Report
on
Study of the Arctic Change Workshop
held
November 10–12, 1997
University of Washington
Seattle, Washington

Report Number 8

August 1998

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Preface

This report describes the results of a workshop held November 10–12, 1997, to discuss the change in the Arctic Ocean and atmosphere seen over the last several years. The workshop was endorsed by the Arctic System Science Ocean-Atmosphere-Ice Interactions (ARCSS-OAII) Science Steering Committee as consistent with the ARCSS-OAII goals. The workshop and this report were funded under National Science Foundation Office of Polar Programs grant OPP-9712315 and a contribution from the Applied Physics Laboratory of the University of Washington. We gratefully acknowledge this support.

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1. INTRODUCTION AND BACKGROUND

An open workshop entitled the Study of the Arctic Change was held at the University of Washington in Seattle, Washington, November 10–12, 1997. The motivation for the meeting was the growing sense that the Arctic is undergoing significant change. This change appears to involve the atmosphere, sea ice, and ocean.

The change is important in its own right if only as a clear example of the coupling among the air, ice, and ocean. Moreover, the Arctic is a significant component of the global climate system in several respects. 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, for example, 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, whether liquid or in the form of desalinated sea ice, has the potential to influence the overturning cell of the global ocean through control of convection in the subpolar gyres, which in turn feed the North Atlantic (Aagaard and Carmack, 1989). For example, 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). Finally, the results of Thompson and Wallace (1998) and others show that the atmospheric circulation of the Northern Hemisphere has been changing as part of a pole-centered pattern. The remarkable recent changes in the Arctic Ocean and the overlying atmosphere discussed below are therefore of wide interest in the context of global climate.

In the last five or six years the change has become apparent in the hydrography of the Arctic Ocean. The results of several recent expeditions indicate that the influence of Atlantic Water is becoming more widespread and intense than previously found. Data collected during the cruise of the *USS Pargo* in 1993 (Morison et al., 1998), the cruise of the *Henry Larsen* also in 1993 (Carmack et al., 1995; McLaughlin et al., 1996), the summer 1994 Arctic Ocean Section of the *Polar Sea* and the *Louis S. St Laurent* (Carmack et al., 1997), and the cruise of the *USS Cavalla* in 1995 (Steele and Boyd, 1998) all indicate that the boundary between the eastern and western water types now lies roughly parallel to the Alpha and Mendeleyev ridges (AMR). In terms of longitudinal coverage, this means the area occupied by the eastern water types is nearly 20% greater than previously observed.

The greater intensity of the Atlantic influence is also manifest in warm cores observed over the Lomonosov and Mendeleyev ridges in the *Pargo* and *St Laurent* data, which show 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 historical data of Gorshkov (1983) and Treshnikov (1977) give no indication of such warm cores and show a temperature over the Lomonosov Ridge nearly 1°C colder. The recently prepared digital atlas of Russian hydrographic data (Environmental Working Group (EWG), 1997) confirms that no temperatures greater than 1°C were observed during numerous investigations between 1950 and 1989.

The observed salinity and temperature differences represent a fundamental change. The start of the change may have been in the late 1980s. The cruise of the *Oden* in 1991 (Anderson et al., 1994; Rudels et al., 1994) showed a slight warming near the Pole, and Quadfasel (1991) reported warmer than usual temperatures in the Atlantic Water inflow in 1990. The differences from climatology are too large and spatially consistent to be attributed to instrument error or normal seasonal and interannual variability.

According to Morison et al. (1998) there are some indications that the observed shift in frontal positions is associated with a decadal trend in the atmospheric pressure pattern (Walsh et al., 1996). The pressure fields and ice-drift data of Colony and Rigor (1993) and Rigor and Colony (1995) show that the whole patterns of pressure and ice drift for 1993 were shifted counterclockwise 40°–60° from the 1979–92 patterns, just as the upper ocean circulation pattern derived from the hydrographic data of the 1993 cruise of the *USS Pargo* is shifted relative to climatology. The yearly average pressure maps in the International Arctic Buoy Program (IABP) data reports indicate the shift in the atmospheric pressure pattern began in about 1988–89. Before that time the Beaufort High was usually centered over 180° longitude. After 1988 the annual average 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 atmospheric surface pressure is decreasing and has been below the 1970–95 mean in every year since 1988. Therefore, the temporal shift in the atmosphere roughly corresponds to our estimate of when the ocean changes began. According to Morison et al. (1998) the atmosphere might drive the observed changes in ocean circulation by Ekman pumping, and the effect of these circulation changes may reach deeper with time.

It is of utmost importance that these changes in the Arctic Ocean be studied in detail since they may represent a decadal-scale change. Some simulations of both wind-forced (Proshutinsky and Johnson, 1996) and thermohaline-forced (Yang and Neelin, 1993; Steele et al., 1996) regimes have suggested decadal-scale variability may occur in the coupled air-ice-ocean system of the high northern latitudes. On the other hand the changes may represent the start of a longer-term shift. While it is difficult to distinguish between anthropogenic climate change and other natural variability, it is also true that climate models are nearly unanimous in predicting amplified polar response to greenhouse warming (e.g., Manabe and Stouffer, 1994). The connection between lower atmospheric pressure in the Arctic and incursion of warm Atlantic water into the Makarov Basin may indicate an important link in how the climate system manifests polar amplification. In any case, examining the evolution of the changes over time will increase our understanding of the interplay of the Arctic with the rest of the globe.

As a first step in exploring the scientific issues and opportunities of such a study, a group of us circulated an open "Dear Colleague" letter (Appendix A) describing the arguments outlined above and a preliminary approach. To date 40 of our colleagues from 25 institutions have co-signed the letter. These include 30 scientists from 17 U.S. institutions and 10 scientists from 8 institutions in 6 other countries. The letter was also endorsed by the Arctic Systems Science - Ocean Atmosphere Ice Interaction (ARCSS-OAII) Steering Committee as consistent with the ARCS-OAII goals. Consequently, the Arctic Systems Science (ARCSS) section of the NSF Office of Polar Programs agreed to sponsor the workshop to explore the extent of the Arctic change and to begin planning a program to study it. The

workshop was open to all, and those with data or modeling results indicating changes in the physical characteristics of the Arctic over the last 10 years were strongly urged to attend. It was anticipated that most of the attendees would be oceanographers, atmospheric scientists, and sea ice experts. In hopes of gaining a broader perspective, we also invited anyone with information on changes in terrestrial ice and snow or changes at lower latitudes over the same period. Invitations to the workshop were spread informally through the Internet. It was also announced by the Arctic Research Consortium of the United States (ARCUS) through their World Wide Web page, Infonet, and in the ARCUS newsletter (ARCUS, 1997). There was a strong response to the invitations. A total of 74 scientists attended the meeting. Of these, 65 were from the United States, and 9 were from 7 other countries. Virtually all the disciplines described above were represented. A list of attendees is presented in Appendix B.

The agenda for the meeting appears in Appendix C. It is broken into three main elements. The first is a presentation by attendees of results related to the Arctic change. This is an effort to establish the full scope of the change. Available abstracts of the talks given during the workshop are given in Appendix D. The results are synthesized by the editors in Section 2. The second element consisted of working group discussions of key questions and observables describing the change. This evolved into a discussion of implications or overarching questions (Section 3) and detailed science issues (Section 4). The third element of the meeting (see Section 5) involved working group discussions of methods and plans.

2. THE OBSERVED CHANGE

2.1　Changes in the Ocean

The Arctic change is especially apparent in the Arctic Ocean because our view of this ocean has been of a rather static pattern, and the changes stand in sharp contrast to this view. Figure 1 illustrates this. It shows the differences between temperature and salinity measured in 1993 and climatological temperature and salinity given in the *Joint U.S.-Russian Atlas of the Arctic Ocean: Oceanography Atlas for the Winter Period* (EWG, 1997; Gore and Belt, 1997). The 1993 data were taken during the cruise of USS *Pargo* (Morison et al., 1998). 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. For this comparison the temperature and salinity from the EWG Atlas have been interpolated to the cruise track of USS *Pargo,* and the differences between 1993 and the climatology are plotted as color contours along the *Pargo* track.

Figure 1a shows that the salinity in the upper 250 m has increased dramatically in a wedge running from the Lomonosov Ridge to a front roughly aligned with the Alpha and Mendeleyev ridges. This represents an advance in the front between the saltier surface waters of the eastern Arctic and fresher western Arctic waters over about 55° of longitude from the Lomonsov Ridge 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‰.*

This salinity increase is comparable to the variation over the whole sea surface. Comparison with statistics in the Atlas indicates that the difference is several times the typical interannual variability in the Makarov Basin. Further, Steele and Boyd (1998) find the winter mixed layer in the Eurasian Basin was saltier during the early 1990s than the maximum salinities ever recorded in the 40-year data set of the EWG Atlas.

Figure 1b reveals that

> *a temperature increase has occurred in a warm core of Atlantic Water over the Lomonosov Ridge.*

The maximum temperature is over 1°C warmer than in the past. Furthermore, the Atlantic Water is shallower than in the past, so 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. These observations reinforce the idea that Atlantic Water has intruded across the whole Makarov Basin. Also, the extent of the Bering Sea Water temperature maximum has retreated behind the advancing Atlantic Water front. Decadal statistics from the EWG Atlas indicate this change is greater than the normal variability. Pawlowicz and Farmer (1997) compared modern data with historical data from the Greenland-Ellesmere Island region of the basin. They showed that while large temperature changes have occurred over the Lomonosov Ridge over the last decade, the spatial gradient of temperature over the eastern end of the Alpha Ridge in the Canadian Basin is fairly small, and temperatures themselves show little interannual change over a 40-year period up to the early 1990s. This suggests that the change in ocean properties is most pronounced in the eastern longitudes.
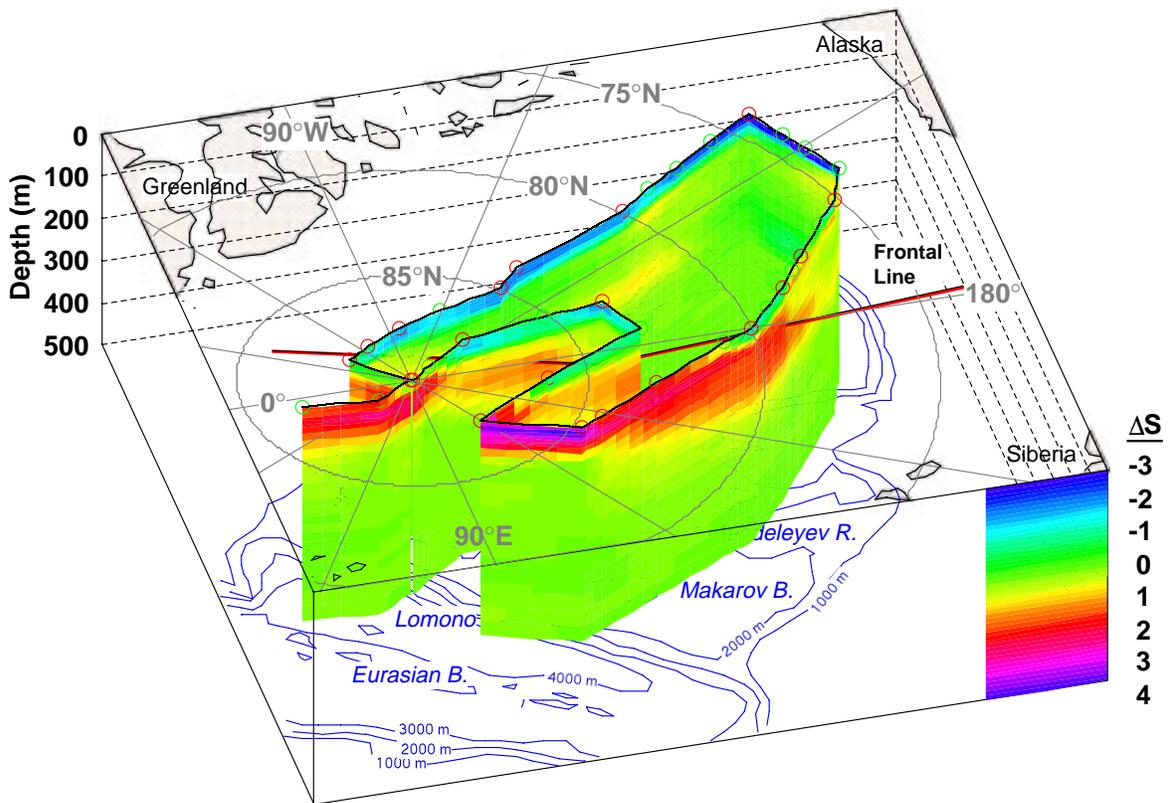
Figure 1a. Contours of the difference in salinity between the 1993 SCICEX cruise (Morison et al., 1998) and (minus) the salinity given in the Joint U.S.-Russian Atlas (EWG, 1997) interpolated to the SCICEX'93 cruise track. The largest difference is due to the shift in the front between Atlantic-dominated and Pacific-dominated waters. The front used to lie over the Lomonosov Ridge. It now lies roughly over the Alpha and Mendeleyev ridges as indicated by the red and black line. The frontal shift results in a 2.5‰ increase in the salinity in the upper 200 m of the Makarov Basin.

