# ICARP II – SCIENCE PLAN 4

## DEEP CENTRAL BASIN OF THE ARCTIC OCEAN


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# Preface

The Second International Conference on Arctic Research Planning (ICARP II) was held in Copenhagen, Denmark from 10 November through 12 November 2005 and brought together over 58 scientists, policy makers, research managers, indigenous peoples, and others interested in and concerned about the future of arctic research. Through plenary sessions, breakout sessions and informal discussions, conference participants addressed long-term research planning challenges documented in twelve draft research plans. Following the conference drafting groups modified the plans to reflect input from the conference discussions and input from the ICARP II web site. This science plan is the culmination of the process.

**ICARP II Science Plans**

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| Science Plan 1 | Arctic Economies and Sustainable Development |
| Science Plan 2 | Indigenous Peoples and Change in the Arctic: Adaptation, Adjustment and Empowerment |
| Science Plan 3 | Arctic Coastal Processes |
| Science Plan 4 | Deep Central Basin of the Arctic Ocean |
| Science Plan 5 | Arctic Margins and Gateways |
| Science Plan 6 | Arctic Shelf Seas |
| Science Plan 7 | Terrestrial Cryospheric & Hydrologic Processes and Systems |
| Science Plan 8 | Terrestrial and Freshwater Biosphere and Biodiversity |
| Science Plan 9 | Modeling and Predicting Arctic Weather and Climate |
| Science Plan 10 | A Research Plan for the Study of Rapid Change, Resilience and Vulnerability in Social-Ecological Systems of the Arctic |
| Science Plan 11 | Arctic Science in the Public Interest |
| Background Document | Contaminants |

## 4.1. Introduction

The isolation of the deep, central Arctic Ocean does not insulate it from climate change. All evidence indicates that a complex suite of interrelated atmospheric, oceanic, and terrestrial changes are now underway in the Arctic, affecting every part of the polar environment. Understanding and quantifying these changes is complicated by the sparseness of oceanographic and geophysical data from the circum-arctic environment. Without these data, it will not be possible to understand contemporary processes, or to predict future change or the consequences of change.

The Arctic Ocean (Figure 4.1) was created by plate tectonic processes, in two episodes, one primarily Cenozoic the other essentially Mesozoic. It is a repository of information about ancient climate and a natural laboratory for the study of ocean circulation processes. Plate boundaries extend across latitudes. Transfer of heat and mass in the oceans and atmosphere do not respect geographical boundaries. Complete understanding of climate change and the geological history of the northern continents awaits comprehensive study of the deep Arctic Ocean. Two complementary approaches are necessary to achieve this goal: contemporary process studies and historical studies.

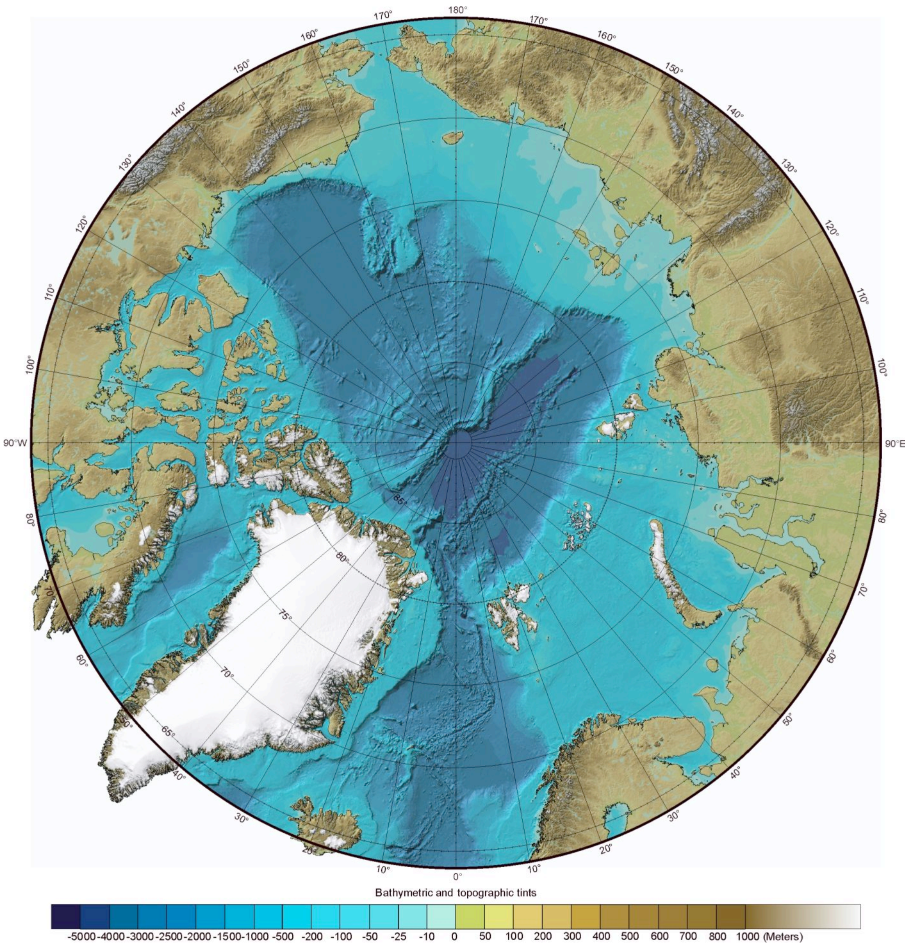


**Figure 4.1.** The deep central Arctic Ocean is known only superficially and is not well understood. Exploration of the basin will enable the construction of truly global climate and plate tectonic models for the last 150 million years of earth history. Bathymetry is from the International Bathymetric Map of the Arctic Ocean (Jakobsson et al., 2000).

### 4.1.1. Contemporary Process Studies

The gross circulation of the Arctic Ocean has not been completely described. This circulation distributes waters from the rivers, continental shelves, and gateways throughout the Arctic Basin. How these waters interact is known only in outline. How fluid fluxes vary in time, perhaps in conjunction with the Arctic Oscillation, and how these variations influence the atmosphere, sea ice, climate and biology is almost unimagined. Meso-scale processes (e.g., eddies) have been inferred but have only been glimpsed in a few locations.

The current push for real-time observations (e.g., SEARCH (Study of Environmental Arctic Change) and DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Longterm Environmental Studies)) will build understanding of the contemporary environment and augment the few locations with relatively long land-based records. The study of the central basin will require building upon the success of the International Arctic Buoy Program (IABP) to develop more sophisticated drifters and the implementation of the Arctic Ocean Observing System (iAOOS). A permanent, autonomous instrumented presence is required in the Arctic Ocean to observe the dramatic seasonal variations in this heterogeneous, locally and seasonally inaccessible basin.

While a year round presence will be necessary to study seasonal changes, larger scale studies will be needed to connect restricted but densely instrumented areas to regional processes. It is known that many of the large bathymetric features in the basin direct and shape circulation. Mapping of these features, in conjunction with detailed oceanographic work, is the best means both to understand the processes in place and to make use of available logistical resources (e.g., icebreakers and submarines).

Essential to studies of change is the ability to integrate data sets across time scales ranging from minutes to centuries. The push for observatories (e.g., SEARCH and DAMOCLES) is critical to the collection of measurements that fully characterize present conditions, but is not sufficient to enable the reconstruction of past conditions. Acquisition of historical records and compilation of archives into coherent structured data bases will be necessary to support synthetic study of the Arctic Ocean and modeling that will link these observations. The legacy of this work will be the data sets that future generations can use to assess the earth and to understand, more clearly than we can today, how the planet has changed.

### 4.1.2. Historical Studies

The unexplored history of the Arctic Ocean may tell much about the future. Arctic climate has changed dramatically since the end of the Cretaceous Period as connections to the World Ocean have opened and closed. These gateways influenced global circulation and substantially modified equator to pole climatic gradients. Since the Mesozoic Era, tectonic, primarily extensional, processes created bathymetry, shaping exchange with the World Ocean and circulation within the Arctic Ocean.

The formation of the Arctic Ocean changed the climate of the surrounding continents. Reconstructing the history of the Arctic Ocean and the opening and closing of its various gateways (e.g., Bering Strait, Fram Strait, Cretaceous Seaway) would define the high latitude boundary conditions for world climate and substantially improve how we understand the surrounding continents.

