ICARP II – SCIENCE PLAN 5

ARCTIC MARGINS AND GATEWAYS

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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 450 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

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

5.1. Introduction

Recent changes observed in the Arctic support contentions that polar ecosystems may respond rapidly to advective processes influenced by global climate change. Changes in sea-ice extent and thickness of the scale projected by climate models are intimately linked to the transport of waters from the Pacific and Atlantic Oceans through the arctic gateways. Changes in sea-ice concentration will alter the timing and magnitude of biological production and thus the cascading effects through the arctic ecosystem. The continental margins of the Arctic Ocean represent the interactive transformation zone between the shelf and deep basin regions, and act as a dynamic boundary for cross-slope shelf-basin interactions. Margins play a major role in the ventilation of the deep basins by transporting dense brine-enriched shelf waters and their associated organic and inorganic carbon to the abyssal region. They are also the main avenues for boundary currents and for the large-scale ocean circulation that transports heat, salt, freshwater, biogeochemical properties, and particulate matter around the Arctic Ocean. A good understanding of the formation of the gateways and margins and of the major processes regulating interactions through these gateways and across the margins is a central requirement for modeling the past, present, and future of the Arctic Ocean and its ecosystem.

Shelf margins are important sites for ventilation and ultimately carbon sequestration in the arctic basins; brine-enriched waters formed over the shelves entrain particulate and dissolved matter before being moved across the shelf break and down to the deep basin system. The shelf break is also an upwelling site for warm Atlantic waters. There are three major types of shelf to shelf-break margins: inflow margins (Chukchi and Barents Seas), interior margins (Kara, Laptev, and East Siberian Seas), and outflow margins (Canadian Arctic Archipelago) (Figure 5.1). The processes occurring over continental margins and the shelf break are critical for large-scale ocean circulation and thus the transport of heat, freshwater, biogeochemical properties, and sediments around the Arctic Ocean. Recent studies from the SBI (Western Arctic Shelf-Basin Interactions; http://sbi.utk.edu) project in the Amerasian Arctic indicate that more heat and freshwater has passed through the Bering Strait gateway complex in recent years (Woodgate and Aagaard, 2005; see Grebmeier and Harvey, 2005 for an overview of the SBI project). These studies identified seasonal and interannual variation in the physical and biochemical processes involved in cross-margin exchange, such as advection, eddy formation, upwelling and along-canyon transport. They also identified seasonal and interannual variation in nutrient fluxes and transformations that affect biological parameters.

Marine mammals are an important component of the arctic food web. Polar bears, walruses, and ice seals (i.e., ringed, bearded, spotted, ribbon, harp, and hooded seals) depend on sea ice as a platform for breeding, feeding, and resting, and so changes in sea-ice thickness and extent have immediate impacts on their populations. Marine mammals and seabirds are top predators in the short food chains common in the Arctic and so are excellent bio-indicators of ecosystem variability (Moore et al., 2003, 2006). In the Arctic, many species also serve the nutritional, economic, and spiritual needs of Native communities (Riedlinger and Berkes, 2001). Thus, environmental changes that affect seabirds and marine mammals also directly affect the health and wellbeing of human inhabitants of the Arctic. Ecological pathways can be explored from the top down using these species as guides to the transformation and fate of carbon, which links directly back to the human dimension and to indigenous insights of climate change in the Arctic.

Successful scientific drilling on the Lomonosov Ridge during summer 2004 has stimulated planning for future IODP (Integrated Ocean Drilling Program) drilling legs to the central Arctic Ocean, and its margins and gateways. A pre-proposal was submitted to the IODP from a group based at the University of Alaska Fairbanks (USA) for drilling in the Bering Sea to recover the sea level record for the Bering Strait. Recognizing the scientific significance of the history of faunal and human exchange between North America and Asia, as well as the history of Pacific water input to the Arctic Ocean, IODP invited the group to submit a full drilling proposal in spring 2006. Other groups are planning to make use of existing multi-channel seismic data to target expanded sections on the arctic shelves to obtain material for determining paleo-oceanographic records similar to those collected on the

Figure 5.1. Major shelf seas and deep basins in the Arctic (from Carmack et al., 2006).

Lomonosov Ridge and ones planned during drilling in the Bering Sea. Locations of particular interest include the Chukchi Borderland and the Mendeleev Ridge.

Despite progress in understanding the circulation, water column structure, geological history, and biochemical processes of the shelf, margins, and deep basins of the Arctic Ocean, there are still vast uncertainties. There are few time series observations over the continental slope. Observations in the main gateways (Bering and Fram Straits, Barents Sea Complex, and the Canadian Arctic Archipelago) are limited and irregular, and causal linkages are speculative. Episodic events are known only from their downsteam effects. The lack of observations and historic data is a major constraint to quantifying variability in heat, freshwater, and material fluxes, and the sub-bottom geological structure, and to predicting future changes in the arctic environment. An integrated, international network of data management and portals for data submission is required for this ICARP II science plan.

5.2. Focus of the Science Plan

To move forward current understanding of arctic margins and gateway this ICARP II science plan outlines the main scientific issues associated with the arctic margins and gateways, evaluates the science needs for study, and presents a plan for action over the next five to ten years.

5.2.1. Goals and Overview

The main aim of this ICARP II science plan is to develop a plan for a coordinated, international research strategy for the arctic gateways and margins, based on modern, paleo-oceanographic and geophysical studies for investigating issues of relevance to global change and climate variability. Priority topics for the margins and gateways will be identified, related specifically to near-field (IPY) and far-field (ICARP II) objectives.

The gateways into and out of the Arctic are key regulators of the forcing factors for the arctic and global climate system, while the margins are the transformation sites for oceanic boundary currents and the sites of water, carbon, and sediment transport from the shelves to the deep arctic basins. The shelf-break is a key location for studying the ecosystem response to climate change. While the gateways can be considered the “front doors” to the Arctic, the arctic system as the “room inside” is changing. This ICARP II science plan proposes studies to investigate the key processes of both sites.

Shelf-basin exchange measurements and sub-bottom studies are required at key locations around the Arctic coincident with measurements in the gateways to/from the Arctic Ocean. The field campaigns must be coordinated with high resolution process studies and large-scale modeling studies to understand the Arctic Ocean and its variability across broad time scales. Time-series data will make it possible to evaluate the role of gateways and slope regions in climate change and the associated ecosystem response. The data will be used to validate regional to large-scale models and will help with the prediction of future change. The science plan outlines a framework for moorings, process studies, sub-bottom structural imaging, and paleo-oceanographic coring that can be coordinated internationally, and can help guide ongoing and planned field operations toward the goal of a long-term observatory network of studies at the arctic margins and gateways.

5.2.2. Gateways and Margins: Now and in the Future

A reduction in both sea-ice extent and thickness will influence local and global climate. Changes in sea-ice formation and thickness influence albedo feedback, as well as the formation of brine and thus the halocline. The greatest reduction and thinning of sea ice in the Arctic is occurring in the Pacific sector, with seasonal retreats in 2002 to 2005 the most extreme in the satellite data record (Stroeve et al., 2005).

