SEARCH

Study of Environmental Arctic Change

Science Plan
2001

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EXECUTIVE SUMMARY

It is clear that a complex suite of significant, interrelated, atmospheric, oceanic, and terrestrial changes has occurred in the Arctic in recent decades. This event is affecting every part of the arctic environment and is having repercussions on society. There is evidence that these changes are connected with the rising trend in the Arctic Oscillation (AO), a mode of atmospheric variability that is potentially active over a broad range of time scales, including climatic time scales, and that involves changes in the strength of the atmospheric polar vortex. There is theoretical evidence that the positive trend observed in the AO index might be indicative of greenhouse warming. It is unclear what feedback processes on climate or ecosystems may be involved in the recent changes, or what the long-term impacts may be. However, observations suggest the impact at high latitudes is substantial and the impact at middle latitudes is significant. Because the observed changes have made it harder for those who live in the North to predict what the future may bring, we have given the name Unaami (the Yup'ik word for "tomorrow") to the complex of intertwined, pan-arctic changes.

The Study of Environmental Arctic Change (SEARCH) has been conceived as a broad, interdisciplinary, multiscale program with a core aim of understanding Unaami. Part of gaining this understanding will be to determine the full scope of Unaami. As a working definition based on present knowledge, we define Unaami as the recent and ongoing, decadal (e.g., 3–50 year), pan-arctic complex of interrelated changes in the Arctic. These changes include, among other things, a decline in sea level atmospheric pressure, an increase in surface air temperature, cyclonic ocean circulation, and a decrease in sea ice cover. The physical changes are producing changes in the ecosystem and living resources and affecting the human population. The changes are affecting local and hemispheric economic activities such as shipping and fisheries totaling billions of dollars. These biological and societal consequences may be considered part of Unaami. Although the dynamics are different, the situation is similar to the El Niño-Southern Oscillation (ENSO) phenomenon.

Activities undertaken as part of SEARCH are guided by a series of hypotheses. The first hypothesis is that:

Unaami is related to or involves the Arctic Oscillation. Here the AO phenomenon is used to broadly describe the strength of the polar vortex as shown by the AO and related teleconnection indices. A key objective of SEARCH will be to understand the arctic-wide interactions inherent in Unaami and their links to a rising AO in a rigorous way. Testing this hypothesis will tell us much about the interaction between the atmosphere, ocean, and land. It will tell us how Unaami is tied to the global atmosphere.

The second hypothesis is that:

Unaami is a component of climate change. Because the AO is a fundamental mode of atmospheric variability, Unaami will be tied to climate change through the AO. Unaami may also be tied to global climate change through its impact on the global ocean thermohaline circulation. The objective is to understand how Unaami fits into the larger picture of climate change.

The third hypothesis is related to the first two:

Feedbacks among the ocean, the land, and the atmosphere are critical to Unaami. These feedbacks could determine the role of Unaami and the Arctic in climate change. Such feedbacks include surface albedo and cloud changes as well as air chemistry processes and the global ocean overturning circulation.

The fourth hypothesis is that:

The physical changes of Unaami have large impacts on the Arctic ecosystems and society. This is true whether Unaami is related to climate change or not. Clearly if Hypothesis 2 is true, Unaami is related to climate change, and the consequences are global, involving changing weather patterns and rising sea level all over the world. We already have indications of the impacts of Unaami at middle to high latitudes. We already see possible changes in fisheries, transportation and resource exploitation. Weather at middle latitudes is affected by the AO and the Arctic response to the AO. For example, precipitation patterns in the Northwest United States and air temperatures in Europe are strongly related to the AO. An increase in the stratification of the

North Atlantic associated with Unaami is likely to reduce global ocean overturning with an immediate effect on European weather and possible long-term effects on global climate. Many important consequences of Unaami involve the complex interaction of Unaami and non-climate-related human activity such as resource exploitation, economic development, and governmental decision making. Thus it is important to determine the impact of Unaami on the ecosystem and society.

The SEARCH strategy is conditioned in part by the knowledge that a number of long-term, large-scale observing systems have disappeared or are in danger of disappearing. The strategy includes four major activities:

- *Long-term observations* to detect and track the environmental changes
- *Modeling* to synthesize observations, to test ideas about the coupling between different components of Unaami, and to predict Unaami's future course
- *Process studies* to understand potentially important feedbacks
- *Application* of what we learn to understanding the ultimate impact of the physical changes on the ecosystems and societies, and to distinguish between climate-related changes and those due to other factors such as resource utilization, pollution, economic development, and population growth

Various components of the SEARCH program are at different stages of readiness. Many of the long-term physical observations, for example, can be started immediately. Much of the application component has yet to be developed. This science plan must, therefore, be considered a living document that will evolve as SEARCH progresses.

1. INTRODUCTION

This science plan is devoted to understanding significant changes in the arctic environment, especially those that have occurred roughly over the past decade. These recent changes stand out in a background of longer-term environmental trends and reinforce ideas that the Arctic is a sensitive indicator of climate change. The recent changes reflect complex couplings among atmospheric, oceanic, and terrestrial processes. In this sense, an analogy can be drawn with the El Niño-Southern Oscillation (ENSO) phenomenon. The physical changes produce changes in the ecosystem and living resources and affect the human population. They are making it harder for those who live in the north to predict what the future may bring. Because they are related to fundamental change in the global atmosphere, they may comprise a template for future global climate change. For these reasons we have named the complex of recent changes Unaami, the Yup'ik word for "tomorrow." Our goal is to understand Unaami.

1.1 The Arctic in Global Climate

It has been argued that the Arctic is a sensitive indicator of global change. Modeling studies such as those of Manabe et al. (1991), Manabe and Stouffer (1994), and Rind et al. (1995) have indicated this. Manabe et al. (1991) show that under a representative global warming scenario, temperature increases will be amplified in the Arctic due to feedbacks involving the snow and ice cover. The salinity of the upper Arctic Ocean will decrease because of enhanced precipitation at high latitudes. Rind et al. (1995) suggest that the pattern of temperature change in the Arctic represents anthropogenic global warming.

The Arctic is a significant component of the global climate system. First, the Arctic Ocean's stratification and ice cover provide a control on the surface heat and mass budgets of the north polar region, and thereby on the global heat sink (Manabe et al., 1991; Rind et al., 1995). If the distribution of arctic sea ice were substantially different from the present, the altered surface fluxes would affect both the atmosphere and the ocean and would likely have significant consequences for regional and global climate. Second, the export of low-salinity waters out of the Arctic Ocean, whether in the form of liquid or desalinated sea ice, has the potential to influence the overturning cell of the global ocean through control of convection in the subpolar gyres (e.g., Aagaard and Carmack, 1989). Recent suggestions that North Atlantic and Eurasian climate variability may be predictable on decadal time scales (Griffies and Bryan, 1997) rest in part on the variability of such upstream forcing in the Greenland Sea (Delworth et al., 1997). Third, arctic marine life is conditioned by sea ice, nutrient availability, and water density. Changes in these factors may affect marine ecosystems and biogeochemical cycling of essential nutrients and dissolved organic matter. Changes in the terrestrial hydrologic cycle may alter soil moisture, impacting plant communities and their grazers. Arctic soils serve as significant sources and sinks of global carbon dioxide and methane and appear to respond sensitively to altered soil moisture and temperature (Oechel et al., 1993, 1995; Oechel et al., 1997; Zimov et al., 1993, 1996). Finally, the results of studies by Thompson and Wallace (1998), Monahan et al. (2000), and others show that the atmospheric circulation of the Northern Hemisphere has been changing as part of a pole-centered pattern termed the Arctic Oscillation (AO). Recent modeling studies suggest the AO is a fundamental mode of atmospheric change and that the positive trend seen in recent decades may be symptomatic of anthropogenic climate change (Fyfe et al., 1999; Shindell et al., 1999a; Randel and Wu, 1999)

1.2 Long-term Trends

There is evidence of multidecadal and longer trends in several key arctic variables. Pronounced warming over northern Eurasian and North American land areas has occurred since the early 1970s. It has been largest during winter and spring and has been partly compensated by cooling over northeastern North America (Chapman and Walsh, 1993). Temperatures have also increased over the Arctic Ocean in spring and summer (Martin et al., 1997; Martin and Muñoz, 1997). These changes are broadly in agreement with those depicted in model anthropogenic change experiments. Reconstructions based on proxy sources indicate that late 20th century arctic temperatures are the highest of the past 400 years. Statistical analysis of this time series against records of known forcing mechanisms suggests that the recent warming has an anthropogenic component (Overpeck et al., 1997). Available observations point to long-term and recently augmented reductions in sea ice cover (Maslanik et al., 1996; Bjorgo et al., 1997; Cavalieri et al., 1997; Zakharov, 1997; Rothrock et al., 1999). Recent data also suggest that past carbon accumulation has changed to a pattern of net loss (Marion and Oechel, 1993; Oechel et al., 1993, 1995, 2000; Zimov et al., 1993, 1996).

1.3 Recent Changes

Most alarming are rapid changes that have occurred in the past decade. These will be described in more detail in sections to follow, but to understand the motivation for this science plan, it is useful to review a few key findings.

In the Arctic Ocean, the influence of Atlantic water is becoming more widespread and intense. Data collected during several cruises in 1993–1995 (Carmack et al., 1995; McLaughlin et al., 1996; Carmack et al., 1997; Morison et al., 1998a; Steele and Boyd, 1998) indicate that the boundary between the eastern and western types of haloclines has advanced from over the Lomonosov Ridge to roughly parallel to the Alpha and Mendeleyev ridges. In terms of longitudinal coverage, this means the area occupied by the eastern water types is nearly 20% greater than previously observed. Results from these cruises all suggest a warming of the Atlantic water cores over the major ridge systems. Historical data of Gorshkov (1983) and Treshnikov (1977) and the Environmental Working Group (EWG, 1997) give no indication of such warm cores and show maximum temperatures over the Lomonosov Ridge 1°C colder. The salinity and temperature changes appear to have begun in the late 1980s. Data from 1991 (Anderson et al., 1994; Rudels et al., 1994) show a slight warming near the Pole, and Quadfasel (1991) reports warmer than usual temperatures in the Atlantic water inflow in 1990, but the differences from climatology seen during the subsequent cruises are much larger.

The observed shift in frontal positions is associated with a change in ice drift (Colony and Rigor, 1993; Rigor and Colony, 1995) and atmospheric pressure patterns (Walsh et al., 1996). The ice drift and pressure fields for the 1990s are shifted counterclockwise 40°–60° from the 1979–1992 pattern, just as the upper ocean circulation pattern derived from the hydrographic data is shifted relative to climatology (Morison et al., 1998a). This change is consistent with the findings of Walsh et al. (1996) that the annual mean sea level atmospheric pressure is decreasing and has been below the 1970–1995 mean in every year since 1988. This change in atmospheric pressure is part of the recent large change in atmospheric circulation of the Northern Hemisphere documented by Thompson and Wallace (1998). The change in atmospheric circulation is also associated with changes in sub-arctic seas (Dickson et al, 2000). Perhaps most alarming, there have also been significant reductions in sea ice extent (Parkinson et al., 1999) and a 43% reduction in average sea ice thickness (Rothrock et al., 1999) in recent decades.

There have been changes in terrestrial variables as well. Changes in air temperature have been attended by reductions in spring snow cover since the mid–1980s (Robinson et al., 1993, 1995). Arctic glaciers have exhibited negative mass balances, paralleling a global tendency (Dyurgerov and Meier, 1997; Dowdeswell et al., 1997). Other studies point to increased plant growth (Mynemi et al., 1997), northward advances of the tree line (D'Arrigo et al., 1987; Nichols, 2000), increased fire frequency (Oechel and Vourlitis, 1996; Stocks, 1991), and thawing and warming of permafrost (Pavlov, 1994; Osterkamp and Romanovsky, 1996, 1999).

1.4 Community Reaction, Organizational Efforts to Date

As the scientific community became aware of the magnitude of recent environmental changes, a number of us took a first step to explore the scientific issues and opportunities by circulating an open "Dear Colleague" letter (April 1997) describing many of the observations outlined above. Ultimately, 40 scientists from 25 institutions co-signed the letter. These included 30 scientists from 17 U.S. institutions and 10 scientists from eight institutions in six other countries. The letter was also endorsed by the Arctic System Science/Ocean-Atmosphere-Ice Interactions Science Steering Committee (ARCSS/OAII SSC) as consistent with the ARCSS/OAII goals. Consequently the Arctic System Science (ARCSS) section of the NSF Office of Polar Programs agreed to sponsor a workshop to explore the extent of the Arctic change and to begin planning a program to study it.

The workshop was held November 10–12, 1997, in Seattle, Washington. It was open to all, and those with data or modeling results indicating changes in the physical characteristics of the Arctic over the past 10 years were strongly urged to attend. Invitations to the workshop were spread informally through the Internet and through the offices of the Arctic Research Consortium of the United States (ARCUS). A total of 74 scientists from many disciplines attended the meeting, 65 from the United States and 9 from other countries. The meeting had two dominant elements. The first was presentation of results summarizing recent changes in the Arctic's environment. The second consisted of working group discussions of key questions and observables describing the changes. This evolved into a discussion of implications and overarching questions. Through the talks, and in preparing the workshop report, we learned of the temporal correlation between the shift in the AO index (Thompson and Wallace, 1998) and the temperature increase of the Arctic Ocean Atlantic water, the increase in the surface air temperature over the Russian Arctic, the Arctic Ocean circulation changes, and the freshening in the upper Beaufort Sea. The observations suggest that recent changes are arctic-wide and at least at decadal-scale, with broad connections to changes at lower latitudes. The workshop participants agreed that this change must be tracked and analyzed. A workshop report (Morison et al., 1998b) describes the results and conclusions. The report was approved and disseminated in the early autumn of 1998.

At its meeting October 20, 1998, the ARCSS/OAII SSC termed the new program the Study of Environmental Arctic Change (SEARCH) and formulated a broad organizational plan for a program of long time series measurements, modeling, and process studies to track and understand the recent changes. The Committee also recognized that the scope of SEARCH might extend beyond the traditional bounds of OAII and even perhaps the polar research community. The ARCSS/OAII SSC directed the formation of a SEARCH Science Steering Committee (SSSC) to work with the scientific community to develop the SEARCH Science Plan for submission to the ARCSS/OAII SSC and NSF-OPP.

With this mandate, a list of SEARCH SSC members was composed and submitted to the ARCSS/OAII SSC. It was reviewed and revised to fit the broad scope of SEARCH. These members of the SEARCH SSC met April 22–23, 1999, to write a preliminary outline for the Science Plan and formulate the agenda and invitation list for the Science Plan Workshop. The SEARCH SSC members in attendance were James Morison (University of Washington), David Battisti (University of Washington), Louis Codispoti (Horn Point Laboratory, University of Maryland), Hajo Eicke (University of Alaska), James Overland (NOAA Pacific Marine Environmental Laboratory), Jonathan Overpeck (University of Arizona), Mark Serreze (University of Colorado). Edward Carmack, Douglas Martinson, Peter Schlosser, and Charles Vorosmarty could not attend. In response to the broadening interest in the program, the SSSC appointed working group leaders in biology (Jackie Grebmeier of the University of Tennessee) and human-dimension issues (Jack Kruse of the University of Alaska and University of Massachusetts).

In the summer of 2000, several members of the SSC rotated off and several new members were added. The members of SEARCH SSC as of spring 2001 are:

Vera Alexander (University of Alaska)

Lou Codispoti (Horn Point Laboratory, University of Maryland)

Tom Delworth (Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey)

Bob Dickson (CEFAS, Lowestoft, UK)

Hajo Eiken (University of Alaska)

Jackie Grebmeier (University of Tennessee)

Jack Kruse (University of Massachusetts and University of Alaska)

James Morison (Chair) (University of Washington)

Jim Overland (Pacific Marine Environmental Laboratory, Seattle, Washington)

Jonathan Overpeck (University of Arizona)

Peter Schlosser (Lamont Doherty Earth Observatory, New York)

Mark Serreze (University of Colorado)

John Walsh (University of Illinois at Urbana-Champaign)

The SSC has also received a great deal of help with the development of the Science Plan from many other members of the polar research community, including Lawson Brigham (Scott Polar Research Institute, Cambridge University), David Bromwich (Byrd Polar Research Institute, Ohio State University), Terry Chapin (University of Alaska), Dennis Darby (Old Dominion University, Virginia), Larry Hamilton (University of New Hampshire), Sue Moore (National Marine Fisheries Laboratory, Seattle), Vladimir Romanovsky (University of Alaska), Gus Shaver (Marine Biological Laboratory, Woods Hole, Massachusetts), and Robert Shepson (Purdue University).

The SEARCH Science Plan Workshop was held June 30–July 2, 1999, at the University of Washington with the support of NSF grant OPP-9978390. (For a list of participants, see page 85.) The invitees included experts from many fields: atmospheric science, oceanography, hydrology and frozen ground, paleoclimatology, glaciology, chemistry, biology, and human dimensions. The meeting was organized to form working groups to address the various sections of the outline. Broadly speaking, the main issues included assessment of the observed changes, their relation to climate, impacts, objectives, and approach.

Program scope was a prime concern of the workshop. Because the increase in the AO index appears to be intertwined with other environmental changes, there was some concern that SEARCH was being narrowed down to a study of the AO, with less consideration for the whole complex of changes in the atmosphere, ice, ocean, and ecosystem. Most felt that a study of change in general would be much too broad. Several suggestions were made to limit SEARCH to particular time or length scales, but the time and space scales of the observed changes are not fully known. In the end, the issue of scope was resolved by agreeing that SEARCH would not be limited to a particular set of disciplines or scales; the discussions at the workshop suggest these boundaries are unknown. Instead, the scope of SEARCH will be defined by a focus on phenomena directly associated with the air-ice-ocean complex of changes we have been observing. As discussed at the outset, we christened this complex Unaami. Like the El Niño-Southern Oscillation phenomenon, the Unaami complex is a climate-driven phenomenon with important effects on the ecosystem and society.

It was agreed that the focus of SEARCH would be to understand Unaami and its implications. The physical science effort will seek to identify and elucidate the feedbacks between land, air, ice, and ocean that drive Unaami and couple it to the rest of the globe. The ultimate benefit will be the ability to predict the course of Unaami and, we hope, to adapt to its consequences. The biological science effort will address associated ecosystem changes, while the social science effort will examine the human impact of Unaami. In drafting the Science Plan, the SSC has used these as guiding foci. We think this will give SEARCH a strong, cohesive backbone from which the subjects may vary by discipline and scale as broadly as appropriate.

The plan that follows is broken into four main sections: (1) background describing the recent changes and long-term trends as we know them and the science and societal issues that make these critical, (2) hypotheses about the changes, (3) the objectives of SEARCH, and (4) our recommended strategy.

2. BACKGROUND: CHANGES IN THE ARCTIC

2.1 Atmospheric Changes

The behavior of the arctic atmosphere is changing (Serreze et al., 1999). There have been clear changes in the pressure field and circulation pattern, surface temperature, and cloudiness. Though the records are spotty, there are indications of changes in precipitation and evaporation.

2.1.1 Atmospheric Pressure and Circulation

Walsh et al. (1996) examined changes in sea level pressure (SLP) over the Arctic Ocean from 1979–1994. Their analysis shows reductions in SLP over the period 1987–1994, compared with the previous eight-year period, which are largest near the Pole and statistically significant for autumn and winter. Serreze et al. (1997) present similar results. The yearly average pressure maps of the International Arctic Buoy Programme (IABP) suggest that the shift in the atmospheric pressure pattern began around 1988 or 1989. Before that time one of the dominant features of the arctic SLP field, the Beaufort High, was usually centered over 180° longitude, but after 1988 the Beaufort High, on an annual average, was weaker and usually confined to western longitudes. This change is consistent with the findings of Walsh et al. (1996) that the annual mean atmospheric surface pressure in the Polar Basin is decreasing and has been below the 1979–1995 mean in every year since 1988. Serreze et al. (2000) also show significant increases in cyclone activity north of 65°N since at least 1958 for all seasons except autumn, and increased cyclone intensity for all seasons. There have been pronounced increases in cyclonic activity at higher latitudes during summer.

Proshutinsky and Johnson (1997) and Johnson et al. (1999) categorize the decadal variations in atmospheric pressure in terms of the response of the sea level in a barotropic ocean model. They report that an anticyclonic mode, with a raised sea level in the center of the Arctic Ocean and high atmospheric pressure over the basin, characterized 1945–1952, 1957–1962, 1971–1980, and 1984–1988. Other periods, especially 1989–1998, have been characterized by a cyclonic mode with a lower sea level in the center of the basin and lower atmospheric pressure in the basin. Their strongly cyclonic trend in the 1990s is in agreement with the findings of Walsh et al. (1996).

Linkages have been found with changes at lower latitudes. Hurrell (1996) argues that almost half of the wintertime (December–March) temperature variance over the Northern Hemisphere (north of 20°N) since 1935 can be explained by the combined effects of circulation variability based on the North Atlantic Oscillation (NAO) index (31%) and the Southern Oscillation (SO) index (16%). The SO index is a common index for the state of ENSO. The positive phase of the NAO is associated with mutual strengthening of the Icelandic Low and Azores High. Under the positive mode, surface winds tend to be northerly over Greenland and eastern Canada, with associated negative temperature anomalies. Correspondingly, west to southwesterly winds tend to advect warm, moist air masses into northern Europe and Scandinavia. The NAO is best expressed during the cold season. While exhibiting considerable interannual variability, the NAO has been in a generally positive phase since about 1970 with several particularly large positive events since about 1980 (Hurrell, 1995, 1996). As will be discussed below, Deser and Blackman (1993), Maslanik et al. (1998), Swift et al. (1997), and Dickson et al. (2000) relate changes in the arctic ice cover and ocean properties to the NAO.

With regard to the Pacific side of the Arctic Basin, Overland et al. (1997) report that the position of the tropospheric cold pool is approximately centered over the Canadian Arctic and the Beaufort Sea, displaced from the North Pole by orographic effects of the North American mountain ranges. The result is advection of atmospheric heat and moisture into the Greenland and Barents seas and the eastern Arctic. The position of this arctic cold pool, in turn, fluctuates with the position of the arctic front and the atmospheric circulation in the western Pacific. New analyses reveal a polar pattern in these fluctuations of the cold pool and North Pacific circulation, and this polar pattern has undergone a marked shift since 1990 that has brought the center of the cold pool closer to North America. This seems to represent a new polar teleconnection pattern relating conditions in the North Atlantic and North Pacific.

The most comprehensive picture of atmospheric variability is presented by considering the leading empirical orthogonal function (EOF) of sea level pressure for the Northern Hemisphere. Thompson and Wallace (1998) show that the variation of this EOF for winter, which they term the Arctic Oscillation (AO), is well correlated with other changes in atmospheric conditions. The time variation of the AO index resembles that of the more regional NAO index. Because the AO describes a hemispheric variation that includes the North Atlantic, the NAO can be considered as an expression of the AO. As shown in Figure 2-1a (Thompson and Wallace, 1998, Figure 1), the strong negative lobe of the AO spatial structure is centered over the Arctic Ocean. The AO has weaker positive lobes over the North Pacific and North Atlantic. The time series of the wintertime AO index is similar to that of the wintertime NAO index (Figure 2-1b). Although the AO was less energetic than the NAO before 1960, both indices have been rising since the mid-1960s, accompanied by an increase in Northern Hemisphere surface air temperature over the same period. Thompson and Wallace find that the AO index is more highly correlated with surface air temperatures over the Northern Hemisphere, and the Eurasian continent in particular, than is the NAO. The positive mode of the AO is associated with reduced pressure over the Arctic Ocean. The particularly rapid increase in the AO index shown after the late 1980s (Figure 2-1b) thus agrees with the results of Walsh et al. (1996). Watanabe and Nitta (1999) also confirm the timing of the change. They compare annual 500-hPa height pattern changes to averages for the previous five and ten year periods, and conclude that the northern hemisphere 500-hPa field underwent significant

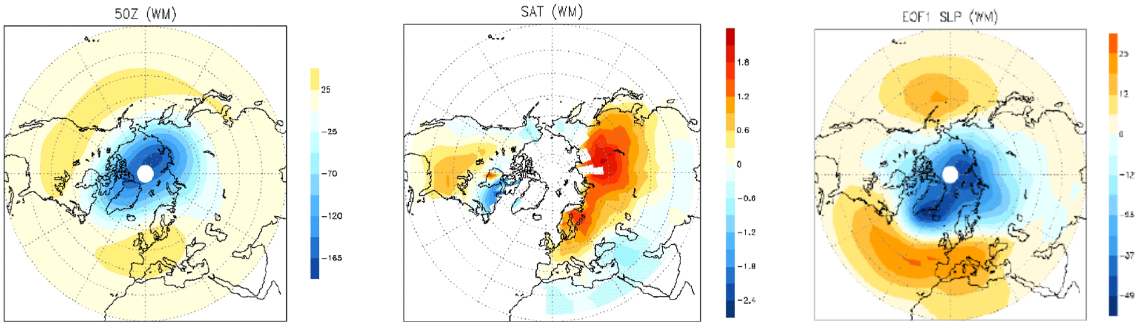


Figure 2-1a Regression maps for geopotential height at 50 mb (Z50), surface air temperature (SAT), and surface sea level atmospheric pressure (EOF1 SLP) based upon the leading principal component of wintertime (November–April) monthly mean sea level pressure anomalies (AO index) for 1947–97. Contour intervals (expressed in units per standard deviation of the AO index) are 30 m for Z50, 0.5 K for SAT, and 10 m for SLP. (Reproduced from Thompson and Wallace, 1998, with permission of American Geophysical Union.)

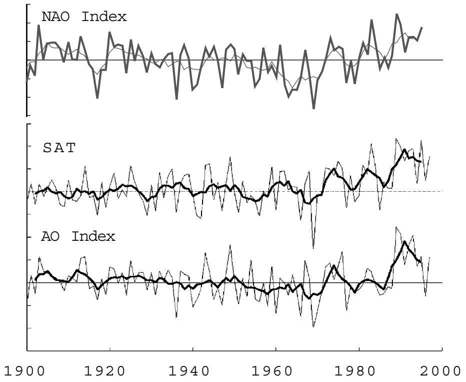


Figure 2-1b Normalized (by standard deviation) wintertime expansion coefficient time series for the SAT and SLP regression maps of Figure 2.1a for 1900–1997. (Reproduced from Thompson and Wallace, 1998, with permission of American Geophysical Union.) The normalized wintertime NAO index (sea level pressure at Lisbon, Portugal minus sea level pressure at Stykkisholmor, Iceland) has been added at top for comparison as in Morison et al. (2000).

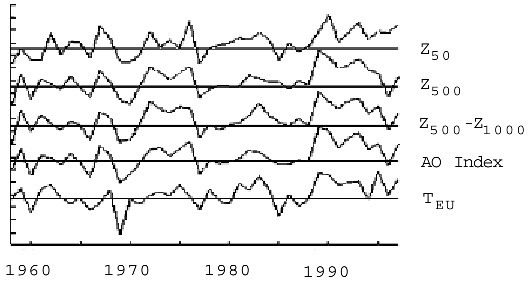


Figure 2-1c Time series of normalized expansion coefficients for the Z50, Z500, Z500–1000, and the mean sea level pressure anomalies (AO index), and Eurasian mean (40–70° N, 0–140° E) SAT anomalies (TEU). (Reproduced from Thompson and Wallace, 1998, with permission of American Geophysical Union.)

change in 1989, with a strong height decrease centered over the Arctic Ocean.

One of the most remarkable aspects of the Thompson and Wallace (1998) atmosphere study is the connection between the leading EOF of pressure at sea level and in the stratosphere (50 hPa). The time series of the 50-hPa geopotential height field and surface coefficients are strongly correlated, indicating that the change in the atmosphere extends from the stratosphere to the surface (Figure 2-1c). The results of Thompson and Wallace (1998) suggest that the atmospheric change may be driven either by radiatively induced temperature changes in the stratosphere or by a barotropic response of the polar vortex to greenhouse warming in the troposphere.

In SEARCH the term Arctic Oscillation has come to take on a broader meaning than the definition of Thompson and Wallace (1998). This reflects a trend in the research community that has been vigorously studying the structure of the AO. It is clear that there has been an increase in the zonal wind speed in the atmospheric polar vortex in the 1990s relative to the 1980s; this is true for the troposphere (Tanaka et al., 1996) and the lower stratosphere (Waugh et al., 1999). These features are associated with a cooling of the stratosphere (Pawson and Naujokat, 1999) and a decrease in sea level pressures over the Arctic (Walsh et al., 1996). Thompson and Wallace (1998) sought to capture the character of this "annular mode" by formulating an "AO index" based on the first empirical orthogonal function (EOF) of the monthly wintertime sea level pressure (SLP). Because upper atmospheric variability correlates strongly with their AO index, there has been much interest in the AO since publication of the Thompson and Wallace paper. Deser (2000) notes that separate Atlantic and Pacific modes may, in fact, project onto the EOF-based AO index. Monahan et al. (2000) suggest that the AO can be split into a more arctic-centric atmospheric mode, plus the NAO. Kodera et al. (1999) also suggest a North Atlantic mode and a more zonal polar night jet. Overland and Adams (2001) show that much of the month-to-month variability of the AO index is associated with the NAO, but that decadal-scale differences are more arctic-centric. Thus, our use of the term "Arctic Oscillation" in the SEARCH Science Plan is associated with the complex of atmospheric changes related to the increased strength of polar vortex rather than only with the EOF-SLP based AO index. The recent set of papers on the AO reinforces the importance of further understanding of the AO as an arctic-wide phenomenon of decadal and/or global change.

2.1.2 Surface Air Temperature and Cloudiness

Serreze et al. (2000), citing the results of Chapman and Walsh (1993) and Jones (1994), indicate that from 1966 to 1995 the surface air temperature has increased markedly over the Eurasian and northwest North American landmasses. Locally, trends exceed 0.5°C per decade. Over the midlatitute ocean basins, temperature changes are generally smaller or negative. Pronounced cooling characterizes the western subpolar North Atlantic and extends into land areas over eastern Canada and southern Greenland. The annual results are primarily due to trends during winter and spring. Spatial trends for summer and autumn are weaker, with autumn showing small negative trends over northern North America and Europe.

Interpretation of temperature trend changes if decades prior to 1970 are included. Based on zonal means for the 55–85°N zonal band, annual mean temperatures fell during the period 1940–1970 (see Serreze et al., 2000). While recognizing sampling problems in the early part of the record, it appears that annual mean temperature from 1920–1940 rose even more markedly than during the post-1970s period. Recent warming, however, is not in doubt and appears to extend into the central Arctic Ocean. By combining all Russian North Pole (NP) drifting station records from 1961–1990, Martin et al. (1997) find statistically significant increases in the May and June air temperatures of 0.89°C and 0.43°C per decade, as well as significant increases for summer as a whole.

