ICARP II – SCIENCE PLAN 6

ARCTIC SHELF SEAS

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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

6.1. Strategic Issues to be Addressed

Arctic shelf seas represent about half the Arctic Ocean and 25% of the entire World Ocean shelves. They are vitally important for coastal arctic communities since shelf seas provide most of the living resources necessary for subsistence and commercial harvest. For example, the Barents Sea and the Bering Sea are among the most productive oceanic areas on earth. Considering the importance of the arctic and sub-arctic seas for global fisheries and the harvesting of other marine resources, the projected changes in arctic climate will have major repercussions at the ecosystem level that will extend throughout various economic and societal sectors.

The arctic shelf seas encompass the seasonal sea-ice zone (which is partly ice free during the summer), and thus are expected in the near future to offer important waterways for major world transportation of goods and natural resources as well as for oil and gas development (Figure 6.1). Arctic shelf seas

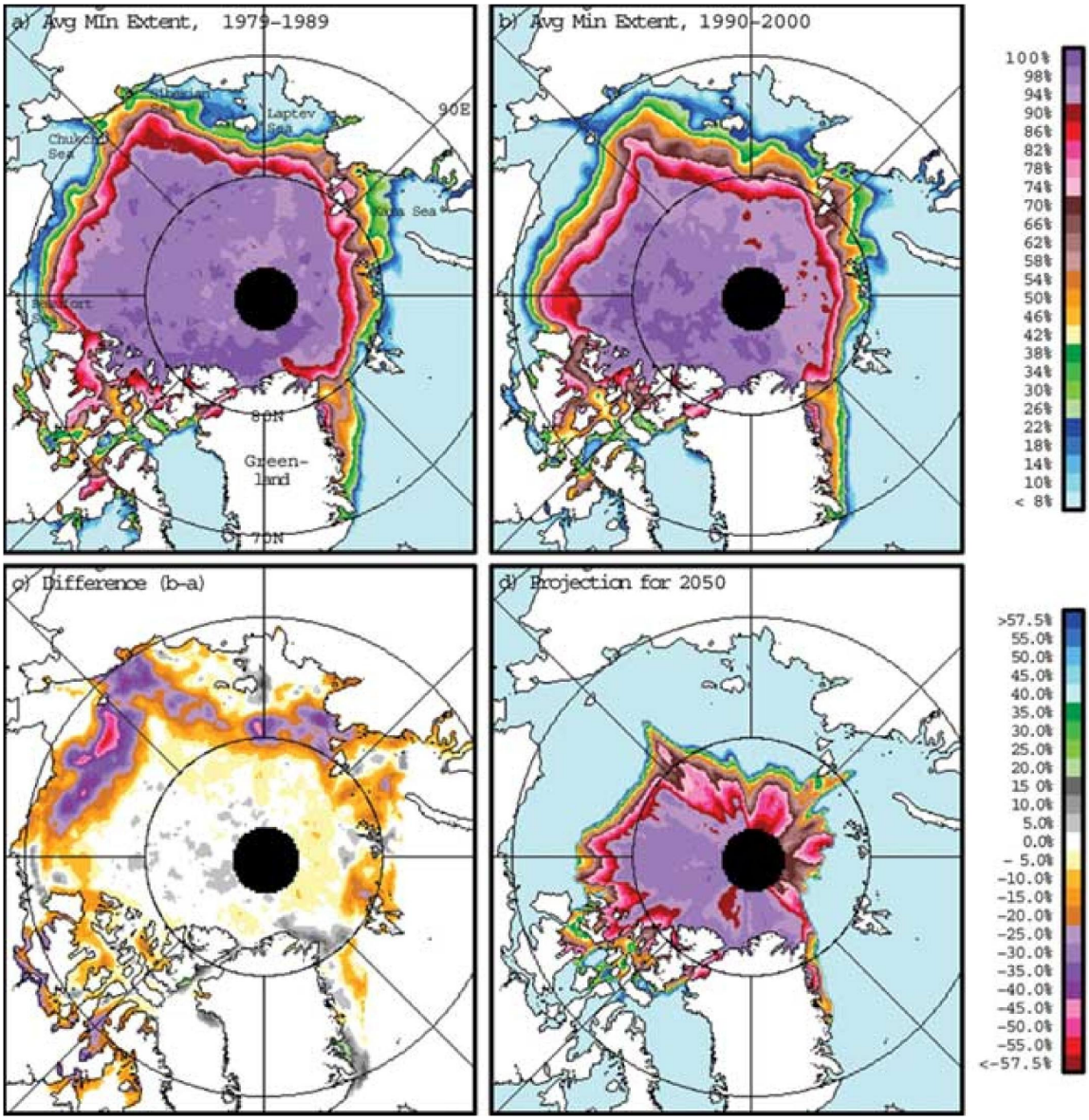


Figure 6.1. Reduction in summer minimum ice extent between 1979 and 2000. Note in particular how ice has retreated from shelves (c). Projection for 2050 is based on linear trend derived for 1980s and 1990s (d).

receive 10% of the global freshwater discharge, including all the freshwater from Siberian and Canadian rivers, and transport it to the deep Arctic Basin. The resulting 100 to 200 m thick layer of low-saline water covers the entire Arctic Ocean and serves a major role in sea-ice formation during freezing periods. Arctic shelf seas are active locations for sea-ice and brine formation, as evidenced by the presence of frequent latent heat and coastal polynyas.

Over the past decade, evidence has accumulated that the Arctic is undergoing significant and sweeping change. The complexity of this change expresses itself across atmospheric, oceanic, and terrestrial realms, including:

- increased air temperatures and enhanced wind mixing over most of the arctic shelf seas;
- reduced sea-ice cover and destabilization of landfast ice with more frequent break-out events;
- significant changes in sea ice-cloud-albedo feedback mechanisms;
- marked changes in amplitude and seasonality of river discharge;
- enhanced coastal erosion due to degradation of permafrost and increases in wave action, sediment transport by sea ice, and sea level;
- changing pathways of suspended particulate matter, nutrients, and contaminants from land across the shelves and continental slopes to the deep Arctic Ocean;
- significant changes in the marine ecosystems and food web structures of the shelf seas; and
- changes to the transfer of gas, mass, and energy across the ocean-sea ice-atmosphere interface.

Most of these changes are already directly manifested on shelf environments. If they continue, as implied by climate models, they will have major implications for circum-Arctic ecology and human activities. Although the mechanisms amplifying or damping these potential changes are not well understood, they are essential for understanding and modeling the entire system across disciplines over the next decades and to project their influence over global climate (Figure 6.1). With respect to increasing levels of shipping, resource exploitation, and traditional subsistence activities in arctic shelf seas a close coordination of multidisciplinary circum-Arctic activities focusing on the following six scientific issues is essential and strongly required to predict changes and improve future assessments.

- Changes in shelf-ocean dynamics and brine production.
- Changes in cross-shelf transport.
- Ecosystem alteration and its impact on marine resources.
- Phenology of key ecosystem events.
- Arctic polynyas in response to climate change.
- Evaluations of the paleo-record in developing future scenarios.

6.2. Focus and Key Scientific Questions

6.2.1. Changes in Shelf-ocean Dynamics and Brine Production

In the context of a highly stratified upper Arctic Ocean, shelves and shelf breaks are of considerable importance from the perspective of vertical mixing, deep ocean ventilation, and transfer of dissolved and particulate matter (Figure 6.2). Mixing is also of critical importance to areas of high biological production over the Bering, Chukchi and Barents shelves. Currently, strong stratification over much of the circum-Arctic shelf seas confines brine production to coastal and flaw polynyas along the landfast ice bordering the coastlines in the Chukchi/Beaufort and Siberian Seas (Winsor and Björk, 2000). However, even in these regions, the substantial supply of freshwater from the large rivers has the potential to greatly limit deep mixing. Hence, only polynyas close to the shelf break in the Beaufort, Chukchi, Laptev, and eastern Kara Seas and in the northern and eastern Barents Sea are likely to contribute in a major fashion to brine transfer into the deep basins.

