafloor

Sponsored by

The National Science Foundation
Monterey Bay Aquarium Research Institute
Woods Hole Oceanographic Institution

October 16–18, 2002
Moss Landing, CA

Executive Summary

An NSF-sponsored workshop entitled, “Instrumentation for Arctic Ocean Exploration: Technology for accessing the water column and seafloor” was held at the Monterey Bay Aquarium Research Institute in Moss Landing, CA from October 16-18, 2002. The workshop was convened in response to the fact that; (1) the Arctic Ocean is a high-priority target for a diverse set of scientific investigations including key topics such as global climate change, life in extreme environments, and the origin of life on Earth, (2) virtually all Arctic oceanography, regardless of discipline, is limited by a small set of common technological barriers, (3) a number of recent technological developments present opportunities to overcome these barriers and truly revolutionize the conduct of Arctic oceanography, and (4) the aggregate national funding for Arctic operations, research, and instrumentation is at alarmingly low levels after being in steady decline for nearly a decade.

There are five over-arching technical challenges that presently limit most types of Arctic research;

- wire and cable management within a dynamic ice pack
- recovery of free-vehicles within ice-covered waters
- under-ice navigation at high latitudes
- remote monitoring of the water column and seafloor
- maintaining an observational presence outside of the short (summer) Arctic field season.

An important outcome of the workshop was the development of a coherent vision for the future of Arctic research that would fundamentally change the way observations are made in the Arctic by exploiting the potential of new technologies to solve these technical challenges and create a new paradigm for Arctic oceanography. The three components of this vision are; (1) expeditions with enhanced capabilities, (2) a basin-wide, mobile network of ice-mounted buoys and free-vehicles (i.e., gliders, drifters, autonomous underwater vehicles), and (3) cabled oceanographic observatories with real-time data and power connections to shore.

All of the technologies required to realize this vision and advance Arctic oceanography are either mature or rapidly maturing, but applying them to the Arctic will require a significant and focused national effort that is beyond the funding presently available through NSF’s Office of Polar Programs. Therefore a key recommendation from the workshop is that a mechanism for securing a long-term source of funding for Arctic instrumentation development be identified and pursued, with potentially relevant programs including the NSF Major Research Instrumentation and Science and Technology Center programs, the ONR Physical Oceanography Program, the Climate Change Research Initiative, and the NASA EOS program. New initiatives may also need to be considered, and potential cooperation between federal agencies should be explored. A complete list of recommendations from the workshop is presented in the body of the report.

The workshop concluded with a plenary session where support for a national commitment to Arctic instrumentation was unanimous and strong. An *ad hoc* steering committee was formed, and a follow-up workshop to revisit key topics is envisioned for 2005.

Introduction

Scientific progress in many aspects of Arctic oceanography is slow to non-existent owing to the technical challenges presented by the extreme environmental conditions. The permanent ice sheet and short summer field season dramatically reduce our ability to study topics such as global climate change, bio-diversity, and life in extreme environments. Many critical oceanographic observations cannot be made with available sea-going instrumentation. The baseline oceanographic dataset for the Arctic is very weak, which, if unmitigated, will result in a "blind spot" during what appears to be a time of rapid change at high latitudes. The need for improved scientific access has motivated researchers at a variety of national and international institutions to consider novel instrumentation and techniques for making observations in the Arctic Ocean. This report summarizes the results of an NSF-sponsored Arctic Instrumentation workshop held at MBARI in Moss Landing, CA from Oct. 16-18, 2002, which was convened on the premise that a variety of recent technological developments, ranging from cabled ocean observatories to underwater robotics, have the potential to revolutionize the way that observations are made in the Arctic. Without new instrumentation, we will never understand the Arctic at a level commensurate with its scientific importance.

Arctic scientists with broad experience in all aspects of Arctic logistics participated in the discussions. Attendees included scientists and engineers from academic institutions and private industry within the U.S., representatives from the U.S. Coast Guard icebreaker corps, NSF program managers, and Arctic scientists from Northern Europe. The workshop incorporated a mixture of keynote and poster presentations, working groups, and plenary discussions, out of which emerged a strong consensus regarding the necessity of Arctic instrumentation development and the types of instruments and observing systems that would enable a wide range of multi-disciplinary science.

Ability to make oceanographic observations in the Arctic is severely limited by the technical and logistical challenges associated with working within and through the ice pack at high-latitudes. Many "standard" observational techniques employed in the open ocean are impossible, impractical, or high-risk in the Arctic (Table 1). As a result, our understanding of Arctic oceanographic processes in most disciplines is primitive compared to the open ocean. Five over-arching technical challenges that prevent or seriously limit many types of Arctic research were identified. These are; (1) wire and cable management (including towed, over-the-side and fixed methods) within a dynamic ice pack, (2) recovery of free-vehicles within ice-covered waters, (3) under-ice navigation at high latitudes, (4) remote monitoring of the water column and seafloor, and (5) maintaining an observational presence outside of the short (summer) Arctic field season. A variety of strategies were discussed for solving these technical challenges, and ultimately it became apparent that these issues could not be considered individually, but rather require a coherent vision for the future of Arctic research and instrumentation

In response to this imperative, workshop participants were asked to develop visions for Arctic research in the next two decades. Three basic approaches to Arctic research are envisioned in the future, each with its own specific technical and logistical requirements. Firstly, the expeditionary format for Arctic research that is prevalent today is envisioned to play an important role in the future, but with important enhancements to the scientific instrumentation deployed from the various expeditionary platforms (icebreakers in particular, but also airplanes, including Unpiloted Aerial Vehicles and Remotely Piloted Aerial Vehicles, and submarines). Secondly, a basin-wide, mobile network of ice-mounted buoys and free-vehicles (i.e., gliders, drifters, and Autonomous Underwater Vehicles (AUVs)) is envisioned to carry out physical, chemical, and biological oceanographic measurements in support of climate studies. And thirdly, cabled oceanographic observatories with real-time data and power connections to shore are envisioned to enable a year round observational presence and permit high-resolution climate and synoptic regional process studies.

Capability In USA	Ice-free Oceans	Ice-covered Oceans
Ship Operations	Four season operations provided by 7 large, 8 ocean, and 8 regional class ships in UNOLS. Operational schedules are usually constructed to allow operations during weather windows. However, when necessary, operations in difficult weather conditions are carried out – e.g. cruises to the Labrador Sea in winter.	US Icebreaker access to Arctic basin provided by USCG. Three ships available, of which one is dedicated to science and two are aging and require frequent repair. Operations typically limited to late spring, summer, and early fall. As fall proceeds, penetration deep into ice by a single ship is not possible. Navy submarines (Sturgeon class) were made available via SCICEX program for science use through the 1990s. Six cruises were dedicated to conducting unclassified science. Subsequent cruises by Los Angeles (SSN688) and Seawolf (SSN21) Class submarines have been made, and are expected to continue as "accommodation" cruises (limited scope, no non-Navy staff onboard). Dedicated science cruises are no longer available due to operational demands on the declining number of available submarines.
Submersibles	ALVIN provides access to water depths to 4500m, approximately 200 dives/year as part of National Facility. Shallow submarines operated by Harbor Branch.	Not used under ice.
Deep-Water ROV	Available at a number of institutions. JASON II (6000 m rated) operated by National Deep Submergence Facility at WHOI. MBARI makes Tiburon (4500 m rated) and Ventana (1800 m capable) available via NURP.	Not currently operated in the ice. Tethers cannot be protected, and icebreakers cannot station keep in ice.
Moorings	Routinely deployed and recovered, including some with surface expressions allow real-time communications with subsea instrumentation	Can be deployed, but recovery is extremely difficult. Surface expressions not used as they expose mooring to damage by ice cover.
Benthic Instrumention	Routinely deployed and recovered.	Can be deployed, but recovery is extremely difficult.

Table 1. Logistics and Scientific Access of Arctic vs. Open Oceans.

Concerted efforts to develop and implement the technology in support of these observational scenarios will dramatically expand our understanding of the biological, physical, chemical, and geological processes in the Arctic Basin. It is clear, however, that these visions cannot be realized with the present funding levels available for Arctic science and instrumentation. Our ability to observe the Arctic Ocean and its seafloor has scarcely improved over the past two decades, a stagnation that is due at least in part to a dramatic decrease in funding for Arctic research from the Office of Naval Research. Historically, the ONR High Latitudes program provided critical funding and infrastructure for Arctic research, but over the past decade funding levels have decreased dramatically. Now that the ONR High Latitude program has been eliminated, NSF is the primary funding organization for Arctic Research, but funding levels with the NSF Office of Polar Programs are still too low to simultaneously fund the scientific investigations, instrument development, and the infrastructure required to meet our national goals. The long-term decline in total US funds for Arctic research has also reduced the pool of engineers and technicians in the U.S. with Arctic experience to a dangerously low level. A significant fraction of researchers with Arctic field expertise in the U.S. are either near retirement or already retired, and critical field capabilities are being lost. The opportunity to train a new generation of Arctic scientists is slipping away.

The workshop concluded with a set of general and specific recommendations to enable achievement of national science goals in the Arctic. Key recommendations include;

- Develop a coherent vision for the future of Arctic research and instrumentation in three basic approaches to Arctic research, expeditionary; a basin-wide, mobile network of ice-mounted buoys and free-vehicles (i.e., gliders, drifters, AUVs); and a cabled oceanographic observatory.
- Initiate a strong, focused program to educate and train Arctic scientists and engineering professionals.
- Undertake a concerted engineering effort, based on available and fairly mature technology to apply acoustic navigation techniques to AUV operations in the Arctic.
- Develop hybrid ROV-AUVs with existing technology.
- Solve the problem of acquiring seismic data in ice-covered waters including improved methods for towing equipment as well as alternative solutions such as free-vehicle receivers and sources.
- Development of communication protocols and physical interfaces for basin-scale networks.
- Coordination of planning and system prototyping in conjunction with ongoing developments in the Arctic (e.g. SEARCH) and elsewhere in the oceanographic community (e.g. NEPTUNE).
- Determination of the degree of central coordination needed.
- Develop and install an Arctic Regional Moored System (ARMS) in conjunction with the Barrow Arctic Science Center, a test bed for cabled mooring technology under ice, moored off of Barrow, Alaska, including the required Information and Communication Technology (ICT) for global, high data rate, wide bandwidth capability
- To identify and pursue integrated mechanisms for securing a long-term source of funding for Arctic instrumentation development, including the NSF Major Research Instrumentation and Science and Technology Center programs, the ONR Physical Oceanography Program, the NOAA CCRI, and the NASA EOS program. Cooperation between federal agencies should be explored.
- To form an *ad hoc* steering committee to advocate on behalf of the Arctic science and technology community, to raise awareness regarding Arctic instrumentation issues in national panels and forums such as DEOS, AICC, and CIRPAS, and to coordinate planning efforts and possible follow-up meetings in the short-term.

Scientific Motivation for Arctic Instrumentation

Scientific motivation for oceanographic observations in the Arctic Ocean has increased significantly in both the earth and life sciences over the past several years. For example, we have recently observed evidence that the Arctic region is particularly sensitive to global climate change (e.g., Macdonald, 1996; Rothrock et al., 1999, Morison et al., 2000, Sereze et al., 2003), and that the Gakkel Ridge in the eastern Arctic Basin hosts some of the most unique and enigmatic deep-sea hydrothermal systems on Earth (Edmonds et al., 2003). Comprehensive discussions of the complete spectrum of present day scientific objectives in the Arctic are provided in numerous documents (e.g., Moritz and Perovich, 1996; Grebmeier et al., 1998; 2001; Aagaard et al, 1999; SEARCH SSC, 2001; Cooper, 2003). We do not attempt to repeat nor summarize the contents of those documents here, but rather we discuss a few examples that are particularly relevant to Arctic instrumentation development, as summarized in Table 2.

Key Arctic Science Issues	**Critical Observations**
1. Arctic Ocean Ecology	• Spatial distribution of biological and chemical components on local, regional, and basin scales. • Temporal variability of organisms on daily, seasonal, and decadal scales. • Amosphere - ice - ocean chemical transformations and exchanges. • Basic rate processes (production, reproduction/growth, grazing, regeneration, flux, uptake, respiration)
2. Hydrothermal Processes on the Gakkel Ridge: A) Nature of Fluid Circulation in Ultra-Slow Spread Crust B) Genetics and Biogeography of Chemosynthetic, Vent Field-Endemic Fauna	• Detection, localization, and mapping of discrete vent fields. • Quantify distribution of vent fields along rise axis. • Samples of exit fluids and hydrothermal minerals. • Images of vent field biological communities • Samples of major vent field fauna
3. Geological History of the Arctic Basin and Exclusive Economic Zone Claims	• Ocean drilling in the ice pack. • Multi-channel seismic imaging. • High-resolution bathymetry. • Under-ice side-scan, gravity, and magnetics data.
4. Climate Change	• Detailed hydrography at local, regional, and basin scales. • Basin-scale acoustic travel time measurements. • Sea-level change. • Temporal and spatial variability of ice thickness. • Ocean currents at all depths and at all length scales. •Primary and secondary production

Table 2. Summary of Key Arctic Science Issues Requiring New Instrumentation or Methods of Observation.