The spatial distribution of surface temperature trends in the Arctic appears to be largely associated with the AO. Generally the trends (Figure 2-1a; Thompson and Wallace, 1998) agree with those described by Chapman and Walsh (1993) and Martin et al. (1997). Further information is available from the gridded Polar Exchange at the Sea Surface (POLES) 2-m air temperature data set for 1979–1997, which blends the NP station data with Inter-

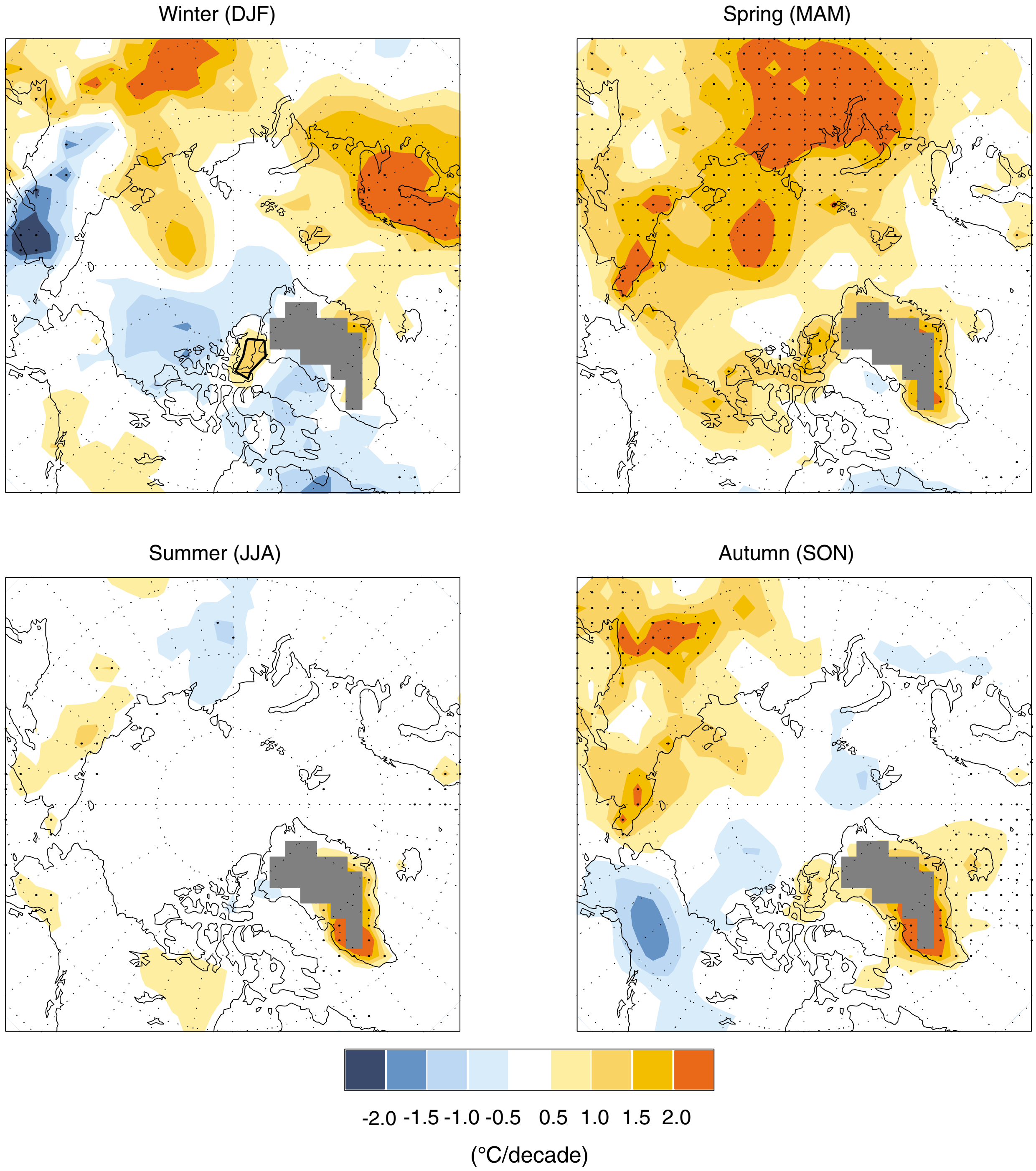


Figure 2-2 *Season surface air temperature trends from IABP/POLES data set for 1979–1997. The black areas indicate trends significant at 99%. (Reproduced from Rigor et al., 2000, with permission of American Meteorological Association.)*

national Arctic Buoy Programme (IABP) drifting buoy and coastal station records. Figure 2-2 from Rigor et al. (2000) shows the seasonal mean temperature trends derived from these data. Rigor et al. (2000) find a trend of +1°C per decade during winter and spring on the Eurasian side of the Arctic but a trend of –1°C per decade on the Canadian side. In spring there is a warming trend over the whole basin, but it is largest (up to 2°C per decade) on the Eurasian side of the Arctic. The data show even larger trends over the Russian Arctic. Rigor et al. (2000) find the AO accounts for more than half the warming trends over Alaska, Eurasia, and the eastern Arctic.

Stone (1997) discusses temperature, snowmelt, and cloud cover measurements at Barrow, Alaska, from 1965 to 1995. These indicate a 31-year warming trend in winter and spring and cooling in fall. Although Stone (1997) does not discuss short-term interannual variations, in the context of this review we note that since 1989 there are enhanced positive trends in temperature and cloud cover for the months of November (counter to the long-term trend), January, February, and April. The strong positive correlation between temperature and cloud cover leads Stone (1997) to the conclusion that the warming is associated with changes in cloud distribution due to changes in atmospheric circulation.

The study of Overpeck et al. (1997) places the recent warming in the perspective of the record for the past several centuries. They attempt to explain variability in a 400-year arctic temperature record reconstructed from proxy sources in terms of the relative roles of changes in trace gas loading, irradiance (solar radiation), aerosol loading from volcanic eruptions, and atmospheric circulation. They conclude that pronounced arctic warming between 1820 and 1920 is primarily due to reduced volcanic aerosols and increasing irradiance. After 1920, both high insolation and low aerosol loading likely continued to influence arctic climate, but exponentially increasing trace gas concentrations probably played an increasingly dominant role. Their record indicates that arctic temperatures in the 20th century are the highest of the past 400 years.

2.1.3 Precipitation and Evaporation

Assessing changes in the atmospheric components of the northern high-latitude hydrologic budget is difficult, even for base variables such as precipitation. The station network is sparse, and there are problems of undercatch of solid precipitation, although some investigators (e.g., Groisman et al., 1991; Groisman and Easterling, 1994) have attempted to correct for gauge biases. Based on available data, annual precipitation for the period 1900–1994 has increased over both North America and Eurasia (Nicholls et al., 1996). For North America, positive trends in annual precipitation as well as snowfall are most apparent (up to a 20% increase) during the past 40 years over Canada north of 55°N (Groisman and Easterling, 1994). For the former Soviet Union, most of the increases occurred during the earlier part of the 20th century and are larger during winter than during summer, with a tendency for reduced precipitation in some areas since the middle of the century (Groisman et al., 1991). As summarized for zonal bands, annual precipitation for the period 1990–1995 has increased for the region 55°N–85°N, with the largest changes during autumn and winter (Serreze et al., 2000). The recent analysis of Dai et al. (1997) confirms these results.

From a hydrologic viewpoint, precipitation minus evaporation (P–E) is arguably more important than precipitation by itself. Two studies (Walsh et al., 1994; Serreze et al., 1995) have utilized the network of northern high-latitude rawinsonde stations to examine P–E averaged over the Arctic Basin north of 70°N via the “aerological approach.” Data from the early 1970s through the early 1990s reveal no obvious trends, with a mean annual value around 16–17 cm. Dickson et al. (2000) reveal a considerable change in the *distribution* of atmospheric moisture flux between the two NAO extreme states, with the main meridional flux to the Arctic through 70°N becoming centered on the Nordic seas sector during NAO-positive extrema. Parallel efforts using analyzed wind and moisture fields from the NCEP/NCAR and European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis archives yield somewhat higher mean annual values (18–19 cm), but also no trends (Bromwich, personal communication, 1997).

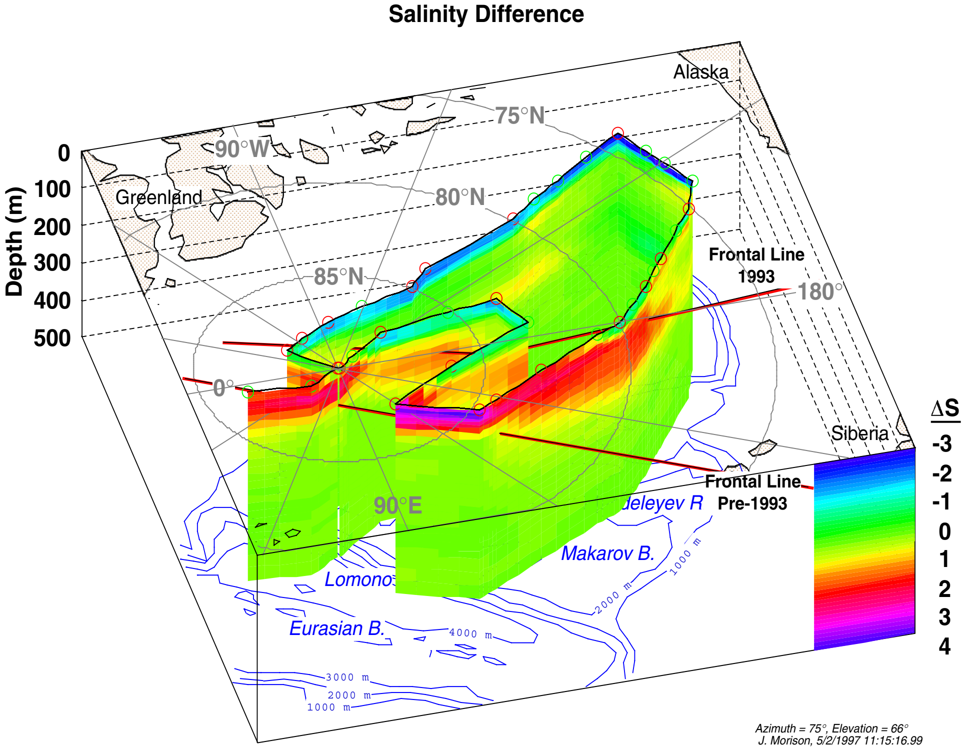
2.2 Ocean and Sea Ice Changes

The Arctic Ocean and sea ice have changed in concert with the change in atmospheric circulation (Serreze et al., 1999; Morison et al., 1998a; Steele and Boyd, 1998; Morison et al., 2000).

2.2.1 Ocean

The results of several recent expeditions indicate that the presence of Atlantic-derived water in the Arctic has increased. Data collected from the USS *Pargo* (Morison et al., 1998a), and the *Henry Larsen* in 1993 (Carmack et al., 1995; McLaughlin et al., 1996), the *Polar Sea* and the *Louis S. St. Laurent* (Carmack et al., 1997) in 1994, and the USS *Cavalla* in 1995 (Steele and Boyd, 1998) all indicate that the boundary between the eastern (Atlantic) and western (Pacific) halocline types has moved. Earlier it was approximately aligned with the Lomonosov Ridge, but now lies roughly over the Alpha and Mendeleyev ridges. The area occupied by eastern water types is therefore nearly 20% greater than previously observed. The greater Atlantic influence is also manifest in warm cores observed over the Lomonosov and Mendeleyev ridges in the USS *Pargo* and *St. Laurent* data, with temperatures over the Lomonosov Ridge greater than 1.5°C. Carmack et al. (1995) and McLaughlin et al. (1996) also observed an Atlantic layer temperature increase over the Mendeleyev Ridge. The earlier data of Gorshkov (1983) and Treshnikov (1977) give no indication of such warm cores over the Mendeleyev Ridge and show a temperature over the Lomonosov Ridge nearly 1°C lower. The recently prepared digital atlas of Russian hydrographic data (EWG, 1997) confirms that no temperatures greater than 1°C were observed during numerous investigations between 1950 and 1989.

Figure 2-3a, taken from Morison et al. (2000), illustrates the differences between temperature and salinity measured in the fall of 1993 from the USS *Pargo* (Morison et al., 1998a) and climatological temperature and salinity in the Joint U.S.-Russian Atlas of the Arctic Ocean: Winter Period (EWG, 1997; Gore and Belt, 1997). The EWG atlas (EWG, 1997) is a compilation of Russian and western wintertime hydrographic data taken from 1948 to 1987. It has been objectively gridded and separated into decadal and total statistics. The differences between the 1993 data and the climatology are plotted as color contours along the USS *Pargo* track in the three-dimensional views of Figures 2-3a and 2-3b. Figure 2-3a shows that the salinity in the upper 250 m has increased dramatically in a wedge extending to a front roughly aligned with the Alpha and


Salinity Difference

Azimuth = 75°, Elevation = 66°
J. Morison, 5/2/1997 11:15:16.99

Figure 2-3a *Contours of the difference in salinity between the 1993 SCICEX cruise (Morison et al., 1998) and (minus) the salinity from the EWG Joint U.S.-Russian Atlas (EWG, 1997) interpolated to the 1993 SCICEX cruise track. The largest difference is due to the shift in the front between Atlantic and Pacific dominated waters. The front was previously over the Lomonsov Ridge. It now lies roughly over the Alpha and Mendeleyev ridges as indicated by the red and black lines. The frontal shift results in a 2.5 o/oo increase in the salinity in the upper 200 m of the Makarov Basin. (Reproduced from Morison et al., 2000 with permission from the Arctic Institute of North America.)*

Mendeleyev ridges. Climatologies (Levitus, 1982; Gorshkov, 1983; EWG, 1997) indicate this front was more nearly aligned with the Lomonosov Ridge in the past. The position of the front between the saltier surface waters of the eastern Arctic and the fresher waters of the western Arctic has advanced about 40° of longitude across the Makarov Basin. As a result, the presence of Atlantic-derived water in the basin has increased, and the surface salinity in the Makarov Basin has increased 2.5%. The increase is likely a conservative estimate in the uppermost layers because the EWG data represent winter conditions, while the *Pargo* data are from the end of summer and early fall when the surface layers would normally be fresher. This is likely part of the reason for the negative salinity difference shown for the surface waters of the Canadian Basin. The salinity increase in the Makarov Basin is comparable to the instantaneous spatial variability over the whole upper Arctic Ocean. Comparison with statistics in the EWG atlas also indicates that the change is several times the typical interannual variability in the Makarov Basin.

Figure 2-3b shows that temperature has also increased in the warm core of Atlantic water over the Lomonosov Ridge, with the maximum temperature over 1°C greater than at any time observed in the past. Furthermore, the Atlantic layer is shallower than in the past, so that the temperature at 200 m is over 2°C greater. A less intense warm core appears over the Mendeleyev Ridge, and there is a general warming in the Makarov Basin centered near 200 m. The slight cooling centered at about 100 m in the Makarov Basin is associated with the influx of more saline water from the Eurasian Basin. These observations suggest that the whole Makarov Basin has taken on a more Atlantic character. Furthermore, the extent of the water temperature maximum in the Bering Sea has retreated behind the advancing Atlantic water front. Decadal statistics from the EWG atlas indicate that this change is greater than the normal variability.

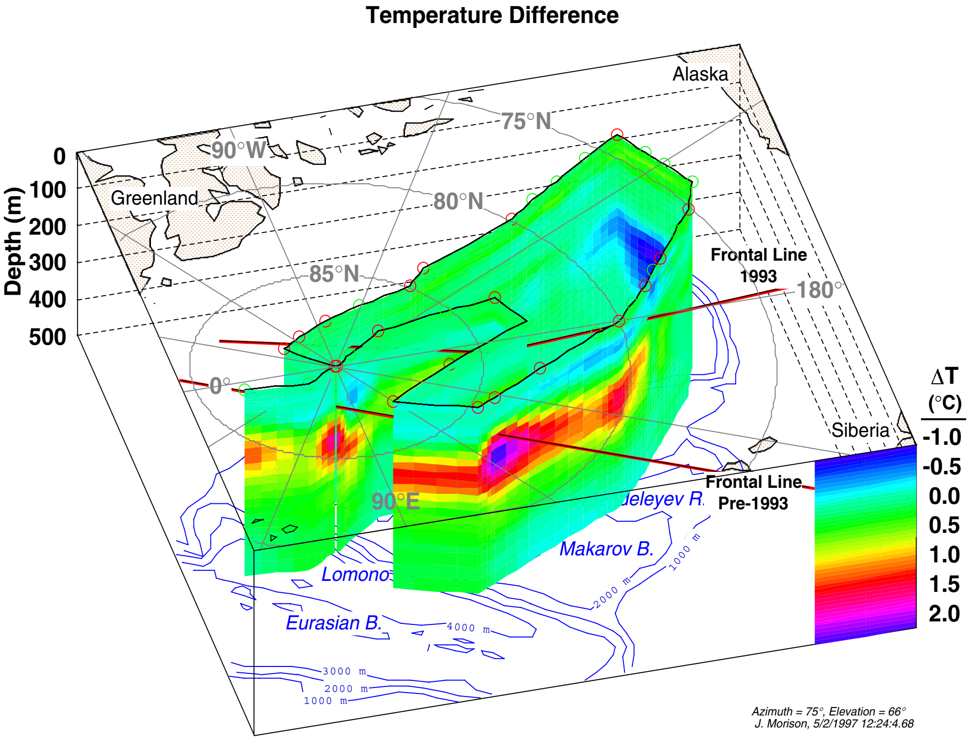


Figure 2-3b *Contours of the difference in temperature between the 1993 SCICEX cruise (Morison et al., 1998) and (minus) the temperature from the EWG Joint U.S.-Russian Atlas (EWG, 1997) interpolated to the 1993 SCICEX cruise track. The 200-m temperature increase in the Makarov Basin region is affected by the frontal shift described in Figure 2-3a. The largest difference is due to the appearance of warm cores over the Lomonosov and Mendeleyev ridges. This results in an increase in the temperature maximum of over 1.5° in the Atlantic water. Over the Lomonosov Ridge the core of the Atlantic water is now at a shallower depth. This results in a temperature increase of over 2° at a 200-m depth. (Reproduced from Morison et al., 2000, with permission from the Arctic Institute of North America.)*

The cooling below 200 m in the Canada Basin is due to a 25–50 m downward displacement of the thermocline in the *Pargo* data relative to the EWG climatology.

The extensive data gathered during the Arctic Ocean Section (AOS) of 1994 (Carmack et al., 1997; Swift et al., 1997) give a measure of the timing, depth, and breadth of the change in ocean structure, particularly the warming of the Atlantic water. The warming in the Atlantic layer represents more than a simple increase of the temperature maximum. Comparison of the 1994 data gathered over the Eurasian slope of the Lomonosov Ridge with data from the same area gathered during the *Oden* cruise in 1991 shows that the temperature maximum has become both warmer and shallower, and that the warming is also seen from the top of the thermocline to depths below 1500 m. The temperature gradient in the thermocline is therefore also greater in the 1994 data.

One of the most remarkable aspects of the AOS observations is the geographic distribution of warm Atlantic water. Besides the temperature maximum over the Lomonosov Ridge, temperature maxima near 1°C were observed at four places over the Chukchi boundary and Mendeleyev Ridge (Figure 2-3b). This region has been visited so rarely in the past that it is difficult to quantify the warming, but it is likely at least 0.2°C. The position of the warm cores suggests that the Atlantic water moves with a barotropic flow following the isobaths along the slopes and ridges, and that the warm water is a tracer that is carried along by this flow. Swift et al. (1997) use the temperature as a tracer to infer the connection to the temperature of the Atlantic water inflow through Fram Strait. At various locations they estimate the time at which the Atlantic water entered Fram Strait, and by comparing the phase-shifted core temperatures with those actually measured near Fram Strait, they argue that the warming in the Arctic Basin is due to changes in the temperature of the Atlantic water inflow.

The changes observed in salinity and temperature appear to have begun in the late 1980s. The differences from climatology illustrated by Figures 2-3a and 2-3b are too large and spatially consistent to be attributed to instrument error or normal seasonal and interannual variability (Grotefendt et al., 1998; Dickson et al., 2000). Data from the *Oden* cruise in 1991 (Anderson et al., 1994; Rudels et al., 1994) show a slight warming near the Pole, and Quadfasel (1991) reports warmer than usual temperatures in the Atlantic water inflow in 1990, but the differences from climatology seen during the subsequent cruises are much larger. Comparison of the sigma-theta profiles from the 1991 *Oden* and 1994 AOS cruises (Carmack et al., 1997; Swift et al., 1997) indicates that the Atlantic water from 200 to 1500 m was less dense in 1994 than in 1991, and the large differences between the 1991 and 1994 data suggest that we are seeing an event unique to the 1990s.

Even more recent observations reveal other aspects of change that have consequences for the thermodynamic balance of the Arctic Ocean. The shoaling of the Atlantic water discussed above suggests that the halocline, which isolates the surface from the warm Atlantic water, is growing thinner. Steele and Boyd (1998) show from observations during the 1995 cruise of the USS *Cavalla* that the cold halocline is indeed continuing to thin. They compare Arctic Ocean hydrographic data sets from the 1990s and the EWG atlas (EWG, 1997) and show that the cold halocline layer in the Eurasian Basin has retreated during the 1990s to cover significantly less area than in previous years. This agrees with a comparison of data from the 1991 *Oden* and the 1996 *Polarstern* cruises by Schauer and Björk (personal communication, 2000). Steele and Boyd (1998) find a retreat of the cold halocline from the Amundsen Basin into the Makarov Basin, and the latter is the only region with a true cold halocline layer found during the cruise of the USS *Cavalla*. Since the cold halocline layer insulates the surface and sea ice from the heat of the Atlantic water, these changes in the halocline could have profound effects on the surface energy balance and sea ice in the Arctic. The winter mixed layer in the mid-Eurasian Basin was also saltier in 1995 than ever recorded in the 40-year EWG (1997) climatology, continuing the Eurasian Basin trend seen in 1993 (Figure 2-3b).

There have been changes in the Canada Basin. McPhee et al. (1998) report that during the SHEBA (Surface Heat Budget of the Arctic Ocean) deployment phase in October of 1997, multiyear ice near the center of the Beaufort Gyre was anomalously thin. The upper ocean was also both warmer (relative to freezing) and substantially less saline in 1997 than in previous years. The total salinity anomaly in the upper 100 m of the water column, compared with conditions observed in the same region during the Arctic Ice Dynamics Joint Experiment (AIDJEX) in 1975, is equivalent to an excess of about 2.4 m of freshwater, and heat content (relative to freezing) has increased by 67 MJ m^{-2}. During AIDJEX the change in salinity over the summer of 1975 implied melt equivalent to about 0.8 m of freshwater. Analogy with the seasonal progression observed during AIDJEX suggests that up to 2 m of freshwater input may have occurred during the summer of 1997, but from salinity changes alone we cannot distinguish between changes in ice melt and runoff. The increased heat content, combined with the thin ice, does suggest that during the summer of 1997 the ice concentration was lower so allowing more solar radiation to enter the upper ocean. McPhee et al. (1998) argue that these effects may be due to reduced ice convergence in the Beaufort Sea.

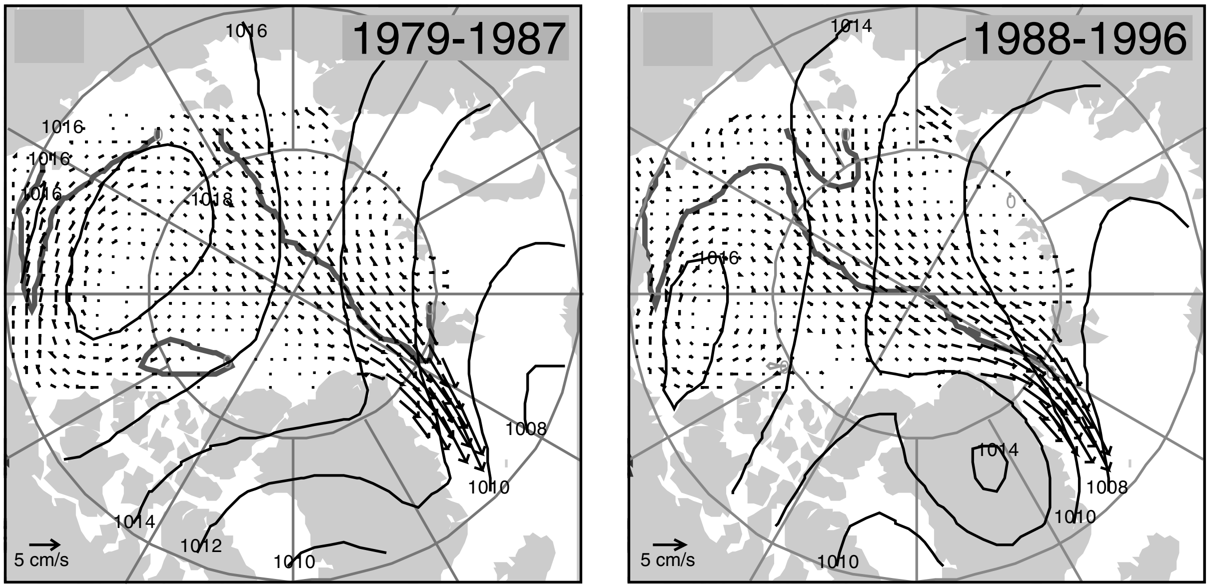


Figure 2-4 Average ice drift (arrows) and surface atmospheric pressure (contours) for 1979–1987 and 1988–1996. The broad gray line is the boundary between areas of cyclonic (upper right) and anticyclonic (lower left) ice drift. The Beaufort high decreased and shifted east in the 1990s, and the transpolar drift axis shifted producing more cyclonic ice motion. (Reproduced from Steele and Boyd, 1998, with permission of American Geophysical Union.)

The oxygen-18 and barium measurements of Macdonald et al. (1999) point to a significant amount (~40%) of the 1997 freshening at the SHEBA site being due to river runoff. They indicate that this was from the Mackenzie River and that the percentage of runoff was even greater farther south in the Beaufort Sea. A time series of observations shows a jump in the amount of sea ice melt in the early 1990s coinciding with other changes discussed here. Freshening may also be associated in part with a freshening of the Bering Strait inflow in the 1990s (Roach et al., 1995).

2.2.2 Surface Currents and Ice Drift

The changes in the Arctic Ocean appear to be related to changes in sea ice drift and atmospheric circulation. Morison et al. (1998a) show that the observed shift in ocean frontal position causes a shift in the geostrophically balanced, along-front surface current. This has shifted (Morison et al., 1998a; Steele and Boyd, 1998) in association with the decadal trend in the sea level atmospheric pressure (Walsh et al., 1996). Figure 2-4 from Steele and Boyd (1998) shows the sea level pressure and ice drift fields of the IABP (Rigor, personal communication, 1997) averaged for 1979–1987 and for 1988–1996. The patterns of pressure and ice drift for 1988–1996 are shifted counterclockwise about 35° from the 1979–1987 patterns, similar to the change in frontal position inferred from Figure 2-3 (about 40°). The shift in ice drift and the pressure fields is consistent with a similar comparison by Morison et al. (1998a). The yearly average pressure maps from the IABP indicate that the shift in the sea level pressure pattern began around 1988–1989. Before that time the Beaufort high was usually centered over 180° longitude, but after 1988 the Beaufort high was weaker and usually confined to western longitudes. This change is consistent with the findings of Walsh et al. (1996) that the annual mean sea level pressure in the Polar Basin has been below the 1979–1995 mean in every year since 1988. The time of the atmospheric shift corresponds approximately to our estimate of when the ocean changes began. Morison et al. (1998a) suggest that the atmosphere might in part drive the observed changes in ocean circulation by Ekman pumping, and that the effect of these circulation changes may reach deeper with time.

Maslanik et al. (1998) give consistent evidence of the change in ice drift as related to atmospheric circulation changes. Comparison of mean ice transport patterns for 1989–1996 estimated from satellite microwave imagery show the contraction of the Beaufort Gyre and shift of the transpolar drift relative to conditions in 1979–1988. They examine the relation of this change to the NAO index. Maslanik et al. (1998) indicate that the change in ice drift patterns has been in conjunction with the positive NAO index since 1989. However, in earlier years of positive NAO conditions this was not always the case, suggesting the low arctic sea level pressure of the 1990s (AO) is a critical ingredient in the circulation change. The ice transport through Fram Strait in the three years since 1989, with both the strongest positive NAO index and lowest arctic sea level pressure, is twice the transport in the three years from 1978–1996 with the most negative NAO index.

Using an ocean model run with atmospheric forcing over the past 50 years, Proshutinsky and Johnson (1997) predict two decadally varying regimes corresponding to anticyclonic and cyclonic circulations of the arctic atmosphere and ocean. The anticyclonic and cyclonic circulations correspond to a "cold and dry" and a "warm and wet" atmosphere, and a "cold and salty" and a "warm and fresh" ocean, respectively. Shifts from one regime to another are forced by changes in the location and intensity of the Icelandic low and Siberian high. Maslanik et al. (1998) indicate the ice transport patterns associated with a positive and a negative NAO resemble weak versions of the cyclonic and anticyclonic modes of ice drift modeled by Proshutinsky and Johnson (1997). They report that wind-driven ice and water motion in the Arctic alternates between anticyclonic and cyclonic circulation states, with each regime persisting for 5–7 years (the period is 10–15 years). Their arguments suggest the recent change in the Arctic Ocean circulation is an extreme expression of the cyclonic pattern.

2.2.3 Ice Extent and Thickness

Chapman and Walsh (1993) show a downward long-term trend in sea ice extent for 1961 to 1990 using weekly U.S. Navy/NOAA National Ice Center charts since 1973 and regional sea ice data sources for earlier years. Johannessen et al. (1995) subsequently found that this downward trend has increased since about 1989. This view is reinforced by the more recent work of Bjorgo et al. (1997), who address concerns over errors in sea ice retrievals from passive microwave data and problems in blending the earlier SMMR (multichanel microwave radiometer) records (1978–1987) (Parkinson and Cavalieri, 1989) with the more recent time series (1987 onward) from the Defense Meteorological Satellite Program's Special Sensor Microwave/Imager (SSM/I). The most recent study using passive microwave data through 1996 (Parkinson et al., 1999) shows arctic sea ice extent decreasing by 2.9 ± 0.4% per decade. Also on the basis of the passive microwave time series, Smith (1998) shows that these ice reductions have been accompanied by a general increase in the length of the ice melt season.