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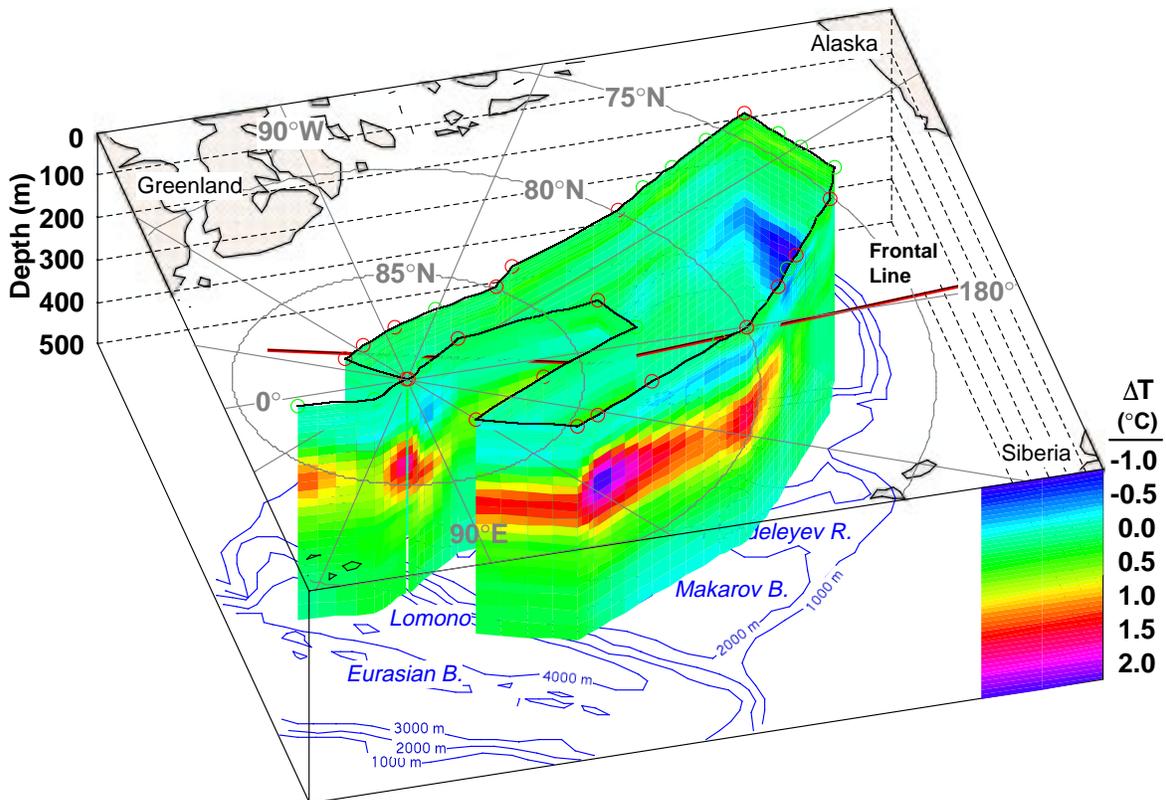
Figure 1b. Contours of the difference in temperature between the 1993 SCICEX cruise (Morison et al., 1998) and (minus) the temperature from the Joint U.S.-Russian Atlas (EWG, 1997) interpolated to the SCICEX'93 cruise track. The 200-m temperature is increased in the Makarov Basin region affected by the frontal shift described in Figure 1a. 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°C 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°C at around 200-m depth.

The shoaling of the Atlantic Water also suggests that

> *the halocline, which isolates the surface from the warm Atlantic Water, is growing thinner.*

Steele and Boyd (1998) examined the results of the 1995 cruise of the submarine USS *Cavalla* and found that the cold halocline is indeed continuing to thin. They compared Arctic Ocean hydrographic data sets from the 1990s and the data in the EWG Atlas (EWG, 1997). The comparisons revealed that the Eurasian Basin cold halocline layer has retreated during the 1990s and now covers significantly less area than in previous years. This agrees with the comparison of data from the 1991 *Oden* cruise and the 1996 cruise of the *RV Polarstern* described by Schauer and Bjork at the workshop. Specifically, Steele and Boyd find a retreat of the cold halocline from the Amundsen Basin back into the Makarov Basin; the latter is the only region with a true cold halocline layer found during the cruise of the *Cavalla*. Since the cold halocline layer insulates the surface layer and thus the overlying sea ice from the heat contained in the Atlantic Water layer, this could have profound effects on the surface energy and mass balance of sea ice in the Arctic. Further, in 1995 the mid-Eurasian Basin winter mixed layer was saltier than the maximum salinities ever recorded in the 40-year EWG (1997) climatology. This agrees with the observation in Figure 1 that in the Eurasian Basin the late summer surface salinity in 1993 was greater than the winter 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 changes in the Atlantic layer represent more than a simple warming of the temperature maximum. Comparison of data gathered in 1994 over the Eurasian slope of the Lomonosov Ridge with data gathered in the same area during the cruise of the *Oden* in 1991 shows a warmer and shallower core to the temperature maximum. However, the effects of the warming are seen from the top of the thermocline to depths below 1500 m. In accordance with these changes, the temperature gradient in the thermocline is higher in the 1994 data. The sigma-theta profiles for the 1991 and 1994 sections also indicate that the Atlantic Water from 200 to 1500 m was less dense in 1994 than in 1991. The large differences between the 1991 and 1994 data suggest that we are seeing an event of the 1990s. One of the most remarkable aspects of the AOS 1994 observations is the geographic distribution of warm Atlantic Water they disclose. The cruise track went from the Chukchi boundary of the Canadian Basin to the central Nansen Basin. In addition to encountering the warm temperature maximum over the Lomonosov Ridge, the cruise observed temperature maxima near 1°C four times over the Chukchi boundary and Mendeleyev Ridge. This region has been visited so rarely in the past that it is difficult to know precisely the size of the warming signal, but the warming is at least 0.2°C. The position of the warm cores suggests that the Atlantic Water moves in a barotropic flow following the slopes and ridges, and that the warm water is a tracer that is carried along by this flow.

Although the changes described so far have been observed in the Eurasian Basin and Makarov Basin, there have been interesting changes in the Beaufort Sea as well. McPhee et al. (1998) report the following during the SHEBA (Surface Heat Budget of the Arctic) 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 Experiment (AIDJEX) in 1975, is equivalent to an excess of about 2.4 m of fresh water. Heat content (relative to freezing) has increased by 67 MJ m^{-2}. During AIDJEX the seasonal change in salinity over the melt season implied melt equivalent to about 0.8 m of fresh water. Analogy with the seasonal progression observed during AIDJEX suggests that as much as 2 m of freshwater input may have occurred during the 1997 summer.

Melnikov et al. (this workshop) report that the physical changes in the upper ocean have caused dramatic differences in the biology at SHEBA as well. A comparison of sea ice and upper water column data collected during SHEBA and Soviet observations taken 20 years ago shows a startling decrease in larger diatoms and microfauna within the ice interior, a marked increase in freshwater algae within the ice interior, and lower chlorophyll and nitrate-nitrogen concentrations in the sea ice and upper water column. The present ice ecosystem includes species more typical of freshwater systems rather than marine systems. This biological community is typical of an ecosystem living on recycled nutrients with very little new production. Melnikov suggests the exceedingly fresh mixed layer and strong stratification have cut off the ice and shallow mixed layer for an extended time from nutrients below, leaving a freshwater or brackish sea ice ecosystem living on recycled nitrogen.

The time sequence of observations suggests the following:

> *The change in the ocean began in the late 1980s or early 1990s.*

The cruise of the *Oden* in 1991 (Anderson et al., 1994; Rudels et al., 1994) found a slight warming near the Pole, and Quadfasel (1991) reported warmer than usual temperatures in the Atlantic Water inflow along the Eurasian continental slope in 1990. Long time series are rare, but the Russian data in the EWG Atlas (1997) cover the period from 1948 to 1987. The Makarov Basin salinity increase and the warming of Atlantic Water over the Lomonsov Ridge are outside the bounds of previous measurements recorded in the atlas.

With respect to the Pacific inflow, Russian and U.S. data gathered from 1932 to the present in Bering Strait indicate a decrease in transport and in salinity and temperature in the 1980s and 1990s.

One unknown that may have an important effect on the freshwater balance of the basin is the flux through the Canadian archipelago. Little is known about this throughflow, but it may drain substantial portions of the relatively fresh water in the surface of the Canadian Basin. The throughflow is the subject of a proposed new initiative (Johnson, personal communication) which may be closely tied to the Study of the Arctic Change.

2.2 Changes in the Atmosphere and Ice Drift

As mentioned in the Introduction,

> *the changes in the Arctic Ocean appear to be related to changes in the atmosphere.*

According to Morison et al. (1998) there are some indications that the shift observed in frontal positions is associated with a decadal trend in the atmospheric pressure pattern (Walsh et al., 1996). The frontal line shown in Figure 1 is aligned with the dominant geostrophic surface current along the track of USS *Pargo* as described by Morison et al. (1998). This current, referred to as the Transpolar Drift, is most apparent in the ice drift. Figure 2, from Morison et al. (1998), shows the atmospheric pressure and ice drift fields of Colony and Rigor (1993) and Rigor and Colony (1995) averaged (a) for 1979–92 and (b) for 1993. The patterns of pressure and ice drift for 1993 were shifted counterclockwise 40°–60° from the 1979–92 pattern. The change in frontal position inferred by comparison of Figures 1 and 2a also amounts to a counterclockwise shift of about 40°. The yearly average pressure maps in the International Arctic Buoy Program (IABP) data reports indicate that the shift in the atmospheric pressure pattern began around 1988–89. Before that time the Beaufort High was usually centered over 180° longitude. 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 atmospheric surface pressure in the Polar Basin is decreasing and has been below the 1979–95 mean in every year since 1988.*

This has been attended by sharp increases in cyclone frequency over the central Arctic Ocean (Serreze et al., 1997).

Swift et al. (1997) and Dickson et al. (1997) suggest that the warming of the Atlantic Water in the Arctic Ocean can be correlated with the North Atlantic Oscillation (NAO). There has been an increase in the winter NAO index since 1960 to the highest ever values in the early 1990s. Dickson et al. (1997) argue that the southerly airflow that accompanies the positive index has resulted in warming of the two streams of Atlantic Water entering the Arctic Ocean across the Barents Sea shelf and along the continental slope west of Spitsbergen. It also has resulted in increased precipitation in the Norwegian Sea and decreases in the salinity of the Atlantic Water inflow. Swift et al. (1997) show that changes in Atlantic Water temperature in the Arctic Ocean can be correlated with the fluctuations in the NAO if the transit time of the water in the basin is accounted for. Using the estimates of the mean current velocities of Atlantic Water in the Polar Basin, they backtrack observed temperatures to a time when the water was near Fram Strait. These hindcast temperatures show a correlation with the NAO index, and Swift et al. (1997) suggest that the ultimate cause of the warming is reduced winter cooling of the Atlantic Water in transit through the Norwegian Sea. This agrees with the suggestion of Dickson et al. (1997) that the advection of atmospheric heat into the Greenland Sea associated with a positive NAO index reduces cooling of Atlantic Water and thus allows warmer water to flow into the Arctic Ocean.

Figure 2a. Average surface atmospheric pressure and sea ice drift velocities from 1979 to 1992 (figure from Morison et al., 1998). The data are from the International Arctic Buoy Program (Colony and Rigor, 1993) courtesy of Ignatius Rigor.