Anomalous spring and summer productivity on the Bering Sea shelf has been related to decadal-scale atmospheric/sea ice/oceanographic processes, and may also reflect regime-induced climate changes in the western Arctic (Stabeno and Overland, 2001; Overland and Stabeno, 2004). These authors reported that the Bering Sea is shifting to an earlier spring transition based on ice melt and changes in atmospheric circulation patterns. The shallow and dynamic northern Bering Sea region appears to be responding directly to changes in climate forcing parameters (Overland and Wang, 2005). Grebmeier et al. (2006) indicated coincident seawater warming and a northward shift in the position of the Subarctic-Arctic Front in the northern Bering Sea, with ecosystem level responses evident from the reduced benthic carbon supply and standing stocks, as well as a northward shift in fish and benthic-feeding marine mammal populations.

The decrease in arctic sea ice is in part due to increased heat fluxes from the North Pacific and North Atlantic via the gateways and across the margins and can be magnified through positive ice-albedo feedback. Thinner sea ice also allows more solar energy to enter the water below the ice, thus heating the underlying water. Studies in the western Arctic (Shimada et al., 2005) found the maximum temperature to occur in the subsurface water, with a close correlation between sea-ice decline and subsurface warming. Ice is also a habitat for many biological species, from light-dependent ice algae to higher trophic organisms such as Arctic cod, walruses, beluga and bowhead whales, ice seals, and polar bears; species unique to polar regions. Significant reductions in sea-ice cover can thus affect the local ecosystem and local climate, which in turn contribute to global change.

Flow through gateways regulates the arctic system while the margins are transformation zones. Margin processes connect the shelves to the deep basins (Figure 5.1), and ultimately to the global system. Different chemical signatures arising in the shelf seas and crossing the continental margins are useful tools for tracing water masses in the central Arctic Ocean, to establish circulation patterns, residence times, and formation processes. Studies over the last decade show considerable variability in the circulation pattern of the upper 500 m of the central Arctic Ocean, especially in relation to the shift in the distribution of freshwater and the position of the front between the Pacific and Atlantic waters, which have exposed a much larger area of sea ice to the warmer underlying Atlantic water. The shelf break is an important site for observing ecosystem responses to climate change since this is where the combined effects of boundary currents, shelf-basin exchange, and retreating ice cover are most pronounced.

On geological time-scales, exchanges with the World Ocean are controlled by a deepening and shallowing of the ocean floor during tectonic opening and closing of the gateways. The tectonic, geodynamic, sedimentary, and paleo-topographic histories of margins and gateways provide the framework for modeling studies that will relate these events to paleo-climate observations from around the world. To better understand past environmental and climatic changes it is essential to investigate these processes using paleo-biological and geochemical proxies, and state-of-the-art techniques for geophysical surveying, sediment coring, and ocean drilling.

Processes such as upwelling, advection, and thermohaline circulation redistribute water masses vertically and horizontally along and across the shelf edge. Although little is known about present-day margins, the connection between margins and gateways suggests an intimate cause-effect relationship such that without ice the arctic slope processes would be similar to slope processes in temperate waters. A recent modeling study indicated that sea-ice retreat is likely to enhance upwelling and primary production at the slope (Carmack and Chapman, 2003), which would have system-wide consequences for carbon processing and sequestration to depth.

The Arctic experiences both positive and negative thermohaline circulation depending on the season and this strongly influences shelf-basin interactions (Macdonald and Carmack, 1991). Thus, the volume of freshwater input in summer (from riverine, ice melt sources) and brine in winter will vary in a changing Arctic. Pacific waters moving across the wide Bering and Chukchi shelves, and the western part of the Beaufort Sea (Figure 5.1) are of major importance to the physical structure of the ocean and sea ice, and to the productivity and carbon transport in the Amerasian Arctic (Grebmeier and Harvey, 2005). Shimada et al. (2001, 2005) showed that summer Pacific water is an important source of heat to the upper layers of the Pacific sector, and is particularly important over the Chukchi Borderland. The density of winter Pacific water is influenced by ice formation and brine rejection, such that the timing, extent, and location of the halocline are intimately tied to these processes.

Certain physical, biogeochemical, and biological oceanographic features distinguish the Pacific and Atlantic sectors of the Arctic Ocean, and these have important implications for shelf-basin exchange at the margins. Pacific water has distinctive downstream and offshore effects within the upper halocline to the Arctic Basin proper and the Canadian Arctic Archipelago. Although some shelf-slope processes are common to all arctic margins (e.g., ice formation, brine rejection, advection, and eddy production for shelf-basin exchange), the “Pacific signature” is distinct in its large and small-scale impacts compared to regions more influenced by North Atlantic waters.

Estimates of water transport, plus knowledge of suspended material and plankton communities, can be used to generate estimates of advective fluxes (Ashjian et al., 2005). Process studies involving vertical and lateral export of organic matter from the shelf and slope are important for identifying the sources of organic matter to the Arctic Ocean (Bates et al., 2005a,b; Moran et al., 2005). In the Atlantic sector, episodic advection of biologically-rich deep water has been detected by moored sediment traps and shown to contribute to the vertical export of organic matter in the deep ocean from the western Barents Sea to the Norwegian Sea (Thomsen et al., 2001). Recent studies in the Chukchi and Beaufort Sea indicate that Barrow Canyon is a major conduit for dissolved and particulate carbon transport to the slope and basin regions (Bates et al., 2005; Cooper et al., 2005; Hill and Cota, 2005; Moran et al., 2005). Such events are probably also occurring along other arctic margins. Moorings measuring flow in gateways and over margins should include sediment traps to monitor advective transport of organic matter over long periods. Episodic pulses of high organic material supply can then be included in budgets.

While a composite of regional investigations can provide some information on local responses to climate change for higher trophic organisms, it is much less than can be achieved through a coordinated pan-Arctic higher trophic research program. Such a program should include dynamic research tools such as satellite tracking, passive acoustic detection, genetic and chemical (e.g., isotope, fatty acid, and contaminant) analyses, and should focus on species that can integrate conditions within arctic ecosystems across a range of ecological scales. The species used should reflect food-web dynamics and the geographic range of the species.