Understanding the contemporary oceanography of the Arctic Ocean will provide context to these historical studies, but the only way to reconstruct the history of the Arctic Ocean, spanning a transition from near tropical conditions in the late Cretaceous Period, through the Pleistocene glaciation, to the present conditions of rapid change, is to recover the long records preserved in the sediments below the seafloor. A coupled program to study the present conditions, map the seafloor, collect geophysical data and, ultimately, to drill into the sedimentary section would make it possible to recover the records of the climate experiments the unobserved earth has conducted since the end of the Mesozoic Era.

It is not possible to understand the earth as a set of isolated fragments. Tectonic and climatic processes connect remote regions of the globe across great distances. Truly global understanding of tectonics, climate, and climate history awaits the results of aggressive study of the deep Arctic Ocean.

### 4.2. Focus

The goal of this ICARP II science plan is to define a set of pressing science questions that can be addressed using available or developing technology over the next ten years. These questions are, in large part, defined by the dramatic changes sweeping across the high latitudes, as revealed by changing sea ice thickness and extent, water temperatures, vegetation distribution, and storm intensity and frequency. These changes have already had serious consequences for human habitation at high latitudes and will, as they progress, have further consequences for humans worldwide and the ecosystems that they inhabit.

By summarizing and reviewing the available information from many disciplines, the Arctic Climate Impact Assessment (ACIA, 2004, 2005) made the first step toward understanding these processes and framing research questions that will motivate study of the deep Arctic Ocean for the next decade. This ICARP II science plan builds on that foundation to highlight particular needs and opportunities for arctic science in the coming decade.

### 4.3. Key Scientific Questions

In the central Arctic Ocean, water can be found in all three phases throughout most of the year. Waters derived from rivers, adjacent continental shelves, and two connected oceans circulate, exchanging heat and material. In this heterogeneous environment, plants and animals thrive and disappear, taking advantage of local habitat and responding to highly variable conditions.

Understanding the contemporary coupled processes that drive the exchange in the basin will require spatially integrated observations unified by modeling. The bathymetry and structure of the Arctic Ocean define circulation in the deep basin today. Knowing when gateways opened and closed and how the bathymetry developed over time are critical boundary conditions for paleo-oceanographic study. Scientific drilling will be necessary to elucidate the transition from near tropical conditions in the Eocene to the present day.

The coupled processes at work in the Arctic Ocean are not amenable to isolated study by the traditional disciplinary divisions of contemporary oceanography. In the following sections, key scientific questions are defined by discipline; however, successful research programs should be integrative, synthetic, and multi-disciplinary to make the most of limited access and logistical resources.

#### 4.3.1. Biology

Life in the Arctic Ocean survives through dramatic seasonal variations. At all trophic levels habitat is defined by ice and mixing seawater. These remote isolated ecosystems may be refugia for unusual life forms unique to the Arctic. Understanding how this heterogeneous environment shapes the contained ecosystems and how these ecosystems will change over time are critical goals for future work.

Because arctic ecosystems are adapted to extreme environmental conditions with large seasonal forcing the increasingly rapid rate of recent climate change poses new challenges to the resilience of arctic life. The entire system – including the central Arctic and the deep basins – is likely to be severely stressed by changing ice and water conditions, varying primary production and food availability to faunal communities, an increase in contaminants, and possibly increased ultraviolet radiation. As the environment changes at a rate beyond the adaptive capacity of some arctic populations, ecosystems may not be strong enough to withstand the sum of these factors which might lead to the elimination of some habitat niches, species, and communities. This is especially the case in the central Arctic Ocean where we can only speculate about the fate of biological communities because the data base on existing species is extremely limited.

*How has life adapted to the strong seasonal cycle in the Arctic and to sea ice?* During numerous international expeditions many biological samples have been taken and analyzed with regard to species distribution, and to the levels of primary and secondary production during summer months in the ice-free areas of the arctic shelf seas. Severe ice conditions restrict access such that little is known about biological processes beyond the easy access areas in the marginal ice zone near shore. As a result, there is only limited information about species composition and distribution in the three marine subsystems (cryosphere, pelagic, and benthic realm) of the central Arctic Ocean. Limited access limits observations to the summer season. The biological seasonal cycle as it is manifest in reproductive cycles, over-wintering strategies, and metabolic adaptations during winter, is almost completely unknown.

*What are the interactions between shelf, slope, and deep-sea ecosystems in the Arctic?* In contrast to the Antarctic, the Arctic Ocean is surrounded by landmasses. The surrounding continents restrict and deliver freshwater through rivers to the basin. About 10% of the global river runoff is delivered to the Arctic Ocean, which contains 25% of the World Ocean's shelf area. The freshwater discharge helps maintain the stable halocline, supports sea ice formation and primary production, and delivers huge amounts of sediments, nutrients, and pollutants from the river mouths via estuaries into the shelf seas and the adjacent deep basins. For the Eurasian Arctic a total annual discharge of 2960 $km^3$ freshwater containing 115 million tonnes of total suspended matter was calculated by Gordeev et al. (1996). Past European projects like OMEX (Ocean Margin Exchange) clearly indicated the importance of particulate matter transport from the shelves into the deep-sea ecosystem.

This transfer of water, sediment, and dissolved species across the shelf influences the deep basin. Freshwater mixes with marine water on its way north, altering dissolved and particulate matter and so modifying the availability and distribution of nutrients in the water column.

*What nutrients pass through the marginal shelves into the deep basins?* In the course of the past decade the importance of marine organisms in the carbon and nitrogen cycles, the so-called biological pump, has been thoroughly investigated. One result of this was the discovery that settling particles transfer carbon from the photic zone down to the seafloor, influenced by complex interactions between phytoplankton and zooplankton. It also became clear that the continuous particle exchange between the sediments and the cloudy zone near the bottom plays an important part in the scheme of individual element cycles. Annual cycles of particle fluxes have previously been studied at great depth in the adjacent Nordic Seas. Particulate organic carbon flux to the seafloor has only been investigated in a few regions adjacent to the Arctic Ocean. In the entire Arctic Ocean, only data from a few short-term deployments along its fringes (north of Spitsbergen, and the Nansen, Amundsen, and Makarov Basins) and one long-term deployment from the Lomonosov Ridge (close to the Laptev Sea) are available.

*What determines the biodiversity in the central Arctic Ocean?* There is evidence that higher species diversity may help stabilize ecosystems against disturbances. During disturbances, closely related species may take over the eco-functional role of an extirpated species. The few quantitative zoobenthos samples taken in some of the permanent ice covered regions of the Arctic gave moderately high diversity indices for the macrozoobenthos. Because large motile epifaunal organisms modify and structure the sediment surface ("benthic engineering"), thus creating microhabitats for smaller species, any loss of large species should consequently also lead to a loss of such habitats and their inhabiting species.

Any discussion about marine biodiversity must be supported by systematic sampling to establish baseline conditions and identify shifts in distribution patterns of species. Systematic sampling of the arctic marine biosphere should be one of the main objectives in future research and should focus on the possible effects of loss of key species at different trophic levels of the ecosystem as well as on the effects of invading ("alien") species favored by environmental changes. Special attention should be paid in the future to bacterial communities because of their significant contribution in organic matter transformation.

*How will climate change affect ecosystems and biodiversity?* Considering the anthropogenic influence on biological diversity, a discussion of the significance of individual species for the stability of ecosystems has been developing. In the marine ecosystem there is a notable tendency toward loss of species diversity in coastal shallow water regions. These areas are important for human use and activity. An important topic of future research is how a change in diversity affects the dynamics of the high Arctic material cycles. This kind of study should consider more strongly the role of individual species – in terms of their ecophysiological and genetic variability – than has previously been done. Some further aspects of future biological research should ascertain the effects of species loss and immigrating species on the biogeochemical material pathways and on the stability of arctic deep basin ecosystems, to elucidate species-specific contributions of the many locally occurring bacteria to the current material turnover and verification as to how this contribution varies with changing environmental conditions, or to clarify the connection between diversity and stability in pelagic and benthic communities of the arctic deep basins.

*What is the nature of the deep biosphere of the central Arctic Ocean?* The microbiology of the deep ocean floor is at the center of interest in marine research. Estimates suggest that highly specialized bacteria living in the sediments down to several hundred meters below the seafloor make up at least 10% of the global biomass. The unique environmental conditions lead to the development of highly specialized communities of organisms. Owing to the great diversity and unique physiological development, micro-organisms and symbionts in the deep sediment layers are suspected to hold important biotechnical potential, for example, for the processing of pollutant-containing waste material or as raw material for pharmacological products. It is therefore an important area of research to determine their life strategies, how large and active these ecosystems are, how they vary with different sediment types and tectonic structures, and the biochemical reactions that are taking place.