Life Sciences

Biological and chemical oceanographic processes in the Arctic Ocean are profoundly affected by the dramatic seasonal variations in temperature, light, and ice cover that characterize this region (Figure 1). These processes are critical to successful modeling and prediction of the Arctic response to climate variability because they transform material through production, repackaging, and regeneration, and modulate fluxes between different regions of the water column.

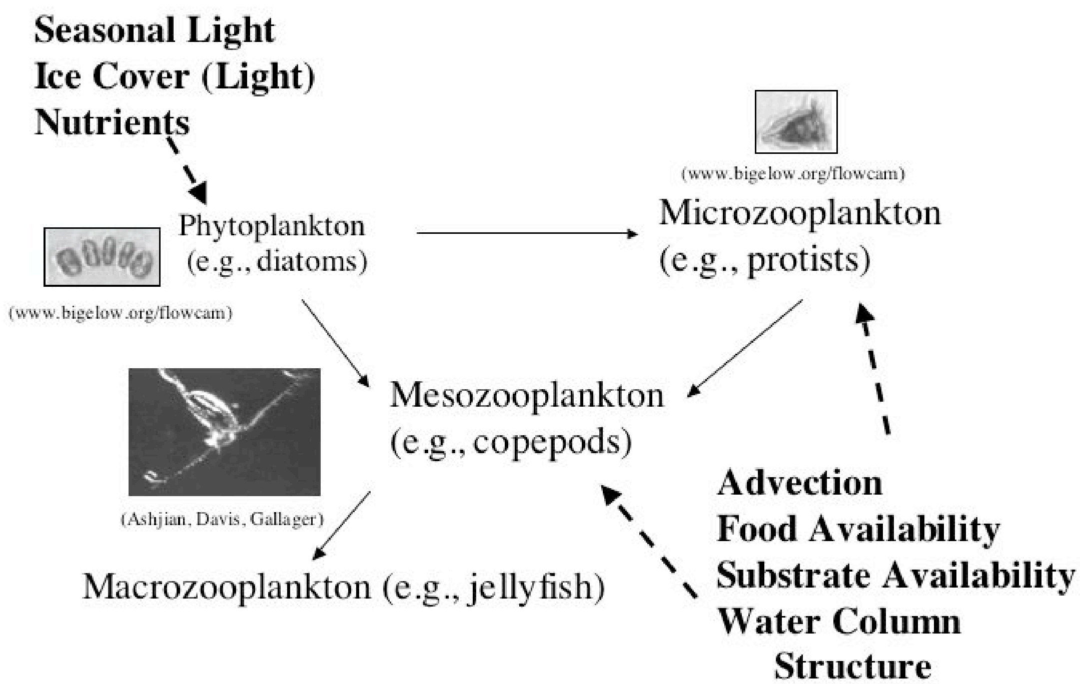

Figure 1. Planktonic food web (solid arrows) and some biological, chemical, and physical forcing mechanisms (dashed arrows).

Unfortunately, despite years of interest and study, our understanding of biological and chemical processes in the Arctic Ocean remains rudimentary in most cases. We do not have the quantity nor quality of data required for ecosystem models, particularly if their impact on climate change is to be evaluated. Some key data types that are presently unavailable include;

- Spatial variability in abundance or concentration, on local, regional, and basin scales
- Vertical distributions of both biotic and chemical components in association with changes in hydrography, especially observations made at high resolution temporal and spatial scales
- Temporal variability in abundance and distribution of organisms and transformations of organic material on daily, seasonal, and decadal scales
- Basic rate processes (production, reproduction/growth, grazing, regeneration, flux, uptake, respiration)

- Unique deep sea environments (e.g., vents, deep sea)
- The food web and microbial loop
- Impact of predators (macrozooplankton, macrobenthos, fish, jellies, marine mammals)
- Life cycles and the influence of the extreme environment on these cycles
- The ice ecosystem
- Amosphere - ice - ocean chemical transformations and exchanges (e.g., dimethyl sulfide production and transformation)
- Distribution and abundance of organisms on the upper (sea ice underside) and lower (benthos) substrates of the Arctic marine environment

Biological and chemical oceanography has traditionally been conducted from platforms such as ships or ice camps rather than from moorings or buoys, although the use of moored instrumentation is increasing. The tools used to conduct these studies include net systems, water collection using Nisken bottles, and some limited instrumentation such as fluorometers and transmissometers. Most ship-based studies have been conducted during the summer months when access to the Arctic is easiest (but NOT easy) because of the reduced ice cover and more favorable environmental conditions (e.g., temperature, light, wind). This period coincides also with the period of greatest biological and chemical activity. Ice camps have offered another platform from which measurement of biological and chemical parameters may be obtained. The advantage to ice camps is that greater seasonal coverage can be obtained if the ice camp is established through the year. In one early study, distributions of zooplankton were obtained from a submersible that transited the Arctic Ocean (Grice, 1962).

Traditional platforms are not only limited in time, but also in space (with the exception of submarines). In all cases, ships, ice camps, and submarines limit the types of process studies that can be conducted because of the lack of appropriate laboratories or incubation facilities that provide ambient light and temperature conditions. The water column also has been difficult to access both from ships and at ice camps because of the ice cover. On ships, rapidly moving ice can close sampling holes and catch cables. Just making an opening in the ice can be difficult. At ice camps, sampling holes must be maintained using heat or circulation to keep them open. Shifting ice floes or melting ice can imperil the ice camp itself. Although ships, submarines, and ice camps are important and essential to Arctic oceanography, particularly for process studies, it is clear that our understanding will continue to be limited if we utilize these platforms alone.

In addition to unique water column and benthic biological environments, the Eastern Arctic Basin contains the Gakkel Ridge, the ultra-slow spreading end-member in the global mid-ocean ridge system. The geological and chemical characteristics of hydrothermal systems hosted on the Gakkel Ridge are not well-understood, and the biological characteristics of these systems are completely unknown. We are only beginning to understand how basic processes such as deformation, crustal accretion, and hydrothermal circulation are accommodated on the Gakkel Ridge, but the results of recent work make it clear that many geologic processes have a completely different character in ultra-slow spreading environments (e.g., Dick et al., 2003; Edmonds et al., 2003; Michael et al., 2003). Many scientists believe that for these reasons the hydrothermal systems on the Gakkel Ridge will provide a unique environment for vent-endemic, chemosynthetic fauna. In addition, vent fields in the Arctic Basin may well be hydrographically isolated from the rest of the world’s oceans owing to the limited flux that occurs across shallow sills. This also has important implications for the evolution and ecology of resident chemosynthetic fauna. Vent-endemic fauna have been characterized in all of the major ocean basins except for the Arctic (Figure 2), and therefore we do not know how vent fauna on the Gakkel Ridge relate to species found in the nearby Atlantic and Pacific basins. Nor do we know how Arctic vent fauna may have evolved in an end-member, hydrographically isolated Arctic ridge system. Characterization of vent fauna on the Gakkel Ridge is the last major piece of the global biogeographic puzzle.

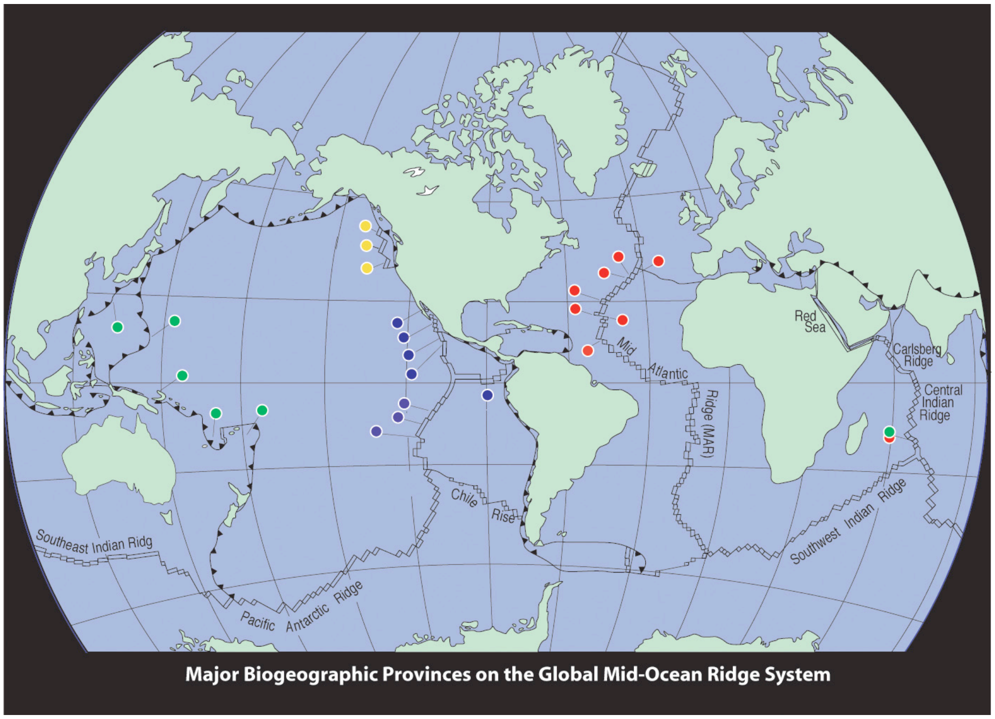

Figure 2. Map of the six recognized hydrothermal vent biogeographic provinces and major mid-ocean ridges. Provinces: green, western Pacific; yellow, northeast Pacific; blue, East Pacific Rise; red, Mid-Atlantic Ridge; orange, Indian Ocean.

At present we cannot study biological communities at vent fields in the Arctic Basin because we do not have the technical ability to collect images or obtain specimen samples beneath the ice cap. It is too dangerous to operate manned submersibles within an ice-covered basin, and tether management issues within the ice also preclude the use of present day ROVs. Technological developments to enable precise positioning of deep-sea imaging and sampling systems under-ice is required to characterize deep-sea vents and hydrothermal circulation on the Gakkel Ridge, and the Arctic Basin, in general.

Earth Sciences

The Arctic Ocean can be divided into two distinct basins, the Eurasian and the Amerasian, of almost independent origin and development. These two basins, both of which are covered in ice most of the year, offer distinct and important opportunities for study in geology and geophysics.

Eurasian Basin

Northward propagation of the Mid-Atlantic Ridge created the Eurasian basin by separating the Lomonosov Ridge from the Barents Shelf, starting about 60 Ma. This feature, the Gakkel Ridge, has throughout most of its history spread at a very slow rate. As a result, it is unusually deep and rugged, and seafloor spreading on the Gakkel Ridge may include a substantial degree of upper mantle exhumation as opposed to pure volcanic accretion. This represents a sharp contrast to other mid-ocean ridges, making it a natural laboratory to study essentially "pure" extension of oceanic crust and the exhumation of mantle material from the Earth's interior.

The recent AMORE cruise on the USCG icebreaker Healy did numerous dredges and detailed seafloor mapping of the axis, building on the more extensive surveys done from USS Hawkbill during SCICEX 1998 and 1999. These cruises were very successful, but a significant fraction of the ridge remains to be studied, in particular the slowest spreading portion at the far eastern end where the ridge disappears beneath the continental slope of the Laptev Sea and is lost in a zone of extensional grabens on the Laptev Shelf. CTD profiles and hydrocasts were conducted during the AMORE cruise, and these data provide an intriguing perspective on hydrothermal processes on the Gakkel Ridge (Figure 3). The large number of plumes detected demonstrates that hydrothermal convection on the Gakkel Ridge is much more prevalent than expected, but vent fields could not be located and imaged on the seafloor because of the primitive survey techniques that were employed of necessity (passive camera tows from the icebreaker). Unraveling the characteristics of these unique and remote hydrothermal systems clearly requires new methods to allow for comprehensive mapping of hydrothermal plumes in the water column beneath the ice, as well as fine-scale seafloor mapping and imaging.

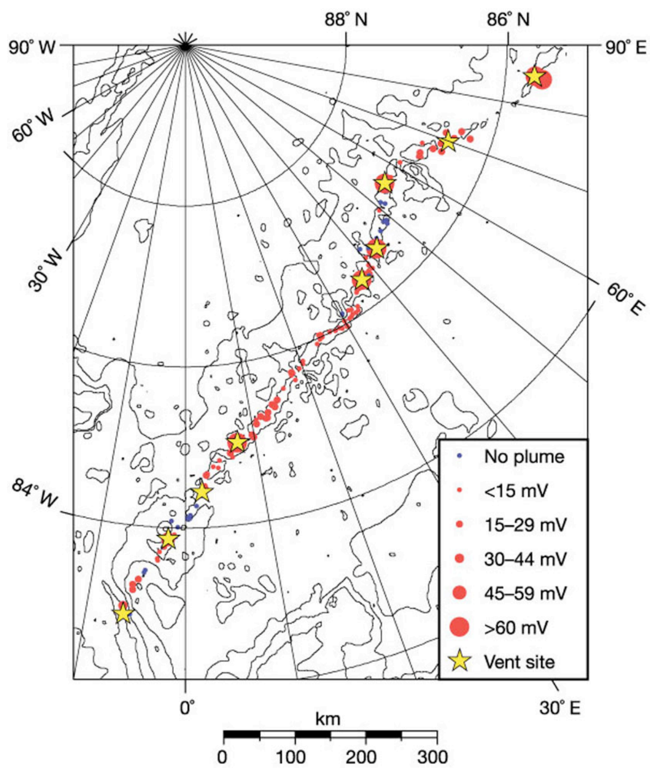

Figure 3. Map of hydrothermal plume surveys carried out during the AMORE cruise (Edmonds et al., 2003). Red dots indicate the size of the optical backscatter anomaly in millivolts above background, and yellow stars represent the approximate location of inferred distinct vent fields on the seafloor.