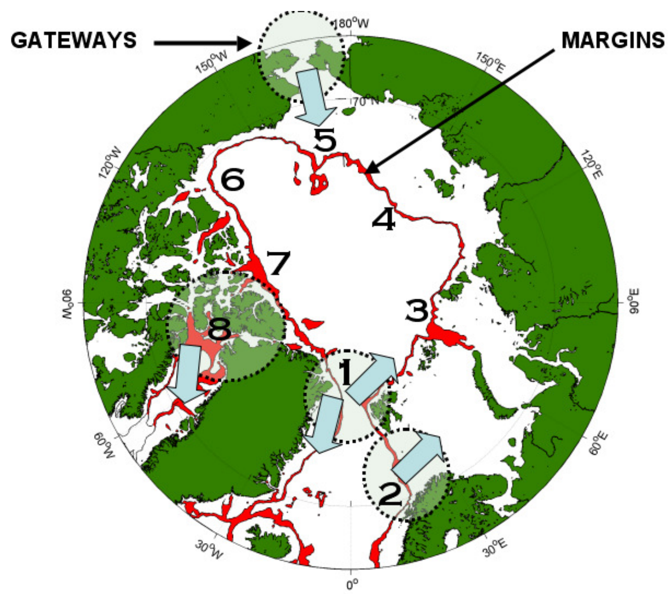
There were no arctic shelves at lower sea levels and the paleo-record shows that shelf break margins in the past played a central role as upwelling sites for the Arctic Ocean. A continued reduction in sea ice and changing atmospheric and seawater temperatures may result in shelf-to-shelf connectivity changing spatially to shelf-to-basin exchange, for example with freshwater inflow to the Arctic Basin from the Kara Sea. The relocation of freshwater transport from shelf to basin would strongly affect boundary current dynamics. This emphasizes the importance of a circum-arctic “snapshot” study, followed by time series monitoring at key sites in the Arctic. In addition, if the Yermak Plateau and Chukchi Plateau are considered deeper parts of the Arctic Ocean margin, circulation dynamics will probably change there as well.

To better understand the Arctic Ocean and its variability at different time scales, the paleo-record must be interpreted within the context of contemporary studies. The Arctic Ocean has passed through various geometrical, physical and chemical stages that show that it has changed over geological time scales from a stagnant and oxygen-deficient ocean through a temperate upwelling basin to a cold and ventilated ocean. However, little information is available for the early (stagnant) period of the Arctic Ocean. In contrast, the sediments of the margins contain paleo-oceanographic records of depositional facies, sea level, and sea ice history that provide a good body of information to provide the long-term context for contemporary margin studies. The important paleo-oceanographic information includes changes in geometrical shape arising from tectonic and sedimentary processes and the physical and chemical changes in water masses. Better understanding of these processes is essential for more realistic parameterization of models for climate evolution through the Cenozoic Era to the present, particularly during the “hothouse-icehouse” transition, the beginning of northern glaciation, and other periods of dramatic changes in climate. This can be achieved through geophysical data acquisition programs and reconstructions of the plate-kinematics and paleo-bathymetry.

The continental slopes play an important role in the mass transport of sediments with consequences for the physical and ecological status of the basins, and for the global carbon budget. Erosion, slope stability, and slope failures, evident at continental margins around the world, have been little mapped in the Arctic, except in the area of the Yermak Plateau (Winkelmann et al., in press). Studies must be undertaken on the causes and potential for slope failure along the arctic margins, because these fast high-volume downslope sediment events affect local and regional ecosystems and cause burst release of methane when a shift in pressure and temperature changes the gas hydrate stability. Such studies require a systematic survey with multi-beam mapping and seismic profiling as well as a search for methane seeps.

Four gateways provide the “front and back doors” to the Arctic and regulate forcing for the arctic system: the Fram Strait Complex, the Bering Strait Complex, the Barents Throughflow Complex, and the Canadian Arctic Archipelago Complex (Figure 5.2). The continental margins are the interactive zones between the shelf systems (addressed by ICARP II Science Plan 6) and the deep basins (addressed by ICARP II Science Plan 4). This ICARP II science plan identifies eight regions (Figure 5.2) and several key processes for focused, pan-arctic studies over the next decade.

<u>1. Fram Strait</u> is the primary deep connection between the Arctic and the World Ocean and represents the main gateway for the flux of warm water from mid-latitudes to the Arctic Ocean. The oceanic heat imported from the North Atlantic has the potential to affect the ice cover in the Eurasian Arctic and to be released to the arctic atmosphere. The outflow of freshwater and sea ice in the East Greenland Current to the south initiates the global thermohaline circulation cell. Fram Strait is the outflow source for North Atlantic Deep Water and is a major source of freshwater to the Nordic Seas deep water convective regions (Aagaard and Carmack, 1989). The bi-directional flow also allows the exchange of Atlantic and Arctic species. Recent findings show an increased northward heat flow through Fram Strait into the central Arctic (Schauer et al., 2004), and that this pulse of warm water took five years to make its way along the continental margins to the eastern Eurasian Basin.



Regional Areas:
Margins and Gateways

1. Fram Strait Complex (gateway)
2. Barents Throughflow Complex (gateway)
3. Santa Anna Trough (margin)
4. Kara/Laptev/East Siberian Sea (margin)
5. Bering Strait Complex (gateway)
6. Beaufort Sea (margin)
7. Northern Canada (margin)
8. Canadian Arctic Archipelago Complex (gateway)

Figure 5.2. Distribution of eight regional areas for margin and gateways studies within this ICARP II science plan (figure courtesy of Eddy Carmack).

Plate-tectonic opening and ocean spreading of the Fram Strait occurred about 10 million years ago. However, it is unclear when the first major deep water passage developed, because the reconstruction of sediment deposition and erosion in this gateway is incomplete. Large sediment drift bodies have been observed along the eastern side of the strait. These drift systems are a result of strong bottom currents and may have blocked substantial proportions of deep water flow at various times. Knowledge of the dynamic behavior of these sediment drifts is an important prerequisite for a detailed paleo-bathymetric reconstruction and will enable modeling of past ocean current systems in this gateway.

<u>2. The Barents Sea Throughflow</u> is the second major region of Atlantic inflow to the Barents Sea shelf and thus the transformation site critical for shelf-basin exchange across the northern margins of this sea. Advection is a major factor influencing ice and seawater dynamics in the region. This is an important site for the inflow of Atlantic species into the Arctic proper.

<u>3. Santa Anna Trough</u> connects the high production on the Barents shelf with the substantial water transport through the Barents Sea and this is believed to be an important route for allochthonous material to the Arctic Ocean. The trough regions are also important for dense water transport to the margins and Arctic Basin. Modifications to the Atlantic water (cooling, brine formation, and mixing) that occur during advection through the Barents Sea (similar to Pacific water modifications during advection through the Chukchi Sea) determine the density of this flow and thus the relative contributions to the upper, middle, or deeper layers of the Arctic Ocean. Vertical position of water type is important for basin circulation as well as for energy input to the food web, and can change as density is influenced by climate change.

<u>4. Kara/Laptev Sea/East Siberian Seas.</u> The largest amounts of sediment enter the Arctic Ocean with the Siberian rivers as they flow into the Siberian shelf seas (Figure 5.2, areas 4 and 5) and the Beaufort Sea (Figure 5.2, area 6) bringing particulate matter, nutrients, dissolved inorganic and organic carbon, as well as heavy metals and other pollutants. Some of this material is buried on the shelves, while the rest enters the deep central Arctic Ocean. The transport and deposition of this material plays an important role in the formation of the continental slope and its stability.