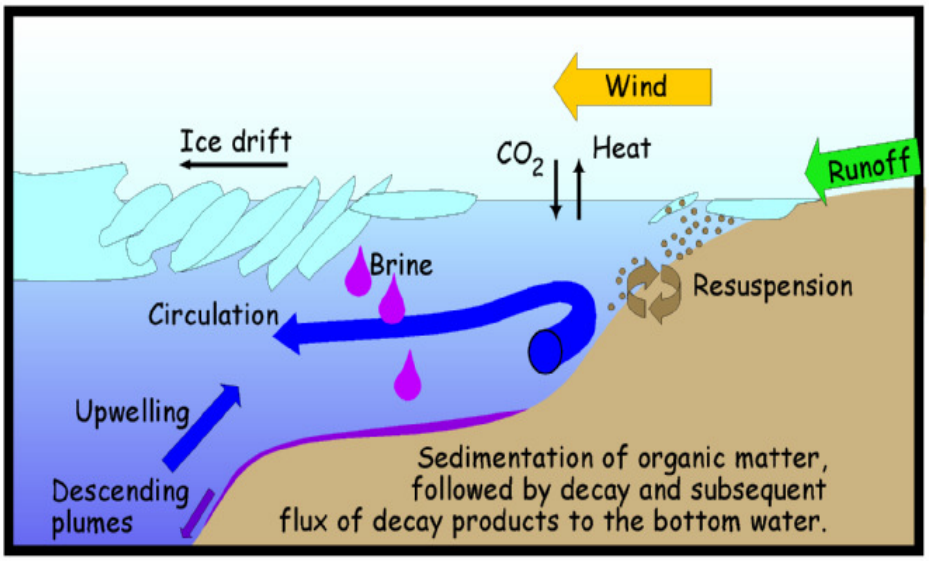


Figure 6.2. Schematic showing shelf-ocean dynamics and brine production.

With lowering of sea-level pressure over the Siberian shelf and increasing pressure gradients, the penetration of storm systems onto the shelf and associated wind-mixing of shelf seas are likely to increase. These effects are, in turn, likely to be amplified by the reductions in ice cover and increase in wind fetch. Storage of summer heat in this mixed surface layer appears to be retarding ice growth in the autumn thus forming a "feedback" which is amplifying the observed reduction of the areal extent of sea ice (particularly in the Chukchi Sea and Amundsen Gulf). During winter, the westward trend of predominant winds over the shelf break combined with an increase in the Atlantic water layer temperature will favor warmer water upwelling and its expansion onto the outer shelf. This may dramatically affect bottom water hydrography, sedimentation, as well as outer shelf biodiversity. It may also feed back into the sea-ice layer providing a ready heat source to either retard growth in the autumn or to increase melt in the spring. Due to changes in wind patterns the Transpolar Drift of ice and freshwater discharge from the Siberian shelf seas is expected to be weaker and turned eastward during winter, while during summer along-shore transport of riverine water will dominate the shelf hydrography. The combination of these anticipated changes may actually result in an increase in surface salinity in the central Kara and Laptev Seas, despite potential increases in river discharge. Weaker density stratification will enhance vertical mixing, affecting the downward fluxes of dissolved oxygen and nutrients that are critical for biological productivity.

The observed thinning and shrinking of the arctic sea-ice cover and its predicted further decline are of central importance to shelf processes. The changes are particularly pronounced in the East Siberian, Chukchi and Beaufort Seas, where thick multiyear ice that occupied much of the shelf during the entire year has now been replaced with thin seasonal ice (Figure 6.1; Comiso, 2002). During the summer months a large fraction of the shelves are now ice free. Changes in the sea-ice regime and global geopolitical and economic change have substantially increased the potential for economic development as well as a re-examination of national interests and sovereignty for most of the arctic shelf seas. In a global context, the subarctic Okhotsk Sea, which has seen unprecedented oil and gas development in an international regime under challenging environmental conditions, may represent a model of what is in store for the arctic shelves proper. In this context, the following topics are in need of study:

- Linkages between formation, persistence and distribution of landfast ice, coastal polynyas/leads, and brine production.

- The impact of increasing freshwater fluxes and reduced ice cover on ocean dynamics and brine production.
- The effect of the changing ice regime on the transfer of gas, mass, and energy across the ocean-sea ice-atmosphere interface, including the impact of enhanced fluxes of water vapor and aerosols on cloud formation and radiative transfer.
- Processes coupling atmospheric forcing to oceanic upwelling at shelf/slope breaks.
- The integrated impact of climate change on marine ecosystems and human activities, in particular on marine transportation and exploitation of natural resources.
- Further collection and interpretation of potential paleo-climatic records to help place present-day change in context with the recent geological past.

6.2.2. Changes in Cross-shelf Transport

An increased mean annual river discharge of 10 to 25% for the rivers that flow into the Arctic, with greater increases in winter and spring and a shift in the timing of peak flows to earlier in the spring is projected by models for the next 100 years (ACIA, 2004). Greater winter and spring runoff will increase flows of sediments, nutrients, and contaminants across the shelves to the Arctic Ocean. Additionally coastal erosion as well as the associated input of sediments, nutrients and contaminants is projected to increase due to increased thawing of coastal permafrost, higher sea levels, and the increased potential for severe coastal storms during the extended open water season (ACIA, 2004).

Owing to the delay of freeze-up the shelf seas are ice free for a longer period and the impact of autumn storms will be stronger. The autumn storms cause vertical mixing of the entire water column as well as the resuspension of bottom material and the enhanced removal of surface reactive contaminants (Wegner et al., 2005). Thus, increased sediment and contaminant export from the shelves to the deep Arctic Ocean can be expected. The distribution and dynamics of suspended matter influence the primary production in terms of the availability of nutrients and of the absorption of light. Many contaminants are hydrophobic and consequently tend to be adsorbed onto and transported by organic and inorganic matter. As a result, the fate and transport of these pollutants may be controlled largely by the distribution, composition, and concentration of suspended matter. A detailed knowledge of the "environmental" pathways of sediments, nutrients, and contaminants and their possible response to climate change is of critical importance to understand and to forecast the impact of environmental changes on land-shelf-ocean interactions. However, this depth of understanding is currently lacking.

Polar marine life is strongly influenced by sea ice, water properties, and nutrient availability. With changes in these factors and in corresponding light conditions will come shifts in biological species composition and the timing of primary production, affecting marine ecosystems as well as the biogeochemical cycling of essential nutrients and dissolved organic matter. To determine which of these forcing factors are most important to an accurate understanding of the system, the response to each factor must be evaluated. Figure 6.3 is a schematic representation of processes influencing cross-shelf transport. Considering the present dominant sources of nutrients to the arctic shelf seas, however, the input of waters from the surrounding oceans (especially for the Chukchi and Barents Seas) and the exchange of those waters with the central basins are clearly critical. Changes in these water fluxes are likely to impact productivity substantially, but how will a major change in primary production impact the air-sea flux of carbon dioxide and particulate transport, both horizontal and vertical? One essential factor in answering this question is the relationship between flux of nutrients and flux of carbon. If the two fluxes balance according to classical ratios of organic matter, then the effect on air-sea flux should be negligible. The particle flux, on the other hand, which usually increases with increasing primary production, is also strongly affected by biological species composition. Added to the marine production are terrestrially derived particles, some of which remain on the shelves and get buried in the sediment where they, and notably their carbon content, can be sequestered for long periods. A significant fraction of both particulate and dissolved matter may be transported by bottom currents into the deep Arctic Ocean or incorporated into sea ice for cross-Arctic transport prior to ice-melt. Time series and process studies on the following issues are needed:

- The dynamics of sediments, nutrients and contaminants in a quantitative context of climate variability and change.
- The effects of changes in the sea-ice regime, an enhanced hydrological cycle, increased coastal erosion, and changes in ocean circulation on cross-shelf to basin transport.
- The role of productivity and ecosystem changes in enhanced carbon transport.
- The role of shelves for carbon sequestration.
- Carbon exchange across the ocean-sea ice-atmosphere interface and the biochemical processes that drive this exchange.

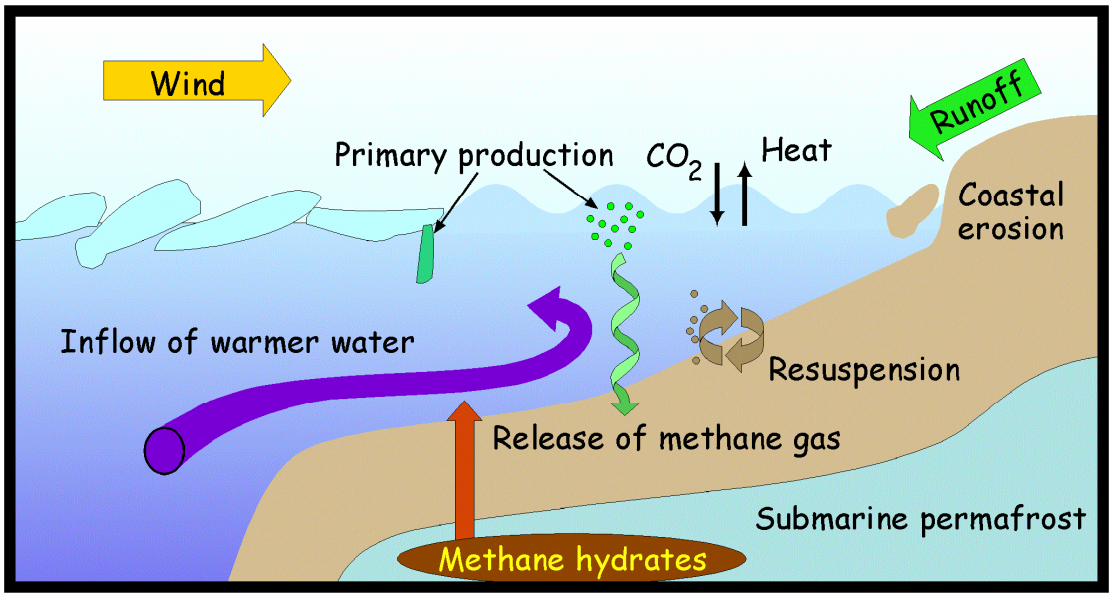


Figure 6.3. A simplified schematic showing processes influencing cross-shelf transport.