The 1800 km long Gakkel Ridge is the segment of the global mid-ocean ridge system with the slowest spreading rate. Despite low heat flow, which would predict little or no hydrothermal activity along such ultraslow-spreading ridge systems, data collected during a joint expedition with the US Coast Guard icebreaker *Healy* and the German RV *Polarstern* indicate hydrothermal activity (Edmonds et al., 2003). Owing to the isolation of the Gakkel Ridge from other ridges (there is only the Fram Strait serving as deep-water connection to the north Atlantic Ocean) faunal exchange between hydrothermal vent communities might be limited, suggesting that the communities along the Gakkel Ridge may be unique.

### 4.3.2. Geology and Geophysics

Based primarily on observation of the circum-arctic continents, the deep polar ocean has evolved over the last 150 million years. It was probably a closed basin through most of the first 100 million years of its history except for one or two shallow seaways. The opening of a deep-water connection to lower latitude water masses is a relatively recent event, developed within the last 10 to 20 million years. Tectonic activity created the basin and has modified its internal structure over time, changing circulation within the ocean and exchange with the World Ocean.

Tectonic motions between crustal blocks have controlled the physiography of the polar basin, constrained paleo-oceanographic circulation and influenced paleo-climate, leaving a record in the sediments draping the bathymetric features. With ACEX drilling on Lomonosov Ridge completed (Shipboard Scientific Party, 2005), there is now an observational record spanning much of the history of the Eurasian Basin. Far less is known about the oldest polar sub-basin, the Amerasian Basin, partly due to lack of recognized plate boundaries. These boundaries must exist to explain the basin history. Identification of these structures will make it possible to reconstruct the development of the basin, and will substantially improve how the history of the surrounding continents is understood.

To establish a tectonic model for the high Arctic, bathymetry, potential field data, seismic reflection data, and cores are needed. Several geophysical expeditions were successfully conducted over the last decades. The resulting data provide a first insight into sediment distribution and the tectonic evolution of the basins and ridges. Continued acquisition of these data is necessary to address the scientific problems outlined below.

Mapping the deep basin, collecting multi-channel seismic reflection data, and sampling the sedimentary record by drilling are the primary means to reveal its history. Despite improved icebreaker support, multi-channel seismic investigations are sparse in the central Arctic Ocean. The present inventory includes approximately 15,700 km of seismic reflection data acquired from drifting ice stations and roughly 6700 km from modern ice-breakers (Kristoffersen and Mikkelsen, 2004). The dense pack ice prevents easy towing of seismic gear (airguns and streamer). Standard seismic operations in the central Arctic use short streamers (300 to 600 m active length) and small airgun arrays to retrieve structural information for the sediments. In addition, sonobuoys are regularly deployed to retrieve seismic velocity information to depth-convert the data. Improving towing methods for multi-channel seismic gear in the pack ice will improve the data, which will enable follow-on scientific drilling legs.

While over 1000 sediment cores have been raised from the deep basin, only a few are longer than 10 m (Kristoffersen and Mikkelsen, 2004). Collecting cores that span the history of the Amerasian Basin and reveal the post-Mesozoic climatic evolution will require dedicated scientific drilling legs to the Arctic Ocean.

### *Amerasian Basin*

The geological history of the Amerasian Basin is poorly understood, in part due to the lack of identified plate boundaries. These boundaries must exist to explain the basin history. Identification of these structures will make it possible to reconstruct the development of the basin, which will substantially improve how the history of the surrounding continents is understood. There are four particular problems to be resolved.

*How did the Canada Basin open?* According to Carey's (1958) model, which is the most widely accepted today, largely due to the absence of new data, the Canada Basin opened like a pair of scissors. This was accomplished by a counterclockwise rotation of the North Alaskan-Chukchi Microplate (Arctic Alaska Plate) by 66 degrees and resulted in a collision with the Siberian/Omolon margin. However, the time and geometry of the opening are not properly constrained. Although many researchers believe it happened between 130 and 120 million years ago, geological data from the Siberian margin tend to suggest a different age for this event. Moreover, a uniform rotation of the North Alaskan-Chukchi Microplate by 60 or 66 degrees causes significant overlap in Eurasia that cannot be explained by later rift-related extension of the East Siberian continental margin.

*What was the pre-drift setting of the Chukchi Borderland?* If the Amerasian Basin is restored to its pre-opening configuration, the Chukchi Borderland prevents complete closure of the Canada Basin between the hypothesized conjugate Alaska and Canadian margins. Geological and geophysical data suggest it was initially part of the North Alaska-Chukchi Microplate. One of its most preferable pre-drift positions could be found close to what is now the northeastern margin of the East Siberian Sea.

*How did the major ridges in the Amerasian Basin form?* What is known today about the Alpha-Mendeleev ridge system may be explained as a hot spot track (Lawver and Müller, 1994). The time and geodynamic framework of this process remain elusive. Some observations are inconsistent with this hypothesis. Exposed on the East Siberian margin, near the southern termination of the Mendeleev Ridge, is a huge area of Mid-Cretaceous flood basalts. Investigation of this volcanic area and the conjugate volcanics on Ellesmere Island near the southern termination of the Alpha Ridge will shed more light on initial stages of the ridge formation. Glimpses into the Late Cretaceous paleo-environment are provided by short cores containing black marine shales suggesting oxygen-deficient or oxygen-free conditions along flanks of a chain of islands and also younger laminated siliceous oozes that may relate to an upwelling system.

*Where are the Early Tertiary plate boundaries in the Arctic?* Intense Late Cretaceous-Cenozoic extension of the Laptev continental margin was related to the opening of the Eurasian Basin. Total opening in the eastern Eurasian Basin adjacent to the Laptev Sea accounts for about 450 km whereas rift-related extension of the Laptev Rift System totals 200 km. This suggests that more than 200 km of the "missing" relative motion between the North American and Eurasian plates have to be attributed to an extensional system elsewhere in the Arctic. Extension structures previously found in the East Siberian and Chukchi Seas as well as at the Chukchi Borderland have to be examined in terms of their contribution to compensate for the total opening of the Eurasian Basin.

***Eurasian Basin***

Propagation of the Gakkel Ridge northward created the Eurasian Basin. Spreading rates range from 0.5 to 1.25 cm/yr full rate, slower than any other ridge. Two important consequences of ultra-slow seafloor spreading are the great depth of the ridge axis, at more than 5000 m, which is, on average, twice as deep as most other ridges, and the strong relief and blocky seafloor morphology on the ridge flanks. The tectonic history of the Eurasian Basin is not controversial, but the ultra-slow seafloor spreading processes that created it raise a wide range of questions about seafloor spreading and continental extension.

*What is the relationship between segmentation of the Gakkel Ridge and ultra-slow spreading processes?* Segmentation was observed during the AMORE cruise in 2001 (Michael et al., 2003). This segmentation was expressed as a change from volcanic crust to altered peridotites and gabbros on the seafloor. The abrupt transition from volcanic crust to non-volcanic crust, predicted by Coakley and Cochran (1998), suggests that a threshold has been exceeded in the seafloor spreading process.

*Why has the axial geometry of the Gakkel Ridge not changed since rifting?* The Gakkel Ridge has no transform faults from Greenland to the Laptev Shelf. The morphology of the ridge conforms to the shape of the Lomonosov Ridge and the Barents Shelf, suggesting it is inherited from the original rifting event. How this morphology has been preserved through approximately 60 million years of seafloor spreading is a critical question for understanding mid-ocean ridge tectonics and the evolution of transform faults.

*What structures connect seafloor spreading on the Gakkel Ridge to continental extension on the Laptev Shelf?* The northern Laptev Sea represents one of five presently known sites of a spreading ridge/continental edge intersection. These areas of rift to drift transition attract increasing attention as unique natural laboratories to study breakup of the continents and the influence of rheology on structures. Moreover this is a unique case when the slowest spreading is happening under a thick pile of the sediments derived from adjacent land.

