Draft Science Plan

Revised 12 March 2002

A Land-Shelf Initiative

Executive Summary

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

The Land-Shelf 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 had 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 which has a goal of transcending the traditional geomorphic boundaries separating marine and terrestrial lines of inquiry in Arctic system science.

Our 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 who would take advantage of coordinated logistical capabilities that would otherwise be unavailable. 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, some 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. Therefore, in undertaking this science planning effort, we are proposing a significant

new investment in near-shore Arctic environmental change research, particularly by the U.S., but coordinated with international efforts, including with U.S. neighbors Russia and Canada, as well as other countries with Arctic research interests.

Many scientific issues requiring complex, interdisciplinary research approaches have been identified at the land-sea margin in the Arctic. A non-exhaustive list would include the impacts of changes in precipitation and runoff patterns on Arctic Ocean circulation, ice formation and distribution, the biogeochemical fate of materials transported in rivers and from eroding coastlines, the impacts of climate warming on on-shore and offshore permafrost and the release of radiatively active gases, and the social stresses on human communities in the North that political and environmental changes in the past few decades have brought. 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 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. In addition, this initiative could 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. It is also worth noting that many uncertainties concerning environmental change in the Arctic can be approached through the study of past changes in biological communities in response to environmental change.

The full report of this science plan describes those scientific problems 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 of the Arctic Ocean. 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 (e.g. archeology, contemporary social science, and preservation of traditional knowledge, language and culture), it also supports the involvement of a broad spectrum of researchers who may ultimately benefit with improved research access and capabilities.

Introduction

A consensus of scientific opinion holds that many important responses of the Arctic system to environmental change will occur, or will involve feedbacks on the continental shelves of the Arctic Ocean (Moritz et al. 1990; ARCUS, 1997a). For example, permafrost on land, and in undersea deposits, currently sequesters large amounts of radiatively active gases such as methane. However, many Arctic shorelines are erosional in nature, so it is possible that significant amounts of this methane, as well as carbon dioxide that is stored in northern peatlands, may be released if current erosion trends continue or, if other processes such as increasing sea level, or temperature and precipitation changes become more important. In many other respects, the Arctic land-sea boundary appears very vulnerable to environmental changes that are likely to occur over the next century. For instance, a continuation of the current decline in sea ice spatial extent and thickness (e.g. Rothrock et al. 2000) 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. walrus, seals). Shoreline erosion rates are also likely to increase with longer open-water periods without protection of sea ice from storm and wave damage. 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. Alternately however, economic circumstances could improve, for example 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, year?).

Despite these general projections, the scientific data currently available to prepare for widespread environmental change in the Arctic as a whole are inadequate. Many Arctic processes that potentially affect global climate are not well studied and associated mechanisms are not well understood. Certain regions of the Arctic Ocean, including its shelves, have a minimal description of the circulation, hydrography, and seasonal variability. 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. For example, recent work with archived Russian river discharge data (Holmes et al. 2000) also show many discrepancies and indicate that we have only an incomplete understanding of the fluxes of nutrients and other materials brought into the Arctic Ocean by rivers. In light of these challenges, specific unknowns need to be addressed using multiple, linked approaches. For example, 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. It is likely that 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.

Background and History of Initiative Development

Relationship of the Land-Shelf Initiative to RAISE

In some respects, this science plan is an outgrowth of the Russian-American Inititive 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. The scientific justifications and bases 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. Results of these scientific deliberations are available in documents available from the RAISE web site (http://www.raise.uaf.edu) 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 U.S. National Science Foundation and the Russian Foundation for Basic Research. Summaries of many of these projects, both Russian and U.S. based, are available at http://www.raise.uaf.edu. 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.

Despite this progress, 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 only very incompletely implemented. A major reason is that marine research requires a higher degree of international 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.

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://www.raise.uaf.edu. 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 that additional planning efforts to improve capabilities for near-shore research in the Arctic 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. Prior to the meeting, an on-line, web-based discussion on the Initiative was also sponsored by the Arctic Research Consortium of the United States with participation through Internet access.