6.2.3. Ecosystem Alteration and its Impact on Marine Resources

Global warming has resulted in an increase in seawater temperature and a reduction in ice cover in the Arctic. This long-term development is complicated by the extensive interannual and regional variation that characterizes arctic shelves. Ecological changes naturally follow ecosystem alteration associated with global warming. For example, Atlantic-invasion species, such as the blue mussel and blue whiting, have been observed recently in the Barents Sea and near Svalbard, as has the presence of capelin in Hudson Bay (e.g., Berge et al., 2005). Climate change-induced alteration in ecosystem function is also clearly indicated by migrations of higher trophic level species (Figure 6.4). In addition, reductions in ice cover and increased run-off of freshwater create a scenario where surface water stratification increases on internal shelves but will decrease over time on inflow shelves such in the Barents and Chukchi Seas (Schauer et al., 2002). Shifts in stratification lead to significant changes in the physical forcing of productivity (light, vertical mixing, length of growing season, availability of nutrients, harvestable production, etc.; Sakshaug, 2004).

Currently, some basic knowledge regarding the food webs and their physical forcing exists for about ten pan-Arctic shelf regions. However, further work in these regions is urgently needed to investigate interannual variability and change. For many pan-Arctic shelves where no or limited information is available, the need to acquire knowledge via time-series and spatially distributed data sets is compelling. Also, as pan-Arctic shelves are difficult to access, modeling investigations, based in particular on physical-biological coupled 3-dimensional models, need to be developed, verified, and

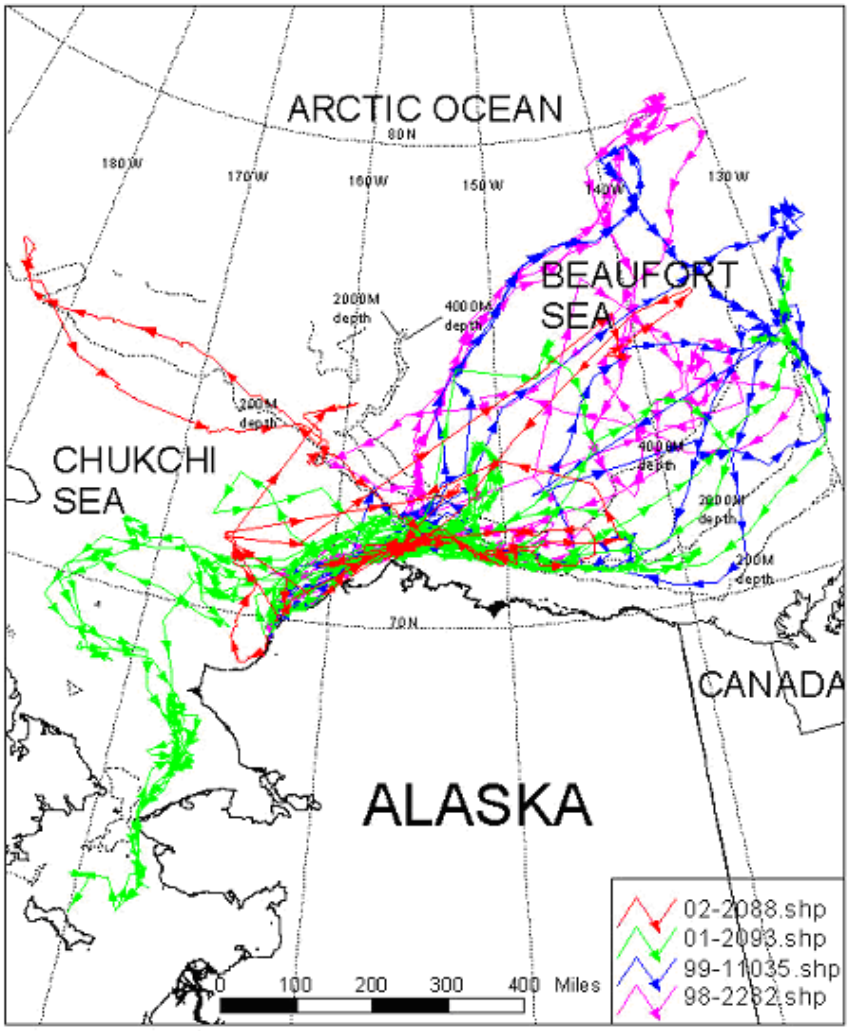


Figure 6.4. Tracks of belugas tagged at Pt. Lay, Alaska, in 1998, 1999, 2001 and 2002, showing broad-scale shelf-to-basin excursion under the influence of ice retreat and global warming (courtesy of R. Suydam).

applied to estuarine circulation and marginal ice zone scenarios on the inner and open shelves, respectively (e.g., Wassmann et al., 2006). Polynyas are particularly sensitive to current changes in oceanic and atmospheric forcing; some appear to be increasing in size while others are beginning to disappear altogether. The effect of warming on polynyas affects all elements of the marine ecosystem, including benthic and pelagic processes as well as biochemical cycling and rate processes.

Marine mammals and seabirds are apex predators in the short food chains common to the Arctic and thus excellent bio-indicators of ecosystem variability. In the Arctic, many species also serve the nutritive, economic and spiritual needs of Native communities, as a primary source of food and as cultural keystones. Thus, environmental changes that affect seabirds and marine mammals also directly affect the health and wellbeing of human inhabitants of the Arctic. Arctic ecological pathways can be explored from the top down, using these higher trophic level species to guide us in comprehending the transformation and fate of carbon, with direct links back to societal concerns and indigenous insights of climate change in the Arctic.

An insightful "top down" view of arctic food webs develops through comparison of habitat use patterns among species that consume dissimilar prey. Regional studies across the Arctic provide insight into seabird and marine mammal responses to climate change. For example, black guillemots expanded their nesting range north to Barrow, Alaska, during the warming period of the last three decades, with the winter Arctic Oscillation index positively correlated with the timing of egg laying. Polar bears, walruses, and ice seals depend on sea ice as a platform for breeding, feeding, and resting, so significant changes in ice thickness or extent have immediate ramifications on populations of these species. Cetaceans can track changes in benthic and pelagic community structure. For example, transport, rather than ice cover, seems to influence grey whale habitat selection. In years of high in-flow at Bering Strait, grey whales are especially tenacious in their use of shoal areas in the Chukchi Sea, presumably due to prey enhancement linked to pelagic-benthic coupling of transported carbon (Moore, 2000). Similarly, grey whales seem to have shifted their primary foraging location from south to north of Bering Strait, in concert with documented changes in benthic productivity and community structure.

One example of what can be achieved by international collaboration is the results of recent efforts to tag belugas in the United States, Canada, Russia, Greenland, and Norway. Tracks of whales outfitted with satellite transmitters have exhilarated researchers and testified to the exciting and dramatic integration of the ecosystem that can be achieved by these whales. Tagged belugas moved swiftly from shallow coastal and continental shelf waters, along the slope and into the deep Arctic Basin, sometimes transiting over 1000 km through heavy ice conditions in a matter of a few days (Figure 6.4). In one case, tagged whales also carried data loggers and provided oceanographers with 540 CTD profiles over a two-week period, sampling a fjord near Svalbard, which was unreachable by conventional means (Lydersen et al., 2002). As apex arctic predators, belugas are subject to comparatively high contaminant burdens through bio-magnification processes, which in turn are passed on to Native consumers. This trophic position, coupled with their broad-scale movements, suggests that belugas are especially suited to integrate ecosystem variability and to act as sentinels to change in the Arctic. Given this preamble, the key science questions should focus around:

- Northward shift of high-production zones.
- Longer and changing periodicity of open-water periods and increased meteorological forcing on nutrient dynamics and plankton succession.
- Invasion of species from lower latitudes and changes in food-web structure, with higher trophic-level species as sentinels of this change.
- Overall and regional changes in productivity as affected by changes in meteorological; oceanographic, hydrological, and biogeochemical boundary conditions.
- Distribution of marine resources as related to changing fronts, hot spots, and polynyas.

