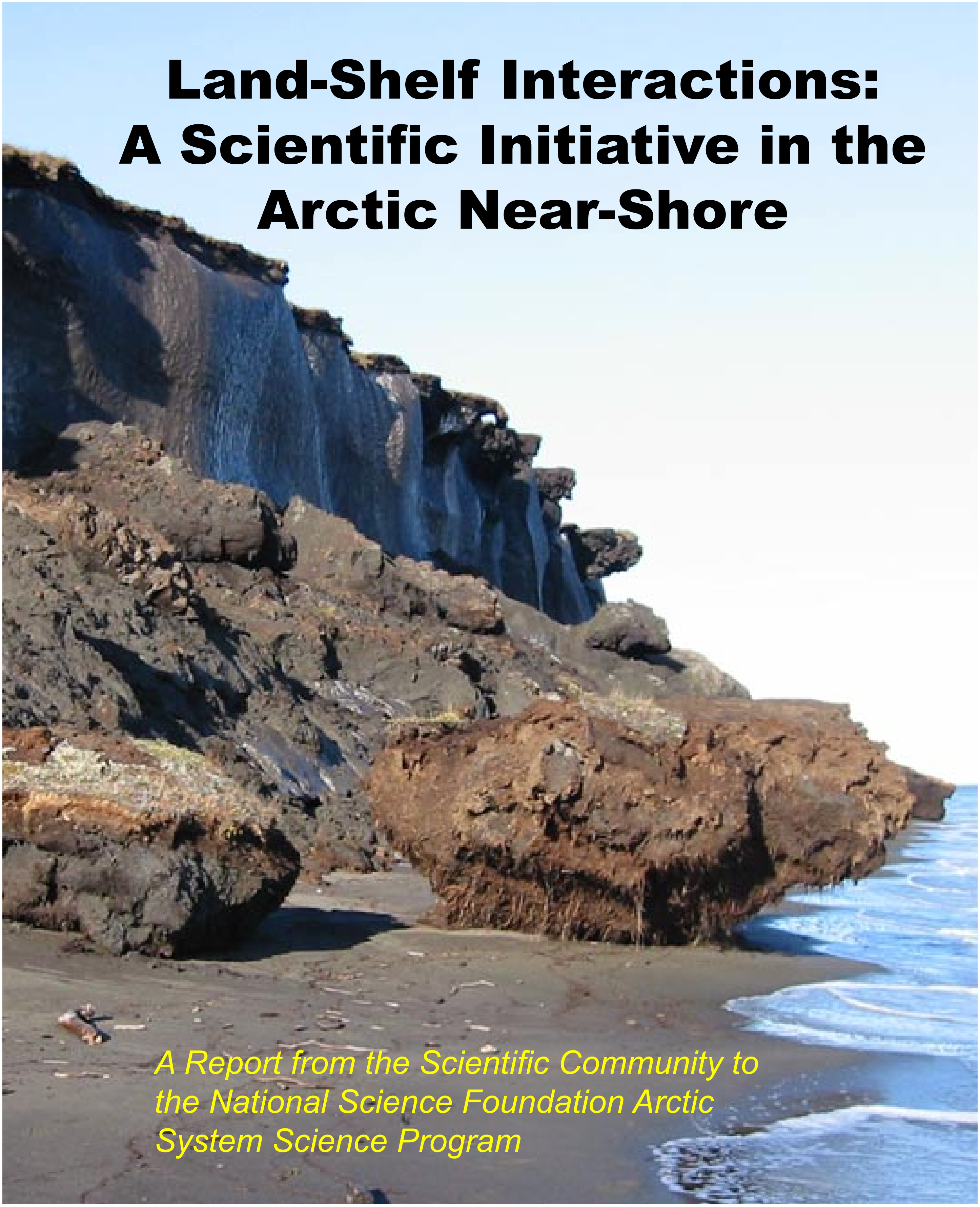
Land-Shelf Interactions: A Scientific Initiative in the Arctic Near-Shore



A Report from the Scientific Community to the National Science Foundation Arctic System Science Program

Frontispiece. Near the head of the Ob' River Estuary, Siberia, summer 2000. Image courtesy of Max Holmes. Cover image is courtesy of Volker Rachold.

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Executive Summary

The Land-Shelf Interactions (LSI) Initiative is a research planning effort centered on the land-sea margin in the Arctic, focusing on the scientific challenges of environmental change on human and biological communities and related physical and chemical systems. The land-sea margin is a critical geomorphic zone in the Arctic. Freshwater runoff, coastal erosion or accretion, sea ice and permafrost formation and melt, atmospheric gas exchange, and biological communities all change in significant ways across the land-sea margin. No comprehensive understanding of the Arctic as a linked biogeochemical and hydrologic system will be accomplished without a coordinated research effort to elucidate the crucial biogeochemical exchanges between land and sea and their impacts on biotic systems.

The goal in this science planning effort is to lay the groundwork for a coordinated, interdisciplinary research opportunity in the Arctic that would focus on the coastal zone, and would support land, river, and sea-based researchers. Because of the substantial influence of the Eurasian landmass on arctic runoff, climate, sea ice formation, water mass formation, and other processes that impact environmental responses to change, the Arctic cannot be properly understood in a systemic manner without coordinated, interdisciplinary efforts in the Russian Arctic. However, many aspects of environmental change at the Arctic land-sea boundary can be appropriately studied outside of Russia, so this science plan is generic, rather than geographically delimited. In undertaking this science planning effort, we are working toward a significant new investment in near-shore Arctic environmental change research.

Many scientific issues requiring complex, interdisciplinary research approaches have been identified at the land-sea margin in the Arctic. Some key topics include the impacts of changes in precipitation and runoff on Arctic Ocean circulation and coastal climate, ice formation and distribution, the biogeochemical fate of materials transported in rivers and from eroding coastlines, and the impacts of climate warming on permafrost and the release of radiatively active gases. The social stresses on human communities in the North brought on by political and environmental changes in the past few decades also deserve attention.

Another important focus should be on the role of food chains and the efficiency of transfers of carbon, nitrogen, contaminants, and other constituents from the environment, through marine and terrestrial organisms to local human communities. Because of the relatively high density of human communities in Arctic coastal zones, these foci provide an opportunity to address the linkages between marine and terrestrial ecosystems in ways that have direct relevance to society. This initiative could also examine the role of people in the arctic system as an important mediator of interactions between marine and terrestrial food webs, which in turn affect the productivity of these systems.

The full report of this science plan describes these scientific issues in more detail, and outlines an interdisciplinary research program that would contribute to anticipating and limiting the negative impacts of environmental change in the Arctic region, particularly focusing on the coastal zones that have not been adequately addressed in recent Arctic System Science research programs. The intended audience of this document includes prospective scientific investigators, U.S. agency personnel, operations and logistics managers, and others interested in the complex biogeochemical exchange processes that occur at the land-sea margin in the Arctic. To the extent that this science planning effort can also provide a logistical platform or mechanisms for supporting other research in relatively inaccessible coastal portions of the Arctic, it also supports the involvement of a broad spectrum of researchers who may ultimately benefit with improved research access and capabilities.

1. Introduction

There is growing community awareness that many important responses of the Arctic system to environmental change will involve feedbacks at the land-sea margin of the Arctic (Moritz et al. 1990; Tynan and Demaster 1997; Aagaard et al. 1999; Morison et al. 2000; Johnson and Polyakov 2001). Terrestrial and marine environments interact most directly in the near-shore zone, and these fluxes of materials (water, nutrients, organic matter, etc) from land greatly impact the functioning of coastal marine ecosystems (Rouse 2000; Chapin et al. 2000; Lammers et al. 2001).

Some of the important processes and feedbacks in the near-shore zone are outlined on Figure 1. For example, permafrost on land and in undersea deposits currently sequesters large amounts of radiatively active gases such as methane (Anisimov and Nelson 1996; Danilov 2000; Lee and Holder 2001). Many arctic shorelines are erosional in nature, so it is possible that significant amounts of this methane, as well as oxidizable organic carbon that is stored in northern peatlands, will be added to the coastal zone and be available for release to the atmosphere. These radiatively active gases will then have a positive feedback on global warming and cause the degradation of additional permafrost. This example illustrated the bi-directional nature of the global change - Arctic System interaction: that is, global change may have significant impacts on Arctic ecosystems including the land-shelf system, and in turn changes to the land-shelf system may impact global climate.