**4.3.3. Oceanography**

In the Arctic Ocean, a relatively thin layer of fresh surface water and its associated cold halocline, whose origins lie partly on the shelf, insulate the ice from an underlying warm and saline water mass of Atlantic origin – the only significant source of heat within the Arctic. During the 1990s, the distribution of this fresh insulating layer was observed to change, while at the same time, the temperature and extent of the warm Atlantic-derived layer were observed to increase, probably due to a warming and strengthening of the Atlantic water inflow from the Nordic Seas. The boundary between the Atlantic and Pacific water types was pushed east into the Canada Basin to an extent not previously observed. Both these changes potentially have crucial consequences for arctic sea-ice cover.

*How is the Arctic Ocean affected by large-scale climate variability and change?* Oceanic heat imported from the North Atlantic has the potential to affect ice cover in the Eurasian Arctic, while the Arctic Ocean itself plays a major role in collecting and delivering freshwater to the North Atlantic. The 10% of the global river runoff that is delivered to the Arctic Ocean is exported into the North Atlantic where it may impact upon the global oceanic thermohaline circulation. A better understanding is needed of the large-scale circulation in the Arctic Ocean, changing sea ice conditions, two-way exchanges with the North Atlantic, and the balance of local and remote forcing which causes this system to change (e.g., the recently discovered connections between the North Atlantic wind stress curl and volume transport in the Norwegian Atlantic Current, or the hypothesized link between successive warming events in the Norwegian Sea, Fram Strait and the Nansen Basin). Since these connections offer the possibility of prediction, they are important to the integration of observations and modeling.

The sources of the freshwater for the Arctic Ocean – the discharge of the circum-arctic rivers and the relatively fresh Pacific surface water which enters through Bering Strait – are both subject to change as are their circulation and residence times within the Arctic Ocean. For example, the more anti-cyclonic Arctic Ocean circulation during the low-index phase of the North Atlantic Oscillation (NAO) is thought to lead to an accumulation of freshwater in the intensified Beaufort Gyre before being released to the North Atlantic Ocean, with the opposite sense of change during the NAO-positive phases. In the cyclonic/NAO-positive phase of the 1990s the upper ocean was more saline in the Amundsen and Makarov basins but both warmer and substantially less saline in the Canada Basin than in previous years. High-density waters form on arctic shelves through brine rejection during freezing and drain down-slope where they encounter the circum-arctic boundary current. Together with the water that they entrain from this current, they contribute about 30% to the dense water that overflows from the Nordic Seas to “drive” the abyssal limb of the Atlantic Meridional Overturning Circulation. The shelves also form the conduit for particulate matter, nutrients, dissolved inorganic and organic carbon, dissolved metals, and a range of other contaminants. Large methane pools within the sediments of the circum-arctic shelf are a potential major contributor to atmospheric greenhouse gases. Changing the ice cover, and heat and freshwater storage and circulation on the shelves will alter the amount, density, and contaminant loading of the sinking shelf water in an as yet unpredictable way.

In order to understand the variability of the ocean circulation and how it relates to the Arctic Oscillation, it will be necessary:

- to document and understand the variation of the exchanges with the North Atlantic and Pacific by observing fluxes through the major gateways;
- to document and understand the pathways and residence times of the freshwater in the Arctic Ocean;
- to study the mechanisms of the redistribution of oceanic heat within the central Arctic Ocean;
- to study the modification of shelf water, its conversion to dense water, and subsequent convection and communication with the central Arctic via the continental slopes;
- to assess the heat flux from the Atlantic layer in the central Arctic to the ice and atmosphere; and
- to identify the “switchgears” that determine to what degree arctic freshwater will be released to the Atlantic “conveyor” or retained in the Arctic Ocean.

To accomplish this it will be necessary to end the bias towards summer observations by implementing observational systems capable of year-round operation. The observations must be integrated by combining them with output from dedicated regional and global scale numerical modeling.

Modeling integrates data by imposing the coherence of physics on a set of diverse observations. To use models well, it will be necessary to study and understand sub-grid scale processes, especially turbulence, and develop effective techniques to parameterize these processes.

*How are tidal and wind energy converted into turbulence in the ocean interior?* Mixing in the deep basins of the Arctic appears to be necessary for the ventilation of the deepest water masses. The traditional view of turbulence in the ocean interior at mid-latitudes is that propagating internal waves are generated at the ocean boundary. The energy sources are tides at the ocean bottom, and winds at the surface. Outside of surface and bottom boundary layers, the energy to support turbulent mixing comes from radiating internal waves. Since the inertial period in most of the Arctic Ocean is shorter than the tidal period one special characteristic of the Arctic is that forcing at tidal frequencies cannot linearly excite propagating waves throughout much of the Arctic Ocean. Therefore, a significant energy input into internal oscillations that would, at lower latitudes, radiate and fill the ocean interior with wave energy is instead trapped near the lateral boundaries or in halos of turbulence above rough topography. This means that in the deep basins of the Arctic Ocean, away from the topography, there is little energy available for mixing. Observations indeed substantiate this. Near lateral boundaries it seems that tidal energy input goes either into topographically trapped waves or boundary layer turbulence.

*Are there other important mixing processes?* Another mechanism for mixing is entrainment as dense overflows cascade from the shelf. Cascading is an episodic phenomenon, whereas the tides are always present, and it is not clear what the relative contributions are of the various mechanisms for mixing at the ocean boundaries. In the interior step-like vertical structures with almost homogenous layers separated by strong gradients and horizontally interleaving water masses forming layers with inversions in salinity and temperature are present. The formation of these structures has not yet been adequately described but they both may, because of the unstable distribution of one of the components and the different diffusivities of heat and salt, release potential energy of the stratification and contribute significantly to the vertical and horizontal redistribution of heat and salt in the interior Arctic Ocean.

*How can vertical mixing be parameterized for ocean modeling?* Arctic Ocean models are sensitive to the parameterization of vertical mixing, yet how to parameterize boundary layer and interior turbulent mixing in manner that is particular to the Arctic is not clear. Process studies of these phenomena are called for. These studies should take the form of coordinated field programs combined with numerical and theoretical investigations. A tremendous amount of progress has been made in the last decade in refining parameterizations of interior mixing in the low-latitude ocean. If efforts are focused on Arctic Ocean specific mixing processes, similar progress in quantifying, and importantly, parameterization of ocean mixing can be expected. Regional ocean models have just begun to achieve resolutions capable of carrying internal wave spectra that are suitable as inputs into such parameterizations.

#### 4.3.4. Paleo-oceanography

Paleo-oceanography and paleo-climate studies deepen understanding of the present by revealing how the earth was once different and how it came to be as it is today. In view of the profound changes that are underway in the Arctic Ocean system such as the shrinkage of ice cover, the increase in freshwater inputs, the warming of water masses, and associated changes in circulation and heat balance – it is necessary to evaluate the past changes in the system and the unique feedback mechanisms that operate within the region on a variety of timescales. These tasks require the use of scientific drilling supplemented by enhanced coring techniques and identification of optimal coring sites. For example, the recovery of pre-Quaternary sediments requires sedimentary records significantly longer than those typically collected in the Arctic Ocean, and the Holocene study needs identification of sites with high sedimentation rates to achieve sub-millennial age resolution.

One goal is to examine records of extensive ice cover as well as ice free and warmer than present day conditions to address how these environmental extremes feedback on global climate/ocean dynamics. Short-term climatic events such as the Little Ice Age and the Medieval Warm Period should be related to longer-term arctic variability expressed in glacial-interglacial cycles and events like the Paleocene Eocene Thermal Maximum (PETM) and the Eocene/Oligocene transition. What role did the Arctic play in driving these events in terms of precipitation, river discharge, and freshwater export? What are the possible feedback mechanisms specific to the Arctic that help to regulate things like temperature, heat and moisture transport, and carbon cycling?

During the Arctic Coring Expedition (ACEX) a unique sedimentary record was recovered. These sediments preserve a record from the "Eocene Greenhouse climate" when the earth was at its warmest, before a long interval of gradual cooling, which led to the Pleistocene Ice Ages and then to today's climate. For much of the Cenozoic, the sediments recovered during ACEX are the first ever seen from this crucial period. The time series extracted from these sediments will complement records collected at lower latitude through scientific drilling in the oceans and ice coring of glaciers. Further scientific drilling in the Arctic Ocean would make it possible to study the history of water fluxes into the basin, latitudinal gradients, and sediment fluxes from shelf to the deep basin.

A necessary condition for successful paleo-oceanographic studies is the development of a reliable chronostratigraphic framework for Arctic Ocean sediments. Currently there exist conflicting views on this chronostratigraphy, which significantly restricts our ability to generate meaningful paleo-oceanographic interpretations as well as correlation and integration of results with regions outside the Arctic Ocean.