6.2.4. Phenology of Key Ecosystem Events

Climate models predict marked changes in amplitude and seasonality of arctic rivers due to thawing of permafrost, regional increases in net precipitation, decreased snowfall, earlier spring-melt, and a delay in the onset of sea-ice cover. The entry, distribution and fate of particulate and dissolved elements (especially carbon and nutrients) in the Arctic Ocean, and thus the development and sustenance of arctic ecosystems, are strongly a function of the timing of physical events. The arrival of sufficient irradiation to drive photosynthesis in the ice and the ocean below is determined certainly by solar-planetary positioning but also by a complex function of cloud cover and the thermodynamic state of the snow/sea-ice system (Mundy et al., 2005). Precipitation plays a pivotal role in that a small temperature change (less than 1 °C) can have a profound impact on when precipitation arrives in the form of rain rather than snow. As ice break-up proceeds, cloud cover becomes a notable differentiator between open water (more and different types of clouds) and the remaining ice-covered ocean (Minnet and Key, 2006). Freshwater input plays important roles in both the formation and decay of sea ice due to the higher freezing point. By transporting significant heat energy to the marine environment, freshwater input (particularly in the spring) can open ice-covered areas earlier than would otherwise be

the case. The input of freshwater also serves to stabilize the upper lighted surface of the ocean which, in turn, enhances primary productivity.

The spring blooms of sea-ice algae and marine phytoplankton, themselves disjunct in time (and space), provide that year's primary supply of resources for the existing ecosystem; riverine input of terrestrial organic matter, albeit of lesser quality, can supplement the system. To the degree that shifts in key physical events alter these resource inputs, an ecosystem can be jump-started by intense ice-algal blooms and maintained for months by extended open-water bloom seasons or stunted in its development by late ice break-up and early freeze-up. The effects of the timing of these various events within the marine ecosystem are not well understood, but they can have length scales ranging from days to years (e.g., survival of one cohort impacting that of another in the next season). A trend towards an earlier bloom season in the Arctic may initially support a richer overall ecosystem, including commercially viable fisheries, but over the long term the supply of key nutrients (nitrate and silicate) will determine ecosystem complexity and the number of trophic levels that can be supported. Most species within the highest trophic levels currently supported, including indigenous human populations dependent on them for sustenance, are also strongly impacted by the availability of sea ice and a stable snow cover over it. For example, ice structure acts as a catchment for the snow, creating critical habitats for ringed seals and polar bears, such as birthing lairs. Liquid precipitation can play a significant role in altering these habits during critical seasons, negatively impacting the future of these higher trophic levels.

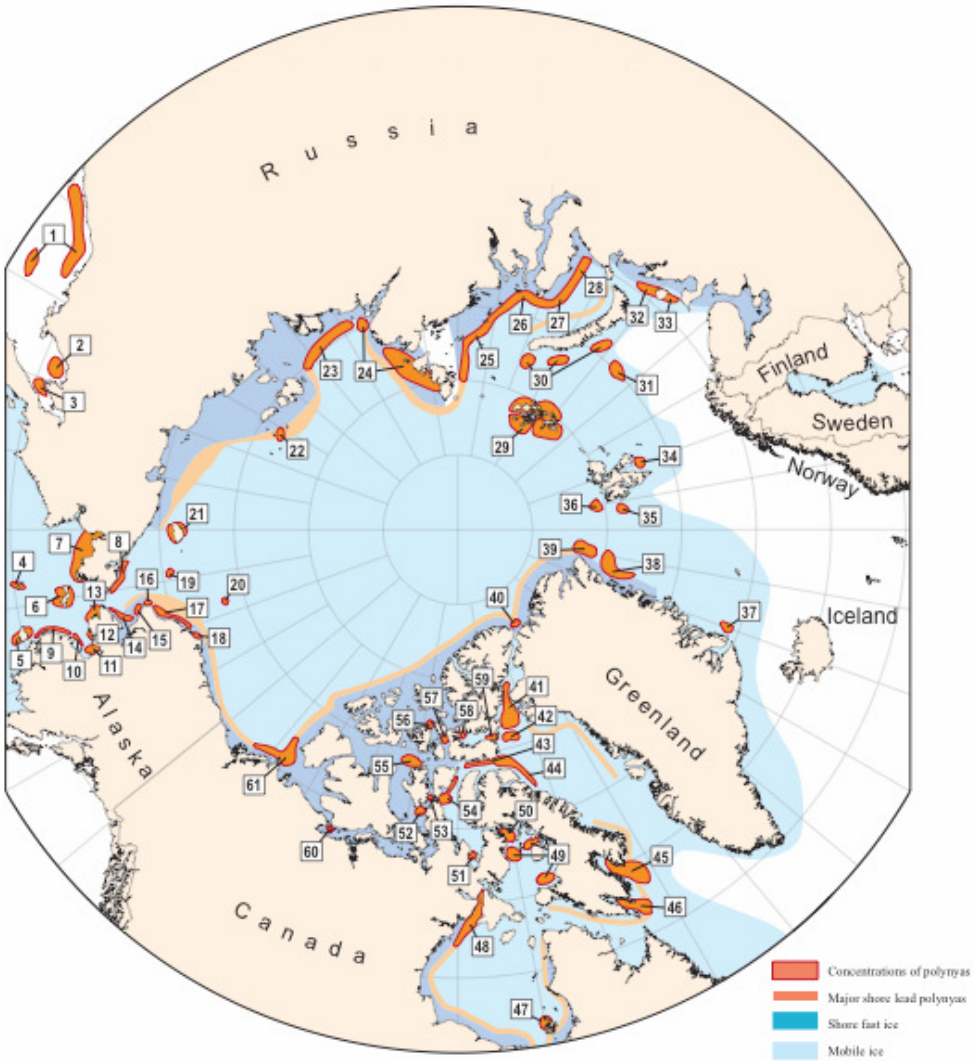
As the hydrological cycle, complete with its nutrient components, is altered by climate change, so will ecosystems change. Enhanced silicate input to a given region will ensure competitive diatom blooms (nitrate also being in sufficient supply; Tremblay et al., 2006), which in turn support larger organisms further up the trophic ladder; reductions in the silicate supply will favor smaller-celled phytoplankton, prey items for different and smaller predators. Changes in the timing of physical events and delivery of key nutrients can thus shift keystone species, leaving an altered ecosystem that may no longer favor the higher trophic levels of today or traditional use activities by native peoples. Such species shifts can also lead to an altered biological pump with less carbon delivered to the seafloor for the support of benthic biota, important food resources for many marine mammals, or eventual burial (carbon sequestration). Thus, the timing of events should be focused in relation to:

- Impacts on shelf ecosystems and marine resources, especially in depositional environments like polynyas.
- Changes in the significance of the biological and dissolution pumps.
- Links between the hydrological cycle and both primary changes (atmospheric pressure, air temperature, ice cover, riverine input, etc.) and complex changes in shelf-ocean interaction and ecological structure and function, especially as they relate to higher trophic levels.
- Critical links between radiative exchange, clouds and snow on sea ice.

6.2.5. Arctic Polynyas in Response to Climate Change

The environmental, socio-economic and geopolitical consequences of an eventual sustained reduction of arctic sea ice will be significant. For example the continuing reduction of sea ice is very likely to lengthen the navigation season and increase marine access to arctic natural resources. Here, polynyas play a central role as they are thought to be model open-water systems for how the Arctic will respond to regional and circum-Arctic oceanic and atmospheric forcing.

Polynyas, currently small components of the arctic system (Figure 6.5), are expected to expand in size and duration in the near future, especially on the arctic shelves, until the entire shelf region is open virtually year-round. The responses on the scale of a polynya, evident for example in increased local cloud formation, generate feedbacks to climatic conditions likely to reach a larger scale. The physical boundaries of some polynyas have already changed over the course of satellite history; others are poised for potentially rapid change (Barber et al., 2001).



