INTERNATIONAL
STUDY OF ARCTIC CHANGE

SCIENCE PLAN

The International Study of Arctic Change
Science Plan

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Foreword

The International Study of Arctic Change (ISAC) was initiated in 2003 by the International Arctic Science Committee (IASC) and the Arctic Ocean Sciences Board (AOSB) following the Study of Environmental Arctic Change (SEARCH) Open Science Meeting in Seattle in October 2003. That conference brought together over 440 researchers from around the world to present and discuss progress in research on rapid environmental Arctic Change. At a following international implementation meeting, participants requested that IASC and AOSB facilitate the development of an international program of arctic change research. In 2004 IASC and AOSB formed the International Study of Arctic Change Interim Science Planning Group (ISPG) and in January 2005 the ISPG published the ISAC Science Overview Document (SOD) www.arcticchange.org. This document formed the basis for the further development of the ISAC Science Program.

The intent of the ISAC Science Plan is to outline an open-ended international research program and a framework for comprehensive study of arctic environmental change in all its dimensions. ISAC builds upon existing efforts to further our understanding of past, present, and expected arctic change to carry over new insights into the public and the decision-making arenas. ISAC is an iterative program growing from the successes of past arctic science programs and those initiated during the International Polar Year (IPY). The science plan provides background information on recent arctic changes and frames science questions to guide integrated research. ISAC includes both basic science and applied science and connects with national and international efforts to observe, understand and respond to pan-Arctic environmental change. ISAC is presently supported by the Swedish Research Council, the United States National Science Foundation, the Swedish Polar Research Secretariat, and the International Arctic Research Center, University of Alaska Fairbanks.

Cover, design, and layout by Russell Mitchell.
Cover photo by M. Tjernström

Contents

Figures

Fact Box 1

Fact Box 2

Fact Box 3

Fact Box 4

Fact Box 5

Fact Box 6

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Executive Summary

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The International Study of Arctic Change (ISAC) is an open-ended, international, interdisciplinary science program. The goal of ISAC is to provide scientific information on rapid arctic change to society and decision makers so they can respond with informed strategies. This requires observation and tracking of arctic changes and understanding their nature, causes, feedbacks and connections among them. ISAC encompasses pan-Arctic, system-scale, multidisciplinary observations, synthesis and modeling to provide an integrated understanding of arctic change and projections of future change.

The ISAC Science Plan provides a vision for integrating research among diverse fields and varied users and stakeholders. ISAC facilitates international cooperative efforts to understand the Arctic System and all its components on a pan-Arctic scale. ISAC is positioned to sustain research and coordination activities relevant to environmental arctic change largely initiated during the International Polar Year (IPY). As an active science program ISAC stimulates and provides guidance to develop, maintain and evolve observational activities and scientific understanding. This approach ensures a legacy of relevant high-quality science in the Arctic for decades to come.

ISAC is motivated by environmental changes that are already large enough to affect life in the Arctic. The changes illustrated in this document focus on the last decade noting shrinking sea ice cover, rising atmospheric temperature, thawing permafrost, shifts in ecosystems, and linkages to human systems. Substantial future changes are projected to have profound impacts on humankind. Ecosystems are changing, species distributions shifting, and wildlife populations and fisheries are experiencing extraordinary pressures – both natural and anthropogenic.

Recent changes in the Arctic have already had significant impacts on infrastructure, on food security, on human health, and on industrial development, and they are influencing domestic responses and international relations. These changes can be measured in economic, social, political and cultural risks and costs and are reflected in human decision-making from the level of the individual to the nation-state, at the international scale, and in feedbacks to the system as a whole. Future system states are uncertain and the lack of predictability hinders efforts to develop strategies for adapting to and managing a changing Arctic.

The following key science questions are prompted by observed changes and our current understanding of the Arctic System.

Question 1. How is Arctic Change linked to global change?

Question 2. How persistent is the presently observed arctic change and is it unique?

Question 3. How large is the anthropogenic component of observed arctic change compared to natural variability?

Question 4. Why are many aspects of arctic change amplified with respect to global conditions?

Question 5. How well can arctic change be projected and what is needed to improve projections?

Question 6. What are the adaptive capacities and resilience of arctic ecological systems?

Question 7. To what extent are social and ecological systems able to adapt to the effects of arctic change?

Question 8. How does environmental change in the Arctic affect the resilience, adaptive capacity, and ultimately, viability of human communities?

Question 9. How can new insight into arctic change and its impacts be translated into solutions for adaptation, management, and mitigation?

The ISAC science program is structured around three concepts: Observing, Understanding and Responding to arctic change. All the components of the Arctic System must be observed across time and space to understand the scope and evolution of change. Understanding how the system functions and projecting future changes requires models using data that flow from the comprehensive arctic observing system. Moving beyond description to understanding change in the past, present, and future is critical. In the integrated ISAC program the observing, understanding and responding components have been developed in concert around a set of objectives. These are:

- Observing the Arctic System covering all domains including the anthroposphere, the atmosphere, the biosphere, the cryosphere, and the hydrosphere. This is based on existing and new long-term observing sites and networks as well as new observing methods. (observing)
- Quantifying the anthropogenically-driven component of arctic change within the context of natural variability. (observing)
- Understanding the causes of pan-Arctic changes, including changes in the human component, in the context of global change. (understanding)
- Improving models to project future changes in the Arctic System, including impact assessment models for responding to change. (understanding)
- Exploring options for adaptation to and mitigation of arctic change and suggesting ways that will lead to a path of sustainable use and development. (responding)
- Disseminating data and results from ISAC activities to the scientific community, stakeholders and the general public. (cross-cuts observing, understanding, responding)

Implementation of ISAC is underway, with activities designed to collect specific information relevant to addressing ISAC science questions. Among numerous programs endorsed by IPY and that have contributed to ISAC are the recently sunsetted European Commission funded DAMOCLES Integrated Project (www.damocles-eu.org), and the ongoing United States Interagency SEARCH Program (www.arcus.org/search/index.php). These two initaitves were formally linked through the EU/US SEARCH FOR DAMOCLES initiative (www.arcus.org/search/internationalsearch/damocles.php). They provide an example of how partnerships within ISAC may work. Partnerships within ISAC continue to expand and program building activities are planned in concert with participating programs.

An integrated observing system that is designed for pan-Arctic coverage is being developed, with much progress on this initiative made during the International Polar Year. This evolving observing system will constitute the ISAC Observing component; it will ultimately cover the atmosphere, ocean and sea ice, hydrology, cyrosphere, marine and terrestrial ecosystems, and aspects of the human dimensions of the Arctic System. The data flow within each of the ISAC program elements is coordinated by dedicated data information systems following standard data policies operated by participating organizations, programs and projects. Efforts are underway within the ISAC Program Office to coordinate the data management functions among these program elements.

Development of the ISAC Understanding component is also underway as modeling is increasingly coordinated among operational ISAC program elements. These activities include model comparisons, as well as coordination of new modeling initiatives, and in the longer-term, expansion of these activities to specifically address societal needs for understanding.

The Responding to Change component of ISAC drives the program with an emphasis on societally relevant science. Implementation of the Responding to Change piece began with planning efforts during the IPY, and is one of the major foci for the near future activities of ISAC.

The International Study of Arctic Change

The International Study of Arctic Change (ISAC) is a science program designed to understand the future state of the Arctic System under anthropogenic stress. The Arctic System is defined to include all of the Arctic land surface, ice, oceans, atmosphere, and its people, and all of the physical, chemical, biological, and social interactions and controls. It is a regional component and an integral part of the Earth System. To isolate the changes in the Arctic System caused by human activity from inherent variability on multiple time scales, ISAC research is situated in the context of past and present changes and variability.

The driving force behind ISAC is the need to build capacity for understanding and predicting Arctic System changes and for developing the necessary strategies to minimize the adverse effects of such changes. ISAC extends the study of the Arctic from basic science to offer insight into options for solutions to the real world problems that are intrinsic to a changing planet. ISAC research encompasses the important science activities outlined in previous initiatives while evolving into an international program informed by stakeholder-defined needs for solutions. ISAC articulates the scientific and societal rationale for arctic observing and understanding activities in collaboration with arctic residents, policy makers, non-governmental organizations and governing institutions, through the development of effective and appropriate responses to change.

Photo: M. Tjernström

ISAC was initiated in 2003 by the International Arctic Science Committee (IASC) and the Arctic Ocean Sciences Board (AOSB) following the Study of Environmental Arctic Change (SEARCH) Open Science Meeting in Seattle in October 2003. In 2004 IASC and AOSB formed the International Study of Arctic Change Interim Science Planning Group (ISPG) and in January 2005 the ISPG published the ISAC Science Overview Document (www.arcticchange.org). This SOD formed the basis for the further development of the ISAC Science Program. ISAC is an International Polar Year (IPY) legacy presently supported by the United States National Science Foundation, the Swedish Research Council (Vetenskapsrådet), the Swedish Polar Research Secretariat, IASC, and the International Arctic Research Center. ISAC is presently developing partnerships among programs and projects in the USA, Canada, the European Union and Asia.

A draft version of the ISAC Science Plan was released for public comment in March of 2009. This document results from that review process.

Why ISAC? Why Now?

ISAC is motivated by the environmental changes that are now affecting life in the Arctic and by projections of substantial future changes that will have profound impacts on humankind. Ice cover is shrinking, atmospheric and ocean temperatures are rising, permafrost is thawing, and ecosystems are changing. Wildlife populations and fisheries are experiencing extraordinary pressures – increasingly through anthropogenic drivers. There are significant impacts on infrastructure, food security, human health, industry and geopolitics. These impacts are measurable in economic, social, political and cultural risks and costs. Environmental change is influencing decision-making from individuals to the nation-states with feedbacks to the Arctic System as a whole. Uncertainty in the future and the lack of reliable projections poses a considerable challenge to developing strategies for adapting to and managing change.

The Arctic, due to its special physical conditions, with extreme climate and unique ecosystem dynamics, is responding fast and with amplified signals to global anthropogenically driven environmental change. Thus, it is a key place for early study of the challenges posed by global change. It is a place where the transition of an entire subsystem of the Earth to a new state can now be witnessed in real time. The lessons learned from studies of this ongoing transition, in addition to relevant retrospective analyses, are of immeasurable value for assessing the effects of anthropogenically caused change on other subsystems of our planet, as well as on the global system in its entirety.

Recognizing the uniqueness of the changes playing out in the Arctic System, the research community has designed and implemented programs to better understand the nature, scale, and expected future extent of environmental changes, as well as possible responses to these changes. Typically this has occurred within national or regional programs. However, in defining the research needed to improve our understanding of arctic environmental change it has become clear that individual and national efforts will not suffice. The required data and information span international borders. The intellectual resources, infrastructure for observing, capacity for synthesis and modeling, and transfer of scientific information into solutions for responding to change clearly exceed the capacities of single nations and even that of alliances among several nations. Such resources can only be mobilized in a truly international effort.

ISAC will provide the international framework for a comprehensive study of arctic environmental change with all its physical, biogeochemical, ecological, and human dimensions. ISAC will build upon existing efforts with the goal to integrate national programs into an international initiative with sufficient scope and intellectual resources and infrastructure to effectively further our understanding of past, present, and expected arctic change, and to also carry over new insights into the public and the decision making arenas. ISAC will promote, facilitate and coordinate new initiatives for national and international collaboration in arctic environmental change research.


Photo: M. Tjernström

Decisive and efficient implementation of ISAC is essential. The Arctic System is changing rapidly and scientific information for designing response options is needed now. Adaptation is already underway but management and solution strategies are underdeveloped. To optimize adaptation, resilience, and sustainability, and to implement effective response measures, existing and emerging knowledge has to be translated quickly – almost in real time – into action. The transition of the Arctic System into a new state due to human activities is an historic moment that poses a momentous challenge: how to rapidly gather knowledge and translate this into options for actions that can be implemented on the same time scale within which changes occur. ISAC is designed to face this challenge. A key scientific focus of research is the clarification of the robustness of arctic change, of the feedback processes responsible, and of the extent to which change is due to regional and/or global processes and driven by human activities. The arctic science community must continue to develop and expand collaborative activities with support from a strong alliance of nations affected by or concerned with the consequences of arctic change. The goals laid out in the ISAC Science Plan can only be achieved through cooperation that transcends the disciplinary, institutional and national boundaries of existing arctic research programs.

Some Recent Observations of Arctic Environmental Change

During the 1980's coupled climate models used for projections of possible future climate scenarios indicated that the effects of anthropogenic climate change would be seen early in the Arctic and that they would have amplified signals. Subsequent observations of the physical climate system did indeed reveal these predicted changes and, as also predicted, the magnitudes of arctic climate changes often exceed that of globally averaged changes. Many of these changes are also globally driven by human activities focused in the low and mid-latitudes.

Arctic environmental change was recognized first in the physical climate domain, where changes were initially most apparent. The better-known examples of Arctic change include the observed summer retreat of the Arctic Ocean sea ice cover (Figures 1,2,3), the plight of the polar bear (Sommerkorn and Hamilton 2008 ; Durner et al. 2009), and the changes to the Greenland ice sheet (Figure 4). However, cumulative and rapid changes have been observed across all components of the Arctic System. From the atmosphere to the anthroposphere change is increasingly well documented, although significant gaps in understanding still preclude an inclusive, optimized, and flexible observing system and the development of comprehensive and effective response strategies.

Surface air temperatures (SAT) in the Arctic continue to rise faster than the global average (Kennedy et al. 2007; Richter-Menge et al. 2008; Kaufman et al. 2009), even as temperature trends vary spatially and seasonally (Liu et al. 2008; Moberg and Jones 2003; Serreze and Francis 2006; Wang and Key 2005). Other significant atmospheric changes include large low-frequency changes (Rigor et al. 2002; Serreze et al. 2000), associated with changes in the polar vortex (Overland et al. 2008a), and increasing intrusions of subpolar/midlatitude weather systems into the Arctic (McCabe et al. 2001; Sorteberg et al. 2008; Zhang et al. 2004).

All key parameters characterizing arctic sea ice have also changed during recent decades. Summer sea ice extent has retreated from about 8 million km^2 in the late 1970's to 4.52 million km^2 in 2008 (Serreze et al. 2007; Richter-Menge et al. 2008). New records of minimum ice coverage were set in the summers of

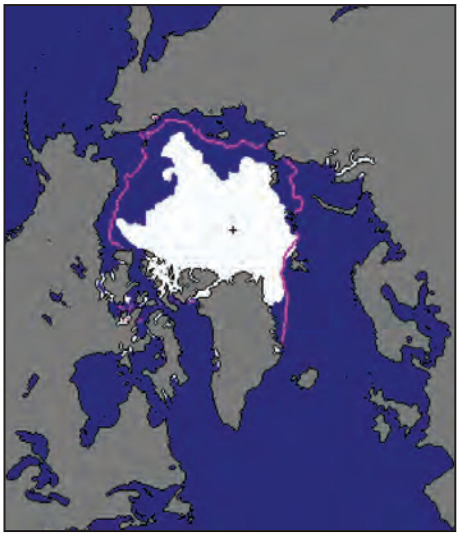

Figure 1: Arctic sea ice extent for September 2010 was 4.90 million square kilometers (1.89 million square miles). The magenta line shows the 1979 to 2000 median extent for that month. The black cross indicates the geographic North Pole. National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews/2010/100410.html

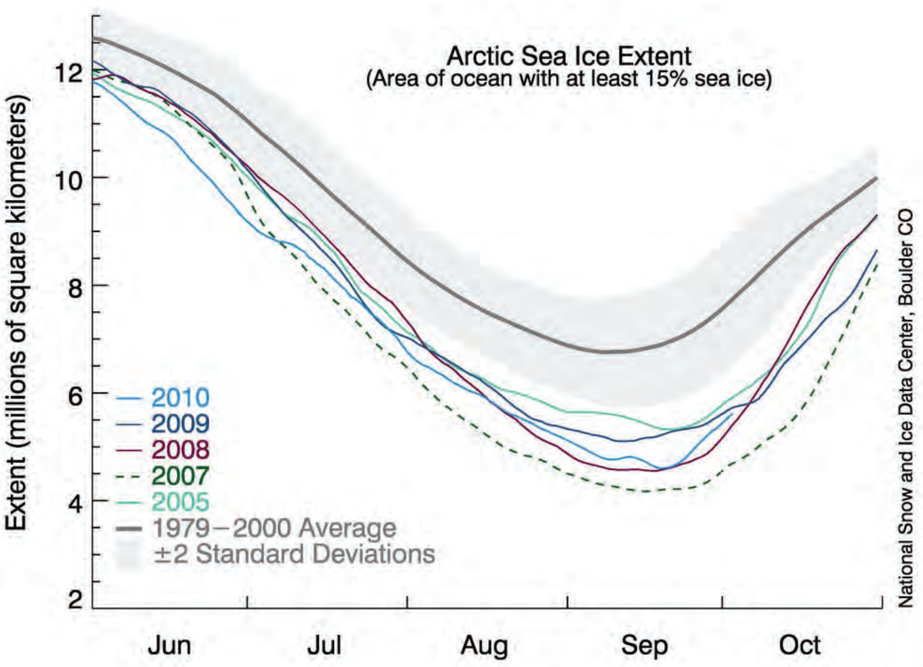

Figure 2: The graph above shows daily Arctic sea ice extent as of October 3, 2010, along with daily ice extents for years with the previous four lowest minimum extents. The solid light blue line indicates 2010; dark blue shows 2009, purple shows 2008; dashed green shows 2007; light green shows 2005; and solid gray indicates average extent from 1979 to 2000. The gray area around the average line shows the two standard deviation range of the data. National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews/2010/100410.html

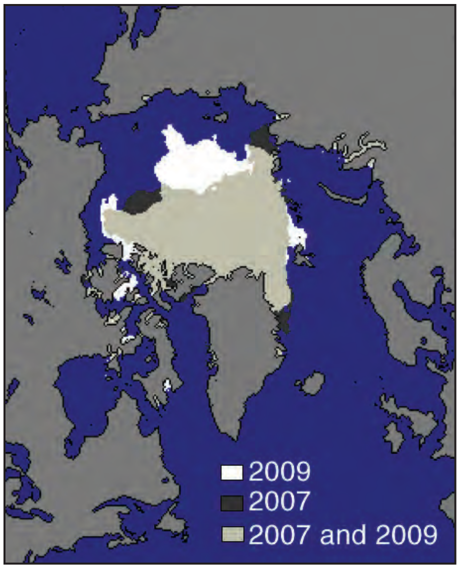

Figure 3: This image compares differences in ice-covered areas between September 12, 2009, the date of the 2009 minimum, and September 16, 2007, the record low minimum extent. Light gray shading indicates the region where ice occurred in both 2007 and 2009, while white and dark gray areas show ice cover unique to 2009 and to 2007, respectively. (National Snow and Ice Data Center. http://nsidc.org/arcticseaicenews/2009/091709.html)

2002, 2005, and in 2007. Although the ice extent for both 2008 and 2009 was larger than that for 2007, the last five years are well below two standard deviations lower than the climatology. Most recently 2008 was a minimum year for sea ice volume. Ice thickness has declined significantly between the periods of 1958-1976 and 1993-1997 (Rothrock et al. 2008). While only a few thickness observations have been collected since 1997, these show that the thinning is continuing in many regions of the Arctic Ocean (Giles et al. 2008; Haas et al. 2008). Buoy and satellite data show that the thinning occurs in concert with loss of older, thicker ice, both as a result of decreasing summer ice extent and increased ice-drift velocities. The Transpolar Drift has accelerated by a factor of two or more (Gascard et al. 2008; Hakkinen et al. 2008) while the age of the sea ice is decreasing with more and more multi-year ice replaced by first-year ice (Maslanik et al. 2007).

Arctic Ocean properties which were believed to be in steady-state when initial field campaigns were begun in the late 1980's were in fact already in the midst of transition, with significant changes in water mass properties and distributions through the upper layers (Morison et al. 1998). These changes could be linked to emerging observations of changes in other domains including SAT, sea ice cover, permafrost, vegetation distribution, and ice sheets (e.g. Hinzman et al. 2005; Serreze et al. 2000). The penetration of warmer waters into the central deep basins Wang et al. 2008), the shrinking and thinning sea ice cover, and shifts in the dominant atmospheric pressure field all suggest that the Arctic Ocean might become sea ice-free during summer sooner than was previously expected (e.g. IPCC 2007). This is of international interest as nations lay claim to sea routes and ocean and mineral resources. In the past difficult ice conditions have presented a natural obstacle to traffic and exploration but with the decreased sea ice cover and potential for a longer open-water season international traffic is already beginning to increase (AMSA 2009).

Marine ecosystems and marine biogeochemistry are being influenced by changes in physical ocean variables linked to climate change (Jin et al. 2009). This includes changes in water temperature, salinity, vertical mixing, currents and sea-ice-cover (Morison et al. 2006). These variables can influence primary productivity, as well as the reproductive health, and growth and development of key species and thus impact fish population dynamics over multiple time scales (cf. Finney et al. 2002; Ottersen et al. 2006). In

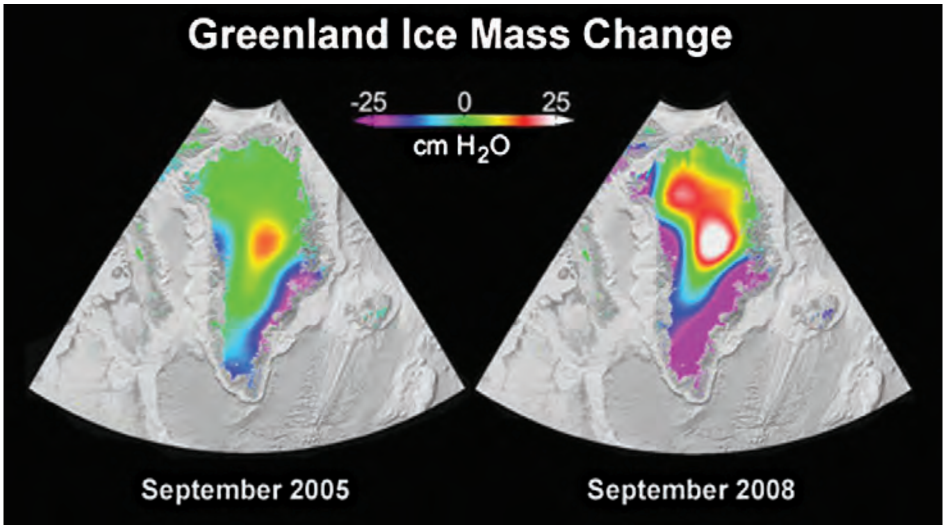

Figure 4: Changes in Greenland's ice mass as measured by NASA's Gravity Recovery and Climate Experiment (Grace) mission between September 2005 (left) and September 2008 (right). Ice losses which have been increasing over the past decade in the southern region, are now spreading rapidly up the northwest coast. The loss of ice sheet mass nearer to the ice sheet margins suggests the flows of Greenland outlet glaciers there are increasing in velocity (Velicogna et al. 2009). (NASA/JPL. http://www.jpl.nasa.gov/news/news.cfm?release=2010-100)

recent years there have been shifts in the geographical extension of plankton species (Census of Marine Life 2009), and changes in the distribution of some fish species (Loeng and Drinkwater 2007). Some predator-prey interactions have also shifted (Dingsør et al. 2007). Other observed changes are the acidification of the surface water caused by the oceanic uptake of anthropogenic carbon dioxide, especially in the Canadian Basin (Shadwick et al. 2009). Fisheries productivity is influenced by these changes as well as by fishing effort and fisheries policies. The fishing grounds of the arctic-influenced North Atlantic and North Pacific are among the most productive in the world (ACIA 2005), and while fishing constitutes a significant source of income for many local residents, it also contributes significantly to the food security and economic prosperity of the arctic nations more broadly and to the global economy (AHDR 2004). Local and commercial fisheries now face new and significant economic, social and environmental challenges and fisheries managers are already beginning to respond to arctic change through the drafting of new fisheries management measures (cf. NPFMC 2008).