5. The Bering Strait Complex (Anadyr Strait, Shpanberg Strait, and Bering Strait) in the northern Bering Sea and Bering Strait region is a valve system for regulating inputs of heat, freshwater and nutrients into the Arctic proper (Cooper et al., 1997; Shimada et al., 2005; Woodgate and Aagaard, 2005; Woodgate et al., 2005), as well as fluxes of biological organisms and organic carbon (Grebmeier, 2003; Walsh et al., 2004, 2005). Shelf transformation processes are critical for biochemical processing of carbon and for exchange of carbon and nitrogen products at the margins. The canyons and troughs, particularly Barrow and Herald canyons, play a central role for water current transport and biogeochemical and biological product exchange between the shelf and basin (Codispoti et al., 2005; Grebmeier and Harvey, 2005; Weingartner et al., 2005). The freshwater inflow through Bering Strait provides around 40% of the total freshwater input to the Arctic Ocean (Woodgate and Aagaard, 2005). Eddy formation is an important mechanism for cross-shelf exchange of physical and biochemical tracers. Changes in the freshwater flux from increased inflow through Bering Strait, sea-ice melt, and river inflow to the Arctic Basin may also influence global climate systems via connectivity to meridional overturning water on the Atlantic side.

6. The Beaufort Sea margin is a narrow and poorly understood site for shelf-basin exchange of freshwater and terrigenous sediments. Boundary current dynamics play a significant role in shelf-basin exchange through eddy formation and along-shore transport.

7. The northern Canada margin is the least studied margin due to its extreme ice cover, yet is the main site for shelf-basin exchange between the Canadian Arctic Archipelago and the deep Arctic Basin. There is virtually no understanding of water current flow and processes in this region. There is an assumption that water exits the Arctic Ocean through various passages leading from the northern Canada margin, but there is no evidence to support this.

8. The Canadian Arctic Archipelago is an important shelf system for carbon processing, Pacific water outflow, and freshwater exchange. It provides a one-way passage for water and organisms out of the Arctic. The outflow of Arctic Ocean water is an important freshwater source for the Baffin and Labrador Seas. Water passing through the Canadian Arctic Archipelago contains progressively higher nutrient levels, with silica increasing by a factor of three to four (although nitrogen:phosphorus ratios stay relatively constant). The presence of ice in the Canadian Arctic Archipelago affects partitioning within the ecosystem and tidally-driven fluxes are important in the formation of biological "hot spots". The Nares Strait is the shortest passage between Baffin Bay and the Arctic Ocean. The tectonic motion and separation between Greenland and Ellesmere Island is not well understood. Recent mapping of vertical tectonic faults indicates recurrent strike-slip motion. It is possible that there has never been a deep water passage, and that sedimentation processes in Nares Strait have blocked shallow water transport at various times. Farther south, Davis Strait is underlain by a block of thinned continental crust, separating the deep basins of Baffin Bay and the Labrador Sea and forcing the Greenland Current to turn back into the Atlantic.

5.3. Scientific Questions

A fundamental objective is to understand how arctic margins and gateways regulate the physical and biogeochemical processes in the Arctic that are linked to sea-ice dynamics, air-sea interactions, the freshwater balance, and associated ecosystem dynamics. The shelf-break is a key site for studying ecosystem responses to climate change as it is a focal zone for evaluating system responses in terms of changing sea-ice cover, boundary current dynamics, and shelf-basin exchange. The gateways can be considered the "front doors" to the arctic system. Because the "room inside" is changing this ICARP II science plan outlines studies to investigate the key processes operating within the arctic system. These should include contemporary oceanographic and biological studies, with longer-term paleo-oceanographic studies that include geophysical aspects to establish the detailed tectonic, geodynamic, sedimentary and paleo-topographic histories of the margins and gateways. Central issues for evaluating the system response to ongoing climatic and ecosystem changes in the Arctic are grouped below according to four overarching themes: sea ice and heat transport; freshwater; ice-ecosystem reorganization; and climate change.

The focal questions should address how changing sea-ice cover alters exchange (e.g., sediment transport) with the margins in different regions of the Arctic, and how overall sea ice concentration and heat content are affected (e.g., shifts in ocean heat transport, interaction with ice/atmosphere/climate). Marine production and terrestrial inputs should be addressed in process studies, carbon budgets, and modeling studies. Planning should include coordination with ongoing and planned field programs especially in relation to the work of other marine groups (see ICARP II Science Plans 4 and 6).

There is a need to identify the major processes occurring at the margins and gateways, especially in relation to natural versus forced variability at a range of temporal scales as this is necessary to predict forcing functions and impacts under future scenarios of climate change. Process studies are necessary as well as a characterization of the biological community and the physical and chemical properties of waters in the marginal seas, such as the Barents and Chukchi Seas. Moorings are important for generating short- and long-term time series data. For example, an episodic advection of biologically rich deep water is known to make a significant contribution to the vertical export of organic material in the deep ocean from the western Barents Sea to the Norwegian Sea, and this process is also likely to be important on the northern shelf. Thus, modern and paleo-oceanographic studies and time series measurements need to be expanded and integrated into a marine pan-Arctic observational network that includes sites at the margins and gateways and that has been coordinated with coupled modeling efforts.

Questions concerning the role of gateways under future climate change scenarios (e.g., decreased ice, increased/decreased temperature, increased precipitation) highlight potential areas of investigation for field and modeling studies. For example, a change in wind transport is anticipated in the Barents Sea that would influence ice on and off shelf. In the past, this region may have been a Baltic gateway. Studies in the eastern Arctic using moored physical oceanographic arrays in Fram Strait and hydrographic transects indicate an increase in northward heat flow from Atlantic water from 1997 to 2000 and observations show that this is still continuing (Schauer et al., 2004). A stronger (or weaker) inflow through Fram Strait will influence the strength of recirculation and compensation within the arctic system having global implications.

The establishment of an international pan-Arctic framework for future studies at the margins and gateways in the Arctic will be an IPY legacy.

Specific scientific questions concerning the continental margins and oceanic gateways in the Arctic are grouped below according to the four overarching themes. Examples of sub-questions thought necessary to better understand the dynamic processes at these sites are also listed.

5.3.1. Sea Ice and Heat Content

Sea ice and heat content, especially shifts in ocean heat transport, interaction with ice/atmosphere/climate, including Western (Pacific Sector) and Barents Sea (Atlantic Sector) interactions with the Arctic Basin.

What roles do processes at margins and gateways play in the recently observed changes in sea-ice extent and thickness in the Arctic?