1 Okhotsk Sea
2 Gizhiga
3 Kamchatka
4 St Mathew Island
5 Nunivak Island
6 St Lawrence Island
7 Sireniki
8 Chukotsk Peninsula
9 Cape Romanzof
10 Yukon Delta
11 Norton Sound
12 Nome
13 Seward Peninsula
14 Kotzebue Sound
15 Cape Thompson - Point home
16 Cape Lisburne
17 Chukchi
18 Peard Bay
19 Herald Shoal
20 Hanna's Shoal
21 Wrangel Island
22 Bennett Island
23 Laptev Sea
24 Severnaya Zemlya
25 Kara Sea
26 Ob/Eniseyskaya
27 Yamalskaya
28 Amderminskaya
29 Franz Josef Land
30 Novaya Zemlya
31 Barents Sea
32 Pechorskaya
33 Cheshskaya
34 Storfjord
35 Hausgarten
36 Whaler's Bay
37 Scoresbysund
38 NEW (Northeast Water)
39 Ob Bank
40 Lincoln Sea
41 NOW (Northwater)
42 Coburg Island
43 Lancaster Sound
44 Bylot Island
45 Cumberland Sound
46 Frobisher Bay
47 Belcher Islands
48 Rosex Welcome Sound
49 Foxe Basin
50 Fury & Hecla Strait
51 Committee Bay
52 Franklin Strait
53 Bellot Strait
54 Prince Regent Inlet
55 Viscount Melville Sound
56 Queens Channel & Penny Strait
57 Dundas Island
58 Hell Gate - Cardigan Strait
59 Lady Ann Strait
60 Lambert Channel
61 Cape Bathurst

Figure 6.5. Minimum estimated number of recurrent polynyas in the northern hemisphere and their locations, based on a review of the literature and an analysis using the PSSM method for detection of polynyas (see Barber and Massom, 2006). Note that some of these polynyas no longer exist in a fashion analogous to their recent history; e.g., the Northeast Water (no. 38). Adapted from Barber and Massom (2006).

For example, the Cape Bathurst polynya that forms on the Mackenzie Shelf is intimately connected to the degree of reduction in average areal sea-ice concentration in the southern Beaufort Sea, in turn driven by scale-dependent atmospheric and oceanic forcing throughout the annual cycle (Barber and Hanesiak, 2004). Atmospheric forcing is believed to drive oceanic upwelling at the shelf break and contribute to early reduction in sea-ice concentration (Lukovich and Barber, 2005). Autumn formation of sea ice is then delayed by surface mixing of a summer warming of the surface layer. These climatic responses and feedbacks have resulted in a polynya that has begun to change in geographic location (to migrate eastward) with a tendency towards increased negative sea-ice anomalies over the past 25 years. This migration eastward along the shelf and overall reduction in sea ice has potentially important implications for higher trophic levels, since this region provides critical feeding grounds for marine mammals, especially whale populations, and the native peoples that derive sustenance from them in traditional ways. Further east in northern Baffin Bay, the atmospheric and oceanic forcings drive the annual formation of a large polynya known as the North Water Polynya, a region of ecosystem productivity that rivals the Barents and Bering Seas. Long-term history recorded in the sediments and in anthropological data suggests that polynya productivity and carbon export have been reliably high over hundreds to perhaps thousands of years (Deming et al., 2002). Although their relative importance requires further study, recent climatic and oceanic changes appear to have reduced the duration of the major ice bridge that forms annually across Nares Strait (connecting Ellesmere Island and Greenland) and that, along with winds and currents, enables polynya formation (Barber et al., 2001). The demise of this ice bridge is expected to bring more ice into the polynya region, potentially reducing primary productivity and the current richness and robustness of the larger ecosystem. The recent demise of an ice bridge with similar physical function on the northeast Greenland shelf has resulted in the conversion of the previously well-defined Northeast Water Polynya to an open-water shelf system of unknown altered ecosystem performance.

Hardly anything, however, is known about the impact of climate changes on the Eurasian continental shelf polynyas, although these are major sources of dense water (Kara, Barents and Chukchi Sea polynyas) and sites of high net-ice production rates in the Arctic Ocean (mainly Laptev Sea Polynya). In addition they are of vital importance for navigation along the Northern Sea Route. These polynyas are understudied as ecosystems but well-studied as dynamic interfaces between hydrological input from the major Siberian river systems, with their particulate and dissolved loads, and the broad depositional shelf areas dropping to the deep sea (Dmitrenko et al., 2005). Since polynyas are focal points for intense biological production and the sustenance of higher trophic levels, changes in the timing of key events associated with their formation, areal extent, and closure can be closely linked to ecosystem structure and bounty.

In order to assess the dynamics and relevance of polynyas for the arctic climate system, it will be essential to investigate both their long-term history and their highly variable annual and interannual dynamics by integrated multidisciplinary studies. Only then will it be possible to model the near future of these historically unique polar oases. Studies should focus on:

- Interannual, decadal, and longer-term variability in oceanic, sea-ice, and atmospheric forcing.
- Dramatic impacts on keystone species, from diatoms to marine mammals, by changes in polynya formation, size, and nutritional inputs.
- The role of scale in atmospheric and oceanic forcing of polynya systems as currently embedded in the circum-Arctic flaw-lead system.
- Feedbacks between polynyas, the existing flaw-lead system, the more regional scales of marginal ice zones, and shelf/basin systems.
- Predictions from observation-based models within and between disciplines.
- Long-term history and paleo-proxies of arctic polynyas.
- Feedbacks to the arctic system.

6.2.6. Evaluations of the Paleo-record in Developing Future Scenarios

The arctic shelves have not been static through time. Global sea level which affects shallow shelves is linked to northern hemisphere glaciation; and the role of sea ice in controlling precipitation levels requires further definition. The history of sea-level fluctuations, including their magnitude, is valuable for determining the ecosystem and environmental impacts of rising sea level on shelf seas and coastal regions. Low sea level also influences arctic oceanography dramatically by eliminating the Pacific Ocean's flux into the basin, increasing sediment supply, and perhaps causing basin stagnation. The present status of the Arctic Ocean and its influence on the global climate system strongly depend on the large river discharge which is equivalent to 10% of the global runoff. Thus, the arctic marginal seas are key areas for understanding the global climate system and its change through time.

The Siberian Shelf Seas occupy the wide continental shelf north of Eurasia (up to 900 km off the coast) and the discharge of the river systems into the shelf seas represents approximately 70% of the Arctic Ocean's riverine input. These river systems drain much of Eurasia and are affected by changes in climate from the steps to the Himalayan Mountains to the arctic perimeter. Sedimentary sequences from the shelf seas record changes in location and volume of freshwater input from the river systems, as well as the influx of Atlantic- and Pacific-derived water, and the movements of large Pleistocene ice sheets (e.g., Bauch and Kassens, 2005). These largely untapped archives record fundamental changes in the hydrology and ice balance in the northern hemisphere.

Because of the relatively shallow water depths in arctic shelf seas, especially along the Siberian margin, these regions became strongly affected by the cyclic global sea-level changes in the Quaternary, essentially leading to the deposition of alternated marine and terrestrial sediment sequences (Mueller-Lupp et al., 2000). Of central interest for arctic paleo-studies is therefore to investigate the influence of past sea-level variability on the shelf environment. Three major paleo-environmental extremes can be recognized. They relate to times of the highest and lowest global sea-level stand in the more recent Pleistocene past: i.e., the last interglacial (c. 125,000 years BP) with a sea level several meters higher than today (Lambeck and Nakada, 1992); the last glacial maximum (c. 20,000 years BP) with a sea level about 120 m lower than today (Fairbanks, 1989); and the transitional phases in between these two periods.

Virtually unexplored territories are subsea permafrost regions beneath the arctic shelf seas. Increasing air and water temperatures over most of the arctic shelves are likely to accelerate thawing of coastal and subsea permafrost along the Siberian shelf seas in particular (ACIA, 2004). A considerable amount of organic carbon is stored in the upper layer of permafrost and gas hydrates are expected within and beneath the subsea permafrost. Thawing of permafrost could release large quantities of greenhouse gases into the atmosphere, further increasing global warming (Nelson, 2003). Subsea permafrost, such as in the Laptev Sea, was formed under subaerial conditions during the last glacial periods and subsequently underwent submersion due to postglacial sea-level rises (Kassens et al., 2001). Therefore its present state is highly transient. After submergence subsea permafrost degrades, thawing from the seabed downwards by the influx of salt and heat as a result of the new oceanographic boundary conditions, even in the presence of negative mean seafloor temperatures (Osterkamp et al., 1989). Changes in temperature and salinity distribution within the water column are of major importance as they directly influence the energetic balance of the subsea permafrost. Even though the subsea permafrost is of importance for the global climate system, our knowledge on its distribution, its recent dynamics, and its stability factors as well as on the microbial processes in it and their impact on the regulation of biogeochemical cycles is inadequate.

The following paleo and subsea permafrost studies that examine shelf history (in particular during sea-level extremes), gas chemistry, and microbial life are essential to improve and refine climate models and develop future scenarios:

- The long-term history of ice sheets and permafrost, land/ocean-sediment flux, river discharge, and arctic biota.