The coastal zone is the interface through which land-ocean exchanges are mediated; it is the transition zone between onshore and offshore permafrost, and it is where much human activity occurs in the Arctic. Coastal processes in the Arctic are strongly controlled by specific phenomena such as sea ice cover, landfast ice (Mahoney et al. 2007), and the existence of onshore and offshore permafrost. The ice-free period is becoming longer (ACIA 2005), and the ice-rich, permafrost-dominated coastlines are rapidly eroding (Rachold et al. 2005; Jones et al. 2009). Gas seepage is occurring in the arctic seas and may be connected with the decomposition of gas hydrates trapped by degrading subsea permafrost (Shakova and Semiletov 2007; Matveeva et al. 2008; Shakova et al. 2010, Figure 5). On land, methane seeps from thaw lakes have also been recently been detected (Walter et al. 2006, 2007), and the pervasiveness of these and the aggregate released to the atmosphere are unknown (Zhuang et al. 2009).

Onshore permafrost zones have experienced significant subsurface warming in regions of Siberia and North America (Figure 6a,b) This warming is consistent with increased air temperatures over northern land areas and with the shrinkage of lakes and wetlands in areas of discontinuous ("warm") permafrost. By contrast in areas of continuous ("cold") permafrost, the areas of lakes and wetlands appear to have increased as a result of increased surface melt (Smith et al. 2005).

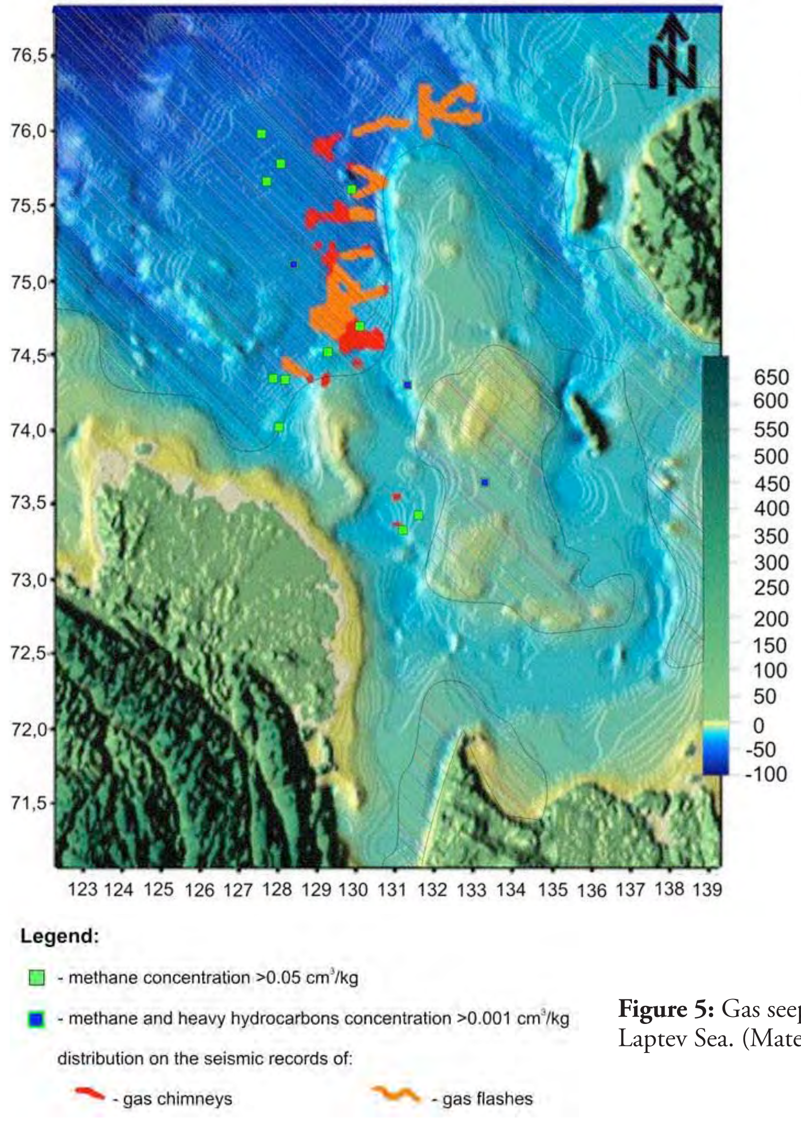

Figure 5: Gas seepage detected by seismic records in the Laptev Sea. (Mateeva et al. 2008.)

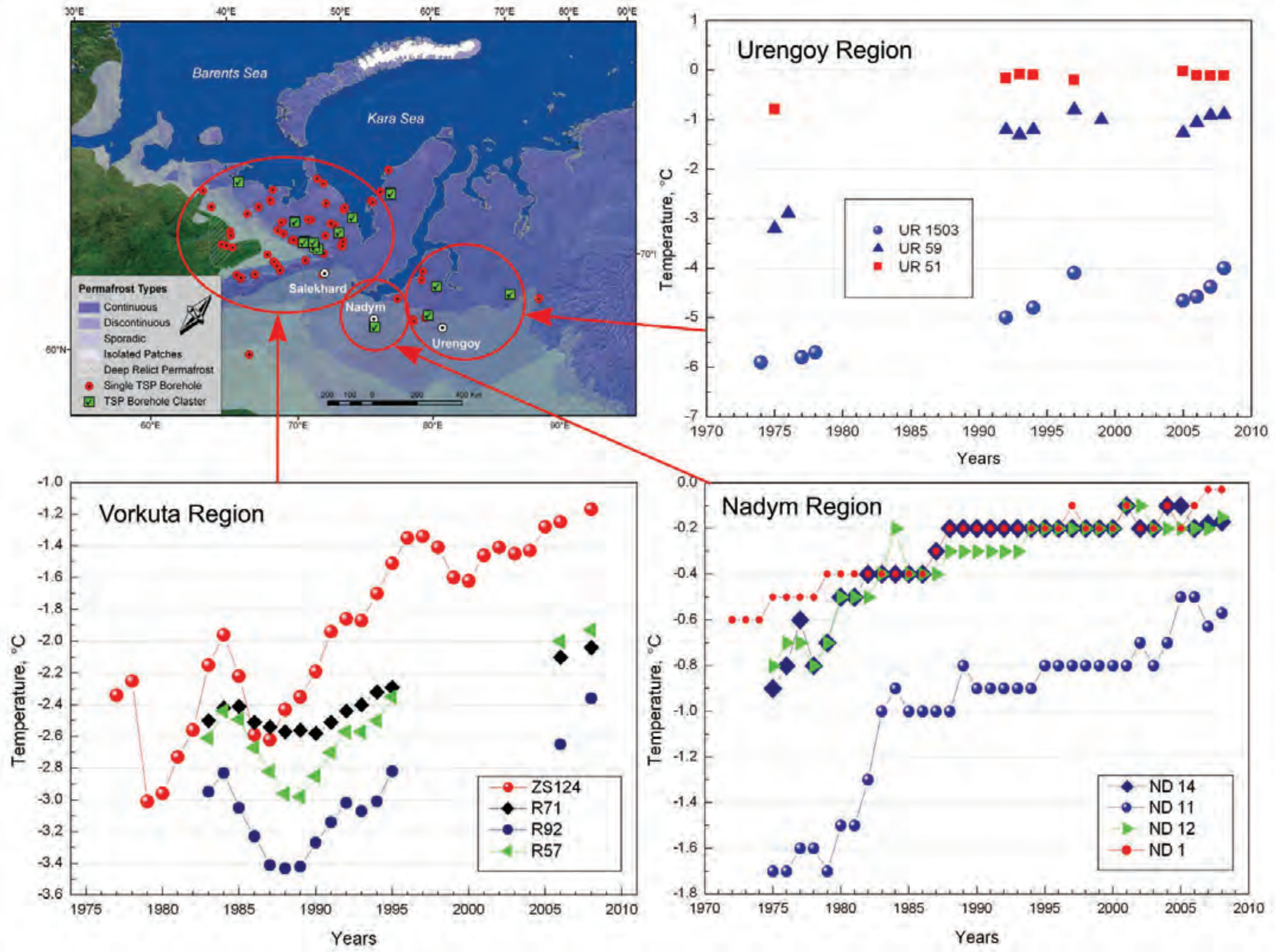

Figure 6a: Location of the long-term MIREKO and the Earth Cryosphere Institute permafrost observatories in northern Russia. Left below: Changes in permafrost temperatures at 15-m depth during the last 20 to 25 years at selected stations in the Vorkuta region. Right: Changes in permafrost temperatures at 10-m depth during the last 35 years at selected stations in the Urengoy (above) and Nadym (below) regions. (Romanovsky et al. 2009.)

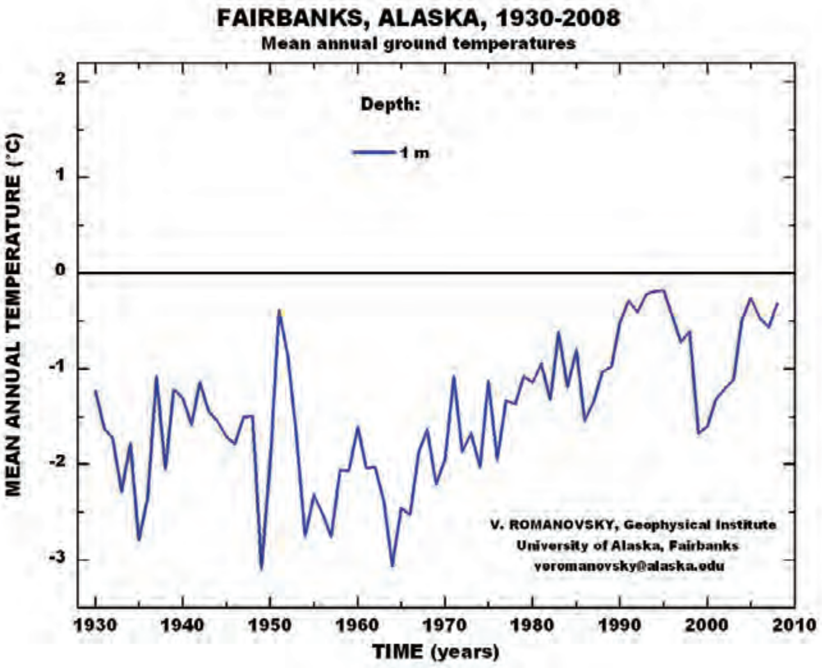

Figure 6b: Mean annual ground temperatures at Fairbanks (Bonanza Creek), Alaska, from 1930-2008. Note that the temperature just 1 meter below the surface has risen very close to the melting point of 0 degrees Centigrade. (Data from the Geophysical Institute Permafrost Lab, University of Alaska Fairbanks, courtesy V. Romanovsky)

Changes in the cryosphere, including the thawing of permafrost, present substantial challenges to the preservation and development of infrastructure. Coastlines, which in many areas are low in elevation and vulnerable to thaw, are increasingly threatened by a combination of the loss of their protective sea-ice buffer, changes in atmospheric cyclonic activity, the slow rise of sea level and high wind events. Global sea level rise represents a threat to coastal communities in many parts of the world, including in the Arctic. Roughly 60% of the current rate of eustatic sea level rise is due to the melting of mountain glaciers and icecaps (Meier et al. 2007), and the Arctic contains the largest area of these on the planet—covering close to 300,000 km^2.

High wind events are generating large waves more frequently as the open water season lengthens and erosion is causing some coastlines to retreat at average rates of several meters per year (Jones et al. 2008). At risk to damage and loss are roads, runways, pipelines, water and sewer systems, housing, public buildings, and cemeteries (Larsen et al. 2007), and in many places the cultural and environmental histories that are preserved in coastal and permafrozen deposits are also endangered (PAN 2007). Damage to infrastructure from thawing permafrost is observed and expected not only in coastal areas but in the entire permafrost domain where thawing occurs.

The warming of the Arctic may be forcing both a 'greening' of Low Arctic tundra landscapes and a "browning" of high latitude boreal regions as detected in both satellite imagery and the annual growth rings of deciduous shrubs (Goetz et al. 2005; Verbyla 2008; Forbes et al. 2010 Figure 7). These changes are almost certainly the result of significant increases in the length of the snow-free growing season, increases in temperatures during the growing

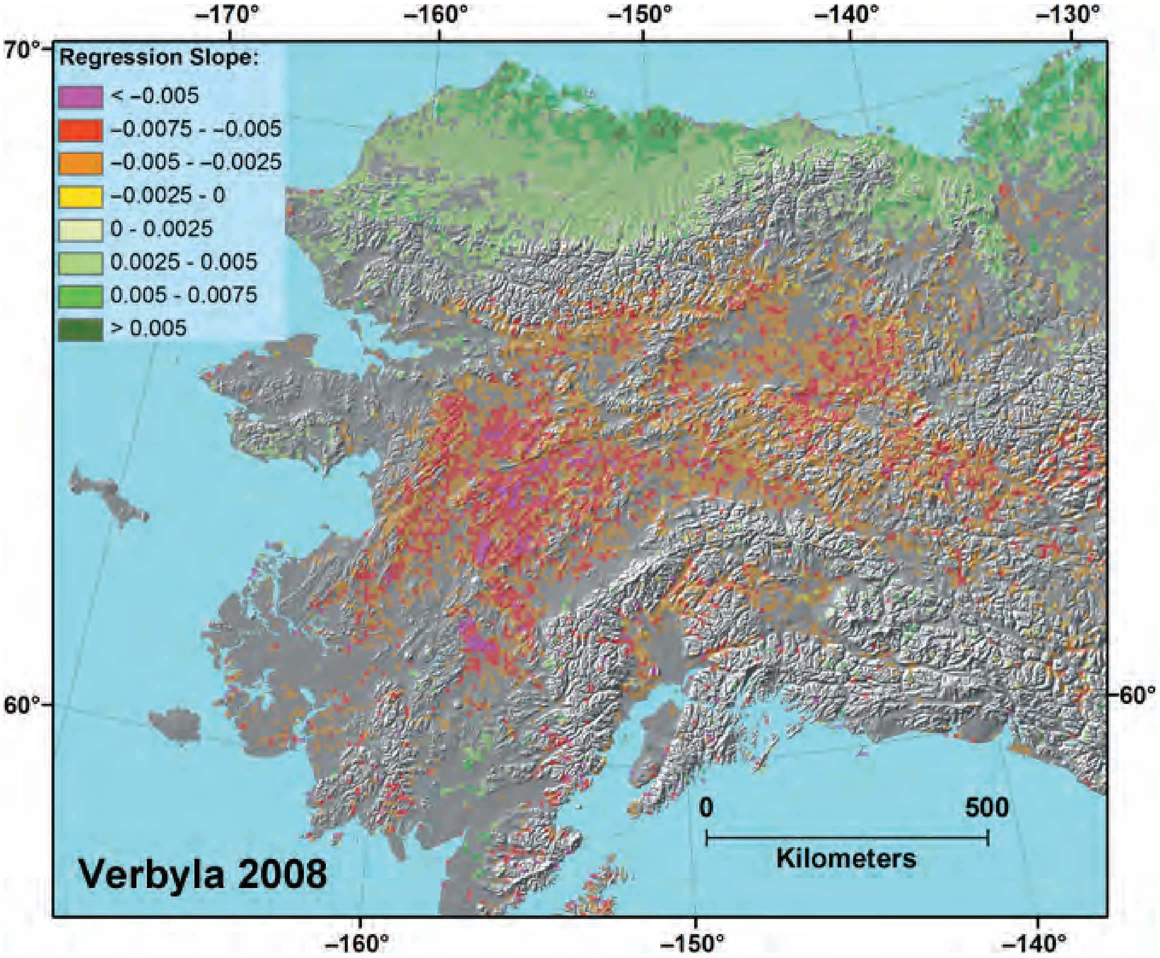

Figure 7: The warming of the Arctic in recent decades is linked to a distinct "greening" of the arctic land surface during the summertime, as well as a significant "browning" in much of the boreal region, as in this map of Alaska by Verbyla (2008). The greening and browning are measures of light reflectance as seen by satellites; they are related to increases (greening) or decreases (browning) in carbon fixation by the vegetation (e.g., Goetz et al. 2005).

season, and increased absorbed solar radiation (Euskirchen et al. 2006). This leads to higher productivity and in many areas shrub expansion into the tundra, lending to changes in surface energy exchange and in carbon and nutrient turnover. Both large (Post and Pederson 2008) and small mammal tundra herbivores (Ims and Fuglei 2005) also significantly impact vegetation structure and primary productivity (Van der Wal 2006). The forest structure, composition, and interactions among plants, soils, and animal populations of boreal ecosystems are changing (Hinzman et al. 2005). The apparently lower productivity ("browning") in northern boreal regions may be due to increased water stress resulting from changes in precipitation and evaporation. The lengthening of the warm season has also led to increased severity of forest fire outbreaks in North America and Eurasia (Balshi et al., 2008), and to increased vulnerability of northern forests to insect outbreaks; these outbreaks are now spreading into the European Arctic (Jepsen et al. 2008). The number of fires has increased and the area burned in North America's boreal forest spanning Alaska and Canada doubled from the 1960's to the 1990's even as human-caused fire starts declined (Kasischke and Turetsky 2006).

Plant and animal resources from arctic marine and terrestrial systems have been central to the cultures and economies of indigenous arctic peoples since the region was first settled during the early and middle Holocene (Damas 1984; Dumond 1987; Maxwell 1985; Pitulko and Kasparov 1996; Murray 2008). Since the Middle Ages the ecosystems services of the Arctic have been utilized by European, Euroamerican and Eurasian societies (Amorosi et al. 1994,1996; McGovern et al. 2006; Murray 2008), and in more recent decades they have assumed increased economic and strategic importance in national and global economies (AHDR 2004). In rural arctic communities many people derive a significant proportion of their food from subsistence hunting and fishing, collection of wild plants, and small-scale gardening (AHDR 2004; Loring and Gerlach 2010; Nuttall et al. 2005). Even in areas where the proportion of food acquired locally is small, local and wild foods are culturally and ideologically important to individual and community identities. Changes in resource productivity and accessibility to resources combined with shifting seasonality are influencing decisions about diet, water and fuel usage, transportation and community viability (White et al. 2007). Moreover, as different components of arctic ecosystems change at different rates, the seasonal synchrony of food availability and animal movements is disrupted, leading to nutritional stresses in some animal populations (Griffith et al. 2001) and exacerbating both animal and human community vulnerabilities.

The seasonal timing of key events (ice break-up and freeze-up, caribou calving, seal whelping etc.) is increasingly decoupled, impacting not only the reproductive success of species important to human subsistence, but it is also hindering the ability of people to plan their annual activities, their movements across the landscape, and to find and put up food for themselves, their families and their communities. Local resources are becoming more difficult to obtain and there is a shift toward purchased and often imported foods with many attendant economic and health costs (Kuhnlein et al. 2004). There are already many health risks for northern peoples and these are compounded by environmental change (Parkinson and Butler 2005).

Arctic Change is complex and manifest across domains on a pan-Arctic scale (ACIA 2005; AHDR 2004; IPCC 2007; Bowden et al. 2006; Lachenbruch and Marshal 1986; Morrison et al. 2001; Overland et al. 2004; Overpeck et al. 2005; Peterson et al. 2002; Serreze et al. 2000). Many component changes are interrelated in time and in space; changes in and of loss in biodiversity are closely linked with changes in the physical components of the system and to shifts in land use, natural resource exploitation, and social and political activities at regional and global scales (Chapin et al. 2000; Hamilton et al. 2003; Rühland et al. 2003; Sommerkorn and Hamilton 2008). These changes are persistent and will continue with impacts globally through climatic teleconnections (McLean et al. 2001; Osvaldo et al. 2000). These teleconnections can be influenced by regional feedbacks from the Arctic (Dethloff et al. 2006). Changes will remain larger in the Arctic than for other regions on Earth (Holland et al. 2006; Serreze and Francis 2006). However, projecting their future degree, extent, and spatial patterns with the desired certainty cannot be accomplished before integrated, cross-domain, long-term observing systems and improved models capable of reliable projections are in place.

The lack of reliable projections poses a considerable challenge to the development of effective strategies for coping with expected future changes. Yet scientists, policy makers, managers, arctic peoples, and other stakeholders need to be prepared to implement measures that will reduce risk as the Arctic System moves to a new state (Overpeck et al. 2005). Attention needs to be focused on changes for which social and ecological systems may be unprepared, as well as changes which will challenge adaptation and mitigation options (Alley et al. 2003; Bowden et al. 2005; Lemmen et al. 2008). Meeting these scientific and societal challenges requires ISAC to enable the research community to continue and to accelerate its move towards a novel way of studying the Arctic; one that is pan-Arctic in scale, highly interdisciplinary, internationally linked, and long-term in nature. ISAC will push science forward through a program that is grounded in understanding and observing the pan-Arctic System and its' role within the Global System. ISAC will provide the critical scientific information necessary for the development of options for responding to rapid and cumulative change in all domains of the Arctic.

Photo: B. Forbes

Fact Box 1

Changes in the Arctic Atmosphere

Surface air temperatures (SAT) are rising faster over the Arctic than the global average. While the global temperature increase since the mid-1960's was ~ 0.6°C–(Climate Research Unit, http://www.cru.uea.ac.uk), the corresponding temperature rise north of 60° was ~ 1.9-2.1°C (Richter-Menge et al. 2008), almost four times as much. In some regions, winter and spring temperatures have warmed more than 2°C. The International Arctic Bouy Program (IABP/POLES) near-surface data from the Arctic Ocean indicate an annual change of +0.23° C during the last two decades of the 20th century (Liu et al. 2008).

These changes show significant spatial and regional detail. Satellite observations (Wang and Key 2005), indicate a winter cooling trend in the skin-surface temperatures over large portions of the eastern Arctic consistent with the IABP/POLES data, while land area data (Moberg and Jones 2003), indicate positive trends for 1970-2003 at most locations during the winter (Serreze and Francis 2006), including some of the largest for the period. All these trends confirm that the Arctic is warming faster than other regions on Earth and this is consistent with changes in other parts of the climate system.

Reasons for this amplified warming are poorly understood and not likely attributable to a single process. The extent to which amplified warming is confined to the near-surface air (e.g. Graversen et al. 2008), is subject to intense discussion.

Other changes include increasing atmospheric moisture and precipitation (Adam et al. 2007), increasing cloud amounts in summer but decreasing in winter (Key and Wang 2005), and changes in atmospheric circulation (Graversen 2006); all these factors likely contribute to the warming trend. The leading mode of Arctic variability, the Arctic Oscillation (AO), was previously believed to be closely linked to many of these changes, but has, since the late 1990s, returned to more neutral values, even as rapid arctic change continues (Graversen 2006; Overland et al. 2008).

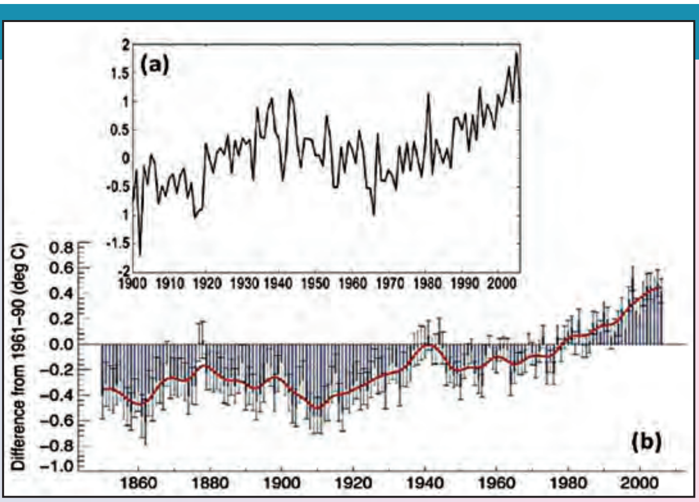

Figure A: Time series of surface air temperature for (a) the area north of 60° N and (b) for the whole globe. The time series in (a) shows the SAT anomaly to the whole of the 20th century average while that in (b) shows the anomaly with respect to the 1961-1990 average.