- *What is the relative role of oceanic versus atmospheric contributions to the changing sea-ice cover at the slope regions and gateways in the Arctic?*
- *How will changing Atlantic and Pacific inflows influence sea-ice cover and atmospheric exchange and what are the potential feedbacks to the system?*
- *Over what lateral extent will the Atlantic and Pacific inflows provide heat to the Arctic Basin and its ice cover?*

- *How will the rates of exchange between the arctic shelves and deep basin be altered by retreating ice cover and how will these affect halocline formation over the slope and in the Arctic Basin?*

How will a trend of decreasing sea-ice cover alter the annual cycle of sea-ice formation and air-sea carbon dioxide flux?

- *What are the feedback mechanisms affecting ice extent at the continental margins and what are their thermodynamic impacts?*
- *What are the consequences for carbon dioxide uptake from the atmosphere of the changing sea ice and river run-off with regard to phytoplankton assemblages, dense shelf water production and ventilation, and biogenic matter fluxes at the margins?*
- *What are the physical and biological impacts on carbon dioxide fluxes of a reduction in sea ice extent and thickness and changes in solar heating at the margins and gateways?*
- *Will changes in the timing and extent of ice formation influence halocline formation and its thickness at the continental margins, and if this layer is altered, what are the implications of a reduction in the density gradients across the halocline in this region?*
- *What are the implications of a change in the freshwater and heat flux at gateways on near-field (Pacific and Atlantic sector) and downstream (Canadian Archipelago and Arctic Basin) ecosystems?*

5.3.2. Fresh Water

What are the main areas of water mass modification in the circumpolar boundary current, and its extension into the North Atlantic Ocean?

- *How sensitive to environmental change are the processes that maintain water sources for the arctic boundary current?*
- *What impact might these changes have on the magnitude of the meridional overflow and on the sequestration of anthropogenic carbon dioxide?*
- *What are the strength and variability of the Fram Strait and Barents Sea branches of the Atlantic Water? What types of new water masses will be formed there?*
- *What are the mechanisms by which the Atlantic and Pacific waters are transformed on their pathways along the slope?*

How have changes in tectonics, sedimentation, and geomorphology of the arctic gateways and margins controlled the paleo-climate?

- *What is the temporal and spatial interaction between the past and present plate kinematics, mantle processes, margin formations, and crustal subsidence and uplift processes?*
- *When did the gateways open, and what is the exact timing for shallow and deep water mass exchange between the Arctic and the global ocean?*
- *What can records of change, preserved in sediment deposits in the gateways and along the margins, reveal for understanding past ocean current systems and the evolution of deep-water circulation?*
- *What can be learned from understanding the long-term paleo-climatic history from Mesozoic-Early Tertiary "Greenhouse" conditions to upper Tertiary-Quaternary "Icehouse" conditions?*
- *What role do gateway openings/closures play in the global carbon cycle, the bio-evolution, and the development of ice sheets and climatic changes?*

5.3.3. Ice–Ecosystem Reorganization

How do gateways and margins regulate physical, biogeochemical, and biological processes in the Arctic?

- *How do the margins and gateways interact in (a) the maintenance of arctic sea-ice cover, (b) air-sea interactions, (c) freshwater balance, and (d) associated ecosystem dynamics ranging from primary production to consumption by top trophic level species?*
- *How does water column structure at different sites in the margins and gateways change over seasonal and interannual time scales and what are the impacts of this variability on shelf-basin exchanges?*
- *How will changes in the valve dynamics of the Bering Strait continental shelf complex and the Fram Strait/Barents Sea shelf-complex associated with altered ice cover affect downstream arctic ecosystems?*

How will a shift northward in the Subarctic-to-Artic Front influence food web dynamics and ecosystem structure?

- *Will a reduction in ice cover change the standing stocks of major arctic species toward temperate species and shift the boundary between them northward through the gateways and over the margins?*
- *If warming surface and bottom waters shift northward, will there also be a northward shift in subarctic predators through the gateways and over the margins, both pelagic and benthic fish species and epifaunal predators, that will compete with arctic species or will biological adaptations occur along contiguous domains?*
- *If ecosystem reorganization occurs due to climate warming, will it be reversible, and if not, what future impacts can be forecast for the arctic system as a whole?*

5.3.4. Climate Change

Climate change via impacts by regions, including variability vs. anthropogenic forcing.

What are the dominant processes occurring at the arctic continental margins and gateways, both contemporary and inferred from the paleo-record?

- *How do water masses as inferred from the paleo-record interact at the margins, and what are their resulting physical, chemical, and biological properties?*
- *What is the water column structure in the Santa Anna Trough and in certain other physiographic areas of the continental slope (e.g., East Siberian Sea slope, Herald and Barrow Canyons)?*
- *Are there any biological indicators at the margins and gateways (e.g., benthic faunal composition/biomass, Arctic cod, beluga whales) that can act as sentinel indicators of key trophic pathways responding to environmental change?*
- *What sediment records can be used as indicators of climate change in water mass circulation and biogeochemical regimes and can paleo-records provide a connection between contemporary studies and the modeling of future change?*
- *How will physical and biogeochemical fluxes vary in a circum-arctic sense and in relation to climate variability and change at lower latitudes?*
- *How can sedimentary transport and deposition processes along the slopes be quantified?*
- *What is the role of slope failures in material transport and methane hydrate stability? Which regions have a high potential for catastrophic methane release and slope failure?*

How can natural vs. anthropogenic change in the arctic ecosystem be differentiated?

- *What is the magnitude of the interannual variability in physical, chemical, biological, and sedimentological properties at the margins now and in the future?*
- *Can an evaluation of natural variability across a range of temporal scales in gateways and at margins be used to evaluate forcing functions and impacts under future climate change scenarios?*

How will the roles of margins and gateways change under future climate change scenarios, such as decreased ice, increased/decreased temperature, and increased precipitation?

- *What field and modeling efforts will best enable predictions of future environmental change scenarios and allow the linking of current and past data records to the margins and gateways?*
- *What are the key influences of the arctic margins and gateways on global processes, for example the Atlantic convection and overturn, and how can modeling advance understanding of far-field impacts of arctic system change on lower latitudes?*

5.4. Scientific Approach

A flexible, system-scale observation network complemented by state-of-the-art numerical models is required to describe the Arctic Ocean circulation, ice cover, and ecosystem in order to predict its variability and change in future decades. Focused studies at the arctic margins and gateways are germane to this task. This ICARP II science plan envisions an internationally coordinated research effort addressing shelf-basin exchange in the circumpolar margins and through the gateways in the Arctic (Bering Strait, the Canadian Archipelago, the Barents throughflow complex, and Fram Strait). The variability observed and modeled in those regions in the past can be used to help identify the most important parameters and processes for current and future studies in the gateways and margins to detect, understand, and predict potential changes to the arctic system.

- Available historical data must be retrieved and assimilated, particularly on ice thickness and concentration, on paleo-climate proxies from sediment records, and on tectonic evolution, to place contemporary changes within the context of past responses to climate forcing, and to apply this knowledge to predict future impacts of environmental change.