Time series of ice extent in the Northern Hemisphere exhibit large variability, superimposed on an overall downward trend. This is shown in Figure 2-5 (from Vinikov et al., 1999), which compares five observational records of ice extent (Bjorgo et al., 1997; Chapman and Walsh, 1993; Parkinson et al., 1999; Ropelewski,1985; Zakharov, 1997). The various results are consistent. Further inspection of the time series shows that the annual trend is strongly driven by the trends in late summer and early autumn. Extreme minima, unprecedented within the passive microwave record, are found during 1990 and 1995. These reflect primarily reduced ice cover over the Laptev and East Siberian seas where (on the basis of data through 1995) ice extent has decreased fairly

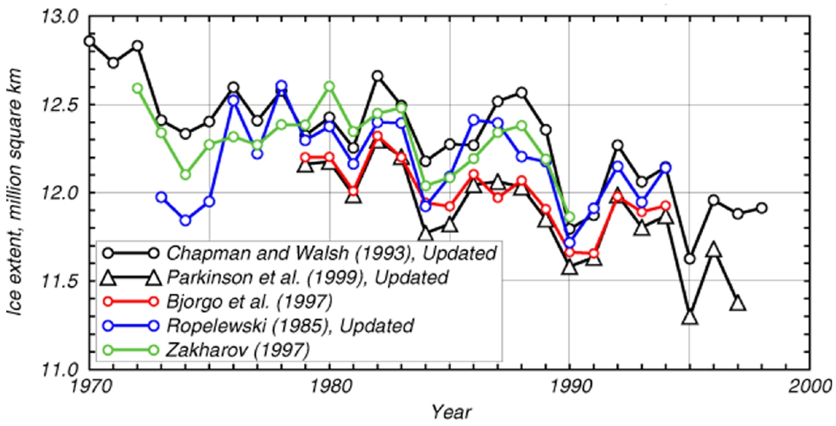


Figure 2-5 *Northern Hemisphere sea ice extent from five different sources. (Reproduced from Vinikov et al., 1999, with permission of the American Association for the Advancement of Science.)*

steadily since about 1990 (Maslanik et al., 1996). Recent data show record low ice extents in the Beaufort Sea in summer 1998, consistent with reports from the SHEBA ice camp. However, in terms of total ice extent, this anomaly is partly offset by more extensive ice on the Eurasian side of the Arctic, contrary to the general pattern seen in the 1990s (Maslanik et al., 1999).

With regard to longer-term (century-scale) changes, Zakharov (1997) has shown a substantial decrease of sea ice coverage in the eastern North Atlantic during the twentieth century. This trend is also apparent in the charts of the Danish Meteorological Institute (Walsh et al., 1998), although the data used in these syntheses are primarily for the spring-summer portion of the year. Vinje and Colony (1998) extend the time series back several centuries in the vicinity of the Norwegian Sea. Large decreases of sea ice extent since the 1890s are apparent. The Koch Index of sea ice near Iceland also indicates that the twentieth century has been relatively ice-free near Iceland in comparison with the previous century.

Recent reports of a decrease in sea ice thickness are compelling evidence of change. The upper Arctic

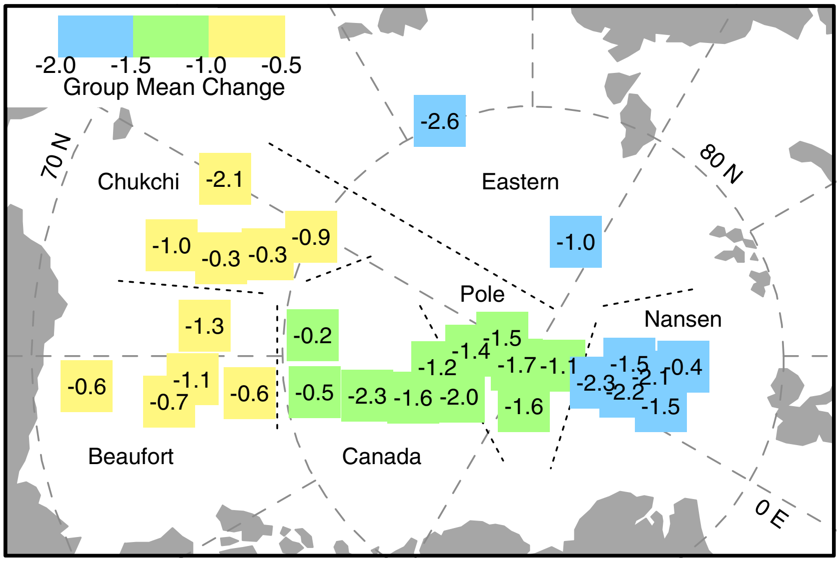


Figure 2-6 *Changes in the mean draft of sea ice between 1958–76 and 1993–97. Submarine under-ice draft data from the two periods were compared for the regions shown and the same season. The crossings within each regional group are given the same shading equivalent to their group mean. Each square covers about 150 km. (Reproduced from Rothrock et al., 1999, with permission of American Geophysical Union.)*

Ocean is essentially an ice bath. Thus, its thermodynamic state is not determined by temperature; this is constrained to be near the freezing point. The thermodynamic state is determined by ice mass. Take away heat and ice forms; add heat and ice melts. As illustrated in Figure 2-6, Rothrock et al. (1999) compare ice thickness measured by U.S. Navy submarines over the past 20 years and find an average reduction of 43% in thickness for the central Arctic Ocean. British submarine data tend to corroborate the thinning of the ice (Wadhams, 1990, 1994). Johannessen et al. (1999) use satellite remote sensing data to determine that the area of multiyear ice decreased 14% between 1978 and 1998. We can infer from this a significant reduction in average ice thickness. The trend suggests a substantial change in the thermal state of the Arctic Ocean, with important implications for the ice cover and the ice-albedo feedback.

2.3 Terrestrial Changes

The patterns of change on land have been highly variable, but generally there has been a decrease in snow cover, an increase in permafrost temperatures in some areas, changes in coastlines, and a long-term trend toward increased runoff in some major rivers.

2.3.1 Snow Cover

Snow cover over the Northern Hemisphere has historically been quite variable but has been significantly below average in recent years, especially during spring. Weekly National Oceanic and Atmospheric Administration (NOAA) Northern Hemisphere charts of snow-covered area (SCA), derived primarily from analysis of visible-band satellite imagery, are available since 1972 (Robinson et al., 1993; 1995). NOAA data analyzed through August 1998, presented as monthly anomalies and 12-month running

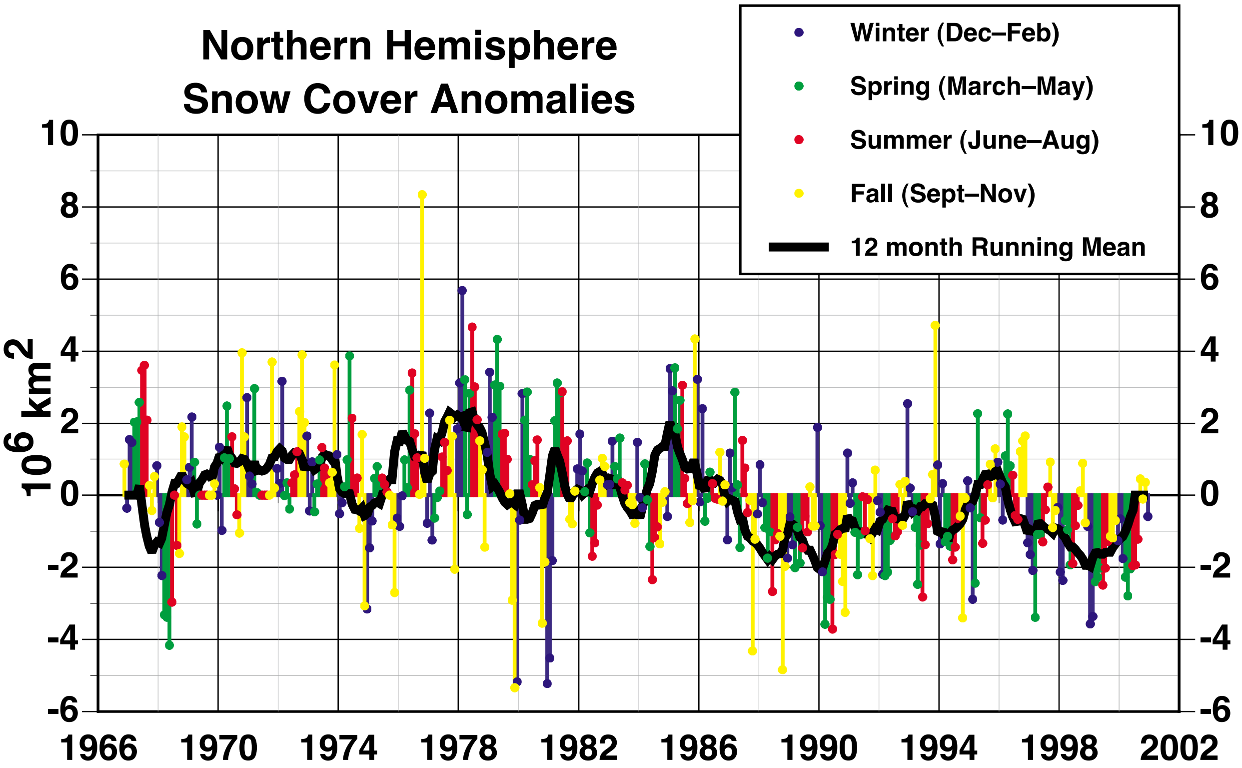


Figure 2-7a Snow cover anomaly in the Northern Hemisphere (updated from Robinson et al., 1995). Continued updates may be found at http://climate.rutgers.edu/climatelab

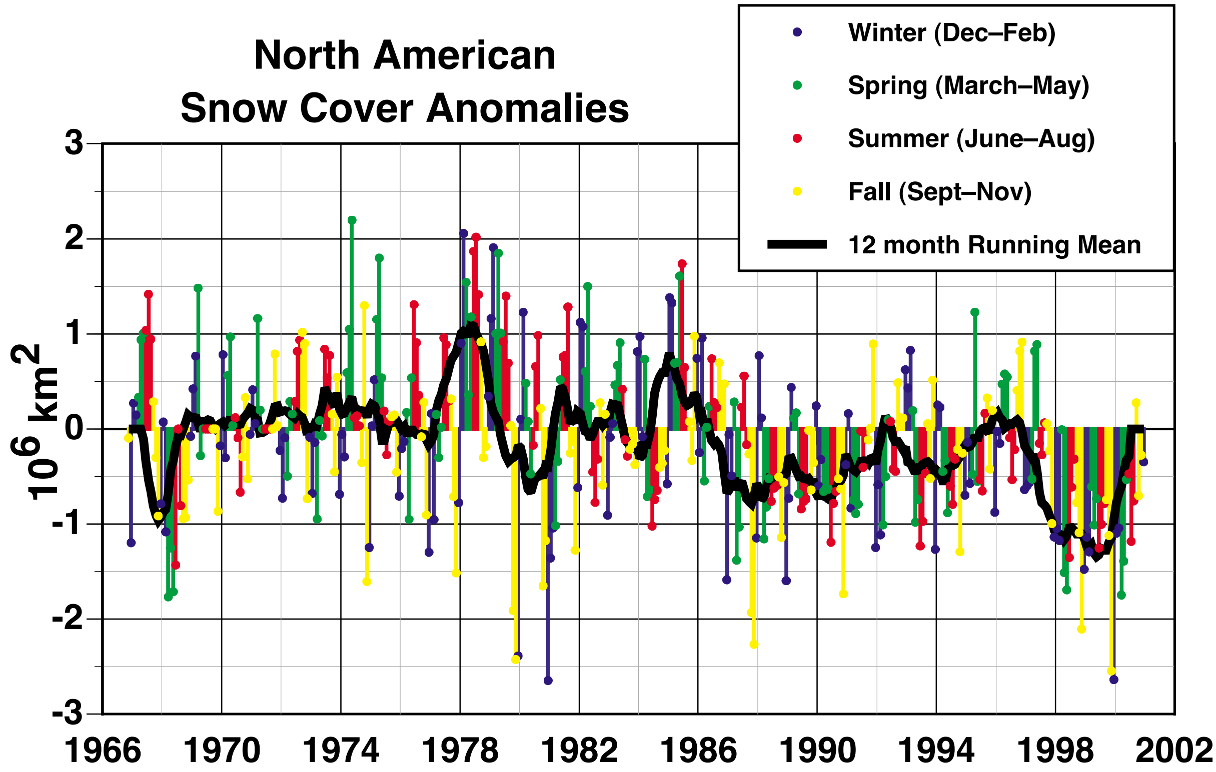


Figure 2.7b *Snow cover anomaly in North America including Greenland (updated from Robinson et al., 1995). Continued updates may be found at* *http://climate.rutgers.edu/climatelab*

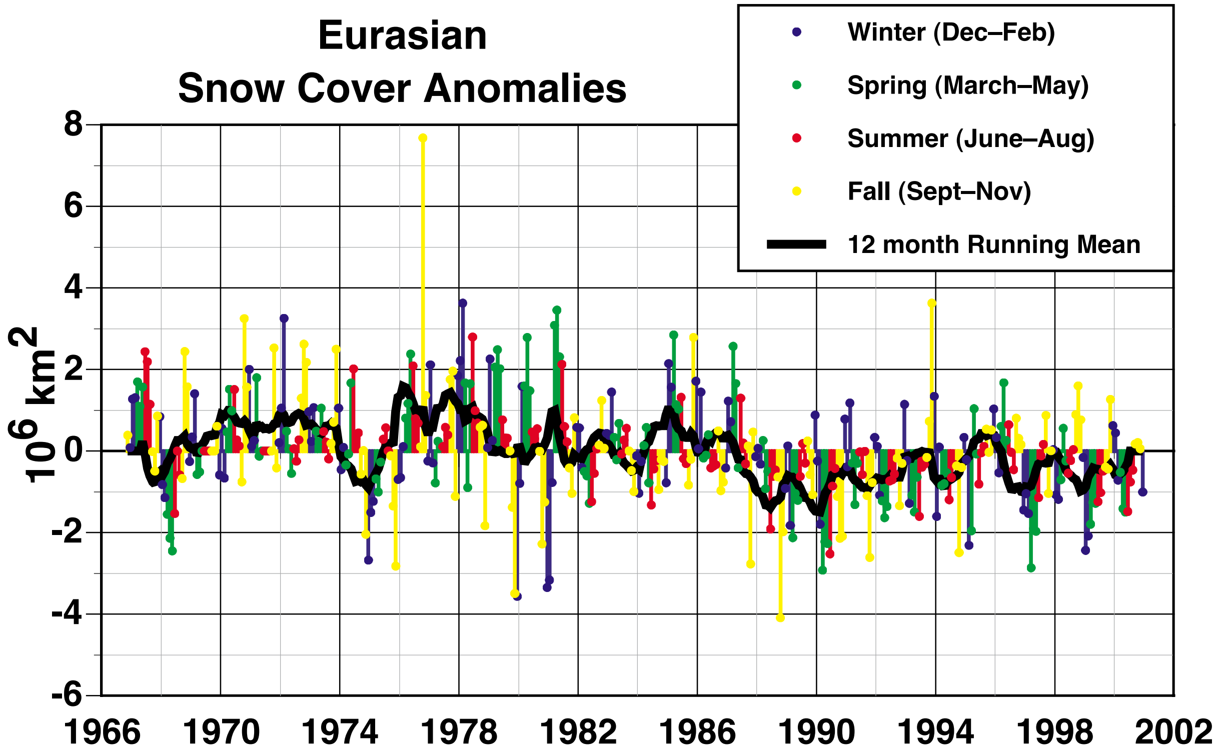


Figure 2-7c *Snow cover anomaly in Eurasia (updated from Robinson et al., 1995). Continued updates may be found at* *http://climate.rutgers.edu/climatelab*

means of Northern Hemisphere SCA (Figure 2-7a–c), show generally (but by no means always) above-average snow coverage from the beginning of the record through the mid 1980s. Within this period, snow cover was particularly extensive in the 1970s and mid 1980s. By comparison, the late 1980s through August 1998 has been a period of generally subnormal SCA. This pattern is seen over both North America and Eurasia. The difference in annual means between 1987–present and the preceding period is statistically significant, and the largest changes have occurred during spring and summer. Overall, the Northern Hemisphere annual SCA has declined by about 10% since 1972 (Groisman et al., 1994a, 1994b).

There is evidence that for Canada (Brown and Goodison, 1996) there has been a general decrease in snow depth since 1946, especially during spring. Winter snow depths have declined over European Russia since the turn of the century (Meshcherskaya et al., 1995; Fallot et al., 1997). However, reconstructions for Canada suggest that while there has been a general decrease in spring SCA since 1915, winter SCA has increased. Winter snow depths over parts of Russia also appear to have increased in recent decades. The common thread among studies that have examined seasonality is an overall reduction in spring snow cover.

2.3.2 Permafrost

Permafrost studies have shown strong warming and thawing trends in many areas of the Arctic (Lachenbruch and Marshall, 1986; Pavlov, 1994; Osterkamp and Romanovsky, 1999). Data from northern Alaska (1983 to 1993) generally reveal a cyclic variation in permafrost temperatures superimposed on the century-long warming with similar amplitude (Osterkamp et al., 1994; Osterkamp and Romanovsky, 1996). The United States Geological Survey has measured permafrost temperatures from

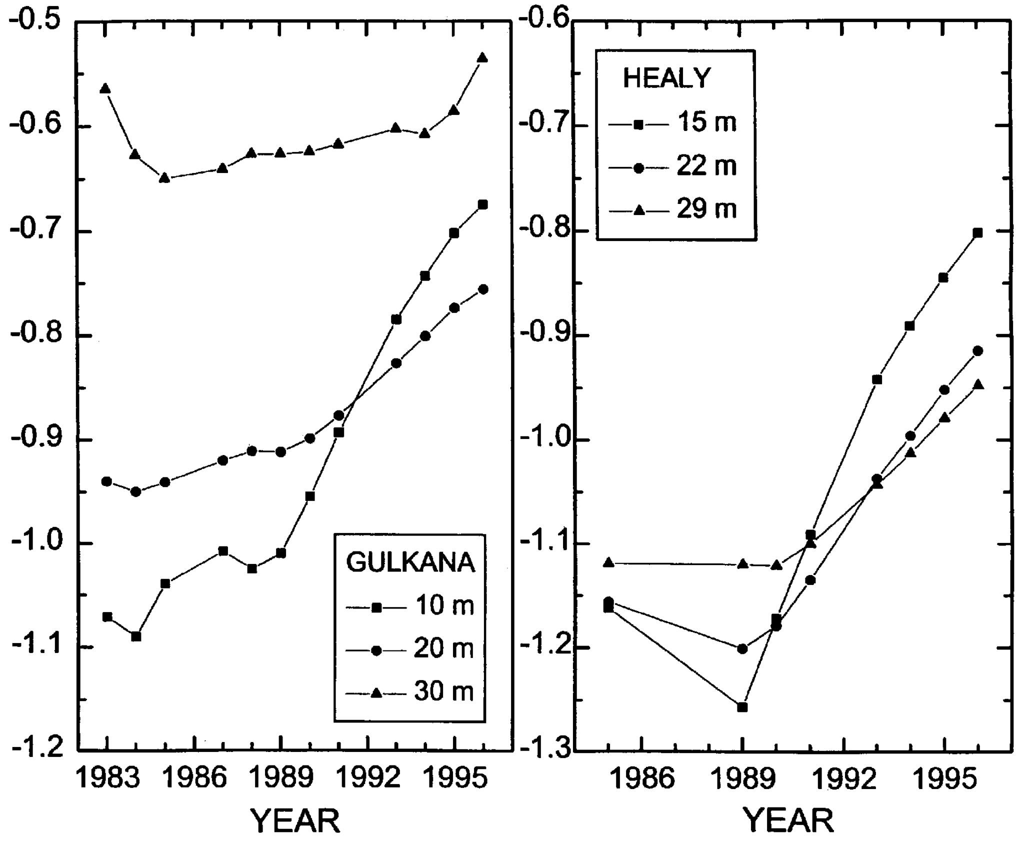
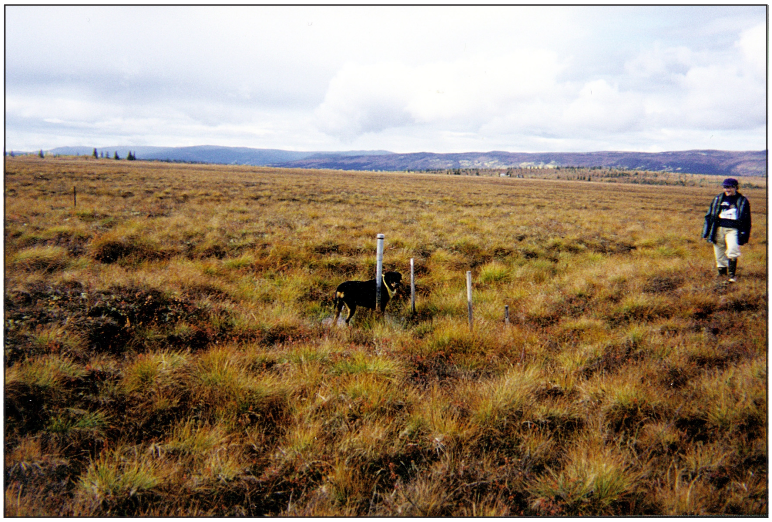


Figure 2-8 Permafrost temperatures at 10, 20, and 30 m in the discontinuous permafrost region of Alaska. (Reproduced from Osterkamp and Romanovsky, 1999, with permission of John Wiley & Sons, Ltd.).

deep drill holes in northern Alaska since the late 1940s. According to data through the mid-1980s (Lachenbruch et al., 1982; Lachenbruch and Marshall, 1986), permafrost in this region generally warmed. Typical changes were 2–4°C although some holes showed little change or a cooling. The recent part of the records points to cooling in the early 1980s. Permafrost then warmed until the early 1990s, cooled until 1993, and has since warmed. This pattern is supported by other investigations for Alaska (Nelson et al., 1993; Lachenbruch, 1994). Osterkamp and Romanovsky (1996) find that in the continuous permafrost region on the North Slope of Alaska, the permafrost was cooling prior to the late 1980s. Since that time, however, and coincident with the changes in the Arctic Ocean, the permafrost has been warming and thawing. Pavlov (1994) indicates that the near-surface temperatures of permafrost in northern Russia have increased 0.6–0.7°C over the 1970s and 1980s. An opposite trend is reported by Wang and Allard (1995) for northern Quebec. They observe decreasing permafrost temperatures that they relate to lower air temperatures observed in that region. The permafrost warming trend therefore is broadly consistent with the spatial variation of surface air temperature trends (Rigor et al., 2000).

Because the permafrost in northern Alaska is relatively cold, warming there has not yet led to any

1985



1997

Figure 2-9 Photographs of a site in warm discontinuous permafrost in Alaska in 1985 and 1997. The uneven surface apparent in 1997 is a result of thermokarst formation when the near-surface, ice-rich permafrost thawed under natural conditions. (Photographs by T. E. Osterkamp, used with permission).

significant change in active layer or permafrost thickness. However, farther south in areas of discontinuous permafrost, the consequences of permafrost warming are more apparent. As shown in Figure 2-8, a warming of 1° to 1.5°C has been observed in areas of discontinuous permafrost in Alaska (Osterkamp and Romanovsky, 1999), owing in part to both higher temperatures and increased snow thickness. The warming in the most recent years has been about 0.5°C at 20 m depth. In some places, the change is sufficient to cause the permafrost to thaw at rates of about 0.1 m yr^{-1}. A considerable change in volume often accompanies this thawing, especially as massive pieces of buried ice melt. The variable terrain produced by this is called thermokarst and is illustrated in the before and after photographs of Figure 2-9. In low-lying areas the thawed ground can sink below the water table, creating a swamp. In upland areas, thawing of permafrost can enhance drainage, effectively converting wetlands to drier ecosystems.

2.3.3 Glacier Mass Balance

Glacier mass balance is also highly variable. The earliest records start in the 1940s. The mass balance is unknown for Greenland, but there has been a generally negative cumulative balance for small glaciers over the Arctic as a whole. Based on a comprehensive data set including the Arctic islands, small glaciers around Antarctica and Greenland, and the mountainous areas of Siberia, central Asia, and the Caucasus, the area-weighted global mass balance of small glaciers evaluated for the period 1961 through 1990 was negative, with the mass loss estimated as 7.36 mm of sea level equivalent (Dyurgerov and Meier, 1997). This represents approximately 16% of the average rate of sea level rise in the past 100 years. Area-weighted balances have been positive only for the European sector. Of the total contribution to sea level rise by small glaciers from 1961 through 1990, the Arctic islands contribute 1.36 mm (about 18% of the total). Alaska makes a smaller contribution of 0.54 mm (7%). The largest contribution, 3.34 mm (45%), has been from Asia. In the Arctic, negative annual balances have been particularly persistent for small glaciers on Svalbard. Over the period of record for the Arctic islands, balances were the most negative in 1991 and 1993. It is stressed that conditions for individual glaciers vary. Dowdeswell et al. (1997) examined 40 arctic ice caps and glaciers with records extending back to the 1940s. They found that, while most arctic glaciers have experienced predominantly negative balances over the past few decades, some, such as those in the montane parts of Scandinavia and Iceland, have experienced a positive balance owing to increased winter precipitation.

2.3.4 River Discharge—Hydrology

Arctic river runoff shows a substantial seasonal variability. For dominant Russian rivers, 65–95% of the total typically occurs in late spring and summer. Interannual variations in peak values are typically 20–30%. Most of these rivers, and certainly the largest, Ob, Yenisey, and Lena, show a trend of increasing runoff from as far back as the 1940s up to 1990 (Pavlov, personal communication, 1999). Changes in summer discharge have occurred, but the summer signal is noisy because of large natural variation. More distinct, however, have been changes in base flow, perhaps brought about by reductions in permafrost and an increase in active layer thickness due to the warmer temperatures. Between 1936 and 1995, for example, the base flow of the Yenisey River increased markedly, a trend masked during the peak flow of the summer months. This change, presumably due to the infiltration of more groundwater coupled with permafrost degradation, has resulted in winter flow rates considerably greater than in the past. Increased winter flow rates could have a wide range of impacts, including changes in stream chemistry and habitat and changes in erosion and sediment flux. Trends in the last decade are uncertain. However, Johnson et al. (1999) compare their two-regime (cyclonic and anticyclonic) sea level height signal (Proshutinsky and Johnson, 1997) with the Ob, Yenisey, and Mackenzie River discharges. They find that the runoff from these rivers is relatively high during the cyclonic regime. Discharge from the other rivers emptying into the Arctic Ocean shows no correlation with these circulation regimes.

River discharge observations are complicated somewhat by changes in river ice. According to Magnuson et al. (2000) there have been noticeable changes in the dates of ice freeze-up and breakup in lakes and rivers. They indicate that the average change over the past 150 years in the Northern Hemisphere was nearly nine days later for freeze-up and almost 10 days earlier for breakup.

2.4 Chemical, Biological, and Ecosystem Changes

Changes in the physical environment are causing changes in the ecosystems of the North. Some of these changes are associated with changes in biogeochemical conditions and some are related to the change in gross physical properties (e.g., ice cover, seawater temperature).

2.4.1 Marine Chemical Changes

Among the unique features of the Arctic Ocean is the distinct difference in nutrient concentrations between the Atlantic and Pacific waters entering the basin. Pacific waters are markedly higher in silicate and phosphate and modestly higher in nitrate (Codispoti and Richards, 1968; Salmon and McRoy, 1994). Carbonate system components in the rivers draining into the Arctic also vary considerably from river to river (Olsson and Anderson, 1997). Thus, it must be expected that changes in the distribution of water masses are reflected in changes in the distributions of the nutrient and carbonate systems.

Changes that affect the stratification of arctic waters, such as the surface heat budget, will also influence nutrient distributions and can thus affect biological productivity. The remarkable freshening of the surface layer noted during the SHEBA experiment, for example, was associated with low nutrient concentrations in the surface waters, suggesting that the increased stratification reduced vertical transport of nutrients into the photic zone. Any reduction of nutrient input to the northern shelves will likely limit primary production, which on these shallow shelves supports water and benthic faunal populations that are tightly linked to marine mammals and birds that are consumed by native populations (Grebmeier et al., 1995).

Nutrients may also be limited at the Bering Sea source. Since inflow through Bering Strait represents a major source of nutrients in the Arctic Ocean, and since the highest nutrient values in this inflow tend to be associated with the highest salinities, the reduction in transport and decreased salinity of the Bering Strait inflow in the 1990s (Roach et al., 1995; Aagaard and Weingartner, unpublished data) may represent a significant reduction of the nutrient transport into the Arctic. Since this system is shallow and water column processes are directly coupled to the underlying benthos (Grebmeier and Barry, 1991), there could well be tight coupling between lower trophic level water column production and higher trophic levels in this region (Aagaard et al., 1999, pp. 37–47).

2.4.2 Marine Ecosystem Changes

The extent, thickness, and duration of the ice cover in the Arctic can have a major impact on ecosystem functioning. The recent overall decline in ice cover can influence primary production and types of algae species as well as the amount of organic carbon available to faunal communities in the water and sediments. Sea ice studies at the SHEBA ice camp, for example, indicate that the sea ice underwent a change in algal species composition from decades before, with the species observed in 1997/98 being characterized by more brackish and freshwater forms (Melnikov et al., 1997). This may be linked to the increased diversion of Mackenzie River runoff into the central and western Beaufort Sea reported by Macdonald et al. (1999) or to increased summer ice melt as suggested by McPhee et al. (1998). Finally, observations indicate a reduced ice extent in the 1990s (except 1999). For example, early ice breakup was observed from 1995–1998. In 1998 many ringed seal pups were abandoned in the Bering and Beaufort seas, and underweight walrus were observed in the Bering Strait area. Recent observations (albeit limited) suggest that walrus populations may be in decline (Brendon Kelly, personal communication, 1999).

Unaami-related change may extend southward into the Bering Sea. The ecosystem there has changed dramatically in the past decade, contemporaneous with some of the most pronounced physical changes in the Arctic Basin. According to Brodeur et al. (1999) the biomass of large jellyfish in the Bering Sea has soared in the 1990s (See Figure 2-10). Brodeur et al. (1999) suggest this may be due to increased sea surface temperatures and reduced ice cover in the region.