Furthermore, the Arctic land-sea margins appear highly vulnerable to environmental changes that are likely to occur over the next century. For instance, a continued decline in sea ice spatial extent and thickness [e.g. Rothrock et al. (1999)] could result in greater water column productivity over the continental shelves while the retreat of sea ice beyond the continental shelf could also lead to the disappearance of habitat for ice-associated organisms that feed on the continental shelves (e.g. gray

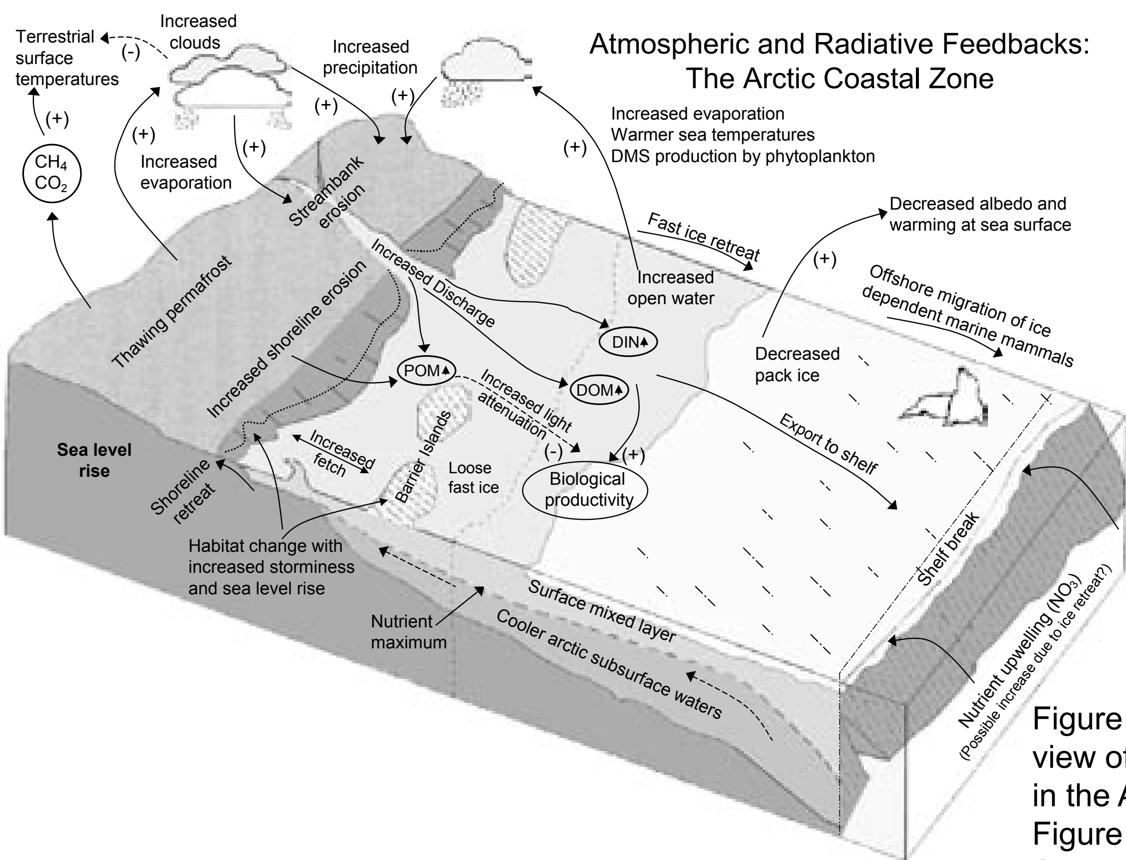

Figure 1. Diagrammatic view of selected processes in the Arctic coastal zone. Figure courtesy of Susan Schonberg

and bowhead whales, walruses, diving ducks, and bearded seals) (Fig. 1). Shoreline erosion rates are also likely to increase with longer open-water periods. Many of these projected changes are likely to have deleterious impacts on human communities that are predominantly located in the Arctic near the land-sea boundary. However, other changes could have positive economic benefits, such as if the Northern Sea Route from northern Europe to East Asia becomes a more practical navigation route with the retreat of sea ice along the north coast of Russia (Brigham et al. 1999; Brigham, 2001) or if climates become less continental with decreases in winter ice.

Despite these general projections, the scientific data currently available to prepare for widespread environmental change in the Arctic are inadequate. Some of the potential feedbacks, most very poorly constrained, are illustrated for the east Siberian region in Figure 2. This figure also

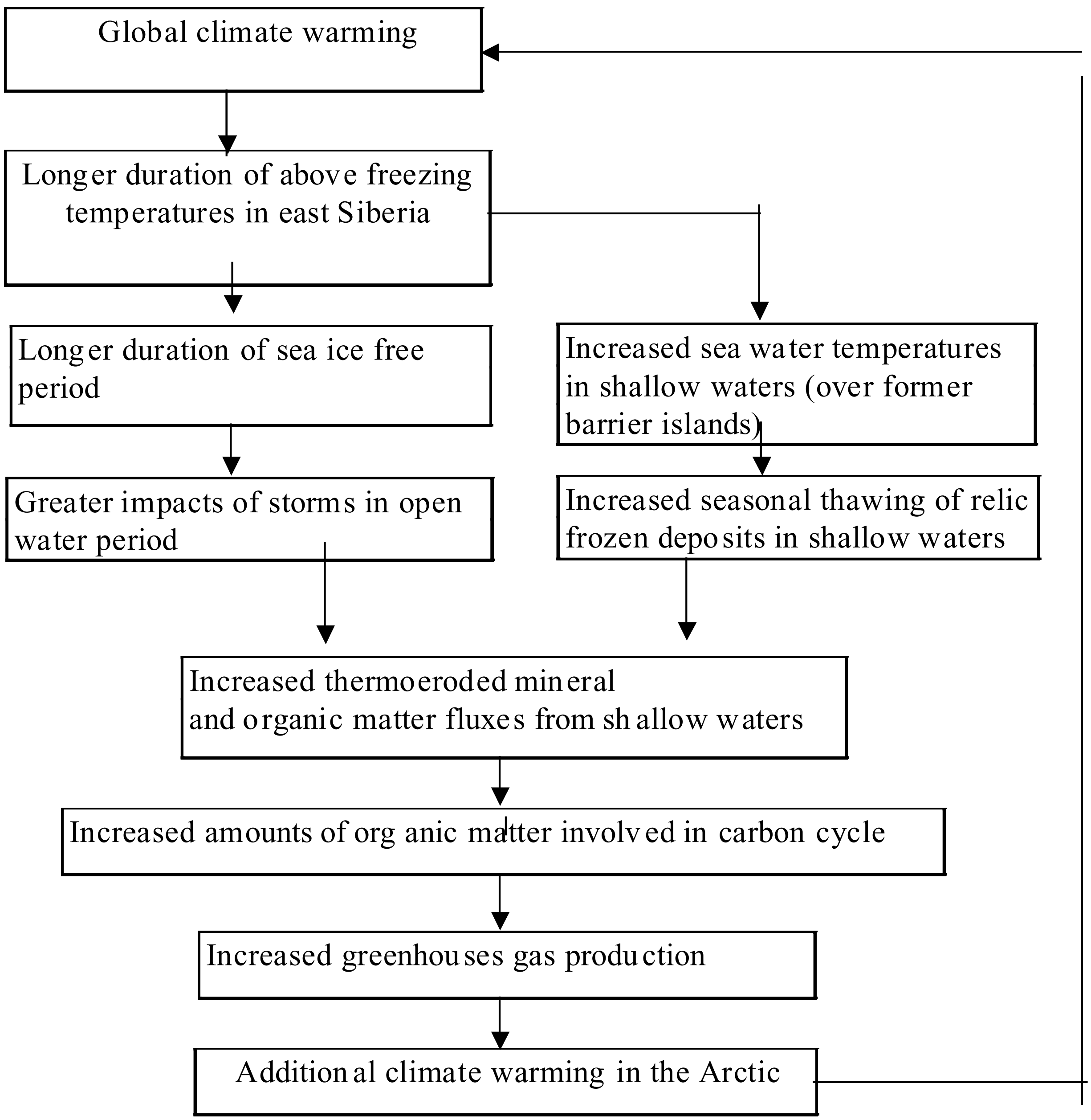

Figure 2. Example of climate global warming influence on modern natural processes in eastern Siberia (positive feedback). Contributed by Nikolai Romanovskii.

emphasizes the point that there is only a minimal description of circulation, hydrography, and seasonal variability of the arctic shelf. Likewise, the few data pertaining to biological productivity and the fate of this production are so broadly distributed in time and space that it is difficult to distinguish temporal from spatial variability. Recent work with archived Russian river biogeochemical data (Zhulidov et al. 2000; Holmes et al. 2000) shows many discrepancies and interpretive difficulties. These complications indicate that we have only an incomplete understanding of the fluxes of nutrients and other materials brought into the Arctic Ocean by rivers. Even less is known about the nutrients and materials fluxes from the eroding shorelines in the Arctic. In light of these challenges, specific unknowns need to be addressed using multiple, linked approaches. Fluxes of water from land to sea are not independent of changes in permafrost distribution, and both are also related to fluxes of nutrients and organic materials into the nearshore waters of the Arctic Ocean. A variation of Figure 2 might involve environmental change that would increase precipitation, leading to higher river erosion rates, greater coarse-grained deposition in deltas and shallow waters, and larger fluxes of dissolved and fine-grained materials to offshore regions. It is also worth considering the impacts of changes in sea ice cover and water temperature upon atmospheric moisture fluxes to land. Terrestrial plant communities, drainage, permafrost and atmospheric feedbacks could be significantly impacted, but our knowledge of these processes is severely limited.

Both from the standpoint of land-to-sea and sea-to-land environmental change, a wide range of analytical tools and interdisciplinary research approaches will be needed to evaluate these processes fully. No one disciplinary approach (e.g. permafrost history, hydrology, coastal physical oceanography, etc.) by itself can produce the synoptic understanding that is needed to predict and respond to environmental change in the Arctic. Thus, a coordinated interdisciplinary approach is required to advance scientific understanding at the land-sea margin. This is the overall objective of the Land-Shelf Interactions Initiative.