The Lomonosov Ridge is a long sliver of continental crust that was split from the Barents Shelf sixty million years ago, similar to the way Baja California is presently being split from the California margin. It was formed as a passive margin during the formation of the Amerasian Basin, and represents the transition between the two basins. Beneath a thick pelagic cap of sediments is a series of horst and grabens created during the formation of both the Amerasian and Eurasian Basin. Working out the internal structure of the Lomonosov Ridge and its margins will fill out the history of both basins.

Amerasian Basin

Over the last fifty years, we have come to understand the continents by mapping and understanding the history of the adjacent oceans. In contrast, the history of the Amerasian Basin has been pieced together from the geology of North America and Asia. From this it is clear that the Amerasian basin was formed in the Mesozoic, primarily the Cretaceous, but in the absence of active or universally recognized fossil plate boundaries, it is not possible to put this basin in context of the other adjacent geologic provinces (eg. the Brooks Range) or the global tectonics of the time.

Several discrete features must be understood to provide a clear understanding of the geologic history of the Amerasian Basin. The Canada Basin is floored by oceanic crust and buried deeply below ten to twelve kilometers of turbidites. Magnetic anomalies have not revealed the history of seafloor spreading that created the basin, though there are indications of a ridge axis extending north out of the MacKenzie Delta. The Chukchi Borderland is a large, high-standing plateau, variously subdivided by extensional grabens. The sediments dredged from the Northwind Ridge, the steep escarpment on the eastern edge, are Permian redbeds, which can be correlated to similar sediments from the Canadian Arctic Archipelago. The plate boundaries that conducted this plateau across the Canada Basin are not in evidence. The Alpha-Mendeleev Ridge extends across the Amerasian Basin. From data collected almost entirely over the Alpha Ridge, it appears to be an oceanic plateau, perhaps formed by active volcanism during transit of the Arctic Oceanic lithosphere over the Iceland hotspot. While the Alpha and Mendeleev Ridges are typically linked as a single feature, it is not clear that they share a common origin. Further study of both features is needed to build the history of the Amerasian Basin.

Ocean Drilling

The history of the Arctic Ocean and climate is preserved in the sediments draped over the bathymetric highs and filling the bathymetric lows of the Arctic Ocean. Very little of this stratigraphic record has been sampled by the various programs in the Arctic Ocean. The first scientific drilling leg appears likely to drill through the pelagic section atop Lomonosov Ridge in 2004, collecting a sedimentary record to complement the ice cores recovered from the Greenland ice sheet and high-latitude sedimentary records from the North Atlantic. Once this sampling is completed, further scientific drilling programs are likely to focus on the Arctic, building on what will be learned from the sediments recovered from the Lomonosov Ridge. Further scientific drilling will require site surveys. Data collected for other projects can be used in support of scientific drilling. Surveys can also be executed for the sole purpose of supporting scientific drilling. There is a strong connection between ocean drilling and ocean observatories, for instance ocean boreholes can be and have been used to implant ocean bottom seismometers or other instruments. A workshop on linkages between the ocean observatory initiative and the integrated ocean drilling program is scheduled for July 2003.

Technical Limitations

In order to obtain geological and geophysical characterization of the Eurasian and Amerasian Basins it is necessary to develop instrumentation and methods for employing standard open ocean survey techniques in ice-covered bodies of water. Specific examples include towing of seismic sources and streamers, acquisition of high-resolution bathymetric, side-scan, gravity, and magnetics data. Development of techniques and instrumentation to enable or improve these types of surveys is required to allow for geological characterization of the Arctic Basin, to support an extended Arctic EEZ claim, and to support ocean drilling.

Arctic Ocean Circulation

Environmental systems are inherently dynamic. Climate variability, bioproductivity, sea ice conditions, bottom sediments, bird, fish, biodiversity, and all other parameters, processes, and relationships significantly depend on the ocean and sea ice dynamics. The dynamics of the Arctic Ocean are a natural indicator of Arctic processes at synoptic to millennium time scales and we need to explore the dynamics of the Arctic Ocean as part of an interacting oceanic, cryospheric, biologic, and geologic system in space and time.

The surface circulation of the Arctic Ocean (sea ice drift) during 1979—present and its variability at seasonal and interannual time scales is more or less known due to information obtained from drifting stations, surface ice buoys, and satellites. Seasonal and interannual variability of this drift is dominated by the anticyclonic circulation, which sometimes occupies nearly the entire basin. Figure 4 shows variability of the Arctic Ocean wind-driven surface circulation (Proshutinsky and Johnson, 1997). But the depth to which this surface circulation extends beneath the ice is not known (Jones et al, 1998).

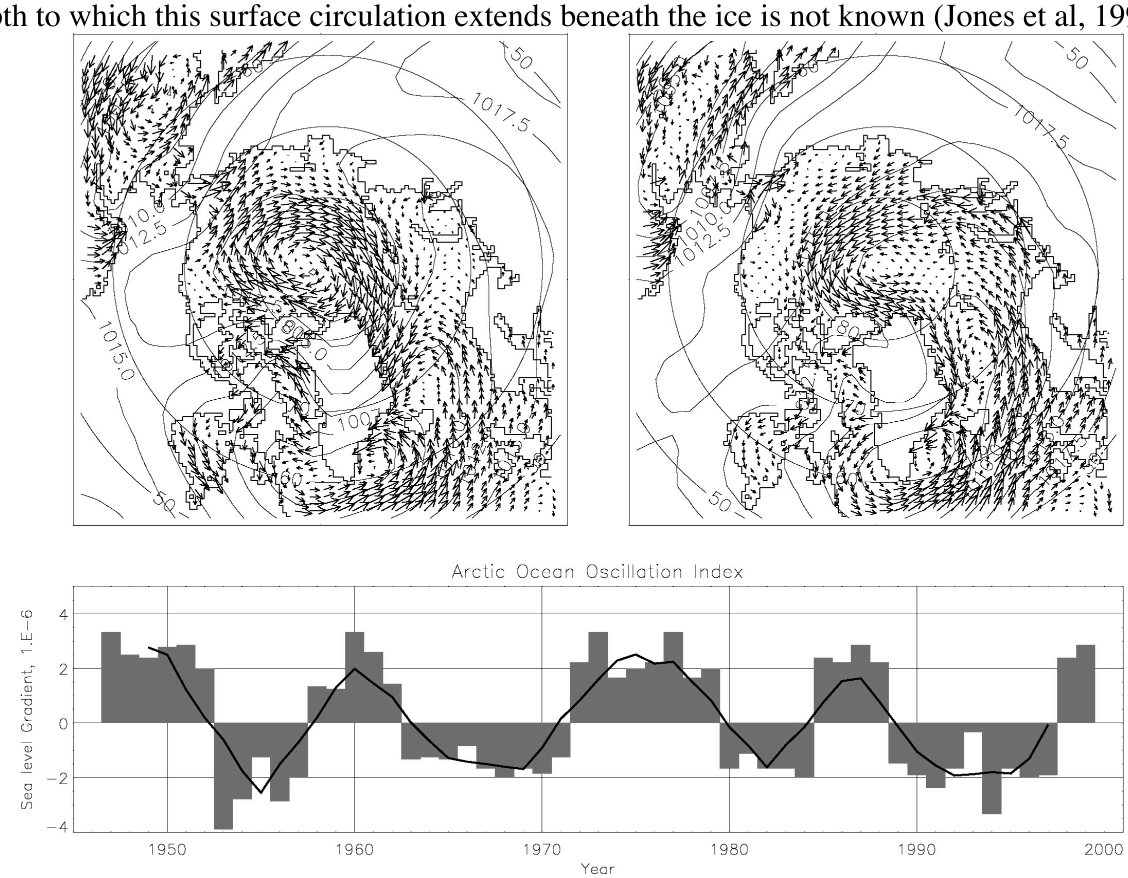

Figure 4. Upper panels: Typical annual wind-driven sea ice and surface water circulation (arrows) and sea level atmospheric pressure (hPa) distribution during anticyclonic (left) and cyclonic (right) circulation regimes. The bottom panel shows the time series of the sea level gradients (Arctic Ocean Oscillation index) simulated using a 2-D coupled ice-ocean model.

In the deeper layers, Coachman and Barnes (1963) suggested a cyclonic circulation for the Atlantic waters but Rudels et al. (1994) have shown a pattern where intermediate Atlantic Water circulates in several cyclonic gyres in each basin. There are no direct observations of the ocean currents in the central Arctic and their vertical and horizontal structure, seasonal, interannual, decadal and longer period variability are unknown.

The principal meso- to small-scale dynamical features of the Arctic Ocean are baroclinic eddies. New instruments and techniques are needed to investigate eddy generation, eddy lifetimes, and the interaction of eddies with the large-scale circulation. The Arctic Ice Dynamics Joint Experiment (AIDJEX) provided the first clear evidence that isolated baroclinic eddies exist in the western Arctic Ocean (Manley and Hunkins, 1985). More than 130 eddy encounters were reported from the AIDJEX ice camp observations. Of particular interest was the rate of encounter (2 eddies per 100 km of ice drift) which indicated that the standing population of eddies was large. The eddies were estimated to be 5-10 km in radius and were found predominantly within in the cold halocline. Several other eddy encounters have been reported since AIDJEX (D'Asaro, 1988; Padman et al., 1990; Muench et al., 2000), but the available information is not sufficient to unambiguously determine their source waters, generation mechanisms, or lifetimes.

Because the eddy core waters undergo only gradual exchange with their environment (eddy decay times may be many years), they represent isolated "packets" of source water with the attendant hydrographic, biological, and chemical signatures. The hydrographic and (limited) geochemical evidence from eddy cores indicate that western Arctic eddies have their source on the surrounding shelf seas. Thus, eddies may play an important role in “ventilating” the Arctic halocline by transporting dense water created on the shelves into the basin (a principal source of the cold, relatively saline water of the halocline is presumed to be the Arctic shelf seas, where brine enriched water with temperature near the freezing point is created during ice formation). Estimates of the total dense water production necessary to maintain the halocline vary from about 1 Sv (Bjork, 1989) to 2.5 Sv (Aagaard et al., 1981), and estimates of production on the Arctic shelves range from 0.2 Sv (Winsor and Bjork, 2000) to 1.2 Sv (Cavalieri and Martin, 1994). The uncertainties in these estimates leave room for debate about the importance of contributions from Arctic shelves to the halocline. Also unresolved is how shelf water is transported to the central basins and what fraction of this transport is by eddies.

Improved understanding of eddy source regions and the age of eddies in the basin would allow estimates of the eddy contribution to the shelf-basin exchange of dense water, and provide an alternative estimate of the shelf water contribution to the halocline. We believe that further progress can be made through improved knowledge of biogeochemical properties within the eddies and radioisotope dating of eddy core waters.

Climate Studies

It has recently become apparent that the Arctic is experiencing significant changes in the atmosphere, land, and ocean, and that these changes are connected to climate change in the Northern Hemisphere. Climate change in the Arctic is believed to be more rapid and to precede changes at lower latitudes (e.g., Manabe et al., 1991; Rind et al., 1995), and thus the Arctic is perhaps the most important natural laboratory for understanding and predicting future climate change on a global scale. Appreciation for the importance of the Arctic in climate research is central to the interdisciplinary Arctic Systems Science Program of the National Science Foundation and has led to the establishment of NSF-sponsored programs such as SEARCH a long-term program of observation, analysis, and modeling in the Arctic Basin, and the Western Arctic Shelf Basin Interactions (SBI) program focusing on the impact of climate change on exchanges between the shelf and basin.

There are at least five key physical parameters of the Arctic Ocean whose monitoring is crucial for the understanding of ocean's variability and its influence on the global climate. These parameters are: freshwater content, sea ice volume (thickness and extent), oceanic heat content, circulation, and sea level. It is common understanding now that the recent history of the Arctic is characterized by: the significant change in circulation; the substantial increase in heat content; the descending trend in summer ice cover extent and in ice thickness; the increase in rate of sea level rise; and the changes in fresh water flux from the Arctic Ocean (The Great Salinity Anomaly). However, interpretation of these trends is uncertain because observations in the Arctic Ocean are scarce and there are huge gaps in the data in space and time.