Goals of a Land-Shelf Initiative and Relationship to Other ARCSS Programs

The consensus of break-out discussions at the Seattle meeting that followed was that the overarching goal of the Land-Shelf Initiative should be to improve our understanding of the biogeochemical, physical, and hydrological processes that occur in the nearshore zone of the arctic shelf with respect to changes in the global climate system, as well as alteration of marine ecosystems and societal resources. Some challenges were not resolved during discussions, include defining operationally what constitutes the coastal zone of interest, including time and seasonal scale variation. Within the NSF ARCSS Program, the Land-Shelf Initiative was seen to be strategically located (Figure 1), landward of the Shelf-Basin Interactions (SBI) research at the shelf-basin boundary, seaward of hydrological studies that will be initiated as a part of the pan-Arctic community-wide hydrological analysis and monitoring program (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 programs laterally and across the Arctic basin. The strong historical linkage to RAISE and the importance of coastal zone processes to human communities, as promoted by the Human Dimensions of the Arctic System (HARC) component of ARCSS were also acknowledged. As programs on biogeochemical and biophysical feedbacks develop, as does the Study of Arctic Change (SEARCH), it is expected that additional specific research opportunities in the coastal zone addressing those topics should also be apparent.

Towards a Thematic Approach to Nearshore Processes

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

Related sub-themes that were discussed at the Seattle All-Hands Meeting included 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, biogeochemistry as a linking feature between land and sea, fate and transport of materials, river discharge connections to oceanic systems, foodweb transfers and dynamics, permafrost status and related trace gas exchange were related sub-themes that were outlined by discussion participants. Participants 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. A few examples of these questions, which are appropriate for addressing in the Land-Shelf Initiative, are outlined below:

Forcing Functions

1. What are the 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?
2. How do changes in atmospheric circulation or specific meteorological events (e.g storm surges) affect runoff and biogeochemistry of the coastal zone? Contaminant dispersion and uptake and foodweb incorporation?
3. What are the mass balances of carbon, nitrogen and phosphorus in the coastal zone?
4. What is the mass balance of organic materials (dissolved and particulate) contributed by Arctic rivers relative to coastal erosion?
5. How do changes in atmospheric circulation and meteorological events affect runoff, erosion, biogeochemistry, dispersal of contaminants, and societies in the Arctic coastal zone?
6. Is the coastal zone ultimately a source or sink for CO_2?
7. For other radiatively-active trace gases, such as CH_4, DMS, N_2O?

Feedbacks

1. What will be the biological responses and changes in biogeochemical cycling that will occur with the projected retreat of sea ice coverage?
2. How will change in the open water season change the distributions of inorganic and organic materials in the nearshore environment?
3. What impact does coastal erosion have on the fluxes of radiatively-active gases such as methane and carbon dioxide?

4. How would a decrease (or increase) in river runoff impact biological productivity, sea ice formation, the flow of nutrient-rich water through Bering Strait, and the potential for ventiliation of the Arctic halocline?

Transformations and Internal Processes

1. How mobile are organic materials introduced into marine systems by coastal erosion versus river runoff?

2. What is the relative importance of microbial, meiobenthic, and macrobenthic communities in different shelf systems?

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 make this system more ecologically vulnerable? Or is it more resilient in the face of change?

Impacts

1. What are the likely impacts on human communities regionally, and across the Arctic of likely environmental changes?

2. What kinds of information will coastal communities need in order to prepare to adapt to rapid 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?

Next steps

One of the outcomes of the Salt Lake City and Seattle meetings, and the ARCUS-sponsored on-line forum was a consensus for advancing the Land-Shelf Initiative by providing adequate opportunities for the Arctic research community to contribute to better defining its research goals and implementation. These opportunities make take the form of additional workshops, and/or an on-line forum, at either the science plan or implementation plan stage, as well as opportunities to contribute to the written science plan. An e-mail list of people interested in being involved in future science plan development was expanded at the Seattle meeting by about 30 names, to a total of approximately 100 people, each of whom have indicated an interest over the past year in contributing to the development of a new science plan supporting Arctic system science research in the Arctic nearshore zone. The RAISE web site has also been used as a mechanism for distributing draft versions of the science plan and soliciting new contribuitions.