A variety of paleo-climatic proxies applied to marine sediment cores to produce high-resolution paleo-environmental records is needed. Any number of geochemical and paleo-oceanographic techniques could be applied. For example, changes in temperature could be addressed through $\delta^{18}O$ and magnesium:calcium (Mg:Ca) ratios in foraminifera and UK37 biomarkers, while changes in nutrients could be addressed though foraminiferal cadmium:calcium (Cd:Ca) and barium:calcium (Ba:Ca) ratios.

There are several specific questions related to the paleo-climatic/paleo-oceanographic history of the Arctic Ocean that are important.

*What is the significance of extrinsic cycles in the deep Arctic Ocean?* Milankovitch cycles are dominated by obliquity prior to 900 ka. Eccentricity dominated 900 ka to present. How does this manifest in the higher latitudes? In order to see the global impact, environmental variability in the Arctic should be examined in relation to climate states at lower latitudes. This could be addressed through high-resolution time series and spectral analysis. It is also important to identify patterns of climatic change on time scales ranging from annual to millennial and to compare these with observed oscillations such as the Arctic Oscillation, North Atlantic Oscillation, and Bond Cycles. Fundamental to understanding cyclicity and driving mechanisms for these climatic events is the availability of accurate stratigraphy and geochronology, calibrated with various modern climatic variables.

*Where do methane hydrates exist in the Arctic and how were they different during warm periods such as the PETM?* How/when were they formed? How much is there now? Is there evidence for methane hydrate flux in the Arctic contributing to global climate change in the past? If the Arctic continues to warm, how will the destabilization of clathrates contribute to the climate system? Seismic mapping and foraminiferal $\delta^{13}C$ and Ba:Ca ratios may be used.

*What is the history of deep draft ice in the central Arctic?* Dramatic changes occurred in arctic oceanography during glacial-interglacial cycles, driven by sea-level variations and the formation of huge ice sheets at the ocean periphery and ice shelves over the deep basin itself. Investigation of paleo-oceanographic changes for the Quaternary period should be coupled with reconstruction of Pleistocene ice sheets on the arctic margins and deep-draft ice in the interior of the Arctic Ocean. Available data indicate that armadas of closed-up mega-bergs and/or cohesive ice shelves with drafts of five hundred meters (Polyak et al., 2001) or more extended into the Arctic Ocean several times during the Pleistocene and from several sides of the basin. Understanding of the extent and pathways of these ice masses and their interaction with ice sheets at the margins is critical for evaluating the glacial mode of the arctic circulation and is much needed for paleo-climatic models. This investigation requires collection of multi-beam bathymetry and/or sidescan records coupled with penetration sonar profiling from the plateaus and ridges in the Arctic Ocean, ground-truthing of these geophysical data with sediment cores, and eventually modeling the distribution of ice masses and their impact on the circulation system.

In the context of dramatic changes in the arctic oceanography and ice cover during the Quaternary, it is also important to understand how the presence or absence of ice affected the arctic biota. Getting insight into this question may help to assess the future changes in the arctic ecosystem that are imminent in view of the modern climatic change.

**4.3.5. Sea Ice**

Under the present climatic conditions, perennial sea ice covers the deep basin of the Arctic Ocean. The extent of the arctic sea-ice cover has been decreasing over the past three decades (Cavalieri et al., 2003). During the peak of the summer melting season in 2002 it reached a record-minimum for the period of satellite observations, and near record minimum conditions have returned in the subsequent summers (Stroeve et al., 2005). In terms of spatial variability anomalously low sea-ice concentration has occurred repeatedly in specific areas such as the Nordic Seas, and parts of the Chukchi Sea and the Canada Basin. Studies have suggested the thinning of the arctic sea-ice cover in recent decades, although it is difficult to quantify changes in sea-ice thickness and their spatial extent (Rothrock et al., 2003). The changes in both the extent and thickness of sea-ice raise the question of whether they are part of natural variability or forced responses as an arctic manifestation of global climate change. In addressing this question, several issues are particularly relevant to the overall theme of this ICARP II science plan.

*Is this sea-ice retreat an isolated event in the historical context?* A significant part of our understanding of sea-ice conditions over the deep basin of the Arctic Ocean comes from satellite observations, which are only available back to the 1970s. For successful development of scientific strategies it is important to recognize two characteristics of the present sea-ice changes. One is a spatial pattern in sea-ice changes and the other is covariability with other climatic changes. The observed retreat of the summer ice is spatially concentrated in a certain section such as the Chukchi Sea and the Canada Basin. This may indicate the presence of a critical region(s) for arctic climate change. It is also known that changes in the arctic sea-ice are co-varied with other climatic changes in the northern high-latitudes (Serreze et al., 2000). This relationship can be exploited for the construction of multi-proxy paleo-climate records. In this regard, an important question is whether there is a critical region in the Arctic in which climate changes are more pronounced or more frequent relative to other areas, in both historical and present timeframes.

*What are the mechanisms for the changes in sea-ice conditions?* The repeated appearance of the low summer ice concentration in specific areas is suggestive of an ice-albedo feedback. To understand the extent to which this mechanism is responsible for the current sea-ice retreat, it is urgent to establish an observational plan for hydrography along with the surface energy balance over a complete annual cycle(s) for this seemingly critical region.

At inter-annual time scales, the summer sea-ice extent of the Arctic Ocean is significantly correlated with hemispheric-scale anomalous atmospheric circulation. The temporal and spatial structure of the northern hemisphere sea-ice variability is closely related to climate changes and variations in the mid-latitudes (Ukita et al., 2006). Inter-annually, the Arctic Oscillation is significantly correlated with the variation in sea surface temperature in the tropics. In agreement with these observations, model studies suggest a forcing role of sea surface temperature variation in the tropics in climate changes in the northern high latitudes (Hoerling et al., 2001). The variations and changes in the sea-ice conditions of the deep Arctic Basin thus must be examined from a global perspective. In this respect, a particularly relevant question is how oceanic and atmospheric influences from the lower latitudes impact on climate changes in the high Arctic, which must be addressed in the context of the global energy balance and the water cycle.

*How does the annual cycle of sea-ice accretion and decay vary across the Arctic Ocean?* Sea ice waxes and wanes with the changing seasons. While the overall pattern is clear, the variations in this process, both regionally and inter-annually are not well understood. Ice buoys, drifting ice camps, and moorings support study of the evolving ice. The role of snow accumulation and its affect on albedo and energy balance is of particular importance.

*What is the predictability of sea ice?* Global models routinely assimilate atmospheric data to produce forecasts. Sea ice and snow cover information are increasingly available at synoptic time scales and for large regions. The ability to assimilate this cryospheric data will help to improve understanding of the way sea ice is represented in models, and the physics of sea ice and snow dynamics, and thermodynamics. In addition, the ability to provide accurate and timely sea-ice forecasts has the potential for greatly improving the planning process. In particular, the ability to relate the global oscillation (such as the Arctic Oscillation) to sea-ice conditions may help to determine the optimum season and year for accessing a specific location.

**4.4. Scientific Approach**

As discussed in the previous sections, many fundamental scientific problems can be addressed in the deep Arctic Ocean. Some of these problems are unique to the Arctic Ocean while others are framed by studies conducted at lower latitudes. Solution of these problems will require new data collected across the individual basins and ridges that make up the Arctic Ocean. The expense, difficulty, and rarity of appropriate logistical support argues against continuing in the single investigator, single hypothesis, single platform mode that has been typical of previous efforts. Advancing understanding of the deep Arctic Ocean through this time of dramatic global change will require multiple coordinated, multi-disciplinary programs.

No single cruise can collect the comprehensive data sets necessary to resolve the coupled, regional problems outlined in this ICARP II science plan. Coordination of multiple programs is an appropriate undertaking for the ICARP II process and will, if well conceived, enhance what can be done with the resources at hand. This coordination can take a number of forms:

- coupling of oceanographic and geophysical research through cooperative utilization of logistical resources (e.g., ships);
- support for full-time underway data acquisition on all arctic research vessels;
- development of coordinated expeditions utilizing multiple platforms (e.g., submarines, icebreakers, aircraft);
- expansion of international cooperation;
- effective sequencing of successive expeditions to build coherent programs;
- preparations for and development of more scientific drilling expeditions; and
- improved sea ice forecasting and data assimilation.