Saar (2000) reviews the causes and impacts of massive blooms of the small phytoplankton *Emiliana huxleyi* (ehux) in 1997 and 1998. Blooms of this coccolithophorid are readily visible in satellite imagery (Figure 2-11) because these phytoplankton possess reflective carbonate plates. The 1997 bloom

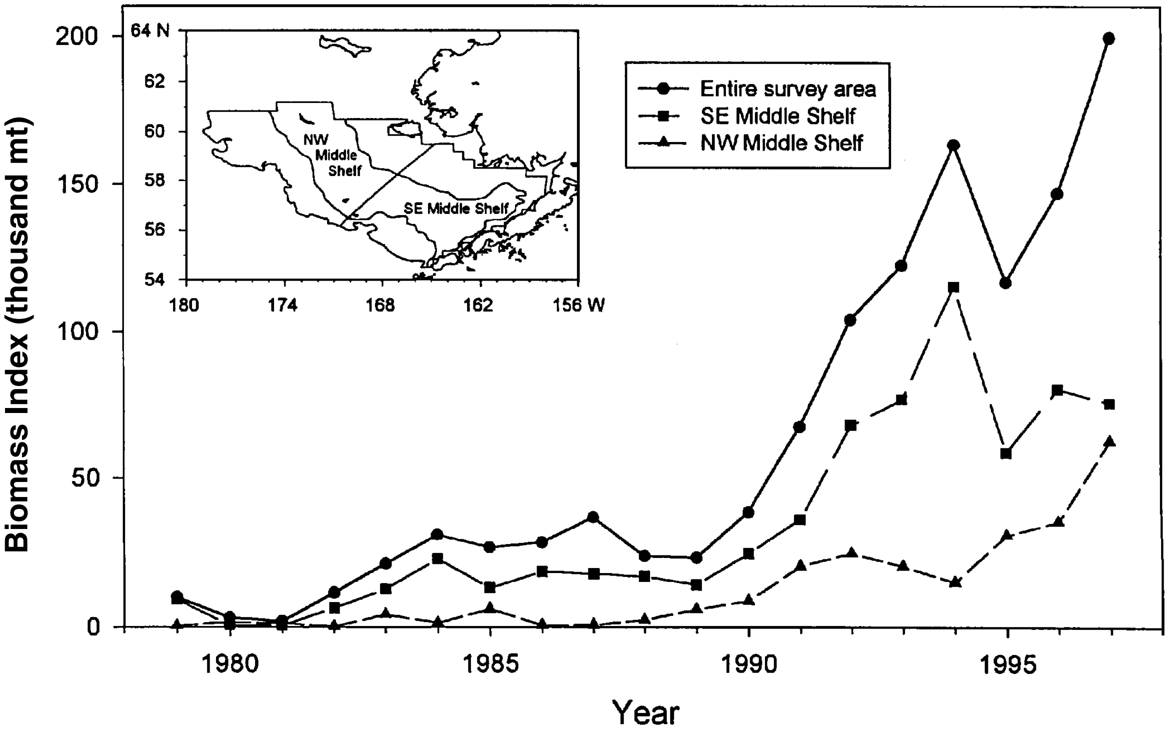


Figure 2-10 The biomass of large medusae (jellyfish) in the Bering Sea. The biomass has soared in the 1990s, apparently due to increased sea surface temperatures and reduced ice cover in the region. (Reproduced from Brodeur et al., 1999, with permission of Blackwell Science.)

was about as large as the state of Nebraska and the 1998 bloom was twice as large. Ehux is smaller than the diatoms that typically bloom in the Bering Sea, and the ehux blooms apparently favored smaller zooplankton such as copepods and resulted in a decrease in the much larger euphausiids. The decrease in euphausiids has, in turn, been suggested as the cause for a massive die-off of short-tailed shearwaters, a seabird that feeds on euphausiids (Stockwell et al. 2000). Unusually warm and sunny conditions in the spring and summer of 1997 (Saar, 2000), corresponding to pronounced ice melt in the Beaufort Sea (McPhee et al., 1998), have been suggested as one of the causes of this ecosystem change.

As further examples, studies in the southeast Bering Sea also provide support for a reduction in overall productivity in the area (Schell, 2000). Recent studies in high benthic biomass regions in the northern Bering Sea indicate population declines during the 1990s that are coincident with reduced transport and a freshening of water transiting Bering Strait (Grebmeier and Cooper, 1995; Grebmeier and Dunton, 2000). These studies indicate a reduction in carbon deposition south of St. Lawrence Island and an increase in the silt and clay content of underlying sediments, indicative of reduced transport conditions. These on-going benthic studies also indicate that the bivalve populations in the region are undergoing species shifts as well as a decline in overall biomass. This, in turn, may be responsible for the decline observed in populations of the threatened diving spectacled eider seaduck in the region (Lovvorn et al., 2000).

Another of the Arctic Ocean's marginal seas, the Barents Sea in the European sector, has also shown evidence of climatically driven and system-wide changes in its ecosystem due to warming during the recent NAO-positive conditions. Since commercial fisheries are involved, this has had major socioeconomic implications. These are discussed further in section 2.5.2.1.

Recent changes have also been observed in fisheries, including sightings of Pacific salmon species entering rivers in the eastern Arctic and more salmon being caught off Barrow, Alaska (Carmack and McLaughlin, 2000; Doug Chipperzak, personal communication, 2000). These shifts in the geographic location of various species are also seen on the other side of the Arctic Ocean in the Barents and White seas. Studies there indicate that fisheries that characteristically were located farther south near the ice edge are in recent years found farther north with the retreating ice edge. Thus, the fisheries migrated north in conjunction with reduced ice extent.

Tynan and DeMaster (1997) have hypothesized that the decreases in ice extent and warming trends may have a profound effect on marine mammals. Bowhead whales were reported feeding very close to shore in 1997, a record light-ice year when the ice edge receded over 200 km from shore in the Alaskan Beaufort Sea (Treacy, 1998). This observation

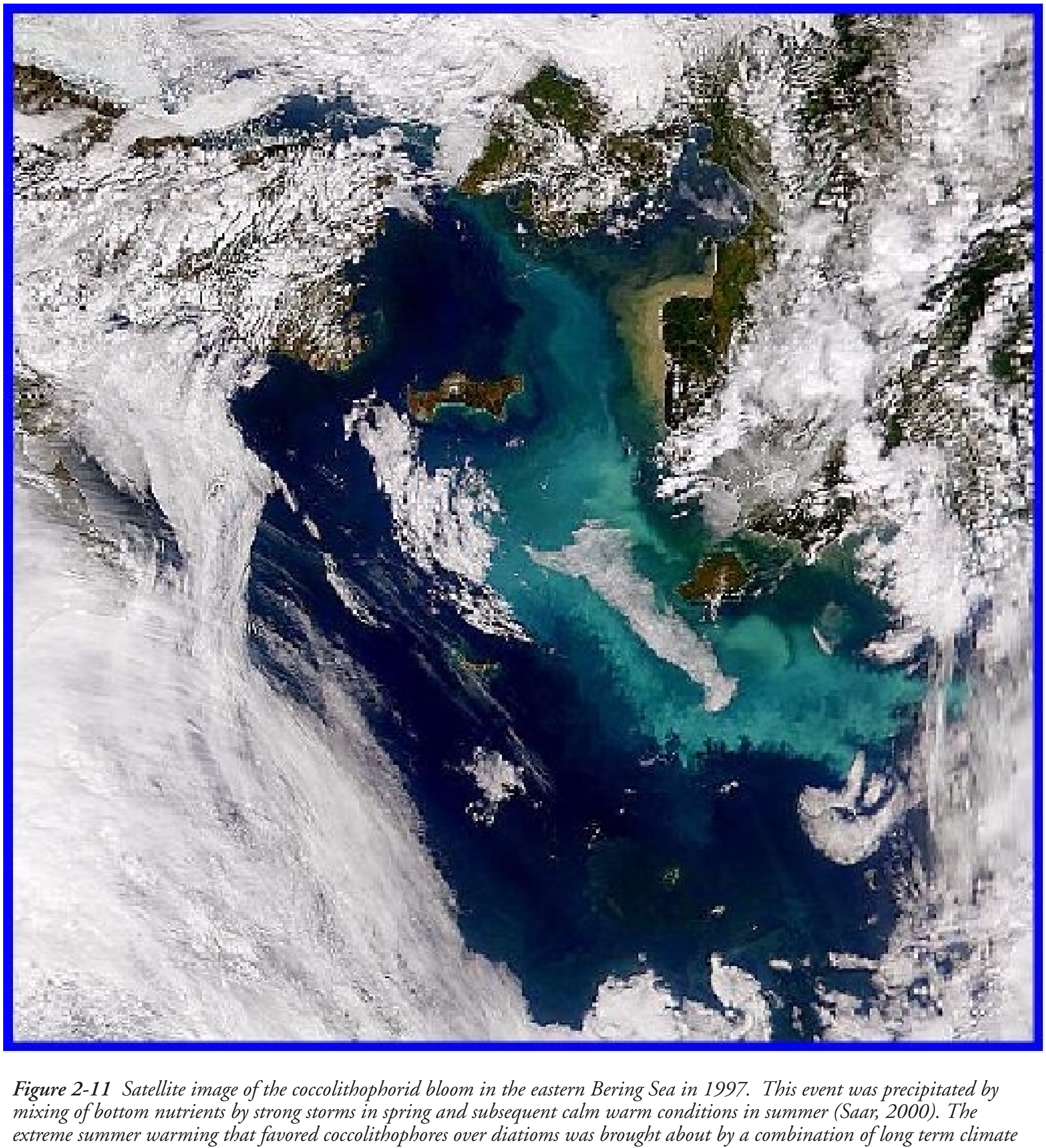


Figure 2-11 *Satellite image of the coccolithophorid bloom in the eastern Bering Sea in 1997. This event was precipitated by mixing of bottom nutrients by strong storms in spring and subsequent calm warm conditions in summer (Saar, 2000). The extreme summer warming that favored coccolithophores over diatioms was brought about by a combination of long term climate trends and a strong local weather anomaly. The coccolithophores, once established, have persisted for the following three years. At the same time there has been a reduction in euphausiids and a die-off of short-tailed shearwater seabirds (Stockwell et al.,1999). Photograph from the SeaWiFS Project, NASA/Goddard Space Flight Center.*

reinforces the results of habitat-selection analyses, which showed that from 1982–1991 bowhead whales selected ice-free inner shelf habitat in light ice cover but remained offshore in slope habitat in heavy ice cover (>70% of the surface).

In the 1980s, gray whales were concentrated north of St. Lawrence Island (Moore et al., 1986; Moore and DeMaster, 1997; Highsmith and Coyle, 1992) but recently are more dispersed. In addition, benthic sampling in this region in recent years suggests a decline in the ampeliscid amphipod populations that support gray whale populations; thus, declining food supply may also be limiting these whale populations (Grebmeier and Dunton, 2000). The number of stranded gray whales reported to the National Marine Fisheries Service (NMFS) in 1999 far exceeded numbers for the preceding five years (Moore et al., mortality event report, in preparation). While the cause for this "event" remains unclear, it is hypothesized that the Eastern Pacific stock of gray whales may be at or near carrying capacity, especially if their primary foraging areas are not as productive as in the past (Rugh et al., 1999; Le Beauf et al., 2000).

In addition to potential biological changes associated with changing ice conditions, an increase in wave action and erosion on shorelines of the Bering and Beaufort seas may both directly impact native village sites and provide a source of carbon to the marine system in the form of peat (http://arctic.bio.utk.edu/).

2.4.3 Terrestrial Species and Vegetation Changes

Paleoecological research, model predictions, and anecdotal, experimental, and other evidence all strongly support the idea that climatic warming should cause major changes in vegetation composition in arctic ecosystems. Because plant species differ widely in their canopy architecture, energy exchange, and water and nutrient use, changes in species composition should have significant impacts on the future hydrology, surface energy balance, and biogeochemical cycles of arctic systems.

The most important of the expected changes in species composition are an increase in the abundance of woody shrub species and, perhaps more slowly, the northward movement of trees. Increased shrub density is known to have major impacts on winter snow accumulation and soil temperature (Sturm et al., 2001), summer surface energy and water balance (McFadden et al., 1998), and soil decomposition processes (Hobbie 1996). To date, however, little if any change in tundra vegetation composition has been observed unequivocally despite considerable climatic warming over the past few decades. Repeated sampling of tundra vegetation, both by harvest methods and nondestructively, suggests a small increase in shrub abundance and canopy height on the North Slope of Alaska since the late 1980s (Shaver et al., 2001; M. Walker, personal communication). However, the observed changes are not yet clearly outside the range of interannual variation. Over a longer time period, comparison of recent aerial photographs with photos taken during the 1940s and 1950s indicates larger increases in shrub density in some parts of Alaska, but analysis of these photos is still incomplete. The clearest results come from long-term experimental warming of tundra ecosystems, which has occasionally (Hobbie et al., 1999; Bret-Harte et al., 2001) but not always (Chapin et al., 1995; Shaver et al. 1998) led to increased shrub abundance.

Myneni et al. (1997) present evidence that photosynthetic activity of terrestrial vegetation in northern high latitudes increased from 1981 through 1991, suggestive of an increase in plant growth and a lengthening of the active growing season. The largest increases in photosynthetic activity (10–12%) are found between 45 and 70°N, which they argue is consistent with marked springtime warmings. Results are based on two independent records of the normalized difference vegetation index (NDVI) derived from NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite records. Further analyses show continuation of the increasing NDVI on the North Slope of Alaska into 1997 (Hope et al., unpublished data). The results appear consistent with an increase of over 20% in the amplitude of the seasonal cycle of atmospheric carbon dioxide since the 1970s at Point Barrow, Alaska, and an advance of up to 7 days in the timing of CO_2 draw down in spring and early summer (Keeling et al., 1996; Zimov et al., 1999).

While interpretation of the NDVI time series and increases in shrub abundance is open to question, observations do point to a northward movement of the arctic tree line in recent decades in some locations (D'Arrigo et al., 1987; Nichols, 2000). By intercepting incident radiation higher above the soil, by trapping snow in winter, by sticking up through the snow in winter, and by altering evapotranspiration and element turnover, changes in tree distribution will have major impacts on feedbacks to climate from terrestrial ecosystems. To put these observations in perspective, it should be understood from paleological studies of past timberline changes that fairly dramatic vegetation changes have occurred over decades to centuries in the past in concert with climate change.

There are some suggestions of recent increases in fire frequency in Alaska over the past 50 years (Oechel and Vourlitis, 1996), in boreal Canada, and in other circumpolar zones that have experienced regional warming (Kasischke and Stocks, 2000). Fires have an immediate and dramatic effect on the surface energy balance, hydrology, and biogeochemistry, as well as long-term impacts on vegetation composition and landscape function. Changes in climate and long-term policies of fire prevention, leading to increased fuel accumulation, are among the major causes of this increase in fire in northern ecosystems (Kasischke and Stocks, 2000).

2.4.4 Carbon Dioxide and Methane Fluxes

The Arctic has been a significant net sink for carbon over historic and recent geologic time scales, resulting in large stores of soil carbon, perhaps 300 gigatons (Miller et al., 1983). Carbon-14 dating of peat accumulation indicates carbon uptake by arctic terrestrial ecosystems on the North Slope of Alaska through the Holocene (Marion and Oechel, 1993). Studies conducted under the International Biological Program (IBP) in the 1970s showed uptake rates of 30–100 g m^{-2} y^{-1} (Chapin et al., 1980; Miller et al., 1983). However, recent data suggest that the past pattern of carbon accumulation changed to a pattern of net loss, with growing season releases of up to 150 g m^{-2} y^{-1} (Marion and Oechel, 1993; Oechel et al., 1993; Zimov et al., 1993, 1996). These changes represent significant deviations from historic and Holocene carbon fluxes. They show the potential for a positive feedback on global change through losses of up to 0.7 Gt y^{-1} of carbon (about 12% of the total emission from fossil fuel use) to the atmosphere (Oechel and Vourlitis, 1994). However, throughout the decade of the 1990s the annual net carbon losses from Alaskan tundra ecosystems have decreased in magnitude, suggesting a system-level acclimation to the warming trend that began in the 1980s (Oechel et al., 2000).

Referring to local regions, the Kuparuk Basin (North Slope of Alaska) now appears as a net source of CO_2. This region is composed mainly of acidic and nonacidic tussock tundra and wet sedge tundra (Walker et al., 1998). Approximately 20% of the growing season loss is from carbon transported to lakes and streams in groundwater and then released from water sources to the atmosphere (Kling et al., 1991). Studies from Europe, Russia, and Canada also show that a preponderance of arctic sites are now losing carbon dioxide to the atmosphere (Zimov et al., 1993, 1996; Zamolodchikov and Karelin, unpublished data). However, there are arctic sites that are neutral or a sink for CO_2 (Sogaard, personal communication, 2000).

Evidence suggests that the sequence of changes in carbon flux in association with climatic warming (i.e., from a net carbon sink in the 1960s and 1970s to a large carbon source in the late 1980s, and then to a smaller source by the end of the 1990s) is due to a lag in the response of plant carbon fixation to warming relative to the more rapid increases in soil carbon loss (McKane et al., 1997; Shaver et al., 2001). Soil carbon losses increased first, probably in response to climatic warming and the resultant effect of a change in precipitation minus evaporation on soil moisture content and soil water table and not to the direct effects of increasing temperature on ecosystem respiration. Drying has been shown to cause increased carbon loss (Oechel et al., 1998), and drying has been observed in Barrow, Alaska, and the surrounding area (Oechel et al., 1995). Similar sequences of change in carbon balance have been observed in several long-term warming experiments (Shaver et al., 2001) and are commonly predicted in ecosystem models (e.g., McKane et al., 1997a; McGuire et al., 1997, 2000).

Thermokarst, which is expected to increase in response to observed warming of permafrost (see Figures 2.8 and 2.9), could increase methane fluxes by increasing the area of wetlands and ponds. High-latitude wetlands currently account for 5–10% of global fluxes of methane (Reeburgh and Whalen, 1992). In addition, Siberian thermokarst lakes, which emit most of their methane in winter, could contribute to the recent increase in seasonal amplitude and winter concentration of atmospheric methane observed at high latitudes (Zimov et al., 1997). Methane release from thermokarst lakes is fueled primarily by Pleistocene carbon of terrestrial origin. However, the time series of methane release are too short to detect trends (Whalen and Reeburgh, 1992).

2.5 Human Dimension

Many of the environmental changes described above have direct human consequences among both arctic and sub-arctic populations. In both cases, the consequences are important because livelihoods in the North are closely tied to natural resources.

2.5.1 Effects on Arctic Populations

The environment dominates many aspects of life in the Arctic; arctic peoples have an immediate awareness of environmental changes (ARCUS, 1997). In 1998, for example, Caleb Pungowiyi, a Yup'ik Eskimo from Western Alaska, expressed his concerns about changes involving arctic marine mammals and the environment in a November 1998 letter to the Marine Mammal Commission (Huntington, 2000).

The National Science Foundation, the Environmental Protection Agency (EPA), the National Marine Fisheries Service, and the National Oceanic and Atmospheric Administration have taken steps in recent years to document native knowledge and observations of environmental change (Cochran and Kruse, 2000; Huntington 2000; Kruse et al., 2001). Other efforts to document native knowledge about the effects of climate change are under way as well (Fox, 2000; Riedlinger, 2000). Through these efforts we learn first-hand the societal effects of environmental change.

Sea ice is both a platform for hunting and a critical component of the habitat of marine mammal species important to native subsistence. Jerry Wongittilin, Sr., of St. Lawrence Island observed (Wongittilin, 2000), "There have been a lot of changes in the sea ice currents and the weather. Solid ice has disappeared and there are no longer huge icebergs during fall and winter. The ice now comes later and goes out earlier and it is getting thinner. The current is stronger. It is windier on the island. We had a bad hunting season with lots of high winds. Some years ago there was a massive amount of dead murres that floated on the water. I think they caught the warm currents from Japan. Our elders tell us that our earth is getting old and needs to be replaced by a new one." The changes appear to be persistent. William Takak of Shaktoolik (Takak, 2000) noted, "20 years ago we used to have ice all the way from Shaktoolik to Unalakleet—now there's no ice about 1.5–2 miles out. The ice that's there is thinner. The thickness changed in the last 20 years." Similarly, Robert Tocktoo (Tocktoo, 2000) of Brevig Mission reported, "A lot of the elders don't read but they know what is coming ahead. If we don't get any ice up here until late March or something the north wind always takes that ice out and then it is open all winter. I couldn't go anywhere last winter. I went out there and got a few seals and took them home but after that I never went out again. It was too tough on me."

A major concern reported by native observers is the lack of predictability of the weather; weather patterns appear to have changed. Herman Toolie of Savoonga (Toolie, 2000) observed, "Last spring we only got 6 walrus because of the weather and ice moving out too quick. I talked to elders about the weather. A long time ago it used to be real nice for weeks and even sometimes for months. Now we only have a day or two of good weather. And a lot of times it is real windy now. They don't know what is causing that either. And the hunters that I talked with about the ice conditions say it is getting a lot thinner. It is going out too quick. Maybe it is because of the weather. Maybe it is because of that global warming." Ellen Richards of Wales (Richards, 2000) also observed, "Especially this time of the year we usually get clams when the northwest and northeast winds would come. But right after the northwest winds come, we are getting a south wind that messes up the cycle. At this time of the year, usually in the fall time, we have clams and starfish, shrimp, crabs, ducks, flounders wash up. The winds keep changing. There are a lot less clams than when I was growing up. It depends on the weather too."

Decreased sea ice extent and changes in storm patterns produce higher seas that are accelerating coastal erosion. Delano Barr of Shishmaref (Barr, 2000) reported, "The sea level is rising and that's why at Sishmaref we've had to move 9 houses and 6 more are scheduled to be moved. The storms undercut right underneath the houses."

Observed changes are not confined to coastal environments. Inland precipitation and wind patterns are also changing. Alfred Adams, Koyuk, observed (Adams, 2000), "It used to snow lots and there used to be not very much wind. I remember when I was a kid when there use to be lots of snow on the river. Now days there is not very much snow on the river because of the wind. Mostly last winter there was hardly any snow. And then it started raining this summer... lots! I think that some of the berries don't grow when there is not much snow in the winter. That is what some people say. And it must have rained too much this summer and maybe that is why there are not any blackberries." Gloria Stickwan of Copper Center reported (Stickwan, 2000), "Our river—we've noticed that it doesn't freeze across in the last 10 years. The temperatures are warmer. The lakes are drying up. The water is low in June, affecting the fish run—over the last two years. Sockeyes are much smaller and so are hatchery fish. When I was growing up, our fish racks were full by June, 8 bales of fish. Now we only have a bale by June."

Native observers see environmental change as a complex interaction of climate and human activities. They worry that these changes will increase contaminant levels in the arctic system, affecting the health of animal, fish, and plant populations as well as humans. Charlie Johnson of Nome (Johnson, 2000) remarked, "Is there going to be some conclusion at the end of three years about the effect of climate change on the observations people are making? When the winds and weather patterns are different, it will bring a lot of change. It could change how contaminants travel. It might not be just the temperature, but it may also be the sand flowing on the ice and melting it faster." Elaine Abraham of Yakutat (Abraham, 2000) also voiced a concern about the effects of climate change on the environment so important to native people: "There's a real hesitancy with clams. We used to eat them raw as my parents were cleaning them out—the buttons. I won't let my kids eat them anymore. Now you don't know. We have a generation that's scared of eating their native foods. It's from so much poison in the red tides."

There is good reason to be concerned about contaminants. It is a mistake to think of the Arctic as being almost pristine. One reason why it is not is the atmospheric transport of semi-volatile organic pollutants (e.g., DDT, PCBs, etc.) that enter the atmosphere in lower latitude regions and condense out in the Arctic. Owing to this mechanism, we find concentrations of pollutants such as PCBs in arctic and antarctic fauna. In addition, there is local atmospheric pollution, and the largest arctic rivers drain some heavily industrialized zones, including portions of the former Soviet Union that were used heavily for the production and processing of radionuclides. Finally, there has been direct dumping of pollutants into the Arctic Ocean (Layton et al., 1997). It is difficult to predict what the future holds for transport of pollutants into the Arctic, except to say that the transports are likely to change, and that for some pollutants such as organochlorines and mercury there is legitimate concern (Macdonald and Brewers, 1996). There is also concern that, just as the rising AO index enhanced the northward flux of heat, there may be an increase in the northward flux of contaminants. These concerns give rise to a lack of confidence in the safety of native foods.

2.5.2 Effects on Sub-Arctic Populations

2.5.2.1 North Atlantic and Barents Sea Fisheries

Climate and circulation variations directly affect commercial fish populations through parameters such as water temperature, salinity, vertical mixing, and currents (Jakobsson, 1992; Jakobsson et al., 1994; Klyashtorin, 1998; Laevastu, 1993). Moreover, fisheries themselves can increase the vulnerability of target populations to climatic change by altering their age structure, increasing predatory fish populations, and reducing populations of food fish (Marteinsdottir and Thorarinsson, 1998).

Fisheries-dependent communities throughout the northern Atlantic have experienced population losses during the past decade (Hamilton and Otterstad, 1998, Hamilton and Haedrich, 1999). Good examples are the west Greenland cod and shrimp fisheries. As illustrated in Figure 2-12a and b taken from Hamilton and Brown (2001) (based on Hamilton et al., 2000), there is a negative correlation between the NAO or AO and sea temperatures along the southwest coast of Greenland: a high NAO/AO index corresponds to colder west Greenland temperature. This correlation strengthened markedly in the

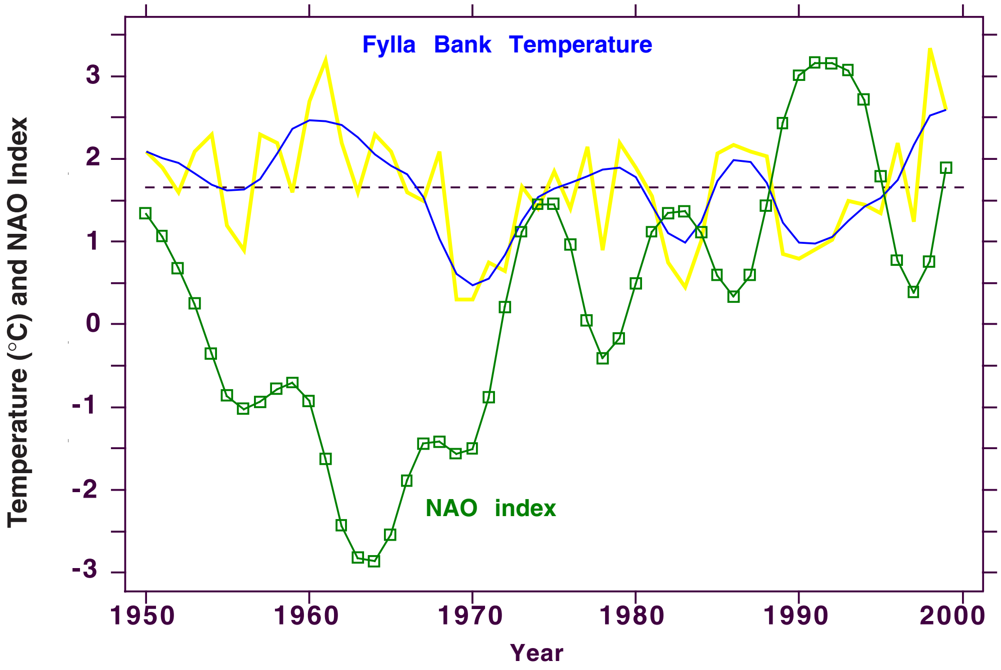


Figure 2-12a *Fylla Bank sea temperature series 1950–99 (yellow) and resistant smoothed values (blue). The NAO index is also shown (dark green). (Reproduced from Hamilton and Brown, 2001, with permission).*

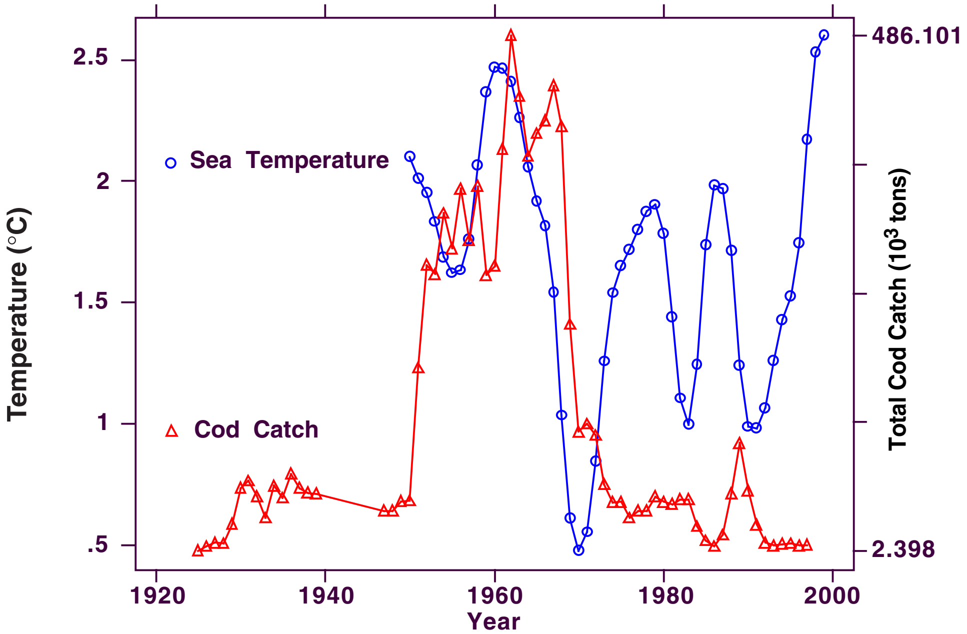


Figure 2-12b *Fylla Bank temperatures (blue) and Atlantic codfish catches off West Greenland (red). (Reproduced from Hamilton and Brown, 2001, with permission).*

early 1970s. The Greenland cod fishery developed from 1920 to 1960 when, in association with a low NAO index, sea temperatures were high along the southwest coast of Greenland due to the northward extension of the Irminger Current. Associated with increasing NAO and AO indices in the mid 1970s, sea temperatures dropped. As fishing pressure remained high and waters cooled (Vilhjálmsson, 1997; see Figure 2-12b), the fishery collapsed. As temperatures fell below 1.8°C, local stocks could not reproduce, and they were also no longer being replenished by recruitment from the Irminger Sea. A final spike of fishing in the late 1980s finished off the remaining cod. Recent temperatures have returned to early 1960s levels, but there are virtually no cod. The removal of cod, a top predator, was followed by an increase in the relative and absolute abundance of northern shrimp. These provide the basis for a new west Greenland shrimp fishery, which has replaced cod in terms of value but exhibits much different socioeconomic characteristics. Shrimp catches vary both with temperature (positive) and cod abundance (negative). Multiple regression analysis finds that cod catches, sea temperature, and the AO and NAO indices together explain more than 70% of the variance in shrimp catches.

There are other examples. Economically critical groundfish populations exhibited steep declines or collapses off Norway, the Faeroe Islands, Iceland, west Greenland, Newfoundland, and New England during the late 1980s or early 1990s (Hamilton and Haedrich, 1999). The collapse of Newfoundland's northern cod fishery in 1991–92 occurred in conjunction with unusual ice conditions and a broadening of the cold intermediate layer of the Labrador Current during a Northwest Atlantic cooling phase of the NAO. Norway's cod fishery was partially recovering from its own crises (1989) during the same years, assisted by a Northeast Atlantic warming phase.

The Barents Sea has warmed in association with probable intensification of the Atlantic Current system west of Norway in recent years. These changes have a significant impact on the ecosystem, as illustrated by the effects on the cod stock of the Barents Sea. The control mechanisms are diverse. Ellertsen et al. (1989) report that, "The temperature dependent spawning of the copepod *Calanus finmarchicus* may be the most important process to cause variability in cod larval survival for the Arcto-Norwegian cod stock." Bogstad and Gjosaeter (1994) indicate that for every 1°C warming of the Barents Sea, the food consumption by the Arcto-Norwegian cod stock increases by 800,000 tons, and Kjesbu (1994) finds that a 1°C drop in temperature during vitellogenesis will delay cod spawning by 8–10 days. Further, for every 1°C increase in temperature, the weight of a 4-year old Atlantic cod will increase by almost 30% and the age of maturity (spawning) will decrease significantly (Brander, 1994).