- This ICARP II science plan includes (a) the integration of classical observation methods with multi-sensor observations of the ocean and ice cover to undertake studies across the Arctic Ocean boundaries and within the gateways; and (b) long-term observatories, comprising oceanographic sections and moorings as well as geophysical monitoring at the margins and gateways to provide continuity for scientific measurements and international collaboration during the ICARP II process, IPY 07/08, and in future years.

- Models must be developed that can properly reproduce and assimilate past and present observations. The models should include improved parameterizations of critical gateway and margin processes and sufficient details of the coupled geo-bio-physical system to determine linkages from the local to the pan-Arctic scale and beyond to the global ocean (both North Atlantic and Pacific). The models should also be integrated in time over decades and centuries to millions of years to differentiate long-term trends from mid-term trends and mid-term trends from interannual variability.

The potential change in the seasonality of shelf dynamics and shelf break upwelling is likely to have a major impact on the total carbon budget and shelf-basin carbon fluxes in the Arctic. To investigate potential oceanographic changes with ice retreat northward over the margins, a network of gateway transects and pan-Arctic marginal exchange transects is proposed on which standard physical, biogeochemical, geophysical, and geological measurements would be built around a backbone of moorings and observatories at the arctic shelf break. Process studies along these transects would place times series stations within the spatial context of key forcing and/or responding-to-change regions in the Arctic. Remote sensing data from satellites for sea-ice extent and thickness, ocean color (chlorophyll), and for tracking marine mammals and seabirds relative to the shelf and shelf break will provide additional information as well as validation of field measurements and numerical model output.

Coupling tectonic and geophysical data will enable focused scientific drilling that will generate a good database for reconstructing the paleo-oceanographic and climatic history of the high latitude areas of the northern hemisphere. With increasing computational power, high-resolution gridded paleo-bathymetric reconstructions will replace the geometrical boundary conditions for paleo-current and coupled paleo-climate model runs. Other developments include the installation of deep-water swath-bathymetry systems on ice-strengthened research vessels, the availability of magnetic survey equipment on helicopters operated from ships, and advances in tectonic and sedimentary reconstruction techniques (e.g., utilization of gridded datasets and animated reconstructions).

5.4.1. Circum-Arctic Observational and Modeling Network

The observational network includes the following measurements from icebreakers and ice-strengthened ships, with reduced data collection from aircraft in spring when ice cover limits ship access, coincident with moorings and satellite coverage. An observation-oriented, multi-disciplinary, and multi-environmental approach must be undertaken in the next decade to capture both ongoing and unforeseen change. Areas of paleo-oceanographic coring on the slope and in the gateways will make it possible to place current arctic change observations within the perspective of past events in order to predict the impact of future climate change scenarios on the arctic system.

Time Series Hydrographic Transects across and along Gateways and Margins

The standard suite of measurements along these transects should include: temperature, salinity, transmissivity, fluorescence, nutrients, dissolved oxygen, stable oxygen isotopes, carbon measurements (particulate organic carbon, dissolved inorganic carbon, dissolved organic carbon), pH, atmospheric measurements, incident and underwater light, and chlorophyll. Knowledge of the levels of the various carbon fractions in the brine formed during sea-ice formation at the circum-arctic scale is required to establish the role of sea ice production in air-sea carbon dioxide fluxes. Tracers studies (for transient and conservative tracers) across the boundaries and at the gateways are needed to define pathways and rates. Chlorophyll, ice algae, phytoplankton, zooplankton, and benthic and higher trophic level species must be sampled to establish the effect of ice decline on population distributions and interactions. Summer and, where possible, winter oceanographic surveys are needed to investigate pan-Arctic synoptic marginal exchange transects, using icebreakers and ice-strengthened ships. A reduced data suite collected from aircraft in spring, coincident with mooring emplacement and satellite coverage, would allow a temporal and spatial network of shelf-basin exchange studies. Higher trophic level species (e.g., marine mammals and seabirds) can be indicators of climate change in the Arctic and can provide an important link between environmental change and impacts on Native community lifestyle and indigenous knowledge.

International Mooring Arrays focused at the Shelf Break and in the Gateways

International mooring arrays focused at the shelf break around the Arctic and in the gateways will provide time series data sets of physical, biochemical, and biological parameters. Standardized measurements will form the “backbone” to the pan-Arctic study. Standard measurements include temperature, salinity, current velocity, oxygen, ice thickness, nutrients, fluorescence, and transmissivity, and if feasible, sediment traps, near-bottom benthic sensors, and profiling sensors for mixed layer biochemical measurements.

Process Studies around the “Backbone” of Observatory Sites, at 300 to 600 m Depth on the Shelf Break and at the Gateways

Process studies around the “backbone” of observatory sites, at 300 to 600 m depth on the shelf break and at the gateways, are necessary to understand the coupling of physical forcing and ecosystem processes associated with change. Physical, biochemical, biological, and geological measurements should be measured simultaneously during the IPY to provide a “snapshot” of conditions, with the aim of identifying key regions for future spatial and temporal monitoring. Coordination of synoptic transects to provide high-resolution measurements and process studies within the transect regions are essential within an "observatory network". Higher trophic level organisms (whales, seals, and walrus) can be used as indicator species of ecosystem status and change as they integrate conditions within arctic ecosystems across a suite of ecological scales. Long-lived marine mammals, such as belugas, seals (e.g., ringed seal), polar bears, seabirds (e.g., diving seaduck, frontal feeders), and Arctic cod that search for prey through key spatially productive regions should be tagged.

Paleo-oceanographic Studies in Canyons, Troughs, and over Slope Regions

Paleo-oceanographic studies are required in canyons, troughs, and over slope regions. Records of past events and gateway transport should be studied as well as the history of freshwater inputs and changes in ice cover in response to sedimentation on margins and in gateways. The lack of adequate site survey data in some areas of the Arctic hampers the development of drilling proposals. Good target areas for paleo-oceanographic, climatic and tectonic studies on margins and in gateways include:

- the Yermak and Morris Jesup Plateaus to evaluate the Atlantic inflow over time, to describe events when glacier ice was present in the Arctic Ocean, and to capture the earliest glacial input into this region;
- the upper slope (east) Laptev Sea, East Siberian Sea, Canadian/Alaska Arctic margins to study the history of sea-ice development and glaciations, thermal and hydrogeological processes controlling methane release from destabilized permafrost-associate gas hydrate accumulations, and the history of Pacific water influx through Bering Strait; and
- the upper slope (west) Lincoln Sea, North Greenland margin, Fram Strait, and Northern Barents Sea to study the earliest glaciation of northern Greenland and the history of Atlantic inflow to the Arctic Ocean, and to evaluate variability in sea-ice cover through glacial cycles, paleo-productivity, and paleo-oceanographic circulation related to climate change (see Kristoffersen and Mikkelsen, 2004).