Heat and Freshwater Content

Melting of the Arctic ice pack appears to be the source of major fresh water anomalies that intermittently appear in the subpolar North Atlantic. These anomalies cause profound changes in deep convection, water mass modification, and possibly the meridional overturning circulation. Thus the freshwater and heat content of the Arctic Ocean are very important variables for understanding the role of the Arctic in climate variability. They are "integral" indices characterizing ability of the Arctic Ocean to warm up the Arctic atmosphere or to provide substantial freshening of the North Atlantic and to shutdown overturning circulation. In order to estimate freshwater and heat content good information about water temperature and salinity in the ocean is needed. While the availability of declassified Russian data and an improvement in icebreaker access to the Arctic has recently improved understanding of Arctic Ocean hydrography, the Arctic hydrographic database is nevertheless extremely sparse in temporal and spatial coverage.

Sea Level Variability

Unlike most other manifestations of climate change, sea level rise (SLR) is already a problem in the Arctic (ARCUS, 1997; Shaw et al., 1998; Brown and Solomon, 2000; Forman and Johnson, 1998; IASC, LOIRA, 2000). Many scientists and engineers expect the effects of arctic warming and SLR to be profound and costly along the Arctic Ocean (AO) coasts. But what is the rate of SLR in the Arctic Ocean? This question is very practical but its solution is a complex scientific problem because sea level change is the net result of many individual effects related to all dynamic and thermodynamic terrestrial, oceanic, atmospheric, and cryospheric processes. About 60 tide-gauge stations in the Siberian Seas recorded the sea level changes from the 1950s through 1990s. Preliminary analysis shows that over this 40-year period, most of these stations have a positive trend in SL change (Proshutinsky et al.,2001). But what are the changes in sea level heights in the central parts of the Arctic Ocean? How do they reflect synoptic, seasonal, and annual scales of the Arctic Ocean dynamics? What is a correlation among sea level variations along coastline and in the open ocean covered by drifting sea ice? Unfortunately, many of the Russian tide gauge stations are no longer in operation. As a result, the quantity of quality of data available to evaluate SLR is degrading.

Three Visions for Arctic Research in the Future

The technical challenges confronting scientists in the Arctic cut across disciplines. Many scientists with completely unrelated and separate research interests are being blocked by the same technical challenges imposed by Arctic environmental conditions. The five most common technical challenges across all disciplines are; (1) wire and cable management (including towed, over-the-side and fixed methods) within a dynamic ice pack, (2) recovery of free-vehicles within ice-covered waters, (3) long- and short-range under-ice navigation at high latitudes, (4) remote monitoring of the water column and seafloor, and (5) maintaining an observational presence outside of the short (summer) Arctic field season. Solutions to these challenges will enable science across all Arctic disciplines.

As discussions at the workshop progressed it became apparent that three distinct formats for scientific investigation are envisioned in the future; expeditionary formats, basin-scale networks of mobile (e.g., gliders, AUVs) and fixed (e.g., buoys) sensor platforms, and cabled oceanographic observatories with real-time data and power connections to land. The second half of the workshop focused on forming visions for the future of Arctic science in each of these three formats.

Expeditionary Science

The scientific achievements of Arctic expeditions are limited by logistical constraints and by the technical difficulties associated with employing traditional open-ocean instrumentation within the ice pack and at high latitudes. There are three principle technical challenges; wire and tether management through the ice, free-vehicle recovery through the ice, and underwater navigation at high latitudes.

A variety of powerful and widely used survey methods require lowering or towing of tethers and cables into the water column. Examples include CTD casts, ROV operations, submarine surveys and multi-channel seismic surveys. While icebreakers can open pools within the ice pack for short periods of time, the ice pack can quickly load cables to failure, resulting in complete loss of the instrument system. Scientific capabilities in the Arctic would be greatly improved if innovative approaches could be found to solve the cable management issues associated with working in the ice. The use of moon pools may be beneficial in this regard, but is not a foolproof solution since ice blocks periodically scrape across the underside of icebreakers, and under the right conditions small chunks of broken ice tend to fill the moon pool.

Presently there are no obvious solutions to over the side cable issues in the ice pack, but autonomous vehicles are increasingly capable of replicating and in some cases surpassing the survey capabilities of tethered systems. Small-medium sized AUVs have demonstrated the capability to return high quality bathymetric, geophysical, and optical data types from deep ocean basins, and the scientific capability of Arctic expeditions would be substantially improved if these vehicles could be reliably used within the ice pack. The primary obstacles to this goal are the difficulties associated with vehicle recovery through the ice and high-latitude underwater navigation. The technology to solve these challenges is available and fairly mature (Figure 5), but a concerted engineering effort to apply acoustic navigation techniques to AUV operations in the Arctic is required.

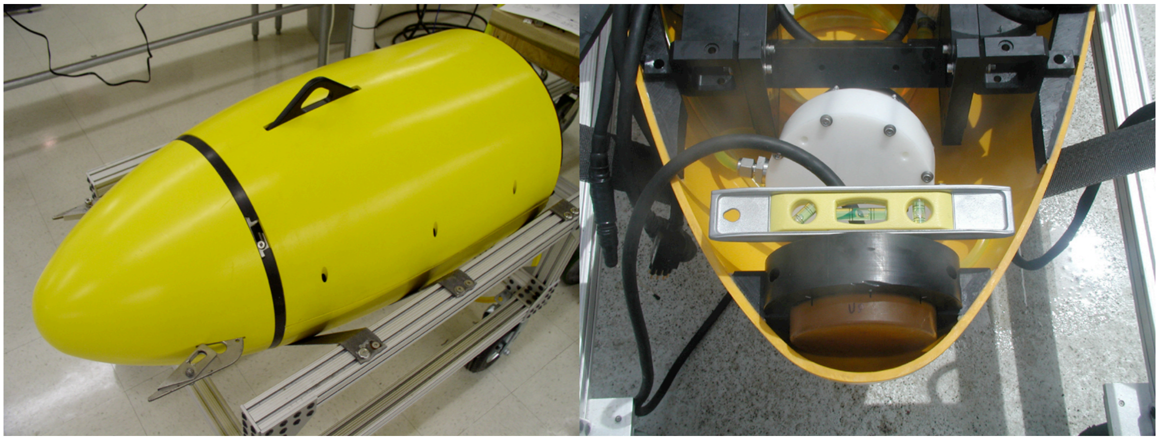

Figure 5. Nose cone detail of APOGEE AUV, and AUV specifically designed for under-ice operation. Left panel shows nose cone with side hooks for latching to a trawl wire suspended from an icebreaker or hole in the ice. Right panel shows acoustic homing transducer inside nose cone that allows the vehicle to determine the azimuth and bearing of an acoustic beacon affixed to a trawl wire for vehicle recovery through the ice.

While AUVs have considerable potential to enable multi-disciplinary surveys and mapping in the ice-covered Arctic, it is unlikely they will be able to completely replace the functionality of remotely operated cabled systems (e.g., ROVs) for retrieving biological and fluid samples from the deep Arctic ocean. Hybrid ROV-AUVs may provide a means to enable sampling in the ice-covered Arctic. These vehicles would be remotely operated for sample retrieval but would be capable of releasing their tether and navigating autonomously back to the tending vessel in the event the tether is severed by the ice. Single fiber fiber-optic cables such as those used to guide torpedoes appear to be a promising technology for this purpose. All of the essential technology exists today, but no hybrid ROV-AUVs have been developed to date.

Seismic surveys in support of ocean drilling, oil and gas exploration, and gas hydrate research require towing of seismic sources and streamers, which is problematic in ice-covered waters. Streamers and air-gun arrays commonly become entangled when they are deployed within the ice pack, and as a result seismic surveys in the Arctic are fraught with difficulty. Nevertheless seismic data is critical for imaging the subsurface structure of the Arctic Basin, which is essential for developing geological models that will be used to guide future ocean drilling initiatives, gas hydrate research, and petroleum exploration. In lower latitiudes, high resolution descriptions of biological, physical, and chemical oceanographic distributions (e.g., hydrography, fluorescence, oxygen, plankton) routinely are obtained using towed, vertically profiling vehicles such as the SeaSoar. Such surveys are very difficult in ice-covered seas. Creative solutions to solve the problem of acquiring seismic and high-resolution oceanographic data in ice-covered waters are therefore needed, including improved methods for towing equipment as well as alternative solutions such as free-vehicle receivers and sources.

Basin-Scale Observing System: Moorings, Ice-Anchored Drifters, AUVs and gliders

The charge to this working group was to consider some technical aspects of a basin-scale observing system that would include moorings, ice-anchored drifters and AUVs (Figure 6). The approach was to identify observing elements that are ready or nearly ready for implementation (short-term), to anticipate developments that would be needed and/or desired in the future (long-term), and to consider areas of potential synergy with other parts of an overall Arctic observing system.

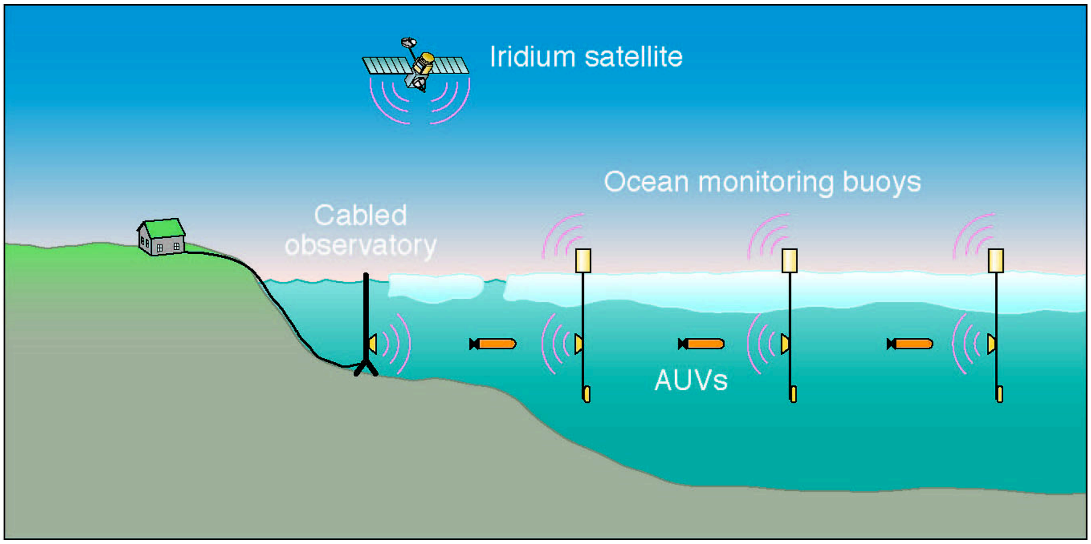

Figure 6. System schematic for a basin-scale Arctic observing system. Ice-anchored buoys and cabled observatory nodes would collect year-round data with real-time capabilities (through Iridium or Argo satellites for buoys). These fixed and drifting assets would act as navigation beacons and data transmission nodes for long-range AUVs that would run transects between nodes.

The broad goal of a basin-wide observing system was considered to be year-round access to the water column beneath the Arctic pack ice, which is presently sampled only intermittently and incompletely. Although the principal focus was on water column observations, it was recognized that remote sensing (e.g. photographic and acoustic) of sea ice from below and of the sea floor from above are important elements.

Some desired characteristics for a basin-scale observing system were:

- Year-round access to the water column beneath the ice. Monthly temporal resolution would represent a significant advance over presently available data.
- High spatial resolution, at minimum resolving basin scale processes (~200 km) and at best resolving the Arctic mesoscale (~10 km) in selected areas.
- Elements with a minimum lifetime of 1-2 years. Some elements (e.g. drifters, AUVs) would be continuously re-deployed. Others (subsurface moorings) could be in place for 3-5 years, but with access to data at intervals of months to a year.
- The ability to accommodate a variety of sensor technologies. Traditional temperature, conductivity, and velocity sensors are a given, but this must be expanded to include camera systems, nutrient sensors, tomographic sources, RAFOS sources, etc.
- A design philosophy to allow both fixed and moving elements to be used as navigational aids and communication nodes for other elements of the system.
- A standardized communication protocol to allow data transfer among observing system elements (e.g. ice-anchored drifters telemeter data from subsurface floats or AUVs).

Initial activities considered important for developing an appropriate infrastructure were:

- Development of communication protocols and physical interfaces.
- Coordination of planning and system prototyping in conjunction with ongoing developments in the Arctic (e.g. SEARCH) and elsewhere in the oceanographic community (e.g. NEPTUNE/MARS).
- Determination of the degree of central coordination needed.

Subsurface moorings

Short-term vision

- Long lifetime (3-5 years) with provisions for monthly to annual data offload (acoustically to ships or automatically via released, ice-penetrating capsules).
- Accommodation of a variety of sensor types (e.g. nutrient samplers, camera systems, acoustic sources).
- Evaluation of sensor performance and calibration/validation techniques to enable long-term deployment.
- Consideration of trade-offs between long platform life and re-occupancy rate necessary for data offload or sensor maintenance.

Long-term vision

- Development of alternate data offload techniques (e.g. docking stations).
- Integration with AUVs or gliders that shuttle between moorings (providing high horizontal resolution in selected areas).
- Use of unconventional power sources, allowing operation of more sophisticated moored sensors and the potential for recharging AUVs.
- Development of common physical interfaces and data protocols to allow virtual connections between moorings and shore stations (e.g. via AUVs shuttling between moorings and a cabled observatory).