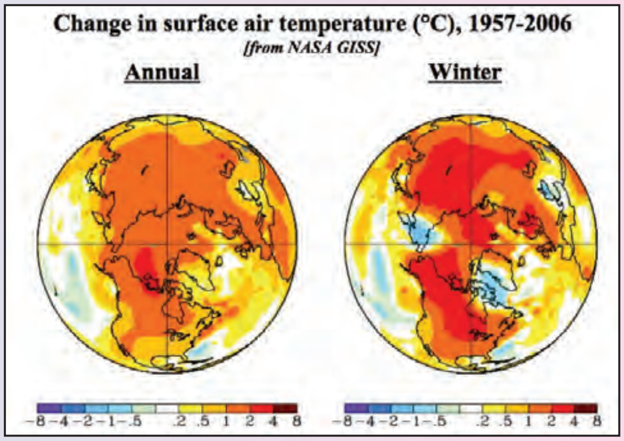

Figure B: The spatial patterns of change of annual (left) and winter (right) air temperature change over the past 50 years, based on data from NASA's Goddard Institute for Space Studies. Areas of warming are shown in yellow and red, areas of cooling in blue. Changes are evaluated as differences between initial and final values of least-squares best fit to temperatures at each grid point. (http://data.giss.nasa.gov/gistemp/).

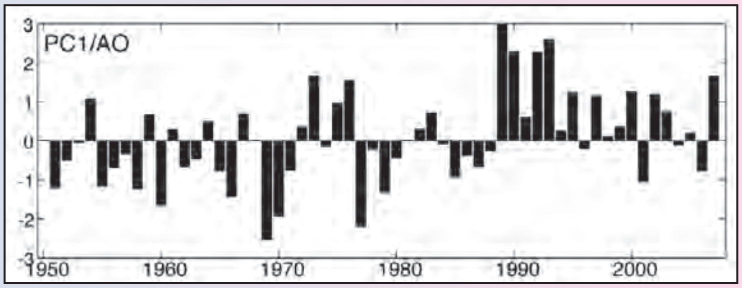

Figure C: Time series of the principle component of the first Empirical Orthogonal Function (EOF) of Arctic Sea level pressure sometimes used to express the Arctic Oscillation.

Fact Box 2

Changes in Arctic Sea Ice Influence Human Activities—Locally and Globally

Along with the increased shrinkage of Arctic sea ice during the summer, more first-year ice (FYI) is populating the Arctic Ocean at the expense of perennial/multi-year ice (MYI). From covering about 6 million km^2 20 years ago, MYI coverage declined by half in 2007-2008. March 2008 had 1 million km^2 less MYI than March 2007 and March 2009 was still 25% below the 1979-2008 average (NSIDC). The 2008 MYI minimum was an immediate consequence of the 2007 extreme summer sea-ice minimum extent. There has also been a sharp increase in sea-ice drift-speed. Changed atmospheric circulation wind regimes favor more export of ice away from the Arctic Ocean into the Greenland Sea (Watanabe et al. 2006, Wu et al. 2006, Wang et al. 2009). The length of the melt season has increased and the number of freezing-degree-days during winter has decreased leading to thinned ice overall. Accordingly there is less second year ice (SYI) available to replenish the MYI supply that melts or exits the Arctic Ocean. During the summers of 2005 and 2007, no net replenishment of MYI was observed (Kwok et al. 2009).

As a consequence of the loss of sea-ice, there is potential for the opening of new shipping routes. The Northern Sea route is the shortest route from Europe to the Pacific Ocean and the Far East but severe ice conditions have presented a natural obstacle and the period for navigation in ice-free waters lasts only from August to November. With the potential for a longer open-water season, international traffic will increase substantially, in transit or under pressure to access arctic natural resources. This may lead to local prosperity in some places – at least in the short term. However, increased marine access also raises issues of sovereignty and increases the risks of accidents such as vessel groundings, and spills of oil, gas, and cargo, and loss of human life (CRRC 2009), not just in Arctic waters but in the adjacent waters through which transit must occur in order to get to the Arctic. Other potential impacts of increased shipping include a significant rise in regional (arctic and subarctic) levels of emissions, and potential conflict over the management and enforcement of regulations in multiple use waters (AMSA 2009).

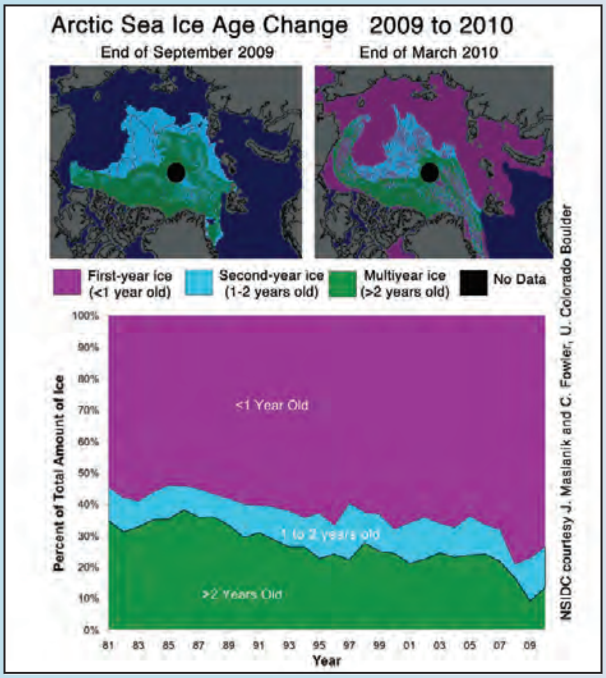

Figure A: These images show the change in ice age from fall 2009 to spring 2010. The export of older ice out of the Arctic was slower this year and as a result, the percentage of ice older than two years was greater at the end of March 2010 than over the past few years. Ice is still primarily two- to three-year-old multiyear ice and older thicker ice ice has continued to decline. Thickness and weather patterns play an important role in summer ice melt. (National Snow and Ice Data Center, courtesy J. Maslanik and C. Fowler, CU Boulder).

Figure B: Selendang Ayu on the north shore of Unalaska Island, Alaska, December 8, 2004. This image shows the two halves of the vessel after it foundered when the engines failed and towing attempts were unsuccessful. Six of the crew died in the accident and 336,000 gallons of fuel oil and diesel were spilled (NTSB 2006). This is the second largest spill in the region, following the Exxon Valdez spill in 1989. The spill and marine accident history of the Aleutian Island provides a guide for understanding the potential impacts of marine shipping incidents in the Arctic (CRRC 2009).

Fact Box 3

Changes in the Arctic Ocean

Despite its central role in global ocean circulation, there were few detailed studies of the Arctic Ocean before the mid-1980's. At the time when ocean observing systems were designed and deployed in other parts of the world (e.g., tropical Pacific), studies of the Arctic Ocean were still exploratory. The exceptions are Russia's NP drift stations (1937 – 1991) and the Sever airborne hydrographic surveys (1948 – 1993). The latter led to an established baseline for the Arctic hydrography by the Environmental Working Group published in its 1997 atlas. In 1991, the first detailed oceanographic sections deep into the central Arctic Ocean (Nansen, Amundsen, and Makarov basins) were completed (Anderson et al., 1994) after traverses across the Nansen Basin and the Gakkel Ridge by the German icebreaker Polarstern (Anderson et al., 1988), the ROSSYIA expedition (Quadfasel et al., 1993), and activities of the American icebreaker Polar Star.

These sections gave new insights into the water mass structure and circulation patterns of the Arctic Ocean and clearly demonstrated that the Arctic Ocean was in the midst of significant changes. These changes initially related mainly to water mass properties (e.g., increased temperature in the Atlantic core) or distributions (e.g., retreat of waters from the Eurasian domain towards the Alpha-Mendeleyev Ridge). Subsequent basin-scale observations of the Arctic Ocean conducted from nuclear submarines in the framework of the SCICEX program revealed that the changes were present throughout the upper layers of the Arctic Ocean (Morison et al., 1998).

Analyses of the few existing repeat observations and climatologies (e.g., EWG climatology), together with new observations, confirmed initial findings of a rapidly changing Arctic Ocean. There is now overwhelming evidence of rapid changes in the properties of the waters that feed the Atlantic layer in the Arctic Ocean. These waters are much warmer than those seen in climatologies; the thickness of the Atlantic layer is increasing and its upper boundary moving higher up in the water column thereby placing its increased heat content closer to the sea ice cover. The warmer layer of Atlantic water can be seen at many locations in the Arctic Ocean and more warm water is on its way into the Arctic Ocean from the North Atlantic through the Norwegian Sea (Polyakov et al. 2007).

Changes in the fresh and buoyant North Pacific water, entering the Arctic Ocean through Bering Strait, are also important. Heat transported by ocean currents at shallow depths can influence sea-ice growth in winter and early onset of sea-ice melting (Sumata and Shimada 2007; Shimada et al. 2006; Wang et al. 2009). Storage of solar heat in the upper ocean during summer due to early sea-ice melting in the East Siberian, the Chukchi, and the Beaufort Seas is delaying the onset of fall freezing by several weeks in this region (Shimada et al. 2006). Most of the Canadian archipelago and the Northwest Passage, recently sea-ice free during the summer, is influenced by North Pacific water.

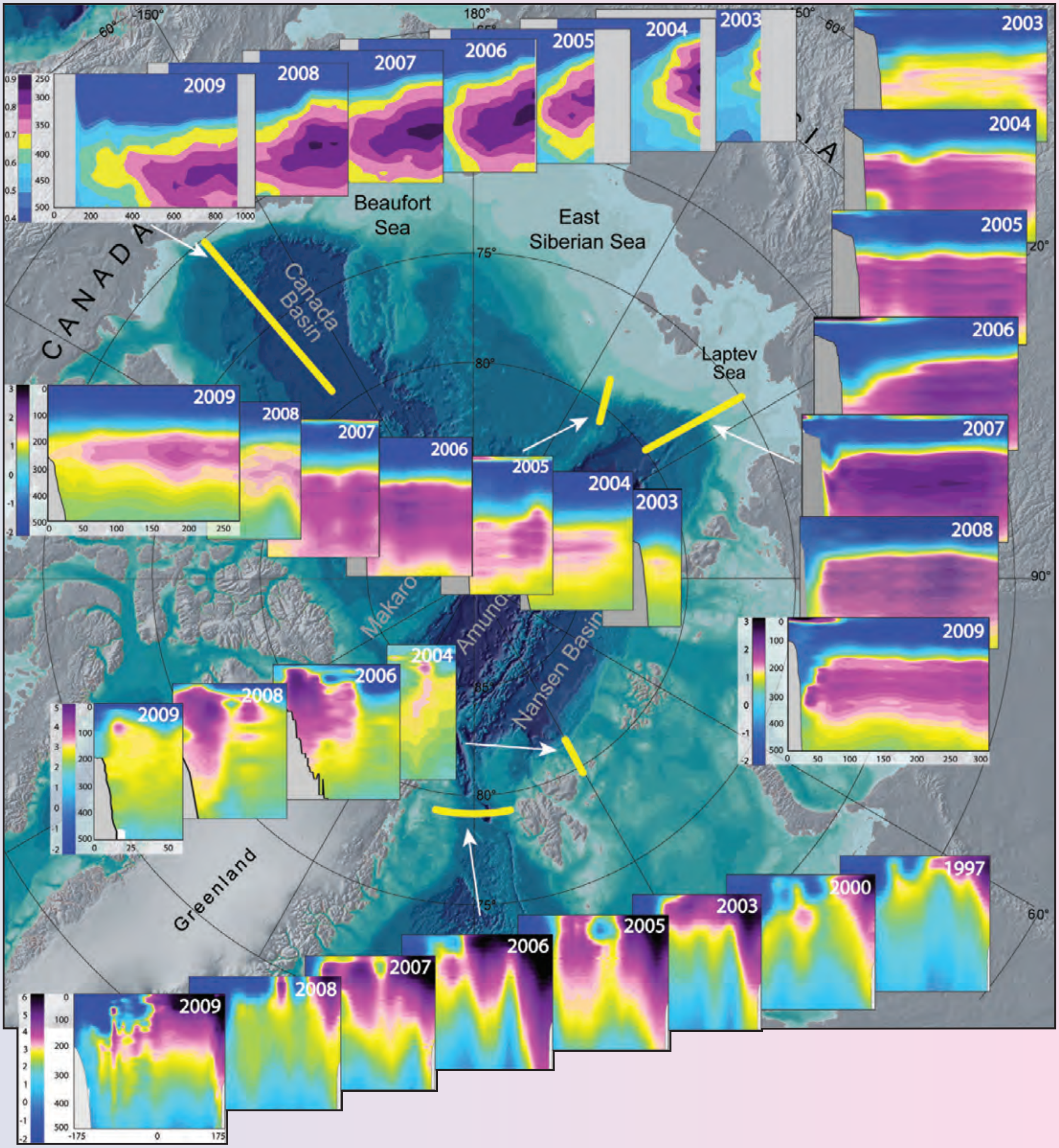

Figure A: From Polyakov et al. 2010. Vertical cross sections of water temperature and mooring-based time series of water temperature anomalies (°C) from the Laptev Sea slope (top; see cascaded plots marked with letter a) and the vicinity of Svalbard (middle, see cascaded plots marked with letter b). Maximum lagged correlation is used to define the anomaly propagation speed (V). These observations provide evidence of unprecedented warming of the Arctic Ocean. Plot marked c shows evidence of warming of AW (observed to a depth of 100 meters) propagating northward to the Fram Strait near Svalbard. Plot marked d shows evidence of warming propagating to the Fram Strait from the North Atlantic. The map gives locations of the time series of sea surface temperature data (red dots).

Fact Box 4

The Synergystic Effects of Climate Change and Human Activities

In the Barents Sea cod fish (*Gadhus morhua*) recruitment is dependent on higher than average temperatures (Dingsør et al., 2007). This may be a result of higher primary production when the ice-free area is larger, a greater influx of zooplankton carried by the increased inflow of Atlantic water masses from the southwest and higher temperatures promoting higher biological activity at all trophic levels. A positive NAO index typically results in warm conditions in the Barents Sea and a corresponding correlation between the NAO index and cod recruitment has been reported (Ottersen and Stenseth 2001), and possibly also between temperature and cod condition (Sandeman et al 2008).

The statistical relationship between temperature and the recruitment of Barents Sea cod has been strengthened during recent decades. This may be related to fishing induced changes in the age of the spawning stock biomass; it was dominated by 13+ year old fish in the late 1940s and early 1950s but by 6-8 year old fish in the 1990s (Ottersen et al., 2006). Retrospective fisheries data from Iceland during the 11th-18th centuries indicates that recent fisheries management strategies of the 20th century were probably based on erroneous assumptions about the distribution of age and size classes in a 'natural' cod population (Amorosi et al. 1996). In combination, climate change, increased fishing effort, and a management model utilizing what was probably an historically unusual cod population structure of the 1970's, forced the collapse of the fishery in many regions. This occurred in eastern Canada (1991-92, the Newfoundland cod fishery), in Norway, and in West Greenland (Lilly et al. 2008). In each instance there was economic hardship and ensuing out-migration from many fisheries-dependent communities, although some were able to profitably shift the focus of their fishery from cod to shrimp (Hamilton et al. 2003).

Impacts of the collapse of these northern hemisphere fisheries are felt worldwide as imports from other parts of the world are used to make up for the shortfall, placing increased pressure on other fisheries. The intensification of commercial fishing to meet these demands and those of a growing global human population has sometimes come at the expense of local, artisanal, and smaller sustainable fisheries in developing countries. Moreover, there has been a gradual decline in global landings and a shift from inshore to offshore and from north to south (Pauly et al. 2004). The combined influence of climate and fishing activities contributes significantly to difficulties in predicting future fisheries production in the Arctic and globally (Brander 2007).

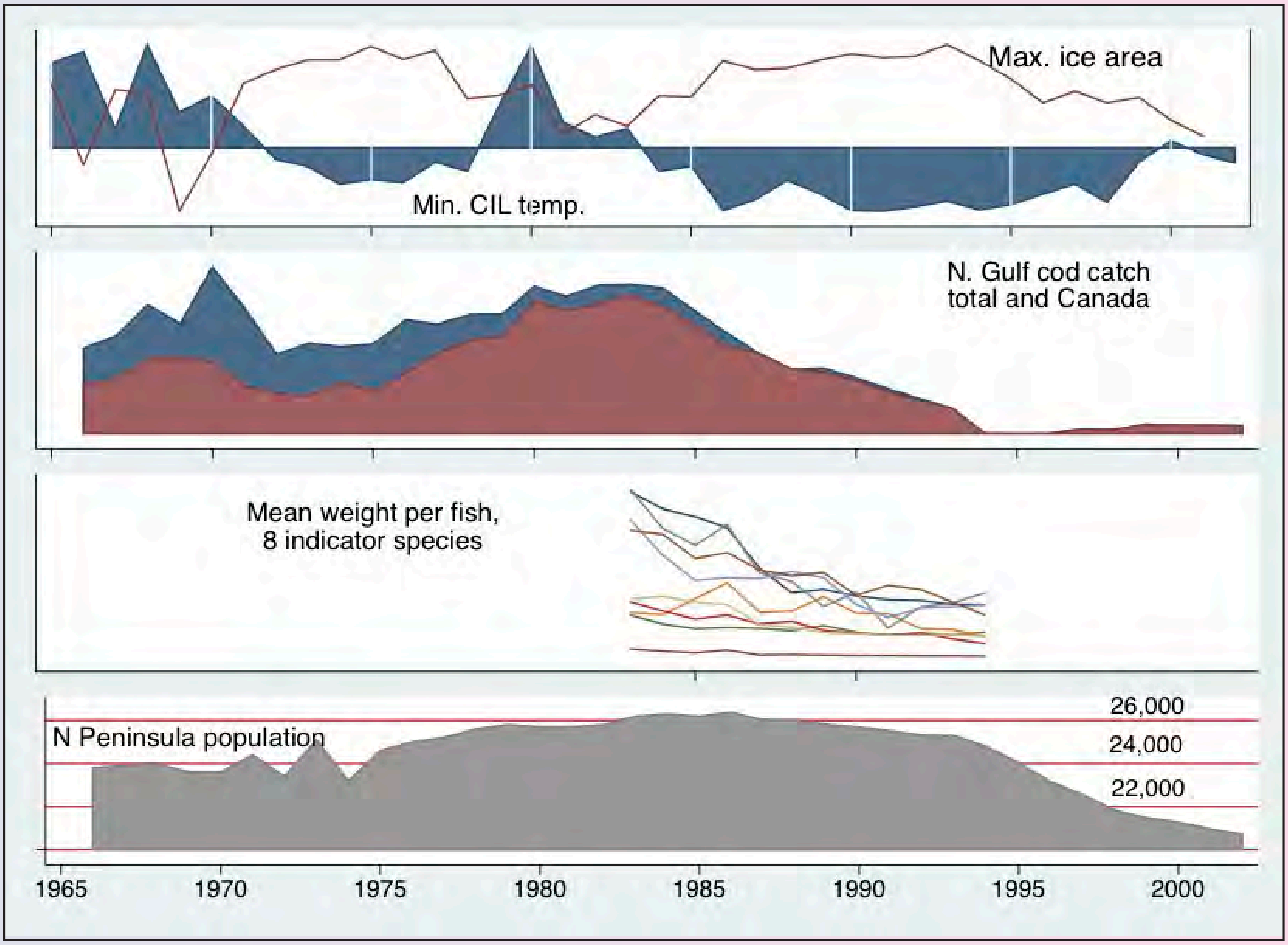

Figure A: Interconnected changes in a social/ecological system around NW Newfoundland. The combination of overfishing with adverse ocean/climate conditions led to an ecological collapse, followed by out-migration from the fisheries-dependent Northern Peninsula (Hamilton et al. 2004). From top: minimum Cold Intermediate Layer temperature and maximum ice extent in the Gulf of St. Lawrence; Canadian and total cod catches in the Northern Gulf; mean weight per fish of 8 indicator species from biological surveys; and the total human population of the Northern Peninsula. Figure courtesy L. Hamilton.

Fact Box 5

Permafrost and Coastal Erosion: Feedbacks to the Global System and to Infrastructure

In the coastal zone change is mostly expressed in erosion processes which result in fluxes of released material and shoreline retreat. The coastal zone is a small, but important, part of the entire permafrost domain where recent permafrost degradation has been observed. Permafrost degradation is connected with the release of permafrost-bound greenhouse gases (GHG) and the volume of components eroded from coastal formations is sufficient to play an important role in the global budget of the lithosphere, hydrosphere, and atmosphere (Romankevich

Source:International Permafrost Association, 1998.
Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.

Figure A: Permafrost distribution in the Arctic. (2005). In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 22:53, May 4, 2010 from http://maps.grida.no/go/graphic/permafrost-distribution-in-the-arctic and Vetrov, 2001; Streletskaya et al. 2008). Offshore, subsea permafrost contains gas hydrates, a solid phase composed of water and gasses formed under low-termparature and high pressure. Large volumes of methane in gas hydrate form are stored below the subsea permafrost and zone stability is sustained by the permafrost. Its degradation and consequent destabilization of gas hydrates could significantly increase the flux of methane to the atmosphere (Rachold et al. 2007). At the same time there is increased interest and effort directed towards extraction of gas hydrates for energy purposes, possibly serving as a bridge, in combination with carbon capture and storage, to lower future emissions of greenhouse gases (Krey et al. 2009).

The rate of coastal erosion is controlled by the type of coast: lithified, glacial, or unlithified. Lithified bedrock coasts are the most stable and their rate of retreat is close to zero. Glacial coasts on the other hand are retreating more quickly in part as a result of the shrinkage of ice sheets; their rate of retreat is a function of thermal and mechanical interaction with sea water (melting and calving). The retreat of unlithified ice-bonded permafrost coasts is most rapid and it depends on thermal and mechanical impact of waves and seasonal/perennial thaw. In winter, a thick and extensive sea-ice cover protects the coastline from hydrodynamic forcing. During the ice-free period, which is increasing in length, unlithified coastlines are rapidly eroded. Retreat is observed during the entire warm season, but mechanisms differ in spring/summer and late summer/fall. In early summer thermal denudation dominates and depends on SAT changes. Retreat rate is dependent on SAT rather than on wave action/sea ice coverage; the warmer the summer temperature the higher the rate of bluff destruction. Storms cause thermal erosion of the bluff base in late summer when sea ice coverage is at a minimum. All mechanisms are controlled by the ice content in permafrost (Vasiliev et al. 2005; Leibman et al. 2008). In Alaska alone, it has been estimated that thawing permafrost and coastal erosion will add between $3.6 and $6 billion dollars (10-20%) to future costs just for publicly owned infrastructure from now to 2030 (Larsen et al. 2008). Such problems are increasingly pan-Arctic in distribution.

Figure B: Types of coasts: (1) lithified, (2) glacial, and (3) unlithified. Photos: (a) V. Khomutov, and (b,c) M. Leibman

Fact Box 6

Changes in Food Systems, Food Security, and Human Health

Northern livelihoods and food systems tend to be tightly connected to climate, weather, and ecosystems. People have relied for millennia upon the land and sea for their food, whether through hunting, herding, gathering, fishing, small-scale gardening, or a mix of all of the above. However the impacts of climate change as currently understood threaten to undermine the viability of these essential ecosystem services (Hovelsrud et al. 2008; Loring et al. 2008; White et al. 2007). In Alaska, for instance, residents have observed changes in the landscape such as landslides and lakes drying, in some cases resulting in the complete or temporary loss of important harvest locations. Many also report that “the world is not the way it used to be,” referring to observed changes to weather, seasonality, and to the distribution, abundance, and migration patterns of fish and game (Krupnik and Jolly 2002; McNeeley and Huntington 2007).

Access to these traditional “country foods” is thus decreasing, but alternatives are limited, especially in remote communities, by a lack of employment opportunities, by the costs and challenges of transport to and from urban supply centers, and by lack of agricultural and manufacturing infrastructure (Colt et al. 2003; Goldsmith 2007:15; Martin et al. 2008;). Finding that their food needs cannot be met with locally-available wild food resources, many now fill their cupboards with imported foods, purchased either from a village store (for those communities with a store), or from costly periodic provisioning trips to urban supply centers (Kuhnlein et al. 2004; Receveur et al. 1997; Ford 2009).