The Land-Shelf Interactions Initiative has grown out of efforts within the Russian-American Initiative for Shelf-Land Environments in the Arctic (RAISE), and a recognition from within that effort that coastal processes have not been adequately addressed in recent Arctic System Science research. Independent of the administrative and logistical challenges of bilateral research in the Russian Arctic, attention in the United States arctic research community has also been directed towards improving scientific understanding of the many key processes and factors in Arctic coastal zones that will influence the response of the Arctic to environmental change, including areas within the North American Arctic. The result of these dual efforts has been the development of this new research initiative that has a goal of transcending the traditional geomorphic boundaries separating marine and terrestrial lines of inquiry in Arctic system science.

Within the NSF Arctic System Science (ARCSS) Program, the Land-Shelf Interactions Initiative is strategically located (Fig. 3), landward of the Shelf-Basin Interactions (SBI) research at the shelf-basin boundary and seaward of hydrological studies that are being initiated as a part of the pan-Arctic community-wide hydrological analysis and monitoring program (Arctic-CHAMP). It also will rest on the foundation of environmental insights provided by the Paleoenvironmental Arctic Sciences Program (PARCS), and interlock with existing and developing international arctic research programs.

The overarching goal guiding the Land-Shelf Interactions Initiative is to improve our understanding of the biogeochemical, physical, and hydrological processes that occur in the nearshore zone of the arctic shelf and its adjoining shoreline with respect to changes in the global climate system. Key questions include:

1) How will global change impacts on the Arctic hydrologic and carbon cycles impact the

sustainability of the Arctic land-shelf system?

2) What are the sources, modes of transportation and fate of fresh water, carbon, nutrients and other materials in the Arctic land-shelf system?

3) How will changes in the land-shelf system affect productivity and coastal lagoonal sytems and feedback to global climate?

2. Towards a Thematic Approach to the Coastal Zone

Among the important themes that have grown out of community-wide discussions on Arctic coastal research were the bi-directional impacts of society and coastal environments, the evolution and landscape dynamics of the shelves and near-shore zone, the fate and transport of materials in and through the coastal zone (including lateral and vertical linkages), the structural and functional patchiness in this ecosystem, and the couplings and feedbacks to-and from- the global system.

Related sub-themes that were discussed at the Seattle ARCSS All-Hands Meeting in February, 2002, including the dynamic variability of the coastal zone, the importance of coastal zone processes to human communities, vertical stratification, advection, and forcing within the water column, and biogeochemistry as a linking feature between land and sea. The fate and transport of materials, river

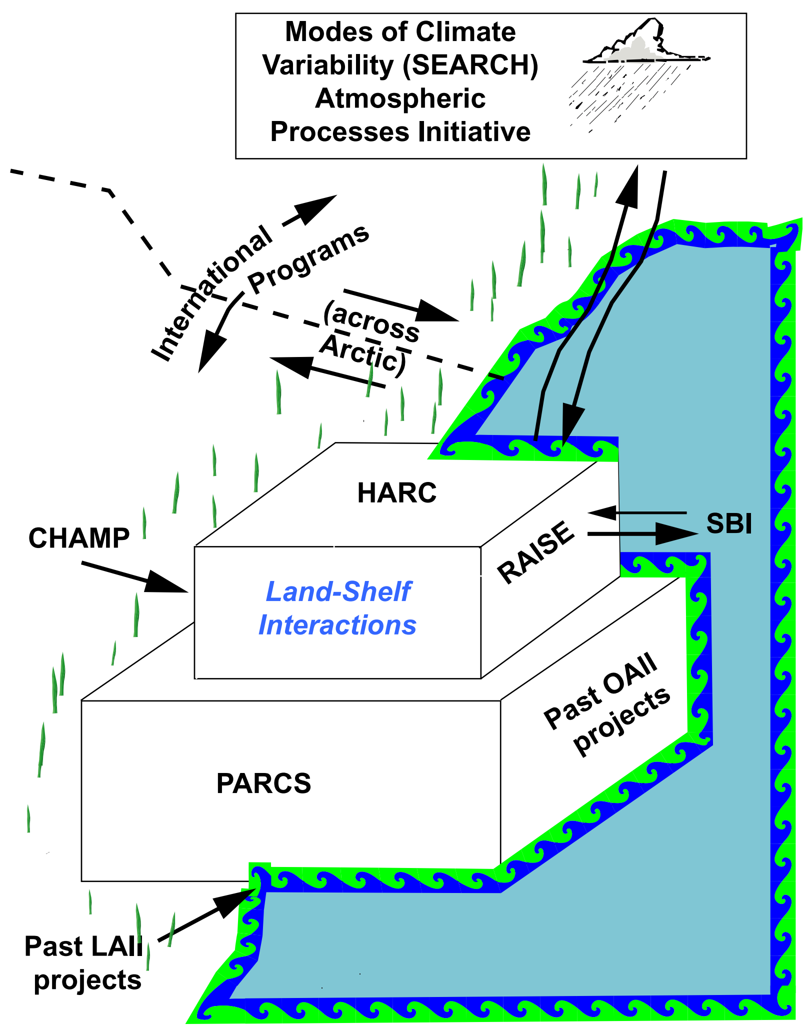

Figure 3. Relationship of the Land-Shelf Interactions Initiative to other national (U.S.) and international arctic research programs. Developed as part of discussions at the February 2002 ARCSS All-Hands Meeting, Seattle, Washington.

discharge connections to oceanic systems, foodweb transfers and dynamics, permafrost dynamics and related trace gas exchange were other sub-themes that were outlined by discussion participants. Participants in this meeting also stressed that gas hydrates, which are closer to the surface in the Arctic than at lower latitudes, may be vulnerable to change, consistent with the fact that cryospheric boundaries in the Arctic give the region many vulnerable characteristics with respect to environmental change.

A number of exemplary research questions were outlined for these themes and were organized in categories such as forcing functions, feedbacks, transformations and internal processes, and greater impacts. Some examples of these questions, which are appropriate for addressing in the Land-Shelf Interactions Initiative, are outlined below:

2.1. Forcing functions

1. What are the mass fluxes of materials (nutrients, organic matter, etc) contributed to the near-shore zone by rivers, coastal erosion, atmospheric deposition, sub-sea permafrost thaw and sea bottom erosion, and transport from offshore?
2. What are the biological, physical and biogeochemical responses to the huge spatial and temporal variability in river discharge, including the impacts on Arctic shelves as well as the connections to the world ocean?
3. How do changes in atmospheric circulation or specific meteorological events (e.g. storm surges) affect runoff, water mass structure and circulation, primary production, and biogeochemistry of the coastal zone? Contaminant dispersion and uptake and foodweb incorporation? How do changes in large-scale ocean circulation or specific near-shore events (e.g., upwelling, eddies) affect these phenomena?
4. Is the coastal zone ultimately a source or sink for CO_2 and other radiatively-active trace gases, such as CH_4, DMS, N_2O?

2.2. Feedbacks

1. How would a change in river runoff impact shelf circulation, biological productivity, sea ice formation, and the potential for ventilation of the Arctic halocline?
2. How significant a role would a decrease in sea ice have on coastal climate, including sea surface temperature, precipitation, insolation, growing season and low-land drainage? Do any of these impacts present a positive feedback for further sea ice decreases?
3. How will changes in sea ice regimes and summertime open water conditions (e.g., sea surface temperature, wave heights) affect the narrow terrestrial strip that is most effected by proximity to the marine environment?
4. What will be the biological responses and changes in biogeochemical cycling that will occur with the projected retreat of sea ice?
5. How will change in the open water season change the distributions of inorganic and organic materials in the nearshore environment?
6. What impact does coastal erosion have on the fluxes of radiatively-active gases such as methane and carbon dioxide?

2.3. Transformations and internal processes

1. How mobile are organic materials introduced into the arctic near-shore zone by coastal erosion versus river runoff?
2. What is the relative importance of microbial, meiobenthic, and macrobenthic communities in different shelf systems for transfer of organic materials from land to sea?
3. How does transformation and fate of ancient organics affect nearshore food webs?

4. How are functional patches of biota structured in the nearshore? Does this structure make the system more ecologically vulnerable, or is it more resilient in the face of change?
5. How will ocean encroachment and conversion of freshwater lakes to lagoons affect terrestrial ecosystems?

2.4. Human community impacts and dimensions

1. What are the likely impacts on human communities regionally and across the Arctic of projected environmental changes?
2. What kinds of information will coastal communities need in order to prepare for rapid environmental change?
3. How do we quantify the effects of national security, development, national environmental responses and other key uncertainties driven by policy upon coastal zone processes?

3. Overview of Key Issues

One of the other major outcomes of working group discussions at the ARCSS All-Hands Meeting (Seattle) and a prior joint ARCSS Land-Atmosphere-Ice Interactions (LAII) and Ocean-Atmosphere-Ice Interactions (OAII) components meeting in Salt Lake City (November 2001) was a recognition that significantly more synthetic and interdisciplinary approaches to Arctic system scientific inquiry are now practical and in fact necessary to advance our understanding of a changing Arctic. Rather than being viewed as an understudied boundary between ocean-based and land-based sets of scientific inquiry, the land-shelf margin is an integral component of the Arctic System that transcends the land and sea boundary (Fig. 4).

We consider below several of the key landscape and seascape processes and variables that are important at the Arctic land-sea margin. We see this as a practical means to construct a near-shore Arctic research strategy within the context of environmental change. We recognize in preparing this list that coverage of some important processes is limited, and no report of this nature can be all-inclusive in identifying significant research gaps.