Ice-anchored drifters

Short-term vision

- Development of small, inexpensive packages, deployable using landed aircraft, with GPS navigation, subsurface sensors, data telemetry, and lifetime of 1-2 years.
- Standardization of communication protocols for sensors on the drifter, and integration of subsurface data stream with satellite telemetry.
- Implementation of short-range (2-5 km) subsurface acoustic communication among ice drifters and between ice drifters and subsurface floats.
- Evaluate potential benefits of integration of data collection and logistics with the International Arctic Buoy Program.

Long-term vision

- Larger-volume data transfer from subsurface sensors to satellites.
- Higher-capacity power sources allowing longer lifetime and accommodation of more sophisticated sensors.
- Development of long-range (100 km), low-frequency subsurface communication for obtaining and transmitting data from autonomous elements (floats, gliders).
- Standardization of quality control and data reporting.

AUVs and gliders

Short-term vision

- Evaluation of existing vehicles for trans-Arctic missions; integrate with design studies for possible scale-down of “mini-sub” AUVs or scale-up of medium size AUVs.
- Consideration of capabilities for automated and/or real-time mission control.

Long-term vision

- Implement alternative power sources to allow long range (including) trans-Arctic missions using more compact, more easily managed vehicles.
- Implement first missions (e.g. Barrow to Spitsbergen) with goal of maintaining equivalent of SCICEX CTD transects over long term.
- Integrate sensors to allow seafloor mapping (e.g. site identification for more detailed surveys by dedicated ships and vehicles).

Cabled Oceanographic Observatories

The third part of the Arctic instrumentation triad is the cabled observatory. The Arctic Ocean is unique because of its difficult, very expensive and often dangerous working conditions for carrying out traditional expeditionary-based research, particularly if one wants to maintain a year-round presence at specific places in the Arctic Ocean. We envision a cabled undersea and under-ice network that will maintain a continuous regional to synoptic observational capability of important parameters at critical points and areas that will be available to all researchers from their desktops. Continuous fixed presence, without power constraints, and with high real-time data rate from in-situ sensors is the payoff of the cabled observatory. Figure 7 is a notional concept for a basin-wide cabled observatory network for the Arctic Ocean. This is one of many concepts for “instrumenting” the ocean to achieve the goal of synoptic, year-round, long-term monitoring.

Arrays of autonomous deep ocean moorings already exist and more extensive cabled systems are in the planning stages. NOAA maintains the Tropical Ocean Atmosphere (TAO) TRITON array of approximately 70 deep-sea moorings in the equatorial Pacific for monitoring El Nino and the PIRATA array of 12 moorings in the equatorial Atlantic (http://www.pmel.noaa.gov/tao). A comprehensive set of data are available for download from all of these moorings, including sea surface and subsurface ocean temperature, ADCP current profiles, winds and other surface met data, etc. all of which are continuously transmitted to shore via ARGOS satellite. Planning for development and installation of more capable fixed undersea networks, either cabled or with high bandwidth comm-links via satellite back to shore, with sufficient power and data bandwidth to accommodate a wide variety of multi-

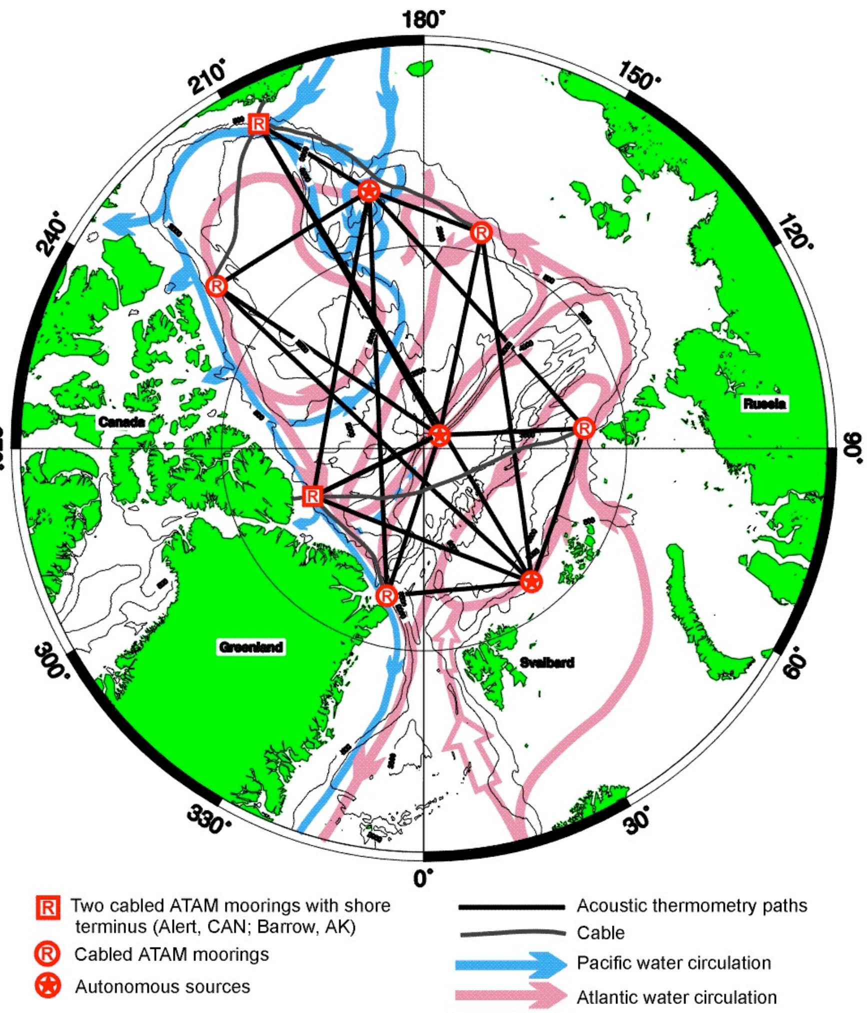

Figure 7. A notional future monitoring network for the Arctic Ocean. This network would support synoptic monitoring of Arctic Ocean temperature using acoustic measurements as well as additional oceanographic, geophysical, biological, and chemistry measurements at each of the mooring locations. This cabled network could come to shore near Alert, Canada where a slant drilled sea-shore terminus already exists and at Barrow, Alaska, where a sea-shore terminus has been proposed. Other sea-shore interfaces could be established through international participation significantly reducing cabling costs.

disciplinary sensors is currently well along within the National Science Foundation (NSF), as part of a new Ocean Observatories Initiative (OOI) with funding to come from NSF's Major Research Equipment account. Two of the most ambitious projects on the drawing boards are the NEPTUNE project (http://www.neptune.washington.edu) and the Dynamics of Earth and Oceans Systems (DEOS) (http://www.deos.org). NEPTUNE envisions laying over 3000 kms of undersea cable to wire-up the Juan de Fuca Plate off the northwest coast of the United States. This power and fiber optic backbone is planned to provide 2-20kW of power and over 1 Gb/s data capacity to each of approximately 30 nodes. Each of the nodes will be instrumented with a plethora of oceaonographic, seismic, biogeochemical, video, and acoustic sensors. The grid will include mobile platforms in the form of AUV's and bottom rovers/robots. DEOS envisions a global system of ocean bottom tethered buoys supporting a bottomed complex of scientific instrumentation similar to a NEPTUNE node. The tethered buoys would include diesel generators for continuous power and high-bandwidth satellite link to shore. While the DEOS model will not work in the Arctic Ocean with the continuous ice cover the NEPTUNE model would be ideal. Such systems as these and that shown in Figure 7 will allow researchers from many fields to harvest data from the interior of the Arctic Ocean on temporal and spatial scales not possible today with our current icebreaker, ice-mounted buoys and ice camp based research alone.

Scientific Opportunities in the Arctic with the Cabled Observatory

While cabled seafloor observatories significantly improve our ability to study oceanographic processes, in general, they offer special scientific opportunities in the Arctic because they enable observations and studies that are otherwise impossible owing to the permanent ice cover and extreme environment. Types of measurements that would be made from a cabled Arctic observatory include;

- Temperature, salinity, and water velocity (CTD, ADCP)
- Ice draft and drift (upward looking multi-beam ice-mapping sonar)
- Biological and marine chemistry such as dissolved oxygen and nutrients
- Seismometry (3-component, broadband particle motion)
- Acoustic ambient noise (e.g., ice, marine mammals, T-phase, etc.)
- Live biology samples (piped water to on-shore lab)
- Optical imaging of sea floor, water column, and under ice (e.g., biology, ice bottom morphology, sea floor sediments
- Acoustic thermometry and basin-scale acoustic tomography
- Reciprocal acoustic measurements for large scale transport and current measurements

In addition to these fundamental scientific contributions, a cabled observatory would also support mobile vehicle operations in support of a basin-scale observing system by providing;

- A base of operations for AUV's, providing power for battery charging and data download
- Navigation support for AUV's and submarines with acoustic beacons and transceivers
- A mooring base for acoustic data relay to/from AUV's, and remote autonomous moorings

Implementation Strategy

An incremental approach is envisioned to lead to the eventual establishment of one or more full-scale cabled observatories in the Arctic. The idea would be to start with a moored system off of Barrow, Alaska similar to the MARS system being implemented in Monterey Canyon off California at MBARI. This moored system, ARMS (Arctic Regional Moored System), would be a test bed for cabled mooring technology under ice, and is anticipated to cost on the order of ~$10M from 2005-7. The initiative could be started by requesting NSF OOI MRE funding for 2006. Activities would include;

- Install slant-drilled sea-shore conduit for water and cables
- Coordinate with proposed Arctic Climate Research Center in Barrow
- Replace autonomous SEARCH, SBI, CliC moorings, or other programs with cabled systems
- Integrate AUV operations
- Operational coincident with International Polar Year (IPY) 2007 (http://ipy.gsfc.nasa.gov/)

Once the ARMS is up and running, some time around 2010 international collaborators would be added along with additional regional observatories (e.g., Lincoln Sea, Svalbard), requiring a budget on the order of ~$100M+. These systems could also be extended to the ocean basins to provide full year-round observation of the Arctic Ocean and basins therein.

Appendix A – Acronyms and major programs cited in report

ADCP – Acoustic Doppler Current Profiler
AICC – Arctic Icebreaker Coordinating committee (http://www.unols.org/aicc/)
AIDJEX - Arctic Ice Dynamics Joint Experiment
AMORE – 2001 Joint US-German Arctic Mid-Ocean Ridge Expedition
APOGEE – Autonomous Polar Geophysical Explorer (http://www.whoi.edu/science/PO/arcticgroup/projects/apogee.html)
ARCSS – Arctic System Science Program (NSF, http://www.nsf.gov/od/opp/arctic/system.htm)
ARCUS – Arctic Research Consortium (http://www.arcus.org/)
ARMS - Arctic Regional Moored System
AUV – Autonomous Underwater Vehicle
CIRPAS – Center for Inter-Disciplinary Remotely Piloted Aircraft Studies (Cal Tech, Naval Postgraduate School, http://www.cirpas.net/public/home.cfm)
CTD – Conductivity, Temperature, and Depth sensor
DEOS – Dynamics of Earth and Ocean Systems (NSF planning effort, http://www.coreocean.org/Dev2Go.web?Anchor=deos_home_page&rnd=4750)
EEZ – Exclusive Economic Zone
EOS – Earth Observing System (NASA Program, http://eospso.gsfc.nasa.gov)
CCRI – Climate Change Research Initiative (http://www.climatescience.gov/about/ccri.htm)
IASC – International Arctic Science Committee (http://www.iasc.no/)
ICT – Information and Communications Technology
IPY – International Polar Year (http://dels.nas.edu/us-ipy/index.html)
LOIRA – Land-Ocean Interactions in the Russian Arctic (http://www.iasc.no/ProjectCatalogue/loira99.htm)
MARS – Monterrey Accelerated Research System (http://www.mbari.org/mars/)
MBARI – Monterrey Bay Aquarium Research Institute (http://www.mbari.org)
MRI - Major Research Instrumentation Program (NSF, http://www.nsf.gov/pubs/2004/nsf04511/nsf04511.htm#toc)
NASA – National Aeronautics and Space Administration (http://www.nasa.gov/home/index.html)
NEPTUNE – (http://www.neptune.washington.edu)
NOAA – National Oceanic and Atmospheric Administration (http://www.noaa.gov/)
NSF - National Science Foundation (http://www.nsf.gov)
NURP – NOAA's Undersea Research Program (http://www.nurp.noaa.gov)
ONR – Office of Naval Research (http://www.onr.navy.mil/default.asp)
ONR High Latitudes Program – former ONR program, now combined with Ocean Modeling and Prediction into Physical Oceanography, http://www.onr.navy.mil/sci_tech/ocean/322_processes/prog_po.asp)
OOI – Ocean Observatories Initiative (http://www.nsf.gov/pubs/2003/nsf03576/nsf03576.htm)
PIRATA – Pilot Research Moored Array in the Tropical Atlantic (http://www.pmel.noaa.gov/pirata/)
RAFOS – (SOFAR, backwards) A subsurface float that listens to acoustic signals in the SOFAR channel (http://www.taygeta.com/rafos.html)
ROV – Remotely Operated Vehicle
SBI – Shelf-Basin Interactions (NSF program, http://sbi.utk.edu/)
SCICEX – Scientific Ice Expeditions (http://www.ldeo.columbia.edu/res/pi/SCICEX)