One of the other major outcomes of the Seattle All-Hands Meeting 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 boundary is an integrative milieu for many landscape-scale processes that transcend the land and sea boundary.

It is therefore useful to consider some of the key topics in Arctic nearshore research individually and use identified research gaps as a mechanism for synergistic research strategies that will promote interdisciplinary development. We consider below several of the key landscape and seascape processes and variables that are important at the Arctic land-sea boundary. We see this as a practical means to construct a nearshore Arctic research strategy within the context of environmental change.

Hydrological fluxes

The Arctic shelves constitute about 25% of the Arctic Ocean, and are the largest continental shelves in the world ocean. These shelves are heavily influenced by runoff from the large Eurasian rivers, including the Ob, Yenesei, and Lena, which in addition to freshwater, also contribute nutrients, dissolved and particulate organic matter, and trace substances into the circulation of waters within the Arctic Ocean. Sea ice is a dynamic element in this system, also, and functions as an additional mechanism for moving sediments (Barnes et al. 1982; Reimnitz et al. 1993), trace contaminants (Cooper et al. 1997; Landa et al. 1997), elements of sea ice biological communities, and freshwater and brine from continental shelves into the deeper Arctic Ocean.

Possible future changes in the runoff of Arctic rivers, the volume of nutrient-rich water flow through Bering Strait, and sea level rise will each have effects on the fluxes of water-borne materials onto the continental shelves. These environmental responses are not immediately predictable, however, and indicate the need for new studies of biogeochemical exchange and processes on between Arctic land and sea. These studies profitably could include analyses of current processes of land-to-sea exchange, as well as modeling of global change scenarios due to changes in precipitation, sea ice coverage, temperature, and food web structure.

An obvious and major link between the land and shelf components of this program are fluxes of water from the landscape into shelf ecosystems. This hydrologic flux includes entrained organic dissolved and particulate materials. 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 to the freshwater input of all rivers draining directly into the Arctic Ocean when scaled against the salinity of the Arctic's deep Atlantic waters (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 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).

Coastal Dynamics and Permafrost

Another area that is of active interest is the contribution of dissolved and particulate organic materials from widespread and significant shoreline erosion. Recent work (Rachold et al. 2000) indicates that in the Laptev Sea shoreline erosion contributes more sediment to the Arctic Ocean than total riverine discharge in that marginal sea. This is particularly striking in light of the presence of the Lena River in the Laptev Sea, which has built one of the world's largest deltas. 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, 1996, 1997; Guay et al. 1999). Recent studies also indicate that Arctic off-shore 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, 1999a; Semiletov et al., 2001).

Understanding the distribution, formation, thickness, and degradation of permafrost on land and the adjacent shelf 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 hypothetical international nearshore program to investigate the dynamics of nearshore permafrost (both onshore and offshore) could be based on the following considerations:

1. 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.

2. Neither of these Arctic shelves and coastal lowlands were covered by Late Cenozoic ice sheets.
3. Transgressions and regressions of the seas were subjected to relatively similar glacio-eustatic conditions and occurred approximately at the same time throughout the region.
4. 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.
5. 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.
6. Thaw-lake formation (thermokarst) started before the beginning of the last transgression and continues today.
7. 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.
8. 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.
9. 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.
10. 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.

These considerations above lead to the following overarching questions:

1. Under what environmental conditions did these permafrost deposits form, and how are they changing?
2. What constituents are moving from the land to the shelf's shallow waters?
3. What are the rates and mechanisms for their removal, transport and /or deposition?
4. What are the fates of these constituents in the nearshore environments, and how do they contribute to the carbon budget and global feedback?

These overarching questions in turn suggest the following specific research approaches for permafrost topical studies as part of the Land-Shelf Initiative:

1. Investigate the quantity and quality of the organic reserves in the coastal zone as a function of their mechanisms of formation, preservation and subsequent transformation (partial thawing under different subaerial and subsea conditions; hydrates formation).
2. Investigate magnitude of biogeochemical processes associated with thermokarst lakes, eroding and submerging coastlines, and submarine taliks, and seafloor thermoerosion inorganic-rich, shallow shelf zone (<20 m).
3. Investigate the fluxes of matter and energy from the land into the shallow coastal waters, with emphasis on estimating sediment yield and deposition from coastal erosion and river runoff.