2.5.2.2 North Pacific and Bering Sea Fisheries

In the North Pacific, a physical regime shift took place with an intensification of the Aleutian low in the mid-1970s. Among the many changes associated with that shift were increased Alaskan salmon catches and a change from shrimp to groundfish dominance in the Gulf of Alaska (Hare and Francis, 1995; Botsford et al., 1997).

An example of the potential interaction of climate and fisheries management is the recent collapse of some western Alaska salmon stocks and the curtailment of groundfish operations in the Bering Sea due to declines in the western population of the Steller sea lion and northern fur seal. These are important current management issues. The basic science problem with resource management is that fisheries agencies with responsibility over stocks important for human harvest are driven toward solving narrow short-term problems. For productive fisheries management, we need to understand how larger scale changes such as AO variability influence ecosystem productivity.

2.5.2.3 Economic Impact of Fisheries

The fisheries potentially affected by Unaami have an economic importance measured in billions of dollars. Commercial fisheries in northern waters accounted for nearly half of the world's total catch by weight in the 1990s, and a larger proportion by value (FAO, 2000). Fishing grounds of the arctic-influenced Northeast Atlantic (10.5 million tons in 1995) and the Northwest Pacific (24 million tons) have been among the most productive. For many northern peoples, fishing constitutes the chief local resource and the foundation for their modern economy. Fisheries' exports from Iceland, for example, were worth roughly $1.2 billion in 1994. Other key northern Atlantic fisheries include those of Norway (exports of $3.8 billion in 1999), the Faeroe Islands ($380 million in 1997), and Greenland ($350 million in 1995). Fishing contributes substantially to the economies of northern regions in larger countries as well— places such as Alaska, northwest and maritime Canada, and Russia's Kola Peninsula. Intensification of Barents Sea fishing efforts is viewed as a promising direction for economic development by planners in the hard-pressed Murmansk region of Russia. Canada's exports from marine fisheries totaled $2.2 billion in 1997. Fishing is a main pillar of Alaska's economy. The Bering Sea ecosystem alone supplies fishers from the U.S., Russia, Japan, Norway, China, Poland and the Koreas with an annual catch worth some $1 billion. Most of these northern fisheries have shown sensitivity to climatic variation (Beamish, 1995).

Apart from their economic value to fish-exporting nations, fisheries contribute an important source of food protein worldwide. They are a critical resource for food security, particularly in poor countries (FAO, 2000).

2.5.2.4 Arctic Shipping

Clearly, the changes in ice conditions and weather in recent years have had an impact on local transportation. This can be seen in the remarks of the native people above. The recent arctic environmental changes, specifically changes in the area and thickness of sea ice, can also profoundly impact arctic marine transportation. Longer melt seasons, thinning ice covers, and reductions in multiyear ice have key operational implications for shipping around the Arctic Basin. For example, greater access and longer navigation seasons may be possible in Hudson Bay, the Chukchi and Beaufort seas, and along the Russian Arctic coast if present sea ice trends continue. The significant reductions in the thickness of arctic sea ice reported by Rothrock et al. (1999) and in the area of winter multiyear ice (Johannessen et al., 1999), suggest the possibility of shipping in the central Arctic Ocean sometime during the 21st century. It is significant to note that at the end of the 20th century nuclear and non-nuclear icebreakers (from Canada, Germany, Russia, Sweden, and the U.S.) have made summer transits to the North Pole and operated throughout the central Arctic Ocean. From 1977 to 1998 icebreakers have made 27 voyages to the Pole for science and tourism (Brigham, 1998, 2000). Thus it is conceivable that surface ships in the future will not have to confine their operations solely to the arctic marginal seas.

The Northern Sea Route (NSR) across the north of Eurasia, long used by the Soviet Union and Russia for arctic commercial shipping, has experienced recent environmental change that could alter shipping patterns between Asia and northern Europe. Sea ice reductions in the Siberian seas have been observed during the last two decades of the 20th century. Parkinson et al. (1999) have shown regional sea ice reductions in the NSR area for 1978–1996: a 17.6% decrease per decade in summer for the Barents and Kara seas, and a 3.7% decrease per decade for a large area of the Arctic Ocean including the Chukchi, East Siberian, and Laptev seas. Record summer sea ice reductions have been identified in the Russian Arctic for 1990, 1993 and 1995 (Maslanik, 1996; Serreze, 1995); a record sea ice retreat was also observed in 1998 for the Beaufort and Chukchi seas (Maslanik, 1999). These significant transformations, coupled with potential sea ice thinning and a shrinking multiyear ice fraction (meaning less multiyear ice in the coastal shipping routes), portend improved conditions for navigation along the NSR. Long-term observations of the decadal and interannual variabilities of sea ice in these regional seas will be critical to future planning and selection of shipping routes. Further, reflecting global interest in the NSR, a comprehensive study — the International Northern Sea Route Programme (INSROP) — was conducted during 1993–1999 and was funded primarily by Japanese and Norwegian interests. The project produced 167 peer-reviewed working papers (involving 318 researchers at 50 institutions in 10 countries) and a comprehensive reference volume (Brigham et al., 1999). An INSROP summary conference in late 1999 confirmed that the NSR's technological and environmental challenges are no longer absolute obstacles to commercial shipping, and that the European Union and Russia are collaborating on programs to better link western Siberia and Europe using arctic marine shipping (Ragner, 2000). Continued sea ice reductions will no doubt influence the initiation of transportation studies similar to INSROP for the Northwest Passage, the coasts of Greenland, the Alaskan Arctic coast, and other regional seas. SEARCH will provide key baseline information for these future efforts.

2.5.2.5 Economic Impact of Northern Shipping

Greater access to ports around the Circumpolar North due to changing climate and sea ice can have substantial economic impact. Longer shipping seasons in the Canadian Arctic may enhance the economic viability of zinc and lead mines on Little Cornwallis Island and at Nanisivik. Grain shipments from Churchill, Manitoba, across Hudson Bay to markets in the south can be increased with a lengthening of the navigation season; bulk cargo carriers without ice strengthened hulls (less expensive ships) will conceivably be able to transit Hudson Strait and reach Churchill during extended open-water seasons of up to 180 days compared with 90–100 days today. For Alaska, similar improvement in the navigation (open water) season can lead to reduced stockpiling and increased shipments of ore from the Red Dog Mine on the Chukchi Sea. A substantial change in the open water season for the Beaufort Sea — from 60 to 150 days (Maxwell, 1997) — can potentially reduce the costs associated with offshore oil and gas exploration and production.

The largest potential economic impact of climate change on arctic shipping may occur in northwest Russia and involve the Northern Sea Route. Shipping access to the large oil and gas reserves in the Barents and Kara seas will be substantially improved if regional warming of the Russian Arctic continues. Cargo exports of 300 million tons generated from the development of fields in the region (the Yamal and Taymyr peninsulas, and the Tyumen and Timon Pechora offshore fields) are possible (Ragner, 1999). Marine transportation systems will compete with pipelines, but with the current building of an icebreaking tanker terminal at Varandey (southeast Barents Sea), shipping appears to be the initial system of choice. Year-round navigation into the Kara Sea has been demonstrated during the past two decades of operations along the Northern Sea Route. However, even small increases in the length of the navigation season (e.g., 60–90 days) can influence the number of transits by fleets moving millions of tons of cargo.

Altogether arctic shipping and offshore development involve millions of tons of cargo and hundreds of millions of dollars annually. For Canada alone offshore operations are frequently interrupted by sea ice and icebergs at a cost of more than 40 million dollars (Canadian) annually (Everett and Blair, 1998). Potential savings of this magnitude may be gained because of longer periods of open water associated with changes in arctic climate. If changes result in opening significant new navigation routes, the size of the shipping industry could be changed several fold. International ship traffic may become substantial if the Northern Sea Route and Northwest Passage are open for longer periods of time. The greatest economic impact of changes in ice conditions may not be in shipping *per se*, but in making new areas economically feasible to develop and thus creating whole new industries.

3. HYPOTHESES

We have identified a complex of related atmospheric, oceanic, and terrestrial changes that have dominated the Arctic in the past two decades. Because they have made it harder for those who live in the North to predict what the future may bring, we have named the complex of recent changes Unaami. It is characterized, among other things, by:

- A decline in sea level atmospheric pressure in the Arctic with associated changes in winds
- Increased surface air temperature in Northern Europe and the Russian Arctic with cooling over eastern North America
- Decreased sea ice extent and thickness
- Alterations in terrestrial precipitation
- Cyclonic ocean circulation and rising coastal sea level
- Increased temperature of the Atlantic water
- Decreased Beaufort Sea surface salinity
- Increased freshwater flux from the arctic to the sub-arctic seas

Discovering the full scope of Unaami will be an ongoing part of SEARCH. However, a working definition based on present knowledge is useful. For this we define Unaami as the recent and ongoing, decadal (e.g., 3–50 year), pan-arctic complex of intertwined changes in the arctic physical system. The physical changes, in turn, alter the ecosystem and living resources and impact the human population. Thus, these biological and societal consequences may also be considered part of Unaami.

We have developed four working hypotheses to guide SEARCH. Our first hypothesis is that:

Unaami is related to the Arctic Oscillation. Associations between changes in the AO and many environmental parameters, such as air temperature and ocean circulation, seem fairly clear. A key goal of SEARCH is to understand the interactions on large spatial scales inherent in Unaami and their links to the AO in a quantitative way. Here we refer to the AO as the complex of atmospheric circulation changes extending from the surface to the stratosphere involving the spin up of the polar vortex as described by the AO and related teleconnection indices. Testing this hypothesis will shed light on the interactions among the atmosphere, ocean, and land. It will also tell us much about how Unaami is tied to the global atmospheric system.

A second hypothesis is that:

Unaami is a component of climate change. The AO is a fundamental mode of atmospheric variability, and the increasing dominance of its positive mode may be tied to anthropogenic climate change. There is also an increasing interaction between the Arctic and the midaltitude atmosphere. Thus, Unaami may be tied to climate change through the AO as well as through other patterns of atmospheric, oceanic, and terrestrial variability. Testing this hypothesis bears directly on the goal of understanding how Unaami fits into the larger picture of global climate change.

A third hypothesis is related to the first two. It is that:

Feedbacks among the ocean, land, ice, and the atmosphere are critical to Unaami. Assessing these feedbacks can determine the extent to which Unaami and the Arctic play critical roles in climate change. For example, a decrease in sea ice and snow cover forced by higher temperatures could lead to further warming due to the reduction in albedo (the well-known ice albedo feedback). This could, in turn, alter patterns of atmospheric circulation. A second example is albedo and sensible heat flux feedback through reduction or expansion of sea ice extent in marginal seas. Particularly sensitive regions are the Barents, East Siberian, and Labrador seas. A third example is increased stratospheric cooling due to development of the "ozone hole."

Our final hypothesis is that:

The physical changes of Unaami have large impacts on the arctic ecosystems and society. This is true whether the recent Unaami is tied to anthropogenic climate change or not. The key issues growing from this idea are that we must describe (and ultimately attempt to predict) the ecosystem effects and societal impacts of Unaami, and we must distinguish between the changes associated with the large-scale physical Unaami phenomenon and the changes due to regional human activity.

3.1 Hypothesis 1: Unaami and the Arctic Oscillation

There is a large body of literature addressing climate and environmental variability associated with the NAO. While the exact relationship between the NAO and the AO is still being debated (e.g., Deser, 2000), the view taken by SEARCH is that NAO is a primary component of the more fundamental AO. By virtue of this reasoning and the hemispheric scope of the AO, Hypothesis 1 considers the recent changes in the arctic environment in the context of the AO rather than NAO. In Figure 3-1 the argument for this hypothesis is overlaid on the sea level pressure pattern of the AO from Thompson and Wallace (1998).

The argument behind this working hypothesis (Morison et al., 2000) is illustrated in Figure 3-1. As the AO index rises, the strength of the polar vortex increases and the surface pressure in the Arctic Basin decreases, weakening the Beaufort High (Walsh et al., 1996). This applies positive vorticity to the sea ice and the ocean circulation (Proshutinsky and Johnson, 1996, 1997), resulting in reduced convergence in the Beaufort Gyre. This, in turn, results in more open water, greater radiative heat input, and increased summer melt (McPhee et al., 1998). The change in circulation may also account for the decreased ice cover on the Siberian shelves (Maslanik et al., 1996). Steele and Boyd (1998) argue that the change in circulation re-routes Siberian river runoff and is thereby responsible for thinning the cold halocline layer. The shift of Siberian runoff to the east may also be in part responsible for the freshening of the upper layers of the Beaufort Sea (McPhee et al., 1998; Macdonald et al., 1999). The increased cyclonic vorticity added to the Arctic Ocean may also act to draw surface water from the lower-salinity, western

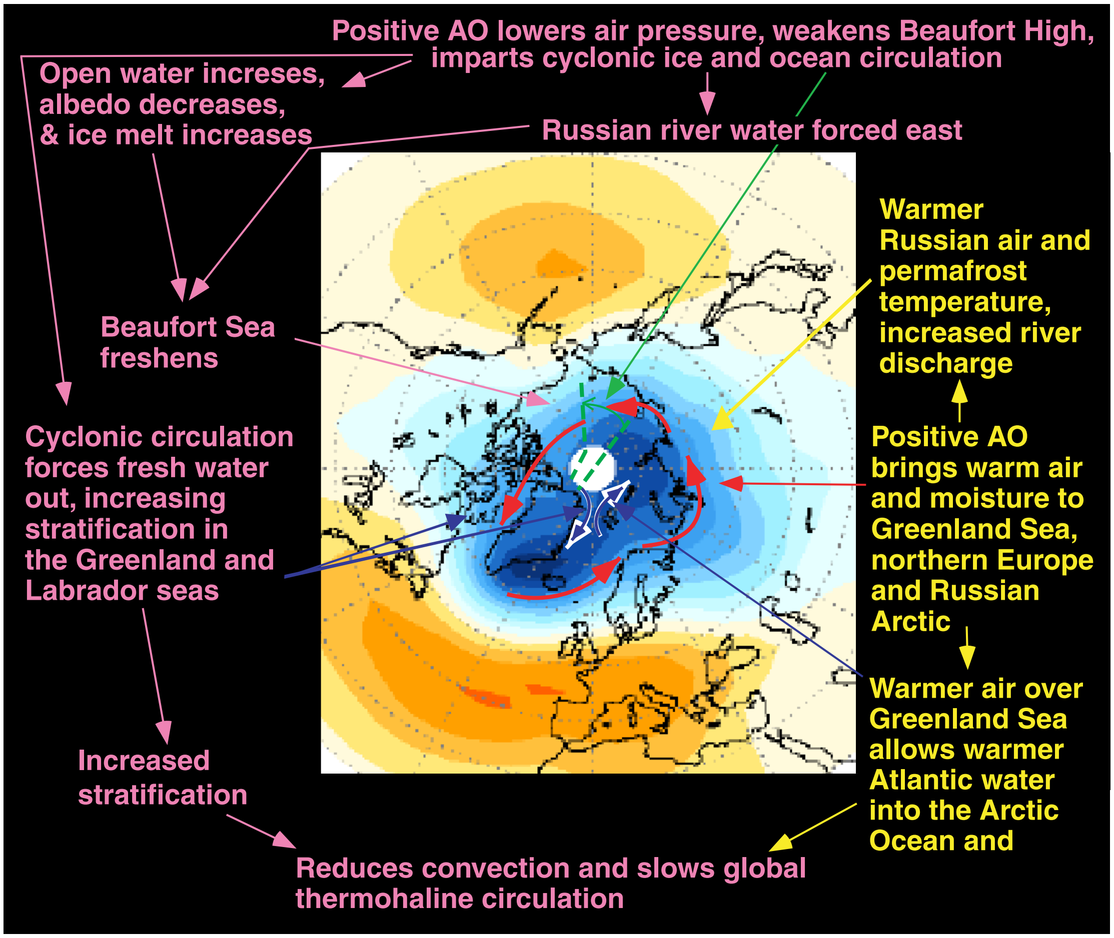


Figure 3-1 *Schematic of how AO (illustrated here by the first EOF of sea level pressure from Thompson and Wallace, 1998) may force the other changes comprising Onami. (Reproduced with permission of American Geophysical Union.)*

region of the basin and increase the amount of fresh surface water flowing out through the Canadian Archipelago and Fram Strait. The freshening of Fram Strait could increase stratification in the Greenland Sea and contribute to the weakened deep convection observed in recent years (Aagaard et al., 1991; Schlosser et al., 1991). The change in the Canadian Archipelago throughflow would have a similar effect in the Labrador Sea.

The positive AO pattern (Thompson and Wallace, 1998) indicates a northward component in the average winds across the Atlantic sector, carrying warm air over the Greenland-Norwegian Sea, Scandinavia, and northern Russia. It also should advect moisture northward to these regions, producing greater cloudiness and enhanced downward longwave radiation (Stone, 1997). An increase in warm air and moisture advection results in an increase in surface air temperature in the Greenland-Norwegian Sea and northern Russia (Thompson and Wallace, 1998; Rigor et al., 2000). The warming over the Norwegian Sea reduces the heat loss from the Atlantic water before it enters the Arctic Ocean, leading to the warmer Atlantic layer observed by Carmack et al. (1997), Morison et al. (1998a), Steele and Boyd (1998), and Swift et al. (1997). The change in atmospheric circulation is also represented in a rising NAO index and the changes observed in Fram Strait inflow temperatures described by Dickson et al. (2000) and Swift et al. (1997).

The advection of warm air into the Russian Arctic and the corresponding positive temperature trend there favors warming and thawing of permafrost (Pavlov, 1994). Rigor et al. (2000) show some of this warming extending eastward from Russia to Alaska, where permafrost warming is also observed by Osterkamp and Romanovsky (1994, 1999). The strengthened AO pattern adds a northerly component to the airflow over eastern Canada, accounting for the surface cooling there (Rigor, 1999) and the decrease in permafrost temperatures (Wang and Allard, 1995).

Several modeling studies have shown the response of the Arctic Ocean to recent changes in atmospheric forcing. Using an ocean model run with atmospheric forcing over the past 50 years, Proshutinsky and Johnson (1997) predict two decadally varying regimes corresponding to anticyclonic and cyclonic circulations of the arctic atmosphere and ocean. The regimes are defined by the sea surface response of a barotropic ocean model, but the average atmospheric circulation for each regime is also examined. They argue that the anticyclonic and cyclonic circulations correspond to a "cold and dry" and a "warm and wet" atmosphere and to a "cold and salty" and a "warm and fresh" ocean, respectively. Shifts from one regime to another are forced by changes in the location and intensity of the Icelandic Low and the Siberian High. Maslanik et al. (1998) indicate ice transport patterns associated with positive and negative NAO resemble weak versions of the cyclonic and anticyclonic modes of ice drift modeled by Proshutinsky and Johnson (1997).

Proshutinsky and Johnson (1997) find decadal oscillations between their regimes even in the 1950s–1980s, when the AO variability was relatively small. This may be in part because their domain is confined to the Arctic Basin while the AO is a larger-scale phenomenon. Also, they consider the total average field rather than the most significant EOF as done by Thompson and Wallace (1998). However, the strong cyclonic regime in the 1990s found by Proshutinsky and Johnson (1997) corresponds to the high AO (cyclonic) index for this period. This suggests the recent change in the Arctic Ocean and terrestrial regions may be thought of at least in part as a response to an extreme cyclonic regional-scale pattern predicted by Proshutinsky and Johnson's (1997) model, brought on by a hemispheric-scale change of the AO. Using a coupled ice-ocean model forced by different years (1987 and 1992) of the Proshutinsky and Johnson two-regime signal, Polyakov et al. (1999) predict how the anticyclonic and cyclonic regimes affect the Arctic Ocean. Their results indicate that under cyclonic forcing, precipitation increases over the ocean and decreases over land. In agreement with our working hypothesis, ice divergence under the cyclonic regime results in thinner ice and a fresher surface layer. Also, the cyclonic regime substantially reduces deep convection in the Greenland Sea by exporting more freshwater from the Arctic Ocean.

Numerical simulations by Zhang et al. (1998) suggest a strengthened inflow of Atlantic water through the Barents Sea in recent years. Their ice-ocean simulation of the past 18 years is driven by observed daily varying winds and air temperatures. It shows significant warming and salinization beginning in 1989, due mainly to a marked increase in the inflow of Atlantic water across the Barents Sea shelf. The result is a warming of the Atlantic layer within the Arctic Ocean, a weakening of the halocline in the eastern Arctic, and a decrease in sea ice volume and extent.

Zhang and Hunke (2001) report on the results of simulations with the Parallel Ocean Program (POP) model of the Los Alamos National Laboratory, which has been adapted to the Arctic Ocean. Simulated surface distributions of tracers under conditions representative of the first half of the 1990s show a significant decrease in the extent of the Beaufort Gyre. The simulation also shows the central Arctic having a cyclonic circulation similar to that discussed by Proshutinsky and Johnson (1996, 1997). The Transpolar Drift is shifted over the Mendeleyev and Alpha ridges. Maslowski et al. (2000) describe similar model results. They trace both the freshwater and the Atlantic water using "dyes" in the model runs. Their modeled response to 1979–1993 winds is similar to the observed changes in the ocean. Taken together, these models suggest that in the 1990s most of the freshwater on the Russian shelves, instead of moving off-shelf and across the basin, drifted eastward and exited through the Canadian Archipelago.

3.2 Hypothesis 2: Relation to Climate Change

There is growing observational and theoretical evidence that the Arctic Oscillation is both a natural pattern of variability of the atmosphere and a distinctive component of climate change. Thompson and Wallace (2000) find strong similarities between the AO and the complementary annular mode in the Southern Hemisphere. Thompson et al. (2000) find that the Northern Hemisphere climate trends of the past few decades display the same pattern as the AO. Thompson and Wallace (1999) indicate that the AO spans a wide range of frequencies and that daily weather as far south as the northwestern United States can be correlated with the daily AO index.

Numerous simulations with different models indicate that the AO is an important natural mode of variability of the global atmospheric circulation. Shindell et al. (1999a, 1999b) find a strong AO signal in simulations with the Goddard Institute of Space Studies (GISS) atmospheric General Circulation Model (GCM). Fyfe et al. (1999) find a strong AO signal in results from the Canadian Center for Climate Modeling and Analysis (CCCMA) coupled GCM. Yamazaki and Shinya (1999) have found the AO to be a dominant mode of variability in simulations with the Center for Climate Systems Research/National Institute for Environmental Studies (CCSR/NIES) atmospheric GCM. Hall and Visbeck (personal communication, 2001) find clear evidence of strong annular modes (such as the AO and NAO) in simulations with the Geophysical Fluid Dynamics Laboratory (GFDL) R15 coupled ocean-atmosphere model.

Because the AO is a natural mode of variability, it is reasonable to think it may be an important component of climate change. *A priori*, the rising trend in the AO appears consistent with greenhouse warming in that it involves heating of the lower atmosphere and cooling of the upper atmosphere. In fact, substantial components of greenhouse warming scenarios from state-of-the-art climate models such as those of Fyfe et al. (1999) and Shindell et al. (1999a) conform roughly to the form and spatial pattern of the observed changes associated with the recent increase in the AO index. However, not only are the recent changes in the AO larger than previously observed in this century, but they are larger and have come sooner than predicted by these 100-year simulations of greenhouse warming. Fyfe et al. (1999) find the Northern Hemisphere long-term climate change includes a 28% contribution from the AO, a 35% contribution from the 3rd EOF, and very small contributions from the other EOFs. Consistent with observations, the simulations indicate that the AO also oscillates at high frequencies (Fyfe et al., 1999; Shindell et al., 1999a, 1999b). Using the GISS Middle Atmosphere Model, Shindell et al. (1999b) find that the simulated response to increased greenhouse gases leads to an increasing trend in the AO index comparable to that observed over the past 30 years. Increased stratospheric aerosols due to volcanic eruptions have a similar effect, but the surface climate's response to solar cycles is more complicated. This suggests that the rising AO trend is a possible fingerprint of anthropogenic change. Similarly, Robock et al. (1999) find in observations and in simulations with the Max Planck Institute 4 and GFDL GCMs that the AO responds positively to volcanic eruptions in the tropics. The tropical lower stratosphere heats up because of the volcanic aerosols.

This increases the pole-to-equator temperature gradient and thus strengthens the polar vortex. The response propagates into the troposphere and, because of the standing wave pattern of the AO, advectively warms much of the Northern Hemisphere landmass.

Many questions remain about how the AO is driven. For example, the role of the stratosphere is unclear. Fyfe et al. (1999) produce an AO response in a model without an active stratosphere. This suggests the AO can be driven from the surface, for example, by CO_2-induced warming. In contrast, the model results of Shindell et al. (1999a, 1999b), Yamazaki and Shinya (1999), Robock et al. (1999), and Christiansen (1999) and the observational results of Baldwin and Dunkerton (1999), Baldwin et al. (1999), and Dunkerton et al. (1999) argue that the stratosphere is critical in changing the AO.

Unaami potentially affects global climate through the ocean as well as through the atmosphere. As noted in the previous section, Unaami includes changes in fluxes from and to the sub-arctic seas (Figure 3-1). It thereby can affect the global ocean thermohaline circulation. The spread of warmth to high northern latitudes in the Atlantic sector includes the vast amount of heat (about 10^{15} W) carried northward by the thermohaline circulation (THC). Most projections of greenhouse-gas-induced climate change indicate a weakening of the THC in the North Atlantic in response to increased freshening and warming in the polar/subpolar region (Delworth and Dixon, 2000). These changes reduce high-latitude upper-ocean density and therefore weaken the THC (see, for example, Manabe and Stouffer 1993; Rahmstorf and Ganopolski, 1999; Wood et al., 1999).

Paleoclimate records confirm that massive and abrupt climate change has occurred in the Northern Hemisphere, especially during and just after the last Ice Age (Broecker and Denton, 1989, Dansgaard et al., 1993; see also Broecker 1997, 2000; Marotzke, 2000). Thermohaline circulation change is a plausible driver for these abrupt changes. Both paleoclimate records and models suggest that the changes in the strength of the THC may occur rapidly, in a few decades.

While there is considerable spread between their projections, most climate models indicate that there will be weakening of the THC (Rahmstorf, 1999). There are also uncertainties about the ocean exchanges between the Arctic Ocean and the world ocean via the sub-arctic seas. However, there is evidence that long-term hydrographic changes in the deep northern overflows are already causing hydrographic changes in the deep and abyssal layers of the Labrador Sea—potential early warning signs of high-latitude effects on the THC. These changes are large and sustained. They include the freshening of both dense overflows by between 0.01 and 0.02 parts per thousand per decade for the past 3.5 decades.

Finally, there are indications that the decreases observed in sea ice extent may represent a fingerprint of greenhouse warming. Vinikov et al. (1999) compare observed trends of decreasing ice extent with trends they find in state-of-the-art global climate simulations. Although there is debate about the significance of some of the findings (Moritz and Bitz, 2000), Vinikov et al. (1999) find the recent observed trends exceed the normal decadal trends in the simulations without greenhouse warming.

3.3 Hypothesis 3: Potential Feedbacks

This hypothesis addresses the extent to which Unaami is simply driven by a large-scale perturbation in atmospheric circulation or whether it involves feedbacks that are now or will be important in maintaining change. Some relevant feedbacks have received considerable attention already, but must be put in the context of Unaami. A leading example is ice-albedo feedback. This is the process whereby a reduction in snow cover and sea ice extent decreases albedo. This allows more radiation to be absorbed, resulting in higher temperatures and promoting additional melt of snow cover and sea ice. It is being investigated extensively at local scales (grid scales of a typical climate simulation model) as part of the SHEBA experiment (Perovich et al., 1999). The ice-albedo feedback has been investigated implicitly in general large-scale simulations (Covey et al., 1991; Curry et al., 1995). Specific to SEARCH, AO appears to be associated with positive albedo feedback. Drobot and Andersen (1999) find that the onset of summer snow melt is earlier during periods of positive AO. Bamzai (1999) indicates the recent positive trend in the wintertime AO index partially accounts for the recent negative trend in Northern Hemisphere snow cover.

Cloud-radiation feedback is another process that may enhance heating in the Arctic via a number of mechanisms. One mechanism is that increased heating at the surface causes more evaporation from open water. This enhances cloud cover, increasing the flux of longwave radiation to the surface and further increasing surface heating. Curry et al. (1996) suggest that cloud-radiation feedback is positive for the Arctic in that clouds lead to surface warming, counter to the cooling effect of clouds globally. This process at the local scale has also been a focus of SHEBA. At larger scales, it is reasonable to speculate that a stronger influx of moisture into the Arctic could result in more cloudiness and higher surface temperatures.

There are important feedbacks in the lower stratosphere involving air chemistry. Increases in CO_2 and decreases in stratospheric ozone result in stratospheric radiative cooling centered on the Pole. This promotes a dynamic response that increases the speed of the polar vortex. Cooling down to 190 K supports stratospheric cloud formation, which further changes the local air chemistry and promotes further ozone reduction. Spring, with the return of the sun, appears to be a particularly important period for this feedback.

Saenko and Holloway (1999) find that their coupled sea/ice/snow model (based on the GFDL MOM model) yields enhanced freshwater storage during positive extremes of the AO. This is consistent with the ice/ocean modeling results of Polyakov et al. (1999). A more vigorous water cycle associated with Unaami, resulting in enhanced precipitation and runoff, could be part of at least one feedback whereby the increased freshwater increases stratification and reduces ocean heat flux to the surface, allowing more ice growth and increased albedo. This might have a negative feedback on AO and Unaami. On the other hand, decreased salinity in the Arctic Ocean increases stratification in the Greenland Sea, cutting off deep convection in that region. This would remove one avenue of dissipating near-surface heat from the world ocean and is a positive feedback for warming on a global scale.

Steele and Boyd (1998) suggest that increasing cyclonic atmospheric and oceanic circulation may be responsible for shifting the discharge from the Russian rivers eastward so that it does not replenish the cold halocline layer. This has resulted in a disappearance of this insulating layer in areas of the eastern Arctic. This may allow a stronger ocean heat flux to melt ice, and thereby promote decreased albedo, and more surface heating which could drive a stronger AO.

The positive mode of the AO exerts a cyclonic stress pattern on the ice cover. Through Ekman dynamics this results in a more divergent surface drift. This results in more open water, which in summer will produce a lower albedo and more surface heating. In winter it will also result in higher temperatures, but may also result in more ice production. Through dynamical interaction with the ice cover and upper ocean, the net result of a positive AO should be thinner ice, more ice melt and growth, and a fresher upper ocean. This is consistent with the modeling results of Polyakov et al. (1999). Saenko and Holloway (1999) find that the positive freshwater storage in response to positive AO anomalies in wind stress is more important than the response to positive AO temperature anomalies.

Unaami has potential long-term global feedback through effects on the ocean circulation of sub-arctic seas and consequent effects on the global thermohaline circulation. Unaami involves freshening of the outflows from the Arctic through Fram Strait to the Greenland Sea and through the Canadian Archipelago to the Labrador Sea. The Fram Strait outflow affects the hydrographic character of the dense northern overflows which cross the Greenland–Scotland Ridge to renew the deep waters of the North Atlantic. They are therefore important in driving the Atlantic meridional overturning circulation, a key component of the global thermohaline circulation. Also associated with Unaami, freshwater fluxes to the Labrador Sea, direct freshwater fluxes along the East Greenland Shelf, and recirculation of warmth from the eastern Fram Strait also tend to inhibit the thermohaline overturning circulation.