Coordination of science programs across international and interdisciplinary boundaries is one way to improve utilization of available resources. It is unlikely that these resources will be adequate to address the pressing science needs in the deep basin. Some of the objectives detailed above will require new instrumentation or the enhancement of existing infrastructure. Owing to the lead-time for engineering and development, these objectives require immediate attention.

**4.5. Linkages / Users**

Linkages to other groups and programs include some dedicated arctic programs as well as others that have or should have an arctic component.

- ACIA (the Arctic Climate Impact Assessment; http://www.acia.uaf.edu/). The ACIA documents and process are the foundation for much of the ICARP II process. Climate change is a global issue and studies indicated that the Arctic is a particularly sensitive region to its effects. If the science issues are not fully engaged in the Arctic, there is a risk of being spectators and victims of climate change.

- DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Longterm Environmental Studies;http://www.damocles-eu.org/). This program is dedicated to developing a wide range of autonomous observational capabilities to support analysis and modeling of Arctic Ocean oceanography and circulation.

- ICARP II Science Plan 5 and ICARP II Science Plan 6. Together with ICARP II Science Plans 5 and 6, this ICARP II science plan covers the full extent of the Arctic Ocean. The distinction between these groups relies on important physiographic boundaries that are of limited significance for the oceanographic and geophysical study of the region. Coordination of the work arising from the three science plans is crucial to create a coherent plan for Arctic Ocean research within the ICARP II process.

- SEARCH (A Study of Environmental Arctic Change; http://psc.apl.washington.edu/search/). Dedicated to the development of onshore observatories, SEARCH has a blind spot in the central Arctic and, for the most part, ignores historical studies. The complementary studies outlined in this ICARP II science plan would substantially augment and extend the work proposed for SEARCH.

- IPY (International Polar Year; http://www.ipy.org/) proposals. An international proposal (POLARGATES; http://www.ipy.org/development/eoi/details.php?id=20) has been designated as one of the primary clusters under IPY. This multi-disciplinary proposal would look at how the gateways between continents have opened and closed over time, affecting polar climate (south and north), and ocean circulation. It is a fully bi-polar proposal grouped under the “global” theme by ICSU (International Council for Science).

- iAOOS (Integrated Arctic Ocean Observing System) is a multi-disciplinary, international proposal that seeks to develop an integrated system of observatories around the Arctic Ocean. It is assigned to the theme “Vantage Point – Observing Systems” by ICSU.

- The United Nations Convention on Law of the Sea (Article 76). The circum-arctic nations are obliged to conduct extensive surveys to document claims to expanded Exclusive Economic Zones under the new Law of the Sea Treaty. These surveys will be a resource for marine geological and oceanographic studies by expanding the available data set for the deep Arctic Ocean (see section 4.7).

- IODP (Integrated Ocean Drilling Project; http://www.iodp.org/). The success of scientific drilling on the Lomonosov Ridge during summer 2005 has opened the door for future scientific drilling in the high Arctic. A group has already submitted a pre-proposal for a drilling leg to the Alpha Ridge. Another group has formed to consider drilling on the Chukchi Plateau. A third group held a workshop in Fairbanks, Alaska in June 2005 to consider drilling in the Bering Sea.

- ARRV (Alaska Region Research Vessel; http://www.sfos.uaf.edu/arrv/). Final plans have been completed for this vessel, which will replace the University of Alaska’s *Alpha Helix*; the oldest ship in the US academic fleet. The new ship will be a light icebreaker, capable of working anywhere in the Bering Sea year round and in the peripheral Arctic Ocean for five to six months a year. It will be equipped with a suite of bottom mapping sonars and will be able to support standard oceanographic and fisheries studies as well as some scientific drilling. It is likely to be funded in the next US Federal budget.

- *Aurora Borealis*. There is broad support in Europe (and some support in the US) to build a new icebreaking drill ship that could work in the central Arctic. Some design work has been done for the *Aurora Borealis*, which is well-ranked for funding among large European Union science projects.

- OOI (Ocean Observatories Initiative; http://www.orionprogram.org/). The OOI is a large initiative at the US National Science Foundation, similar in scope and funding to the Ocean Drilling Program, that aims to develop a set of cabled seafloor observatories in US coastal and adjacent ocean waters. While the planning phase did not explicitly include an arctic component, groups are organizing to take advantage of OOI to support Arctic Ocean research (Coakley et al., 2005).

- AOOS (Alaska Ocean Observing System; http://www.aoos.org/). A group in Alaska has formed to coordinate ocean observations around the state. This program includes the Barrow Cabled Observatory (Coakley et al., 2005), which would place cabled seafloor instrumentation on the seafloor north of Barrow, Alaska.

- IABP (International Arctic Buoy Program; http://iabp.apl.washington.edu/). The IABP has been one of the most consistent, reliable sources of information about the central Arctic Ocean for many years. Expansion of this project would be a good start on future observatory efforts for the central Arctic.

- Galileo Project (http://polarfoundation.org/index.php?s=3&rs=home&uid=75&lg=en). There is an effort underway to repeat the drift of the *Fram*; the first arctic science cruise. This project could offer excellent opportunities for study of the Eurasian Basin and the ice pack.

**4.6. Outcomes / Achievements**

Over the last fifty years, much of the progress made in continental geology has built on the success of plate tectonics. Mapping of the arctic seafloor will establish the location, extent, and ultimately the history of the major ridges and basins that make up this composite basin. Understanding these features is critical to understanding the continents that ring the Arctic Ocean.

Establishing the linked oceanographic/climatic/tectonic history of the basin would eliminate much of the uncertainty that limits how global climate change can be interpreted, permitting better understanding not merely of linkages to events and processes at lower latitudes, but also to better study of the leads and lags in these systems. Ultimately this would lead to better understanding and predictions about the consequences of climate change, especially with respect to the arctic circulation and ice cover.

**4.7. Implementation**

The next round of study of the deep Arctic should begin with examination of the critical features in the basin. These initial studies can collect sufficient marine geophysical data to support planning for scientific drilling, outline the important oceanographic processes and collect baseline data sets for future cruises to build upon. Given the diverse questions to be answered, the wide range of spatial and time scales of interest and the urgency of the questions outlined in this ICARP II science plan, it will be necessary to utilize all available resources to understand the central Arctic Ocean:

- <u>Satellite observations</u>. Only satellites deliver synoptic data of the surface of the Arctic Ocean. Limited resolution and uncertain calibration require high resolution data to support good use of the excellent spatial coverage and repeat observations provided by satellites.
- <u>Expeditionary observations</u>. Icebreakers, ice camps, autonomous underwater vehicles, submarines, and aircraft, can study extensive areas and provide densely sampled data along tracks, supplementing remotely sensed images with ground truth. Different platforms have distinctive capabilities, opening possibilities and requiring intelligent planning for appropriate use of available resources. Only ships can directly sample the seafloor and the sediments beneath it.

- Autonomous instrumental monitoring. Ice buoys, drifters, and seafloor observatories can give a comprehensive view of the basin at times when and where expeditionary access is limited or precluded. Lagrangian drifters and buoys should be inexpensive enough to be widely dispersed, giving regional coverage. Cabled seafloor observatories should be considered for certain critical areas where inter-annual and seasonal variability are particularly important.
- Computer modeling and data analysis. Integration of data collected with varying resolution and over different intervals of time will require computer models that constrain the possible with the necessary physics of the ocean and atmosphere.

It is only in the last few years that we have had maps (e.g., the International Bathymetry Chart of the Arctic Ocean, Jakobsson et al., 2000, see Figure 4.1) of sufficient resolution to confidently formulate and test specific hypotheses about the various features, to understand how bathymetry and circulation interact, and to plan cruises to study particular provinces. By building on this regional understanding through a sequence of cruises, each dedicated to the problems defined by its predecessor, it should be possible to progressively focus on the critical regions necessary to answer the most important questions. A sequenced deployment of ships to resolve particular problems of progressively greater definition will make the best use of limited resources.

In many ways, the ICARP II process must rely on the initiative of individual researchers, mobilized by opportunities outlined in this ICARP II science plan, to create projects from the logistical resources they can mobilize and the funding they can arrange. One of the primary uses of this document is to identify limitations on science that will require planning (e.g., technological developments that are needed) and support opportunities that may not be widely known or understood.

***Article 76 Opportunities***

Article 76 of the United Nations Convention on the Law of the Sea allows certain coastal states with wide continental margins to establish sovereignty over non-living resources of the seabed beyond the customary 200 nautical mile limit (Exclusive Economic Zone or EEZ), when certain bathymetric and geological criteria are satisfied. All five coastal states that border the Arctic Ocean are eligible to extend their sovereignty in this fashion, into the so-called Outer Continental Shelf (OCS).