There have been changes on the Pacific side of the basin as well. Overland et al. (1997) report that the position of the tropospheric cold pool is roughly centered over the Canadian Arctic and the Beaufort Sea. It is displaced from the pole by orographic effects of the North American mountain ranges. These result in the southerly advection of atmospheric heat and moisture in the Greenland Sea, Barents Sea, and eastern Arctic. However, the position of this cold pool, in turn, affects 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. This seems to represent a new polar teleconnection pattern.
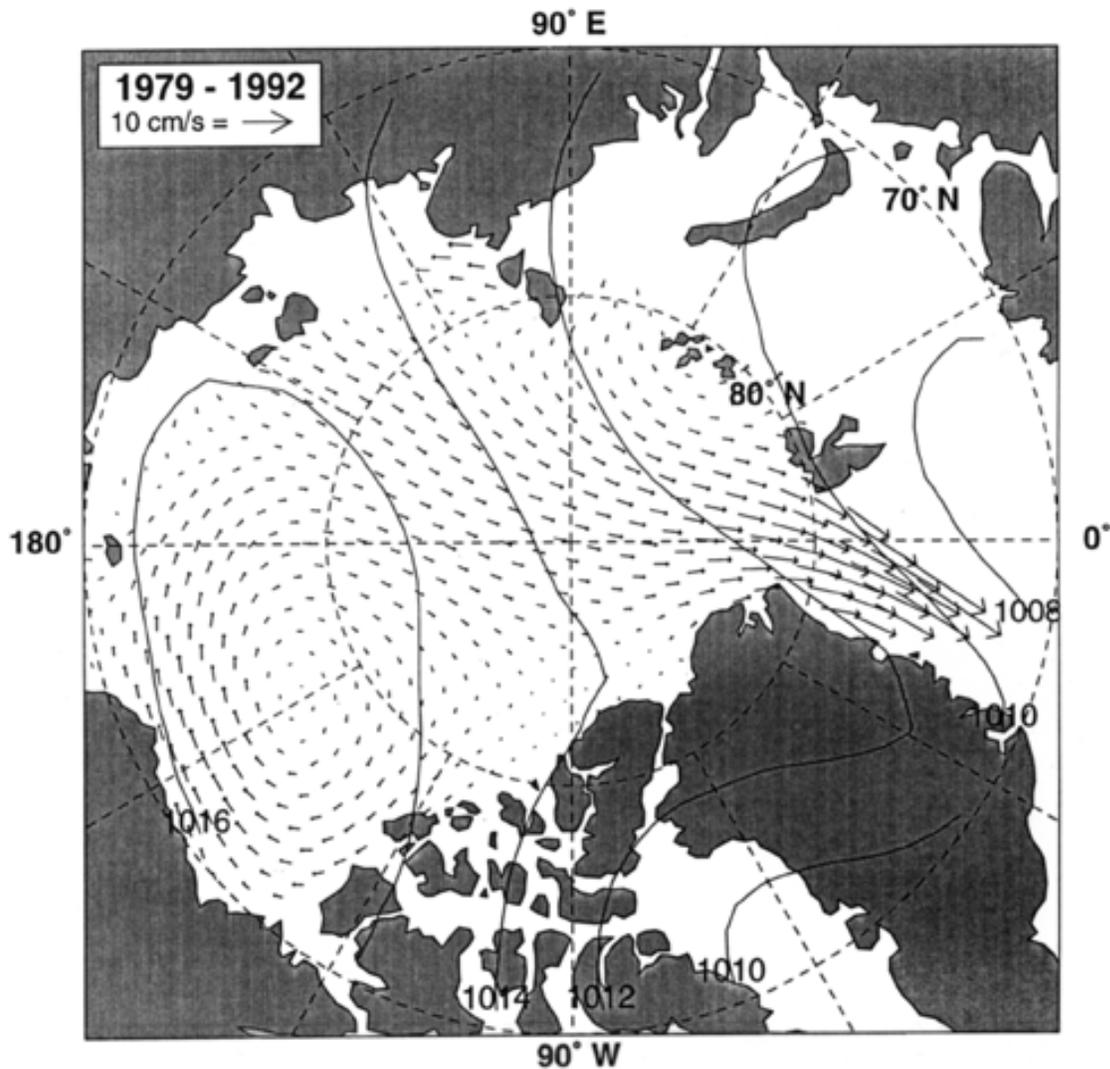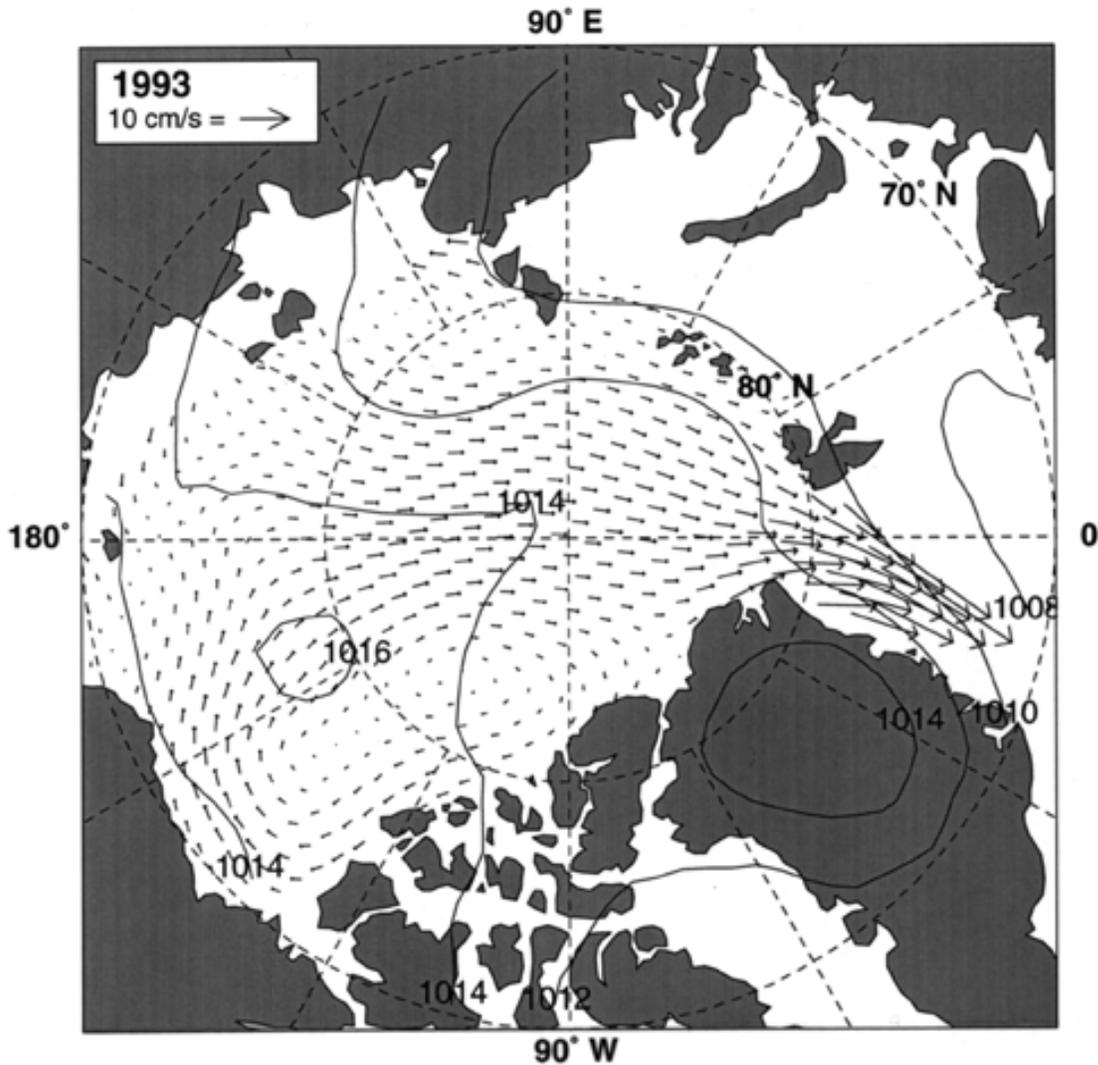
Figure 2b. Average surface atmospheric pressure and sea ice drift velocities for 1993 (figure from Morison et al., 1998). The data are from the International Arctic Buoy Program (Colony and Rigor, 1993) courtesy of Ignatius Rigor. Note that the pressure and drift patterns are shifted counterclockwise in the Beaufort Sea relative to the 1979–1992 patterns.

A more comprehensive picture of the atmospheric change is presented by considering the leading empirical orthogonal function (EOF) of sea-level pressure for the Northern Hemisphere. In work that was being completed at the time of the Arctic Change Workshop, Thompson and Wallace (1998) show that this EOF is more strongly coupled to surface air temperature variations over the Eurasian continent than to the NAO. As shown in Figure 3a, from Thompson and Wallace, it resembles the NAO, but its strong negative lobe is more nearly centered over the North Pole. It has strong positive lobes over the North Pacific and North Atlantic. As shown in Figure 3b, it has been rising since the mid 1960s. The figure also shows the increase in Northern Hemisphere surface air temperature over the same period.
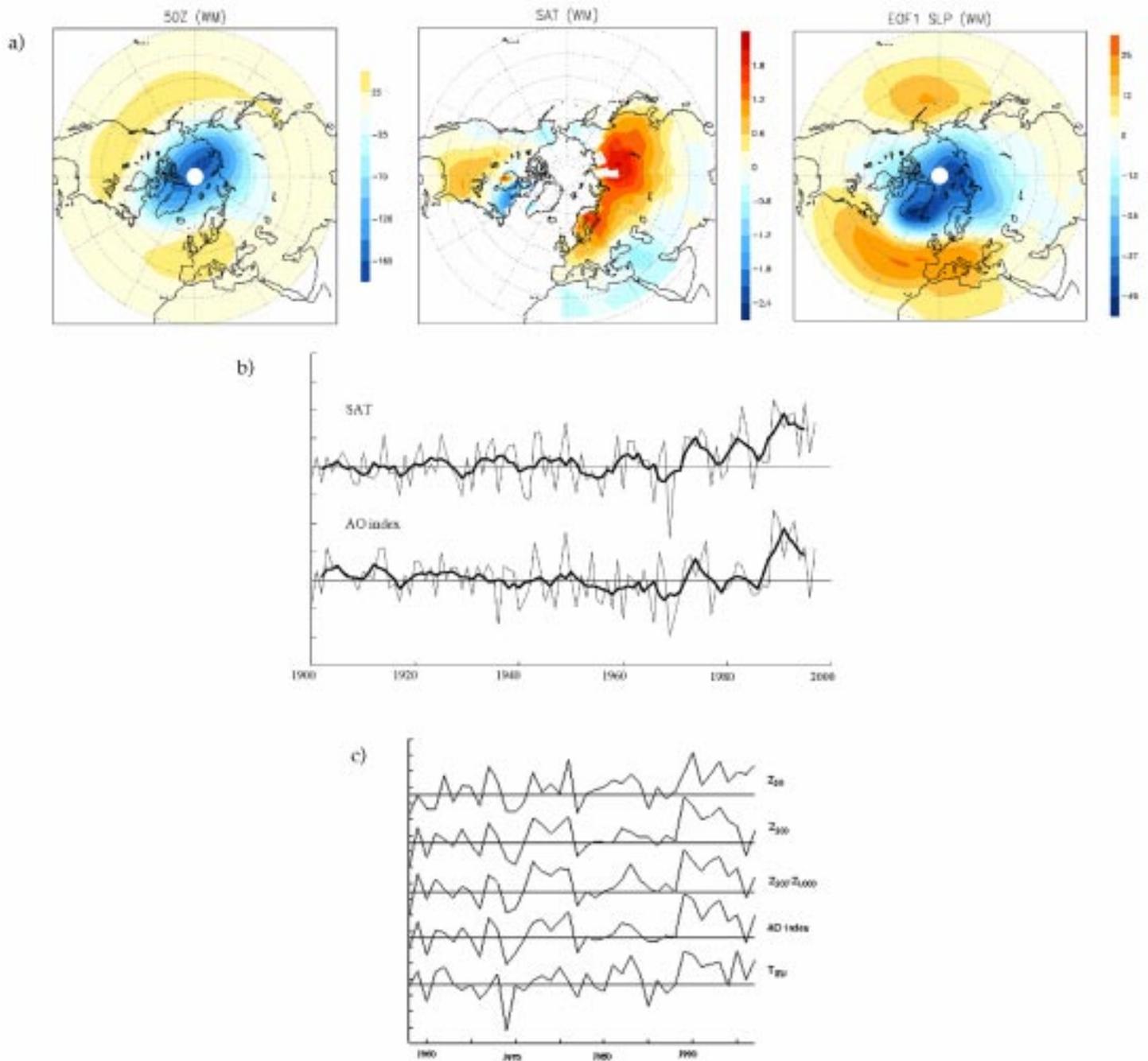
Figure 3. (a) Regression maps for surface air temperature (SAT), surface sea level atmospheric pressure (SLP EOF-1), and geopotential height at 50 mbar (Z_{50}) based on the leading principal component of wintertime (November–April) monthly mean sea-level pressure anomalies (AO-index) for 1947–97 (from Figure 1 of Thompson and Wallace, 1998). Contour intervals (expressed in units per standard deviation of the AO index) are 0.5 K for SAT, 10 m for SLP, and 30 m for Z_{50}. (b) Normalized wintertime expansion coefficient time series for the SAT and SLP regression maps of Figure 3a for 1900–1997 (from Figure 5 of Thompson and Wallace, 1998). (c) Time series of normalized expansion coefficients for the Z_{50}, Z_{500}, $Z_{500-1000}$, and the mean sea level pressure anomalies (AO index) and Eurasian mean (40–70°N, 0–140°E) SAT anomalies (T_{EU}) (from Figure 1 of Thompson and Wallace, 1998).