The effect of arctic warming on global climate could be especially large if warming trends continue to release methane, a greenhouse gas, from the tundra as described earlier. This is especially true if warming begins to melt extensive areas of methane-bearing clathrate deposits in coastal regions. A potentially extreme case would be if warming in the ocean (e.g., the Barents Sea) were to cause a massive release of methane from clathrate deposits. The relatively shallow clathrate deposits of the arctic shelves are already considered to be a great potential energy resource (Max and Lowrie, 1992). Clathrates are a potentially large source of greenhouse gas even in temperate waters (Suess et al., 1999). Recent investigations suggest that massive releases of marine clathrates may have been globe-altering events in the past (Kerr, 1999). The shallow depths at which clathrates are found in the Arctic, and the potentially massive consequences of release, suggest that this feedback should be investigated within SEARCH.

Feedbacks due to changes in the composition and structure of terrestrial ecosystems may be part of Unaami. The mix of time scales inherent in terrestrial ecosystem changes raises interesting complications. Both the species composition and the physical structure of terrestrial ecosystems are likely to change on time scales of decades. These multidecade changes may have very different feedbacks on climate than those due to short-term (1–10 year) responses of ecosystems to atmospheric change. For example, long-term warming experiments in several northern ecosystems have shown that initial net carbon losses are followed after several years by net carbon gains (Shaver et al., 2000). The initial carbon losses are driven mainly by the greater sensitivity of respiration versus photosynthesis to temperature, often combined with changes in soil moisture that increase the temperature sensitivity of soil respiration. Longer-term carbon gains are likely to be driven by changes in the nitrogen cycle and species composition, processes that have much longer time constants than respiration and photosynthesis.

Changes in marine ecosystems arising from Unaami may also produce feedbacks. For example, coccolithophorids are major producers of sulfur compounds that can, in turn, produce DMS (dimethylsulfide) that may be lost to the atmosphere and produce aerosols that encourage cloud formation. Thus, the recent coccolithophorid blooms that have occurred in the Bering Sea may produce a feedback due to the increase in cloud condensation nuclei arising from increased DMS production.

3.4 Hypothesis 4: Impacts on the Ecosystem and Society

As discussed previously, changes in the arctic ecosystem associated with Unaami have affected arctic and sub-arctic peoples. The physical changes such as increased variability in weather and ice conditions have affected society directly. We already see possible changes in fisheries, transportation and resource exploitation. The impacts extend south, beyond the Arctic. Weather at middle latitudes is affected by the Arctic Oscillation and the Arctic's response to the AO. For example, the state of AO affects storm tracks at middle latitudes; the frequency of cyclonic storm passages increases in the Atlantic (Dickson et al., 2000) and decreases in the Pacific (Overland et al., 1999) with a rise in the AO. Precipitation patterns in the Northwest United States (Thompson and Wallace, 1999) and air temperatures in Europe are strongly related to the AO (Thompson and Wallace, 1998). An increase in the stratification of the North Atlantic associated with Unaami is likely to reduce global ocean overturning with an immediate effect on European weather and possible long-term effects on global climate (Kwok and Rothrock, 1999).

Our goals are to understand Unaami and the causes of the trends seen in recent decades. This includes understanding the impacts on the ecosystem and society. We hope to be able to predict the general course of these impacts (e.g., predict good ice years versus bad ice years) much as is done with ENSO impacts today.

A key challenge is to distinguish between the changes associated with large-scale physical Unaami phenomena and those due to direct human activity. Our northern fisheries provide a good example of this problem. We know some fisheries (pollock in the west and cod in the east) and the ecosystems upon which they are based have changed dramatically in recent times. Society is trying to adjust to these changes. We hypothesize that a continued Unaami excursion could have substantial economic effects on commercial fisheries and native subsistence. However, the effects of Unaami are difficult to separate from the effects of altered fishing practices and regulations. These may interact with the normal population dynamics of the fish and Unaami in nonlinear ways. This makes it all the more important to understand the interplay of climate change and human intervention and to learn whether the physical effects of Unaami will persist.

4. OBJECTIVES

4.1 Overall Objective

Our overall objective is to understand Unaami. This requires that we:

- Determine if Unaami has happened before
- Determine if Unaami is continuing
- Understand the forcing mechanisms and feedbacks that control Unaami
- Learn the impact of Unaami upon ecosystems and residents of the Arctic

To test and utilize our understanding we wish to:

- Assess the predictability of Unaami
- Assess and predict the impact of Unaami on ecosystems and society

These overall objectives must be pursued differently for different components of the arctic system. For example, Unaami relationships are clearly apparent in atmospheric and oceanographic data; thus research to understand processes and feedbacks can proceed without delay. However, a large amount of initial assessment is still needed in the biological realm, and distinguishing between social and environmental effects remains a challenge for human dimension research. It is important to highlight special aspects of the overall objectives applicable to individual components.

4.2 Component Objectives

4.2.1 Atmosphere

The atmospheric component of SEARCH aims to fully understand the recent changes observed in the Arctic from the surface through the stratosphere. Observation of atmospheric variables is necessary to track Unaami and understand the key mechanisms and feedbacks that affect the AO's persistence beyond purely stochastic variations. A critical aspect of the atmospheric component is to extend relevant observations into the future. This is especially important at a time when key observing stations are being closed or are being automated. A key example is the degradation of the terrestrial temperature and precipitation networks. While efforts must be made to provide an adequate network of stations, these must be coupled with efforts to use other techniques such as optimal blending of observations with model output. Because the vertical structure of the AO is important to understanding its relation to the global circulation and climate, we aim to extend the spatial information vertically using new measurement or analysis techniques. Efforts must also be made to rescue at-risk data sources that can help to provide more complete historical time series for retrospective analysis. For example, large amounts of precipitation data in the former Soviet Union remain to be digitized.

4.2.2 Ocean and Sea Ice

A key to determining the evolution of Unaami in the ocean will be the continued provision of oceanographic data. Unfortunately, many valuable programs, such as the Russian hydrographic surveys and ice camps, have ceased. We must continue to gather enough hydrographic data to monitor changes in the ocean circulation, the thickness of the cold halocline, the freshwater balance, and the heat content of Atlantic water on time scales long enough to understand the decadal rhythms of global change. We must improve our understanding of interaction with the shelves by improving the analysis of old data and then extending new measurements into the shelf seas. To understand the connections between the Arctic and lower latitudes, we must monitor critical inflows and outflows. Understanding the coupling of the ocean, ice, and atmosphere requires long-term observations of the upper ocean over a wide area. Understanding processes requires that observation programs be coupled with modeling studies. For example, we need to understand how ocean circulation changes in response to the atmospheric changes characteristic of Unaami. How long does it take a change in atmospheric circulation to affect the ocean at depth? Can the change in atmospheric circulation over the Siberian shelves actually starve the cold halocline?

Because the upper Arctic Ocean is essentially an ice bath, the mass of the ice cover is the primary indicator of its thermal state. The ice cover also exercises primary control over the energy balance at the surface. Thus understanding its condition is critical to all our objectives. Clearly, we will have to continue and improve measurements of the ice cover, including extent and concentration. A systematic method must be found for combining disparate measurements of spot thickness, ice motion, surface mass balance, concentration, and occasional under-ice profiles into a coherent record of the thickness distribution. Meeting this objective will require development of new observational techniques and data assimilation methods. Developing these will teach us a great deal and test our understanding of many of the mechanisms and feedbacks critical to Unaami.

4.2.3 Terrestrial

The first objective for the terrestrial component of SEARCH is to systematically assess recent changes in the hydro-climatology of the pan-arctic landmass and terrestrial ecosystems. Second, we must diagnose the extent to which these changes are linked to and consistent with changes in other components of the arctic system, such as atmospheric circulation and permafrost dynamics. Third, we must initiate large-scale experiments that test the presumed controls over the dynamics of change in the terrestrial system and their consequences for the atmosphere and oceans. Finally, we must compare modern data against paleoclimate records enhanced through a) retrospective analysis of changes that have occurred over the past century, b) an expanded measurement program of current and future changes, and c) modeling experiments in which atmospheric models that have been calibrated to the paleo data of the arctic system are used to simulate the recent past and potential future changes. To achieve these objectives we must develop a program for long-term monitoring of the hydro-climatology and terrestrial ecosystems drawing on emerging remote-sensing and modeling capabilities, retrospective studies, and large-scale experiments.

4.2.4 Biological System

The first objective of the biological component of SEARCH is to identify those components of the biological system that are sensitive indicators of Unaami, with an emphasis on those processes that retain a long-term record of change. We must identify indicator species and processes diagnostic of Unaami. For example, tree rings on land, foraminifera in ocean sediments, or invertebrate head capsules in varved lake sediments provide clear records of past changes in the physical system and can be used to extend instrumental records into the past. We must then test, through experimentation, the mechanisms by which these biological proxies respond to the physical system.

The second major objective is to monitor changes in those components of the biological system that strongly affect the biophysical components of the arctic system and to determine experimentally the factors that regulate these components. For example, changes in the treeline location strongly influence regional flux of heat and moisture to the atmosphere. The location of this vegetation boundary responds sensitively to climate, vegetation composition, and fire regime, in ways that are not well understood. Other biological components with strong biophysical effects include grazer effects on plankton and sedimentation of organic carbon, tree species effects on the Bowen ratio (the ratio of sensible to latent heat flux), and effects of aquatic mosses on nitrogen flux in streams and rivers.

The third major objective of the biological component of SEARCH is to monitor changes in those components of the biological system that have important cultural and economic impacts on society and to determine the factors that regulate these components.

The fourth major objective is to identify the role of biocomplexity in the functioning of the arctic system. This builds on the first three objectives and recognizes that the structural and biological diversity of the arctic system has an unusually large effect on system function because of its low diversity. Large changes in the abundance of even a single species or functional type, such as sphagnum moss or grazing daphnia, can substantially change the way in which the biological system responds to and affects the physical system or its impacts on society. With the rapid physical changes in some arctic ecosystems, we can expect reductions in numbers of species as existing species are rapidly forced out and replacements only slowly take their place. Thus, we must begin to document, understand, and place into context changes in biocomplexity associated with Unaami.

4.2.5 Human Dimension

The primary objective of the human dimension component is to understand the impact of Unaami on society. A major challenge to overcome is that the relevant time series are scattered. Another challenge is separating the effects of Unaami from the independent actions of society. Approaches to overcoming this problem may be to compare social systems in regions with different Unaami impacts but similar social pressures, and to compare modern conditions with past environmental and cultural records. It should be recognized that for the biology component as well as the human dimension component, the impacts of Unaami spread beyond local effects in the Arctic. Some species spend only part of their lives in the Arctic and migrate to other regions. Fishing industries worth billions of dollars and based far away depend on conditions in the Arctic. Opening of arctic shipping routes could also be worth billions of dollars. Not only does ship trafficability affect the exploitation of natural resources in the Arctic, it may also affect global shipping patterns. Hence, SEARCH must assess the human impacts of Unaami outside the Arctic as well as in the Arctic.

Ultimately, the objective of predicting the impacts of Unaami on society may be the most influential part of SEARCH. If we can achieve predictability, we will have performed a tangible service to society. It will require a novel collaboration between physical, biological, and social scientists and the people of the North.

5. STRATEGY

The SEARCH strategy includes four fundamental elements: observations, modeling, process studies, and application. All SEARCH hypotheses involve Unaami, a complex of related, pan-arctic but regionally varying, atmospheric, oceanic, and terrestrial changes observed in recent decades. Observations are needed to track these changes many years into the future. Modeling is required not only to understand the relationship between the changes, but in many cases to evaluate critical variables that cannot be measured directly. Process studies will be needed to develop reasonable models. The application of what we learn to explaining and predicting the impact of Unaami on society is the ultimate benefit of SEARCH.

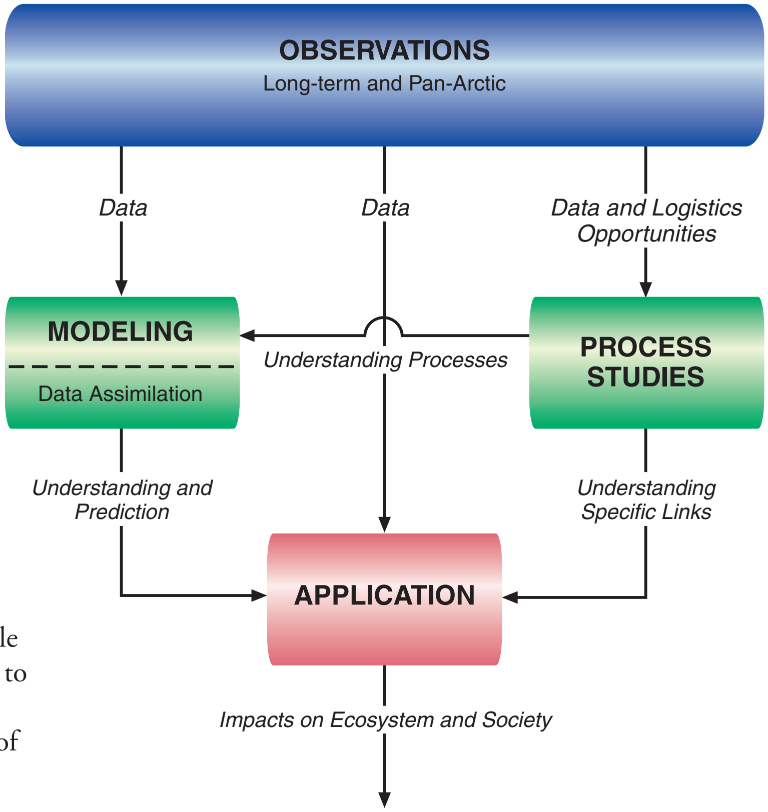


Figure 5-1 SEARCH strategy.

SEARCH is an interdisciplinary program. As such we have to recognize that the different disciplinary elements of SEARCH will start at different stages of development. For example, the atmospheric science component has some critical long-term observations already under way, and Unaami is even described in part by these observations. In contrast, we have recognized the effects of Unaami in the ecosystems and society only recently. As a consequence, SEARCH must begin with allowance for these disciplinary differences in level of development. Initially some disciplines will be continuing old observation series, while others are still holding workshops and planning observations. Consequently, the SEARCH strategy should be considered an evolving plan, but one that maintains the guiding philosophy of understanding Unaami.

To understand Unaami will require the collection, distribution and analysis of multi-faceted and truly interdisciplinary data from an extreme environment. It is useful to point out that there should be many opportunities for SEARCH to interface with NSF's Information Technology Research (ITR) initiative. Relevant ITR-supported research could include developing methods of transmitting data to shore-based laboratories from under-ice moorings and autonomous vehicles. Another ITR issue would be the development of systems for effective and rapid amalgamation of data from traditional shipboard and terrestrial observations with remotely sensed data and model outputs.

5.1 Long-term Observations

Long-term observations are central to SEARCH. The changes that have alerted us to Unaami have only become apparent in the context of historical data collected prior to 1990. Ironically, many of the operational observing programs that produced those data are now gone. For example, the Russian hydrographic programs of the Cold War era have stopped. Many Russian and Canadian meteorological stations are being closed or automated. If Unaami is to be understood, we must rededicate effort to fundamental observations in the ocean, in the atmosphere, and on land that continue on a regular basis for decades into the future. SEARCH aims to begin this program of crosscutting pan-arctic observations in a research mode, and ultimately see it shift into a more operational mode as we begin to understand Unaami and learn more about the critical variables. In this section we describe the types of observations needed for each component of the arctic system.

5.1.1 Atmosphere and Energy Budget Observations

Several types of measurements will contribute to the evaluation and diagnosis of variability and recent changes in the arctic atmosphere and energy budget:

- *In situ* observations
- Products of data assimilation by models (reanalyses)
- Remote sensing data
- Traditional knowledge

A challenge in SEARCH will be the leveraging and synthesis of these various types of information into a coherent picture of arctic change. We present here a survey of key issues pertaining to each category of information.

5.1.1.1 *In Situ* Measurements

Considerations that will guide the choice and location of *in situ* measurements include (1) model studies or analyses of existing data to determine which locations are likely to be sensitive indicators of change in the Arctic; (2) the availability of historical data to provide context and data continuity; and (3) the relevance of location to the impacts of change in the ice and/or atmosphere. In addressing these considerations, it is convenient to divide the measurements into terrestrial and marine components.

In situ measurements of atmospheric and surface-energy budget variables have long been provided by synoptic observing stations. While the array of such stations is less dense than desired, it has been sufficient for the detection of large-scale patterns of change in surface air temperature, pressure, surface radiation fluxes, and, through data assimilation by numerical weather prediction models, atmospheric circulation and moisture flux. With the recent closure of high-latitude stations in Canada, Russia, and the United States, the Arctic terrestrial observing network is degrading. Even when stations are converted to autonomous operation, observations of variables such as cloudiness, type of precipitation, and visibility are seriously compromised. A priority for *in situ* measurements in the Arctic is the continuity that is potentially achievable by siting observations at or near locations for which existing records already span several decades. Upper air observation sites such as Mould Bay and several Siberian sites are high-priority locations.

There is a primary need for quality time series of air temperature over the Arctic Ocean. Several related issues appear to be relevant to SEARCH. The first is the development and deployment of autonomous instruments to provide reliable aspirated measurements of the air temperature over sea ice. It must be demonstrated convincingly that such instruments eliminate the uncertainties in the temperatures (Martin et al., 1997) obtained from the array of automated buoys maintained by the IABP (available since 1979). Second, there is a need to reconstruct historical temperature variations over the Arctic Ocean spanning at least the past half-century. Such a reconstruction will likely require blending the air temperature measurements from ice stations (Russian NP and various U.S. drifting stations) with results from data assimilation models. Given the spotty database of past temperatures over sea ice, a promising approach is the use of next-generation buoy measurements, together with existing ice station data, to develop credible data assimilation products.

A goal of SEARCH is to identify and understand the linkages between atmospheric variability driven by the AO and its impact on the ocean and sea ice cover. This requires the acquisition and analysis of data on the surface energy balance. These data will address, in particular, the coupling between the atmosphere and the ice surface, which controls the seasonal cycle of ice albedo. This represents a key component of one of the feedback processes strongly affecting the arctic system and climate change (Curry et al., 1995).

An important issue is the thinning of ice in the central basin. The IABP needs enhancement with observations of radiation, ice thickness, and winds at selected locations.

A key region that is presently poorly sampled is the far northern North Atlantic. Past studies have repeatedly shown that the largest flux of atmospheric moisture into the Arctic is through this region, and the same is true of the influx of sensible heat.

Svalbard's infrastructure and its location at the "crossroads" of the North Atlantic provide the potential for science-driven observing programs to complement those in the central Arctic.

The emphasis of both the terrestrial and marine measurements of the atmosphere will inevitably be the so-called "surface" atmospheric variables. However, inclusion of broader *in situ* measurements in the boundary layer should be a priority in SEARCH because alternative data sources (satellites, atmospheric models) are generally most deficient in the boundary layer, where these other approaches are limited by resolution and, in some cases, cloudiness.

5.1.1.2 Data Assimilation Products

Assessing trends and variability in the arctic atmosphere requires recognition that numerical weather-prediction models and the amount and quality of available assimilation data have changed considerably. Until 1979, *in situ* observations for the central Arctic Ocean were largely limited to rawinsonde profiles from the Russian North Pole stations. Since that time, incorporation of IABP surface pressure measurements (Colony and Rigor, 1993) has improved the quality of analyzed arctic fields. The NCEP/ NCAR reanalysis project provides gridded atmospheric analyses from the late 1940s to the present using a "frozen" numerical weather prediction/assimilation system whereby biases due to changes in the model are eliminated (Kalnay et al., 1996). However, inhomogeneities associated with temporal changes in assimilation data remain.

Existing global atmospheric reanalyses by NCEP, ECMWF, and NASA/DAO are rich sources of data for analyzing variability in the arctic atmosphere. In the case of the NCEP effort, record lengths are sufficiently long to permit determination of how key atmospheric variables change with the AO. However, deficiencies in existing reanalysis products, particularly as they relate to their simplified representation of polar physics, require caution in their use. The major reanalysis data sets of NCEP and ECMWF have received some assessment by Arctic researchers (e.g., Serreze and Hurst, 2000; Adams et al., 2000; Cullather et al., 2000). However, differences between the reanalyses, and the shortcomings of each, need more systematic documentation. For example, the adequacy of reanalysis-derived precipitation for arctic freshwater budget applications needs further assessment. ECMWF is now embarking on a new global reanalysis project extending back to the 1950s (ERA-40). ERA-40 will make use of a new model with higher resolution and improved treatment of important variables such as sea ice cover, snow cover, and 2-m air temperature. NCEP is also planning for a new global reanalysis effort.

In spite of their shortcomings, global atmospheric reanalyses will play key roles in SEARCH. Changes in the sea ice mass balance, for example, may be diagnosed most expeditiously through sea ice model simulations forced by atmospheric fields (winds, temperature, radiative fluxes, precipitation) obtained from atmospheric reanalyses. It has already been established that atmospheric reanalyses permit evaluations of atmospheric moisture transport that are superior to those obtained from rawinsonde data alone (Cullather et al., 2000). As discussed in section 5.2 (modeling strategy), it is proposed that SEARCH develop a dedicated Arctic System Reanalysis that will ensure incorporation of the most appropriate polar physics. Development of such a system will require close liaison between SEARCH and the major reanalysis centers.

5.1.1.3 Remote Sensing

The timeliness of SEARCH is enhanced by the availability of remote-sensing products of potential use in documenting and diagnosing environmental changes over the past 20+ years. This period is sufficiently long to permit evaluation of how some of the satellite-derived variables change with the phase of the AO.

A key NASA/NOAA Pathfinder data set is the recently released series of TOVS (Tiros operational vertical sounder)-derived vertical profiles of temperature and humidity in the Arctic (Francis and Schweiger, 2000; also at http://psc.apl.washington.edu/pathp). These profiles are gridded daily, providing an opportunity to address variations in the arctic energy and moisture budgets. Daily grids of cloud fraction for the same time period have been computed from the TOVS measurements. For the Arctic Ocean surface, SSM/I and TOVS measurements have provided grids of ice conditions from 1979 onward. Ice motion fields from SSM/I should also find applications in validation of sea ice models and in studies of variations in ice deformation and the ice mass budget.

Launched in 1999, the Multiangle Imaging SpectroRadiometer includes maps of cloud cover, cloud reflectance, aerosol characterization, and surface albedo at a spatial resolution of 1.1 km. A second sensor, the Clouds and the Earth's Radiant Energy System, measures daily radiative fluxes and clouds, monthly gridded cloud amounts and top-of-atmosphere (TOA), and surface fluxes and clouds. The Geosciences Laser Altimeter System (GLAS) has a planned launch for late 2001. GLAS products include sea ice roughness, ice sheet elevation, thin cloud and aerosol optical depths, cloud heights, and surface reflectivity. The Moderate-resolution Imaging Spectroradiometer (MODIS) produces daily and 8-day composites of global snow cover, sea ice cover, and ice surface maps at 500-m resolution, a 16-day composite of land surface albedo with a spatial resolution of 1 km, and maps of vegetation cover and their changes at a resolution of 1 km over 96-day intervals.

5.1.1.4 Traditional Knowledge

A largely untapped source of information relevant to arctic ice–atmosphere interactions is the base of "traditional knowledge" accumulated by long-time residents of the Arctic, particularly the native communities. Information on sea ice conditions, storminess, beach erosion, vegetation changes, and other quantities relevant to arctic change are inadequately documented in conventional data sets, yet these variables are closely tied to climate-change impacts. The record of springtime sea ice conditions in the Chukchi-Beaufort sectors, for example, may be augmented substantially by the experience of native residents during whaling expeditions. A challenge in using such information is to synthesize standard digital data sets with information that is often unwritten, qualitative, and anecdotal. The potential for significantly augmenting SEARCH in this manner calls for the inclusion of native residents and social scientists into SEARCH.

5.1.1.5 Air Chemistry and Contaminants

Model simulations show that episodic cooling from volcanism, increased atmospheric CO_2, and decreased ozone can influence the polar vortex and thus may help to initiate or maintain changes in the AO. For example, an ozone hole has developed in the Arctic, and reductions in ozone of up to ~60% have been observed in the arctic stratosphere. This has an impact on stratospheric cooling and the spin-up of the polar vortex (Randel and Wu, 1999). Thus, we must attempt to predict how future changes in these variables are likely to influence the AO.

The high-pressure cell that forms over the Arctic during winter restricts exchange with the rest of the atmosphere. Northern industrial activities (primarily in the former Soviet Union) have led to the creation of arctic haze. This haze can influence the radiation balance, and changes in this pollutant may therefore influence the Unaami signal. It has been established that arctic haze concentrations in March at the Barrow baseline site have decreased by 50% between 1982 and 1997 owing to a reduction in its sources in Russia. We must continue to document changes in arctic haze and begin to predict how they may affect Unaami.

The role of the biota is an important consideration. We need to know how changes in the extent of ice cover in the Arctic will impact biogenic emissions from newly opened waters or snow-covered surfaces. Similarly, it is not known how the natural sulfur budget in the arctic atmosphere may be affected by the recent and vast blooms of the coccolithophorid *Emiliania huxleyi*.

Understanding how Unaami may influence fluxes of carbon dioxide to and from the Arctic may turn out to be important despite the relatively small portion of the globe that is involved (Marion and Oechel, 1993; Serreze et al., 2000).

The atmosphere is an important transport mechanism of semi-volatile organic compounds and mercury from lower latitudes to the Arctic, where the cold temperatures favor deposition. How Unaami may alter the atmospheric transport of pollutants is a question that the SEARCH initiative should attempt to answer.

5.1.1.6 Climate Diagnostics

In addition to the importance of maintaining an observational database, it is also important to emphasize retrospective analyses. These activities should include data rescue, data access, and data utilization. One important topic is the need to better understand feedbacks that may affect the AO. In particular we need to understand the mechanisms that affect decadal-scale trends in the AO as well as those that lead to longer-term trends (e.g., increasing atmospheric CO_2 and decreased stratospheric ozone). In particular, the persistence of the AO beyond purely stochastic variations is poorly understood. There is an increase in eddy/mean flow interaction associated with an increased polar vortex. There are changes in atmospheric transports, particularly on a regional basis. There is the potential influence of stratospheric chemistry on the radiation field, and potential albedo and cloud/radiation feedback from the surface. Separating processes that favor persistence from the large background of atmospheric variability is a task for SEARCH and will provide the baseline for understanding further changes.

5.1.2 Ocean and Sea Ice Observations

As noted in section 4.2.2 under Objectives, long-term ocean and sea ice observations are a critical component of SEARCH. It is unfortunate that most of the programs that monitored the arctic environment from the 1950s to the early 1990s have stopped. The data with which the SCICEX 93 data are compared in Figure 2-3 were gathered mainly in 1950–1990 by Russian investigators at the manned North Pole drifting stations or as part of large airborne Sever (North) hydrographic surveys. The Russian drifting ice stations and the U.S. ARLIS (Arctic Research Laboratory Ice Island), AIDJEX, and SHEBA stations have been very useful in assessing the seasonal cycles of the ice cover and providing atmospheric, ice, and oceanographic data. However, the last Russian station was NP-31 in 1992, and SHEBA (1997–1998) was the only long-term Western station in over 20 years. The broad spatial coverage of the EWG (1997) atlas is due to the Sever surveys. There has not been another program of that scope. The SCICEX submarine cruises that have provided much survey information in the 1990s are likely to be curtailed after 2000, because the U.S. Navy 637-class of ice-capable submarines is being decommissioned. The new U.S. Coast Guard icebreaker *Healy* will be able to make surveys into the perennial ice during summer, but it is not designed to penetrate far into the central basin. Consequently, just as the Arctic Basin environment is undergoing major change, we are losing the programs to make long time series of measurements. SEARCH needs a rededication of effort to collect ocean and ice observations.

We envision five general types of observations. These include:

- Eulerian time series (moorings)
- Lagrangian time series (drifting buoys)
- Hydrographic and water sampling surveys (repeated sections)
- Ice thickness (measured ice draft and remote sensing)
- Water and ice properties (acoustic remote sensing and other new techniques)

5.1.2.1 Eulerian Time Series—Moorings

Moorings can be used to measure temperature, salinity, and water velocity. Deep moorings were first deployed and recovered in the interior Arctic Ocean in 1979 (Aagaard, 1981), and the general techniques for doing so without the advantages of shipborne infrastructure are now well established (Aagaard et al., 1978; Moorhouse and Melling, 1987; Melling et al., 1995). The physical oceanographic instrumentation is well proven, especially the temperature and conductivity recorders, mechanical current meters, and acoustic Doppler profilers used for measurements in the upper water column. In addition, moorings can support upward-looking sonars to measure ice draft, and upward-facing Doppler profilers can also be used in a bottom-tracking mode to measure the ice drift directly. There is a growing array of other internally recording sensors that can be used on moorings to sample biological and marine chemistry variables such as dissolved oxygen and nutrients (see, for example, http://www.wsocean.com).

We envision an array of several moorings monitoring ocean conditions in key locations. These locations include segments of the major ridges and continental slopes and points in the major basins, such as the Makarov Basin, where change has been observed.

Additional moorings will be needed to monitor the inflow and outflow regions: Fram Strait, Bering Strait, and the Canadian Archipelago. These will be an international effort. They will be important to understand Unaami and its effect on the global thermohaline circulation. The Arctic and Sub-arctic Ocean Flux (ASOF) study is being developed to monitor these critical straits and make other measurements in the sub-arctic seas to understand the overturning circulation and the factors such as Unaami that control it (see http://psc.apl.washington.edu/search/asof). ASOF grows out of the European Community VEINS (Variability of Exchanges in the Nordic Seas) and MAIA (Measuring the Atlantic Inflow to the Arctic) projects and a UK-Norway program to measure the flow through Fram Strait and in the Greenland Sea. It is taking steps to achieve long-term funding internationally and will be the part of SEARCH responsible for monitoring these critical straits.

5.1.2.2 Lagrangian Time Series—Drifting Stations

In most seasons it is impractical to reach the central Arctic Ocean and make surface or near-surface observations, especially with any regularity. Only manned or automated drifting stations can give the needed regular, multiseason records of the near-surface parameters. These records are invaluable because they can tell us the state of the mixed layer, and they can be used to infer the seasonal fluctuation in ice thickness (Morison and Smith, 1981). For over 50 years the Russian NP stations and several U.S. stations provided the only ocean time series in the central Arctic Ocean. However, over the past 20 years hydrographic buoys have been developed that use satellite telemetry to transmit data from ocean sensors. With other buoy data available for near-surface water velocity and ice and atmospheric parameters, the ocean data can be related to the changing state of the ice and to atmospheric and oceanic heat fluxes.

We visualize maintaining an array of drifting oceanographic buoys in the central Arctic Ocean. These would be deployed in clusters with other buoys measuring ice and atmospheric properties (see above) and would greatly expand on the data from the simple atmospheric pressure/temperature buoys deployed under the IABP. These buoys would be deployed to drift through each of the major basins of the Arctic Ocean: the Nansen, the Amundsen, the Makarov, and the Canadian basins.