For a given coastal state, the decision to proceed with the implementation of Article 76 depends almost entirely upon the perceived nature and dimension of the submerged component of its land mass, defined as the *natural prolongation of its land territory*. Determination of the limits of a claim depends on analysis and interpretation of the shape of the seabed, the depth of water, and the thickness of the underlying sedimentary material.

In most cases, a review of the relevant morphological and geological data will first be undertaken to identify the seabed features beyond 200 nautical miles that the coastal state proposes to include within the new outer limit of its continental shelf. This initial assessment will seek to determine whether a geological or morphological continuity exists between the terrestrial framework and distant seabed features. The US has completed a significant inventory of existing information (Mayer et al., 2002), and is now mobilizing surveys within the Arctic region in order to augment existing databases.

This preliminary work is normally performed through an analysis of existing databases. In many if not most cases, it is likely to prove necessary to conduct fieldwork in order to acquire new data sets that better define the morphological and/or geological factors with a view to substantiating the coastal state's proposed OCS limit. In this context, defining the "natural prolongation" that serves as a basis for determining the OCS limit may require consideration and clarification of a region's tectonic framework and history, which in the process could be expected to shed new light on the transition zone between continent and deep Arctic Ocean.

Constructing the OCS limit also creates a need for better descriptions of the seabed and subsoil in areas that have been poorly mapped, leading to the mobilization of surveys that could transcend

Article 76 by shedding new light on the composition, distribution, and transport of seabed material – information that is essential for understanding erosional and depositional processes, and which can be of immense benefit for a broad range of scientific and environmental applications.

There is no more primary objective for a nation than establishing the limits of its territory. In some of the circum-arctic nations, Article 76 work has been extensive. In others, it lies mostly in the future. In the future work there is a logistical opportunity that could support science beyond the geophysics and seafloor mapping necessary to establish the limits of a claim.

***The Need for Further Scientific Drilling***

The sediments beneath the seafloor of the deep basin of the Arctic Ocean and the seafloor itself preserve the history of the Arctic Ocean. Scientific drilling is a necessary complement to contemporary time series as advocated by SEARCH.

Sediment accumulation in the deep polar basin is intimately linked to environmental factors such as erosion on the surrounding continents, oceanographic circulation, and water mass productivity. Scientific drilling is needed to access this formidable archive of paleo-environmental history beyond the short geological time spans captured by conventional sediment cores. In 2004, the first scientific drilling expedition into the central Arctic Ocean demonstrated that such cores could be recovered despite moving fields of sea ice. More than 400 m of section were recovered from the top of Lomonosov Ridge (Figure 4.2). This record of the polar environment spans the last 55 million years but marine sequences representing upper the Eocene to lower Miocene have not been recovered to date (Shipboard Scientific Party, 2005).

More drilling will be required to complete Cenozoic stratigraphic representation, to expand the coverage in time back to the initial birth of the deep polar basin about 155 million years ago, and to sample spatial differences imposed by evolving paleo-geography and latitudinal gradients. For instance, the implications of occurrences of glendonites are that even in a so-called “greenhouse” period, the arctic Cretaceous climate was not uniformly warm and equable, but experienced considerable variation where seawater temperatures were, at times, close to freezing.

Retrieving continuous records of the Cenozoic and Mesozoic stratigraphy of the Arctic will require sediment cores of several hundred meters length. The exact drilling locations are identified with geophysical surveys. This standard procedure prior to any deep scientific drilling worldwide is critical not only to locate sample sites, but also to provide stratigraphic and tectonic context to any drilling. New surveys will also enable the development of new theories about the history of the deep basins. Existing regional lines establish, with other geophysical information, a first order evolutionary model for the high Arctic. Before deep-drilling campaigns can be conducted such regional surveys have to be extended to show how typical the drilled structure for the region is, and especially to judge the success of drilling from experience of low latitude areas.

Two types of drilling targets can be identified: condensed sections on basinal highs and expanded sections in basin lows and close to continental shelves.

<u>Condensed sections on basinal highs.</u> On the Lomonosov Ridge, Chukchi Plateau, and Alpha-Mendeleev Ridges, the basinal highs are isolated from both turbidite sediments, which flood across the deep basin from the continental slopes, and from suspended sediments, due to their distance from major rivers discharging into the Arctic. Low sedimentation rates mean that long time records can be extracted from relatively short cores, which reduces time on site and may make it possible to drill into older sediments.

<u>Expanded sections in basin lows and close to continental shelves.</u> Higher sedimentation rates, found near the continental shelves, may be useful for better stratigraphic time resolution.

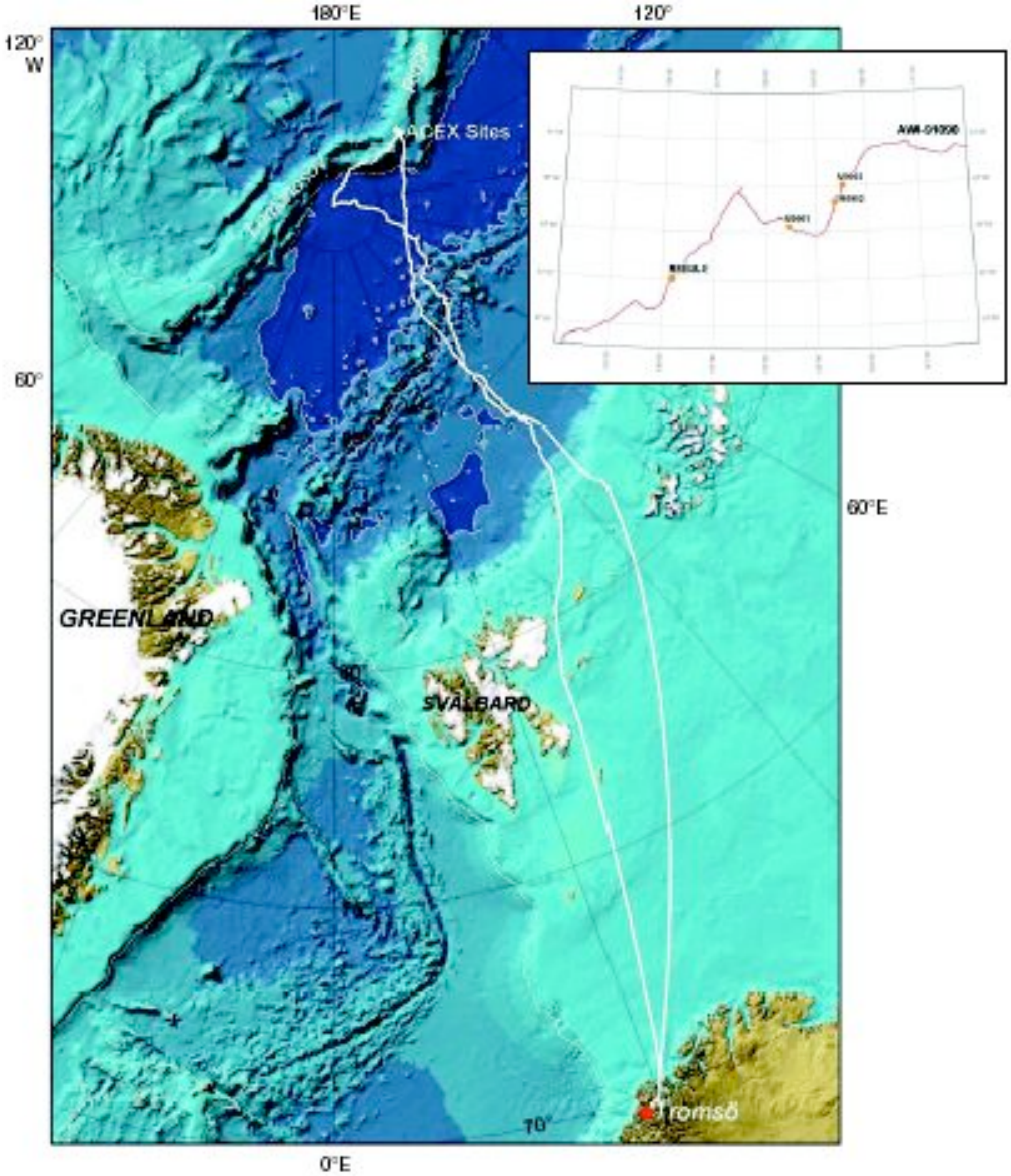


**Figure 4.2.** Track and location of the ACEX drilling on Lomonosov Ridge (Shipboard Science Party, 2005).

In addition to the global issues that will be addressed through scientific drilling, the Amerasian and Eurasian sub-basins of the central Arctic Ocean offer distinctly different opportunities for study. An integrated geophysical program could advance the study of particular features while developing the data base necessary to support scientific drilling.