In the North American Arctic, this dietary change, or “nutrition transition,” comes at great economic, physical and psychological expense, with precipitous declines seen in both physical and psychological health. Near-epidemic increases are being observed and projected for Type II diabetes, obesity, coronary heart disease, and cancer, as well as for depression, substance abuse, alcoholism, and violence (ADHS 2006; Degal and Saylor 2007; Graves 2005; McLaughlin et al. 2004; Wolsko et al. 2007). The extent to and manner in which these health trends are directly and indirectly linked to changes in community food systems, climate-driven or otherwise, still needs extensive research and quantification, but it is clear that similar trends are duplicated elsewhere around the circumpolar north (cf. Egeland et al 2010).

Figure A: Patrick Smith, Minto Village, Alaska, with fresh produce from the Minto Village Community Garden. Gardening is both a customary and a traditional means of supplementing subsistence foods in interior Alaska. Environmental, social and economic factors condition the success of such activities. Photo: P. Loring.

ISAC Objectives and Science Questions

ISAC will engage in pan-Arctic system-scale multidisciplinary observations and synthesis and modeling activities to provide an integrated understanding of past and present arctic change and projections of future changes. The ultimate goal of ISAC is to provide authoritative and timely scientific information to society, stakeholders, and decision and policy makers so that they can develop informed responses to rapid arctic change. ISAC will work to achieve a series of critical objectives guided by key questions that are prompted by our current observations of change and our present understanding of the Arctic System.

Open Questions Framing Arctic Change Programs

The need for better understanding and predictive capability, and therefore continued and improved observations, is apparent not only for the ecosystem and human components of the Arctic System, but also for the atmosphere-ocean-ice components that have historically been the foci of much Arctic research.

ISAC Key Science Questions

1. **How is the Arctic linked to global change?**
2. **How persistent is the presently observed arctic change and is it unique?**
3. **How large is the anthropogenic component of observed arctic change compared to natural variability?**
4. **Why are many aspects of arctic change amplified with respect to global conditions?**
5. **How well can arctic change be projected and what is needed to improve projections?**
6. **What are the adaptive capacities and resilience of arctic ecological systems?**
7. **To what extent are social and ecological systems able to adapt to the effects of Arctic Change?**
8. **How does environmental change in the Arctic affect resilience, adaptive capacity, and, ultimately, viability of human communities?**
9. **How can new insight into arctic change and its impacts be translated into solutions for adaptation, management and mitigation?**

Atmosphere

While it is established that Arctic atmospheric temperatures are increasing more than twice as fast as the global average, there is no consensus as to specific reasons for this sensitivity. Several positive feedback processes have been suggested but no single one explains this process. This is true for changes in other atmospheric parameters and in many cases the data are insufficient to construct hypotheses about changes. For example, the atmosphere is believed to have played a large role in the summer sea ice loss of 2007, but it is unclear if this was due to abnormal surface radiation balance resulting from an unusual cloud field, to an exceedingly large transport of ice across the Arctic resulting from anomalous circulation, or to abnormal meridional sensible heat transport.

The atmosphere is known to be receiving anthropogenic inputs manifested as increasing concentrations of greenhouse gases as well as changes in aerosol particles and other chemical species. Yet the Arctic's role as sources and sinks of these is poorly understood and is subject to large quantitative uncertainties (Hayes et al. 2007). Past work has included *in situ* terrestrial measurements of surface fluxes of trace gases and has identified local sensitivities, but a spatially and temporally integrated perspective is needed in order to assess the Arctic's role in global change. The role of the Arctic Ocean in global carbon and sulfur budgets is notably uncertain, and it may be changing rapidly with the reduction of the perennial sea ice cover.

Another indication of large uncertainties in our understanding is the change of stratospheric ozone, which appears to have stabilized in recent years (Newchurch et al. 2003). This followed the concern expressed about ozone depletion that led to the Vienna Convention for the Protection of the Ozone Layer, the development of the Montreal Protocol in 1987, and subsequent amendments (UNEP 2000). However, the Arctic remains vulnerable during very cold spring seasons, which appear to have been increasing in duration (Lemmen et al. 2008). The atmosphere is also a primary vehicle for contaminant transport into the Arctic, bringing poorly understood risks to humans, wildlife and ecosystems (AMAP 1998, 2002, 2003a, 2003b, 2004, 2006).

Ocean

The changes in the Arctic Ocean and sea ice are related to changes in the inflow of near-surface waters from the North Pacific and North Atlantic oceans. Pulses of abnormally warm Atlantic Water have been tracked from the Norwegian Sea through Fram Strait and along the shelf break of the Siberian seas (Polyakov et al. 2007). Since the surface and its sea ice cover are shielded from this water by the strong and cold halocline, a central question is whether the enhanced heat content of the Atlantic water has played a role in the extreme ice retreat north of Eurasia in recent years. The warm Pacific water, especially the Pacific summer water, has been implicated in the ice retreat in the Chukchi and East Siberian sectors. Shimada et al. (2006) have proposed a feedback loop that includes an enhancement of the transmission of wind stress to the ocean under conditions of reduced sea ice concentration. Farther to the south, there is evidence of northward ecosystem migration in the Bering Sea (Grebmeier et al. 2006) and in the Northeast Atlantic (Edwards et al. 2010), where two of the world's largest fisheries are important economic resources for northern communities. The downstream consequences of enhanced Pacific inflow to the Arctic require additional investigation because of the potential for increased migration of Pacific marine species into the Arctic Ocean.

Figure 8: Benthic samples, initial expedition to the Bering and Chukchi Seas (Arctic Ocean), Russian-American Long Term Census of the Arctic (RUSALCA). Photo: B. Bluhm.

The reduction of Arctic Ocean sea ice cover is one of the most dramatic signs of arctic and global environmental change. However, the understanding of these sea ice changes is complicated by the interaction of thermodynamic and dynamic processes which contribute to melting and freezing as well changes in ice motion and deformation. The present changes may have been initiated by high rates of ice export during the late 1990s and early 2000s. During this time, the Arctic Oscillation was predominantly in a positive phase and the associated wind patterns facilitated increased export of sea ice. This preconditioning led to a thinning and areal reduction of ice extent that has continued through the most recent decade despite a more neutral Arctic Oscillation. The relative importance of short-term wind forcing, enhanced inputs of surface radiation and heat provided by the underlying ocean remains to be determined.

For a more complete assessment of Arctic sea ice changes, information about the volume of ice from thickness measurements is critical. Only a few ice thickness observations have been collected since the 1990s. However, these show that the thinning is continuing in many regions of the Arctic Ocean, and that it affects the thickness of level ice as well as the thickness and frequency of ridges. Buoy and satellite data show that the thinning is in concert with reductions of multi-year ice, as a result of both decreasing summer ice extent and increased drift speed of the ice.

Of critical importance to the energy balance of the ice surface is the distribution and size of the snowmelt ponds that appear during the summer (Figure 10). These areas of melted snow on top of the ice are difficult to observe with satellites but they have a dramatic effect on the reflectivity of the ice and must be included in modeling of the ice energy balance. In general, our understanding of the spatial and temporal variability of ice cover needs to be improved as does our understanding of the impacts of changing ice cover on marine productivity and ecosystem services.

Figure 9: Melt ponds are typical features on the surface of Arctic sea ice in the summer. Due to their low albedo they play a crucial role in sea ice mass balance during the summer. Changes in melt pond coverage and their relation to ice thickness require further study. Photo: M. Tjernström.

Ecosystems

In the marine ecosystem changes in biogeochemistry are largely a result of changes in the marine climate, e.g. changes in ocean dynamics, seawater temperature, seasonal sea ice coverage, surface water light regime, input by river runoff, etc. Beyond this direct coupling to the marine climate the exchange of gases between the atmosphere and sea surface water can have a direct impact on the chemical status of the seawater, e.g. the decrease in pH is caused by increased uptake of carbon dioxide from the atmosphere. However there is no simple coupling between changes in the marine climate and biogeochemical processes. For example, with decreased summer sea ice coverage the light penetration increases, boosting primary production as enhanced river runoff adds nutrients to the photic surface water zone. At the same time less sea ice coverage increases coastal erosion and adds particles to the water column, as does increased runoff, which in turn hampers the light conditions and thus primary production. Decreased sea ice coverage may also increase stratification and hamper mixing of nutrients from below to the photic surface water. To determine how primary production might be impacted by these changes one must know the relative effect of each individual process. This is only possible with sufficient process knowledge in combination with a process-resolving modelling activities. Thus it is essential to closely combine process-oriented fieldwork with model development, and have sufficient time series data to force the models once they are adequately developed.

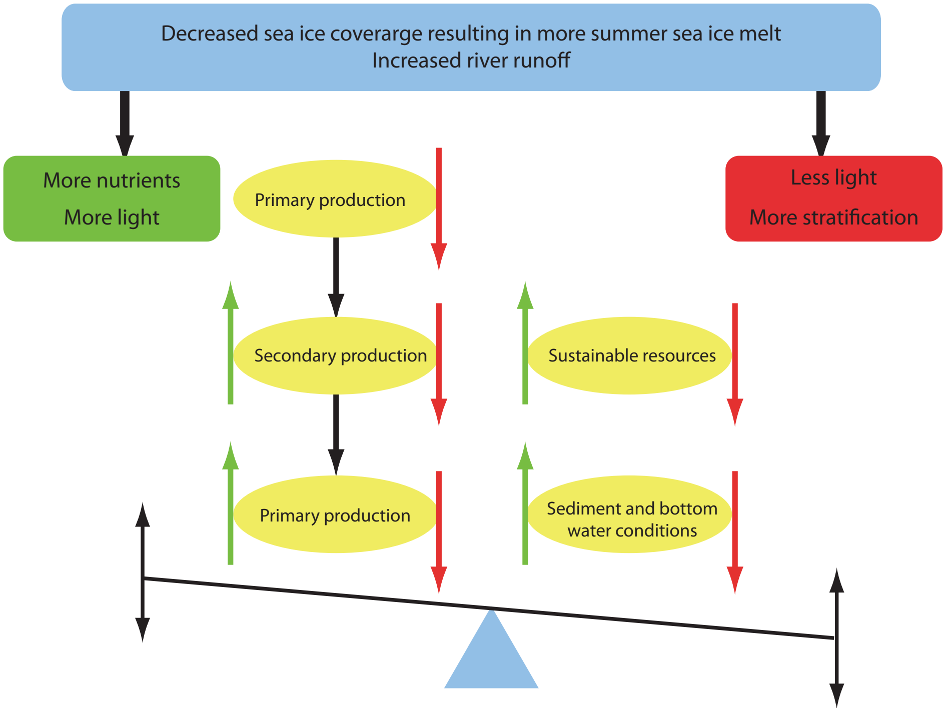

Figure 10: Schematic illustration of one example of multiple feedbacks of the same change in the forcing factor. Green arrows relate to the green box and red arrows to the red box. The resulting balance is determined by the balance of the red and green arrows.

The effect of changes in the arctic climate, sea ice, and marine biogeochemistry on the sea ice biome, including primary productivity, biodiversity and biogeography are uncertain (Frey et al. 2007; Hop et al. 2006; Wassman et al. 2006, 2008). Some higher trophic organisms, such as polar bears (*Ursus maritimus*), have already shown sensitivity to changes in the arctic environment (Derocher et al. 2004; PBSG 2006). In areas there are declining population trends for marine species, such as ringed seals (*Phoca hispida*) (Stirling 2005; Kovacs and Lydersen 2008), and salmon (*Onchorhychus sp.*) (BEST 2004). Although we have some understanding of the levels of sensitivity of arctic marine mammals to climate induced habitat changes (Laidre et al. 2008), the adaptive capabilities of these and of other arctic species remain unclear. Arctic biodiversity inventories are incomplete, and historic and paleo-ecological baseline data is scarce in many instances (ABA 2009; McRae et al. 2010).

Challenges to arctic species from arctic change, whether marine or terrestrial, can be grouped in four categories 1) habitat modification, 2) ecosystem alteration, 3) stresses to condition and health, and 4) human interaction (cf. Moore and Huntington 2008). Observation and modeling of impacts and feedbacks at the species, community and ecosystem level in marine, terrestrial and freshwater systems are critical. On land, where the growing season is changing, the impacts on wild plant resources, horticulture, agriculture and forestry are only partially understood. For example, the extent to which existing forestry practices may influence the adaptation of peripheral forest zones and of managed forests to arctic change is unknown (cf. Guariguata et al. 2008). Other examples come from the recently documented 'greening' of the Arctic detected by satellite (Goetz et al. 2005, Raynolds et al. 2008; Verbyla 2008), and related changes in the growing season (Karlsen et al. 2009). In freshwater systems the drying and draining of lakes in permafrost regions is of concern (Smith et al. 2005, Hinzman et al. 2005), and the impact of thermokarst development on hydrobiogeochemistry and vegetation is still poorly understood (Gooseff et al. 2009).

People

Among many other issues, it is critical to know how changing access to resources will impact health, well being, human security, including food security, and individual, community and cultural identity. The feedbacks from arctic environmental change to local interests, to national and international economies and geopolitics, and to global sustainability are not clear. There is great uncertainty in our understanding of how these variables interact to either amplify or mitigate arctic changes (cf. Huntington et al. 2007). Understanding change is the basis for providing good stewardship of ecosystem services (cf. BEST 2004), and ensuring community viability, yet the measures that could and should be taken to facilitate such resilience are underdeveloped (Sommerkorn and Hamilton 2008). Moreover it is uncertain to what extent changing human demographics, plans for development, and the varied governance strategies of the Arctic countries and other nations will facilitate the implementation of response strategies for mitigating and adapting to change in the wider system (ACIA 2005; AHDR 2004; Sommerkorn and Hamilton 2008; Larsen et al. 2010).

Figure 11: Reindeer herding in the Russian Arctic. Photo: E. Andreeva.

Detailed Science Questions

ISAC key science questions are broadly conceived. They encompass the issues that need addressing in the context of rapid environmental change in the arctic while at the same time highlighting problems that have been identified as of pressing scientific and societal concern (cf. ACIA 2004; AHDR 2004; BEST 2006; Bowden et al 2006; IPCC 2007; SEARCH 2005; Sommerkorn and Hamilton 2008).

Question 1: How is the Arctic linked to global change?

There is a wide scientific consensus that global climate change is anthropogenically driven (IPCC 2007). However it is not clear to what degree the corresponding changes in the Arctic are driven primarily by processes outside and imported into the Arctic or are due to internal Arctic System processes, such as local and regional feedbacks (ACIA 2004).

External processes include emissions into the atmosphere of increased amounts of greenhouse gases and changes in aerosols that occur primarily in lower latitudes, and that are then transported into the Arctic. Of particular interest are the emissions of greenhouse gases such as methane, and aerosols with a potentially more direct impact in the Arctic, such a black carbon (soot).

Atmospheric circulation experiences natural modes of variability (the North Atlantic Oscillation e.g. Hurrell 1995; the Arctic Oscillation e.g. Thompson and Wallace 2000; the Pacific Decadal Oscillation, Quadrelli and Wallace 2004; and the recently identified Arctic Rapid Change Pattern, Zhang et al. 2008b), that play major roles in the meridional fluxes of heat and moisture into the Arctic, thereby altering temperatures over timescales of days to decades. The effects of these circulation modes often overwhelm the direct radiative effect of slowly increasing greenhouse gas forcing and contribute significantly to the internal variability (e.g. Graversen 2006). Changes in the moisture content of the global atmosphere also have the potential to modify Arctic climate through water vapor transport into the Arctic from middle latitudes, causing changes in cloudiness and in the radiation balance; water vapor is the major greenhouse gas (Graversen and Wang 2009; Vellinga and Wood 2002). Variations in the oceanic transport of heat into the Arctic, through North Atlantic pathways and the Bering Strait, are also likely players in arctic change (Smedsrud et al. 2008).

As Arctic warming is greater than the average global warming, the pole-to-equator temperature differences must change. This should have effects on the global circulation in the atmosphere but we only have a limited understanding of this. The Arctic also has the potential to affect the global climate through feedbacks involving the surface exchanges of greenhouse gases (carbon dioxide and methane), for example through thawing permafrost (Zhuang et al. 2009), impacts on deep ocean convection and thus thermohaline circulation, and changes in the surface heating associated with changes in the coverage of snow and sea ice (Perovich et al. 2007). The potential importance of these feedbacks has long been recognized, but quantitative understanding is lacking because the individual feedback loops are notoriously difficult to identify and evaluate in a complex system with interacting processes.

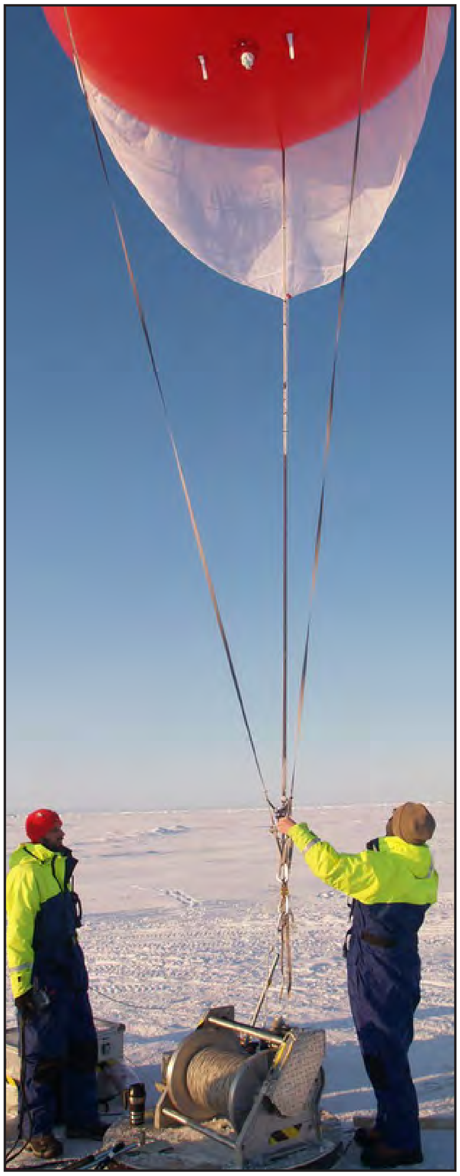

Figure 12: A tethered sounding is made ready during the Arctic Summer Cloud-Ocean Study (ASCOS). Tethered soundings provide a possibility to sample inside clouds in remote areas difficult to reach with research aircraft.

An enhanced melting of the Greenland ice sheet has the potential to both affect both global sea-level rise and global thermohaline circulation. While the summer-melt area has increased over the time of the satellite record (ACIA 2004; Tedesco et al. 2008), it is unclear if recent enhanced outlet-glacier melt is part of a long-term trend. The processes that govern this are poorly understood. Changes in the mass balance of the ice sheet are complicated; there is accelerating ice mass loss but little change in surface mass balance (Sommerkorn and Hamilton 2008; Box et al. 2006). Similarly the melting of smaller ice caps and glaciers will contribute significantly to global sea level rise, with some estimates placing their current contribution to eustatic rise at as much as 60% (Meier et al, 2007). This has serious ramifications for the global community, with social and economic impacts from sea level rise widespread, and varying in cost, well-fare, and land loss (Anthoff et al. 2010).

Detailed Questions Needing Attention

- What determines the modes of natural atmospheric variability and how are they likely to evolve and affect arctic change over the coming decades?
- To what extent is arctic change driven by changes in temperature and humidity?
- To what extent are emissions of the different greenhouse gases and aerosols (e.g. methane and 'black carbon') outside the Arctic affecting arctic change?
- How will amplified Arctic warming affect the large-scale northern hemisphere atmospheric and oceanic circulation?
- How will the spatially aggregated effect of changes in trace gas fluxes from Arctic surfaces alter global concentrations of greenhouse gases?
- What roles do oceanic exchanges of heat and freshwater between the Arctic and lower latitudes play in arctic-global climate linkages?
- How is the Greenland ice-sheet mass balance changing and how are such changes related to the mass flux from outlet glaciers. Is this accelerating?
- What are the consequences of accelerated melting of the Greenland ice-sheet on global sea-level rise and thermohaline circulation?
- What are the consequences of melting of the smaller ice caps and glaciers?

Question 2: How persistent is the presently observed arctic change and is it unique?

The Arctic System demonstrates a larger internal variability than that observed in many other regions on Earth (Manabe and Stoufer 1996; Johannessen et al. 2004; Overland et al. 2008a). This is the signature of a sensitive system, one consequence of which is difficulty detecting trends in the presence of excessive noise. For example, the Arctic experienced a substantial warming towards the end of the first half of the 20th century. Although not fully understood, changes during this period seem to have been regional in character, mostly confined to within the Arctic, and not part of a global signal (Delworth and Knutson 2000; Bengtsson et al. 2004; Overland et al. 2008b). In contrast, the current Arctic temperature amplification is part of a global warming trend and it is pan-Arctic in nature.

The traditional methods for separating secular trends from intrinsic variability, and for comparing trends against long-term observations, have limited value as instrumental records of climate indicators are shorter in the Arctic than elsewhere. This places high priority on establishing quasi-permanent long-term observing systems in the Arctic and at the same time on the production of multi-parameter proxy records of environmental variables including those for paleoclimate (temperature etc.), paleoenvironment, salinity, vegetation, ice cover, ecosystem structure and function, species population dynamics, and use of ecosystem services. For example, recent analysis of paleo shrub-tundra fire regimes in the early Holocene suggests the potential for an analogous period of greater fire activity as shrub expansion and warming continue in the 21st century (Higuera et al. 2008). However, the influence of climate on the fire regime is not straightforward—temperature rise does not explain increased fire frequency during the early Holocene and effective moisture and vegetation composition must also be considered. There is a general need for more emphasis on modeling to determine the climate sensitivity and the signal-to-noise ratios in this system, and to determine the quality of the models.

Detailed Questions Needing Attention

- What conditions govern the presence of the perennial Arctic ice cover and for how long has the perennial ice been present?
- What are the differences in system-scale changes between the current warming, that in the mid 20th century, and that of earlier periods in the Holocene, and in the more distant past (i.e., mid-Pliocene)?
- During the Holocene, did the Arctic experience ecosystem changes similar to those presently observed?
- To what extent were past changes in the human component of the Arctic System coupled to and/or forced by aspects of arctic environmental change and global change?

Question 3: How large is the anthropogenic component of observed arctic change compared to natural variability?

The large changes observed in the Arctic environment over the past decades pose a unique challenge to attribution. The inarguable increases of greenhouse gas concentrations and aerosol loadings, globally as well as in the Arctic, are consistent with a warming which may be amplified locally or regionally by feedbacks within the Arctic System (Serreze and Francis 2006; Serreze et al. 2007). On the other hand high-latitude winds and ocean currents are characterized by substantial natural variability and by poorly understood feedbacks. These winds and ocean currents directly affect the climate of the Arctic. While anthropogenic forcing does contribute to arctic change there are still unanswered questions concerning its relative importance, especially on the regional and local scales. The complex spatial changes of Arctic temperatures during winter imply that answers concerning attribution will vary by location (Serreze and Francis 2006).

Two particular examples highlight the challenges of distinguishing anthropogenic and natural components of observed arctic change. The first is the warming of the early-middle 20th century, 1920s-1940s (Johannessen et al. 2004; Overland et al. 2008b). This warming was likely a consequence of natural variability in the atmospheric and ocean circulations, and had increasing amplitude with northerly latitudes. Yet greenhouse gas and anthropogenic aerosol concentrations had begun to change and the subsequent cooling of the decades from 1940-1970 has been linked to increase in anthropogenic aerosol concentrations. A second example is the recent retreat of summer sea ice in the Arctic. The extreme 2007 minimum has been related to interannual variations of the atmospheric circulation (wind-forcing), and cloudiness (Kay et al. 2008; Overland et al. 2008b; Zhang et al. 2008a). However, the 2008 summer minimum occurred in the absence of unusual wind forcing during the spring and summer. Preconditioning through a warming of the Atlantic layer of the Arctic Ocean, together with a wind-driven thinning of the Arctic's sea ice over the preceding decade, have also been cited as factors in the 2007 retreat (Kay et al. 2008; Schweiger et al. 2008).