The specific permafrost and coastal dynamics research that would be guided by these research approaches would of course be influenced by research implementation plans and individual research proposals, but the following developmental plan is provided as a practical scenario:

Developmental Phase (Year 1)

1. Based on a series of comprehensive literature review, develop community- based hypotheses for specific research questions.
2. Based on theory and models develop simulations to test hypotheses.
3. Identify appropriate field locations for initial observations, and required logistics.

Field Phase (Years 2-4;simultaneous land and nearshore investigations)

1. Establish a series of land-based sites to assess permafrost degradation, carbon stocks and transformation, and coastal changes
2. Conduct nearshore geophysics and geothermal programs, sediment dynamics studies, and continue modeling modifications

Synthesis Phase (Year 5)

1. Produce final synthesis as a series of integrated papers in the form of dedicated journal or a book (include paleo-reconstruction of coastline, seafloor, and sediment and carbon budgets, and feedback scenarios)

Carbon transport and fate

(Editor's note: This section is largely about sea ice biota, contributed by Igor Melnikov. We also need discussion here of river-borne and terrestrial sources of organic carbon, transport and fate.)

It has been widely hypothesized (e.g. Maslowski et al. 2000) that the Arctic Oscillation (AO) plays a significant role in the global carbon cycle via 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, but processes on shelves, and in the coastal zones also.

Sea ice does not only determine the ecology of ice biota, but 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 (Legender and Le Fevre, 1991).

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 (Legender 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 CO2 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 CO2 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 CO2 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?*

Organic production in the Arctic Ocean consists of the water column production in shelf areas, water column production in offshore areas (primarily under the ice), and production within the sea ice cover. Since the permanent ice cover persists year-round in the deep water regions of the Arctic Ocean, production is limited there, being characterized by limited under-ice production and mainly by algal production within the multy-year ice. Production of biogenic carbon in the AO varies widely, according to the regions considered. Averaging over the shelf regions, Subba Rao and Platt (1984) picked an average annual production value of 27 g C m^{-2} $year^{-1}$; offshore open water (>200 m depth) were estimated (Melnikov and Pavlov, 1978; Subba Rao and Platt, 1984) to have production one third that of the shelf waters, during the high irradiance summer period (120 days). According to Melnikov (1989), an annual production values in Arctic multi-year ice is of 0.03 x 10^{14} g C. This value is relatively small compared to first-year ice production, which lies between 0.06-0.7 x 10^{14} g C $year^{-1}$ suggesting strong variability. Our knowledge about the biogenic carbon production in the coastal zone is limited. The question is: *What is the carbon production and how is it related to the water column in nearshore zones?*

Export and sequestration of biogenic carbon

(Editor's note: Again this is largely specific to sea ice biogenic carbon, contributed by Igor Melnikov.)

It is important to note that the export of biogenic carbon does not necessarily mean sequestration in sediments or deep water. The main components are an accumulation of carbon in sea ice, especially in multy-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.

Editor's note: Other text that is likely needed and volunteers identified in Salt Lake City:

- More hydrology, including connections to thermohaline circulation, impacts of variability (Steve Forman, Larry Smith, Richard Lammers, Igor Semiletov)
- Carbon transport (besides sea ice): Larry Smith, Jason Neff, Jim Randerson, Igor Melnikov, Igor Semiletov
- Land-shelf history: Lyn Gualtieri and Julie Brigham-Grette
- Nutrients: Lee Cooper, Max Holmes, Igor Semiletov
- Human dimensions: Vladimir Pitulko, Daniel Odess
- Sea ice and physical processes: Lawson Brigham, Andrey Proshutinsky, Hajo Eicken, possibly Igor Dmitrenko (dia@aari.nw.ru) and other AARI colleagues
- Albedo/radiative balance
- Atmospheric interactions

Relationship to other national and international programs and geographical considerations

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 ecoystem 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.

Another 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. Fortunately, previous and on-going work of other national and international research programs suggest some practical regions 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 et al. (2000), 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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Appendices:

Contributors

1. Salt Lake City (November 2001) meeting
2. e-mail list
3. Seattle (February 2002) meeting