SEARCH – A Study of Environmental Change in the Arctic (multi-agency program, http://psc.apl.washington.edu/search/index.html)
SLR – Sea Level Rise
SOFAR – Sound Fixing And Ranging
STC – Science and Technology Centers Program (NSF, http://www.nsf.gov/od/oia/programs/stc/index.htm)
TAO – Tropical Ocean Atmosphere Project (http://www.pmel.noaa.gov/tao)
UNOLS - University National Oceanographic Laboratory System (http://www.unols.org/)
USCG – United States Coast Guard (http://www.uscg.mil/)
WHOI – Woods Hole Oceanographic Institution (http://www.whoi.edu)

Appendix B – Workshop Participants

Robert Anderson
Hawai'i Mapping Research Group
University of Hawaii
1680 East-West Road
Post Bldg., 814B
Honolulu, HI 96822
Ph: (808) 956-9729
Email: Robert@soest.hawaii.edu

Carin Ashjian
Woods Hole Oceanographic Institution, MS 33
Woods Hole, MA 02543
Ph: (508) 289-3457
Email: cashjian@whoi.edu

Alberto Behar
JPL, M/S 198-235
4800 Oak Grove Dr.
Pasadena, CA 91109-8099
Ph: (818) 354-4417
Email: alberto.behar@jpl.nasa.gov

James Bellingham
MBARI
7700 Sandholt Rd.
Moss Landing, CA 93905
Ph: (831) 775-1731
Email: jgb@mbari.org

Diane Bentley
Arctic Submarine Laboratory
Ph: (619) 553-7451
Email: dbentley@nosc.mil

Paul Bienhoff
Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Rd., MS 24W445
Laurel, MD 20723-6099
Ph: (240) 228-4323
Email: Paul.Bienhoff@jhuapl.edu

Timothy Boyd
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331-5503
Ph: (541) 737-4035
Email: tboyd@coas.oregonstate.edu

April Brown
US Coast Guard
USCG Pacific Area, BLD 51-5
Coast Guard Island
Alameda, CA 94501
Ph: (510) 437-3850
Email: AABrown@d11.uscg.mil

Dale Chayes
Lamont Doherty Earth Observatory
61 Route 9W
Palisades, NY 10964
Ph: (845) 365-8434
Email: dale@ldeo.columbia.edu

Lisa Clough
Department of Biology
East Carolina University
Greenville, NC 27858-4353
Ph: (252) 328-1834
Email: cloughl@mail.ecu.edu

Bernard Coakley
University of Alaska, Fairbanks
Geophysical Institute
900 Yukon Drive
Fairbanks, AK 99775-5780
Ph: (907) 474-5385
Email: Bernard.Coakley@gi.alaska.edu

Edward Cokelet
NOAA/PMEL
7600 Sand Point Way NE
Seattle, WA 98115
Ph: (206) 526-6820
Email: cokelet@pmel.noaa.gov

Dennis Conlon
Program Manager, Cyberinfrastructure and Sensors
Office of Polar Programs
National Science Foundation
4201 Wilson Blvd
Arlington VA 22230
Ph. (703)292-4658
Email: dconlon@nsf.gov

Trine Dahl-Jensen
Geological Survey of Denmark and Greenland
Department of Geophysics
Volgrade 10, DK-1350
Copenhagen, Denmark
Ph: 45 38 14 25 19
Email: tdj@geus.dk

Knud Falk
Danish Polar Center
Strandgade 100H, DK-1401
Copenhagen, Denmark
Ph: 45 3288 0130
Email: kf@dpc.dk

David Forcucci
US Coast Guard
1519 Alaskan Way South
Seattle, WA 98134
Ph: (206) 217-6648
Email: Dforcucci@d11.uscg.mil

Jason Gobat
Applied Physics Laboratory
University of Washington
1013 NE 40th St.
Seattle, WA 98105
Ph: (206) 543-2439
Email: jgobat@apl.washington.edu

Michael Hacking
Arctic Submarine Laboratory
Ph: 619-553-7456
email: hacking@nosc.mil

David Hutchinson
US Coast Guard, ESU
Seattle, Ice Breaker Science Sup
1519 Alaskan Way S.
Seattle WA 98134
Ph: 206.217.6552
Email: dhutchinson@pacnorwest.uscg.mil

Alexandra Isern
Ocean Technology and Interdisciplinary Coordination
National Science Foundation
4201 Wilson Blvd
Arlington, VA 22230
Ph: (703) 292-8582
Email: aisern@nsf.gov

Bill Kirkwood
MBARI
7700 Sandholdt Road
Moss Landing, CA 93905
Ph: (831) 775-1707
Email: kiwi@mbair.org

Richard Krishfield
Woods Hole Oceanographic Institution, MS 23
Woods Hole, MA 02543-1541
Ph: (508) 289-2849
Email: rkrishfield@whoi.edu

Eldridge McFadden
US Coast Guard, ESU
Seattle, IceBreaker Science Sup
1519 Alaskan Way S.
Seattle,WA 98134
Ph: 206.217.6552
Email: emcfadden@pacnorwest.uscg.mil

Phil McGillivary
USCG
PO Box 5082
Alameda, CA 94501
Ph: (510) 437-5355
Email: pmcgillivary@d11.uscg.mil

Nick Millard
Ocean Technology Division
Southampton Oceanography Center
Empress Dock SO14 3ZH UK
Ph: 44 (0)23 80596150
Email: nic@soc.soton.ac.uk

James Morison
Applied Physics Lab
University of Washington
1013 NE 40th St.
Seattle, WA 98105
Ph: (206) 543-1394
Email: morison@apl.washington.edu

Rob Pinkel
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093
Ph: (858) 534-2056
Email: rpinkel@ucsd.edu

Al Plueddemann
Woods Hole Oceanographic Institute, MS 29
Woods Hole, MA 02543
Ph: (508) 289-2789
Email: aplueddemann@whoi.edu

Andrey Proshutinsky
Woods Hole Oceanographic Institution, MS 23
Woods Hole, MA 02543
Ph: (508) 289-2849
Email: aproshutinsky@whoi.edu

Thomas Pyle
Office of Polar Programs
National Science Foundation
4201 Wilson Blvd
Arlington, VA 22230
Ph: (703) 292-7424
Email: typle@nsf.gov

Robert Reves-Sohn
Woods Hole Oceanographic Institution, MS 24
Woods Hole, MA 02543
Ph: (508) 289-3616
Email: rsohn@whoi.edu

Eberhard Sauter
Alfred Wegener Institute for Polar and Marine Research
Am Handelshafen 12, 27570
Bremerhaven, Germany
Ph: 0049-471-4831-1517
Email: esauter@awi-bremerhaven.de

Val Schmidt
Lamont Doherty Earth Observatory
61 Route 9W
Palisades, NY 10964
Ph: (614) 286-3626
Email: vschmidt@ldeo.columbia.edu

Timothy Shank
Woods Hole Oceanographic Institution
2-14 Redfield
Woods Hole, MA 02543
Ph: (508) 289-3392
Email: tshank@whoi.edu

Mark Sibenac
MBARI
7700 Sandholdt Road
Moss Landing, CA 93905
Ph: (831) 775-2028
Email: sib@mbair.org

Hanumant Singh
Woods Hole Oceanographic Institution, MS 7
Woods Hole, MA 02543
Ph: (508) 289-3270
Email: hsingh@whoi.edu

Tim Stanton
Naval Postgraduate School
Oceanography Department, Code OC/St
Monterey, CA 93943
Ph: (831) 656-3144
Email: Stanton@nps.navy.mil

Wayne Sternberger
Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Rd., MS 24W445
Laurel, MD 20723-6099
Ph: (240) 228-5086
Email: Wayne.Sternberger@jhuapl.edu

Nicole Tervalon
MBARI
7700 Sandholdt Road
Moss Landing, CA 93905
Ph: (831) 775-1824
Email: tervalon@mbair.org

Hans Thomas
MBARI
7700 Sandholdt Road
Moss Landing, CA 93905
Ph: (831) 775-1976
Email: hthomas@mbair.org

Geoff Wheat
U. Alaska, Fairbanks
PO. Box 475
Moss Landing, CA 95039
Ph: (831) 633-6872
Email: wheat@mbari.org

Sean Wiggins
Marine Physical Laboratory, 0205
Scripps Institution of Oceanography
La Jolla, CA 92093
Ph: (858) 822-2744
Email: swiggins@ucsd.edu

Peter Wilkniss
Polar Kybernetes International, LLC
1305 West 7th Ave.
Anchorage, AK 99501
Ph: (907) 278-2085
Email: PolarKI@aol.com

Appendix C - Abstracts

Concepts for New Expendable Instruments for Arctic Oceanographic Measurements.

Robert Anderson
University of Hawaii

Discussions with oceanographers at the recent Arctic Circulation workshop at Lamont revealed a desire to make observations down to 4000-5000 meters depth in the Arctic Ocean. This is not feasible from an ice camp with presently available instruments. A concept will be presented for an expendable instrument, which reports measurements back to the surface by acoustic modem. Acoustic modem technology has been demonstrated to provide reliable digital data transmission at distances up to 5000 meters. A modem transmitter can be incorporated into an expendable probe containing a CTD sensor or other instruments, and telemeter measurements back to a receiver supported by a transducer suspended in the water beneath the ice canopy. The same concept can be extended to provide deep measurements from a submarine operating beneath the ice, in which case the probe would be deployed through the ship's trash disposal unit, and the modem receiver supported by a transducer mounted on the submarine's hull.

Arctic Plankton Ecology in the 21st Century

Carin Ashjian
Woods Hole Oceanographic Institution

Arctic plankton ecology is profoundly impacted by the seasonal variations in temperature and light and ice cover. However, the very ice that is both a critical substrate and an integral environmental variable also presents logistic barriers to plankton ecology studies. Although exploration of the Arctic ecosystem has been conducted for over a century, our ability to understand even its basic characteristics has been hampered by difficulty in accessing the region and by limitations to the facilities and equipment we have been able to utilize. The status of and current issues in Arctic plankton ecology will be reviewed, particularly in reference to the ongoing Shelf-Basin Interactions study, with discussion of the instrumentation development, study area access, and facilities that are critical to advancing studies of Arctic plankton ecology.

Basin-scale Autonomous Vehicles

Dale Chayes
Lamont Doherty Earth Observatory

The Arctic basin is among the least explored realms on Earth. Many of the classic methods developed for studying the Earth_s other basins are inefficient and/or impractical in this ice-covered basin. Reconnaissance scale mapping of the bathymetry, gravity field and shallow sub-surface sediments from nuclear submarines (in the SCICEX program) has provided significant new insights in the small percentage of the basin that has been explored. These results have raised as many new questions as they answered.

Substantial portions of the deep basin and virtually all of the shelves remain explored for want of suitable tools. While the possibility of future use of submarines should not be discounted, and existing autonomous vehicles are too small, we need to be working toward large (~10m by 4m by 3m) long range (10,000 km), long duration (weeks) autonomous vehicles. Such a vehicle is certainly attainable in the five-year time frame and could support multiple simultaneous instruments that would enable serious mapping of the seafloor and synoptic views of the water column.

In addition, such a large vehicle could act as a mother-ship for small (Remus) or medium (Dorado/Bluefin/ABE) sized vehicles to transport them to and from areas where detailed, near bottom survey and/or sampling programs are necessary.

Current Issues in Arctic Benthic Ecology

Lisa Clough
East Carolina University

A large proportion of the benthic biomass on Arctic shelves is found on and immediately above the seafloor. These epibenthic organisms are poorly sampled via traditional mechanisms such as coring. Photography has proven to be the best method for quantifying the abundance and distribution of larger organisms. The challenges of sampling the epibenthc microbial community are many, and include both temporal and spatial concerns (a microbial lifetime may be on the order of a day, and its habitat may be on the order of a centimeter). Perhaps real-time in-situ sampling using either autonomous or remotely operated vehicles is the best option for both marcofaunal and microbial work. And an understanding of the epifaunal communities is critical- our recent analyses show up to 30% of the organic carbon reaching the seafloor cycles through the epifauna.

In the much deeper, perennially ice-covered regions of the Arctic, where benthic microbes prevail, in-situ work is even more critical because rates obtained from ship-board incubated samples clearly do not reflect in-situ rates unless the extreme pressures of the seafloor can be replicated. As the waters are continuously ice-covered, any surface based technologies must be able to handle the rigors of a continuously moving surface ice pack, which is notorious for parting cables and leading to lost gear. And recovery of any autonomous vehicles or benthic landers must take into account the challenges of finding a piece of equipment that surfaces under the ice. In summary then, benthic ecology has questions that remain unanswered for want of the technological capabilities of working in the deep Arctic Ocean.