To separate anthropogenic influences from internal variability we need to know both how internal variability manifests itself and also how it may change in a changing Arctic. In addition, anthropogenically driven trends need to be quantified. This requires the synthesis of observations, modeling, and reanalysis.

Detailed Questions Needing Attention

- To what extent are abrupt changes in the Arctic climate affected by preconditioning that may have been anthropogenically driven?
- What role, if any, did anthropogenic forcing play in the mid-20th century warming and subsequent cooling of the Arctic?
- How can the effect of natural variability be removed from the patterns of recent change in order to identify the anthropogenic fingerprint?
- Will natural variability, particularly the interannual to multidecadal modes of variability, be affected by anthropogenic forcing in the future?
- What observations are most critical in order to constrain reanalysis efforts for the Arctic?

Question 4: Why are many aspects of arctic change amplified with respect to global conditions?

The high sensitivity of the Arctic System has two aspects; high internal variability and high response to forcing. This is because of several feedback processes that occur on global, regional and local scales. This also includes human feedbacks; actions and reactions to change by society which may enhance arctic change at least on a local and regional scale. Many of the reasonably well understood feedback processes in the Arctic have a positive feedback, i.e. act to enhance change.

On the broader scale, changes in global climate might alter the general circulation in the atmosphere and oceans, thereby changing the meridional transport that in turn alters the import of heat and water vapor into the Arctic; this could cause the Arctic to warm faster (cf. Graversen et al. 2008). On the regional scale, the loss of ice and snow changes the surface albedo also leading to an amplified warming. Loss of sea ice increases the absorption of solar energy to the Arctic Ocean in summer (Perovich et al. 2008); the ice/ocean albedo-feedback (Ikeda et al. 2003, Wang et al. 2005). Clouds remain an uncertainty in Arctic climate.

Change in aerosol emissions may alter the optical properties of the clouds such that they either cool or warm the climate additionally. Increasing acidity of aerosols in winter may enhance their ability to act as freezing nuclei, thereby limiting the amounts of liquid water in clouds in winter. This enhances precipitation, reducing the lifetime of clouds and the water vapor in the atmosphere (Blanchet and Girard 1994). A larger number-concentration of aerosols in summer could act to make the clouds brighter; the "indirect effect of aerosols" (Covert et al 1996; Curry et al. 1996; Heintzenberg et al. 2006).

Our understanding of the rate and nature of Arctic ecosystem and societal changes is increasing although feedbacks to environment from society are articulated only in very general terms. The extent to which human activities in the Arctic accelerate change is unclear. For example in the Canadian High Arctic human influence on the terrestrial system has been limited as compared to in more southern latitudes. Nevertheless human activities, beginning in the mid-Holocene, have contributed to the development of spatially constrained ecosystems in locations of human settlement (Forbes 1996). These areas are comparatively highly fertilized serving as locations of increased biological productivity; to what extent might they function as places where new and invasive species can take hold? As human activity in the Arctic increases due to changing local and global political and economic processes, we can expect many as yet unidentified feedbacks that may amplify changes in both terrestrial and marine settings.

Detailed Questions Needing Attention

- How are conditions (temperature and its' spatial structure, cloud and surface albedo, cloudiness and cloud properties etc.) changing across the central Arctic Ocean and how do these changes relate to global feedbacks?
- What feedback mechanisms are most important for amplification and are they specific to the Arctic System?
- What controls changes in the vertical structure of the Arctic atmosphere and ocean?
- What ecological changes are accelerating?
- Are ecological vulnerabilities amplified with respect to global conditions?
- Are human vulnerabilities amplified with respect to global conditions?

Question 5: How well can arctic change be projected and what is needed to improve projections?

The combined effects of high sensitivity to change with many poorly understood feedback processes limits the ability to predict the Arctic System as compared to other regions (Chapman and Walsh 2007; Walsh et al. 2002). In practical terms, this issue also reflects back on the quality and the resolution of the models that are used to generate projections for the Arctic. For example, to the extent that Arctic-specific feedbacks are important and not properly included in global climate models, the realism of projections for the Arctic may be called into question. This problem concerns parts of the physical climate system such as the descriptions of clouds and aerosols, permafrost, and sea-ice dynamics. If the models are not capable of describing the current climate, even the most ambitious ensemble scenario calculations may be questionable.

Coupled modeling is vital in order to explore the interrelationships between different parts of the system, and to benefit from the inclusion of those parts of the system that may enhance the predictability. Special attention thus needs to be given to the coupling between different scales and spheres and to avoid artificial constraints in the coupling.

Current state-of-the-art global climate models do not have the resolution to provide useful information to policy makers and effects on ecological or societal system are therefore often modeled off-line. There needs to be a coordinated effort to downscale information from the global models, but also to include processes from the biosphere and the human domain directly into the projections, from both regional and global modeling. System-change projections rather than climate-change projections are needed. Such models will be valuable tools for management and mitigation of future changes and should include spatially explicit projections of change.

Detailed Questions Needing Attention

- How robust are Arctic projections from global models?
- How well are drivers of arctic change known and how is the forcing evolving?
- How well do we understand the dynamics of the whole system and especially the links among the different subsystems?
- How well can we downscale global projections to the Arctic System and how should interdependencies among the different components of a coupled system be incorporated into downscaling?
- Is predictability achievable on seasonal and interannual scales and for how far into the future?
- How can spatial and temporal scales be integrated to enable projections of ecosystems productivity and sustainability?

Question 6: What are the adaptive capacities and resilience of arctic ecological systems?

Arctic plants, animals, and ecosystems are well-adapted to the extremes of the current and recent past arctic environment and are notably resilient to variation within the ranges of the climate and disturbance regimes in which they evolved. Arctic ecosystems are also heterogeneous in their composition and their distribution, including a diverse array of organisms of different “functional types” that represent a broad potential range of responses to new climates and disturbance regimes. What is unknown, however, is how arctic ecosystems will respond to novel changes in climate and disturbance regimes, changes that are outside the range of variability they have experienced in the past.

Predicting the adaptive capacities and resilience of arctic ecological systems in future climates and disturbance regimes (catastrophic, episodic, and cumulative) will require long-term observations and, experimental manipulations. It also requires understanding of how these systems responded to similar changes in the past. Key issues include improved understanding of ongoing and anticipated changes in relation to rate of change in climate, sustainability of initial responses, and changes in timing and synchrony of interacting processes.

Detailed Questions Needing Attention

- How will changes in composition and physical structure of arctic ecosystems feed back on the drivers of climate change?
- Can changes in arctic plant and animal populations and ecosystem processes keep up with the rate of change in climate?
- Which components of arctic ecosystems will change most slowly or rapidly and how will lags in response affect the overall trajectory of change?
- What components of arctic ecosystems are more or less well-buffered against change?
- How will changes in the seasonality and synchrony of ecosystem processes and animal movements affect the response of arctic ecosystems to climate change?
- How will changes in composition and structure of arctic vegetation feed back on changes in surface energy balance and soil processes that maintain permafrost and drive carbon and nutrient turnover?
- How will large-area changes in disturbance regime (e.g., fires, thermokarst, ocean acidification, etc.) interact with direct effects of changes in climate factors like temperature and precipitation to determine overall change in the arctic ecosystems. land and seascapes, and biota?

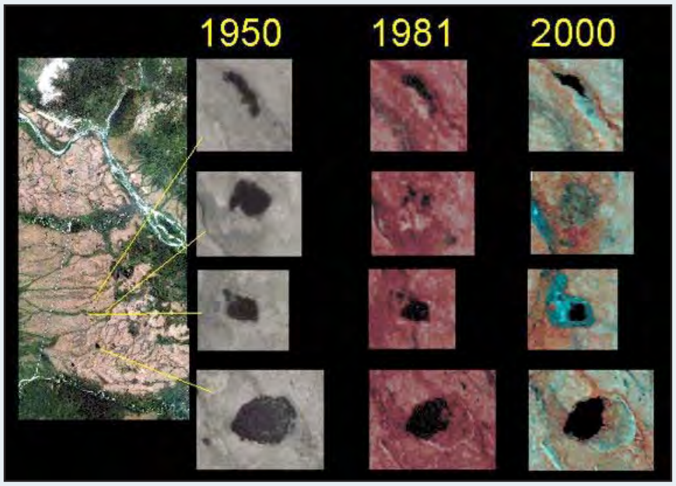

Figure 13: Tundra ponds near Council, Alaska (64°51_N, 163°42_W) that have decreased in surface area over the last 50 years (from Hinzman et al. 2005), probably due to degradation of shallow permafrost (Yoshikawa and Hinzman 2003).

Question 7: To what extent are social and ecological systems able to adapt to the effects of arctic change?

The principal cause of ongoing climate change as manifest within the Arctic is believed to be the historically recent increase in greenhouse gases within the global atmosphere coupled with direct and indirect feedbacks derived from this buildup. The extent to which such a broad scale driver can be mitigated is beyond the scope of ISAC. Some scientists argue that by reducing emissions of pollutants with a shorter atmospheric residence time, e.g. 'black carbon' or soot, it would be possible to achieve some reduction of radiative forcing targeted on the Arctic. However, it is not certain that the benefits from such a geopolitically complex and costly initiative will be sufficient to manage the shorter-term aspects of change affecting arctic ecosystems.

A more practical approach may be to assess potential climate change adaptation strategies at spatial and temporal scales (e.g. local to regional) subject to management via the existing political institutions (community, state, federal, international etc.). These vary considerably within and between nations (AHDR 2004). In other words, effective adaptation strategies developed in North America may not be transferable to Europe, just as European approaches might not work for neighboring Russia. By the same token, even in regions already experiencing rapid climate change, local populations may be faced with other factors, such as industrial development, that present greater day-to-day challenges in terms of mitigation. Key issues include improved understanding of the pace and extent of recent ecological changes, of the linkages across trophic levels in terrestrial, freshwater and marine ecosystems, of the implications for the human communities dependent upon them, and the identification and evaluation of potential adaptation strategies to best manage these.

Detailed Questions Needing Attention

- Can we develop integrated approaches for adaptation that encompass linked social-ecological systems and functions across scales?
- If we cannot develop integrated approaches for adaptation is it appropriate to target ecosystem components and services that are deemed less well buffered against change?
- How can we transcend the institutional barriers to developing and implementing more comprehensive adaptation governance in cases where the threats are reasonably recognized or anticipated?
- Are there viable models of flexible resource management approaches such as adaptive co-management for involving northern residents in decision-making when renewable resources are at risk?
- To what extent are mitigation regimes transferable across political and cultural borders?

Question 8: How does environmental change in the Arctic affect the resilience, adaptive capacity, and ultimately, viability of human communities?

Arctic environmental change encompasses multiple drivers, including rapid and long-term shifts in climate as well as land use. Resilience and adaptive capacity are expressed at several levels from individuals to ecosystems and humans are an integral part of the system. At the same time, there is a large degree of geographic variation in anthropogenic drivers of change, as well as the susceptibility of Arctic ecological systems (Forbes et al. 2004). An optimal strategy would seek to build resilience and adaptive capacity across scales from local to regional by enhancing adaptive governance of linked social-ecological systems, rather than focusing on select ecosystem components in isolation from one another (cf. Berkes and Folke 2000; Forbes et al. 2009). Resource relationships vary widely from urban centers dependent on large outside subsidies (energy, food, raw materials) to smaller and relatively self-sufficient communities relying greatly on local resources. This degree of contrast across the inhabited portions of the northern high latitudes translates into a significant degree of heterogeneity in terms of vulnerability to arctic change (Forbes et al. 2004). In the worst-case scenarios, some communities are already faced with abandonment and their viability is therefore in question.

For most communities, serious threats to their viability presently seem theoretical, providing them with some time to explore the possible pathways for strengthening resilience and adaptive capacity. Key issues and challenges include drawing the appropriate lessons from the diverse array of ongoing examples of Arctic Change across the circumpolar North (i.e., Lynch and Brunner 2007; Forbes et al. 2009), as well as cases from the historical and archaeological records in which communities have either survived or collapsed in the face of past changes.

Detailed Questions Needing Attention

- To what extent are arctic communities exposed and sensitive to anticipated changes in the composition and structure of arctic terrestrial, marine and freshwater ecosystems?
- To what extent are arctic communities exposed and sensitive to anticipated changes in the physical components of the system that may impact infrastructure, economies, and well-fare?
- To what extent are communities, institutions, industries, and other stakeholders that are located outside the Arctic exposed and sensitive to anticipated changes in the Arctic System?
- What are the relevant scales of reference for historical or palaeoecological cases of successful adaptation to past arctic change?
- As new models anticipate even more rapid environmental change, are contemporary governance structures adequate for responding to change?

Figure 14: Thermokarst depression on the edge of the Geophysical Institute University of Alaska Fairbanks parking lot (Fairbanks, Alaska). Surface disturbance related to the parking lot construction triggered permafrost degradation and ground ice melting. From: http://www.arctic.noaa.gov/essay_romanovsky.html Photo: V. Romanovsky

Question 9: How can new insight into Arctic Change and its impacts be translated into solutions for increased adaptatation, management, and mitigation?

Arctic regions and communities differ dramatically in terms of whether or not they see Arctic Change as a threat to their own long-term viability. The degree to which future adaptation and mitigation are deemed necessary is partly a function of framing and agenda-setting on the part of scientists and policy makers, and the related questions of how local residents do or do not perceive elements of change affecting community-level vulnerability. Overall, arctic indigenous peoples, as well as many long-term non-indigenous residents, have a long history of adapting to shifting conditions (environmental, social, economic), and recognize their own abilities in this regard (Forbes et al. 2009). Understanding and responding to arctic change must therefore include the exchange of knowledge and experience relevant to adaptation, adaptive capacity, and resilience, rather than a set of inquiries and activities based purely on conventional modes of developing scientific knowledge (Forbes and Stammler 2009).

Arctic societies have adapted to strong climatic and resource-driven pressures over millennia and any effort must strive to build on the lessons available from historical and palaeoecological data sources. In the past shifting settlement strategies was a primary adaptive mechanism for dealing with change on the local and regional scale (cf. Damas 1984). However, over the last century, settlement options in most regions of the Arctic have become increasingly fixed and movements on land and sea therefore restricted; this is exacerbated in the face of unprecedented development and globalization (ACIA 2005; AHDR 2004). Thus adaptation to rapid change is becoming ever more challenging. In some cases, the impediments to adaptation to change are more institutional than societal or ecological; removing these impediments requires the melding of diverse lines of inquiry as well as action. Key issues include anticipating trends and potential non-linear feedbacks that could threaten community viability and enhancing resilience and adaptive capacity to handle surprises and absorb shocks.

Detailed Questions Needing Attention

- Can arctic observing networks be successfully exploited to incorporate relevant input from communities experiencing arctic change and to address stakeholder needs for information?
- What information about arctic change and related impacts is needed to enhance adaptation, adaptive capacity and resilience?
- Can relevant research findings be efficiently translated to human communities to support adaptation to change?
- Can relevant research findings be translated beyond particular cases to facilitate and enhance adaptation within the Arctic and beyond?
- What effective science-based management strategies are needed to maintain a sustainable and diverse Arctic?

Figure 15: Community of Vardø, coast of the Barents Sea, Finmark, Norway. Photo source: www.barentsinfo.org

Figure 16: Houses at the retreated coast of the Kara Sea. Photo: I. Streletskaya.

Meeting ISAC Objectives

The ISAC science program is structured around three broad activities – observing, understanding and responding to Arctic Change. The Arctic System must be well-observed across time and space and all components in order understand the nature, scope and evolution of change. Understanding how the system functions and projecting future changes requires models using the data that flows from these observations. Moving beyond description to understanding of past, present and future change is critical for responding to change. This requires an integrated program whereby observing, understanding and responding components are developed in concert around a set of clear objectives which include:

- Developing an integrated Arctic observing system covering all domains including the anthroposphere, the atmosphere, the biosphere, the cryosphere, and the hydrosphere. This is based on existing and new long-term observing sites as well as new observing methods. (observing)
- Quantifying the anthropogenically driven component arctic change within the context of natural variability. (observing)
- Understanding the causes of pan-Arctic changes, including changes in the human component, in the context of global change. (understanding)
- Improving models to project future changes in the Arctic System, including impact assessment models for responding to change. (understanding)
- Exploring options for adaptation to and mitigation of arctic change and suggesting ways that will lead to a path of sustainable use and development. (responding)
- Disseminating data and results from ISAC activities to the scientific community, stakeholders and the general public. (cross-cuts observing, understanding, responding)

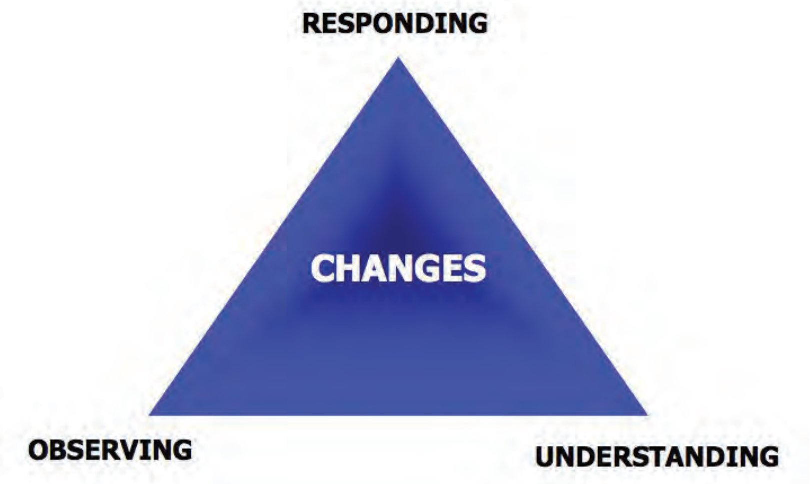

Figure 17: ISAC components.

ISAC Components

Observing, Understanding, and Responding to Arctic Change

Arctic change is a matter of urgency. As laid out in the previous chapters, the ISAC science program requires strong observing, understanding and responding to change components in order to meet its objectives. The speed of change and the rapid evolution of our knowledge of how changes are materialized and how they interact require a flexible approach. Flexibility will ensure continued acquisition of the necessary scientific data and will ensure that these data are effectively translated into information that is useful for meeting the scientific and societal challenges of arctic change. The individual components of ISAC are described below along with ways for using the results from different activities within ISAC to inform one another.

Figure 18: Wave-cut cliff near the Varandei oil terminal, Perchora Sea (Ogorodov 2005).

Pan-Arctic Observing System

Critical to achieving ISAC objectives is the documentation of arctic change at multiple spatial and temporal scales, and across all system components. This is too large a task for any one nation and therefore requires a multinational commitment to long-term, multidisciplinary, system-scale observing programs to record past, present, and future changes. These observing programs must be sustained to establish meaningful time series, and they must be flexible enough to respond to changing scientific requirements, new insights and shifting theoretical, methodological, and political frameworks. They must be integrated into an international, pan-Arctic Observing System that will build upon and grow from efforts initiated prior to and in the context of the International Polar Year (NRC 2006). Examples of such initiatives include the recent European Union Sixth Framework Integrative Project "Developing Arctic Modeling and Observing Capabilities for Long-Term Environmental Studies" (DAMOCLES), the U.S. interagency Study of Environmental Arctic Change (SEARCH) Program. Other related arctic observing efforts are those of the Arctic Net Networks of Centres of Excellence Canada, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Russian-American Long-Term Census of the Arctic (RUSALCA), and some of the activities of the International Union for Circumpolar Health (IUCH) to note just a few. Such existing platforms and programs form a solid foundation for collection of the observations required for ISAC. Over the long-term, the design of the Arctic Observing Systems should ultimately draw on the data generated through it, as well as from modeling activities and the needs for responding to change.

New efforts to enhance already existing observation activities and infrastructure that form the basis for the Arctic Observing System must be relevant to addressing ISAC questions about system-level arctic change. Such enhancements should focus on current gaps. There is a particular need for:

- better spatial coverage of the terrestrial sphere,
- improved efforts on the subarctic seasonal ice zones,
- more information on the marine biological system, including higher trophic levels,
- hypothesis targeted monitoring of biodiversity and ecosystem resilience
- focused efforts on paleodata collection,
- data collection for studies of the human dynamics relevant to arctic environmental change.

International collaboration in synthesis activities indicates that there are also gaps in observations of the atmospheric boundary-layer characteristics (SEARCH 2008), and of the broader features of the vertical structure of the atmosphere. Other observation needs with immediate global relevance include increased information on ice sheets, freshwater input to the Arctic

Ocean, sea level rise (Flöser et al. 2007, SEARCH 2008), greenhouse gas fluxes from permafrost zones (Zhuang et al. 2009), acidic inputs into arctic and subarctic coastal ecosystems (Salisbury et al. 2008), and observation of changes in marine and terrestrial biodioversity (CAFF 2010).

Effective use of arctic change observations requires an integrated approach that allows for easy merging of the data streams that flow from the different elements of the observing system. Such integration must be focused around central science questions and address past and current changes in all components of the Arctic System. To capture the signals of change, observations are needed in all seasons (cf. BEST 2004). Similarly observing efforts must consider societal needs – in the Arctic these include, among others, the need for information on snow and ice cover, ecosystem services, ocean conditions, and information for the maintenance and development of infrastructure and observations needed for weather forecasting. Thus observation activities must include data that is of relevance to people's lives and to decision-making and policy.

A special focus of the ISAC observing efforts should be directed towards observing-system design (cf. Dickson 2008, 2009). There is presently no readily accessible, fundamental theoretical framework for such design. As such, ISAC should utilize available tools such as Observing System Simulation Experiments (OSSESs) to move towards an objective and scientifically grounded procedure for optimization of the Arctic Observing System. This system must be responsive to the needs of the understanding and responding to change components of ISAC as well as to stakeholders and society at large.

The Arctic Observing System must also be integrated with global observing systems such as the Global Earth Observing System of Systems (GEOSS). ISAC is designed with the right scope and connections among many arctic research programs to facilitate this integration into the global context.