Systematic Geophysical Surveys of the Continental Slopes from the outer Shelf to Deep Basins

Swath-bathymetric surveys along the margins constrain the present seafloor morphology at high resolution. A prerequisite for systematic bathymetric mapping will be bathymetric data acquisition, and the compilation and archiving of these data through a coordinated international infrastructure. Seismic investigations are needed to determine the original limits of continental margins, to image areas of potential slope instability, and to identify the nature and origin of shallow banks that might have blocked water passage through gateways. They are required as pre-site investigations for deep drilling at sites in gateways to obtain stratigraphic and biostratigraphic data. Dense marine magnetic and aeromagnetic surveys reveal the precise positions of key marine magnetic lineations and tectonic boundaries in the vicinity of the gateways. Detailed onshore geological studies will further constrain the deformation of the continental areas flanking the gateways during and since their opening.

Coupled Paleo-climate Models

Integration of the gateway development histories, including paleo-bathymetry, with the latest ocean and coupled climate models will enable predictions of the impact of these events on the earth system. Testing these predictions would provide the basis for future geological and ocean drilling investigations.

Satellite Coverage focused on the Polar Region

Satellite coverage focused on the polar region, particularly during IPY, then selectively during subsequent years to place the "snapshot" measurements into a more spatially expansive study. The time series and process studies should be coordinated with remote sensing observations to place the regional studies into a pan-Arctic framework.

Modeling Effort

Modeling effort, using a variety of approaches (e.g., process-specific, and coupled biophysical regional and pan-Arctic models), is essential to synthesize retrospective studies, to plan the "snapshot" pan-Arctic SBE/gateway studies during IPY, and to evaluate current and future scenarios of arctic change. Modeling is necessary to understand the multi-scale observations and to enable scenario building and the prediction of climate change impacts on shelf-basin and gateway exchanges.

Technological Development

Technological development is needed to incorporate biochemical sensors into the slope and gateway mooring arrays, and to develop new physical and tracer technology for autonomous sampling in rapidly changing margin systems. Autonomous underwater vehicles, as well as gliders and ice-tethered moorings are examples of advanced technology that could be used within a snapshot gateways and margins study. Drilling in the ice-covered Arctic is a serious problem and new ship-borne drill platforms must be developed.

Public Outreach

A public outreach component is essential. The Arctic is defined by the people who live there – their harvestable production, resource use, and transportation issues associated with ice retreat from shelves are important societal issues. Including arctic inhabitants (students to adults to elders) in scientific discussions will engage the public in the importance of observing and understanding the arctic system and the complex factors influencing and responding to change.

5.4.2. Data Management

There is a need for data rescue and archiving of past results related to gateway dynamics and shelf-basin exchange in the Arctic. There is also a need to develop a strategy to achieve this ICARP II science plan in IPY and beyond through an integrated, international network of data management and portals for data submission. A data management plan must be developed that includes national and international cooperative agreements for data submission, access, and release, and allows free access to data across international boundaries. Data management could be approached through an internationally agreed, web-linked "virtual electronic" data base for linking the international arctic margin and gateways data from each country via a web page to the data housed in national data archives. Ultimately, it will be necessary to develop a protocol for long-term archiving of margins and gateway data within the context of the entire arctic system, and which will require a dedicated working body across all the ICARP II working groups. A data management group is under development for IPY and this body should be consulted in relation to the development of a coordinated data management plan.

5.5. Linkage / Users

5.5.1. Coordination with Planning Groups

International efforts to establish time series observatories are already underway, comprising oceanographic sections and moorings at the margins and gateway regions of the Arctic, together with geophysical surveys and geological sampling/drilling plans. A circum-Arctic internationally coordinated gateways and margins effort would provide continuity for scientific measurements and international collaboration as part of the ICARP II process, during IPY07/08 and beyond. The work of ongoing planning groups should be coordinated with ICARP II planning, such as the Arctic Ocean Sciences Board (AOSB), the International Shelf-Basin Exchange planning committee, the IASC International Study of Arctic Change working group, the Arctic-Subarctic Ocean Fluxes Study efforts, and IPY planning. The AOSB SBE planning committee is working to coordinate the following IPY projects within the integrated Arctic Ocean Observing System IPY network:

- Canadian Arctic Margin Expedition (CAME) for a circum Arctic slope study;
- Chinese CHINARC Chukchi/Arctic Ocean studies;
- German Synoptic Pan-Arctic Climate and Environment Study (SPACE);
- Greenland shelf-margins study;
- International Study of Arctic Change (ISAC) program;
- Joint Pacific Arctic Climate Study (JPACS);
- Nordic Land-Shelf-Basin Interactions Study for working in the Russian Arctic;
- Russian Kara Sea margins project;
- US-Russian-Canadian MAOSS project for studies of Arctic boundary current;
- US-led Shelf-Basin Exchange Study (US-SBE) for linked physical, biogeochemical and biological measures at the shelf break;
- US-led Study of Environmental Arctic Change (SEARCH) program.

5.5.2. Outreach to the Public

Circum-Arctic projects should engage coastal communities through active participation in international research projects and through educational opportunities. For example, educational web-based opportunities would bring research-based projects to both the near-field arctic communities and far-field global communities, thus highlighting the Arctic as a region of global interest. The changes being observed in the arctic oceanographic and ice systems could lead to dramatic impacts for higher trophic level fauna, including benthic-feeding animals such as walrus, bearded seals, and grey whales, and pelagic-feeding bowhead and beluga whales that are of cultural and subsistence significance to Native peoples. Sea ice conditions and their effect on marine mammals and seabirds are of particular interest to Native peoples as they are important traditional food items. These higher trophic organisms integrate and so demonstrate ecological change in ways that human experimentation can not. Community-based circum-arctic studies can contribute vital information to climate change research. A synergistic research approach that combines traditional science and local expertise could be the vanguard of a pan-Arctic climate change program, providing key data to scientists and relevant information to local inhabitants. Coordination with marine-related aspects of ICARP II Science Plan 2 is important. Ultimately, the educational outreach component of this ICARP II science plan could coordinate with bodies such as the “Nordic Network”, the Canadian ArcticNET, and the University of the Arctic.

5.5.3. Interactions with other ICARP II Planning Groups

The integrated approach of this ICARP II science plan requires an overarching approach. Strong coordination during the planning process is expected with ICARP II Science Plans 6 and 4. Good coordination is necessary to address issues of coast-shelf-slope-basin transport and exchange rates of physical, biochemical and biological products, plus coordinated investigations of opening and subsidence within gateways and the Arctic Basin. Investigations of sea-ice extent and thickness, seasonality of sea ice and melt, and the associated change in coincident seasonal biochemical and biological processes for all marine groups should also be coordinated. Evaluation of coupled heat-ice-wind connections are important to understand change. With less sea ice there will be more flow through the marginal seas, and coincidently more oceanic heat is likely to be transported into the Arctic through both the Pacific and Atlantic gateways. The boundary current is an integrating pan-Arctic linkage that influences heat budgets and the spatial variability of vertical heat fluxes, both upstream and downstream of the gateways. Paleo-climatic extremes establish boundary conditions that help with an understanding of the Arctic and its role in global climate change. They are relevant to predictions of future climate change and provide targets for models. Extremes include marine and terrestrial glacial minima and maxima, sea-level minima and maxima, ice-shelf extent, paleo-oceanographic circulation and freshwater budgets. Plate tectonic events, such as gateway opening and closure, are the main drivers of climatic changes in the earth history. Coordination with ICARP II Science Plan 3 will also be important to coordinate studies on these issues.