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The spatial distribution of the temperature increase confirms the results of Chapman and Walsh (1993) and Martin et al. (1997) that surface air temperatures in the Arctic have been increasing.

The first EOF is associated with low pressure over the Arctic Ocean, so the particularly rapid increase in the Arctic Oscillation (AO) index shown in Figure 3b after the late 1980s agrees with the results of Walsh et al. (1996) and the timing and sense of changes in upper Arctic Ocean circulation. The timing of the change is confirmed by Watanabe and Nitta (1997). On the basis of a statistical test comparing pressure pattern changes over the past five and ten years, they conclude that the Northern Hemisphere 500-hPa pressure underwent significant change in 1989, with a strong pressure decrease centered over the Arctic Ocean. One of the most remarkable aspects of the Thompson and Wallace (1998) work is the connection between the surface pressure leading EOF and the leading EOF at 50 hPa. The 50-hPa leading EOF is an almost perfect bull's-eye over the North Pole. Figure 3c shows that the time series of the 50-hPa and surface coefficients are very well correlated. In other words, the change extends from the top of the atmosphere to the surface of the ocean, and by our arguments here down into the ocean.

Thompson and Wallace postulate that the atmospheric change may be driven by radiatively induced temperature changes in the stratosphere or a barotropic response of the polar vortex to greenhouse warming in the troposphere.

To summarize the observations:

The Arctic is in the midst of change extending from the top of the atmosphere to below 1000 m in the ocean. The strengthening of the polar vortex has resulted in lower surface pressure and a consequent weakening and distortion of the Beaufort Gyre. The added positive vorticity or weakening of the Beaufort Sea ice gyre is apparent in drifting buoy data (Moritz, this workshop), and it is associated with divergence of the ice pack as well. The increased divergence has been postulated by McPhee et al. (1998) to cause increased summer ice melt and the observed freshening of the Beaufort Sea mixed layer. The change in circulation may also account for the decreased ice cover on the Siberian shelves described by Maslanik et al. (1996) and Brigham (this workshop). The change in atmospheric circulation has also resulted in a rising NAO index and an increased advection of heat and moisture into the Greenland Sea and Barents Sea regions. This, in turn, has resulted in the temperature increase of the Atlantic Water inflow to the Arctic Ocean.

2.3 Model Results

What do modeling efforts tell us of the mechanisms of these changes? So far the modeling efforts have been aimed at understanding the response of the ocean to changes in atmospheric forcing. Proshutinsky, Polyakov, and Johnson, building on the results of Proshutinsky and Johnson (1997), report two regimes of the arctic system decadal variability that correspond to the anticyclonic and cyclonic circulation of the arctic atmosphere and polar ocean with "cold and dry" and "warm and wet" atmospheres and with "cold and salty" and "warm and fresh" ocean water, respectively. Shifts from one regime to another are forced by changes in location and intensity of the Icelandic low and the Siberian high. They report that wind-driven ice and water motion in the Arctic alternates between anticyclonic and cyclonic circulation, with each regime persisting for 5–7 years (period is 10–15 years). They are uncertain what processes are responsible for these different atmospheric circulations, but they argue that the recent change in the Arctic is but an extreme expression of a cyclic pattern.

Maslowski et al. reported on results of simulations with the Parallel Ocean Program (POP) of the Los Alamos National Laboratory (Smith et al., 1992), which has been adapted to the Arctic Ocean. Simulated surface distributions of passive and active tracers from the Lena River under conditions representative of the first half of the 1990s show the Beaufort Gyre being significantly decreased. This simulation also shows the central Arctic having a cyclonic type of circulation similar to that discussed by Proshutinsky and Johnson (1996, 1997). The Transpolar Drift is absent over the Lomonosov Ridge, and its new position (if we continue to define this feature along the eastern part of the Beaufort Gyre) is now located somewhere over the Mendeleyev-Alpha Ridge.

> *The difference in tracer distributions between the passive and active experiments shows the sensitivity of the large-scale upper ocean circulation to the water mass stratification.*

Holloway (this workshop) posed the question: "How does climate-forced change come into the Arctic Ocean?" His modeling of ocean circulation accounts for the Neptune Effect which, in the absence of any other forcing and through the interaction of the ambient eddy field with bottom topography and the earth's rotation, sets up a bathymetrically steered barotropic current system (Holloway, 1987, 1992, 1995; Nazarenko et al., 1998). He argues that on the basis of these modeling results the ocean circulation can change in part because of altered characteristics of inflowing Atlantic Water (by Fram and Barents branches), and in part because of changes in the thermal and freshwater forcing over the Barents Sea and Siberian shelves. Changes in wind forcing are reflected in altered circulation in and above the halocline. These results are consistent with the observed changes. Below the halocline, the circulation is remarkably constant. The overall pattern is fixed by topography, and circulation changes are localized to fewer than a half dozen key diffluences (off northern Norway, at Fram Strait, at the Laptev-Lomonosov juncture, at the intersection of the Mendeleyev Ridge with the Siberian margin, and near the Lincoln Sea). At these diffluences, the relative fractions of flow apportioned to diverging branches can be modified by interaction with a changing suprahalocline circulation and with remote (lateral) buoyancy forcing.

Finally, Rothrock reported on recent model simulations that indicate a strengthened inflow of Atlantic Waters through the Barents Sea in recent years (Zhang et al., 1998). An ice-ocean simulation of the past 18 years was driven by daily varying winds and air temperatures. The Fram Strait branch of Atlantic Water inflow was relatively constant, whereas the Barents Sea branch increased in magnitude from the period 1979–1988 to 1989–1996. The result was a warming of the Atlantic Water layer within the Arctic Ocean, a weakening of the halocline in the Eastern Arctic, and a decrease in sea ice volume and extent.

3. IMPLICATIONS

The observations and modeling studies described during the first day of the meeting indicated that the Arctic change is a real event. This raised many questions. The attendees were polled as to what the key questions were, and this initiated a wide-ranging discussion. In an attempt to bring this discussion into focus the attendees were then asked to write down what they felt were the key overarching questions concerning the Arctic change and what were other important scientific questions. We then compiled the responses to these questions and have attempted to extract their essence. It is possible to generalize the attendees' questions in three main categories.

1. Is the Arctic change part of a cycle or does it represent a climatic shift?

Proshutinsky and Johnson (1996, 1997) argue that the Arctic Ocean circulation can be divided into anticyclone and cyclonic regimes that oscillate back and forth with a period of about a decade. They argue that the present change is simply a large expression of the cyclonic phase. Pisarev reported anecdotal Russian information suggesting a similar warming period during 1920–1940. However, examination of the last 40 years of Russian hydrographic data in the EWG (1997) Atlas shows no deviations of the magnitude described for the 1990s (Steele and Boyd, 1998). The trend of increasing NAO or the Arctic leading EOF since the 1960s suggests a longer term shift. It seems entirely plausible that

> *the present change may be the result of a combination of a long term trend and normal oscillations.*

This is the appearance of the AO index in the late 1980s shown in Figure 3b, and it would explain the apparent suddenness of the change around that time. If this is so, we can expect to see the conditions of the 1990s reverse somewhat, but to recur and become more prevalent. Obviously only time and long-term monitoring will reveal the answer to this question.

2. What are the interconnections between the changes we see in the physical properties of the arctic atmosphere, sea ice, and ocean and other changes both in and outside the Arctic region?

Perhaps the most important aspect of this question is what are the interconnections between the atmosphere, sea ice, and ocean that might constitute a positive feedback and reinforce the change? For example, could the changed circulation cause ice divergence and increased ice melt in summer, and might this result in more heat being stored in the mixed layer for release the following winter? Might this, in turn, reinforce the changed atmospheric pressure pattern? Clearly, another critical issue is the connection with lower latitudes. Can effects in the Arctic drive hemispheric changes in the atmosphere? Conversely, are the Arctic changes driven by lower latitude processes? These major interconnection questions are composed of many detailed questions such as

- What are relative contributions of dynamic and thermodynamic factors in variability of ice conditions and their present trends?

- How much of the upper ocean circulation is locally forced by way of the sea ice, and how much is forced by other means such as inflow from the boundaries?

- How do changes in Arctic Ocean inflows and outflows relate to global climate? What is the role of inflow variability in change in the Arctic Ocean, and what is the effect of variability in Arctic Ocean buoyancy export on North Atlantic ventilation?

- What is the relation of the changes to river runoff? How is runoff processed on the shelves, and what is the variability of the products? What influence does variability in shelf conditions have on ocean stratification and ice cover? Is the convective regime in the Arctic Ocean and its adjacent seas undergoing a change?

- Is the invasion of Atlantic water into the Canadian Basin increasing, declining, or remaining the same? When might we expect the Atlantic layer warming to penetrate into the Canadian Basin?

- What and where are the Arctic Ocean's "pressure points," or points of sensitivity to global changes?

- Is there an increase in the length of the melt season associated with the observed subsurface changes in the Arctic Ocean?

- How do arctic ice and ocean variability drive atmospheric teleconnections with lower latitudes?

- Will reductions in sea ice permanently shift the climate of the subarctic?

3. What are the probable long- and short-term consequences in the Arctic region?

This concerns consequences outside the realm of atmospheric and oceanic interactions that might relate to climate change. They have to do with habitability and effects on the Arctic ecosystem, and as such they are related to concerns of other programs outside ARCSS-OAII such as the Human Dimension of Arctic Climate Change (HARCC). The concerns include detailed questions such as the following:

- What are the implications of the changes we're observing for ecosystems and for delivering and retaining contaminants? Will climate and circulation changes in the Arctic affect nutrients, productivity, and carbon sequestering in the Arctic?

- With a significant change in ice cover over the Arctic shelves, to what extent will the primary productivity processes change? How will the ecosystem change, including species changes that could greatly impact higher trophic levels (fish, benthos, mammals, birds)?

- Will the thinning of sea ice affect the rate of exchange of carbon dioxide with the atmosphere?

- Will modification of sea ice extent significantly affect ecosystem dynamics in the marginal ice zone?

4. FUTURE STUDY

The changes in the Arctic warrant study through a multifaceted approach of measurements, data analysis, and modeling. The change obviously involves the ocean, ice, and atmosphere at high latitudes, and the atmosphere and ocean effects likely extend to lower latitudes. It is on these areas that most of the discussion of measurements focused, and we discuss these below. The effects of change should be noticeable on land as well. Changes in wind, temperature, and snow accumulation on the Greenland Ice Cap may be affected, and evidence for such changes in the ice core record may give us a proxy time history of previous similar changes. There may be important effects on the marine ecosystem and human activity in the Arctic as well.

The efforts required to track and understand the change in the Arctic can be broken into four main categories: Time Series Observations, Analysis and Modeling, Process Studies, and Synthesis and Application to Broader Questions.

4.1   Time-Series Observations

Time-series measurements are the backbone of the observational program. They are needed to track the change in the future.

The crucial feature of these observations will be duration. A measurement program should be designed that can be maintained for many years. This may require compromises in accuracy and resolution to ensure that broad time and spatial coverage can be maintained. Such a program may require a new approach in funding and operations, an approach in which investigators pool their efforts to obtain a community data set. At this point we can only describe the observations needed. The method of making them must be developed in a larger effort.