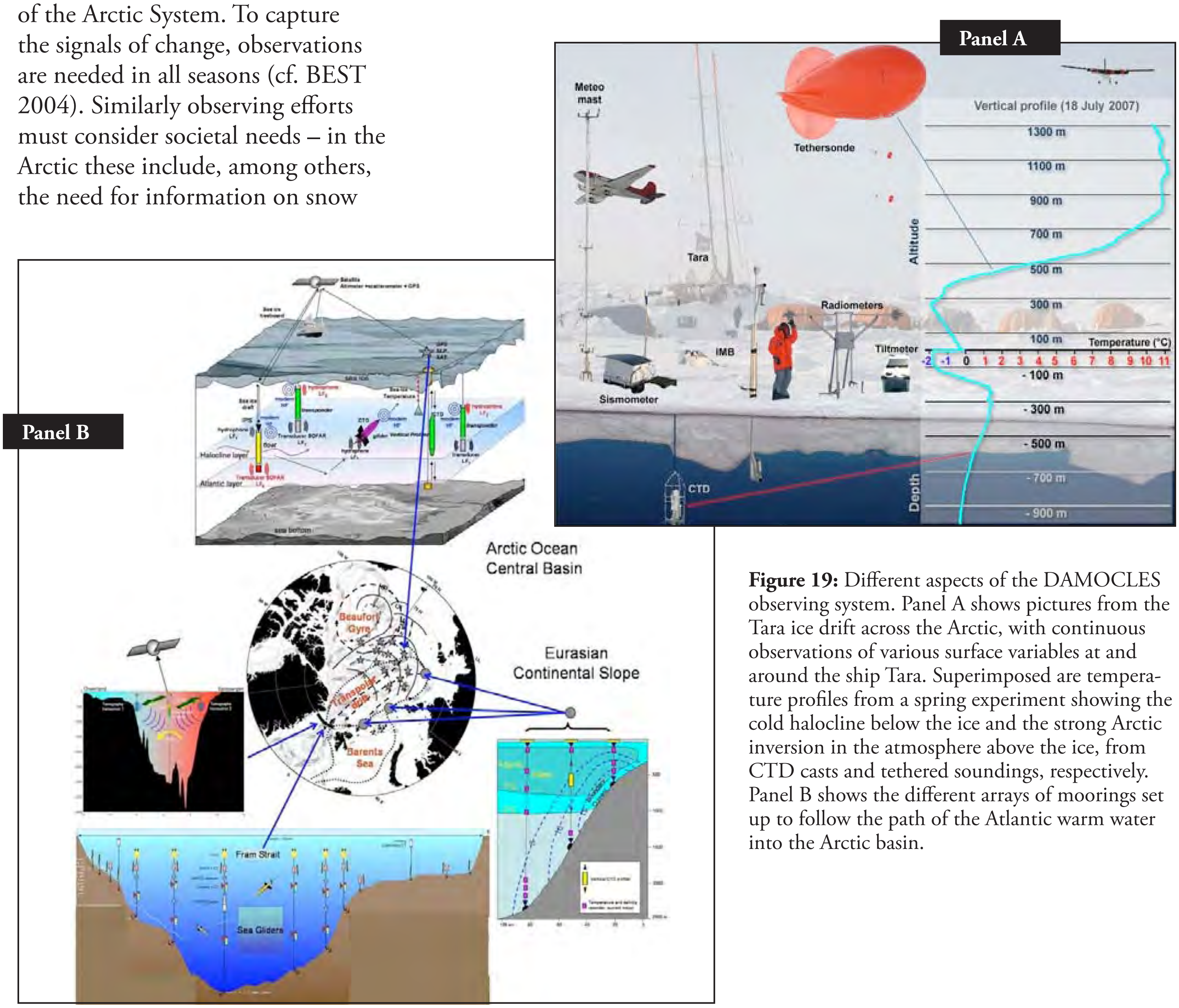

Figure 19: Different aspects of the DAMOCLES observing system. Panel A shows pictures from the Tara ice drift across the Arctic, with continuous observations of various surface variables at and around the ship Tara. Superimposed are temperature profiles from a spring experiment showing the cold halocline below the ice and the strong Arctic inversion in the atmosphere above the ice, from CTD casts and tethered soundings, respectively. Panel B shows the different arrays of moorings set up to follow the path of the Atlantic warm water into the Arctic basin.

Understanding Change: Synthesis and Modeling

Understanding change is a key component of ISAC; without it projections of future change are not possible. Such projections underpin any response option and thus any structured design of solutions to problems arising from arctic change. The limits of our understanding *de facto* determine our capability to utilize science for addressing societal issues stemming from or linked to rapid arctic change.

There is a need to understand the Arctic system as both a "functioning unit, and as a set of interacting parts" (Ritchey 1991). Such understanding has to be developed through synthesis of results from the observing system and from process studies, as well as from studies of system dynamics and modeling activities on several levels of sophistication, reaching from conceptual models to high-resolution coupled numerical models. Naturally, the modeling activities will be informed by data streams from the observing system—some in a real-time mode—and they will also be informed by synthesis results. These activities must incorporate multiple and diverse datasets drawn from the human component of the Arctic System, and where relevant, the global system (Huntington et al. 2007). Moving beyond coordinated observation efforts to integrated synthesis (cf. Fisher et al. 2000; McGuire et al. 2002), and a new generation of collaborative modeling activities (Allen and Ingram 2002; Rastetter et al. 2003), requires syntheses activities to acknowledge and account for the different processes that operate within the Arctic System, whether these are biogeochemical, physical, or social. Synthesis activities within ISAC are aiming to produce results that take into account the complexity of the system approach in a fashion that is suitable for planning effective response to change (cf. Fisher et al. 2000).

Projecting arctic change relies on model simulations. These models are in turn informed by data streams from the observing systems. They have to be tested with respect to their capability to reproduce observed past and present patterns. They also have to be designed in a fashion that allows consideration of impacts at local, regional and pan-Arctic scales (SEARCH 2008). Among others, the group of models utilized for projections can include community integrated systems models (synthesizing knowledge from disparate domains), and models that can provide a unified and coherent framework elaborating on causal relationships and possible system responses (Nicolson et al. 2002). Models must be improved and further developed to consider not just the physical components of the Arctic System but also the ecosystems and the human component and to integrate among these. Model output needs to be made useable and relevant to local and regional responding needs. There must be effort placed on upscaling current data through reanalysis activities and downscaling pan-Arctic models to the regional and local level. People need regional and local scale information on projected environmental and ecosystem changes among many others. Thus projections should be targeted at specific parameters (e.g., ice extent, marine mammal reproductive viability), in regions within the pan-Arctic (e.g., Northern Sea Route/Northeast Passage), and at the probability of particular responses within the system (e.g., extreme events such as catastrophic fires, human relocations, shifting biodiversity, and changes in ocean circulation (cf. SEARCH 2008).

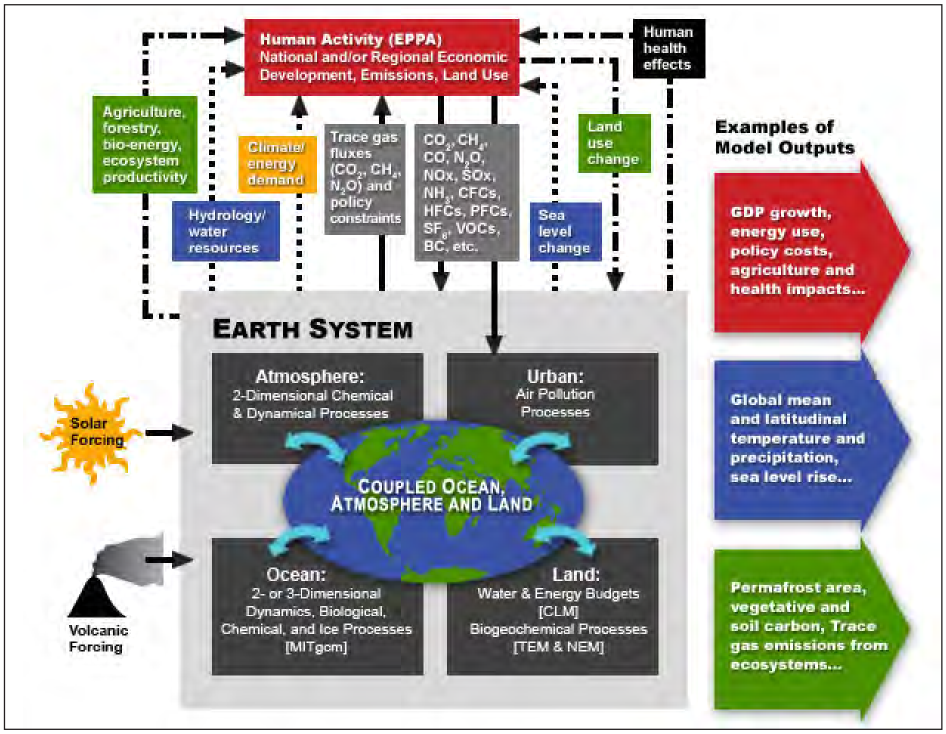

Figure 20: Schematic of earth system model. Dotted links await implementation. From http://globalchange.mit.edu/igsm/#igsm.

Responding to Change

Responding to rapid environmental change is particularly challenging in the Arctic because of the fragile nature of the terrestrial and marine ecosystems. There is increasing convergence of rapid environmental change, and socio-economic and political change across the pan-Arctic region, yet people still connect to the Arctic System through the ecosystems and their services - whether through access to country food (Loring et al. 2008) and water resources (White et al., 2007), or via mineral extraction possibilities, for example. There is real need to understand how ecosystems might be restructured and how they might function in the near and distant future. Ecosystem management strategies that consider potential alternatives, the recent and remote past, and the present, and that are responsive to ongoing rapid system changes are needed. The resilience and vulnerability of human communities, and of individuals, are dependent upon multiple variables – many of which are tied to ecosystem services and environmental condi-

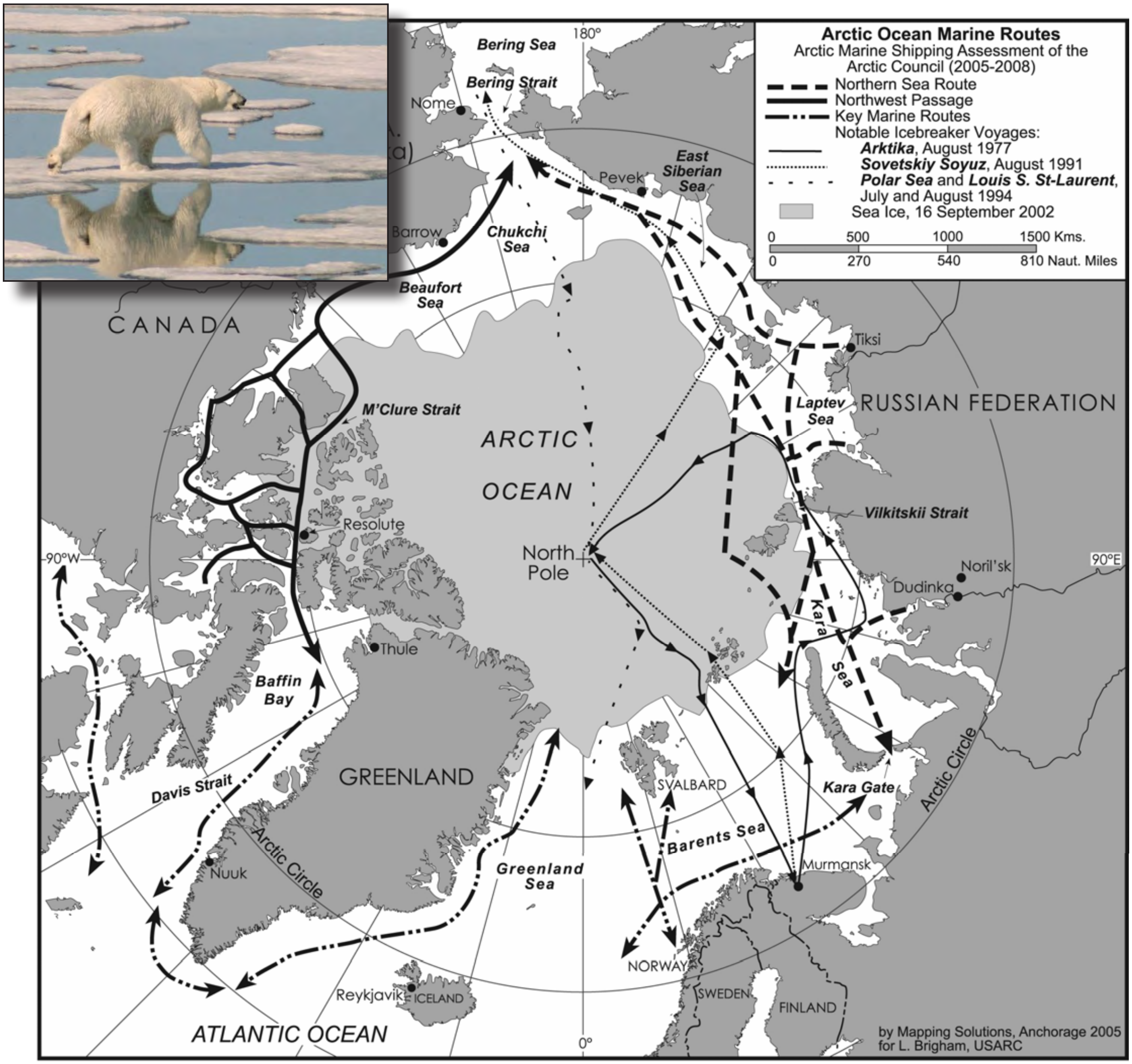

Figure 21a: Responding to change may require targeting specific parameters and regions. For example, what are the projected impacts on other arctic predators as a result of declines in polar bears populations and how can these projections be used in management? Photo: S. Romaine. **Figure 21b:** from Brigham and Ellis 2004, shows the major Arctic marine routes. What are plausible scenarios for ship-ice interactions over the next century given improved projections of inter-annual and regional variability in ice conditions and of decreasing summer sea-ice extent?

tions. Socio-political, economic, governance and health factors also condition response to change and influence capacity to absorb and use scientific information for adaptation, management, and mitigation purposes.

Among other things, people respond to changed spatial, temporal distribution of resources and changed access to the resources. To do so effectively they must develop strategies that are informed by science (e.g., projections of future environmental conditions in individual regions of the Arctic), and by society. An overarching challenge for the science community is better understanding of the human and policy decisions that need to be made, as well as improved understanding of how those decisions are made and what information is needed to make them. Arctic stakeholder groups are diverse, ranging from resident rural small-scale farmers, fishers and hunters, to urban dwellers, industry and government, non-governmental organizations and to the general public globally. Each group has unique and diverse needs and wants and these must be factored into the development of solutions for coping with change. Responding to arctic environmental change must include stakeholder participation in building research activities that lead to useful observation and predictive capabilities (Krupnick and Jolly 2002; AHDR 2004; ACIA 2004; SEARCH 2005; Forbes et al. 2009).

Responding to arctic change encompasses assessment of the effectiveness of institutional responses to change, and developing scientific guidance for the implementation of integrated assessments (cf. MA 2005). It also includes the development of co-management and risk mitigation strategies, hazard assessments, and planning initiatives (cf. Flöser et al. 2007; Kellert et al. 2000).

There are needs to access relevant data in real-time, in formats that are technologically, linguistically, and culturally accessible. The utility of such data must be continually assessed for relevance to place-based interpretation and use, even as global social and economic systems influence arctic change and are linked to arctic ecosystem services. There is also great need for data that is relevant and useful to stakeholders outside of the Arctic. ISAC science considers solving real-world problems associated with environmental change in the Arctic as the driver behind the need for international, interdisciplinary and integrated system science. Translation and dissemination of good scientific information to a wide audience is therefore critical.

The three components of ISAC proceed in concert. There are specific needs that must be met for responding to change and these needs can, in conjunction with needs for understanding, guide observational priorities (SEARCH 2005). ISAC will find ways to enable people to make informed response decisions while at the same time enable assessment of how decision-making affects and drives change more broadly. Scientific observations need to be useful for advancing scientific understanding but also for adaptation and management of the changing arctic.

Figure 22: Boat launch sign. In Alaska, important fishing and hunting areas are often managed under state or federal jurisdiction. This sign stands at the Minto Village boat launch, which is within the boundaries of a state game refuge. During prime hunting and fishing seasons, boat launches such as this overflow with tourist activity, and local residents face much competition for, and witness much waste of, the wild food resources on which they depend. Photo: P. Loring

ISAC Implementation

The ISAC program and science questions spring from over a decade of consensus building among the arctic research community, arctic residents, and other stakeholders. There are now identified a series of critical scientific issues necessary to investigate for a better understanding of arctic environmental change and for addressing related societal needs (see for example ACIA 2004; AHDR 2004; Allison et al. 2007, 2009; Dickson 2008, 2009; Bowden et al, 2005; Flöser et al. 2007; Morison et al. 2001; SEARCH 2005, 2008; and Rapley et al., 2004 among many others). ISAC will be successful in advancing research and application of research findings to real world problems through diverse partnerships that enable implementation. The ISAC implementation strategy defines ways in which ISAC can guide observing, understanding and responding to change activities that are best suited for addressing ISAC-relevant questions and that build on the successes of the IPY and prior initiatives. ISAC implementation is iterative, reflecting the evolution of knowledge and the changing needs of the international arctic research community and of stakeholder communities.

International collaborations in arctic research are not new, and they have increased in recent years, especially as a result of the IPY (Allison et al., 2009). They must, however, continue to grow; scientific questions are increasingly more sophisticated and system-oriented, and the societal relevance of scientific inquiry in the Arctic is evermore pressing. ISAC is an IPY legacy that will provide a venue for international co-ordination of activities that will guide arctic observation efforts and that will contribute to an integrated understanding of arctic change and projections for future changes (cf. Dickson 2008, 2009). The intent of ISAC is not to duplicate ongoing and developing arctic research activities and programs but rather to inspire programs and foster a community of arctic researchers and stakeholders that are united in efforts to remove obstacles to observation, understanding and responding to arctic change. As such, ISAC will provide a framework for enabling national arctic change research communities to achieve their goals and continue to expand their collaborations at the international level to the benefit of society. International support is critical for success.

There are a number of arctic environmental change programs and projects that are committed to ISAC or have stated interest in ISAC as structure for linking and coordinating small and large programs and working towards common goals. Many, both large and small, have components that align with the ISAC Science Plan and the general objectives of ISAC. Some existing programs are open ended while others have a sunset date. ISAC will be the international entity that works to keep arctic change research programs on a growth trajectory and to ensure that programs that are part of ISAC, and that have a sunset clause, are replaced by new initiatives. Collaboration with the International Arctic Science Committee (IASC) and its working groups should facilitate communication of scientific information and needs to appropriate national and international agencies and entities.

Pan-Arctic Observing of Change

ISAC will be a venue for international collaboration in the evaluation of the Arctic Observing System and for making recommendations for optimization and addressing gaps in observing as related to ISAC goals. ISAC will ensure that observing systems will continue to evolve with respect to tracking ongoing changes in the Arctic including improving integration of cross-disciplinary and international observing efforts. Observing arctic change for the purposes of understanding and real-world problem solving requires the development of a system that serves both science and society. ISAC will facilitate co-ordination among existing and emerging observation programs to improve international exchange of information and joint planning and co-ordination of observation programs. A focus on relevant scientific questions and societal needs can guide system design and implementation. To fully develop the Arctic Observing System will require increased collaboration in efforts to expand instrumentation, improve methods for observation, and further investment in logistics.

Near-Term Implementation Activities

ISAC can play a role in providing scientific guidance to the Sustaining Arctic Observing Networks (SAON) process and related activities (SAON IG 2009). Collaboration can be accomplished by offering the scientific rationale for arctic observations and the continued update of the design of an Arctic Observing System informed by the results from arctic change observing and understanding studies as well as responding to change needs. In the build-up phase to the utilization of an Arctic Observing System sustained through SAON efforts, ISAC can link existing arctic environmental change observations through a Memorandum of Understanding among the programs that control the presently deployed observing systems. In addition, to facilitate optimization of the Arctic Observing system ISAC will partner with the relevant groups to initiate a series of Observing System Simulation Experiments (OSSEs). Partnerships with those working to collect observational data on arctic biodiversity and on ecosystem parameters more broadly, as well as those focused on physical system observations and stakeholders who need information from the observing system are key.

Implementation Over the Lonsger-Term

ISAC will co-sponsor a series of activities designed to provide continued direction for future development of the Arctic Observing System. These will include opportunities for international collaboration on the identification of what new technologies are needed, and on methods for their development and deployment. ISAC will develop connections with global observation programs including the Global Earth Observation System of Systems (GEOSS) to ensure that arctic observation data and products are shared for the widest possible benefit. Working with the appropriate entities, ISAC can facilitate information sharing efforts at data compatibility, and timely access to data.

Understanding Change in the Arctic System

Understanding the Arctic System entails a wide variety of activities, ranging from analysis of process studies, analysis of pan-Arctic observations including paleodata, to model development and reanalysis of the whole system or parts thereof using existing data and models jointly. The development of particular understanding tools and activities may also be directed by societal needs. Developing and expanding the observational efforts without building a strong understanding component is ineffective; understanding rests on the observations. However, understanding also feeds back to the observations in the sense that improving understanding highlights gaps in the observational activities. Ultimately improved understanding is what makes informed response, management and mitigation strategies possible.

Near-Term Implementation Activities

ISAC will participate in the planning activities of the Understanding Change component of the SEARCH program and in synthetic activities that follow the SEARCH for DAMOCLES (S4D) program, including the recent Sea Ice Outlook initiative (SEARCH 2008), and the Sea Ice Outlook for Walrus (SEARCH 2010). By building on such collaborative science exercises, ISAC will provide a venue for the rapid interpretation and syntheses of new data.

Implementation Over the Longer-Term

Over the longer-term ISAC understanding activities will be directed towards resolving mismatch in observed and predicted patterns of change. This will require providing a venue for discussions of data compatibility, of scaling issues in modeling, of scenarios for changes in ecosystems and human systems, and for capacity building. Expansion of modeling efforts is critical. The general lack of coordination in this area is a barrier to progress on responding to change.

ISAC will establish connections to programs with a global perspective on system science and which function to integrate regional information into global databases and into earth systems models (see for example the International Geobiosphere Program) for the purposes of applying science to real world problems.

Responding to Change

In order to respond to change in an effective matter there is a need to prioritize what science is of immediate societal relevance. To the extent that it is possible it is also necessary to obtain more precise information as to what will be needed in the near and distant future. Current and planned observing and understanding activities should be evaluated with respect to meeting societal needs as well as scientific needs. As the arctic scientific community is increasingly engaged in conveying information to the public, to policy makers, and to resource managers ISAC will serve as a venue for the discussion of best practices for communicating scientific information including models results, and predictions, (with error ranges), in aid of decision-making. Effective communication methods and communication streams are necessary so that it is clear what changes may be mitigated, what changes may not, where there are vulnerabilities in the system and how best to facilitate adaptation, management, and mitigation, when it is an option.

Near-Term Implementation Activities

Through key workshops, building in part on the human dimensions of arctic environmental change research successes of the IPY, a framework for the Responding to Change component ISAC will be developed. In addition to the ISAC environmental science community, development of the responding to change component will require the participation of arctic residents and other stakeholder groups. It is critical to engage those with expertise in science/policy interaction, those with expertise in solving environmental change-related ecological and societal problems, and those with expertise in conveying scientific information to a broad public. Widening the community of scholars working on arctic change research is vital. In framing the Responding to Change component of ISAC both the Arctic and the globe should be considered. Connections to programs with a similar mandate such as the International Human Dimensions Program on Global Environmental Change (IHDP) and the United Nations Environmental Program (UNEP) need to be established.

Implementation Over the Longer-Term

ISAC is committed to facilitating activities that will move solutions forward at national and international scales. This will require the development of cooperative mechanisms for sharing information and providing data to relevant entities dealing with mitigation, remediation, problem solving and policy. At the international level such entities include intergovernmental organizations like the Arctic Council and its working groups (CAFF, Sustainable Development), and the Indigenous Peoples Secretariat, non-governmental organizations such as the WWF International and the International Union for the Conservation of Nature (IUCN), as well as policy bodies like the Marine Mammal Commission, and the International Whaling Commission to cite just a few examples.

Other Implementation Activities

Implementation in the near-tem requires open discussion with existing arctic research programs and projects to establish overall fit with the ISAC science objectives and interest in and commitment to the vision of an open-ended collaborative international arctic system science program that is ultimately solution oriented. In practical terms the extent of present pan-Arctic coverage of observing, understanding and responding to change activities needs to be established (cf. Dickson 2008, 2009). Synthesis of existing inventories, such as those collected during the International Conference on Arctic Research Planning (ICARP) and SAON processes and during the IPY, among others, is necessary in building connections among programs that may contribute to ISAC.

Over the longer-term ISAC will assist with coordination among committed national programs to improve international exchange of information relevant for joint planning of research programs. Similarly ISAC can facilitate integration of data derived from component-specific research into system and regional models to further understanding of arctic system change. This will involve the development of data coordination efforts so that access to data and model outputs can be achieved within a unified environment to better guide future observations and to facilitate development of response strategies.

ISAC can contribute to the establishment of an international clearinghouse for information related to ongoing and planned activities addressing arctic environmental change, including assessments. ISAC science will build upon the impact assessments and outcomes presented in the AHDR (2004) and the ACIA (2005) and others described by AMAP (cf. 2006), the IPCC (2007), the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) project of the Arctic Council, the Arctic Biodiversity Assessment and the Census of Marine Life among many, to provide data that will improve future assessments of the Arctic and the planet.