United States Coast Guard Icebreakers

Lisa Clough
East Carolina University

The US arctic science community currently draws on two types of polar icebreakers for research in ice-covered waters- the multi-mission Polar-class Coast Guard cutters POLAR STAR and POLAR

SEA, and the research vessel, Coast Guard cutter HEALY. In addition, plans are well underway to replace the R/V ALPHA HELIX with an intermediate sized, ice-strengthened vessel (more information on the Alaska Region Research Vessel can be found at: http://www.unols.org/fic/#arrv). The Polar class icebreakers are 399 feet long, and have a crew of approximately 150, including a 14 person and two helicopter aviation detachment. They can accommodate a scientific party of greater than 20 depending on the mission. Both the POLAR SEA and POLAR STAR have modified science spaces, and include a dry lab, two wet lab spaces, a CTD hanger and vestibule, three general purpose cranes (two 15 ton, one 3 ton), and two oceanographic winches linked to J-frames. The HEALY is 420 feet long, has a crew of 75 plus a modified aviation detachment of 10 people and two helicopters, and can accommodate up to 51 scientists in a total of 18 staterooms. HEALY contains extensive lab spaces (~3000 square feet), as well as in-hull science systems including Acoustic Doppler Current Profilers (ADCPs), a SeaBeam 2112 multibeam sonar system, and two types of sub-bottom profiling systems. HEALY has two oceanographic winches, and a double drum trawl/core winch linked to stern and starboard A-frames.

More information on the ships, and assistance with things such as expeditionary planning is available to the community through the UNOLS Arctic Icebreaker Coordinating Committee (AICC) and the US Coast Guard Icebreaker Operations Science Liaison office.

Development of Arctic Science and Instrumentation for Geology and Geophysics

Bernard Coakley
University of Alaska

Exploration of the Arctic Ocean has always relied on the availability of equipment suitable for Arctic deployment and access to Arctic-capable platforms. After World War II, national security needs dictated an active research presence in the Arctic. This research presence was supported through air-serviced ice islands and occasional ice-breaker cruises. These arduous programs deployed sensors similar to those used at lower latitudes, collecting the data that began to fill in the blank spot of the Arctic map.

While these programs produced much "new" knowledge, establishing the broad outlines of the basin morphology and oceanography, they were severely limited by the restricted mobility of ice islands and icebreakers, which, limited by or borne by the pack ice, prevented the execution of structured surveys. Airborne magnetic surveys provided the first comprehensive view of the Arctic Ocean basin, but, limited by the lack of co-registered bathymetric data, these data have not been of much use outside of the Eurasian basin.

Early nuclear-powered submarine cruises in the Arctic Ocean sometimes visited ice island research stations. The drifting scientists were impressed by this mobility, unhindered by ice, and speculated about how it might be used for science. While much of the bathymetry data collected during these classified cruises was recently declassified and released, systematic surveys of the Arctic seafloor were not conducted until the SCICEX program of unclassified cruises on Sturgeon class fast-attack submarines.

The initial SCICEX cruises utilized only the ship's own narrow-beam bottom sounder and a Bell BGM-3 marine gravimeter. With NSF funding, new sonars, designed for submarine operations in the Arctic Ocean, were developed and installed on the USS Hawkbill. These sonars were used during SCICEX 98 and 99 to collect swath bathymetry and chirp sub-bottom profiler data across the entire

Arctic Ocean basin, focusing on the Lomonosov and Gakkel Ridges in the Eurasian basin.

We now know a good deal about the Gakkel and Lomonosov Ridges and the eastern edge of the Chukchi Plateau. The primary objectives for future cruises are obscured by the wind-thickened ice pack north of Greenland and Arctic Canada (eg. Alpha Ridge and the northern shelf and slope of North America) or are remote and difficult to achieve (eg. Mendeleev Ridge). The instruments and platforms used to explore these features will need to solve the same problems that have been solved before. A particular problem for submarines and AUVs is automating data acquisition and acquiring precision under-ice navigation.

The development of Arctic Ocean exploration from drifting ice islands to structured surveys conducted with purpose built instruments is continuing today, as evidenced by this meeting. A variety of science problems, articulated by results from lower latitude and the need to develop fully global models of climate and plate tectonics are driving the development of new research platforms and new, appropriate tools for basin exploration. As a result of this work, it appears likely that in the next decade there will be a coherent program of scientific drilling and AUV exploration of the Arctic Ocean.

Physical Oceanography from an Arctic AUV: Field Comparison with CTD Casts

Edward Cokelet
NOAA/PMEL

An autonomous underwater vehicle (AUV) designed for operation at high latitudes and under ice completed its first Arctic field tests from the USCGC Healy in October 2001. The AUV has been under development since 1998, and is being created to provide: unprecedented endurance, ability to navigate at high latitudes, a depth rating of 1500 to 4500 meters depending on payload, and the capability to relay data through the ice to satellites via data buoys. The ALTEX (Atlantic Layer Tracking EXperiment) AUV's initial applications are focused on tracking the warm Atlantic Layer inflow - the primary source of seawater to the Arctic Ocean. Consequently the primary payloads are twin, pumped CTD systems. Oxygen and nitrate sensors provide the ability to use NO (dissolved oxygen corrected by nitrate to account for biological respiration) as a nearly conservative tracer. An ice profiling sonar allows the AUV to estimate the ice thickness in real-time and is designed to generate high quality post-processed ice draft data comparable to that collected through the SCICEX program.

The cruise generated 24 water column and under-ice data sets. Fifty-two CTD casts were made to the depth of AUV operations and often to the ocean bottom. Their purpose was to provide AUV-CTD comparisons and to track the Atlantic Layer inflow across 5 transects. Reasonable agreement in temperature, salinity, and tracer concentrations was obtained between the vertical CTD casts and the along-track AUV measurements when one considers temporal and horizontal variability. The field comparison suggests some improvements to AUV sensor configuration and some advantages to sensor redundancy. The post-processed ice draft results show reasonable ice profiles and have the potential, when combined with other science data collected, to shed some additional light on upper water column processes in ice-covered regions. The AUV proved its worth in making autonomous measurements under sea ice too thick for the icebreaker to penetrate effectively. Overall cruise results include: operating the AUV from the USCGC Healy in the ice pack, demonstrating inertial navigation system performance, obtaining oceanographic sections with the AUV, obtaining ice draft measurements with an AUV born sonar, and testing the data-buoy system.

Preparation for a possible claim beyond 200 NM north of Greenland - The need for more geophysical data.

Trina Dahl-Jensen
Geological Survey of Denmark and Greenland

The Geological Survey of Denmark and Greenland (GEUS) together with other Danish Institutions is presently planning acquisition of bathymetric, reflection and refraction seismic data in the Arctic Ocean north of Greenland in preparation for a possible claim beyond 200 NM in relation to UNCLOS §76. Funding for up to 5 acquisition seasons are presently considered by the Danish Government. We would therefore like to discuss technical possibilities and logistical cooperation for a number of data acquisition seasons in the Arctic Ocean. Main topics of interest are:

- Acquisition of bathymetric data (primarily ship and submarine based)
- Methods for acquisition of reflection and refraction seismic data (two ship operations and /or from sea ice)
- Logistical cooperation and co-funding
- Exchange of data

An Expendable, Ice-tethered Instrument for Sustained Observation of the Arctic Ocean

Richard Krishfield
Woods Hole Oceanographic Institution

In recent years, ice-tethered drifters with discrete subsurface instrumentation, including the SALARGOS, IOEB and J-CAD buoys, have been successfully fielded in the Arctic. These instruments demonstrate that automated buoys are a viable means of acquiring long-term, in situ data from beneath the ice pack. However, the vertical resolution of the temperature and salinity observations from these systems has typically been limited to only a few depths due to the costs associated with outfitting multiple sensors on a single package. Even with limited sensors, total system costs has meant that only a small number of such devices have been fielded at any one time. Building on the successful Moored Profiler technology, we propose to develop an automated, long-lived, ice-tethered buoy capable of returning daily high-vertical-resolution profiles of upper ocean temperature and salinity in the Arctic Ocean during all seasons over several years. Our design requirements are: 1) to return in real time, 1-m-vertical-resolution, high-accuracy temperature and salinity profiles to at least 500 m depth for three years (assuming deployment in robust ice floes), 2) to be deployable from light aircraft (Twin Otters) and helicopters through a conventional 16" ice-auger hole, and 3) to be modestly priced allowing them to be considered disposable. Ultimately we envision a loose array of these ice-tethered profilers being maintained throughout the Arctic Ocean to observe the annual and inter-annual variations of the upper ocean: the Arctic extension of the international ocean observing system.

Acoustic Remote Sensing Instrumentation for the Arctic Ocean

Peter Mikhalevsky
Ocean Sciences Division
SAIC, McLean, VA

The large changes in the Arctic Ocean documented over the last 10 years, including increases in the temperature of the Arctic Intermediate Water (AIW), and thinning of the Arctic sea ice reveal an ocean that is much more variable than previously thought. The need for real time synoptic monitoring of the Arctic Ocean is evident. Acoustic remote sensing, namely acoustic thermometry, was first demonstrated in the Arctic Ocean in 1994 revealing the basin scale warming of the AIW. Acoustic thermometry and tomography provides an integrated measurement of temperature and currents that can be applied to a variety of observational scales. For basin scales acoustic thermometry integrates over mesoscale and higher wavenumber phenomena to provide large scale averages of temperature and heat content that are needed for climate oriented studies and are difficult, if not impossible, to obtain with an ensemble of point measurements, especially in the Arctic Ocean. Measurement of transport, thermocline depth, even salinity and sea ice properties are also possible and are in various stages of development. Acoustic remote sensing requires an acoustic source and hydrophones. These can be installed on "conventional" oceanographic moorings and can therefore extend the point measurements obtained at the moorings with integrated measurements between the moorings. If the acoustic capability is designed into the moorings at the planning stages the marginal cost is comparable to other sensor packages. Connecting such Arctic Ocean moorings back to shore is envisioned exploiting an existing sea-shore link in the Lincoln Sea and a planned link into the Beaufort Sea from Barrow, Alaska providing the real-time synoptic capability for Arctic Ocean observations.

Upper ocean observations from ice-anchored drifters

Al Plueddemann
Woods Hole Oceanographic Institution

Ice-anchored surface drifters have been used extensively in the Arctic during the last 50 years, but only a few include instrumentation below the ice. Here we describe upper ocean velocity observations from Ice-Ocean Environmental Buoys (IOEBs), special purpose platforms designed for long-term measurement of meteorological and oceanographic variables in the Arctic. Data were available from three IOEB deployments within the Beaufort Gyre between 1992 and 1998. The data are suitable for examining tides and near-inertial internal waves, but the dominant signal comes from subsurface eddies. Physical properties were determined for 81 eddies from 44 months of buoy drift. The majority of center depths were between 50 and 150 m and the mean vertical extent was 126 m. Thus, eddies were found predominantly within the cold halocline. Maximum rotation speeds were typically 20-30 cm/s, with some greater than 40 cm/s. Typical radii were 3-6 km. The sense of rotation was predominantly anticyclonic. Dynamical properties were determined for 29 eddies. Relative vorticity was maximum in the eddy cores, whereas strain was largest outside the radius of maximum velocity.

Basin-Scale Oceanographic Problems of the Arctic Ocean and a Monitoring System for Their Solution

Andrey Proshutinsky
Woods Hole Oceanographic Institution

There are at least five key parameters of the Arctic Ocean whose monitoring are crucial for understanding the ocean's variability and the Arctic's influence on global climate. These parameters are: freshwater content, sea ice volume (thickness and extent), oceanic heat content, circulation, and sea level. It is a common perception now that the recent history of the Arctic is characterized by: a significant change in circulation, a substantial increase in ocean heat content, a descending trend in summer ice cover extent and in ice thickness, an increase in rate of sea level rise, and changes in fresh water flux to the North Atlantic (Great Salinity Anomaly), but these trends could be erroneous because observations in the Arctic Ocean are scarce and there are huge gaps in the data in space and time. In order to fill these gaps in future studies, we propose an observational Arctic Ocean Monitoring System (AOMS) that can serve for sustained, long-term efforts to document and understand variability in the ocean and sea ice. Building on the successful Moored Profiler technology, we propose to initiate development of an automated, long-lived, ice-tethered buoy capable of returning daily high-vertical-resolution profiles of upper ocean temperature and salinity in the Arctic Ocean during all seasons over several years. An array of such buoys would monitor arctic conditions from the surface to 500-800 meters providing sufficient information about the key oceanic parameters mentioned above.

Autonomous Strategies for Studying Hydrothermal Venting on the Gakkel Ridge

Robert Reves-Sohn
Woods Hole Oceanographic Institution

The nature of hydrothermal circulation along the Gakkel Ridge in the eastern Arctic Basin is presently unknown, but the limited data acquired to date is enigmatic. Thermal and particulate signatures indicative of hydrothermal fluids were found in nearly 80% of the CTD casts from the recent AMORE expedition to the ridge, an astonishing number considering that hydrothermal activity is generally expected to decrease as the spreading rate, and hence thermal structure, of a ridge decreases. Is hydrothermal activity truly ubiquitous on the Gakkel Ridge, or are there a few very large systems that fill the axial valley with hydrothermal tracers, or is it even possible that circulation in the deep axial valley is so restricted that plumes linger exceptionally long periods of time?