5.1.2.3 Hydrographic and Tracer Surveys

Repeated hydrographic surveys are needed to provide snapshot descriptions of ocean properties. Hydrographic sections provide two unique benefits. They can be designed to cut across fronts and current paths in specified areas, and they allow a wide variety of water samples to be taken that may not be possible with automated equipment. Measurement of a variety of tracers and geochemical properties in these water samples allows us to infer sources, spreading patterns, and mean residence times of specific water masses. Repeated hydrographic sections, including tracers, across the major circulation paths such as the ridges and continental slopes provide information on water velocity, heat content, and salt content along these pathways. Periodic hydrographic/tracer stations in each of the major basins will help us track the shifts in the position of the Atlantic and Pacific hydrographic regimes that appear to be part of Unaami. Some sections in the sub-arctic seas will be conducted as part of ASOF.

Changes observed in the Arctic have been rapid, and annual sections would be beneficial, but Steele and Boyd (1998) suggest that hydrographic and tracer sections every two years are adequate. A variety of platforms can be used for hydrographic surveys. For 50 years the Soviet Union staged the Sever airborne hydrographic surveys in springtime all over the basin. Ice and weather conditions in springtime are ideal for aircraft operations. The Soviets used a few small temporary ice stations as fuel caches in order to range over large areas. Surface ships such as the USCGC *Healy* will provide platforms for sections at least in the shelf seas and across the continental slopes in summertime. In principle, submarines are able to gather water samples and drop expendable CTD (conductivity-temperature-depth) units in any season. However, this tool can be fully utilized only if dedicated submarine cruises, modeled after the SCICEX program carried out in the second half of the 1990s, can be established.

Ideally, the hydrographic data would be collected to WOCE/JGOFS standards (e.g., SCOR, 1996), and the “core” (essential) variables determined would include salinity, temperature, Winkler dissolved oxygens, ammonium, chlorophyll, nitrate, nitrite, reactive phosphorus, dissolved silicon, and inorganic carbon. Determination of transient tracers such as the freons and of oxygen-18 should also be given a high priority. Because the samples are easy to collect and because of the concerns about changing phytoplankton species such as the recent coccolithophorid blooms in the Bering Sea, collection of samples for on-shore determination of phytoplankton species may also be desirable.

5.1.2.4 Ice Thickness Observations

Sea ice concentration, extent and thickness distribution are critical in determining both the total mass balance of ice and the thermohaline forcing of the Arctic Ocean. Changes in ice-atmosphere interactions should manifest themselves as changes in the sea ice mass balance. A NASA workshop in March 1999 identified ice thickness as the polar variable for which climate modelers have perhaps the greatest need. Recent evaluations of ice thickness data derived from submarine sonars point to a substantial thinning of sea ice in the central Arctic since the 1960s (Rothrock et al., 1999). We need to track this change. Continued monitoring of ice thickness is clearly a priority, whether by moored sonars, submarines, underwater vehicles, or new applications of satellite remote sensing. While the central Arctic Ocean is a geographic priority for reasons of continuity, the waters offshore of the Canadian Archipelago also merit consideration. This reflects the possibility that the recent cyclonic circulation regime may have advected ice from the central Arctic Ocean into these Canadian waters, resulting in enhanced thickness in a relatively unsampled region. If such thickening were the case, it would partially offset the recent thinning near the Pole and in the remainder of the region examined by Rothrock et al. (1999).

The thickness distribution is an elusive measurement, but can be inferred from measurements of the ice draft. Submarines have provided occasional transects of ice thickness inferred from ice draft. These are now being declassified, but they can be difficult to interpret because of seasonal variations (McLaren et al., 1992) and the lack of repeated sections. Moored upward-looking sonars (ULSs) (Moritz, 1992) have provided time series of ice thickness in strategic near-shore regions and straits.

The SEARCH oceanographic program should contribute to monitoring ice thickness by installing ULSs at the top of each of its moorings. These will provide time series of ice draft as the ice drifts over the mooring at speeds measured by the upward-looking acoustic Doppler current profiler (ADCP). The automated drifting stations will also make representative measurements of the surface heat balance and ice thickness. These measurements, combined with data taken during submarine transects and remote sensing measurements of concentration, will be assimilated by ice models to derive optimum thickness estimates as has been done in a limited manner in the RADARSAT Geophysical Processing System (RGPS) (Kwok, 1998). Such procedures can also be applied to European Space Agency (ESA) SAR data. Remote sensing and the IABP buoy array will provide measurements of the ice velocity over large areas, which can be used to infer kinematic changes in thickness. To quantify the thermodynamic component of thickness change, we must have measurements of the heat fluxes to the ice at the automated stations. Given the heat flux estimates and the ice velocity field, a sea ice model can be used to infer changes in the ice thickness distribution. These estimates can be improved by assimilating the time series data and occasional profiles from submarine transects.

5.1.2.5 Acoustic Remote Sensing Observations and Other New Technology

The Arctic Climate Observations using Underwater Sound (ACOUS) program (Mikhalevsky et al., 1995, 1999) will use arrays of low-frequency acoustic transmitters and receivers to measure the temperature in the Arctic Ocean. ACOUS uses a tomographic technique of inverting acoustic travel time data. In conjunction with the SCICEX program of the 1990s, the ACOUS technique showed promise for measuring ocean temperature. It has been argued that the technique may also yield ice thickness estimates. ACOUS receivers can be added to SEARCH moorings and surface drifters to improve temperature coverage and resolution.

Various other new technologies are on the horizon that may be helpful. An extensive effort, for example, has gone into the development of profiling Lagrangian floats (Davis, 1998) and virtual mooring gliders (Ericksen, personal communication, 2000). These hold the promise of repeated autonomous CTD profiles, but await a workable scheme for transmitting their data through the ice cover. At least two autonomous profiling CTDs have been developed which might improve the vertical resolution of moored and drifting oceanographic buoys (Eckert et al., 1989; Toole, personal communication, 2000). Autonomous underwater vehicles (AUVs) have already been used under sea ice at scales from 1–100 km (Morison and McPhee, 1998), and longer range vehicles are being developed. These might take the place of submarines in providing large-scale horizontal profiles of water properties and ice draft.

5.1.2.6 Coordinated Efforts

To deploy Eulerian and Lagrangian stations and perform sections in an efficient manner, efforts must be carefully coordinated. Ideally, a given platform, aircraft or ship should contribute to all three types of activity on every mission. In the springtime, we envision aircraft establishing small, short-duration ice camps where moorings and automated buoy stations would be deployed. The short-term camps would also serve as fuel caches for hydrographic surveys. In the summer, surface ships would service the moorings and conduct surveys in the shelf and slope regions. Surface ships have been able to penetrate the central pack far enough to service or recover many of the drifting buoy stations. Operating in this way carries the added benefit of sampling the upper ocean in both the high-salinity, post-winter phase (with aircraft) and the low-salinity, post-summer phase (with ships). This helps reduce the problem of seasonal aliasing and provides information on the seasonal heat and mass balance.

SEARCH sampling can succeed only through international cooperation. If nothing else, many of the operations may involve ships operating in the Exclusive Economic Zones (EEZ) of a variety of countries. For the aircraft surveys, the economics and effectiveness will be greatly enhanced if we operate out of air bases all around the basin. This will require the participation of Canada, Greenland, Norway (Svalbard), and Russia. Fortunately, international partners are already working together in key areas. The European community has had an energetic program to monitor Fram Strait (Dickson et al., 1999; Cattle et al., 2000) and other key choke points and sections essential to the aims of SEARCH and ASOF (see section 5.1.2.1 above). Also of importance to that program, the U.S. and Russia have been collaborating to monitor Bering Strait. Canadian scientists are planning measurements of the throughflow in the Canadian Archipelago (Melling, 2000; Carmack, 2000). Japanese researchers have been working with U.S. investigators on deploying both moorings and drifting stations over many regions of the Arctic Ocean.

The ultimate decision on the number and location of moorings, drifting stations, and sections will depend on the commitment of international partners and the efficiency of our operational plans. It will also depend on determining the deployment locations that offer an optimum combination of scientific benefit and logistical efficiency. Analysis of existing data can tell us the location of key indicators of ocean change and Unaami in particular. The assimilation and analysis of existing data and simulations of the ocean's response to the AO will be critical in designing the sampling scheme.

5.1.3 Terrestrial Hydrologic and Cryospheric Observations

SEARCH recognizes that evidence for terrestrial change including changes in species composition, canopy height, photosynthetic activity, northward movement of the treeline, and tundra gas fluxes requires further assessment. This in turn requires further assessment of changes in the arctic hydrologic budget and cryosphere, including snow cover and permafrost characteristics. Resolving inconsistencies in these measurements promises to be a challenging task. Recent work by Lammers et al. (2001) discusses the complex spatial patterns associated with hydrologic variability over the past several decades and relates these to atmospheric anomalies such as the NAO. The network of precipitation stations is sparse and prone to measurement error. The terrestrial precipitation network has also been degraded by the closure of many monitoring stations in the former Soviet Union and a trend toward automation in Canada.

Concerted efforts must be made to compile and analyze the longest possible records of relevant variables with the best possible spatial and temporal resolution. A considerable amount of precipitation data from Russia that would assist in trend analyses is presently undigitized. Evaporation data are also available, but need to be acquired. Efforts are needed to assemble these records. They also need to be harmonized with respect to methodology, time domain, and time step and used in consistent ways to develop spatially distributed fields.

SEARCH must take advantage of emerging capabilities. Cullather et al. (2000) demonstrate that gridded time series of precipitation minus evaporation (P–E) back to the late 1950s can be obtained via analysis of the vapor flux convergence using historical atmospheric fields from the NCEP/NCAR reanalysis (Kalnay et al., 1997). The NCEP/NCAR reanalysis also provides atmospheric fields to assist in diagnostic studies of observed change (e.g., possible linkages with the AO). Data from the improved ERA-40 reanalysis (Gibson et al., 1999) are attractive because of their much higher horizontal and vertical resolution compared to the NCEP/NCAR and ERA-15 efforts and the more realistic treatments of soil moisture, snow cover, and sea ice cover. While arctic precipitation fields from NCEP/NCAR are of generally poor quality (Serreze and Hurst, 2000), those from ERA-40 may be accurate enough to be blended with station time series. In addition, even if absolute precipitation amounts are not accurate, the anomaly fields are likely to be useful. Statistical down-scaling methods to compile precipitation fields using atmospheric variables such as the vapor flux convergence, vorticity, and vertical stability should also be explored. ERA-40 also provides a potential source of other variables such as surface radiation fluxes. The planned Arctic System Reanalysis under SEARCH (section 5.2) should prove invaluable in assessing the hydrologic budget.

Hydrologic models driven by precipitation and other meteorological parameters such as temperature, radiation, vapor pressure, and winds can provide fields of evapotranspiration and runoff. Such models can also provide time series of river discharge from ungauged portions of the arctic land mass to more fully assess freshwater input to the Arctic Ocean (Vorosmarty et al., 1996). Also of concern is the typical 4–5 year delay in obtaining discharge records for Russian rivers. SEARCH should seek to acquire these data in a timely fashion. A recent compendium of nearly 4000 station records (R-ArcticNET, described by Lammers et al., 2001 and available through the NSIDC) represents a major step forward but will require constant vigilance to maintain its currency and relevancy to SEARCH.

Monitoring should make use of improved satellite-derived estimates of snow cover and snow-water equivalent (SWE) from EOS-era platforms, including MODIS and the NASA EOS AMSR-E. The Advanced Land Imager (ALI) will map subtle surface topography of ice sheets for use in ice motion studies and photoclinometry. The National Snow and Ice Data Center (NSIDC) has passive microwave data available since 1978 that provides SWE fields (Tait, 1998) as well as information on the near-surface freeze-thaw status (Zhang et al., 1999).

Permafrost is a key feature of arctic terrestrial regions, and changes in permafrost can be used as indicators of changes in atmospheric conditions. An effective observational strategy will detect terrestrial climate change signals and indicate the spatial variability of these signals across the high latitudes. Locations in which permafrost is degrading or may soon degrade are priorities for monitoring. Existing data on permafrost temperatures can guide the selection of specific locations for additional measurements. Complementary monitoring of snow cover will be required to diagnose changes in permafrost. In this context, simple models driven by temperature and precipitation data can provide information on the thickness of active permafrost layers (Zhang et al., 1997). Two ongoing national and international programs are involved in monitoring permafrost and active layers. These are the WMO/GCOS Global Terrestrial Network-Permafrost (GTN-P) and the Arctic Coastal Dynamics (ACD) program. In the Northern Hemisphere the active layer observations are part of the Circumpolar Active-Layer Monitoring (CALM) network. Globally over 300 borehole sites have been identified as potential observation sites for temperature measurements. The ACD science plan calls for long-term observation sites throughout the Arctic to assess coastal erosion rates and sediment transport.

Given the pronounced atmospheric variability on interannual to decadal time scales and the sparseness of longer-term meteorological records in the Arctic, glacier mass-balance monitoring and glacial paleo-records can provide valuable proxy data on the surface climatology. At the same time, the glacier mass balance filters out some of the high-frequency, interannual variability. At suitable locations, ground-based mass-balance programs augmented by satellite remote sensing employing ASTER and other new sensors available through NASA EOS (e.g., Dowdeswell et al., 1997) may contribute substantially to the overall goals of SEARCH in the context of significantly reduced coverage by operational weather stations.

5.1.4 Paleoenvironmental Science and Archeology

5.1.4.1 Paleoenvironmental Science

Our current understanding of climate variability relies heavily on the study of decades-long instrumental time series. Paleoclimate research is recognized as the source of the multicentury time series. A primary goal of paleoenvironmental research in the SEARCH initiative is to determine whether Unaami has occurred before. Reconstructions from continuous natural archives such as lake sediments, ice cores, marine sediments, and tree rings should provide a context for recent changes by documenting the range of natural variability, including the rates and amplitudes of past change, as well as the geographic patterns of response to past environmental forcing.

Of particular interest to SEARCH are those changes in the paleoenvironmental record that are outside the range of change seen in the 20th century, in terms of both rates and spatial patterns. Examples include periods when the average warmth was above that in the 20th century, periods of negative glacier mass balance, and periods of decreased sea ice extent. Also of interest are periods when the discharge of freshwater into the arctic seas was altered, and periods when marine and terrestrial biota were clearly responding to climate change.

The key to reconstructing and understanding patterns of arctic variability in the past that are related to Unaami will be the use of high-resolution (i.e., sub-decadal), well-dated proxy records. It will also be critical to develop extensive, spatially dense networks of such records. Overpeck et al. (1997), for instance, reconstructed summer temperatures for the past 400 years from annually laminated lake sediments, tree rings, marine sediments, and annual layers in ice cores. Their reconstruction indicates that the 20th century is the warmest in the past 400 years, but observations over the past several decades reveal significant regional variability in trends (Serreze et al., 2000) that still need to be placed in a more detailed paleoclimatic context. Furthermore, the annually dated paleoclimatic record does not extend back to known periods of warmer climate in the Arctic (Bradley, 1990) or through past periods of rapid change (e.g., the abrupt warming and "neoglaciation" in the early Holocene). A denser, pan-arctic network of millennia-long, high-resolution paleoenvironmental records is thus critical for putting the 20th century instrumental record in perspective and for understanding the natural patterns of sub-decadal and longer-scale environmental variability (such as Unaami) in the Arctic.

Paleoclimatic and paleoecological work in the Arctic has emphasized the development and analysis of tree-ring and lake-sediment records. Tree-ring records (e.g., Jacoby and D'Arrigo, 1989; Briffa et al., 1998) are absolutely dated and provide information on past climate and ecosystem responses extending back more than 1000 years. Lake sediments are increasingly being used to extend such records northward beyond the tree line and further back in time. Most recently, technologies are being perfected to exploit annually dated (varved) sediments (e.g., Lamoureux and Bradley, 1996; Hughen et al., 2000), just as AMS carbon-14 technology is making it possible to obtain high-resolution sediment records from a larger range of lakes than previously tapped.

Studies of ice cores, such as the core recovered during the Greenland Ice Sheet Project 2 (GISP2) (e.g., Alley et al., 1993; Zielinski et al., 1994, 1996) and several cores recovered from ice caps in the Canadian Archipelago (Fisher et al., 1995, 1998), are also revolutionizing our ability to study seasonal to longer climate variability (e.g., from paleotemperatures, accumulation rates, and summer melting), atmospheric chemistry, adjacent sea ice cover, and volcanic/climate interaction. Rapidly expanding field and laboratory expertise in the U.S. and elsewhere is leading to ice-core drilling in a wider range of locations around the Arctic, and it is now possible that we could eventually have a dense network of high-resolution tree-ring, lake-sediment, and ice-core records spanning the Arctic.

Although borehole paleoclimate records are of lower temporal resolution than the proxies mentioned above, they are also critical for understanding decadal and longer patterns of terrestrial environmental variability in the Arctic (Huang et al., 2000). The use of borehole records combined with annually dated records may be the best way to constrain the full range of terrestrial paleoclimatic variability.

Marine sediment records can be tapped to provide estimates of the full range of variability in the Arctic Ocean. These sediment records can provide wide spatial coverage and longer records that extend back several glacial cycles. However, most marine-sediment records do not have the same high temporal resolution provided by terrestrial records. High-sedimentation-rate marine records can resolve changes on decadal to multi-millennial scales. On one end of the spectrum is the high-resolution marine record that was produced for Nansen Fjord in east Greenland by Jennings and Weiner (1996). They reconstructed a detailed record of IRD flux and diatom assemblages that correlates well with the historical sea ice record around Iceland and also extends back over all of the past millennium. Although the continental shelves of the Arctic Ocean are generally shallow, and thus subject to erosion during the last glacial maximum, they can provide records for the past 8,000 – 10,000 years. The deep Arctic Ocean may yet yield high-resolution records if more acoustical surveys can be carried out in the ice-covered ocean to discover prime coring sites. Recent coring on the continental slopes has also shown that higher-resolution cores of marine sediment can be obtained in the Arctic Ocean beyond the shelves.

Two programs that address the paleoscience issues related to SEARCH are the International Geosphere-Biosphere Program's Core Project titled "Past Global Changes" (IGBP-PAGES) and Paleoenvironmental Arctic Sciences (PARCS). PAGES pursues a broad range of paleoscience studies and has several synthesis efforts underway. SEARCH should link to this initiative. PARCS is a program with the goals of understanding the range of natural climate variability in the Arctic, evaluating the impacts and causes of rapid changes, determining the sensitivity of the Arctic to altered forcing, documenting the history and controlling mechanisms of biogeochemical cycling, and evaluating state-of-the-art numerical climate models. SEARCH should work with PARCS to help provide a paleoscience perspective on the changes that SEARCH sees now and in the future.

SEARCH will investigate data to examine:

- To what extent Unaami is related to natural (pre-anthropogenic) arctic variability prior to the period of instrumental coverage
- How the AO manifests itself over time scales longer than decadal
- How AO-related variability was affected by altered climate forcing prior to the 20th century (e.g., during the "Little Ice Age" and the mid-Holocene)
- How ocean, land, ice, and atmosphere feedbacks quantified via SEARCH monitoring and process studies operate over the longer paleoclimatic record
- How pan-arctic environmental changes of the past have influenced biotic (paleoecological) and human (archeological) systems

5.1.4.2 Archaeology

Archaeological studies can provide a means to isolate the effects of modern human impacts from those that occurred during prehistoric times, because prehistoric northern peoples did not have large populations or use technologies that could cause regional environmental change. Early arctic archaeological sites capture information about past environments in the form of temperature-sensitive isotopic proxy records in animal bones and plant and insect remains that allow reconstructions of former environments over thousands of years. Culture changes, including the distribution of cultures adapted to forest, tundra, or maritime coasts and the evidence of local and regional culture extinctions and population movements allow archaeologists and paleoecologists to reconstruct and interpret culture history and the effects of climatic and environmental change on human populations. When these records are compared with modern conditions, the task of isolating modern human impacts on the environment and climate from natural, non-human-driven change can be discerned with more accuracy, and predictions about the impacts of future change on human systems can be made with greater reliability. The usefulness of such studies has been shown especially clearly in Greenland and Iceland, where farming economies and even entire societies have flourished or perished due to fluctuating climatic conditions.

5.1.5 Biological and Biogeochemical Change Measurements

Understanding how Unaami affects ecosystems and the fluxes of pollutants and biologically influenced radiatively active trace gases requires long-term seasonally resolved observations. We need to know the effects of Unaami on water, carbon, and nutrient cycling (e.g., nitrogen and phosphorus) as well as on arctic flora and fauna. We cannot do this without an improved knowledge of seasonal variability and variability arising from intrinsic biological cycles such as the approximately decadal lynx/hare cycle, etc. As noted previously, the study of changes in the arctic biological system is complex. In addition, the availability of relevant time-series data, etc., is extremely poor. To make progress on understanding the influence of Unaami on arctic biogeochemistry and ecosystems, we propose the following activities.

5.1.5.1 Data Rescue

We suspect that there is much relevant information on the Arctic's biological system—information arising from management of living resources, environmental impact statements, etc.—in the gray literature or languishing in file cabinets. SEARCH attempts to unravel the impact of Unaami on the Arctic's biological system should therefore include data-rescue efforts.

5.1.5.2 Workshops

It is fair to say that the biogeochemical and ecosystem components of SEARCH lag the physical components in documenting the relationship of recent changes to factors such as the AO. To help rectify this situation, SEARCH has obtained NSF funding to support workshops under the aegis of the NSF biocomplexity initiative. These workshops will provide an opportunity to assess existing data and to prioritize SEARCH studies that relate to the Arctic's biological system.

5.1.5.3 Time-Series Studies

Studies that resolve the seasonal cycle are critical to differentiate between "natural" variability and the effects of climate change. Because of access problems, seasonal studies of biological processes in the arctic marine environment are particularly scarce. Long-term studies are also rare. For example, there is a need for long-term biological and biogeochemical measurements at key sites in the Arctic to act as sentinel indicators of global change. Such sites could be in known "hot spot" areas of biological productivity, such as the Bering Strait region and portions of the Barents Sea that have tightly coupled trophic connections resulting in cascading impacts from physical to biological change. Determination of select measurements at these sites, such as nutrient composition and specific trophic level indicators, are critical to interpreting biological variability in a changing ecosystem.

With respect to the Arctic's terrestrial environment, seasonal and long-term studies do exist, and they demonstrate striking changes in carbon dioxide fluxes in the Kuparuk Basin (see, e.g., Oechel et al., 1993, 2000; Serreze et al., 2000). However, we do not have sufficient areal coverage, long enough records on methane (Whalen and Reeburgh, 1992), or sufficient knowledge of the hydrologic regime and how it changes.

Prioritizing the ensemble of possible seasonal and longer-term studies relating to Unaami's influence on arctic biogeochemistry and ecosystems should wait for the completion of the workshops mentioned above. However, we can suggest one study that could build on a multi-decade suite of data from physical oceanography moorings in the Bering Strait as well as on-going studies in the region currently funded through the NSF Long-term Observatory program. The time is right to begin comprehensive long-term monitoring of biological conditions in the Bering Strait region, because of the biological richness of this area and the changing populations that have previously been noted, and because the inflow to the Arctic Ocean via Bering Strait is a major source of nutrients and biological populations. This effort can build on recent support from the NSF-OPP Long-term Arctic Observatory Program, which has supported supplementing the physical moorings with nutrient sensors and water samplers, and which is supporting the establishment of an environmental observatory on Little Diomede Island.

5.1.5.4 Process Studies

To interpret the results of time-series experiments dealing with biogeochemistry and ecosystems, it will also be necessary to conduct some relatively short-duration process studies. For example, coccolithophorid blooms could have an impact on dimethylsulfide (DMS) emissions to the atmosphere, but little is known about how these plankton function at high latitudes. Similarly, we know that ice algae are implicated in DMS release and the spring "bromine explosion," but we lack sufficient knowledge of the mechanisms to predict how these factors may change with changes in sea ice thickness and distribution.

Process studies are a central element of the Western Arctic Shelf-Basin Interactions (SBI) project funded by NSF (ARCSS) and ONR to investigate potential global change impacts on biological systems in the Arctic (Grebmeier et al., 1998, 2001; http://utk-biogw.bio.utk.edu/SBI.nsf). The overall goal of the SBI project is to provide a better understanding of the physical and biogeochemical connections between the arctic shelves, slopes, and deep basins that could be influenced by global change. This project currently focuses on the outer shelf and slope region of the Chukchi and Beaufort seas, as well as investigating the water input through Bering Strait and its resultant transport into the arctic halocline. Coincident studies of the biological impacts of global change and determination of key indicator species as sentinel indicators of change are also objectives of the SBI project.

5.1.5.5 Remote Sensing

Remote sensing and satellite tracking of birds and mammals should also play a strong role in assessing the biogeochemical and biological response to change. For example, there has been considerable success in identifying coccolithophore blooms from space, and we know that in recent years unprecedented blooms of coccolithophores have occurred in the Bering Sea (Saar, 2000; Stockwell et al., 2000). The use of satellites to monitor ice cover, chlorophyll, and temperature is well established, and there has been progress in remote sensing of salinity (Lagerloef et al., 1995). Satellite sensing of tagged marine mammals has also proven remarkably effective. Satellites are, of course, also extremely useful to monitor changes in the terrestrial environment (vegetation indices, changes in snow cover, etc.)

5.1.6 Human Dimension

Examining the human dimensions of Unaami should break new ground by considering the physical, biological, and human facets of change together. Here we can only express our ideas on possible ways to start. Two components are envisioned: an observation component to assess how Unaami is impacting society, and a prediction-application component that tells what society might expect in the future.

Unaami impacts society indirectly through its effects on biological resources and directly through its effects on local weather and sea ice conditions. Assessing the human dimensions of Unaami requires databases in both categories. The weather and ice databases can be assembled in appropriate forms drawing from existing sources and records collected as part of new SEARCH efforts. The information on biological resources should include a pan-arctic data compilation plus selected local sampling (ITEX Model) for focused studies of different regions. This information should include primary production measurements and food web relationships such as those produced by SBI and ATLAS (Arctic Transitions in the Land-Atmosphere System).

The human impacts and responses will be measured by compiling databases on such variables as:

- Fisheries and marine mammal harvests
- Population (birth rate, death rate, migration)
- Health/well being (social indicators of living conditions)
- Observed erosion rates and flooding

An important aspect of these efforts will be to transfer traditional knowledge and local observations of the indigenous population into the physical and biological databases. As discussed in section 5.1.1.4, traditional knowledge can provide important information on climate changes, including:

- Retrospective examination of local weather, ice, and ocean conditions
- Descriptions of current local weather, ice, and ocean conditions
- Definition of important climate variables

The challenge is to develop relationships between traditional knowledge and physical measurements. For example, we must learn how to relate descriptions like “a bad ice year” and “a deep snow year” to measured sea ice concentration and precipitation. This step will also help to assess what observations are socially meaningful.

There are a variety of methods for including traditional knowledge, ranging from community meetings to discuss how the SEARCH results compare with what the indigenous populations are seeing, to undertaking a full-scale documentation effort. SEARCH should take an intermediate approach by holding regular community meetings to assess the community interests and determine intersections with SEARCH observations. Including traditional knowledge in the human-dimension component will require a considerable amount of design effort, but is justified if we are to amass a substantial amount of information on this subject. This is especially true where SEARCH addresses issues of concern to many residents of northern communities. Determining what information the residents need will take time, but may be as useful in the long run as determining what traditional knowledge can contribute.

5.2 Modeling Strategy

5.2.1 Defining and Quantifying Unaami, Arctic System Reanalysis

An underlying research problem for SEARCH is a quantitative characterization of Unaami. This will involve both modeling and statistical/pattern analyses of multivariate data sets.

Applications of models would include, for example, using GCMs to simulate the spatial patterns and statistics of an Unaami index. GCM sensitivity studies can help identify the components of the model earth system that must be allowed to interact freely to simulate Unaami. For instance, how do simulated Unaami responses differ in experiments with a fully coupled ocean and with prescribed sea surface temperatures?

Diagnostic modeling, including data assimilation studies that make use of long-term observations, are needed to confirm, refute, and modify the list and sequence of events that constitute our provisional definition of Unaami (section 2.1). For example, one might start with a matrix of time-series data sets hypothetically related to Unaami and define an appropriate Unaami index and Unaami (multivariate) pattern. Investigators could then search for correlations (including lagged correlations) between this index and other independent parameters (e.g., the AO index, precipitation, poleward heat flux, and economic factors).

A critical problem in quantifying Unaami is that many of the most important variables, such as precipitation-minus-evaporation, soil moisture, and sea ice thickness have few direct measurements. To overcome this problem, SEARCH will expand on the philosophy of atmospheric reanalysis to produce an Arctic System Reanalysis (ASR). Global reanalyses of atmospheric observations from the late 1940s to today have been and are being carried out by NCEP and ECMWF with a temporal resolution of four times per day and spatial resolutions ranging from 60 to 250 km. The data span the Earth’s surface to the middle stratosphere. Significantly, the most appropriate polar physics, cloud paramterizations, and boundary layer dynamics, for example, have not been applied to such exercises thus far, creating significant opportunities for progress over the next few years. Such a reanalysis can make use of polar-corrected TOVS temperature sounding data. Key variables quantifying Unaami can be determined by expanding this concept to the development of an ASR where the optimum reanalysis for the atmosphere, land surface (rivers, snow cover, etc.), and ocean (including sea ice) can be performed in an integrated framework. Such a reanalysis will combine all available observations with model physics to produce optimum estimates of critical variables. Subsequently, it may be possible to consider reanalysis of aspects of the biosphere, the chemical composition of the atmosphere, aerosols, etc. It should be noted that the three-dimensional wind fields produced by reanalyses are likely to provide the soundest basis for trajectory computations of pollutants, tracers, etc. Atmospheric reanalyses also provide the optimum forcing for surface/subsurface models (e.g., in ocean data assimilation). The benefit would be to synthesize the wide variety of climate-related variables produced by many different disciplines and put the current behavior into the perspective of the past few decades. The central concern of SEARCH of looking for and understanding current change in the Arctic would thus be addressed. This activity can be continued into the future and thus take on the role of monitoring future change.

Development of a polar system reanalysis is a natural focus for interagency effort. The proposed reanalysis system will take advantage of the wealth of information sensed remotely. One example is SAR and SSM/I data, which can be applied to produce optimum reanalyzed descriptions of sea ice and the land surface. Arctic tropospheric air temperatures and upper air anomalies, for example, would enable NCEP to fill a void in its suite of regional and teleconnection indices used in monitoring as well as in diagnostic and predictive activities. NOAA/NCEP might take a leading role in developing and implementing the ASR, similar to its regional reanalysis for the United States.

The resulting ASR data sets would describe how the physical components of climate relate to one another and make it possible to identify Unaami along with its decadal variability. The connection with hemispheric (e.g., the AO) and global climate variability (e.g., ENSO) and change can be readily diagnosed. The evaluations provide the foundations for modeling strategies to address the main SEARCH hypotheses.