In the not too distant future, ISAC should be positioned to quickly organize the research community so that it may respond to rapid and unexpected changes in the Arctic. This will require the capacity to enable short-notice efforts to rapidly synthesize new and incoming data and support from national agencies and international entities. Given what we know about the current rates and nature of changes in the Arctic, this is envisioned as critical role for ISAC if understanding and dissemination of information is to evolve at pace with change itself.

Photo: M. Murray

References Cited

ACIA (Arctic Climate Impact Assessment), 2005. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment: The Scientific Report*. Cambridge University Press, Cambridge, U.K.

ADHS (Alaska Department of Health and Social Services), 2006. Health risks in Alaska among adults. In *Alaska Behavioral Risk Factor Survey*, R. Mandsager (ed.), Alaska Department of Health and Social Services, Anchorage.

AHDR, 2004. *Arctic Human Development Report*. Stefansson Arctic Institute, Akureyri.

Allison, I., M. Béland, K. Alverson, R. Bell, D. Carlson, P. Cutler, K. Danell, C. Ellis-Evans, E. Fahrback, G. Hovelsrud, J. Huber, V. Kotlyakov, I. Krupnik, J. Lopes-Martinez, T. Mohr, H. Odmark, D. Qin, V. Rachold, C. Rapely, O. Rogne, E. Sarukhanian, C. Summerhayes, T. Yamanouchi, 2009. *The State of Polar Research: A Statement from the International Council for Science/World Meteorological Organization Joint Committee for the International Polar Year 2008-2009.* World Meteorological Organization, Geneva.

Allison, I., M. Béland, and the ICSU/WMO Joint Committee for IPY 2007-2008, 2007. *The Scope of Science for the International Polar Year 2007-2008*. WMO/TD-No. 1364. World Meteorological Organization, Geneva.

Allen, M.R. and W.J. Ingram, 2002. Constraints on future changes in climate and the hydrological cycle. *Nature* 419: 224-232.

Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pilke, R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace, 2003. Abrupt climate change. *Science*, 299(28): 2005-2010.

Anderson, L.G., E.P. Jones, K.P. Koltermann et al., 1989. The 1st Oceanographic Section Across the Nansen Basin in the Arctic Ocean, *Deep Sea Research Part A – Oceanographic Research Papers* 36(3): 475-482.

Anderson, L.G., G. Bjork, G. Holber et al. 1994. Water masses and circulation in the Eurasian Basin: results from the Oden 91 expedition. *Journal of Geophysical Research – Oceans* 99: 3273-3283.

AMAP (Arctic Monitoring and Assessment Program), 1998. *AMAP Assessment Report: Arctic Pollution Issues.* Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMAP (Arctic Monitoring and Assessment Program), 2002. *Arctic Pollution 2002: Persistent Organic Pollutants, Heavy Metals, Radioactivity, Human Health, Changing Pathways.* Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMAP (Arctic Monitoring and Assessment Program, 2003a. *AMAP Assessment 2002: The Influence of Global Change on Contaminant Pathways to, within, and from the Arctic*. Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMAP (Arctic Monitoring and Assessment Program, 2003b. *Human Health in the Arctic*. Arctic Monitoring and Assessment Program (AMAP), Oslo.

AMAP (Arctic Monitoring and Assessment Program), 2004. *AMAP Assessment 2002: Heavy Metals in the Arctic.* Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMAP (Arctic Monitoring and Assessment Program), 2006. *AMAP Assessment 2006: Acidifying Pollutants, Arctic Haze and Acidification in the Arctic*. Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMSA (Arctic Marine Shipping Assessment), 2009. *Arctic Marine Shipping Assessment 2009 Report*. Arctic Council, April 2009, second printing.

Amorosi, T., T. McGovern, and S. Perdikaris. 1994. Bioarchaeology and the cod fisheries: a new source of evidence. *ICES, Marine Science Symposium* 198: 31–48.

Amorosi, T., J. Woollett, S. Perdikaris, and T. McGovern. 1996. Regional zooarchaeology and global change: problems and pitfalls. *World Archaeology* 28: 126–157.

Anderson, L.G., E.P. Jones, R. Lindegren, 1988. Nutrient regeneration in cold, high salinity bottom water of the Arctic Shelves, *Continental Shelf Research* 8(12): 1345-1355.

Anthoff, D., R.J. Nicholls, R.S.J. Tol, 2010. The economic impact of substantial sea level rise. *Mitigation and Adaptation Strategies for Global Change*, 15: 321-335.

Balshi, D. McGuire, P. Duffy, M. Flannigan, J. Walsh and J. Melillo, 2008. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology,* doi: 10.1111/j.1365-2486.2008.01679.

Bengtsson L, V.A. Semenov, O.M. Johannessen, 2004. The early twentieth-century warming in the Arctic - a possible mechanism. *Journal of Climate* 17: 4045-4057.

BEST (Bering Sea Ecosystem Study), 2004. *Bering Ecosystem Study (BEST) Science Plan*. Arctic Research Consortium of the United States (ARCUS), Fairbanks.

Bowden, S., R.W. Corell, S. J. Hassol, and C. Symon (eds.), 2006. *Arctic Research, A Global Responsibility: An Overview of the 2nd International Conference on Arctic Research Planning (ICARP II).* McCallum Printing Group, Canada.

Blanchet, J.-P., and E. Girard, 1994. Arctic greenhouse cooling, *Nature*, 371: 383.

Box, J.E., D.H. Bromwich, B.A. Vennhuis, L.-S. Bai, J.C. Stroeve, J.C. Rogers, K. Steffen, T. Haren, and S.-H. Wang, 2006. Greenland ice sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output. *Journal of Climate* 19: 2783-2800.

Brigham, L. and B. Ellis (eds.), 2004. *Arctic Marine Transport Workshop*. Report of the Arctic Marine Transport Workshop, 28-30 September 2004. Northern Printing, Anchorage.

CAFF (Conservation of Arctic Flora and Fauna), 2010. *The Arctic Biodiversity Trends – 2010: Selected Indicators of Change*, Arctic Council. http://www.arcticbiodiversity.is/index.php/en/downloads

CRRC (Coastal Response Research Center), 2009. *Opening the Arctic Seas: Envisioning Disasters and Framing Solutions*. Coastal Response Research Center, University of New Hampshire, Durham, NH.

Census of Marine Life, 2009. http://www.coml.org/comlfiles/press/CoML_Ice_Oceans_Public_Release_02.15.2009.pdf

Chapin III, F.S., E.S. Zavaleta, V.T. Eviners, R.L. Naylor, P.M. Vitousek, H.L. Reynolds, D.U. Hooper, S. Lavoret, O.E. Sala, S.E. Hobbie, M.C. Mack, and S. Diaz, 2000. Consequences of changing biodiversity. *Nature* 405(6783): 234-242.

Chapman, W.L., and J.E. Walsh, 2007. Simulations of arctic temperature and pressure by global coupled models. *Journal of Climate* 20: 609-632.

Colt, S., S. Goldsmith and A. Wiita, 2003. *Sustainable Utilities in Rural Alaska: Effective Management, Maintenance and Operation of Electric, Water, Sewer, Bulk Fuel, Solid Waste*. Anchorage: Institute of Social and Economic Research (ISER), UAA.

Covert, D. S., A. Wiedensohler, P. Aalto, J. Heintzenberg, P.H. McMurry, P.H. and C. Leck, 1996. Aerosol number size distributions from 3 to 500 nm diameter in the arctic marine boundary layer during summer and autumn. *Tellus* 48B: 197–212.

Curry, J.A., W.B. Rossow, D. Randall and J.L. Schramm, 1996. Overview of arctic cloud and radiation characteristics. *Journal of Climate* 9: 1731-1764.

Damas, D. (ed.), 1984. *Handbook of North American Indians, Vol. 5. Arctic.* Smithsonian Institution, Washington, D.C.

Degal, B, and B. Saylor, 2007. Social transition in the north: comparisons of drug-taking behavior among Alaska and Russian Natives. *International Journal of Circumpolar Health* 66 (1): 71-76.

Dethloff, K., A. Rinke, E. Sokolova, S. Kumar Saha, D. Handorf, W. Dorn, A. Benkel, B. Rockel, H. von Storch, M. Køltzow, J.E. Haugen, L.P. Røed, E. Roeckner, J.H. Christensen, and M. Stendel, 2006. A dynamical link between the Arctic and the global climate system, *Geophysical Research Letters* 33, L03703.

Derocher, A.E., N.J. Lunn, and I. Stirling, 2004. Polar bears in a warming climate. *Integrative and Comparative Biology* 44: 163-176.

Dingsør, G.E., L. Ciannelli, K.-S. Chan, G. Ottersen, and N.-C Stenseth, N.-C., 2007. Density dependence and density independence during the early life stages of four marine fish stocks. *Ecology* 88: 625-634.

Dickson, R.R., 2008. *The Integrated Arctic Ocean Observing System (iAOOS) in 2007.* A report of the Arctic Ocean Sciences Board, R.R. Dickson and iAOOS Principle Investigators.

Arctic Ocean Sciences Board (AOSB), aosb.arcticportal.org/pdf.iAOOS.pdf.

Dickson, R.R., 2009. *The Integrated Arctic Ocean Observing System (iAOOS) in 2008*. A report of the Arctic Ocean Sciences Board, R.R. Dickson and iAOOS Principle Investigators, Arctic Ocean Sciences Board (AOSB), aosb.arcticportal.org/pdf/iAOOS2008_final.pdf.

Dumond, D. E., 1987. *The Eskimos and Aleuts*. Thames and Hudson, London, UK.

Durner, G.M., D.C. Douglas, R.M. Neilson, S.C. Amstrup, T. L. McDonald, I. Stirling, M. Mauritzen, E. W. Born, Ø. Wiig, E. DeWeaver, M. C. Serreze, S. E. Belikov, M. M. Holland, J. Maslanik, J. Aars, D. A. Bailey, and A. E. Derocher, 2009. Predicting 21st century polar bear habitat distribution from global climate models. *Ecological Monographs* 79(1):25-58.

Edwards, M., G. Beaugrand, D.G. Johns, P. Licandro, A. McQuatters-Gollop, and M. Wootton, 2010. Ecological Status Report: results from the CPR survey 2009. *SAHFOS Technical Report* 7: 1-8. Plymouth, U.K.

Euskirchen, S.E., A.D. McGuire, D.W. Kicklighter, Q. Zhuangand and J.S. Clein, 2006. Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. *Global Change Biology* 12: 731–50.

Finney, B. P., I. Gregory-Eaves, M.S.V. Douglas, and J.P. Smol, 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2200 years. *Nature* 416: 729-733.

Fisher, T.R., D. Correll, R. Constanza, J.T. Hollingbaugh, C.S. Hopkins Jr., R.W. Howarth, N.N. Rabalais, J.E. Richey, C.J. Vorosmarty, and R. Wiegert, 2000. Synthesizing drainage basin inputs to coastal systems, in *Estuarine Science*, J.E. Hobbie (ed), Island Press, Washington D.C. pp. 81-101.

Flöser, G., A. Kremer and V. Rachold, (eds.), 2007. *Arctic Coastal Zones at Risk*. Workshop Proceedings, Tromsø, Norway 1-3 October 2007.

Forbes, B.C., 1996. Plant communities of archaeological sites, abandoned dwellings, and trampled tundra in the eastern Canadian Arctic: a multivariate analysis. *Arctic* 49(2): 141-154.

Forbes, B.C., N. Fresco, A. Shvidenko, K. Danell and F.S. Chapin III, 2004. Geographic variations in anthropogenic drivers that influence the vulnerability and resilience of high latitude social-ecological systems. *Ambio* 33:377-382.

Forbes, B.C. and Stammler, F. (2009) Arctic climate change discourse: the contrasting politics of research agendas in the West and Russia. *Polar Research* 28: 28–42.

Forbes, B.C., F. Stammler, T. Kumpula, N. Meschtyb, A. Pajunen, and E. Kaarlejärvi, 2009. High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia. *Proceedings of the National Academy of Sciences* 106: 22041-22048.

Forbes, B.C., M. Macias Fauria and P. Zetterberg, 2010. Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology* 16: 1542–1554.

Ford, J.D., 2009. Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. *Regional Environmental Change* 9(2): 83-100.

Frey, K.E., J.W. McClelland, R.M. Holmes, and L.C. Smith, 2007. Impacts of climate warming and permafrost thaw on the riverine transport of nitrogen and phosphorus to the Kara Sea, *Journal of Geophysical Research,* 112, G04558, doi: 10.1029/2006JGG000369.

Gascard, J.C., and 26 others, 2008. Exploring Arctic transpolar drift during dramatic sea ice retreat, *EOS Transactions* 89(3): 21-22.

Giles, K. A., S. W. Laxon, and A. L. Ridout, 2008. Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum, *Geophysical Research Letters* 35, L22502, doi:10.1029/2008GL035710.

Goetz, S.J., A.G. Bunn, G.J. Fiske, and R.A. Houghton, 2005. Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences* 102: 13521-13525.

Goldsmith, S., 2007. *The Remote Rural Economy of Alaska*. University of Alaska Anchorage, Anchorage.

Gooseff, M.N., A. Balser, W.B. Bowden, and J.B. Jones, 2009. Effects of hillslope thermokarst in northeast Alaska. *Eos Transactions* 90(4): 29.

Graves, K., 2005. *Resilience and Adaptation Among Alaska Native Men*, University of Alaska Anchorage, Fairbanks.

Graversen, R.G., 2006. Do changes in the mid-latitude circulation have any impact on the Arctic surface air temperature trend? *Journal of Climate* 19: 5422-5438.

Graversen, R.G., T. Mauritsen, M. Tjernström, E. Källén and G. Svensson, 2008. Vertical structure of recent arctic warming, *Nature* 541: 53-56, doi: 10.1038/nature06502.

Graversen R. G. and M. Wang, 2009. Polar amplification in a coupled climate model with locked albedo. *Climate Dynamics* 33(5): 629-643.

Grebmeier, J.M., J. E. Overland, S.E. Moore, E.V. Farely, E.C. Carmack, L.W. Cooper, K.E. Frey, J.H. Helle, F.A. McLaughlin, and S.L. McNutt, 2006. A major ecosystem shift in the northern Bering Sea. *Science* 311: 1461-1464.

Griffith, B., D. C. Douglas, D. E. Russell, R. G. White, T. R. McCabe, and K. R. Whitten, 2001. *Effects off recent climate warming on caribou habitat and survival.* In Green, R. E., M. Harley, M. Spalding, and C. Zockler, eds. Impacts of climate change on wildlife. Royal Society for the Protection of Birds, Sandy, UK. Pp 17-19.

Guariguata, M.R., J.P. Cornelius, B. Locatelli, C. Forner, and G. A. Sanchez-Asofeifa, 2008. Mitigation needs adaptation: Tropical forestry and climate change. *Mitigation and Adaptation Strategies for Global Change* 13: 793-808.

Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J. -L. Etienne, and I. Rigor, 2008. Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat, *Geophysical Research Letters, 35,* L17501, doi: 10.1029/2008GL034457.

Hakkinen, S., A. Proshutinsky, and I. Ashik, 2008. Sea ice drift in the Arctic since the 1950s, *Geophysical Research Letters* 35, L19704, doi: 10.1029/2008GL034791.

Hamilton, L.C., B.C. Brown, R.O. Rasmussen, 2003. West Greenland's cod to shrimp transition: local dimensions of climatic change. *Arctic* 56(3): 271-282.

Hamilton, L.C., R.L. Haedrich and C.M. Duncan. 2004. Above and below the water: Social/ecological transformation in northwest Newfoundland, *Population and Environment* 25(3): 195-215.

Hayes, D.J., L. Guo, and A.D. McGuire, 2007: A scientific synthesis and assessment of the arctic carbon cycle: AMAP/CliC/IASC Arctic Carbon Cycle Assessment Workshop, Seattle, Washington, 27 February - 1 March 2007, *Eos Transactions 88*(26): 270.

Heintzenberg, J., C. Leck, W. Birmili, B. Wehner, M. Tjernström and A. Wiedensohler, 2006. Aerosol number–size distributions during clear and fog periods in the summer high Arctic: 1991, 1996 and 2001. *Tellus* 58: 41-50.

Higuera, P.E., L.B. Brubaker, P.M. Aderson, T.A. Brown, A.T. Kennedy and F.S. Hu, 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for arctic environmental change. *PLoS One* 3(3): e0001744. doi: 10.1371/journal.pone.0001744.

Hinzman L.D., N.D. Bettez, W.R. Bolton, F.S. Chapin III, M.B. Dyurgerov, C.L. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A.M. Jensen, G.J. Jia, T. Jorgenson, D.L. Kane, D.R. Klein, G. Kofinas, A.H. Lynch, A.H. Lloyd, A.D. McGuire, F.E. Nelson, M. Nolan, W.C. Oechel, T.E. Osterkamp, C.H. Racine, V.E. Romanovsky, R.S. Stone, D.A. Stow, M. Sturm, C.E. Tweedie, G.L. Vourlitis, M.D. Walker, D.A. Walker, D.J. Webber, J. Welker, K.S. Winker, and K. Yoshikawa, 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change* 72(3): 251–298.

Holland, M.K., C.M. Bitz, and R. Tremblay, 2006. Future abrupt reductions in summer Arctic sea ice. *Geophysical Research Letters* 33, L23503.

Hop, H., S. Falk-Petersen, H. Svendsen, S. Kwansniewski, V. Pavlov, O. Pavlova, and J.E. Søreide, 2006. Physical and biological characteristics of the pelagic system across Fram Strait to Kongsfjorden, *Progress in Oceanography* 71: 182-231.

Hovelsrud, G.K., McKenna, M., and Huntington, H.P., 2008. Marine mammal harvests and other interactions with humans. *Ecological Applications* 18(2): S135-S147.

Huntington, H., M. Boyle, G. Flowers, J. Weatherly, L. Hamilton, L. Hinzman, S.C. Gerlach, R. Zuluta, C. Nicolson, and J. Overpeck, 2007.The influence of human activity in the Arctic on climate and climate impacts. *Climatic Change* 82(1-2): 77-92.

Hurrell, J. W., 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* 269: 676–679.

Ims, R.A. and E. Fuglei, 2005. Trophic interactions cycles in tundra ecosystems and the impact of climate change. BioScience 55(4): 311-322

IPCC (Intergovernmental Panel on Climate Cahnge), 2007. Climate Change 2007: *The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge.

Johannessen, O.M., L. Bengtsson, M.W. Miles, S.I. Kuzmina, V.A. Semenov, G.V. Alekseev, A.P. Nagurnyi, V.F. Zakarhov, L.P. Bobylev, L.H. Pettersson, K. Hasselmann, and H.P. Cattle, 2004. Arctic climate change: observed and modeled temperature and sea-ice variability. *Tellus* 56: 328-341.

Jin, M., C. Deal, J. Wang and C.P. McRoy, 2009. Response of lower trophic level production to long-term climate change in the southeastern Bering Sea. *Journal of Geophysical Research* 114, C04010, doi:10.1029/2008JC005105.

Jones, P.D. and A. Møberg, 2003. Hemispheric and large scale surface air temperature variations: An extensive revision and update to 2001. *Journal of Climate* 16: 206-223.

Jones, B.M, C.D. Arp, K.M. Hinkle, J.A. Schmutz, P.L. Flint, B.M., 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. *Geophysical Research Letters* 36: L03503.

Kasischke, E.S. and M.R. Turetsky, 2006. Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* 33, L09703, doi:10.1029/2006GL025677.

Karlsen, S.R., K. A. Høgda, F. E.l Wielgolaski, A. Tolvanen, H. Tømmervik, J. Poikolainen, E. Kubin, 2009. Growing-season trends in Fennoscandia 1982–2006, determined from satellite and phenology data. *Climate Research* 39: 275-286.

Kay, J.E., T. L'Ecuyer, A. Gettelman, G. Stephens and C. O'Dell, 2008. The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum, *Geophysical Research Letters* 35: doi:10.1029/2008GL033451.

Kellert, S.R., J.N. Mehta, S.A. Ebbin, and L.L. Lichtenfeld, 2000. Community natural resource management: promise, rhetoric, and reality. *Society and Natural Resources* 13(8): 705-615.

Kennedy, J.J., H.A. Titchner, J. Hardwick, M. Beswick, and D.E. Parker, 2007. Global and regional climate in 2007. *Weather* 62(9): 232-42.

Kovacs, K. and C. Lydersen, 2009. Ringed seals and climate change: Arctic ice loss seals the deal. *Species and Climate Change" More than Just the Polar Bear*. IUCN Red List of Threatened Species, Species Survival Commission, http://www.iucn.org/what/tpas/biodiversity/resources/publications/?4562/Species-and-Climate-Change.

Krupnik, I., and D. Jolly, 2002. *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*, Arctic Research Consortium of the United States, Fairbanks, Alaska.

Kuhnlein, H.V., Receveur, O., Soueida, R., and G.M. Egeland, 2004. Arctic indigenous peoples experience the nutrition transition with changing dietary patterns and obesity. *The Journal of Nutrition* 134:1447-1453.

Kwok, R., G.F. Cunningham, and S.S. Pang, 2004. Fram Strait sea ice outflow. *Journal of Geophysical Research* 109, C01009, doi:10.1029/2003JC001785.

Kwok, R. 2007. Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005 summer. *Geophysical Research Letters* 34, L05501, doi:10.1029/2006GL028737.

Kwok, R., G, F. Cunningham, M. Wensnahan, I. Rigor, H.J. Zwally, and D. Yi, 2009. Thinning and volume loss of the Arctic Ocean sea ice cover: 2003-3008. *Journal of Geophysical Research* 114, C07005, doi:10.1029/2009JC005312.

Lachenbruch, A.H., and B.V. Marshall, 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* 234: 689-696.

Laidre, K.L., I. Stirling, L.F. Lowrey, O. Wiig, M.P. Heide-Jørgensen and S.H. Ferguson, 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications* 18(2): S97-S125.

Larsen, P., S. Goldsmith, O. Smith, M. Wilson, K. Strzepek, P. Chinowsky and P. Saylor, 2008. Estimating Future Costs for Alaska Public Infrastructure at Risk from Climate Change. *Global Environmental Change* 18(3): 442-457.

Larsen, J.N., P. Schweitzer and G. Fondahl, (eds.), 2010. Arctic Social Indicators: a follow-up to the Arctic Human Development Report. *TemaNord* 2010:519. Nordic Council of Ministers, Copenhagen, pp. 109-127.

Leibman, M.O., A.A. Gubarkov, A.V. Khumutov, A.I. Kizayakov, B.G. Vanshtein, 2008. Coastal processes at the tabular-ground-ice-bearing area, Yugorsky Peninsula, Russia. *Proceedings of the 9th International Conference on Permafrost*, University of Alaska Fairbanks, Fairbanks. Pp. 1037-1042.

Lemmen, D.S., F.J. Warren, J. Lacrois, and E. Bush, (editors), 2008. *From Impacts to Adaptation; Canada in a Changing Climate 2007*. Government of Canada, Ottawa.

Lilly, G.R., K. Wieland, B.J. Rothschild, S. Sundby, K.F. Drinkwater, K. Brander, G. Ottersen, J.E. Carscadden G. B. Stenson, G.A. Chouinard, D.P. Swain, N. Daan, K. Enberg, M.O. Hammill, A. Rosing-Asvid, H. Svedäng, A. Vázquez, 2008. Decline and recovery of Atlantic Cod (*Gadus morhua*) stocks throughout the North Atlantic. *Resiliency of Gadid Stocks to Fishing and Climate Change* 39 Alaska Sea Grant College Program • AK-SG-08-01, 2008.

Loeng, H., and Drinkwater, K., 2007. An overview of the ecosystems of the Barents and Norwegian Seas and their response to climate variability. *Deep-Sea Research II* 54 (2007) 2478–2500.

Loring, P.A., F.S. Chapin III, and S.C. Gerlach, 2008. The services-oriented architecture: ecosystem services as a framework for diagnosing change in social ecological systems. *Ecosystems* 11 (1): 478-489.

Loring, P.A. and S.C. Gerlach, 2010. Outpost gardening in Interior Alaska: food system innovation and the Alaska Native gardens of the 1930s through the 1970s. *Ethnohistory* 57(2): 183-199. DOI:10.1215/00141801-2009-060.