The biological characteristics of vent fauna on the Gakkel Ridge are also of great interest. Vent-endemic fauna have been characterized in all of the major ocean basins except for the Arctic, and thus we presently do not know how vent fauna on the Gakkel Ridge relate to species found in the nearby Atlantic and Pacific basins. Nor do we know how Arctic vent fauna may have evolved in an isolated Arctic system since hydrographic communication with the rest of the world's oceans is limited to exchange across shallow sills. Vent fauna on the Gakkel Ridge constitute the last major piece of the global biogeographic puzzle, with implications that extend beyond domain characterization.

In order to develop an inter-disciplinary understanding of hydrothermal processes on the Gakkel Ridge a comprehensive set of geological, chemical, and biological data is needed. The data will be difficult to obtain, however, because the ridge is covered with a permanent layer of ice that precludes many of the standard oceanographic and deep-sea technologies employed to find and study hydrothermal systems in the open ocean, including towed vehicles and ROVs.

Building on AUV technology developed to enable ocean bottom seismic studies in the Arctic, we have devised an AUV-based, nested survey strategy that will allow us to map hydrothermal plumes in the water column, find and image vent fields on the seafloor, and obtain biological samples of vent fauna. The major technological challenges include under-ice navigation for surveys, acoustic communication in the Arctic sound channel, and recovery of AUVs through the ice sheet.

Innovative Technologies in Arctic Research: (1) Recent Activities Conducted at AWI

Eberhard Sauter
Alfred Wegener Institute

The Alfred Wegener Institute for Polar and Marine Research (AWI) has focused on Arctic research for many years. Four recent research approaches using advanced technologies are presented here as an example.

1) Combining the institute's icebreaking vessel R/V "Polarstern" with the French remotely operated vehicle (ROV) "Victor6000", a powerful polar research facility was created. Besides visual and acoustic imaging of Arctic deep-sea environments, a variety of in situ experiments and micro sensor measurements have been conducted on the scientific maiden voyage of Victor6000 in order to investigate biological, geochemical, and physical gradients at the sediment-water interface. For example, benthic respiration and interfacial solute exchange is quantified under consideration of bottom current profiles using special devices designed for ROV manipulation.

2) ROV-based investigations are complemented by benthic lander technology. The latter is used for in situ flux measurements as well as for long term observations of benthic responses to large food falls and temporal variabilities of fluid discharge at an arctic mud volcano, respectively. A module concept allows to implement different payload modules onto the lander's base frame.

3) Ice and bad weather conditions hamper shipborne oceanographic observations in arctic regions especially during the winter period. Oceanographic moorings provide a solution as they are able to record physical parameters throughout all seasons of the year. However, since the number of instruments is limited, observations can only be carried out at some distinct depth levels of the water column. To monitor temporal dynamics of descending water masses over the entire water column of the central Greenland Sea, a profiling CTD mooring has been developed. This "yo-yo" system monitors the water column of 4000 m once per day throughout a period of up to 400 days. The system complements oceanographic investigations annually conducted along 75°N and 79°N.

4) Evidences from submarine sonar measurements as well as from satellite observations suggest a considerable thinning and waning of the Arctic sea ice cover during the last decades. However, the limited time and space coverage of submarine sea-ice thickness data requires additional measurements, which allow for more systematic thickness surveys. Therefore, we applied and operationalised electromagnetic (EM) induction sounding for ice thickness measurements. This geophysical technique, classically used on land to map ore or groundwater deposits, was implemented initially onto a sled towed over the ice. In a second step, the system was transferred into a helicopter-borne EM sensor ("EM-Bird"). First deployments in the Arctic yielded high-resolution thickness data of good quality. With the EM-Bird, we will now be able to perform systematic large-scale studies of the ice thickness

distribution, improving our ability to better judge observations and predictions of possible climate changes.

Innovative Methodologies in Arctic Research: (2) Future Activities Scheduled at AWI

Eberhard Sauter
Alfred Wegener Institute

Being one of the leading polar research organizations in Europe, the Alfred Wegener Institute for Polar and Marine Research (AWI) acts as a motor for the development of polar research technologies. A couple of scheduled Arctic projects has been selected out of a large variety of future activities to be presented here:

1) Subsequent to the AMORE expedition to the Gakkel Ridge jointly performed in 2001 by the two research icebreakers USCGC “Healy” and RV “Polarstern” a further two ship mission is scheduled for 2004. AWI will participate again with RV “Polarstern” and will host the remotely operating vessel (ROV) “Victor6000”. The main focus will be laid on a detailed sampling of the Gakkel Ridge system by means of the ROV, which is well appropriate for visual and experimental investigations of ridge structures. The vehicle will take samples at sites surveyed and pre-investigated by geophysical techniques in 2001. Besides, it is also envisaged to conduct ROV-based experiments and sampling on the Siberian Shelf. Based on the results of the joint Russian-German project on "Siberian River Run-off (SIRRO) the river fans of Ob and Yenesei are targeted. Geological, geochemical and biological processes relevant for the understanding of the input of fresh water, sediments, and organic matter from the rivers to the Kara Sea and the adjacent Arctic Ocean will be subject to ROV investigations.

2) AWI is currently purchasing an autonomous underwater vehicle (AUV) for under-ice research, seafloor and water column surveys. Equipped with acoustic tools like side scan sonar, sub-bottom profiler, swath bathymetry as well as with visual imaging systems the vessel shall perform e.g. autonomous pre-site surveys for future Arctic drill campaigns and further seismic investigations at Arctic ridge systems. Moreover, the AUV is planned to be used for surveying arctic sediment and fauna distribution and tracks of grounded icebergs. In addition, special payload modules capable to trace geochemical parameters in the water column will be developed for the AUV in order to quantify submarine fluid discharge plumes etc.

3) The ARGO system of vertically profiling floats is expected to become the backbone of a global ocean observing system. However, their use under Arctic conditions remains difficult, since the floats have to get to the sea surface to be located and to transmit the measured data via satellite. Instead, AWI promotes a Hybrid Arctic/Antarctic Float Observation System (HAFOS) which shall combine different technologies. It comprises ice resistant profiling subsurface floats, surface drifters on the ice and moored stations. The envisaged system consists of RAFOS (ranging and fixing of sound) type subsurface profiling floats which obtain their position by ranging of sound sources on moored stations. The floats measure vertical profiles of temperature and conductivity/salinity, but do not surface while floating under the ice. As a first stage of development, data will be stored until the floats reach ice-free waters. Later, the floats will be able to communicate with receivers installed on moorings and ice drifters allowing fast satellite data transmission.

4) The central Arctic Ocean has hitherto not been visited by a deep-drilling research vessel (DSDP/ODP) and therefore its long-term environmental history as well as the tectonic structure are poorly known. A European contribution to IODP is needed. A newly designed research ice breaker

with a deep ocean drilling capability would provide the opportunity to conduct international, interdisciplinary expeditions during all seasons of the year and to penetrate into permanently ice-covered basins of the central Arctic Ocean. AWI promotes a European consortium of interested institutes/countries to share responsibilities for the planning and construction of a multi-purpose Arctic ice breaker and to coordinate scientific programs.

Arctic Acoustic Positioning System for Submerged Vehicles

Val Schmidt
Lamont Doherty Earth Observatory

Experience conducting research with the US Naval submarine fleet and other Arctic endeavors has shown that both manned and unmanned submarine vehicles operating in Arctic waters for extended periods suffer from significant navigational inaccuracies. Ice cover prevents these systems from acquiring GPS or other fixes to correct inertial systems that have drifted. Ice camp and ship support is limited to their respective immediate areas. For the Naval submarine fleet and the research conducted aboard these ships, correcting navigational inaccuracies translates to days of lost time. Locating surfacable features and obtaining GPS fixes requires on the order of 12 to 48 hours or longer - a significant portion of a 40 day cruise if it must be repeated weekly. To provide navigational information to submarines, AUVs, rovers, and other sensors operating in the Arctic, small self deploying buoys containing GPS receivers and a simple transducer/acoustic modem could be launched from airplanes over wide areas. Time synchronized with the GPS time standard, a buoy could transmit its location exactly on the minute. Vehicles in the area could, in turn, get a bearing and range to determine their own position. The result would be an effective extension of the Global Positioning System to subsurface operations in the Arctic.

Hydrothermal Processes on The Gakkel Ridge

Timothy Shank
Woods Hole Oceanographic Institution

The Gakkel Ridge in the Eastern Arctic Basin is the ultra-slow spreading end-member in the global mid-ocean ridge system. As such, it presents a model system for studies in crustal structure, duration and magnitude of apparent volcanic seismicity, and a variety of dynamic geochemical and biological processes. The Gakkel Ridge is also unique because of Arctic's hydrographic isolation from other oceans. There has been no apparent deep-water connection between the Arctic and other ocean basins during its history, and modern communication with the rest of the world's oceans is limited to exchange across shallow sills. As a result, Arctic hydrothermal species have likely evolved in isolation from other vent-endemic fauna. The Gakkel Ridge affords the opportunity to address hypotheses linking spreading rate to hydrothermalism and crustal generation, as well as an opportunity to characterize key processes in the evolution of isolated marine organisms, new species and novel ecological systems. Despite the impact of potential scientific insights, the geological, chemical, and biological characteristics of hydrothermal systems hosted on the Gakkel Ridge remain unknown given the difficulties posed by surface ice conditions. New instrumentation, technologies, and field strategies are critical to advance deep-sea investigations in this ice-covered region, and permit detailed multidisciplinary studies (e.g., mapping hydrothermal plumes, and locating, imaging, and sampling biological communities and associated vent fluids) of hydrothermal systems on the Gakkel Ridge.

Observing Vertical Ocean Fluxes of Heat Salt and Momentum in the Central Arctic

Tim Stanton
Naval Postgraduate School

As the ocean provides a critical "thermal flywheel" in the Arctic heat balance on seasonal and longer time scales, accurate measurement of vertical heat fluxes through the upper ocean is critical in determining the balance between radiative and sensible heat fluxes at the ice surface, changes in ice cover, thickness and heat content, and ocean heat content which all interact over seasonal scales to maintain ice cover in the Arctic. The insulating properties of the Arctic ice cover largely decouple rapid, strong variations of surface heat fluxes from the ocean interior. Furthermore, since still water is also a very good insulator, the vertical transport of heat to and from the salt stratified ocean interior is determined primarily by the rate at which the upper ocean is stirred. This stirring occurs when wind blows over the ice and moves, forming a turbulent boundary layer extending down from the ice toward the stratified pycnocline, typically at 30m depth. The flux buoy measures these fluxes within the stirred "mixed" layer below the ice. I have been funded to develop autonomous, ice-deployed drifting buoys (http://www.oc.nps.navy.mil/~stanton/fluxbuoy/) capable of measuring vertical fluxes of momentum, heat and salt in the upper ocean in Polar regions through the NSF "Polar Instrumentation and Technology Development" program. The first of a series of buoys has been deployed as a component of the North Pole Environmental Observatory (http://psc.apl.washington.edu/northpole/index.html) near the North Pole in April 2002 in a cluster of observing systems that measure the local ocean/ice/atmosphere vertical fluxes. The approach taken in the buoy design and progress of the program will be discussed.

Autonomous Acoustic Recording Packages (ARP's) for long-term monitoring of Arctic whales

Sean Wiggins
University of California, San Diego

Advancements in low-power and high data capacity technology during the past decade have been adapted to autonomously record acoustic data from vocalizing whales over long periods of time. Acoustic monitoring of whales has advantages over traditional visual methods, especially in the Arctic where weather conditions make visual surveys expensive and seasonally limited. An autonomous acoustic recording package (ARP) is described that uses a tethered hydrophone above a bottom-mounted frame. ARPs have been deployed at high latitudes to record baleen whale sounds in the Bering Sea and near the West Antarctic Peninsula. ARP data have provided new information on the seasonal abundance, and calling patterns of vocalizing whales.

The Arctic Ocean - A Complex System: Important Considerations for the Development of Instrumentation.

Peter E. Wilkniss
Polar Kybernetes International, LLC
Anchorage, Alaska 99501

The Arctic Ocean, a vital component of the Earth System, is little understood. Urgently needed progress in scientific exploration of this "Mare Incognitum" requires a concerted effort in which scientific instrumentation and the underlying technologies play an essential role. Major advances in scientific understanding are often a consequence of new plateaus reached in relevant technologies that enable innovative instrumentation and data acquisition. A plethora of new, emerging programs aimed at Arctic Ocean exploration offer a unique opportunity to capitalize on necessary technology development. Important considerations are the upfront coordination of the investment in the new technologies to assure consistent quality, inter-operability, inter-calibration, reliability and appropriate maintenance in remote, taxing operating environments, and last not least user friendly data acquisition and dissemination. The most important consideration however is that instrumentation must not be developed in isolation and that development must be directed towards the overall strategic goals of scientific exploration of the Arctic Ocean. New directions in research that are emerging must be fully recognized in the technology community. For the Arctic Ocean the evolving understanding is that it is represents a holistic nature system, where innovative interdisciplinary research, i.e. between biologists and climate scientists will advance the understanding how large scale patterns of climate variability have significant impact on associated ecosystems from inter-annual to long term timescales. It is imperative that these trends are recognized in instrumentation development in order for it to become an integral part of the interdisciplinary research endeavors.

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