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5.6. Outcome / Achievements

A major outcome of this ICARP II science plan will be a network of internationally coordinated arctic slope and gateway transect lines, survey areas, and sampling stations, at which standardized measurements are undertaken; continued opportunities for process studies; and moored instrumentation at key sites in the Arctic. An ocean observing network of moored technology on the slope region will increase understanding of seasonal and interannual variability at the pan-Arctic level. Coincident regional modeling studies will allow results to be scaled to a pan-Arctic and ultimately global perspective. A coordinated, sustained international network of pan-Arctic margin and gateway measurements, interfaced with a public education component, will be a lasting legacy of the ICARPII process.

The paleo-studies will focus on data acquisition and analyses of select projects within the arctic gateways and margins that are critical for understanding large time-scale paleo-climatic processes. The new data on the lithospheric and crustal structures, their ages and evolution, sedimentary formations, petrological fabrics and chemistries, as well as high-resolution bathymetry, will be integrated to provide a basis for paleo-topographic and paleo-geographical grids. Existing data sets will be compiled and integrated with these new data. Dynamic models will be developed to reveal the links between tectonic evolution, sedimentary processes, and paleo-oceanography. For instance, modeling will demonstrate when opening/closing of ocean gateways became effective for global paleo-oceanographic changes, and will help understanding of biodiversity evolution. These highly resolved spatial and temporal paleo-grids allow more accurate paleo-climatic reconstructions using earth system models. Paleo-topographic grids will be made accessible through data centers to other groups working on global paleo-climatic processes.

A key achievement will be to develop and facilitate a network for international research cooperation on understanding the extent of the Pacific, Atlantic, and freshwater influence in the Arctic. Additional outcomes would be to identify the drivers and responders to change, and to evaluate the downstream impacts on the arctic system, including its connectivity to the World Ocean. Internationally coordinated margin transects and mooring emplacement, with standardized measurements, will help scale regional models to a pan-Arctic perspective.

5.7. Implementation

Limiting factors – people, icebreakers, functioning ice camps – must be identified in order to implement this ICARP II science plan. Logistics will include utilizing multiple-country assets, such as ships (icebreakers and ice-strengthened ships), aircraft, ice camps, and satellites. Questions related to the implementation of this science plan have been raised, such as what are the minimum standardized measurements needed versus those achievable within an international network of regional studies to scale the regional to the pan-Arctic? There is a need to scale regional models to a pan-Arctic perspective, and ultimately to a global level. Spatially collected, standardized measurements will assist in developing scenarios to evaluate the decrease in ice extent, the change in ice melt/brine production and ventilation events, and ultimately the ecosystem impacts of climate change.

5.7.1. Ships

Field studies will include moorings, process studies, sub-bottom structural imaging, and paleo-oceanographic coring that can be coordinated internationally, used to validate and improve models and their predictions of change, and to leverage ongoing and planned field operations. There is a requirement for open-water ships, ice-strengthened ships, and icebreaker use for pan-Arctic sections and for gateway access into national waters by multi-national science projects, especially access to the

Russian EEZ by non-Russian countries since Russian waters cover over half the total arctic shelf and margin area.

There is a finite limit to the availability of surface ships (icebreakers and ice-strengthened) for scientific studies in the Arctic. Moorings (current meters, ice-profiling sonar, CTD profilers, biochemical sensors, marine mammal acoustic recorders, benthic video cameras), ice-strengthened marine geophysical survey equipment, and air support for work in heavy ice regions and marginal land regions are needed. Implementing this ICARP II science plan requires international logistical assets, specifically ships (e.g., Germany: *Polarstern*, *Maria S. Merian* (ice strengthened); China: *Xuelong*, U.S.: *Healy*, *Polar Star*, *Nathaniel B. Palmer*; Sweden: *Oden*, Russia: *Federov*, *Dranitsyn*, *Khromov* (open water); Japan: *Mirai*; Canada: *Louis. S. St. Laurent*, *Admunsen*, *Sir Wilfrid Laurier*, *Henry Larsen*; Norway: *Lance*, *Jan Mayen* (ice-enforced); EU: *Aurora Borealis* pending; Finland: *Aranda* (ice-strengthened); Poland: *Oceania* (open-water to Spitsbergen)), and private icebreakers for lease. Logistical needs also include aircraft and ice/land-camps for work in late winter and spring.

A pan-Arctic approach requires that these assets be shared among oceanographic and geo-scientific projects, or at least closely linked, meaning that close cooperation is needed with national vessel/logistic operators. FARO (Forum of Arctic Research Operations) is a critical body for addressing the needs of this ICARP II science plan.

5.7.2. Remote Sensing

More *in situ* observations are needed to study the warming process through spring to autumn in marginal seas and the ice edge area. Remote sensing data for infrared and visible wavelengths will be used to establish ice thickness and the extra heat absorbed by seawater due to thinner ice.

5.8. Funding

Many of the research objectives outlined in this ICARP II science plan are included in the planning for the International Study of Arctic Change (ISAC), the EU-funded DAMOCLES project, and the US-led Study of Environmental Arctic Change (SEARCH) program, as well as national and international planning for IPY.

There are several potential sources of national funding for this ICARP II science plan. Canada has committed Can$150 million to the IPY, with China soon to commit a substantial sum for IPY. The EU has initiated IPY-type activities by funding the DAMOCLES project. The National Science Foundation is the lead coordinating agency within the United States for IPY, with funding support pending from the NSF (National Science Foundation), NASA (National Aeronautics and Space Administration), and NOAA (National Oceanic and Atmospheric Administration). The EU-funded EUROPOLAR ERA-NET is a potential source of arranging funding. There is also a Nordic initiative for future co-operation in arctic studies (Arctic Frontiers, lead in Tromsø, Norway). In addition, ECORD (European Consortium for Ocean Research Drilling) as a part of the IODP has been developed internationally to provide mission specific platforms to arctic paleo-oceanographic drilling targets.

5.9. Summary

The purpose of this ICARP II science plan has been to evaluate the current understanding of arctic margins and gateways, to identify the science needs for study, and to present a plan for action over the next five to ten years. A fundamental objective is to understand how arctic margins and gateways regulate the physical and biogeochemical processes in the Arctic that are linked to sea-ice dynamics, air-sea interactions, the freshwater balance, and associated ecosystem dynamics. An "arctic snapshot" approach is presented for short-term IPY studies, with long-term transects and moorings proposed for an arctic observing network that is intended to increase understanding of margin and gateway dynamics and future impacts of climate warming on these key processes.

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