3.1. Hydrological fluxes

The Arctic shelves constitute about 25% of the Arctic Ocean surface area and are the largest continental shelves in the world ocean. Many of these shelves are heavily influenced by runoff, which in addition to freshwater also contributes nutrients, sediments, dissolved and particulate organic matter, and trace substances into the waters of the Arctic Ocean. Sea ice is also a dynamic element in this system, and functions as an additional mechanism for moving sediments (Barnes et al. 1982; Reimnitz et al. 1993), trace contaminants (Cooper et al. 1998; Landa et al. 1998), elements of sea ice biological communities, and freshwater and brine from continental shelves into the deeper Arctic Ocean.

Changes in the runoff of Arctic rivers, the volume of nutrient-rich water flow through the Bering Strait, and sea level rise will each have effects on the fluxes of water-borne materials onto the continental shelves. Already there is evidence that discharge of major Eurasian arctic rivers is increasing, and this trend may well continue with future global warming (Peterson et al. 2002). These environmental responses are not immediately predictable, however, and indicate the need for new studies of biogeochemical exchanges and processes between Arctic land and sea. These studies might include

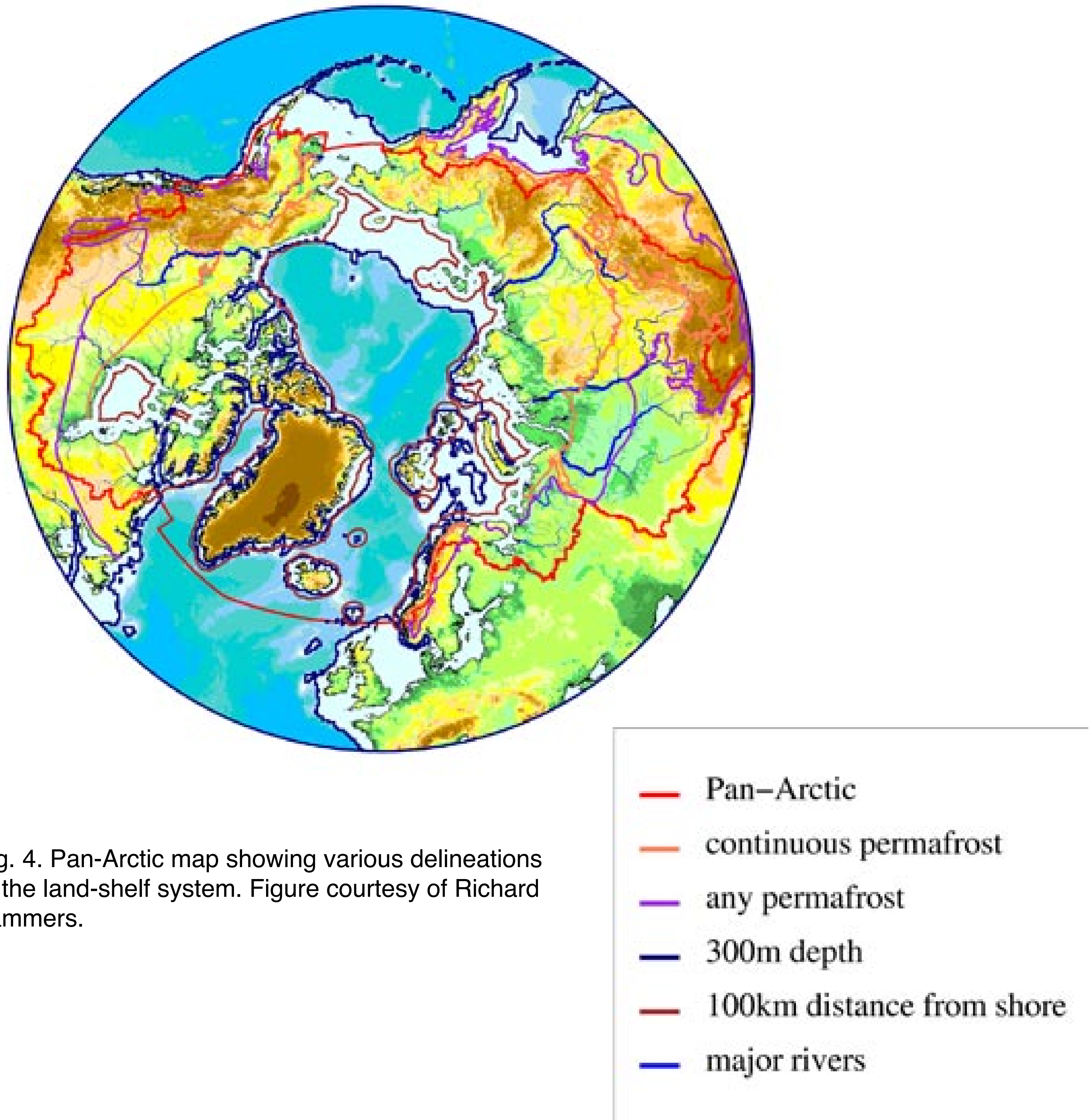

Fig. 4. Pan-Arctic map showing various delineations of the land-shelf system. Figure courtesy of Richard Lammers.

analyses of current processes of land-to-sea exchange, as well as modeling of global change impacts due to changes in precipitation, sea ice coverage, temperature, and food web structure.

A major link between the land and shelf components of the near-shore zone is the flux of freshwater, which includes entrained dissolved and particulate materials (Opsahl et al. 1999, Holmes et al. 2000, Holmes et al. 2002). In the Arctic, major components of the freshwater flux include rivers and the freshwater component of the Bering Sea inflow through Bering Strait, which is quantitatively similar in volume of freshwater to the input of all rivers draining directly into the Arctic Ocean (Aagaard and Carmack 1989; Carmack 2000). Arctic sea-ice also represents a large reservoir of freshwater and the Arctic Ocean is an important path for inter-hemispheric freshwater transport. Wijffels et al. (1992) found that nearly all the freshwater gained by the North Pacific Ocean (through an excess of precipitation over evaporation) is returned to the North Atlantic via the Bering Strait and the Arctic Ocean. Perturbations in the flux of freshwater from the Arctic Ocean could alter the stability and internal variability of the ocean's thermohaline circulation on decadal-century time scales (Bryan 1986; Weaver et al. 1993) and may be the dominant climate signal in the upper portion of the North Atlantic (Reverdin et al. 1997).

Once runoff is entrained within coastal waters, little information on its intermediate and final fate. Little information is available, for instance on what controls mean along-shore currents and water mass structure on the shelf, including variability forced at all temporal scales, from daily to interannual/decadal. However, recent evidence shows the importance of interannual variability of these currents to the deep ocean (Steel and Boyd 1998, Guay et al. 2001). These currents will interact with sea level changes and other processes (including river discharges) to affect coastal erosion and other near-shore processes. Unfortunately, near-shore conditions and processes are very poorly resolved in today's numerical ice-ocean models (e.g., Steele et al. 2001).

3.2. Sea ice, coastal dynamics, and permafrost

The seasonal ice cover on rivers, lakes, lagoons and the open ocean is a key component of the land-shelf system in the Arctic. As a barrier and a transport agent, sea-ice cover in particular controls a number of important aspects of the coastal zone and the adjacent shelf region. Specifically, ice cover:

1. Limits the amount of fetch and onshore wave action, thus providing a critical check on the amount of coastal erosion;
2. Represents a key component in the climate system of shelf-land environments by controlling heat transfer between ocean (and submarine permafrost) and the atmosphere, in particular as pertaining to the absorption of solar radiation by the coastal ocean;
3. Functions as an important geological agent in arctic coastal seas, through a number of processes including entrainment and export of particulate matter, scouring of the sea floor by pressure ridges, sustenance of ice-bonded sediments in the near-shore zone through formation of bottom fast ice, etc.;
4. Is of critical importance to Arctic ecosystems as a platform for marine mammals such as seals, polar bears and walrus, as a habitat for a diverse and productive community of microorganisms, and as a key constraint in limiting the amount of water-column primary production;
5. Prominently affects human activities in the arctic system and beyond by serving as a platform for indigenous subsistence activities, as both a hindrance and a facilitator in coastal development and finally as a navigational hazard that essentially controls opportunities for transport pathways of global significance.

Hence, an understanding of land-shelf systems and coastal environments requires a thorough, quantitative understanding of the role of ice and other key oceanic and atmospheric variables in governing the exchange of energy and matter between different components of the system as well as controlling critical processes in this system. Changes in the Arctic atmosphere-ice-ocean system recorded during the past decade by both scientists and stakeholders alike (Serreze et al. 2000; Huntington 2000)), and in particular a reduction in the ice season combined with a shrinking and thinning of the Arctic sea-ice cover (Rothrock et al. 1999; Serreze et al. 2000), are likely to have

Figure 5a (left): Aerial photograph of sediment-laden ice in Elson Lagoon (left, ca. 100 m across, courtesy R. Storvold). The image was taken in June and and shows remnants of snow cover and clean ice in upper right and in smaller patches between sediment-laden ice fragments. Figure 5b (right) Sediment distribution in a vertical ice slab (black marks 10 cm apart) cut from Elson Lagoon in May 1999 (Stierle and Eicken 2002). This type of sediment-laden ice is found throughout the interior Arctic and marginal seas, dispersed with the prevailing direction of ice drift (Pfirman et al. 1997).

profound impacts on the coastal environment. These range from substantial increases in the rate of coastal erosion and thermal degradation of submarine permafrost (Rachold et al. 2000), enhanced release and export of organic carbon and greenhouse gases to dramatic changes in the life cycle of marine mammals and impacts on infrastructure and development in the circum-Arctic. The importance of the ice cover and the difficulties arising out of our limited understanding of the coupling between different components of the system may be illustrated by the following two examples.