The critical variables in the Arctic Ocean include its hydrographic state, circulation, and inflows and outflows to and from the Arctic Basin. At the surface the key variables are the distribution, thickness, and motion of sea ice. In the atmosphere the circulation, moisture, and heat content are the primary variables.

4.1.1 Ocean

It is convenient to think of the Arctic Ocean as a box with well-defined inflow and outflow regions, exchanging heat and momentum with the atmosphere. The thermodynamic state of this box is defined primarily by the temperature and salinity of the ocean and, because it is essentially an ice bath, the mass of the ice cover. To assess the change in the Arctic we will need to measure this thermodynamic state. Inflows, outflows, and exchange with the atmosphere must be monitored to explain the observed changes in the state.

4.1.1.1 Repeated Hydrographic Sections

Hydrographic sections of temperature and salinity reveal the thermodynamic state of the ocean. From them the baroclinic currents can be estimated as well. Ideally, we would have a detailed, high-resolution CTD survey of the Arctic Ocean once per year for an indefinite period. A well-justified selection of chemical tracers should also be measured, because

there are instances when temperature and salinity alone are inadequate to answer circulation questions essential to understanding the cause of observed changes. Examples include distinction between sea-ice melt and river water and distinction between halocline water mass contributions.

Such sequences of large-scale hydrographic observations were made by the former Soviet Union in the 1970s by means of airborne hydrographic surveys conducted in the spring months. The largest of these covered the whole basin with a resolution of about 200 km. These were augmented by data from some of 31 long-term ice stations. Repeating such intense sampling every year may not be practical. However, it would be feasible to establish a hierarchy of frequent surveys at a few locations and less frequent large surveys at higher resolution. Recent developments facilitate hydrographic measurements. Recent icebreaker cruises have been able to penetrate far into the basin. Drifting buoys measuring hydrographic parameters have been used by the U.S. to gather sections similar to those obtained from a long-term drifting ice camp for a fraction of the cost. New icebreaker capabilities will make establishing such automated sites easier. In the 1990s the use of Navy submarines has provided a new tool for gathering hydrographic information.

These tools should be used to begin gathering a regular sequence of hydrographic sections. A minimum set of records should be obtained annually to observe changes at key locations. For example, these might be performed by aircraft making sections from shore stations across the topographically controlled boundary currents. Samples in the interior of the basin could be gathered by automated stations, on submarine cruises, and by aircraft staged from small ice camps. A complete survey measuring a wider array of hydrographic variables and at greater spatial resolution might be done every few years. The platforms mentioned above could be augmented by extended icebreaker cruises to make the deeper and more detailed measurements including tracers and biology. The recent results from SHEBA show it is important to measure at least a few hydrographic variables seasonally; the thermodynamic exchange between the ocean and atmosphere is recorded in the differences between upper ocean conditions in the fall and spring. The automated stations can provide seasonal and greater time resolution.

4.1.1.2 Time Series of Ocean Inflow and Outflow

Monitoring of inflows and outflows to the Arctic Ocean is a large task, but it is important that it be done to understand the mechanisms of change. It is also crucial to assess the effect of Arctic change on lower latitudes such as on convection in the Greenland and Labrador seas. There are four oceanic portals: Bering Strait, the Canadian Archipelago, Fram Strait, and the Barents-Kara throughflow. Bering Strait, Fram Strait, and the Barents-Kara throughflow are already the subject of international programs.

Bering Strait has been continuously monitored since mid-1990, although not fully satisfactorily. For example, coverage of the western channel has been spotty, and there are years without salinity measurements. Nonetheless, an important time series is beginning to accumulate. When this time series is combined with earlier estimates based on a wind-driven flow algorithm, it appears that the last two decades have seen relatively low transport through the strait, and that during the 1990s both the salinity and the amplitude of the annual cycle in salinity in the strait have decreased considerably. The former may represent

a general freshening in the North Pacific, such as has been seen at Station P. On the other hand, the decrease in the amplitude of the annual salinity cycle likely reflects a reduction in the amount of sea ice produced over the Bering Sea shelf in recent years. We note that these changes have occurred over the same period in which the distribution of Pacific waters within the Arctic Ocean has changed. We also note that support for the accumulating time series in Bering Strait is rather fragile, with short-term (typically 1–2 year) contributions thus far from the National Oceanic and Atmospheric Administration (NOAA), the Russian HydroMet Service, the National Science Foundation (NSF), the Department of Fisheries and Oceans in Canada (DFO Canada), and the Japan Marine Science and Technology Center (JAMSTEC). There is a distinct need to place this work on a firmer basis with a longer temporal perspective. An additional perspective on the Bering Strait throughflow is that it represents a key element in the global water balance, transporting excess fresh water from the Pacific to the Atlantic (Wijffels et al., 1992).

Considerable effort has gone into monitoring Fram Strait over the past decade, based primarily on contributions from Germany, Norway, and the U.S. The strait is a large and complex area, with a significant recirculation, but the main exchanges with the Polar Basin are concentrated over the continental slope on either side, and these slopes provide a natural focus for monitoring. The slope on the Spitsbergen side is ice-free and easily accessible; it provides the conduit through which the main warming signal discussed earlier propagated. Keys to identifying this mechanism were the annual hydrographic sections taken by the Marine Research Institute in Bergen, and the long-term monitoring program of this institute should be taken into account in future planning for work in this region. The emphasis on the Greenland side has been on the outflow of ice from the Polar Basin, since it is variability in this buoyancy flux that has been implicated in causing the so-called Great Salinity Anomaly in the North Atlantic during the 1970s (Aagaard and Carmack, 1989). The recent measurements over the Greenland slope suggest that interannual variability in the ice flux can, in fact, be large enough to create such anomalies (Vinje et al., 1997). A European effort, Variability of Exchanges in the Nordic Seas (VEINS), to determine the fluxes through the Greenland-Norwegian Sea system is presently under way and includes Fram Strait, but the focus is on defining the mass budget, not on monitoring, and the program is of limited duration, with perhaps two years of field work. There is nevertheless a considerable base upon which to build a sustained monitoring program in Fram Strait, and enough is known to enable realistic planning.

It has recently been recognized that the flow of Atlantic Water into the Arctic Ocean has two branches of roughly equal volume: One that enters the Arctic through Fram Strait and one that transits through the Barents Sea (see, for example, Schauer et al., 1997). The Barents Sea branch is significantly modified during its transit as it is cooled by the atmosphere and freshened by ice melt and river inflows. Recent field work on the continental slopes of the Kara and Laptev seas demonstrates that the two branches of Atlantic Water (Barents Sea and Fram Strait) rejoin in this region, although their hydrographic signatures are distinct (Schauer et al., 1997). The result is the formation of two streams that flow together along the continental shelf break, but that (it is conjectured) diverge downstream from the Laptev Sea continental slope. Recent modeling results (Zhang et al., 1998) suggest that variations in the strength of the Barents Sea branch are mainly responsible for the warming of Atlantic Water within the Arctic Ocean. The European VEINS program will

monitor the exchange between the Nordic and Barents seas; it seems clear that further monitoring of the exchanges between the Barents and Kara seas and the Arctic Ocean is also necessary. While the European VEINS program will monitor the entry of Atlantic waters onto the Barents shelf, the large and probably highly variable modification of these waters on the shelf argues strongly for the additional monitoring of the exchanges between the Barents and Kara seas and the Arctic Ocean.

Though oceanographic data have been gathered at both Fram Strait and Bering Strait, our knowledge of the flow through the Canadian Archipelago is more limited. Fissel et al. (1988) carried out a series of investigations of the physical oceanography in the Canadian Archipelago in the early 1980s. These provide insight into how to study the area, but no other long-term measurements exist to describe the heat and salt exchange through the Canadian Archipelago. As pointed out above, the observed changes in Arctic Ocean circulation may be linked to two regimes described by Proshutinsky and Johnson (1997): the typical anti-cyclonic circulation pattern that favors flow out through Fram Strait, and a cyclonic circulation that enhances flow out through the Canadian Archipelago. Thus, these circulation regimes drive variations in the freshwater flux out of the Arctic that could be observable in data from current-meter moorings deployed in the Canadian Archipelago. Variations in the freshwater flux rate between Fram Strait and the Canadian Archipelago are measurable and would provide evidence for the phasing of the two regimes. A dedicated program has been proposed by Mark Johnson of the University of Alaska to monitor the Canadian Archipelago Throughflow (CAT) (See Appendix E). This program could and should be consolidated with a program to study the Arctic change as a whole. In CAT, current-meter and CTD moorings would be deployed across several key choke points.

4.1.2 Ice

To know the thermodynamic state of the Arctic Ocean one must know the mass of ice present. This requires time series of ice extent and ice thickness. The monitoring of ice extent by remote sensing techniques has been going on for the past 20 years and will be continuing as part of existing programs such as the Pathfinder program. These techniques provide other useful parameters as well. The Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) passive microwave satellite remote sensing systems have provided measurements of ice extent, concentration, and velocity for first-year and multiyear ice types to a resolution of about 25 km. The new Advanced Microwave Scanning Radiometer (AMSR) is expected to provide improved measurements into the future. The Advanced Very High Resolution Radiometer (AVHRR) has provided measurements of surface temperature, albedo, and cloud properties to a resolution of 1–5 km. These measurements can also be used to estimate ice extent and velocity. The AVHRR-type measurements will be continuing using the Moderate Resolution Imaging Spectroradiometer (MODIS). The new Canadian Radar Satellite (RADARSAT) active microwave satellite images the ice with 100-m resolution. The data are being processed by the RADARSAT Geophysical Processor System (RGPS) to produce ice velocities with 5- to 10-km resolution.

Measurement of ice mass or thickness is more problematic. This requires measurements of ice draft, which must be provided by surface or in-water observations. The most obvious method is by surface observation—drilling holes in many random locations and

measuring the ice thickness. However, the number of samples required for a meaningful average is substantial, and practical considerations probably lead to underestimates in thickness. The other approach is to measure ice draft and derive thickness and mass by assuming isostasy. Ice draft has been measured operationally as part of past submarine cruises. Many of these data are now being made available for scientific research. The recent SCICEX submarine cruises have provided detailed ice-thickness profiles. In the future autonomous underwater vehicles (AUVs) may duplicate the type of measurement currently being made by submarines. Ice thickness has also been measured by moored upward-looking sonars (ULS). An upward-looking acoustic depth sounder measures distance to the bottom of the ice. A sensitive pressure sensor measures the depth of the instrument, and this value minus the distance to the bottom of the ice is the ice draft. The ULS approach relies on the ice drift to advect a wide range of ice types past the instruments. In the future a mix of these measurement techniques will be necessary. Direct sampling, submarine sampling, and AUV sampling will give snapshots of the spatial distribution of ice thickness. Moored ULSs, when placed in strategic locations and combined with measurements of ice velocity, can conceivably provide time series of ice thickness for large areas. This requires the thoughtful integration of various measurement types, but may provide substantial insight into the mass balance of the basin.

4.1.3 Atmosphere

The atmosphere appears to be the driving force behind the observed changes in the Arctic. Fortunately, monitoring the arctic atmosphere is part of ongoing programs. Changes in the atmosphere have been observed by the International Arctic Buoy Program via its network of drifting buoys measuring atmospheric pressure and temperature. These buoys tell us the surface wind field and thermodynamic forcing acting on the ice. Soundings into the upper atmosphere are conducted around the periphery of the Arctic Ocean by various nations. Satellite remote sensing provides some profile measurements. The TIROS-N Operational Vertical Sounder (TOVS) can yield vertical profiles of air temperature and vapor content to 100-km resolution over the whole basin. The Atmospheric Infrared Sounder/ Advanced Microwave Sounding Unit (AIRS/AMSU) will be continuing these types of measurements. AVHRR provides spatial maps of surface temperature, albedo, and cloud properties. What these satellite soundings lack in accuracy is compensated by the statistical value of the large amount of data provided. These satellite systems work especially well when surface ground-truth measurements of air temperature are available from buoys. It probably would be beneficial if added atmospheric soundings were available at a few sites in the basin. The critical element for the study of the Arctic change is that the existing atmospheric measurement programs continue.

4.2. Process Studies and Related Programs

As the time series measurements, analysis, and modeling progress, process-oriented questions are bound to arise. These will warrant process-oriented experimental programs.