- The influence of a major change in seasonal temperatures on the hydrological cycle.
- The contribution of shelf brines to deep-water formation in the Arctic Ocean through time.
- The influence of evolving ocean gateways on the depositional setting along the shelf margins and the development of shelf water masses during transitional extremes.
- The influence of meltwater release from circum-Arctic sea ice on global ocean circulation and climate during glacial-interglacial transitions.
- The impacts of sea-level extremes on oceanic and atmospheric circulation patterns.
- The stability factors and biogeochemical cycles in subsea permafrost, in particular methane formation and/or oxidation.

6.3. Scientific Approach, Logistical Requirements, and Key Regions

The scientific approach for the study of the arctic shelf seas is driven and defined by the overarching hypothesis that past and predicted future changes in the arctic shelf regimes result in an increase of transport in the broadest sense; i.e., enhanced fluxes of energy, matter, organisms, goods, and natural resources, etc. both across and along the shelves. Enhanced transport is expected to impact on the inflow, outflow, and inner shelves differently but overall is expected to tie the arctic system more closely to lower latitudes through oceanic and atmospheric processes and the political, societal, and economic ramifications. Most importantly, the integrated impact of such increases in transport is expected to enhance seasonal, interannual, and regional variability, rendering the arctic shelves more dynamic than they already are and, in many cases, less predictable. More dynamic shelf scenarios will strongly affect human activities at a time when changes in the geopolitical, economic, and environmental regimes have greatly increased global interest in arctic shelf seas.

A multi-disciplinary, synchronous circum-Arctic approach in cooperation with ICARP II Science Plans 3, 4 and 5, covering transects from the coast across the shelf-slope into the deep Arctic Basin, is required to meet the challenge of evaluating increasingly dynamic scenarios on arctic shelves. Ideally, expeditions should be carried out during all seasons, but especially during the polynya season when many types of measurement can be undertaken, including measurements on water column and bottom structure and key vertical flux and transport processes (i.e., salinity, temperature, currents, oxygen, nutrients, chlorophyll, plankton, suspended particulate matter). Shipboard work must be complemented and extended via remote time-series measurements from both one-year and multi-year seafloor observatories equipped for basic measurements of conductivity, temperature and depth (CTD meters, as well as other biogeochemical sensors, Acoustic Doppler Current Profilers (ADCPs), water samplers, and sediment traps (continuous and event-driven). Technological development is needed for autonomous and event-driven sampling methods in the highly variable arctic shelf and polynya systems and for biogeochemical sensors which can be implemented at long-term mooring stations.

An important new approach that can free long-term (mooring-based) observatories from the challenges of overlying surface constraints due to sea-ice and weather conditions is the development of cabled seafloor observatories. In the coming decade, cabled observatories can be expected to provide continuous, high bandwidth (gigabits per second) and high power (tens of kilowatts) observations, as well as docking functionality for Autonomous Underwater Vehicles (AUVs). They can offer the means for continuous, real time access to the water column, the underside of the ice, and the sediment surface, both by adapting existing instrumentation and new sensing technologies as they come on line. Planning is underway in the United States, for example, to develop a cabled observatory on the inflow Chukchi shelf, most likely using the Barrow Global Climate Change Research Facility (now under construction) to provide shore support, connecting seafloor instrumentation to a power source and to science support facilities in Barrow. The potential for making observations that will couple atmospheric and oceanographic processes is substantial; the opportunities for research, environmental evaluations, education and outreach will be unique.

Owing to the seasonal and highly dynamic ice cover that extends over most of the arctic shelf seas, observations in these regions, except for the still relatively brief summer, are sparse. To ensure

systematic observations of ocean and ice cover in important and contrasting areas of the arctic shelf seas, in particular through time-series observations, attention to concentrated efforts in specific areas has merit. Because the Eurasian continental shelf polynyas are important sites for dense water and sea-ice production, one or more of these polynyas should become the focus of a long-term observatory program. Interannual sampling should consider at least a ten-year period because of the growing evidence for a periodicity in the synoptic scale processes that drive sea-ice dynamics, thermodynamic processes, and changes in productivity and marine resources. Research teams from Canada, Germany, Russia, and the United States have begun to install sea-floor mooring-based observatories in the Siberian Laptev Sea polynya to complement those initiated in the Greenland-North American polynyas, the North Water Polynya, and the Cape Bathurst polynya (as well as further south in Hudson Bay).

A major challenge that both the scientific community and stakeholders face in the coming years is the relative absence of surface-based data across the expanding seasonal ice zone. The International Arctic Ocean Buoy Programme (see http://iabp.apl.washington.edu) has excellent coverage across the perennial sea ice, but the types of buoys or drifting sensor systems needed for the dynamic and less accessible (from the perspective of autumn/winter sensor deployment) seasonal ice zone are missing. Here, a coordinated effort that networks existing and planned coastal observation sites (such as the Alaska Ocean Observing System, http://www.aoos.org) and develops a next-generation drifting sensor system may help to address some of these critical issues. Remote sensing will also continue to play an extremely important role, with a number of new sensor systems (such as Envisat, http://envisat.esa.int/ or NASA's Aquarius Surface Salinity Sensor, http://www.esr.org/aquarius/aquarius_main.html) likely to provide critical data on the hydrography and ice cover of the arctic shelf seas. A key challenge will be to ensure continuity and full access to time series of climatological relevance (such as ice concentration data and ice drift data from the Special Sensor Microwave/Imager, SSM/I, instrument; http://www.ssmi.com/), in particular in light of realignment or commercialization plans at various national agencies. The ideal configuration would consist of a suite of instruments that provide data on sea- or ice-surface temperature, salinity, and spectral reflectance, as well as concentration, type, and velocity of sea ice along with surface elevation for indirect derivations of ice thickness. For the marine ice cover and underlying ocean, the World Climate Research Programme's Climate and Cryosphere project (CliC, http://clic.npolar.no) specifically aims to integrate remote sensing, in-situ observations, and modeling to follow the status of the marine cryosphere in the Arctic.

The remoteness and difficulties in adequately sampling the vast pan-Arctic shelf seas oblige more concerted attention to modeling efforts. With very few exceptions, most large-scale oceanic circulation models do not resolve the shelf seas (due to limitations in vertical grid size) and frequently do not include processes critical to the dynamics and heat budget of the shelves, such as landfast and mobile ice cover. Further, few address carbon flux and marine productivity. The importance of transport and exchange at interfaces (coast-shelf, shelf-slope, slope-deep-sea) needs careful consideration that will require additional development and validation work. Atmospheric models are in a similar state of infancy, requiring development to handle the complex couplings that occur within marginal ice zones and polynyas. The key role of water within this system should be a focal point, since water in all three of its phases defines the marginal and seasonal sea-ice zones. Finally, biophysical models need to be developed and improved to help address some of the key questions outlined above. These problems are addressed in detail by ICARP II Science Plan 9, as well as by CliC Project Area 4 (CPA4), which specifically considers improved modeling of polar ice and ocean processes.

Owing to their seasonal dynamics, lack of accessibility in some seasons, and overall climatic extremes, large regions of the arctic shelves constitute a major logistical and technical challenge for many types of paleo-studies. Developing new strategies for retrieving long sediment archives from the inflow, inner, and outflow shelves is essential to achieving logistical and scientific success. These strategies should include the possibility to conduct long-sediment coring from conventional icebreaking research vessels during summer, as well as to drill sediment cores of up to several hundreds of meters in length from the shallower shelf regions during the ice-covered season using ice-based platforms. National and international coordination of paleo-efforts with other types of seagoing

projects will be essential. In this respect a unique and novel infrastructure will be *Aurora Borealis*, a dedicated European research icebreaker with a deep drilling capability.