Rates of coastal erosion in the Alaskan and central and eastern Siberian Arctic have recently been estimated as several meters to tens of meters per year (Are 1999). In the Laptev Sea, supply of sediment and organic carbon from coastal erosion appears to exceed that from riverine input (Rachold et al. 2000). The lengthening of the ice-free season in summer and the retreat of the summer minimum ice edge further away from the coasts observed during the past decade is likely to increase the transfer of wave and thermal energy to the coasts, potentially accelerating rates of coastal retreat in the future. Paradoxically, however, the shortened ice season not only results in a loss of protection of the coastline but it furthermore increases the action of ice as an erosional agent on the coastline. Thus, it has been well established for the North American and Siberian Arctic that sea ice keels not only rework sediments in waters shallower than approximately 20-30 m, but that entrainment and export of resuspended particulates constitutes a major term in the sediment budget of the Arctic shelves and basins (Reimnitz et al. 1993; Pfirman et al. 1997; Eicken, in press). These processes are likely to grow in importance with increases in wind fetch due to reduced ice cover and more frequent and stronger storm events (Serreze et al. 2000; Proshutinsky et al. 1999). Figures 5 and 6 help illustrate these points and underscore the importance of nearshore processes on much larger scales.

Currently, we are far from understanding the processes responsible for entrainment and export of

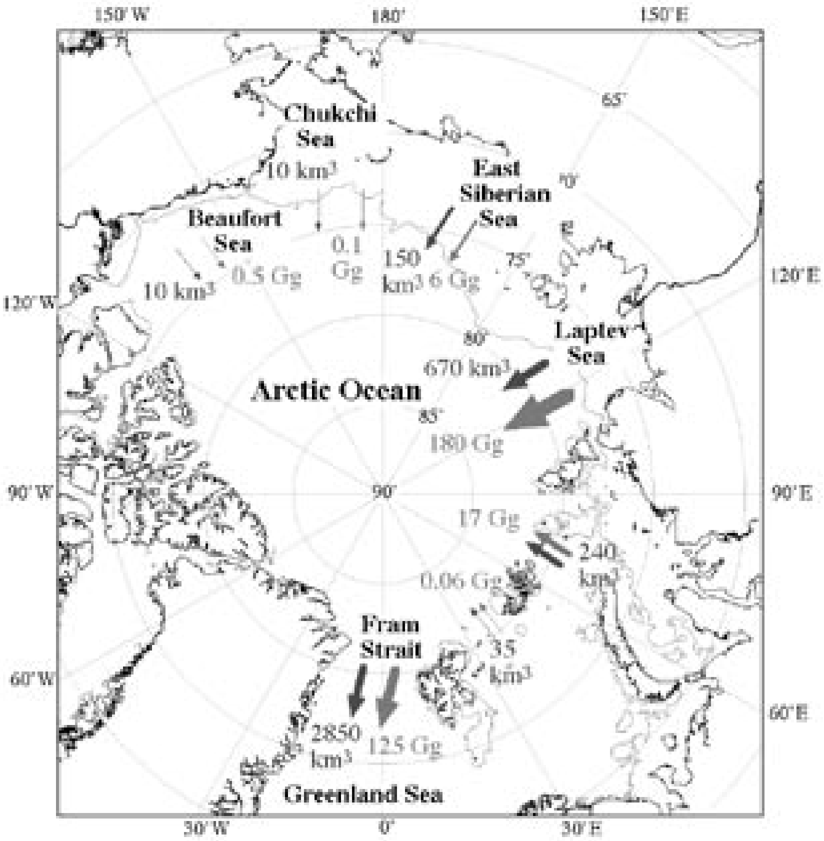

Figure 6. Volume fluxes of sea ice and transport of terrestrial carbon by sea ice, providing an indirect indication of the extent of interactions between the terrestrial and marine regime as mediated through sea ice in the nearshore regions. (Eicken, in press).

sediments as well as their interannual and long-term variability in the context of a changing Arctic, and the systemic approach of a land-shelf initiative would be crucial identifying the critical environmental variables as well as the coupling and interplay between different atmospheric, terrestrial and marine processes in shaping the evolution of the nearshore regime. A combination of remote sensing, field studies and modeling can also be expected to improve our knowledge and understanding of the present balance between supply and export of particulate and dissolved matter to the shelves and help predict how the system will evolve in future years. Here, recent work that has demonstrated the overriding importance of large-scale atmospheric oscillatory patterns in forcing much of the variability observed in the surface oceans and coastal systems (Thompson and Wallace 1998; Proshutinsky et al. 1999) can prove particularly useful in providing a theoretical framework within which to discuss spatial-temporal variability and longer-term evolution. Owing to the importance of nearshore and shelf-based ice growth and decay for the transfer of organic carbon (Macdonald et al. 1998) as well as for the thermohaline circulation of the Arctic Ocean and the stability of its perennial ice cover (Aagaard and Carmack 1989), the impact of the processes discussed may extend well beyond the Arctic realm. With sediments originating from coastal retreat and rich in terrestrial organic carbon, the export of such ice into the Arctic Ocean and Eurasian Nordic Seas constitutes a major component in the sediment and terrestrial organic carbon budget of Arctic region (Fig. 6).

While the importance of the ice cover for the biology of the shelf regions is discussed in other sections of this document, the role of sea ice in land-shelf interaction is of critical importance in the context of human activities, both in the Arctic and well beyond. Thus, as the strategic role of the Arctic ice pack in a cold-war scenario is diminishing, its importance in controlling access to transportation pathways in the Russian and North American Arctic should not be underestimated. This applies not just to the development of fossil fuel and mineral resources in seasonally ice-covered coastal regions, but more importantly is central to the future of the Northern Sea Route (Brigham et al. 1999; Ostreng 1999). During the past decade, a thinning and retreating ice cover has greatly increased the potential viability of a major global passageway that represents not only considerable economic advantages but is of substantial geopolitical, strategic importance in the more complex world order of the 21st century. As illustrated by recently implemented infrastructure in the western Siberian Arctic for year-round marine transportation of natural gas (Ivanov et al. 2000), any further developments depend critically on processes and changes in the coastal and nearshore environment. At the same time, this very environment is exposed to anthropogenic impacts and risks that need to be assessed in the context of the whole system.

Understanding the distribution, formation, thickness, and degradation of permafrost at the land-shelf margin are based on direct field investigations including temperature measurements, drilling and geophysical studies, from paleo-reconstructions and mathematical simulations. Findings from these field investigations can be extrapolated over poorly investigated regions having similar geological structure, history, and climate. A vast region between the eastern Russian Arctic and northwestern North American Arctic represents an environment with common historical development and representative modern atmosphere and ocean climates. Much of this region is marked by an erosional shoreline that has been significantly changing for thousands of years regardless of varying temperatures or trace gas emissions. Environmental change is therefore an intrinsic constant of the North American and Asian shelves. This includes both the historical evolution and development of the land-shelf system and its human interactions.

It is worth noting that neither the North American nor the East Siberian shelves and coastal lowlands were covered by Late Cenozoic ice sheets. Transgressions and regressions of the seas were subjected to relatively similar glacio-eustatic conditions and occurred approximately at the same time throughout the region. During periods of regressions, thick, low temperature, ice-bonded permafrost formed on the exposed shelves, and ground ice continued to accumulate in the older, onshore permafrost zones. The maximum age of the permafrost in the coastal zone and inner part of the shelf ranges from several hundreds of thousand of years to several million years, and reportedly preserves viable microorganisms in the organic-rich substrates. Thaw-lake formation (thermokarst) started before the beginning of the last transgression and continues today. These vast shelf zones and coastal lowlands (soils, lakes, lagoons, estuaries, and marine deposits) were areas of sediment and abundant carbon accumulation during the Pleistocene, and subsequent preservation in the permafrost. At present, this stored carbon contributes to the release of greenhouse gases due to permafrost degradation from the thawing of organic rich soils, thermokarst lakes, and submarine taliks, erosion and thermal abrasion of the frozen coasts, seafloor thermoerosion, and input from rivers that discharged into the Arctic Ocean. Most of river basins are underlain by the continuous permafrost zone resulting in significant input of slowly dissociating organic matter and products of frost weathering to and in the Arctic Ocean. Historical and modern coastal dynamics result in destruction of sites of former human habitation, drowning and submergence of lakes and lagoons, rapid retreat of the coast due to erosion, seafloor thermoerosion, and cross shelf sediment transport by sea ice and current. This description of permafrost processes helps to illustrate that successful land-shelf initiative will be required to take an interdisciplinary, systemic approach in addressing the role of sea ice, permafrost, and other oceanic and atmospheric environmental parameters in the dynamic coastal margin. For example, under what environmental conditions did these permafrost deposits form, and how are they changing? What constituents are moving from the land to the shelf's shallow waters? What are the rates and mechanisms for their removal, transport and /or deposition? What are the fates of these constituents in the near-shore environments, and how do they contribute to the carbon budget and global feedback?