These experiments may involve many investigators in complex, multidisciplinary studies. Ideally, many of these will already be part of active initiatives. Examples of such studies are the Surface Heat Budget of the Arctic (SHEBA) being carried out now and the Western Arctic Shelf Basin Interaction (SBI) program proposed for the future. SHEBA is looking at the exchange of heat at the surface of the Beaufort Sea with a year-long observation program. As pointed out by McPhee (this workshop) the observations of thin ice and a fresh and warm mixed layer show a connection with other observed changes in the basin. The SHEBA process-study results will tell us if there is a feedback from the oceans to the atmosphere that might reinforce the changes.

The SBI is an initiative of the ARCSS program that has important connections to the Study of the Arctic Change. The SBI program aims to study shelf processes and their effect on the rest of the Arctic Ocean. Because some of the changes we see, such as the salinity increase in the Makarov Basin, may be connected to changes on the shelves, SBI process studies can contribute to our understanding of the Arctic Change.

In general it is hard to predict the types of process studies that will be needed for the Study of the Arctic Change, but almost certainly they will be needed. These will have to be initiated and developed as the needs arise. Fortunately, the logistics and operations involved in a time-series study will provide a significant base for the process studies to take advantage of. This will help whether or not the process studies are ever explicitly part of the Study of the Arctic Change initiative. The connections to other process-oriented programs can be clarified during further development of the Study of the Arctic Change.

Although the Study of the Arctic Change is an atmosphere-ice-ocean oriented study, it has connections to programs outside the ARCSS-OAII area. Proxies to extend our records back in time and look for evidence of changes in the past may be found in ice cores of the Greenland Ice Sheet Program (GISP) and the records of the Paleontology of Arctic Lakes (PALE) program. The results of the Arctic Change work may affect the direction of the Human Dimension of Arctic Climate Change program of ARCSS.

4.3. Analysis, Modeling, and Application to Overarching Questions

Modeling will be an integral component of the Study of the Arctic Change.

First, simulations can be used to extend the field data in both space and time. An example was provided by Steele et al. (1996), who assimilated satellite and buoy data into a model that predicts freshwater outflows from the Arctic Ocean. Another example is given by Proshutinsky and Johnson (1997) who used meteorological forcing data to find decadal-scale variability in an ocean circulation model. Second, models can be used to test various geophysical scenarios, such as the response to increasing CO_2 concentration (Manabe and Stouffer, 1994). Third, models can assist in guiding field programs, by identifying locations and/or seasons where measurements are most crucial. An example is the SHEBA project, which is driven by the need to parameterize the surface energy balance more accurately. Similarly, a study by Harder et al. (1998) involving the modeling of sea ice thickness has identified regions of high variability, which might be used to guide the placement of moored buoys.

5. INITIAL ORGANIZATION, INTERNATIONAL COORDINATION, AND ARCSS METHODOLOGY

Our intent is to make the Study of the Arctic Change a long-term ARCSS initiative. Presently the workshop and report preparation are funded by a grant from NSF-ARCSS and support from the Applied Physics Laboratory of the University of Washington. Further development of the program will continue in a way that has become common for ARCSS projects. This report will serve as a prospectus for the study. It will be submitted to the ARCSS-OAII Science Steering Committee (OAII-SSC) and for approval. The OAII-SSC will guide further development. We recommend establishing a Study Steering Committee and convening a second workshop to develop a Study Science Plan. This Science Plan will define the study objectives, measurement requirements, and modeling requirements. The Committee will briefly explore operational and logistical possibilities and make initial budget projections. The Science Plan, along with this report, will allow ARCSS and NSF to start working out budget commitments.

A special emphasis should be placed on encouraging international cooperation and cost sharing. This is already a facet of observations of the important inflow and outflow regions. The European community has a strong program in the Fram Strait. The U.S. and Russia are working cooperatively in the Bering Strait, and Canada and Japan have also been involved in recent work there. CAT will involve substantial Canadian and U.S. cooperation. The Arctic Climatic System Study (ACSYS) program is international and is meant to examine the role of the Arctic in global climate. Many of its activities will support the objectives and measurement requirements of the Study of the Arctic Change. Close cooperation with ACSYS will be important. Similarly, cooperation with VEINS and other international groups monitoring the various inflows and outflows of the Arctic Ocean will be crucial. The new International Arctic Research Center (IARC) in Fairbanks, Alaska, is focused on long-term climate change and will, in particular, support the modeling and data analysis goals of the Study of the Arctic Change. At an early stage small working committees should be established to ensure cooperation with these international programs to avoid duplication of effort and seek ways of making the required time series measurements efficiently. These liaison committees should also begin to address the issues of future data sharing and development of intergovernmental memoranda of agreement to study the Arctic Change.

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APPENDIX A

An Open Letter Describing a Program For
A Study of Arctic Change

4/7/97

Dear Colleague,

This open letter is a first step in development of a program to track and understand major changes in the Arctic environment. The program is tentatively called the Study of Arctic Change.

It is becoming increasingly clear that the Arctic is in the midst of a significant change. This appears to involve both the atmosphere and ocean, but we first became aware of it in the hydrography of the Arctic Ocean. The results of several recent expeditions indicate that the influence of Atlantic Water is becoming more widespread and intense than previously found. Data collected during the cruise of the *USS Pargo* in 1993 (Morison et al, 1997), the cruise of the *Henry Larsen* also in 1993 (Carmack et al., 1995; McLaughlin et al., 1996), and the Summer 1994 Arctic Ocean Section of the *Polar Sea a*nd the *Louis S. St Laurent* (Carmack et al., 1996) all indicate that the boundary between the eastern and western halocline types now lies roughly parallel to the Alpha and Mendeleyev Ridges (AMR). In terms of longitudinal coverage, this means the area occupied by the eastern water types is nearly 20% greater than previously observed.

The greater intensity of the Atlantic influence is also manifest in the warm cores observed over the Lomonosov and Mendeleyev ridges in the *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. Results of the Transarctic Acoustic Propagation (TAP) experiment conducted in April, 1994 also suggest warmer waters in the Atlantic layer (Mikhalevsky, et. al., 1995, and Mikhalevsky, et. al., 1996). The historical data of Gorshkov (1983) and Treshnikov (1977) give no indication of such warm cores and show a temperature over the Lomonosov Ridge nearly 1°C colder. The recently prepared digital atlas of Russian hydrographic data (Environmental Working Group, 1997) confirms that no temperatures greater than 1° were observed during numerous investigations between 1950 and 1989.

The observed differences represent a fundamental change. The start of the change may have been in the late 1980s. The cruise of the Oden in 1991 (Anderson et al., 1994, and Rudels et al., 1994) shows a slight warming near the Pole, and Quadfasel (1991) reports warmer than usual temperatures in the Atlantic Water inflow in 1990. The differences from climatology are too large and spatially consistent to be attributed to instrument error or normal seasonal and interannual variability.

According to Morison et al. (1997) there are some indications that the observed shift in frontal positions is associated with a decadal trend in the atmospheric pressure pattern (Walsh et al., 1996). The pressure fields and ice drift data of Colony and Rigor (1993) and Rigor and Colony (1995) show the whole patterns of pressure and ice drift for 1993 were shifted counterclockwise 40°–60° from the 1979–92 pattern, just as the upper ocean circulation pattern derived from the hydrographic data of the 1993 cruise of the *USS Pargo* is shifted relative to climatology. Examination of the yearly average pressure maps in the International Arctic Buoy Program (IABP) data reports indicates the shift in the atmospheric pressure pattern began in about 1988–89. Before that time the Beaufort High was usually centered over 180° longitude. After 1988 the annual average Beaufort High was weaker and usually confined to West longitudes. This change is consistent with the findings of Walsh et al. (1996) that the annual mean atmospheric surface pressure is decreasing

and has been below the 1970–95 mean in every year since 1988. Therefore, the temporal shift in the atmosphere roughly corresponds to our estimate of when the ocean changes began. According to Morison et al. (1997) the atmosphere might drive the observed changes in ocean near surface circulation by Ekman pumping, and the effect of these circulation changes may reach deeper with time.

We feel it is of utmost importance that these changes in the Arctic Ocean be studied in detail. They may represent a decadal-scale change. Some simulations of both wind-forced (Proshutinsky and Johnson, 1996) and thermohaline-forced (Yang and Neelin, 1993; Steele et al., 1996) regimes have suggested decadal-scale variability may occur in the coupled air-ice-ocean system of the high northern latitudes. On the other hand the changes may represent the start of a longer term shift. While we are cognizant of the difficulty in distinguishing between anthropogenic climate change and other natural variability, we are also aware that climate models are nearly unanimous in predicting amplified polar response to greenhouse warming (e.g., Manabe and Stouffer, 1994). The connection between lower atmospheric pressure in the Arctic and incursion of warm Atlantic water into the Makarov Basin may indicate an important link in how the climate system manifests polar amplification.

In either case examining the evolution of the changes over time will likely tell us much about the interplay of the Arctic with the rest of the globe. This study warrants a multifaceted approach of measurements, data analysis, and modeling. However, the urgent need is for repeated hydrographic measurements over the whole basin. We do not want to miss the change as it is taking place. We are therefore formulating a plan for repeated large-scale hydrographic surveys along with buoy, mooring, and remote sensing observations. One experimental plan is patterned after the Russian Sever expeditions from 1950–1987. We would set out two or three small mother camps each spring. These camps would be manned by small crews and serve as refueling stations for survey aircraft that would employ the camps and shore bases to make short (1 hour) CTD-stations at 40 to 100 locations in the Arctic Basin. The survey flights would also provide for deployment of the IABP buoys measuring atmospheric pressure and temperature. In addition to serving as base camps for the survey flights, the mother camps would also be the site of drifting buoy and mooring installations. These unmanned buoy stations and moorings would provide year around time series at a few key points and provide a high temporal resolution perspective.

In addition to the aircraft surveys we hope to take advantage of the SCICEX submarine cruises for CTD measurements. At present no major surface ship cruises are planned for the central basin for the rest of the decade, but our interests fit in with other ship-borne expeditions. Sections in the Canada Basin have been suggested to ARCSS/OAII for 1999 or later. Also, as demonstrated by the cruises of the *Polarstern* in 1993, 1995, and 1996, it is possible to gain important insights into the basin hydrography by completing short sections from the shelves into the deep basins. Such sections would help our effort and could be done as adjuncts to planned work on the arctic shelves (ex. ARCSS-OAII Shelf Basin Interactions).

The survey program will have to be an international program. Russian participation is essential since we need to use Russian airbases to reach many of the most important areas. Their experience and facilities for this type of airborne survey are essential. For similar reasons Canadian, and perhaps Greenland participation is vital. Other nations with long-standing and emerging arctic interests should be involved. These include Norway, Sweden, Germany, and Japan.

Another area where international cooperation will be crucial is in monitoring the variability of the inflows and outflows to the basin. One explanation for the observed changes is that they are forced by changes in the inflows and outflows. In this area we hope to tie in with ongoing programs where possible. For example, Fram Strait will probably be monitored by a Scandinavian-German

consortium. The exchange through the Canadian Archipelago is a major open question that might be addressed in this initiative by a Canadian and American effort. American and Russian scientists have been monitoring Bering Strait.

The logistics and experimental techniques required for such a program are not new. The community knows how to do the surveys. At its full scope it is a large undertaking, but it can be started with a subset of the full program and provide critical information. Indeed, if we do not make some measurements very soon, there will be a tragic gap in the record of Arctic change. Also there are several logistical factors that may provide tremendous logistical advantage at reasonable cost. For example, we can use the SHEBA drift station as one of the mother-stations in 1998. The U.S. Forest Service has two new turbine-powered DC-3 aircraft which they use for fire fighting in the summer months. If the NSF were to take over operation of these aircraft in the Spring and equip them with skis, they would provide ideal long-range survey and supply aircraft for this and other programs. The Alaska Air National Guard (ANG) has provided Blackhawk helicopters with air-air refueling capability and C-130 tankers for long range buoy deployments in the past. The ANG 109th Squadron has similar capabilities and through their relation with NSF might provide unparalleled support for aircraft CTD surveys and buoy deployments.