The intertwined nature of the processes that occur on arctic shelves has already been recognized by numerous scientific steering committees to require an integrated, multi-level and synchronous circum-Arctic approach. The necessity for synchrony derives from the broad scientific goal to place shelf seas with contrasting characteristics into the context of the larger arctic system. For example, what similar or differing roles do the western/North American Arctic and the central and western Siberian shelves play in northern hemispheric issues? Current large national projects (all of which are also international), each focused on multiple aspects of a given arctic shelf region, have made important starts in this direction, even though they have lacked initial cross-project coordination; e.g., the Canadian Arctic Shelf Exchange Study (CASES; http://www.cases.quebec-ocean.ulaval.ca/), the Nansen and Amundsen Basins Observational System (NABOS; http://nabos.iarc.uaf.edu/), and the Laptev Sea System. Such coordination is now happening naturally among researchers and project leaders, especially given some overlap in participation between projects; future coordination can benefit from a more formalized structure. The IPY provides strong new motivation to plan efforts in 2007/08 in concert in order to identify key regions for focused research and to guide logistics. The formation of IPY clusters, such as the Climate Forcing of the Pan-Arctic Marine Ecosystem (PAN-AME; http://www.ipy.org/development/eoi/proposal-details.php?id=26), Integrated Arctic Observing System (iAOOS; http://www.ipy.org/development/eoi/proposal-details.php?id=14), IASC-IPA project Arctic Coastal Dynamics (acd@awi-potsdam.de), International Arctic System for Observing the Atmosphere (IASOA; http://www.ipy.org/development/eoi/proposal-details.php?id=196), and Arctic Palaeoclimate and its EXtremes (APEX; http://www.ipy.org/development/eoi/proposal-details.php?id=39) clusters in particular, will bring together large national programs explicitly to examine the response of the arctic marine system in all its facets to changes in oceanic and atmospheric forcing caused by the changing climate. An important legacy of IPY that will help to meet the long-term goals of ICARP II, but especially those concerning arctic shelf seas, will be the emerging model for international coordination at all levels to achieve common goals in the Arctic. The goals of this ICARP II science plan are also included in the Arctic Ocean Sciences Board (AOSB; http://www.aosb.org/) programs Arctic Paleo-River Discharge (APARD), International Arctic Polynya Program - Polynyas in the Arctic's Changing Environment (IAPP-PACE), Shelf-Basin Exchange Initiative (SBE), and Pacific Arctic Group (PAG).

6.4. Education and Outreach

From the perspective of education, the pan-Arctic and integrated nature of the scientific questions and approach are an ideal fit with recent developments for concerted circum-Arctic educational efforts. We can build upon the excellent models for successful, international arctic education and outreach at all levels, including K-12, undergraduate and graduate students, that already exist. Notably, all of them are directly related to arctic shelf seas.

For example, Canada has developed a number of highly successful programs through the international CASES project and the ArcticNet Centres of Excellence of Canada (http://www.arcticnet-ulaval.ca), operating on the Mackenzie Shelf, as well as in northern Baffin Bay and Hudson Bay. The Schools on Board program brings high school students, including from local Inuit villages, aboard research icebreakers for direct experience of a scientific expedition. This model program is planned for international expansion as part of the Circumpolar Flaw Lead (CFL) system study, a proposal to the Canadian IPY program. Inuit field schools, media workshops, and Inuit-Science workshops are also envisioned aboard the CCGS *Amundsen* as part of Canada's IPY programming. A successful model for multi-national graduate-level education can be seen in the International Summer School on Climate Change in the Arctic, conducted aboard the Russian icebreaker *Kapitan Dranitsyn* in the Laptev Sea during the NABOS expedition of 2005 (http://www.iarc.uaf.edu/highlights/summer_school_05), with joint funding from the United States (NSF and NOAA), Japan (Jamstec), Canada (ArcticNet) and Russia (Foundation for Basic Research, Academy of Sciences, Ministry of Education and Science, State Research Center for Arctic and

Antarctic Research of ROSHYDROMET). Other models for graduate-level education and outreach also exist, with the Barents Sea as the focal point; e.g., through the Norwegian Arctic marine ecosystem research network known as ARCTOS (http://www.nfh.uit.no/arctos/index.html), which is developing new plans to internationalize educational efforts through an ARCTOS-related Center of Excellence.

Germany and Russia look back on 15 years of successful cooperation in the field of polar and marine research in the Siberian Arctic. Joint research projects such as the Laptev Sea System project led to a joint initiative focusing upon the support of young scientists in Russia and Germany, which culminated in the establishment in 2000 of the Otto Schmidt Laboratory for Marine and Polar Research (OSL) at the State Research Center for Arctic and Antarctic Research in St. Petersburg (http://www.otto.nw.ru). Through its fellowship program, the OSL enables young highly qualified scholars to carry out specific research projects in polar and marine sciences. The program pairs master students, graduated research assistants, postdoctoral fellows etc. with experienced collaborating scientists in Russia and Germany to work on well-focused tasks of mutual interest. Summer school courses are offered and an exchange of guest scientists is realized. The OSL is equipped with a state-of-the-art standard laboratory for polar and marine research and an international library. In order to encourage the involvement of students in arctic research, the international Master Program in Applied Polar and Marine Sciences was established at the State University St. Petersburg (POMOR; http://www.pomor.org/) in 2002. POMOR imparts knowledge of the polar and marine environmental systems from coastal to deep-sea regions and applied aspects including the scientific approaches and methods of the disciplines of oceanography, marine geosciences, and marine biology. Courses (mainly in English) and practical training are held at the State University of St. Petersburg in close cooperation with the OSL. After two years study, the students are awarded two diplomas of Master of Science in Applied Polar and Marine Sciences – one from the State University of St. Petersburg and one from the University of Bremen, Germany.

The potential for direct and continuing ties to the University of the Arctic (UArctic; http://www.uarctic.org), whose goals closely parallel the needs identified in this ICARP II science plan, is substantial. The implementation of specific education efforts at the undergraduate and graduate levels can take different forms. The IPY 07/08 can serve as a test bed for new ideas, including innovative workshops or specific courses offered by UArctic member institutions in on-line or field course format (see www.uarctic.org/Frontpage.aspx?m=3), such as the International Sea Ice Summer School 2007 proposed for IPY. Guidance and support for these efforts will be available through UArctic's newly established Education and Outreach Office, hosted at the University of Alaska Fairbanks.

A component of utmost importance that straddles the realms of outreach and scientific activity is the involvement of local experts and traditional environmental knowledge. Here, guidance for the implementation of such programs can be obtained from highly successful efforts of community-based observations such as the Arctic Borderlands Ecological Knowledge Co-op (see http;//www.taiga.net and the Canadian Community-Based environmental Monitoring Program (CBM; http://www.eman-rese.ca/eman/ecotools/common/intro.html) which operates through the ArcticNet program. While more challenging to implement for the marine environment, such community-based observations are nevertheless feasible and demonstrably productive (e.g., through ArcticNet). They provide important links between the local and scientific communities and help to refine and guide research programs through the exchange with local experts. At the same time, this provides for a much more efficient channel in ensuring that local stakeholders and planners, including local governments, have direct access to observations and predictions that can help with planning and impact on mitigation.

6.5. Linkages / Users

As many of the changes in the shelf-sea environment strongly impact on the open ocean and the coastal zone – where levels of shipping, resource exploitation, and traditional subsistence activities are increasing – the identification of key strategic issues and major activities needs to be coordinated with

ICARP II Science Plans 1, 2, 3, 4, 5, 10 and 11. Addressing the key issues will also require efforts to ensure that disciplinary divisions (both within and between different working groups) will be overcome in order to adequately understand fluxes of energy and mass as well as the propagation of climate signals and anomalies through the arctic system. Adopting strategies that address a complexity of questions in explicit terms of transport across the different boundaries within the system may help in this regard. Forecasting of future states of the arctic shelf seas and variability on different time scales will also require close coordination with ICARP II Science Plan 9.

The changing shelf seas have already effected a response both at the level of coastal communities who have adapted their subsistence strategies as well as at the geopolitical level with recent or planned filings by Russia, Canada, and Denmark for an extension of territorial waters northward from their current locations. Traditional use by aboriginals in fast-ice regions continues as a priority even with increasing uncertainty regarding changes outside of the local traditional knowledge. Natural hazards and disasters are also seen as a high priority requiring linkages within and between the various ICARP II working groups.

6.6. Implementation

The implementation of specific programs naturally depends strongly on the availability of funding and the level of support through national funding agencies. International programs, such as CliC or programs under the auspices of the International Arctic Science Committee (IASC) can help with development of implementation plans, but the particular challenge lies in ensuring that approaches are integrated and holistic. Ongoing efforts to establish a network for an International Study of Arctic Change (ISAC; http://www.aosb.org/isac.html) may provide substantial guidance over the coming five to ten years, with several existing initiatives helping to focus and steer implementation efforts. The European Program on Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES; http://www.ipy.org/development/eoi/proposal-details.php?id=40) is devoted to the study of environmental arctic change in the ocean-ice-atmosphere system, focusing on the Eurasian shelves and the central Arctic. In the United States, the Study of Environmental Arctic Change is gaining momentum, with a comprehensive implementation plan published in 2005 (www.arcus.org/search/resources/reportsandscienceplans.php). In Canada, the ArcticNet Centres of Excellence of Canada was recently funded for a seven-year program. This NCE focuses on changes in the coastal Canadian Arctic through a multidisciplinary approach to understanding both the scientific basis of this change as well as an assessment of how Canadians can adapt to these changes. ArcticNet operates as an international research consortium with about half the science teams coming from Canada and the other half from partner nations. The NCE is renewable for a maximum of two terms (14 years). Observatories installed in Baffin Bay, the southern Beaufort Sea, and Hudson Bay have begun and are providing baselines to ascertain aspects of variability and change in these regions.