3.3. Carbon transport and fate

Globally significant changes in the Arctic System's carbon cycle might occur with future global warming, including erosion and mobilization of coastal peat deposits and degradation of clathrate deposits. Vast amounts of peat are stored in the tundra that comprises large portions of the Arctic coastline, and under warming, increased coastal erosion is likely to lead to a globally significant increase in the transport of carbon to the ocean via the breakdown and seaward transport of this peat. In addition, there is a substantial dissolved organic matter component associated with eroding shorelines. We have little information on the quantitative importance of dissolved organic carbon released from river discharge relative to coastal erosion, although allochthonous contributions appear to be of relatively greater importance in the Arctic than in other oceans (Wheeler et al. 1996; Wheeler et al. 1997; Guay et al. 1999; Opsahl et al. 1999). Recent studies also indicate that Arctic offshore transport of organic materials resulting from coastal retreat demonstrates that this source of organic matter is more significant over the wide and shallow Siberian shelves (Semiletov 1999; Romankevich et al. 2000; Semiletov et al. 2001). An important question is how much of this peat and dissolved organic matter is biologically labile on the <100 yr time scale when it moves from anoxic shore side deposits into the well-oxygenated Arctic Ocean. If a significant fraction is labile, then carbon stored as peat and associated dissolved organic matter could be converted to carbon dioxide, much of which would be released to the atmosphere. As pointed out previously (Fig. 2), this process would represent a positive feedback with respect to global warming. Additional climate warming, increased precipitation and increased ultraviolet radiation fluxes are all factors that could lead to higher remineralization rates in oxidized waters and sediments on Arctic shelves (Dixon et al. 1994; Freeman et al. 2001). While these processes and feedbacks are clear, no comprehensive study exists that would allow us to model the effect on atmospheric carbon dioxide arising from increased erosion of coastal peat deposits and associated feedbacks.

Methane stored in clathrate deposits may comprise the largest reservoir of reduced carbon on our planet, exceeding the sum of all other gas, oil and coal deposits combined (Lee and Holder 2001). These deposits are stable over a narrow portion of temperature-pressure phase space, and the cold temperatures of the Arctic allow them to occur at relatively shallow depths that may already be experiencing significant warming. Geophysical surveying suggests that the Arctic is rich in shallow clathrate deposits. As a greenhouse gas, methane is ~40 times more powerful than carbon dioxide on a per molecule basis, and we need to know the fate of clathrates in the nearshore Arctic System in order to understand how atmospheric carbon dioxide and methane concentrations may change. It is clear that warming would accelerate the release of methane from clathrates and therefore represents another positive feedback in the Arctic climate system. We do not know, however, how rapidly the methane would be released to the atmosphere, oxidized to carbon dioxide by soil and water microbes, etc.

Another interesting question that surrounds the issue of the mobilization of the carbon in peat and clathrates is how much these releases would stimulate benthic metabolism and contribute to increases in the globally significant denitrification that is already known to occur in arctic marine sediments.

3.4. Export and potential sequestration of biogenic carbon

It has been widely hypothesized (e.g. Maslowski et al. 2000) that the Arctic Oscillation (AO) and other large-scale phenomena play significant roles in influencing the connections of arctic biological processes with the global carbon cycle. This includes the connection between production and vertical flux (and subsequent lateral advection) of organic matter on the shelves and by the incorporation of inorganic carbon into deep water formed during winter in the North Atlantic. However, the role of biological processes in sequestrating carbon has not yet been investigated at appropriate spatial and temporal scales. To understand the role of the AO in the global carbon cycle, there is a need to quantify the magnitude and variations in space and time of the production, cycling and vertical flux of biogenic material. This knowledge cannot be obtained without studying sea ice-associated processes in the deep basins, on shelves, and in coastal zones also.

Within the context of global climate change, two concepts must be distinguished concerning the fate of biogenic carbon in Polar oceans, i.e. export and sequestration (Legendre et al. 1992). Export refers to the flux of biogenic materials from the sea-ice cover and surface waters to depth, while sequestration concerns the removal of dissolved inorganic CO_2 from atmosphere and sea ice and surface waters for period of interest to global warming (i.e. decades or hundred years). Export of biogenic carbon and sequestration of carbon are generally not equivalent, since a large fraction of the exported biogenic carbon may sometimes be rapidly respired during its downward transit and recycled back to the atmosphere. For global biogeochemical budgets, the really significant term is not the export but the actual sequestration of carbon. Volk and Hoffert (1985) identified three CO_2 pumps in oceans: one physical (solubility pump) and two biological (carbonate pump and soft-tissue pump). The relative importance of biological versus physical pumping of atmospheric CO_2 into oceans is a subject of intensive discussion [e.g. (Broecker 1991; Longhurst 1991)]. Little is known about various aspects of production export in the nearshore ice-covered regions, as well as some of the processes involved in carbon sequestration. Aside from the uniqueness of the ice-associated production, one question of interest is: How much biogenic carbon, both absolutely and relatively, is produced at ice edge, in waters under ice, and within the sea ice in the coastal zone of the Arctic Ocean?

It is important to note that the export of biogenic carbon does not necessarily mean direct sequestration of phytoplankton cells in sediments or deep water. The main components are an accumulation of carbon in sea ice, especially in multi-year ice, whose fate may potentially be similar to ice-related blooms, i.e. mass sedimentation. This accumulation is especially important since >90% of the primary production in multi-year ice-covered waters occurs in the ice (Melnikov 1989). The accumulated biomass will be exported through sedimentation. According to Legendre (1990), when in-situ grazing and recycling are moderate, algal blooms often result in high sedimentation of intact cells and fecal pellets. Mass sedimentation of large intact cells, at rates that may exceed 100 m/day, mainly occurs under bloom conditions and is also expected to take place at the time of ice melt. Active grazing by herbivores leads to sedimentation of fecal pellets (Alldredge 1984).

In the case of first-year ice, export occurs several weeks, and in some cases months, after biomass has accumulated in the ice matrix. In multi-year ice, organic matter is accumulated over several years, and the bulk of it is released rapidly at the time of ice melt. In the case of land-fast ice, biogenic carbon is flushed into water column at the production site, while the organic load of drifting pack ice may be released far from the production zone. This is especially true of multi-year ice, which accumulates organic matter over many years in the Beaufort Gyre and releases it upon melting in Fram Strait (Melnikov and Pavlov 1978); (Pfirman et al. 1989). According to (Melnikov 1989), sea ice transports 0.4-0.8 x 10^6 tonnes of particulate and 5.6-12.5 x 10^6 tonnes of dissolved organic carbon every year through Fram Strait.

These data indicate that sea ice transport is a significant term influencing the transport and fate of biogenic carbon within the Arctic Ocean. From the standpoint of planning additional research in the context of carbon export and sequestration, it follows that additional work is needed on mineralization rates and the proportion of organic carbon ultimately sequestered from sources transported off land and from sea ice, and pelagic production.

3.5. Marine primary production

Investigations of primary production in the marine environment of the Arctic remain scarce. Most of our knowledge is based on brief snapshots from cruises or shore-based studies of small areas with little seasonal resolution. The Arctic remains grossly undersampled in most senses, but this is particularly true for primary productivity because many spatial and temporal details are still lacking.

Primary production on arctic continental shelves has three main sources: 1) phytoplankton in the water column, 2) ice algae on sea ice, and 3) benthic algae. Snow algae also contribute a very small amount to overall shelf primary production. Very few studies have considered all three main groups of producers (e.g. Matheke and Horner, 1974; Clasby et al 1976), and these observations tend to be highly localized. While there can be some regional variation related to environmental characteristics and forcing, the three groups above are listed in order of their relative contribution to marine productivity over the shelf ecosystem as a whole. While regionally variable, these contributions scale something like 100:10:1.

These three functional algal communities each have characteristic spatial distributions and growth seasons. Phytoplankton are ubiquitous in the surface layers of the water column, whereas ice algae and benthic algae colonize substrates. Even within the water column there are a variety of habitats, and microhabitats are of special interest for communities associated with substrates. The seasons of growth are generally limited to the lighted period when photosynthesis occurs, although some macrophytes may accumulate photosynthate in summer and take up nitrogen in winter for somatic tissue growth "off-season". All of these microalgal groups bloom in spring or summer when light becomes sufficient to sustain growth, and one group, the ice algae, may shade other populations below and delay their development.

The ice algae bloom earliest in spring (~March-June) under mostly snow-covered ice, which is nearly continuous except for leads. Ice algae colonize many ice surfaces on first year and multiyear ice floes, but bottom ice communities are the predominate form in most locations in the Arctic (Cota et al. 1991; Horner et al. 1992)). Ice algal production is important because it occurs before most phytoplankton growth, it is highly concentrated food source in thin layers, it serves as a nursery for certain invertebrates, and it augments total marine production. Ice algae may also have smaller fall blooms, but this is little studied and logistically challenging. Sea ice determines the ecology of ice biota, and it also influences the pelagic systems as well as the nearshore systems under the ice cover, especially, in tidally influenced zones, and at ice edges. A fraction of the carbon fixed by algae growing in the ice or in relation to the ice, is transferred out of the production zone. This includes particulate material sinking out of the euphotic zone, and also material passed on the food web. Biogenic material may be transferred from the production zone either horizontally through passive transport associated with circulation or active migration of large animals or vertically through passive sedimentation or active vertical plankton migration (Legendre and Le Fevre 1991).