Liu, J., Z. Zhang, Y. Hu, L. Chen, Y. Dai, and X. Ren, 2008. Assessment of surface air temperature over the Arctic Ocean in reanalysis and IPCC AR4 model simulations with IABP/POLES observations. *Journal of Geophysical Research* 113: doi:10.1029/JD009380 2008.

McLaughlin, J.B., J.P. Middaugh, C.J. Utermohle, E.D. Asay, A.M. Fenaughty, and J.E. Eberhardt-Phillips, 2004. Changing patterns of risk factors and mortality for coronary heart disease among Alaska Natives. *Journal of the American Medical Association* 291: 2545-2546.

McNeeley, S, and O. Huntington, 2007. Postcards from the (not so) frozen North: talking about climate change in Alaska. In *Creating a Climate for Change*, S.C. Moser, and L. Dilling (eds), Cambridge University Press, Cambridge.

McCabe, G.J., M.P. Clark, and M.C. Serreze, 2001. Trends in northern hemisphere surface cyclone frequency and intensity. *Journal of Climate* 14: 2763-2768.

McLean, R.F., A. Tsybyn, V. Burkett, J.O. Codignotto, D.L. Forbes, N. Mimura, R.J. Beamish, and V. Ittekkott, 2001. Coastal zones and marine ecosystems. *Climate Change 2001: Impacts Adaptations and Vulnerability. Contributions of Working Group II to the Third Assessment Report of the IPCC.* Cambridge University Press, Cambridge. Pp. 343-379.

McGovern, T. H., S. Perdikaris, A. Einersson, and J. Sidell, 2006. Coastal connections, local fishing, and sustainable egg harvesting: patterns of Viking Age inland wild resource use in M´yvatn district, Northern Iceland. *Environmental Archaeology* 11: 187–205.

McGuire, A.D., C. Wirth, M. Apps, J. Beringer, J. Clein, H. Epstein, D.W. Kicklighter, J. Bhatti, F.S. Chapin III, B. deGroot, D. Efremov, W. Eugster, M. Fukuda. T. Gower, L. Hinzman, B. Huntley, G.J. Jia, E. Kasischke, J. Melillo, V. Romanovsky, V. Shvidenko, E. Vaganov, D. Walker, 2002. Environmental variation, vegetation distribution, carbon dynamics and water/energy exchange at high latitudes. *Journal of Vegetation Science* 13: 301-314.

McRae, L. C. Zöckler, M. Gill, J. Loh, J. Latham, N. Harrison, J. Martin and B. Collen. 2010. *Arctic Species Trend Index 2010: Tracking Trends in Arctic Wildlife.* CAFF CBMP Report No. 20, CAFF International Secretariat, Akureyri.

Mahoney, A., H. Eicken, A.G. Gaylord, and L. Shapiro, 2007. Alaska landfast sea ice: links with bathymetry and atmospheric circulation. *Journal of Geophysical Research* 112, C02001, doi:10.1029/2006JC003559.

Martin, S.M., M. Killorin, and S. Colt, 2008. *Fuel Costs, Migration, and Community Viability*. Institute of Social and Economic Research (ISER), University of Alaska Anchroage, Anchorage.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery, 2007. A younger, thinner Arctic ice cover: increased potential for rapid, extensive sea-ice loss. *Geophysical Research Letters* 34, L24501, doi: 10.1029/2007GL032043.

Mateeva, T., P. Rekant, E. Bektov, T. Schwenk, E. Gusev, G. Cherkashov, H. Kassens, 2008. Shallow gas occurrences in the Laptev Sea and implications for possible gas hydrate presence. *Minerals of the Ocean – 4: Future Developments.* International Conference Proceedings 12-14 May 2008. VNIIOkeangeologia, St. Petersburg, pp. 131-132.

Maxwell, M. S., 1985. *Prehistory of the Eastern Arctic*. Academic Press, Orlando, Florida, USA.

MEA, 2005. *Millennium Ecosystem Assessment*. Washington, DC.

Meier, M.F., M.B. Dyurgerov, U.K. Rick, S. O'Neel, W.T. Pfeffer, R.S. Anderson, S.P. Anderson, and A.F. Glazovsky. 2007**.** Glaciers dominate eustatic sea-level rise in the 21st century. *Science* 317: 1064-1067.

Moore, S. E. and H.P. Huntington, 2008. Arctic marine mammals and climate change: impacts and resilience. *Ecological Applications* 18(2): S157-165.

Morison, J., M. Steele, and R. Anderson, 1998. Hydrograph of the upper Arctic Ocean measured from the nuclear submarine USS PArgo. *Deep Sea Research Part 1 – Oceanographic Research Papers* 45(1): 15-38.

Morison, J., V. Alexander, L. Codispotti, T. Delworth, B. HIckson, H. Eicken, J. Greibmeier, J. Kruse, J. Overland, J. Overpeck, P. Schlosser, M. Serreze, and J. Walsh, 2001. *SEARCH SSC, SEARCH: Study of Environmental Arctic Change, Science Plan*. Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle.

Morison, J., M. Steele, T. Kikuchi, K. Falkner, and W. Smethie, 2006. Relaxation of central Arctic Ocean hydrography to pre-1990s climatology. *Geophysical Research Letters* 33, L17604, doi:10.1029/2006GL026826.

Murray, M.S. 2008. Zooarchaeology and Arctic marine mammal biogeography, conservation and management. *Ecological Applications* s18(2): 41-55.

Newchurch, M. J., E.-S. Yang, D. M. Cunnold, G. C. Reinsel, J. M. Zawodny, and J. M. Russell III, 2003. Evidence for slowdown in stratospheric ozone loss: First stage of ozone recovery, *Journal of Geophysical Research* 108(D16), 4507, doi: 10.1029/2003JD003471.

Nicolson, C.R., A.M. Starfield, G.P. Kofinas, and J.A. Kruse, 2002. Ten heuristics for interdisciplinary modeling projects. *Ecosystems* 5: 376-384.

NPFMC, 2008. DRAFT – *Fisheries Management Plan for Fish resources of the Arctic Management Area*. North Pacific Fisheries Management Council, Anchorage. http://www.fakr.noaa.gov/npfmc/current_issues/Arctic/ArcticFMP1208.pdf

NRC (National Research Council), Committee on Designing an Arctic Observing Network, 2006, *Toward and Integrated Arctic Observing Network*. Polar Research Board, Division on Earth and Life Studies, National Research Council of the National Academies Press, Washington, D.C.

Nuttall, M., F. Berkes, B.C. Forbes, G. Kifinas, T. Vlassova, and G. Wenzel. 2005. Hunting, herding, fishing and gathering: indigenous peoples and renewable resources in the Arctic. In: *Arctic Climate Impacts Assessment*, Cambridge University Press, Cambridge. Pp. 649-690.

Osvaldo, E.S., F.S. Chapin III, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Pestered, N. Leroy Puff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. Wall, 2000. Global biodiversity scenarios for the year 2100. *Science* 287:1770-1774.

Ottersen, G., D.O. Hjermann, and N.C. Stenseth, 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. *Fisheries Oceanography* 15: 230–243.

Ottersen, G., and N.C. Stenseth, 2001. Atlantic climate governs oceanographic and ecological variability in the Barents Sea. *Limnology and Oceanography* 46(7): 1774-1780.

Overland, J.E., M.C. Spillage and N.N. Storewide, 2004. Integrated analysis of physical and biological Pan-Arctic change. *Climatic Change* 63: 291-322.

Overland, J., J. Turner, J. Francis, N. Gillett, G. Marshall, and M. Tjernström, 2008a. The Arctic and Antarctic: two faces of climate change, *EOS* 89: 177-184.

Overland, J. E., M. Wang, and S. Salo, 2008b. The recent Arctic warm period, *Tellus* 60: 589-597.

Overpeck, J. T., M. Sturm, J.A. Francis, D.KJ. Perovich, M.C. Serreze, R. Benner, E.C. Carmack, F.S. Chapin III, S.C. Gerlach, L.C. Hamilton, M. Holland, H.P. Huntington, J.R.Key, A.H. Lloyd, G.M. MacDonald, J.A. McFadden D. Noone, T.D. Prowse, P. Schlosser and C. Vörösmarty, 2005. Arctic system on trajectory to new, seasonally ice-free state, *Eos Transactions* 86(34): 309.

PAN, 2007. *Polar Archaeology Network*, http://arcticportal.org/iasc/science-development/iasc-networks-and-other-activities

Parkinson, A.J. and J.C. Butler, 2005. Potential impacts of climate change on infectious diseases in the Arctic. *International Journal of Circumpolar Health* 64(5): 478-486.

Pauly, D., Watson, R., and J. Adler, 2005. Global trends in world fisheries: impacts on marine ecosystems and food security. *Philosophical Transactions of the Royal Society: Biological Sciences* 360:5-12. doi:10.1098/rstb.2004.1574

PBSG (Polar Bear Specialist Group), 2006. Proceedings of the 14th working meeting of the IUCN/SSC Polar Bear Specialist Group, Aars, J., N.J. Lunn, and A.E. Derocher (eds.), International Union for the Conservation of Nature, Seattle.

Perovich, D.K., B. Light, H. Eicken, K.F. Jones, K. Runciman, and S.V. Nghiem, 2007. Increasing solar heating of the Arctic Ocean and adjacent seas, 1979-2005: attribution and role in the ice-albedo feedback. *Geophysical Research Letters* 34: 1-5.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light, 2008. Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007. *Geophysical Research Letters*, 35: L11501, doi: 10.1029/2008GL034007.

Peterson, B.J., R.M. Homes, J.W. McClelland, C.J. Vörösmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov, S. Rahmstorf, 2002. Increasing river discharge to the Arctic Ocean. *Science* 298: 2171-2173.

Pitul'ko, V. V., and A. V. Kasparov, 1996. Ancient arctic hunters: material cultural and survival strategy. *Arctic Anthropology* 33: 1–36.

Polyakov, I., L. Timokhov, E. Hansen, J. Piechura, W. Walczowski, V. Ivanov, H. Simmons, E. Fahrbach, J. Hölemann, M. Steele, R. Pickart, L. Fortier, U. Schauer, A. Beszczynska-Möller, N. P. Holliday, I. Dmitrenko, R. Dickson, J.C. Gascard, C. Mauritzen. 2007. Observational program tracks Arctic Ocean transition to a warmer state, *Eos Transactions*. 88(40): 398. Doi 10.1029/2007EO400002.

Post E. and C. Pederson, 2008. Opposing plant communities response to warming with and without herbivores. *Proceedings of the National Academy of Science* 105:12343-12358.

Quadrelli, R. and J.M Wallace, 2004. A simplified linear framework for interpreting patterns of northern hemisphere wintertime climate variability. *Journal of Climate* 17: 3728–3744.

Quadfasel, D., A. Sy, and B. Rudels, 1993. A ship of opportunity section to the North-Pole: upper ocean temperature observations. *Deep-Sea research Part 1 – Oceanographic Research Papers* 40(4): 777-789.

Rachold, V., F. Are, D. Atkinson, G. Cherkashov, S. Solomon. 2005. Arctic coastal dynaminics (ACD): an introduction. *GeoMarine Letters* 25: 63-83.

Rachold V., D.Bolshiyanov, M. Grigoriev, H-W Hubberten, R. Junker, V. Kunitsky, F. Merker, P. Overduin. and W. Schneider, 2007. Near-shore arctic subsea permafrost in transition *Eos* 88: 149–56

Rapley, C., R. Bell and the ICSU/IPY 2007-2008 Planning Group, 2004. *A Framework for the International Polar Year 2007-2008*. ICSU, Paris.

Rastetter, E.B., J.D. Aber, D.P.C. Peters, D.S. Ojima, and I.C. Burke, 2003. Using mechanistic models to scale ecological processes across time and space. *BioScience* 53(1): 68-76.

Raynolds, M.K., D.A. Walker, C.A. Munger, and A.N. Kade, 2008. A map analysis of patterned-ground along a North American Arctic transect. *Journal of Geophysical Research – Biogeosciences* 113(G3): 18.

Richter-Menge, J. Overland and 44 coauthors, 2008. *Arctic Report Card 2008*. http://www.noaa.arctic.gov/reportcard/.

Rigor, I. G., J. M. Wallace and R. L. Colony, 2002. Response of sea ice to Arctic Oscillation. *Journal of Climate* 15: 2648–2663.

Ritchey, T. 1991. Analysis and synthesis on scientific method: based on a study by Reimann, Bernhard. *Systems Research* 8(4): 21-41.

Romankevich E.A. and A.A. Vetrov, 2001. *Carbon Cycle in Russian Arctic Seas* [in Russian], Nauka, Moscow.

Romanovskii, N.N., H.W. Hubberten, A.V. Gavrilov, A.a. Eliseeva, and G,S, Tipenko, 2005. Offshore permafrost and gas hydrate stability zone on the shelf of the East Siberian Seas, *GeoMaine Letters* 25: 187-182. Check with revised text

Romanovsky, V., N. Oberman, D. Drozdov, G. Malkova, A. Kholodov, and S. Marchenko, Permafrost, in: *State of the Climate in 2008, Special Supplement of the Bulletin of the American Meteorological* Society, T.C. Peterson and M.O. Baringer (eds), BAMS 90(8): S105-S106.

Rothrock, D. A., D. B. Percival, and M. Wensnahan, 2008. The decline in arctic sea-ice thickness: Separating the spatial, annual, and interannual variability in a quarter century of submarine data. *Journal of Geophysical Research* 113, C05003, doi:10.1029/2007JC004252.

Rühland, K., A. Priesnitz, and J.P. Smol, 2003. Paleolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian Arctic tree line. *Arctic, Antarctic, and Alpine Research* 35(1): 110-123.

Salisbury, J., M. Green, C. Hunt, and J. Campbell, 2008. Coastal acidification by rivers: a threat to shellfish? *Eos Transactions* 89(50): 513.

Sandeman, L.R., N.A. Yaragina, and C.T. Marchall, 2008. Factors contributing to inter- and intra-annual variation in condition of cod *Gadus morhua* in the Barents Sea. *Journal of Animal Ecology* 77:725-734.

SAON IG (Sustaining Arctic Observing Network Initiating Group) 2009, *Final report of the Sustaining Arctic Observing Networks (SAON) Initiating Group* (SAON-IG). January 2009.

Schell, T. M., T. J. Moss, D. B. Scott, and A. Rochon (2008), Paleo–sea ice conditions of the Amundsen Gulf, Canadian Arctic Archipelago: Implications from the foraminiferal record of the last 200 years, *Journal of Geophyical Research* 113, C03S02, doi:10.1029/2007JC004202. Check with revised text.

Schweiger, A.J., J. Zhang, R.W. Lindsay and M. Steele, 2008. Did unusually sunny skies help drive the record sea ice minimum of 2007? *Geophysical Research Letters* 35: doi:10.1029/2008GL033463.

SEARCH 2005. *Study of Environmental Arctic Change: Plans for Implementation During the International Polar Year and Beyond*. Report of the SEARCH Implementation Workshop, 23-25 May 2005. Arctic Research Consortium of the United States, Fairbanks.

SEARCH 2008. *Arctic Observation Integration: Workshop Report*. SEARCH Project Office, Arctic Research Consortium of the United States, Fairbanks.

Serreze, M.C., J.E. Walsh, F.S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W.C. Oechel, J. Morison, T. Zhang, and R.G. Barry, 2000. Observational evidence of recent change in the northern high-latitude environment. *Climatic Change* 46:159-207.

Serreze, M.C. and J.A. Francis, 2006. The Arctic amplification debate. *Climatic Change 26* (3-4): 241-264.

Serreze, M.C., M.M. Holland, and J. Stroeve, 2007. Perspectives on the Arctic's shrinking sea-ice cover, *Science* 315: 1533-1536. Doi: 10.1126/science.1139426.

Shadwick, E.H., R. Papakyriakou, A.E.F. Prowe, D. Leong, S.A. Moore and H. Thomas, 2009. Carbon cycling in the Arctic Archipelago: the export of Pacific carbon to the North Atlantic. *Biosciences Discuss., 6*, 971-994.

Shakova, N. and I. Semilitov, 2007. Methane release and coastal environment in the East Siberian Arctic Shelf. *Journal of Marine Systems* 66: 227-243.

Shakhova, N., I. Semiletov, A. Salyuk, V. Yusupov, D. Kosmach, and Ö. Gustafsson, 2010. Extensive methane venting to the atmosphere from Sediments of the East Siberian Arctic Shelf. *Science* 327(5970): 1246-1250. DOI 10.1126/science.1182221

Smedsrud, L.H., A. Sorteberg, and K. Kloster, 2008. Recent and future changes of the Arctic sea-ice cover. *Geophysical Research Letters* 35: L20503, doi: 10.1029/2008GL034813.

Shimada, K., T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. McLaughlin, S. Zimmermann, and A. Proshutinsky, 2006: Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophysical Research Letters, 33*, L08605, doi: 10.1029/2005GL025624.

Smith, L.C., Y. Sheng, G.M. McDonald and L.D. Hinzman, 2005. Disappearing Arctic lakes, *Science* 308: 1492. doi:10.1126/science.1108142.

Sommerkorn, M. and N. Hamilton (eds), 2008. *Arctic Climate Impact Science: an Update Since ACIA*. WWF International Programme, Oslo.

Sorteberg, A., J.E. Walsh, et al. 2008. Seasonal cyclone variability at 70 degrees N and its impact on moisture transport into the Arctic. *TELLUS* 60: 570-586.

Stirling, I., 2005. Reproductive rates of ringed seals and survival of pups in Northwestern Hudson Bay, Canada, 1991-2000. *Polar Biology* 28: 381-371.

Streletskaya, I.D., A.A. Vasiliev, B.G. Vanstein, 2008. Organic carbon spatial distribution in quaternary sediments of Russian West Arctic (fresh data), in 6th Annual Arctic Coastal Dynamics Workshop, P.P. Overduin and N. Couture (eds), *Reports on Polar and Marine Research* 567: 83-84.

Sumata, H. and K. Shimada, 2007. Northward transport of Pacific summer water along the Northwind Ridge in the western Arctic Ocean. *Journal of Oceanography*. 63(3): 363-378.

Tedesco, M., X. Fettweis, M. Van Den Broeke, R. Van De Wal, and P. Smeets, 2008. Extreme snowmelt in northern Greenland during summer 2008. *Eos Transactions* 89(41): 391.

Thompson, D.W.J., and J.M. Wallace, 2000. Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate* 13: 1000–1016.

UNEP (United Nations Environmental Programme) 2000. *The Montreal Protocol on Substances that Deplete the Ozone Layer as either adjusted and/or amended in London 1990 Copenhagen 1992 Vienna 1995 Montreal 1997 Beijing 1999.* UNEP Ozone Secretariat, United Nations Environment Programme, Nairobi, http://www.unep.org/ozone.

Van der Wal, R., 2006. Do herbivores cause habitat degradation or vegetation state transition? Evidence from the tundra. *Oikos* 114(1): 177-186

Vasiliev, A., M. Kanevsky, G. Cherkashov, and B. Vanshtein, 2005. Coastal dynamics at the Barents and Kara Sea sites. *GeoMarine Letters* 25: 110-121.

Velicogna, I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical Research Letters 36*, L19503, doi:10.1029/2009GL040222.

Vellinga, M. and R.A. Wood, 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change* 54(3): 251-267.

Verbyla, D. 2008. The greening and browning of Alaska based on 1982-2003 satellite data. *Global Ecology and Biogeography* 17(4): 547-555.

Walsh, J. E., V. M. Kattsov, W. L. Chapman, V. Govorkova, and T. Pavlova, 2002. Comparison of arctic climate simulations by uncoupled and coupled global models. *Journal of Climate,* 15: 1429-1446.

Walter, K.M., S.A. Zimov, J.P. Chanton, D. Verbyla, and F.S. Chapin III, 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming, *Nature* 443: 71-75. Doi: 10.1038/nature05040.

Walter, K.M, L.C. Smith and F.S. Chapin III, 2007. Methane bubbling from northern lakes: present and future contributions to the global methane budget. *Philosophical Transactions A Math Phys Eng Sci* 365: 1657-1676.

Wang, J., M. Ikeda, S. Zhang, and R Gerdes, 2005. Linking the northern hemisphere sea ice reduction trend and the quasi-decadal Arctic Sea Ice Oscillation. *Climate Dynamics* 24: 115-130, doi: 10.1007/s00382-004-0454-5.

Wang, J., M. Jin, J. Takahashi, T. Suzuki, I.V. Polyakov, K. Mizobata, M.Ikeda, F.J. Saucier, and M. Meier, 2008. Modeling Arctic Ocean heat transport and warming episodes in the 20th century caused by intruding Atlantic Water. *Chinese Journal of Polar Science: Special Issue of Pacfic Arctic Group (PAG) Model-Data Fusion Studies in the Arctic Ocean and Subpolar Seas,* 19(2):159-167/

Wang, J., J. Zhang, E. Watanabe, K. Misobata, M. Ikeda, J.E. Walsh, X. Bai, and B. Wu, 2009. Is the dipole anomaly a major driver to record lows in the Arctic sea ice extent? *Geophysical Research Letters* 36, L05706, doi:1029/2008GLO036706

Wang, X. and J.R. Key, 2005. Arctic surface, cloud, and radiation properties based on the AVHRR Polar Pathfinder dataset. Part I: Spatial and temporal characteristics. *Journal of Climate* 18:2558-2574.

Wassmann, P., M. Reigstad, T. Haug, B. Rudels, M.L. Carroll, H. Hop, G.W. Gabrielsen, S. Falk-Petersen, S.G. Denisenko, and E. Arashkevich, 2006. Food webs and carbon flux in the Barents Sea. *Progress in Oceanography* 71: 232-287.

Wassmann, P., J. Carroll, and R.G.J. Bellerby, 2008. Carbon flux and ecosystem feedbacks in the northern Barents Sea in an era of climate change: An introduction. *Deep Sea research Part II: Topical Studies in Oceanography* 55(20-21): 2143-2153.

Watanabe, E., J. Wang, T. Sumi and H. Hasumi, 2006. Arctic Dipole and its contribution to sea ice exports in the last 20th century, *Geophysical Research Letters* 33, L23703, doi:10.1029/2009GL028112.

White, D., S.C. Gerlach, P. Loring, and A. Tidwell. 2007. Food and water security in a changing arctic climate. In Focus Issue: Northern Hemisphere High Latitude Climate and Environmental Change. *Environmental Research Letters* 2(045018): 1-5.

Wolsko, C., C. Lardon, G. Mohatt and E. Orr, E. 2007. Stress, coping, and well-being among the Yup 'ik of the Yukon-Kuskokwim Delta: the role of enculturation and acculturation. *International Journal of Circumpolar Health* 66 (1): 51-61.

Wu, B., J. Want, and J.E. Walsh, 2006. Dipole anomaly in the winter Arctic atmosphere and its association with Arctic sea ice motion. *Journal of Climate* 19(2):210-225, doo: 10.1175/JCLI3619.1

Yoshikawa, K. and L. Hinzman, 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost. *Permafrost and Periglacial Processes.* 14(2): 151-160.

Zhang, J., R. Lindsay, M. Steele, and A. Schweiger, 2008a: What drove the dramatic retreat of arctic sea ice during summer 2007? *Geophysical Research Letters* 35: L11505, doi:10.1029/2008GL034005.

Zhang, X., A. Sorteberg, J. Zhang, R. Gerdes, and J.C. Comiso, 2008b. Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system, *Geophysical Research Letters* 35, L22701, doi:10.1029/2008GL035607.

Zhang, X., J.E. Walsh, J. Zhang, U.S. Bhatt, and M. Ikeda, 2004. Climatology and interannual variability of arctic cyclone activity: 1948-2002. *Journal of Climate* 17: 2300-2317.

Zhuang, Q., J.M Melack, S. Zimov, K.M. Walter, C.L. Butenhoff, and M.A.K. Khalil, 2009. Global methane emissions from wetland, rice paddies and lakes. *Eos Transactions* 90(5): 37-38.