5.2.2 Modeling the Connection between AO and Unaami

Continued efforts are needed to force a variety of ice/ocean models with the boundary conditions observed over the past few decades. Examples of such modeling studies are those by Proshutinsky and Johnson (1997), Zhang et al. (1998), and Zhang and Hunke (2001). A primary objective of modeling studies is to determine how well observed changes are simulated. This includes the spatial and vertical structure of the AO and attendant patterns of surface variables such as temperature, precipitation, P–E, and sea ice extent. These efforts should seek to include assessments of shelf/basin exchanges. While one goal of these efforts is to improve our understanding of the physics driving the AO and Unaami, these efforts could also lead to new techniques for data assimilation and be used to design sampling plans.

5.2.3 Modeling the Global Climate Connection of AO and Unaami

This component seeks to understand the causes of the decadal variability and trend in the AO. Is it a simple stochastic variation of a fundamental circulation mode? Is it a result of only atmospheric processes, or are feedbacks with the land, ocean, and ice involved? Finally, could altered radiative forcing due to greenhouse gases, sulfates, volcanic dust, or solar properties drive the variability and trend? The key contribution of the modeling program to answering these questions is that mechanisms can be deduced from the models via sensitivity experiments.

Examples include comparisons of the simulated Unaami patterns and indices in coupled global models integrated with fixed and time-dependent concentrations of anthropogenic greenhouse gases and aerosols. This kind of study would help distinguish human influences from natural climate variability. These efforts should be related to IPCC, CMIP (Coupled Model Intercomparison Project), and Atlantic CLIVAR (International Program on Climate Variability) efforts. Another approach will be to use idealized atmosphere models to study zonally uniform cases with nonzonal aspects of the changes superimposed.

Finally, modeling should be undertaken to explore the effect of Unaami on the global ocean thermohaline circulation. This will involve modeling the effect on the freshwater budget of the Arctic and its affect, in turn, on the ventilation of the sub-arctic seas.

5.2.4 Modeling for Critical Arctic Feedbacks

This effort can be thought of as initially being composed of two fundamental steps. The first step consists of modeling efforts to determine the effect of the AO on the ice cover, snow cover, and ocean by either dynamic or thermodynamic forcing (as in section 5.2.2). Efforts toward this end are already under way in independent research activities (Proshutinsky and Johnson, 1996, 1997; Polyakov et al., 1999; Zhang et al.,1998, Zhang and Hunke, 2001, 1999; Saenko and Holloway, 1999; Maslowski et al., 2000).

The second step is to determine the impacts of increased temperature, decreased ice and snow cover, and altered sea surface temperatures on the atmospheric circulation. We should use a variety of atmospheric models to allow assessment of differences between models. These efforts might be similar to the studies by Herman and Johnson (1978) and Hines and Bromwich (1999) to examine the response of the atmosphere to an ice-free Arctic, or the studies of Simmonds and Budd (1991), Bromwich et al. (1998), and Hines and Bromwich (1999) to examine the atmospheric effect of the removal of the antarctic ice cover. However, the studies could be done in the context of extreme variations in a complex of many variables associated with Unaami. These efforts should employ improved small-scale models for which SHEBA data are providing improved parameterizations. This effort will allow us to predict the possible effect of closing the Unaami ice-albedo feedback loop. The ultimate test will be performed with completely coupled ice/ocean/atmosphere models run for cases representing extreme levels of the AO index.

To understand the terrestrial responses to Unaami and possible feedbacks through the freshwater balance, it is critically important to better understand the hydrologic process. One viable strategy is to focus on the use of nested regional models such as the Arctic Climate System Model (ARCSYM), taking advantage of their more robust treatment of hydrologic and land-surface processes. At the same time, efforts are needed to improve the treatment of hydrologic and land-surface processes in these models, drawing from work ongoing under ATLAS. This in turn can relate back to development of the ASR. We should also work toward coupling hydrologic and atmospheric models through statistical downscaling (for example, use outputs of precipitation, evaporation, and radiation from global and regional models). We should experiment with both physically and conceptually based hydrologic models.

The availability of data on even precipitation and temperature (needed for even simple “stand-alone” hydrologic models) is very uncertain in the future because of the closure of stations in the former Soviet Union. Therefore the provision of data needed for model input might itself need to rely heavily on models. The NSF Long-term Observatory Program is developing gridded time series of all major components of the arctic hydrologic budget (for terrestrial regions), as well as a monitoring system. The approach combines observations (e.g., precipitation) and modeling approaches (e.g., P–E from flux convergence estimates, statistically down-scaled precipitation based on the NCEP reanalysis, and estimates of evaporation/runoff from hydrologic models).

Another important feedback may be through the effects of Unaami on atmospheric chemistry. Ultimately, it will be important to develop a hemispheric-scale 3-D model of the photochemical processes that occur in the Arctic, particularly those related to ozone depletion and snowpack chemistry in the spring. Before that can occur, it is necessary to develop detailed 1-D models of the chemistry and dynamics that occur in the atmospheric boundary layer and in the snowpacks, so that our understanding of these complex heterogeneous processes can be tested and developed further. This task is a priority for the atmospheric chemistry community.

5.2.5 Testing Model Response to Past Altered Forcing

The paleoenvironmental record (e.g., of past climate, ocean, cryosphere, and biosphere dynamics) provides a valuable opportunity to test how well climate system models respond to altered climate forcing (e.g., astronomically induced changes in insolation). The WCRP/IGBP Paleoclimate Modeling Intercomparison Project (PMIP), for example, already has most major global modeling groups entrained into efforts to simulate selected periods in recent earth history (e.g., 6ka and 21ka) in efforts to see how well 3-D global models (atmospheric, as well as coupled) simulate the response to large past changes in global forcing. Model simulations of past periods can be compared, and their realism checked against growing compilations of paleoenvironmental data. This evaluation of paleoclimatic models is proving to be particularly useful for narrowing uncertainty about overall model sensitivity to altered forcing and the nature of key feedbacks (e.g., land, ocean, and ice) that contribute to this forcing. Efforts to simulate the details of climate variability over the past several centuries are also under way, complemented by the growing arrays of paleoenvironmental data (including those for the Arctic) that can be used to assess the realism of the simulations.

5.2.6 Is Unaami Predictable?

The final element of the modeling component of SEARCH is to investigate the predictability of Unaami. Prediction will be a major concern when we speak of application for the benefit of society. At this stage, we must still make diagnosis a key element of SEARCH modeling. We must also use modeling for the analysis and assimilation of existing observations as discussed in the atmosphere, ice, and ocean observation sections.

5.3 Process Studies

Process studies must be an integral part of SEARCH. Many of these are yet to be identified and prioritized, and approach strategies will come to light as SEARCH matures. Many process studies might best be done in collaboration with other programs, especially where efforts are already under way such as the Atmospheric Radiation Measurement (ARM) program (see below). Conversely, other programs may take advantage of SEARCH data and platforms to study SEARCH-related processes. While some process studies might require gathering special data at smaller scales or shorter intervals than required by SEARCH, others might draw from the wealth of steady, long-term observations SEARCH will make along with the associated SEARCH modeling and data-assimilation efforts.

As a general statement, process studies should focus on understanding the mechanisms that couple parts of the Unaami system or elucidating feedback mechanisms that couple two or more components in such a way that amplifies the Unaami process (positive feedback) or dampens the process (negative feedback).

We might, for example, examine the transfer of heat and buoyancy from the ocean's margin into the interior. This is already an objective of the Shelf Basin Interaction (SBI) program. Another example would be a study of how the increased cyclonic vorticity associated with a positive AO index is propagated into the ocean and how deep it progresses with time. This might be largely a modeling process study.

Potentially important feedback mechanisms are described in section 3.3. One of the best known examples is ice-albedo feedback. At local and smaller scales, this is the subject of the SHEBA project. However, SEARCH may want to examine ice-albedo feedback at basin and larger scales. For example, using data or models, we might want to examine changes in ice extent and radiatively sensitive properties of the Arctic Basin under positive and negative AO conditions. This might tell us if the fluctuations were in the right phase and magnitude to contribute to Unaami.

Large-scale cloud-radiation feedback is another logical process study for SEARCH. Reanalysis data (e.g., moisture flux convergence) and remotely sensed cloud data might be analyzed relative to the AO index to look for correlations suggesting positive or negative feedback. The appropriate time-series data should be gathered in the future to examine this issue. At present this is the focus of the ARM program of the Department of Energy (DOE). The objective of ARM is to improve the treatment of cloud-radiative forcing and feedbacks in global climate models. It addresses the radiation budget and the radiative and other properties of clouds. To do so ARM operates field research sites in several climatically significant locations including an arctic site in Barrow, Alaska. Scientists collect and analyze data obtained over extended periods of time from large arrays of instruments to study the effects and interactions of sunlight, radiant energy, and clouds on temperature, weather, and climate. SEARCH will work cooperatively with ARM to improve our understanding of cloud-radiation feedback and other atmospheric processes in order to learn their role in Unaami.

SEARCH will examine the long-term, large-scale feedback of Unaami on global climate through effects on the sub-arctic seas and the global ocean thermohaline convection. This is controlled in part by the salinity of the outflow from the Arctic Ocean, which according to greenhouse warming simulations, decreases owing to increased P–E at high latitudes (Manabe et al., 1991, 1992). SEARCH-ASOF time series will be used to examine the freshwater balance of the Arctic Ocean and the outflow to the sub-arctic seas under different phases of the AO. This will give one indication of the connection between the Arctic and the global climate system.

An alarming aspect of Unaami is the recent retreat of the cold halocline (Steele and Boyd, 1998). This is a potentially important positive feedback mechanism that would bring Atlantic water heat to the surface, melt ice, decrease the albedo of the ocean surface, and lead to further warming. Data analysis and modeling studies should be used to see if deflection of Russian river outflow eastward toward the Beaufort Sea is responsible for eliminating the cold halocline.

A related and seemingly simple large-scale feedback process is the effect of cyclonic circulation on the ice cover. As discussed in section 3.3, the increased cyclonic atmospheric circulation due to Unaami exerts a cyclonic stress pattern on the ice cover. Through Ekman dynamics this results in a more divergent surface drift and should result in more open water. In summer this will produce a lower albedo and more surface heating. In winter it will also result in higher temperatures, but it may also result in more ice production. The net effect is unclear. Can these processes affect the atmosphere? A study using long time series and models might investigate the relationship of divergence, ice concentration, and thickness distribution with Unaami and the sign of the AO index.

There are biogeochemical processes that may warrant special study if they are found necessary to understanding the impact of Unaami. Perhaps the most obvious and critical of these is the release of methane and CO_2 with warming of the tundra.

Examples of mechanisms that may require process studies in the marine sphere include the impact of warming on shallow clathrate deposits and the impact of benthic metabolism on any released methane. We also need to understand how Unaami-induced changes in the flux of organic material to sediments affect CO_2 production (e.g., What happens to the carbon introduced by increased coastal erosion?), and the removal of fixed nitrogen by benthic denitrification. Another example would be investigating how changing ice cover affects the population density and distribution of marine mammals.

Process studies are essential to improving our understanding of controls on vegetation composition and its rate of change in response to climate change. Processes in the terrestrial ecosystem that may require long-term study are those related to decade-scale change in species composition, canopy structure, species dispersal and establishment, and plant growth. For example, how fast can forest invade tundra, or how fast can grassland become a shrubland, and what will be the trajectory of change? Such studies should include research on clonal growth and interspecific competition as well as seed production, dispersal, and establishment. The work should be done across ecosystems that differ in their species composition and feedbacks to climate, and especially in ecosystems that are actually changing. Ecosystems undergoing change in species composition may include large areas (e.g., watersheds) that have been manipulated experimentally, areas that are recovering from disturbances such as fire, and areas where climate is changing rapidly.

In the human-dimension area, primary mechanisms in the impact of Unaami on fisheries and northern societies are the complex interactions of human responses and a variable ecosystem. Process studies will be needed to elucidate the effects of these interactions.

5.4 Application

Application means two things: analysis of observed impacts and prediction of future impacts. Analysis of observed impacts has already begun to some degree. As discussed earlier, we have already seen impacts of Unaami on the ecosystem and society. The challenge is to separate the effects of Unaami from other forcing factors. SEARCH must develop more precise measures of impact, and strive to understand more clearly the connections between society, the ecosystem, and the physical environment. To this end, we plan to extend the identification of Unaami and ASR so that one day they will incorporate biological and possibly human-dimension variables. With this effort SEARCH can work toward describing the arctic ecosystem's state under both positive and negative AO conditions. The state variables for application purposes should be factors, such as ice cover and biological productivity, that affect society. While the goal is similar for reanalysis, the biological and human-dimension components are at a disadvantage relative to the physical components because the underlying mechanisms are less well established. Partly for this reason SEARCH has established the beginnings of a biocomplexity effort that will explore the interrelation of the physical environment, ecosystem, and society. A major portion of the SEARCH application will be developed by this biocomplexity effort.

This topic highlights the issue of cause and effect of the Unaami impacts. Especially in the areas of ecosystem change and societal impacts, we need to distinguish between changes that have occurred through the physical effects of Unaami and those that have occurred through the direct actions of society through such things as fisheries exploitation and land use practices. Resolving these issues will require innovative collaborations between many disciplines and between researchers and human populations affected by, and responding to, Unaami.

An important goal of SEARCH is to develop the capability of predicting the state of the AO and Unaami for 6 months ahead as we do now with ENSO. An important first step in prediction is the identification of socially relevant state variables. Since human responses are important to shaping the effects of Unaami, this step will require consultation with potentially affected human populations. With knowledge of the appropriate, socially relevant state variables, we could supply useful predictions to northern communities and policy makers. The experience with TOGA (tropical ocean global atmosphere) and ENSO has shown that even if the predictions are qualitative (conditions will be wetter than usual, warmer than usual, etc.) they can be useful to society. Attempting any kind of prediction will improve our understanding of the processes.

A special component of the SEARCH program will be to document observations on and perspectives of recent environmental change shared by local residents of the Arctic. These people are experiencing drastic changes in their ecosystems in numerous ways, and they are pressed hard to develop successful responses in terms of their economy, life-style, mobility, and social institutions. Through their direct exposure to the changing arctic environment, local residents offer an invaluable pool of expertise and the record of detailed observations on many aspects of the ongoing processes. They also possess historical knowledge of former environmental changes as well as of the past social and economic responses. Those will be of tremendous help in our efforts to model current and future impacts.

Given the societal importance of the questions and their intrinsic interest, SEARCH investigators will have a strong obligation to see that their results are communicated to the public. It will be important to include outreach activities from the planning stages of individual research projects until their completion. Consideration should be given to the roles that indigenous populations might play in assisting with proposed research and to how the results will be disseminated to the scientific community, indigenous populations, K-12 education programs, and the general public. Acceptable plans may include new media outlets, special presentations, and direct research experiences. The updated OAII Science Plan (Codispoti et al., 2001) gives some examples of programs that can lead to greater outreach and, at the same time, enhance research efforts. For example, the NSF Teachers Experiencing Antarctica and Arctic (TEA) program places K-12 science teachers into research teams in the Arctic for mutual interactions and participant enhancement (see http://tea.rice.edu). Also, NSF support for undergraduate assistants in arctic research programs is available through the Research Experience for Undergraduates (REU) program, as well as support for graduate education through the Graduate Research Fellowships program. Visit the NSF Web site http://www.nsf.gov for further information.

Public interest in the Arctic is growing as issues of global warming and environmental change are increasingly discussed in the media, and the Arctic holds a special fascination for a great proportion of the public, including many members of the press. The extent to which arctic research can capture the public imagination is illustrated by the OAII SHEBA program. Major newspapers, radio stations, and TV stations devoted considerable attention to this program. SEARCH investigators should be cognizant of this interest and work with public relations officers at their home institutions and within the funding agencies to ensure that the results are accurately and efficiently distributed to the public.

6. ORGANIZATION AND RELATION TO OTHER PROGRAMS

SEARCH was born in the ARCSS/OAII program because in many cases the change in the Arctic first became apparent in the ocean and sea ice. However, it has rapidly become clear that the recent arctic changes go well beyond the marine environment and include terrestrial changes and changes in the atmosphere of the Northern Hemisphere. Consequently, we soon began to visualize SEARCH as a thematic program extending across NSF-ARCSS. Now we have come to realize the importance to SEARCH of a long-term observation program, the importance of international activities, and the need for remote sensing. SEARCH should therefore be supported by international collaboration and multiple U.S. agencies. Consequently, organizational efforts since the 1999 Science Plan Workshop have been directed toward making SEARCH part of the International Program on Climate Variability (CLIVAR) and developing an interagency effort for SEARCH.

6.1 SEARCH as a Component of CLIVAR

The main efforts within the U.S. portion of the CLIVAR program are represented by panels. These enable the program to (1) provide a critical mass of resources, (2) ensure coordination and communication between climate research activities (both within the U.S. and internationally), (3) ensure a proper program balance by identifying and filling crucial gaps in the program, and (4) strengthen the multiagency support for high-priority climate research in the U.S. Presently there are three CLIVAR panels: the Atlantic Panel, the Pacific Panel, and the Pan American Panel. The panels are equally represented on the CLIVAR Science Steering Committee (SSC), which is also responsible for providing oversight of the panels. The CLIVAR SSC was set up by an interagency team representing NSF, NOAA, DOE, and NASA.

In November of 1999 we presented a discussion of SEARCH to the U.S. CLIVAR Science Steering Committee. We requested they consider inclusion of SEARCH as a component of the U.S. CLIVAR program. The response of the CLIVAR SSC was positive, and SEARCH was invited to be a component of CLIVAR. The CLIVAR SSC expressed the opinion that there will be major benefits to SEARCH if it is an official U.S. contribution to CLIVAR. These benefits are engendered by the four items mentioned above. Perhaps the most compelling reason for SEARCH to be an integral component of U.S. CLIVAR is that the hypotheses that are at the heart of SEARCH are implicitly global in scope. Thus, progress on the goals of SEARCH will require participation from a community of scientists covering a wide range of expertise. Establishing SEARCH as a part of U.S. CLIVAR should facilitate this coordination.

Consequently, we accepted CLIVAR SSC's formal invitation in time for their meeting on February 14, 2000. Discussion of SEARCH at this meeting centered largely on how to integrate it into the CLIVAR structure. CLIVAR, like SEARCH, is focused on the physical aspects of climate change. However, SEARCH is also concerned with ecosystem and societal impacts. Thus, our approach has been to make the physical component of SEARCH a type of CLIVAR panel, but keep the ecosystem and societal aspects of SEARCH semi-independent. This would allow a separate but overlapping mix of agencies and investigators to participate in the two aspects of SEARCH. The relationship between SEARCH and CLIVAR is not meant to detract from relationships with other programs dealing with climate and high latitudes. We expect SEARCH to maintain close ties with international programs such as the Arctic Climate System Study (ACSYS), its future successor Climate and Cryosphere (CliC), and the Japanese Frontier Program in the Arctic (associated with the International Arctic Research Center, IARC).

6.2 SEARCH and the ACSYS/CliC Program

The Arctic Climate System Study (ACSYS) was organized under the auspices of the World Climate Research Program (WCRP). The scientific goal of ACSYS is to ascertain the role of the Arctic in the global climate. To attain this goal, ACSYS seeks to develop and coordinate national and international arctic science activities aimed at the following main objectives:

1. Understanding the interactions between Arctic Ocean circulation, ice cover, and the hydrological cycle

2. Initiating long-term climate research and monitoring programs for the Arctic
3. Providing a scientific basis for an accurate representation of arctic processes in global climate models

ACSYS has helped to organize a wide range of ocean, ice, and atmospheric measurement programs in the past 10 years. The program will end in 2003. In its place the WCRP has established the Climate in Cryosphere (CliC) program to study the impact on and response of the cryosphere to the global climate system and the use of cryospheric change indicators for detecting climate change. All elements of the seasonal and perennial cryosphere, including sea ice, glacial ice and snow, and permafrost, are addressed. Also included is the interaction between the cryosphere and the atmosphere and ocean on a global scale, as well as between the atmosphere, snow/ice, and land, between land ice and sea level, and between sea ice, oceans, and the atmosphere.

Though SEARCH is different in trying to understand particular changes that have begun recently, it shares many of the goals of ACSYS and CliC. Like ACSYS and CliC, SEARCH aims to understand the climate links between the Arctic and the rest of the globe. It also aims to establish better long-term observations. Consequently, SEARCH is developing a cooperative arrangement with ACSYS/CliC so that research and observational efforts will dovetail rather than be duplicated and so that results are shared appropriately to enhance the goals of both programs.

6.3 IARPC and the Interagency Working Group for SEARCH

The effort to make SEARCH an interagency effort is promising. In the summer of 1999 a description of SEARCH was submitted for inclusion in the Interagency Arctic Research Policy Committee (IARPC) 5-year plan as a major interagency research effort. This draft plan was approved by the White House. At a December 1999 meeting of Program Managers from NSF, NOAA, ONR, NASA, and DOE, it was agreed that an informal Interagency Working Group (IWG) for SEARCH be formed to promote SEARCH as an interagency program. A working group presentation package was prepared by the NSF-funded SEARCH project office at the University of Washington. In February 2000 the IARPC met and formally established the Interagency Working Group for SEARCH and directed that it come up with an Interagency Research Plan for SEARCH, including budget estimates. This report was submitted in June 2000 for inclusion in the budget request for Fiscal Year 2001. The working assumption for this science plan should be that SEARCH will be a large, well-integrated, multiagency effort. The developing connection with CLIVAR fits naturally because CLIVAR already enjoys a unique form of multiagency cooperation.

6.4 SEARCH Organizational Structure

SEARCH will include its own Science Steering Committee and Project Office structure. However, because of the broad scope of the project, SEARCH will probably encompass groups with their own Science Steering Committees or subcommittees to deal with the various disciplinary, regional or international issues. The ASOF group dealing with Eulerian measurements in critical straits is a good example. Other examples we can envision are an Arctic Ocean Observatory Group to establish moorings, drifting stations, and hydrographic sections in the Arctic Ocean, a Terrestrial Observatory Group to establish observatories on land, an Arctic System Reanalysis Group, and a SEARCH Biocomplexity Group. Regional differences will require that some organizational elements of SEARCH be affiliated with non-U.S. programs as in the case of ASOF.

Many issues must be resolved as the Interagency Working Group on SEARCH expresses its desires for SEARCH, and the organizational aspects of our connection with CLIVAR are sorted out. However, the central organizational elements will be as follows.

6.4.1 Science Steering Committee

The present SEARCH Science Steering Committee was formed to write this Science Plan. A new committee will be formed after the Science Plan is finished. Its responsibility will be the implementation of the Science Plan in the Principal Investigator (PI) community. The funding agency counterpart to the SEARCH SSC will be the IWG, and the IWG and SSC will work closely to implement SEARCH. Because of the broad scope of SEARCH, the SSC and IWG will require subcommittees to deal with various disciplinary, regional, or environmental spheres (e.g., marine, terrestrial, Eurasian Basin). These subunits will be determined during the implementation phase. It is in this breakdown that the organizational character of the connection of SEARCH to CLIVAR will be resolved.

may be taken on by a group with experience in this area, while direction of marine investigations might be done elsewhere.

Data archiving will be a major task for SEARCH because of the heavy emphasis on long-term observations. Here, various data archival facilities with experience in editing, storing, and displaying the wide variety of data types might be used, but their data must be available centrally. It should be possible with the use of the World Wide Web to create a distributed data bank that appears as a centralized site to the user. A similar paradigm should work to some extent for information dissemination. The model provided by the SHEBA data archival system should be a great help in developing the SEARCH system.

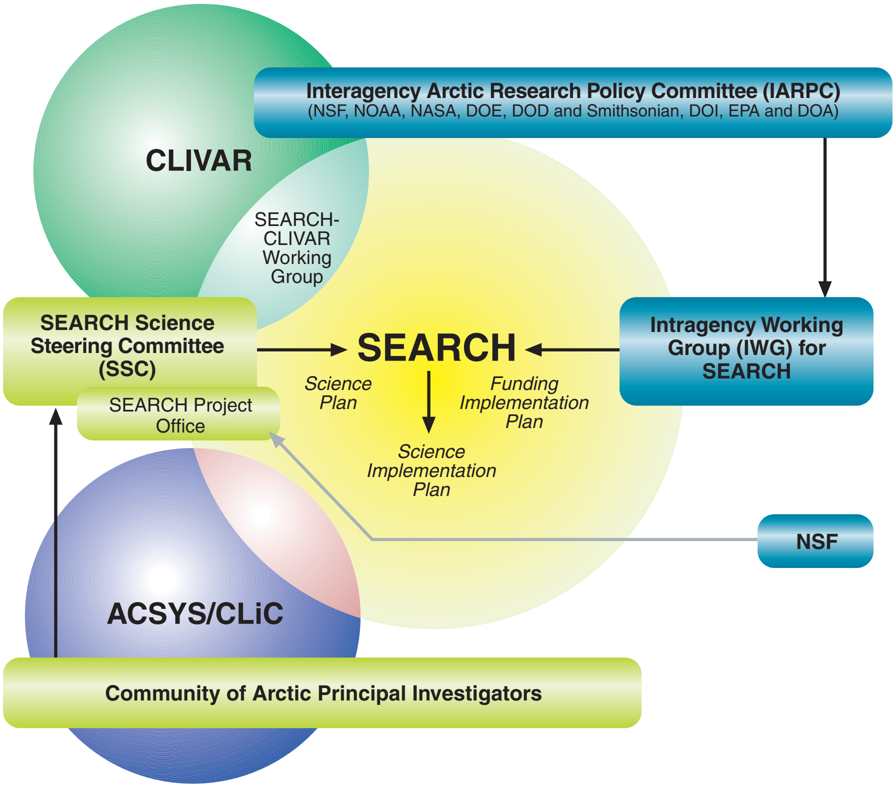


Figure 6-1 Organizational schematic for the development of SEARCH.

6.4.2 Project Office

Traditionally, the Project Offices have played three types of roles: (1) executive day-to-day direction of the program, (2) information and data dissemination and archiving, and (3) logistics coordination. Again owing to the broad scope of SEARCH, these roles may be taken on by subunits of a distributed Project Office. For example, the day-to-day direction of terrestrial SEARCH observations

Logistics coordination will be facilitated greatly by the NSF Arctic Logistics Office and NSF's retention of the Arctic Logistics Contractor. However, it can be quite helpful to have some logistics capability or at least an understanding at the Project Office level. This will aid in developing logistics support in some of the specialized field investigations. It may be critical, for example, to have a logistics coordinator dealing only with investigations in the Russian Arctic, and this coordinator may be a Russian. The logistics coordination may thus be a shared responsibility between the agency logistics office and nonagency experts, including the PIs themselves. The proper form of logistics coordination will be worked out by the SSSC and IWG during the implementation phase.

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9. LIST OF ABBREVIATIONS AND ACRONYMS

ACD	Arctic Coastal Dynamics Program
ACOUS	Arctic Climate Observations Using Underwater Sound Program
ACSYS	Arctic Climate System Study
ADCP	acoustic Doppler current profiler
AIDJEX	Arctic Ice Dynamics Joint Experiment
ALI	Advanced Land Imager
AMS	accelerator mass spectrometry
AO	Arctic Oscillation
AOS	Arctic Ocean Section
ARCSS	Arctic System Science
ARCSS/OAII	Arctic System Science/Ocean-Atmosphere-Ice Interactions
ARCSYM	Arctic Climate System Model
ARCUS	Arctic Research Consortium of the United States
ARLIS	Arctic Research Laboratory Ice Island
ARM	Atmospheric Radiation Measurement Program
ASOF	Arctic and Sub-Arctic Ocean Flux
ASR	Arctic System Reanalysis
ASTER	Advanced Space-borne Thermal Emission and Reflection
ATLAS	Arctic Transitions in the Land-Atmosphere System
AUV	autonomous underwater vehicle
AVHRR	Advanced Very High Resolution Radiometer
CALM	Circumpolar Active-Layer Monitoring
CCCMA	Canadian Center for Climate Modeling and Analysis
CCSR/NIES	Center for Climate Systems Research/National Institute for Environmental Studies
CliC	Climate and Cryosphere
CLIVAR	International Program on Climate Variability
CMIP	Coupled Model Intercomparison Project
CTD	conductivity-temperature-depth
DMS	dimethylsulfide
DOE	Department of Energy
ECMWF	European Centre for Medium Range Weather Forecasting
EEZ	Exclusive Economic Zone
ENSO	El Niño-Southern Oscillation
EOF	Empirical Orthogonal Function
ESH	Earth System History

EWG	Environmental Working Group
FSU	Former Soviet Union
GCM	General Circulation Model
GCOS	Global Climate Observing System
GFDL	Geophysical Fluid Dynamics Laboratory
GISP2	Greenland Ice Sheet Project 2
GISS	Goddard Institute of Space Studies
GTN-P	Global Terrestrial Network-Permafrost
IABP	International Arctic Buoy Programme
IARC	International Arctic Research Center
IARPC	Interagency Arctic Research Policy Committee
IBP	International Biological Program
IGBP	International Geosphere-Biosphere Program
INSROP	International Northern Sea Route Programme
IPCC	Inter-governmental Panel on Climate Change
IRD	ice rafted debris
ITEX	International Tundra Experiment
IWG	Interagency Working Group
MAIA	Measuring the Atlantic Inflow to the Arctic
NAO	North Atlantic Oscillation
NCEP/NCAR	National Center for Environmental Prediction/National Center for Atmospheric Research
NDVI	normalized difference vegetation index
NISE	near-real time ice and snow extent
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOAA PMEL	National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory
NP	North Pole
NSF	National Science Foundation
NSF-OPP	National Science Foundation Office of Polar Programs
NSIDC	National Snow and Ice Data Center
NSR	Northern Sea Route
PAGES	Past Global Changes
PALE	Paleoclimates from Arctic Lakes and Estuaries
PARCS	Paleoenvironments of the Arctic System
P–E	precipitation minus evaporation

PI	Principal Investigator
PMIP	Paleoclimate Modeling Intercomparison Project
POLES	Polar Exchange at the Sea Surface
POP	Parallel Ocean Program
RADARSAT	Radar Remote Sensing Satellite
REU	Research Experience for Undergraduates
RGPS	RADARSAT Geophysical Processing System
SBI	Shelf Basin Interaction
SCA	snow-covered area
SCOR	Scientific Committee on Oceanographic Research
SEARCH	Study of Environmental Arctic Change
SHEBA	Surface Heat Budget of the Arctic
SLP	sea level pressure
SMMR	Multichannel Microwave Radiometer
SO	Southern Oscillation
SSC	Science Steering Committee
SSM/I	Special Sensor Microwave/Imager
SWE	Snow water equivalent
TEA	Teachers Experiencing Antarctic and Arctic
TOGA	Tropical Ocean Global Atmosphere
TOVS	Tiros Operational Vertical Sounder
ULS	upward-looking sonar
VEINS	Variability of Exchanges in the Nordic Seas
WCRP	World Climate Research Program
WMO	World Meteorological Organization
WOCE/JGOFS	World Ocean Circulation Experiment/Joint Global Ocean Flux Study