The combined production of biogenic carbon attributable to all functional algal communities (water column, sea ice, and benthic) in shelf waters varies widely. Averaging over the shelf regions, (Subba Rao and Platt 1984) estimated an average annual production value of 27 g C m^{-2} $year^{-1}$ relative to offshore open waters (>200 m depth), which were estimated to have production that was one-third that of the shelf waters, during the high irradiance 120-day summer period (Melnikov and Pavlov 1978; Subba Rao and Platt 1984). According to Melnikov (1989), annual production in Arctic multi-year ice is 0.03×10^{14} g C. This value is relatively small compared to first-year ice production, which lies between $0.06\text{-}0.7 \times 10^{14}$ g C $year^{-1}$.

Benthic algae include microphytes, such as benthic diatoms, and macrophytes or seaweeds. The benthic algae are mostly restricted to shallow (~10-30m) subtidal waters in the nearshore or shoals in offshore regions, but may also occur into the intertidal zone. Microphytes can colonize most substrates, whereas macrophytes often require solid substrates. Ice scour limits colonization of both groups to some extent, but have more impacts on macrophytes with their longer life histories. Microphytes may have generation times on the order of a week, and therefore can more readily recover from and recolonize after disturbances.

Under land-fast ice phytoplankton and benthic blooms commence about the time the ice algae slough off of the ice, which coincides closely with snow melt. Break out of the sea ice may not occur until 1-2 months later. Under pack ice there is little benthic production because of depth. However, phytoplankton may bloom within the pack ice zone when there is sufficient divergence of the ice field and before the snow melts. Many details of seasonal dynamics of these groups are poorly understood and await further study.

Light, nutrients, and temperature are usually the most important environmental variables influencing algal growth. Light levels differ in these subsystems in that the top of the euphotic zone starts at lower levels (e.g. ~1-10%) for ice algae and (e.g. ~1-50%) for subtidal benthic algae. In addition to pronounced but well-known seasonal variations in solar radiation, snow and ice cover have a major influence on light availability. Snow cover dominates both albedo and attenuation in sea ice systems. All of the algae have their own cellular diffusional sublayers, but nutrients must diffuse across an additional interface for the ice algal and benthic communities. The principal source of nutrients for phytoplankton and ice algal blooms is the water column, whereas benthic algae may receive much of their supply from sediments. Temperature variations are most acute on intertidal zones, while the water column undergoes the smallest fluctuations and over seasonal time scales. Ice algae may experience temperatures ranging from subarial to submarine. In most cases grazing seems to play a minor role in the demise of blooms, especially in the water column and sea ice.

In contrast to the numerous studies on the biology and primary productivity of polar microalgae, high latitude macroalgae (and seagrasses) have been little studied, although dense populations of these highly productive macrophytes are locally important in the Arctic Ocean and in marginal seas such as the Bering and Barents. Coupled with uncertainties about sea ice algal and water column production, important questions remain about many aspects of arctic near-shore primary production. Lagoonal systems in particular are among the most prominent and characteristic features of arctic coastlines and have immense ecological significance. These systems are biologically rich and productive, owing in part to the inputs of freshwater from streams and runoff that transport enormous quantities of organic materials and inorganic nutrients into these shallow semi-enclosed basins. Mixing with more saline offshore waters occurs in lagoons, and as a consequence, they are important sites of intense biogeochemical cycling of carbon and nitrogen. The presence of benthic primary producers, including attached macroalgae, provide habitat and additional sources of carbon that support some of the most diverse and productive communities on the arctic coast. Large numbers of birds and fish concentrate in these shallow systems since the warm and less saline waters of coastal lagoons support enormous concentrations of zooplankton. Because of the high physical integrity of lagoonal systems, mixing with offshore waters is sufficiently slow to allow the temperature/salinity regimes of the two waters to remain fairly distinct through the summer, and consequently lagoons often support different populations of neustonic invertebrates than shelf waters. In addition, since lagoons have more locally variable physical conditions (eg. temperature/salinity regimes), this has an important influence on the biogeochemical and ecological processes that ultimately effect the coupling of carbon and nitrogen within these nearshore food webs.

3.6. Numerical modeling

Numerical modeling should play a key role in the Land-Shelf Initiative, providing a means to synthesize observations and theories into an integrated geophysical framework. An example for the large-scale Arctic Ocean is the assimilation of sea ice motion observations into a numerical model to provide the best estimate of ice/ocean circulation over the previous 20 years (Zhang et al., 2002). Unfortunately, the properties and process of the land-shelf environment have generally been neglected in many types of numerical models. For example, most ice-ocean models have very simple river discharge physics (e.g., Steele et al., 2001), and inadequate spatial resolution of broad, shallow shelves. An accurate simulation of sea level elevation is possible in some types of models, although many still have problems (Proshutinsky et al., 2001).

3.7. Remote sensing

Satellite remote sensing should also play an important role in the Land-Shelf Initiative, providing a pan-Arctic perspective and producing long-term observations. It can be used to evaluate spatial and temporal variability more readily than many other approaches and is the only practical means to study large scales. It may also provide the means to scale up local empirical observations to regional and larger scales. A variety of sensors are already in orbit, or will be launched in the near future. Geophysical parameters of interest from satellites include (but are not limited to) sea ice cover, glacier mass balance, snow depth, surface temperature, cloud cover, and solar radiation. Biological retrievals are more limited but plant biomass on land and in the ocean are now available from several sensors. Important processes are also observable from space such as the onset of snow melt, river discharge, breakout patterns, coastal erosion, frontal boundaries, eddies, and plant “blooms” on land and in the ocean. Improved algorithms may even provide the means to distinguish between dominant groups of primary producers.

3.8. Human dimensions

The nearshore area is vital for many Arctic residents. Coastal communities depend on access to the sea and to sea ice, but are vulnerable to flooding and erosion. Significant subsistence activities take place in the nearshore area. The interactions among terrestrial, freshwater, and marine systems govern the boundary conditions associated with the nearshore as well as feedbacks on each of those systems. These interactions have a human element too, as people affect the nearshore and are in turn affected by it. These critical environmental, socioeconomic, as well as defense issues have focused the nation’s attention on the coastal zone. Key human impacts identified by Arctic residents and past research include coastal erosion, recent declines in ice extent and thickness, less stable shore-fast ice, changes in permafrost depth, gouging of shelves and coast by sea ice, pile-up of ice on shore, rise in sea level, and storm hazards, including flooding. Because of the ice content of coastal sediments, rapid coastal erosion and movement of large amounts of sediments are common and highly variable. The impacts of these processes are not uniform in terms of how they affect individual settlements. Further, coastal wetlands and moist tundra are particularly vulnerable to climatic variation and extreme events. Many of these areas are unstable and easily or frequently changed by erosion, flooding, or the invasion of salt water.

In order to involve natural scientists, social scientists, and arctic residents in a discussion of this topic, the HARC Science Management Office organized an online workshop in April 2002 as part of the science planning effort for the Land-Shelf Interactions initiative. Transcripts of the discussions in PDF format, the participants list, and further information about HARC and the workshop can be found at http://www.arcus.org/harc. The report of the workshop that is posted at this site is intended to highlight research ideas and opportunities that arose during the workshop. These ideas are neither exhaustive nor exclusive. There is considerable overlap, and potential projects may well include ideas from more than one section of this report. The subjects of discussion were defined by the participants, so many topics relevant to human interactions with arctic environmental change in the coastal zone were not discussed, or incompletely addressed. For example, near-shore environmental change will have significant impacts upon the petroleum industry in the globally important arctic oil and gas fields in Russia, the United States, and Canada. Despite the non-comprehensive nature of the discussion, a number of important topics were raised during the workshop, including community planning, waste management, near-shore biota in relationship to human communities, and vulnerability and past responses. These issues are of significance either to how global change will impact human communities in the arctic near-shore region, or how human communities in the near-shore zone will impact coastal system functioning.

4. Relationship of LSI to other Programs

In many respects, this science plan is an outgrowth of the Russian-American Initiative for Shelf-Land Environments in the Arctic (RAISE). It is worthwhile to review briefly the history of the RAISE program to understand the origin of the Land-Shelf Initiative and the broad scientific consensus supporting new interdisciplinary work in the Arctic near-shore zone.

RAISE has been a key research initiative for facilitating bilateral (U.S. – Russian) research at the land-sea margin in the Eurasian Arctic, focusing on the scientific challenges of environmental change in human and biological communities, and related physical and chemical systems. It is the only jointly supported research project in any field shared by both the Russian Foundation for Basic Research (RFBR) and the U.S. National Science Foundation (NSF). The scientific justifications for the RAISE umbrella of research priorities were identified by participants in three international workshops held in Columbus, Ohio, St. Petersburg, Russia, and Arlington, Virginia in 1995, and in annual follow-up meetings of RAISE investigators, and the RAISE International Science Steering Committee over the past seven years. Results of these scientific deliberations are available in documents available from the RAISE web site (http://arctic.bio.utk.edu/#raise) or from the RAISE project office. Since the publication of the RAISE prospectus (Forman and Johnson 1998) that resulted from these science planning efforts, a number of land-based, remotely sensed, or archived data recovery research projects involving both U.S. and Russian scientists have been initiated, with support from the Arctic System Science program of the NSF and the RFBR. Summaries of many of these projects, both Russian and U.S. based, are available at http://arctic.bio.utk.edu/#raise. While the ARCSS Land-Shelf Initiative is broader geographically than the RAISE program focus on the Russian Arctic land-shelf region, the RAISE program has historically been one of the key ARCSS mechanisms for supporting global change research beyond the relatively small portion of the Arctic shared by the United States. The objective of RAISE specifically has been to facilitate cooperation between Russian and U.S. scientists that would improve knowledge of Arctic system science at the land-sea margin of the large portion of Arctic coastline that is in the Russian Federation.