We have focused here on the need for field observations because we do not want to miss observing the change, and it may take considerable time to get the fieldwork started. However, analysis of existing data and modeling should also play a major part in this study. We must look at historical records of atmospheric parameters in studies like that of Walsh et al. (1996). There is considerable historical hydrographic data collected by the Russians that is now becoming available (Environmental Working Group, 1997). In addition they have other data such as river runoff and sea level that have been routinely collected for many years. These data sets should be analyzed in detail for evidence of past changes. Over the last several years the exchanges through Fram and Bering Straits have been monitored, and these data can be analyzed for their relation to the observed changes. All these should be compared to decadal and longer period changes at lower latitudes in the ocean and atmosphere. A number of Arctic Ocean models (ex. Hakkinen, 1992; Pavlov, 1995; Maslowski et al., 1996; Proshutinsky and Johnson, 1996; Zhang et al., 1996) could be run with atmospheric forcing representative of the last 15-20 years to examine the role of atmosphere in the ocean change. Taken further these models could predict the further ramifications of such change.

There are several existing programs under whose auspices the Study of Arctic Change might be carried out in whole or in part. These include ACSYS and the ARCSS-OAII (ex. SHEBA and Shelf Basin Interaction). The program should be closely coordinated with ongoing international activities. The international coordination would be especially well served through the ACSYS connection.

We are circulating this letter as a first step in exploring the scientific issues and opportunities. We plan to propose to NSF at least a pilot survey in the Spring of 1998 and to ONR/NSF the collection of hydrographic data from future SCICEX cruises. Finally, we would like to propose to NSF to hold an open international meeting on the Arctic change as a spring-board to further work on this urgent issue. We feel now is a very good time to propose a project that is driven by such a strong science question and that is large enough to address various elements of the observed changes in the Arctic. We are very interested to hear of your thoughts on this program and your interest in participating. Would you as an investigator be willing to join us and sign this letter? You may respond by

email or regular mail. Regular mail may be addressed to Study of Arctic Change, c/o Polar Science Center, 1013 NE 40th St, Seattle, WA 98105. Finally, we also ask that you forward this letter to other scientists who you feel would have an interest in this program.

Thank you,

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APPENDIX B

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Study for Arctic Change Workshop
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APPENDIX C

Agenda for the Study of the Arctic Change Workshop
Nov. 10–12, 1997
University of Washington
Seattle, Washington

Day 1 - Nov. 10, 1997

Room 316
South Campus Center
University of Washington
Seattle, Washington

0800: Coffee and Pastries

OPENING REMARKS

0830: Morison and Ledbetter - 20 min

    Welcome, Motivation, Progress, Meeting Objectives, Meeting Logistics

PRESENTATION OF RESULTS RELATED TO ARCTIC CHANGE

OCEAN (Schlosser, monitor)

0850: Aagaard and Swift - (15 min / 5 min for questions)

    Atlantic Water Warming

0910: Steele and Boyd - (10/5)

    Disappearance of the Cold Halocline

0925: Schauer and Bjork - (15/5)

    Comparison of Hydrographic Measurements in the Nansen/Amundsen Basin between 1991 and 1996 and Differences between 1991 and 1996 Eurasian Basin Sections

0945: Pawlowicz - (10/5)

    Modern Comparisons with Arlis-II

1000: TBA -(10/5)

1015–1035 Break

MODEL AND OBSERVATION COMPARISONS (Aagaard)

1035: Schlosser and Maslowski - (15/5)

Freshwater, Tracers and Modeling Results

1055: Holloway - (10/5)

How Change Can Occur Within an Unchanging Circulation

1110: Proshutinsky - (10/5)

Numerical Simulation of the Arctic Ocean Ice and Water Dynamics

1125: Rothrock and Zhang - (10/5)

Arctic Ice Ocean Model Results

1140–1300 Lunch

ICE, ATMOSPHERE, AND LAND (Overland)

1300: Serreze - (10/5)

Observations of Ice, Atmosphere, and Terrestrial Changes

1315: Moritz - (10/5)

Observed Variability of Monthly Sea Ice Velocity and Air Pressure Patterns, 1979–1996

1330: Brigham - (10/5)

Remote Sensing Observations of Russian Coastal Seas

1345: Pfirman - (10/5)

Links Between Changes in Atmospheric Conditions and the
Fate of Contaminants Transported by Sea Ice

CONNECTIONS TO LOWER LATITUDES (Pfirman)

1400: Overland - (10/5)

Changes in the North Pacific Atmospheric Conditions

1415: Quadfasel and Dickson - 15/5

Decadal Variability in the Nordic Seas and its Impact on the Hydrography of the Atlantic Layer in the Arctic Ocean,

Arctic Warming from A European View

1435: Pisarev - (10/5)

Comparison of Eastern Arctic Oceanographic Data from the 90s with Historical Data

1450–1510 Break

1510: Pavlov - (10/5)

Baring Strait Salinity Since the 1930s

1525: Top - (10/5)

The Temporal Variation of Tritium

1540: McPhee - (10/5)

The SHEBA '97 Mixed Layer compared to past Measurements

1555: Whitledge - (10/5)

SCICEX'97 Preliminary Results

1610–1700: Group discussion and plans for Day 2

TIME SERIES OBSERVABLES, and KEY QUESTIONS

Define disciplinary Working Groups for Time Series Observables
(Ocean, Ice, Atmosphere, and Terrestrial/Glaciological).
Each group will

1) Identify key observables to track Arctic Change
   including time and space resolution.

2) Identify possible operational methods to make key measurements:
   ex ships, air surveys, etc.

3) Identify possible proxy observation and historical databases
   and related lower latitude coupling.

4) Identify key questions or hypotheses to be tested with models
   or special experiments.

1700: Adjourn

Study of the Arctic Change Workshop

Day 2 - Nov. 11, 1997

Hardisty Conference Room
6th Floor
Applied Physics Lab
University of Washington
1013 NE 40th St
Seattle, Washington

0800: Coffee and Pastries

RESOURCES and METHODS (Morison)

0830: Ledbetter - (10/5)

The ARCSS Program

0845: Tanis and Timokhov - (10/5)

Development of the EWG U.S.-Russian Joint Arctic Atlases

0830: Shimada - (10*)

Buoy Observations in the Beaufort Sea

0840: Mikhalevsky - (10*)

Arctic Climate Observations Using Underwater Sound (ACOUS)

Fram Strait Acoustic Monitoring for Arctic Ocean Climate Study

0900: Zhao - (10*)

New Chinese Initiatives in Arctic Research

0910: Neshyba - (10*)

Remote Sensing of Clouds

* Hold methods questions until working groups

TIME SERIES OBSERVABLES, and KEY QUESTIONS WORKING GROUPS

0920: Separate into Observables Working Groups defined on Day 1. Get room assignments.

0925: Break

0940–1200: Observables Working Groups meet and prepare short summaries and matrix of questions, observations, scales, and possible methods.

1200–1300: Lunch

1300–1340: In plenary Observables Working Group reports

Representatives present results in matrix form (10 min each). Everyone comments

1340–1430: Discussion; Form interdisciplinary Key Question Working Groups, each focusing on key questions growing out of plenary discussion of issue (4) in the morning.

Example Questions:

- Role of atmospheric forcing in changing ocean circulation?
  Role of River Runoff in Changing Salinity?
- Atlantic Water warming due to changed inflow or changing heat flux in basin?
- Coupling to NAO?

Question Working Groups will:

1) Identify key observables and strategies to answer the question. Include time and space resolution required.

2) Identify possible proxy observation and historical databases and related lower latitude coupling.

3) Identify model tests or special experiments to answer questions.

1430: Break

1445–1630: Question Working Groups meet and work on short summaries of questions, observations, scales, methods.

1630-1730: In plenary Question Working Group Presentations

Representatives present results in summary form for each question. (10 min each)
- Comments from the floor

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Study of the Arctic Change Workshop - Day 3

Nov. 12, 1997

Room 312
South Campus Center
University of Washington
Seattle, Washington

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0800–0830: Coffee and Pastries

PLANNING ISSUES

0830: Morison (15/5)

A Strawman Plan for the Study of the Arctic Change

0850–1020 Roundtable discussion of program planning issues such as:

- Long time series observations vs 2-year funding cycle

- Connection with national and international programs
- Costs and funding avenues
- Balance of observations, modeling, process studies

- Logistics/operations/methods with possible short presentations on funding agencies, parent programs and allied programs:

- NSF-OPP and ARCSS (Pyle, Lebetter)
- ARCSS-OAII and SBI (Grebmeier)
- ONR (Briscoe)
- ACSYS and the AOSB Freshwater Balance Project (Colony)
- CLIVAR (Martinson)
- EOS (Rothrock)

1020–1040 Break

1040–1200: Break into Planning Issue Working Groups to discuss and summarize thoughts on issues raised in morning session

1200–1300: Lunch

1300–1400: Continue Planning Issue Working Group sessions

1400–1500: In plenary Planning Issues Working Groups make brief reports. Morison, Aagaard, and Steele solicit any additional writing assignments for Workshop Report, and discuss schedule for further action

1500–1600: Presenters turn in copies of viewgraphs. Working group representatives turn in Observations Working Group, Key Questions Working Group, and Planning Issue Working Group summaries

1600: Workshop Ends

Appendix D
Abstracts of Presentations

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Atlantic Water Warming

Knut Aagaard

Polar Science Center, Applied Physics Laboratory,
University of Washington, Seattle

Jim Swift

Scripps Institute of Oceanography
University of California, San Diego

In the late 1970s and early 1980s oceanographers found that a coherent view could be assembled from a large number of reports of much fresher water than expected in various domains in the northern North Atlantic and Nordic Seas. The evidence was so compelling, and the effects so large and widespread, that this freshening event became known as the Great Salinity Anomaly.

This event fostered a much improved view of how the Arctic Ocean exports buoyancy through the Canadian Archipelago and the Nordic Seas, and how shifts in that export can affect production of dense waters in this part of the global ocean climate system.

In conjunction with these observations of changes in the freshwater part of the Arctic Ocean's contributions to the water mass spectrum, there were observations in 1981 of a cooling and freshening of the densest waters in the northern North Atlantic, which are fed from the Denmark Strait overflow.

This turned out to be tied to the after-effects of the Great Salinity Anomaly. But it was also recognized that similar shifts in deep water properties should have been ongoing. Some impressive detective work by Lazier has, in fact, established that in the northwest Atlantic average properties on the deep isopycnal surfaces associated with the Denmark Strait Overflow have been fluctuating on "decadal" time scales, the largest in size of any deep water property shifts yet observed in the principal ocean basins.

The point here is that these observations in the North Atlantic have come in advance of our rather recent understanding of the role of the Arctic Ocean in production and modification of the dense waters which eventually contribute to the Arctic outflows. So perhaps it is not surprising that with the exception of the signal of the Great Salinity Anomaly we have not yet been able to establish a clear link between fluctuations in the properties of the overflow water and specific variability or change within the Arctic Ocean and Nordic Seas.

This is relevant to Arctic change because changes in water properties in the Arctic Ocean are coming at the same time that we are trying to decipher the overall role of the Arctic Ocean in the North Atlantic ocean climate system. We are studying a system that is changing before our eyes, not conveniently "standing still" long enough for us to come to grips with its present manifestation, let alone with what it has been doing in the recent past or will be doing in the not-so-distant future.

The recent temperature changes in the Atlantic Layer are more broad than a simple warming of the temperature maximum. Comparison of potential temperature profiles across the Eurasian slope of the Lomonosov Ridge in 1991 and 1994 shows a warmer and shallower core to the temperature maximum in 1994 than in 1991, and the effects of the warming are seen from the top of the thermocline to about 2000 m. Also the temperature gradient in the thermocline is higher in 1994.

The potential temperature-salinity correlation through this warm anomaly shows that the differences

are not just in the thermal fields, and in fact exhibit some complexity. For example, there is an intermediate range under the temperature core that is actually colder (in theta-S space) in 1994 that in 1991.

The sigma-theta profiles for those same 1991 and 1994 sections show that from 200 to 1500 m the density was less in 1994 than in 1991. This difference makes the 1994 0/1000 dynamic height higher than in 1991 by about 2 dynamic centimeters, which is about the same as the total dynamic relief across this current in either year.

This is but one piece of evidence telling us about the structure and geography of recent temperature shifts. Taking one step slightly back, and looking at the 1994 Arctic Ocean section as a whole along a track from the Chukchi boundary of the Canadian Basin to the central Nansen Basin, we crossed a temperature maximum near 1°C four times over the Chukchi boundary and Mendeleyev Ridge in addition to the Lomonosov Ridge crossing of the temperature maximum. This region has been visited so rarely in the past that it is difficult to know precisely the size of the warming signal, but the warming here is at least 0.2°C.