A further, key component in implementing arctic shelf seas studies is to take into consideration local and general stakeholder interests. Thus, in many instances this means the development of tools and mechanisms through which input from such sources can be integrated into research programs; a particular challenge when melding sociological, political, economic, and environmental science. However, the integrated nature of the changes apparent in the Arctic and outlined above clearly requires more efforts along these lines in the future. Also, such local and corporate stakeholders should be integrated into the development of funding schemes. For example, oil and gas development typically requires detailed information about the marine environment, obtaining such data both from the scientific literature and through hired consultants. Ensuring that the collected data eventually enter the public domain and become part of relevant databases is an important aspect of implementation planning.

6.7. Funding

Funding for research in the United States is expected to come primarily from the Office of Polar Programs at the National Science Foundation. NOAA's Office of Arctic Exploration also continues to support programs, particularly in the arctic shelf seas. New sources of funding are expected, however, from potentially novel sources, including private foundations increasingly showing an interest in the potential for discovery in the world's oceans (e.g., the Gordon and Betty Moore Foundation) and industrial sources increasingly turning north for their investments and activities, precisely because of the changes anticipated on arctic shelf seas in the coming years.

Funding for research in Canada is available from a number of different federal agencies. The ArcticNet program is already funded for a seven-year period through the NCE of Canada program. The Canadians have also made a commitment of Can$150 million for IPY programs. The Natural Sciences and Engineering Research Council (NSERC) has also committed Can$6 million to the IPY program and supports ongoing Arctic Research Networks such as the Canadian Arctic Shelf Exchange Study. The social sciences (SSHRC) and medical sciences (CIHR) granting councils are also involved in funding arctic research pertinent to this ICARP II science plan. Government agencies continue to support a variety of ongoing research in Canada mostly associated with Fisheries and Oceans Canada, Environment Canada, Indian and Northern Affairs and the Department of Defense.

China is expecting a special funding program for international expeditions (research icebreaker *Xuelong*) to the Bering Sea, Chukchi Sea, Beaufort Sea and the Canadian Basin during IPY 07/08 through the Chinese Arctic and Antarctic Administration. Also the Chinese Natural Sciences Foundation will support arctic research projects related to this ICARP II science plan.

To meet the goals of this ICARP II science plan, funding in Germany is available from the Ministry for Education and Research (Otto-Schmidt-Laboratory for Polar and Marine Research; Laptev Sea System project (in consideration of funding)) and the German Academic Exchange Service (POMOR) with further support expected from the German Research Foundation. During IPY 07/08 the Alfred Wegener Institute for Polar and Marine Research plans the international expedition SPACE onboard RV *Polarstern* to the central Arctic Ocean and the Siberian Shelf seas. The goals of this expedition are strongly related to the aims of this ICARP II science plan.

References

ACIA, 2004. Impacts of a Warming Arctic. Arctic Climate Impact Assessment. Cambridge University Press, 139p.

Barber, D.G. and J. Hanesiak, 2004. Meteorological forcing of sea ice concentrations in the southern Beaufort Sea over the period 1978 to 2001. Journal of Geophysical Research, 109. C06014, doi:10.1029/2003JC002027.

Barber, D.G. and R.A. Massom, 2006. The role of sea ice in Arctic and Antarctic polynyas. In: W.O. Smith and D.G. Barber (eds.). Polynyas: Windows into Polar Oceans. Elsevier Series in Oceanography (in press).

Barber, D.G., J. Hanesiak, W. Chan and J. Piwowar, 2001. Sea ice and meteorological conditions in Northern Baffin Bay and the North Water Polynya between 1979 and 1996. Atmosphere-Ocean, 39:343–359.

Bauch, H.A. and H. Kassens, 2005. Arctic Siberian Shelves. Global and Planetary Change, Special Issue, 48:1–3, 1–8. doi: 10.1016/j.gloplacha. 2004.12.003.

Berge, J., G. Johnsen, F. Nilsen, B. Gulliksen and D. Slagstad, 2005. Ocean temperature oscillations enforce the reappearance of blue mussels in Svalbard after 1,000 years of absence. Marine Ecology Progress Series, 303:167–175.

Comiso, J.C., 2002. A rapidly declining perennial sea ice cover in the Arctic. Geophysical Research Letters, 29:1956. doi:1910.1029/2002GL015650.

Deming, J.W., L. Fortier and M. Fukuchi, 2002. The International North Water Polynya Study (NOW): A brief overview. Deep-Sea Research II, 49:1–6.

Dmitrenko, I.A., K.N. Tyshko, S.A. Kirillov, H. Eicken, J.A. Hölemann and H. Kassens, 2005. Impact of flaw polynyas on the hydrography of the Laptev Sea. Global and Planetary Change, 48:9–27. doi:10.1016/j.gloplacha.2004.12.016.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature, 342:637–642.

Kassens, H., H. Bauch, I. Dmitrenko, S. Drachev, G. Grikurov, J. Thiede and K. Tuschling, 2001. Transdrift VIII: Drilling in the Laptev Sea in 2000. The Nansen Icebreaker, 12:8–9.

Lambeck, K. and M. Nakada, 1992. Constraints on the age and duration of the last interglacial period and on sea-level variations. Nature, 357:125–128.

Lukovich, J. and D. Barber, 2005. On sea ice concentration anomaly coherence in the Southern Beaufort Sea. Geophysical Research Letters, 32. L10705, doi:10.1029/2005GL022737.

Lydersen, C., O.A. Nost, P. Lovell, B.J. McConnell, R. Gammelsrod, C. Hunter, M.A. Fedak and K.M. Kovacs, 2002. Salinity and temperature structure of a freezing Arctic fjord – monitored by white whales (*Delphinapterus leucas*). Geophysical Research Letters 29:2119–2122.

Minnet, P.J. and E.L. Key, 2006. Meteorology and atmosphere-surface coupling in and around polynyas. In: W.O. Smith and D.G. Barber (eds.). Polynyas: Windows into Polar Oceans. Elsevier Series in Oceanography (in press).

Moore, S.E., 2000. Variability of cetacean distribution and habitat selection in the Alaskan Arctic, Autumn 1982–91. Arctic, 53:448–460.

Mueller-Lupp, T., H.A. Bauch, H. Erlenkeuser, J. Hefter, H. Kassens and J. Thiede, 2000. Changes in the deposition of terrestrial organic matter on the Laptev Sea shelf during the Holocene: evidence from stable carbon isotopes. International Journal of Earth Sciences, 89:563–568.

Mundy, C.J., D. Barber and C. Michel, 2005. Variability of snow and ice thermal, physical and optical properties pertinent to sea ice algae during spring. Journal of Marine Systems, 58:107–120.

Nelson, F.E., 2003. (Un)frozen in time. Science, 299:1673–1674.

Osterkamp, T.E., G.C. Baker, W.D. Harrison and T. Matava, 1989. Characteristics of the active layer and shallow subsea permafrost. Journal of Geophysical Research, 94 (C11):16227–16236.

Sakshaug, E., 2004. Primary and secondary production in the Arctic seas. In: R. Stein and R.W. Macdonald (eds.). The Organic Carbon Cycle in the Arctic Ocean, pp. 57–81. Springer.

Schauer, U., H. Loeng, B. Rudels, V.K. Ozhigin and W. Dieck, 2002. Atlantic water flow through the Barents and Kara Seas. Deep-Sea Research, 49:2281–2298.

Tremblay, J.-E., C. Michel, K.A. Hobson, M. Gosselin and N.M. Price, 2006. Bloom dynamics in early opening waters of the Arctic Ocean. Limnology and Oceanography, 51:900–912.

Wassmann, P., D. Slagstad, C. Wexels Riser and M. Reigstad, 2006. Modelling the ecosystem dynamics of the marginal ice zone and central Barents Sea. II. Carbon flux and interannual variability. Journal of Marine Systems, 59:1–24.

Wegner, C., J.A. Hölemann, I. Dmitrenko, S. Kirillov and H. Kassens, 2005. Seasonal variations in arctic sediment dynamics – evidence from 1-year records in the Laptev Sea (Siberian Arctic). Global and Planetary Change, Special Issue, 48:1–3. doi:10.1016/j.gloplacha.2004.12.009.

Winsor, P. and G. Björk, 2000. Polynya activity in the Arctic Ocean from 1958 to 1997. Journal of Geophysical Research, 105:8789–8803.