The original and continuing vision of the RAISE program is to couple studies of processes that occur on land (e.g. fluxes of organic materials into rivers and from eroding shorelines) with impacts and feedbacks that occur in the marine environment (e.g. productivity) of the Arctic Ocean. It is clear, however, that the coastal marine research component of RAISE has been incompletely implemented. A major reason is that marine research requires a higher degree of logistical coordination than is required for land-based research. Ship support is expensive, particularly in remote areas of the Arctic, requiring the assembly of relatively large, effective teams of interdisciplinary researchers, rather than smaller teams more often appropriate for land-based campaigns. While permitting is required for almost all international scientific studies in the Russian Federation, additional time and effort is required for consideration of proposed scientific work in offshore Exclusive Economic Zones under international law. Coordinating marine-based researchers with parallel work on land is a difficult challenge although past German - Russian cooperation (Fig. 7) and the 30-year history of US-Russian cooperation under the U.S. - Russian Environmental Agreement in the Bering Sea show the potential for success.

Within the United States arctic scientific research community in general, it has also been widely recognized that many crucial research questions relating to environmental change in the Arctic have not been adequately addressed because interdisciplinary research efforts in Arctic coastal zones have been rare. In November 2001, in Salt Lake City, Utah, at a joint plenary session of arctic researchers funded through the U.S. National Science Foundation's Land-Atmosphere-Ice Interactions (LAII) and Ocean-Atmosphere-Ice Interactions (OAII) components of the Arctic System Science (ARCSS) program, considerable attention was devoted to the development of a "Nearshore Initiative," or Land-Shelf Initiative, that would help address many crucial environmental research problems that are intrinsic to the land-sea boundary. A copy of a Microsoft PowerPoint presentation used at the Salt Lake City meeting, which outlines the research needs that could be met with the development of a Nearshore Initiative, can be downloaded from the RAISE web site, http://arctic.bio.utk.edu/#raise. Following these presentations and open discussions in Salt Lake, a joint meeting of researchers serving on science steering committees for the LAII, OAII, and RAISE components of ARCSS formally considered the desirability of a Nearshore (or Land-Shelf) Initiative in the Arctic. It was jointly resolved

Fig. 7. Launch transport to shore, with the ship "Pavel Bashmakov" waiting offshore.
Summer 2002, Laptev Sea. (photo courtesy of Volker Rachold)

that additional planning efforts to improve opportunities for appropriately integrated and synthetic Arctic near-shore research should be supported.

Consistent with this recommendation, additional discussion of scientific research needs at the land-sea boundary in the Arctic took place at the ARCSS All-Hands Workshop, which was held 20-23 February 2002 in Seattle, Washington (http://www.arcus.org/ARCSS/allhands2002/index.html) The purpose of the ARCSS All-Hands Workshop was to assess the state of the art in research on global change, environmental impacts, and biocomplexity, emphasizing arctic and global aspects. In addition, gaps in knowledge and areas for research integration were identified, and several new research initiatives, including Arctic nearshore and coastal processes were considered in working group discussions and plenary sessions.

Because of this linkage with on-going earth system history (PARCS) and hydrological (Arctic-CHAMP) research programs, this LSI science plan will not seek to duplicate the well-developed scientific rationale for those research approaches that have been reported in other science and implementation plans [e.g. Forman and Johnson (1998); Vörösmarty et al. (2001)]. Earth system history and the hydrology remain entirely appropriate nearshore Arctic research approaches based upon these prior scientific planning efforts. Likewise, there is a very strong research infrastructure available to support atmospheric research at the Arctic land-shelf boundary, particularly at Point Barrow, where facilities to support this high latitude reference site are maintained by the Department of Energy, the Minerals Management Service, the National Oceanic and Atmospheric Administration, as well as the NSF. In light of this infrastructure and other on-going plans to develop a new science initiative for atmospheric research in the Arctic, we will not outline in detail here the science needs for atmospheric research at the land-shelf boundary in the Arctic, although it is clear that moisture and atmospheric chemical fluxes across the land-sea boundary are ultimately important in land-shelf interactions. Similarly, as programs on biogeochemical and biophysical feedbacks develop, such as the emerging Pan-Arctic Cycles, Transitions, and Sustainability (PACTS) program, the opportunities will increase for cross-cutting collaboration on biotic-abiotic interactions. Similarly, with the development of a multi-agency program for the Study of Arctic Change (SEARCH), it is expected that additional specific research opportunities in the coastal zone addressing many topics outlined in this science plan should also be apparent.

A new interdisciplinary research opportunity focused on the arctic land-sea boundary will have the potential to contribute to reducing gaps in scientific knowledge of probable Arctic ecosystem responses to environmental change. Such a research opportunity also has the potential to provide a natural interlocking framework to the research program on Land Ocean Interactions in the Russian Arctic (LOIRA), which is an initiative of the International Arctic Science Committee (IASC) that is focused on research opportunities and needs identified by Russian scientists. This program can provide a framework for involving Russian scientists, institutes, and agencies that have contributed to a parallel scientific development and planning effort as has been undertaken during the evolution of RAISE. Coordination with this international program would also facilitate a larger involvement of LSI researchers within international coastal zone research such as the Land-Ocean Interactions in the Coastal Zone (LOICZ), which is a component of the International Geosphere-Biosphere Programme (IGBP).

The timing of this initiative may also intersect well with other international research programs. In particular, Sweden is planning to send the research icebreaker Oden to the Beringia region in 2005 as part of a multidisciplinary, multi-national research program that will work in Russian, U.S. and international waters and on land. Previous work on the Swedish Tundra Expeditions in the 1990's in Russia and Canada can be cited as excellent examples of interdisciplinary efforts in nearshore regions that have succeeded in sampling across international boundaries in the Arctic.

5. Implementation Considerations

Although the overall LSI program is still in the relatively early stages of development, it is not too early to begin considering in general terms how it might be implemented. In the broadest sense, LSI could either be implemented as a tightly focused and coordinated effort, or as a group of related efforts. An advantage of a focused interdisciplinary research opportunity is that it can help facilitate scientific coordination by groups of investigators who will address different aspects of Arctic environmental change research on the same shelf regions of the Arctic, using complementary and synergistic approaches. A disadvantage of focused, coordinated research, of course, is that the region of any investigation cannot be easily as broad as pan-Arctic. As we move forward from this Science Plan towards implementation of the actual research program, reconciling two somewhat different research models will have to be carefully weighed. At one end of the spectrum is a research model that would coordinate a sea, river, and land-based research campaign, where a team of investigators would intensively study a given region, including terrestrial and marine components of the land-shelf system. This approach is commonly used on oceanographic expeditions and has also been utilized in the Kuparuk River basin in northern Alaska. Another model would be to select individual proposals driven by individual investigator's questions and interests, and then strive to build an integrated program from the funded proposals. This model is being used with recently funded Arctic-CHAMP projects, as well as previously in RAISE. Following this second model in which individually funded projects are melded into an integrated research process is not without advantages. The intellectual and scientific merit of individual proposals would be clearly paramount. However the difficulties and expenses of mounting interdisciplinary research where shiptime is required suggest that some judicious compromise between individually directed and focused, coordinated research would probably be most effective.

From the standpoint of possible geographic points of focus, the shallow shelf from the Lena delta to the international convention line in the Chukchi Sea, incorporating the eastern Laptev, East Siberian and western Chukchi Seas, are some of the poorer known of the Arctic continental shelves, but these waters are also the closest of the Eurasian Arctic to the shared boundary between Russia and the United States. U.S. research programs that have conducted work in the Chukchi Sea, including the Outer Continental Shelf Assessment Program, the Inner Shelf Transfer and Recycling (ISHTAR) program, the Arctic Nuclear Waste Assessment Program (ANWAP), the U.S. Canada Arctic Ocean Section, numerous individual investigations, and the on-going SBI program can provide a potential linkage of Arctic system research that will transcend the international convention line. To the west of the Lena River, bilateral research on the Eurasian shelves has been much more readily accommodated through joint research by Russian and western European scientists. The Russian-German cooperative program in the Laptev Sea in the 1990's, highlighted in (Kassens 1999), is considered by many to be the standard for a successful bilateral research program, and much of the Laptev Sea has now been recently investigated using modern methods and techniques. Further west, the initial focus of the predominantly Russian-led LOIRA program has been in the Pechora Sea basin: successful bilateral work on the Barents and Kara shelves has also been conducted by Norwegian-Russian and German-Russian teams. While a number of U.S. researchers have also worked in the Kara and Barents Seas on various research problems in recent years, a coordinated program focused on locations within the shelves and coastline of the Beaufort, Chukchi, East Siberian, and eastern Laptev Seas is justifiable on the basis of geographical proximity to the shared U.S.-Russian boundary, and the historical paucity of interdisciplinary research. Based upon the adjoining locations of recent and current national and internationally coordinated research programs to both the east and west, research in this region will contribute to the larger national and international efforts to improve understanding of Arctic ecosystem and biogeochemical function. A transect of the eastern Laptev, East Siberian, and Chukchi Seas also corresponds to a number of geographically-critical contrasts in the Arctic Ocean system. Traveling west-to-east, summer open water coverage becomes greater, sea ice formation sources decrease, the influence of river discharge on shelf waters decreases, the influence of nutrient-rich waters derived from Bering Strait become greater, and biological productivity and biomass increases in the benthos and water column.

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