### *Technology and Infrastructure*

Study of the deep Arctic Ocean, across disciplines, could be linked through a common vision for the future of arctic oceanography, where scientists will be able to access real-time data from a basin-scale network of year-round observing systems, and expeditions to study specific regions will be equipped with state-of-the-art underwater robotic systems as well as arctic-specific shipboard and towed instruments. Implementation of this vision will require substantial development effort.

To study the Arctic Ocean effectively, it will be necessary to adapt existing oceanographic and geophysical tools and techniques to the high Arctic environment. The arctic environment imposes unusual restrictions on instruments and operations. Unfortunately, instruments deployed in the Arctic have often been designed for use at lower latitudes and adapted for arctic use. To comprehensively study the Arctic Basin, both spatially and temporally, it is necessary to develop instruments specifically designed for (a) deployment from arctic research platforms and (b) long-term operation in the harsh environment (Pyle et al., 1997). To gain continuous access to the heterogeneous Arctic Ocean, development of real-time observational capabilities will be necessary. The cabled, seafloor instruments will augment occasional and seasonal ship access to the seabed, water column and sea ice.

Sea ice is both a hazard for cables and instruments and an object of study. Adapting oceanographic and geophysical instrumentation for the central Arctic Ocean and installing it on the seafloor is largely a matter of developing techniques to cope with the ice pack. This activity is critical to ending the bias toward summer observations in the central Arctic.

Satellite systems provide information on sea ice thickness, concentration, and velocity, and snow cover. Reliable access to continuous satellite observations is critical for continued monitoring of changes in the Arctic. The difficulties in access to the Arctic make satellite observations the only feasible means to monitor the region on a synoptic basis.

*Technological Needs*

With increasing instrumental and logistical demands, practical central Arctic Ocean research has developed into a high-tech operation, often requiring close international cooperation. For future missions, such as monitoring water mass modification and circulation, or seafloor observations, existing systems must be further developed. A mix of Lagrangian samplers (Proshutinsky et al., 2004) and fixed seafloor monitoring stations operating in conjunction with Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV) would be able to study the water column and seafloor in complementary ways that would maximize data coverage.

Cabled observatories will allow for the first time in arctic research dense real-time observation and control of the sensors via the Internet and satellites. Such long-term data are urgently needed to evaluate the actual status of the arctic ecosystem and to develop prognostic models about its future development. Guaranteed regular access to key locations should help to initiate interdisciplinary measurement programs. Deep basins, gateways, the ridges and locations at the continental margin should be considered for this arctic network.

Data acquisition from mobile platforms (both drifting and programmed) will complement the temporally very dense, but spatially restricted, data sets acquired at cabled seafloor observatories. A mix of instruments will be necessary to study the Arctic Ocean at the important spatial and time scales:

- bottom-moored instruments in key areas such as gateways, boundary currents, and identified slope convection sites;
- low cost, but numerous Ice Tethered Platforms (ITPs) equipped with vertical CTD (conductivity-temperature-depth) and velocity profilers;
- sea-gliders measuring profiles of temperature and salinity for dedicated missions along transects (communicating with ITPs and moorings through acoustic transponders);
- neutrally buoyant floats drifting at constant depth (communicating with ITPs and moorings through acoustic transponders);
- underwater acoustic technology for navigating AUVs, floats, and gliders under sea ice; and
- short-range navigation and data transfer using acoustic modems on instruments fixed on moorings or Lagrangian floats for satellite data transmission.

Utilizing cabled seafloor observatories where processes are expected to vary rapidly over time (e.g., shelves and gateways) and supplementing these measurements with short-range acoustic tomography and mobile measurements is a sound strategy.

*Icebreaker Support*

Installation and maintenance of cabled seafloor observatories will require ship time well in excess of what is presently available. Developing the next generation of arctic research vessels (e.g., see ARRV and *Aurora Borealis* below), capable of supporting cabled observatories, seafloor drilling (either directly or indirectly), and towing instrumentation will be necessary to fully study the deep Arctic Ocean.

For many applications, towed instruments provide the highest resolution data. There are no other means to collect multi-channel seismic (MCS) reflection data. Towing equipment through the ice pack requires a clear wake and well-designed, durable instruments that can withstand ice impact and pinch. For MCS systems, this has been achieved with overbuilt towing rigs and by relying on unusually large quantities of spares; expecting the equipment to be consumed during the course of a cruise. A deep-towed system, with tuned gun arrays, could ride under the ice, collecting high quality MCS data. This would make it simpler and more likely that expeditions could and would collect this necessary data. Adaptation of MCS techniques for submarine deployment would be a substantial step forward. Developing this technique for MCS data acquisition would make it possible to tow other instruments as well.

To operate such systems in the arctic pack ice three expeditions in the last 15 years have shown that the most advisable setup uses two research icebreakers; one for ice breaking and one for undertaking measurements. This is also expensive. While single geophysical ship experiments work well at the edge of the arctic ice, such expeditions have a high risk of failure if they aim for specific geological targets (specific geographical coordinates). Regional single ship surveys are less risky, since the vessel can move in areas with lighter ice conditions or can follow open leads. An additional parameter is the engine power of the icebreaker; the stronger the icebreaker, the more reliable its movement through the pack ice. This is a critical issue for access to the deep central basin.

Future ship design should emphasize a clear wake, greater power, adaptation for towing, and AUV/ROV deployment. For future work in the central Arctic Ocean a stronger ice breaker (>30000 hp) is needed to enable single ship operations even in difficult ice conditions. Specific modifications at the stern of the ship should be made to allow multi-channel seismic or other towed gear to enter into the water just 1 to 2 meters behind the ship. Developing and retaining trained crew, who are aware of the specific problems associated with pack ice and towing seismic gear in pack ice is essential for any success.

***Unusual Research Platforms***

During the last twenty years, military resources have occasionally been made available for scientific research in the Arctic Ocean. The Naval Research Laboratories aeromagnetic and aero-gravity data sets, collected from a modified P-3 airplane set the standard for extensive arctic mapping (Brozena et al., 2003). The SCICEX (Scientific Ice Expeditions) program (Edwards and Coakley, 2003), which consisted of six cruises to the central Arctic aboard US Navy nuclear powered submarines, supported extensive oceanographic and geophysical study of the deep basin. While these programs have ended, there remains some hope that in the future military resources will be made available for science.

Air independent submarines, both nuclear and those that rely on combustion, have the potential to survey the ocean independent of ice conditions. The near-synoptic, regional data sets collected during SCICEX could not have been collected by any other means. An international group should contact navies with submarines (US, France, UK and possibly Germany and Sweden) to develop a collaborative program. While success would not be certain, the data that would result would be an exceptional resource for tracking the changing upper water column of the Arctic Ocean.

Hovercraft technology has over the last 30 years progressed from aircraft inspired gas turbine propulsion to conventional air-cooled diesel engines. While earlier tests over arctic sea ice were obsessed with speed, a more sensible approach is to emphasize endurance and total distance. Based on recorded ice surface information from low altitude flights along a 250 km segment in the Eurasian Basin, the estimated range of a medium-sized craft carrying 2 tonnes of scientific pay load would be over 300 km (Kristoffersen, pers. comm., working group member). Such a platform has a hover height of 1.2 m and a cabin area of 50 $m^2$ for science and may include a moon pool. Use of hovercrafts in conjunction with icebreaker expeditions would significantly enhance opportunities for total scientific return.

### 4.8. Funding

There are a variety of potential national funding sources for the activities outlined in this ICARP II science plan. In Europe, direct European Union funding as well as logistical support from the various European arctic science groups (Alfred Wegner Institute, Swedish Polar Research Secretariat, and Russian Institutes) are possible. Various agencies in the United States, specifically the National Science Foundation, the National Oceanic and Atmospheric Administration, and National Aeronautics and Space Administration have programs that might support these activities as they have in the past. There are also a number of programs underway that might fund particular programs (e.g., SEARCH, OOI, and IODP).

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