There is reasonably clear evidence from past physical and tracer studies that changes in the water properties of the upper layer in the Iceland and Greenland gyres are transmitted into the deep North Atlantic. But with evidence growing that the Atlantic Layer also plays a strong role in overflow water production, what these changes imply for the role of the Arctic Ocean in modulating the properties in the dense outflows to the North Atlantic is still largely ahead of us to determine.

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Retreat of the Cold Halocline Layer in the Arctic Ocean

Michael Steele

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Timothy Boyd

College of Oceanic and Atmospheric Sciences, Oregon State
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We present a comparison of Arctic Ocean hydrographic data sets from the 1990s, with a focus on changes in the upper few hundred meters of the Eurasian Basin. The most recent observations discussed here were collected during the spring 1995 Scientific Ice EXpedition (SCICEX'95), the second in a series of scientific cruises to the Arctic Ocean aboard U.S. Navy nuclear submarines. Although the 1990s have seen an abundance of synoptic cruises to the Arctic, this was the only one to take place in winter/spring conditions. Other data considered here were collected during the first SCICEX cruise in summer 1993 (SCICEX'93) and during an icebreaker cruise to the Eurasian Basin in summer 1991 (*Oden*'91). A new Russian-American winter climatology is also used as a reference. These comparisons reveal that the Eurasian Basin "cold halocline layer" has retreated during the 1990s to cover significantly less area than in previous years. Specifically, we find a retreat from the Amundsen Basin back into the Makarov Basin; the latter was the only region with a true cold halocline layer during SCICEX'95. Changes are also seen in other halocline types and in the heat content and depth of the Atlantic Water layer. Since the cold halocline layer insulates the surface layer (and thus the overlying sea ice) from the heat contained in the Atlantic Water layer, this should have profound effects on the surface energy and mass balance of sea ice in this region. Using a simple mixing model, we calculate maximum ice–ocean heat fluxes of 1–3 W m^{-2} in the Eurasian Basin, where during SCICEX'95 the surface layer lay in direct contact with the underlying Atlantic Water layer. The overall cause of water mass changes in the 1990s might have been a shift in the atmospheric wind forcing and resulting sea ice motion during the late 1980s, which we speculate influenced the location where fresh shelf waters flow into the deeper basins of the Arctic Ocean. Finally, we discuss two different mechanisms that have been proposed for cold halocline water formation, and propose a compromise that best fits these data.

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Comparison of Hydrographic Measurements in the Nansen/Amundsen Basin Between 1991 and 1996.

Dr. Ursula Schauer and Göran Björk

Departement of Oceanography
Goteborg University, Sweden

The *Oden* made its pioneering voyage across the Nansen Basin to the North Pole in 1991. The *Polarstern* repeated much of this cruise track in 1996. A comparison indicates the water in the Barents Sea has become less saline, and the halocline in the basin is deeper and saltier. The cold halocline appears to be disappearing with the shoaling and warming of the Atlantic Water.

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Comparisons of Modern Data with ARLIS-II

Rich Pawlowicz

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Temperature profiles from ARLIS-II, a drifting ice camp north of Greenland occupied in 1964, and other ice stations from that era are re-examined in light of current ideas about the circulation of the Atlantic Water layer in the Arctic. The analysis shows the presence of sharp fronts in the Atlantic Water core in the Eurasian Basin that are aligned with bathymetry. Large temperature changes have occurred over the Lomonosov Ridge over the last decade. Conversely, the spatial gradients of temperatures over the eastern end of the Alpha Ridge in the Canadian Basin are fairly small, and temperatures themselves show little interannual change over a 40-year period up to the early 1990s.

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Modeling Fresh Water Sources, Their Distribution, and Sinks in the Arctic Ocean

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The stratification of the Arctic water masses, being mainly determined by the distribution of salinity, is a result of the combined effects from river runoff, seasonal ice melt, and the inflow of relatively fresh water of Pacific origin through Bering Strait. With the exception of Mackenzie River, fresh waters from all major rivers, including the inflow through Bering Strait, enter the Arctic at the wide and shallow shelf region between the Chukchi and the Barents seas. These waters are mixed and distributed over the shelves by the joint action of winds and tides, eventually enter the large-scale circulation of the deep basins, and then exit the main Arctic through Fram Strait and the Canadian Archipelago.

Studies of the freshwater circulation on the shelf, its communication with the deep basins, and its effect

on the large-scale surface circulation and on convective activities in the subpolar seas are needed to gain the most new insights relevant to climate change.

A high-resolution coupled Arctic Ocean and sea ice model has been used to address some issues related to the freshwater budget in the Arctic. The model has been integrated for +200 years using repeatedly 1990–1994 realistic atmospheric forcing from ECMWF. Analysis of early model results shows a good agreement with earlier estimates of the exchanges between the Arctic and North Atlantic (Maslowski et al., 1997) and with the large- and small-scale features of the sea ice circulation (Zhang et al., 1997).

The Parallel Ocean Program (POP) of Los Alamos National Laboratory (Smith et al., 1992), which has been adapted to the Arctic Ocean, uses a free-surface approach and allows multiple tracers. The latter feature of the model is ideal for numerical studies of the freshwater circulation and the dispersion of contaminants from the arctic rivers and shelf regions. Multiple tracers can also be used to address issues related to distribution of Atlantic and Pacific waters in the Arctic. The free surface approach combined with the high resolution (18 km and 30 levels) allows a realistic unsmoothed bathymetry, including the Canadian Archipelago and other small islands, which are of special importance for a study of the freshwater circulation and its outflow into the North Atlantic.

Two separate multiple-tracer experiments have been designed and integrated for ~50 years each, in collaboration with a group of colleagues from Lamont-Doherty Earth Observatory led by Peter Schlosser. The first experiment, called the passive river tracer experiment, simulates distribution of dye-type multiple tracers; a realistic annual cycle of daily mean volume concentration at each source (i.e., the Mackenzie, Dvina, Pechora, Ob, Yenisey, Kotouy, Lena, Indigirka, and Kolyma rivers and the Bering Strait inflow) is prescribed from observations (P. Becker and A. Roach, private communication). This approach is useful for studying the distribution of such tracers as pollutants and nutrients, which are being (passively) advected and mixed by ocean currents and eddies. In the second experiment, called the active river tracer experiment, each river source has prescribed realistic annual cycles of daily mean fluxes of heat and salt as a function of daily mean volume concentrations. Each source actively contributes to the ocean density fields and at the same time can be traced separately throughout the Arctic Ocean and into the North Atlantic.

Surface distributions of the passive and active tracers from Lena River after a simulation of 20 years in response to conditions representative the first half of the 1990s show the Beaufort Gyre being significantly decreased and the central Arctic having a cyclonic type of circulation similar to that discussed by Proshutinsky and Johnson (1997). The Transpolar Drift is absent over the Lomonosov Ridge, and its new position (if we continue to define this feature along the eastern part of the Beaufort Gyre) is now located somewhere over the Mendeleyev-Alpha Ridge. The difference in tracer distributions between the passive and active experiments shows the sensitivity of the large-scale upper ocean circulation to the water mass stratification. Results from those two experiments are presented, including estimates of residence time of water originating from different sources and comparisons with observational data (e.g., Schlosser et al., 1994; Jones et al., 1997; McLaughlin et al., 1996). Animations of active tracer fields at different depths (available from a recent CD-ROM) will be also shown.

The atmospheric forcing plays the major role in driving the upper ocean and sea ice circulation. Zhang and Hunke (this workshop) describe a difference in patterns of sea ice circulation between the early 1980s and the 1990s (with the former one representing climatology), using the new ECMWF re-analyzed atmospheric fields for 1979–1993 to force the coupled Arctic model. In the ongoing freshwater experiment this new ECMWF product is being used to study the freshwater balance, the upper ocean circulation, and its variability during the last 18 years. Some new results from this simulation will be shown.

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How Arctic Property Distributions Change in an (Nearly) Unchanging Circulation

Greg Holloway

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How does climate-forced change come into the Arctic Ocean? It occurs in part by altered characteristics of inflowing Atlantic Water (by Fram and Barents branches), and in part by changes of thermal and freshwater forcings over the Barents sea and Siberian shelves. Changes in wind forcing are reflected in altered circulation in and above the halocline. Below the halocline, I believe that circulation is remarkably Unchanging. The overall pattern is fixed by topography, and circulation changes are quite localized to fewer than a half dozen key diffluences (off northern Norway, at Fram Strait, at the Laptev-Lomonosov juncture, where the Mendeleyev join the Siberian margin, and about the Lincoln sea). At these diffluences, the relative fractions of flow apportioned to diverging branches can be modified by interaction with changing suprahalocline circulation and with remote (lateral) buoyancy forcing.

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Numerical Simulation of the Arctic Ocean Ice and Water Dynamics

A. Proshutinsky, I. Polyakov, and M. Johnson

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University of Alaska, Fairbanks

This research seeks to examine the major mechanisms of Arctic variability at decadal scale using obser-vational data and numerical models. The major goal of the research is to document robust variations of the arctic system and the most important factors maintaining variability and interdependence of the processes occurring in the Arctic.

We identify two regimes of the arctic system decadal variability which correspond to the anti-cyclonic and cyclonic circulation of the arctic atmosphere and polar ocean; these regimes are associated with "cold and dry" and "warm and wet" atmospheres and with "cold and salty" and "warm and fresh" ocean water, respec-tively. Shifts from one regime to another are forced by changes in the location and intensity of the Icelandic low and the Siberian high. Wind-driven ice and water motion in the Arctic alternates between anti-cyclonic and cyclonic circulation, with each regime persisting for 5–7 years (period is 10–15 years). We do not know very well what processes are responsible for these different atmospheric circulations, but we try to identify a set of distinguishing features that can characterize each regime of the arctic system. We test the idea of two regimes of circulation using observational data and 2-D and 3-D coupled ice-ocean models.

For the first time, the vertically averaged currents and ice drift in the Arctic Ocean from 1946 to 1993 have been simulated using a two-dimensional, barotropic model that includes frictional coupling between the ocean and ice and is driven by the atmosphere, river run-off, and an imposed but realistic sea level slope between the Pacific Ocean and Atlantic Ocean. The model has a spatial resolution of 55.5 km. The atmo-spheric forcing fields were obtained from NCAR (daily gridded sea surface pressure data). We have compared the modeled ice motion with the data from 630 drifting surface buoys and 31 drifting "North Pole" stations for the period 1953–1993. The good agreement between modeled results and observed buoy drift suggests a generally accurate reproduction of the observed ice circulation over basin scales at periods from days to months. The correlation coefficient between the simulated and observed buoy drift velocities with 5-day averages is more than 0.75. The 2-D model results show two wind-driven circulation regimes in the Arctic:

(a) an anticyclonic ice drift is observed in the model results during 1946–1952, 1958–1963, 1972–1979, 1984–1988;

(b) a cyclonic ice drift is observed in the model results during 1953–1957, 1964–1971, 1980–1983, 1989–1993. It is expected that during 1994–1995 the ice drift is cyclonic too.

The existence of inter-annual variations of environmental characteristics in the Arctic is well docu-mented in the scientific literature. We have compiled a number of extensive oceanic, terrestrial, and meteoro-logical data sets collected throughout the Arctic over the last 50 years. Analyses of these data and results of previous investigations demonstrate the existence of variations in these parameters with a period of 10–15 years. The river run-off, permafrost temperature, ice cover of the Bering Sea, temperature of the intermediate cold water layer southeast of Kamchatka, index of the North Atlantic Oscillation, water temperature in the Icelandic Sea, sea ice anomalies in Davis Strait, dynamic heights in the center of the Beaufort Gyre, and many other environmental parameters have a similar period of oscillation which is consistent and confirms our conclusion about two major regimes in the arctic system variability.

We cannot yet demonstrate existence of two regimes based on observed temperature, salinity, and ocean

currents in the Arctic Ocean. To compensate for the lack of observational data we analyze results of numerical experiments using a 3-D dynamical/thermodynamical model of the Arctic Ocean. The experiments were specially designed to test the existence of two regimes.

Two 15-year simulations were carried out for 1987 and 1992, which are typical years for the anticyclonic and cyclonic atmospheric regimes, respectively. We analyzed seven major parameters characterizing the state of ice and water conditions in the Arctic Ocean for each circulation regime. They are ice thickness, ice concentration, ice drift, sea surface heights, water currents, temperature, and salinity.

Analyses of available observed data and results of numerical experiments reveal a significant difference between environmental parameters during the two regimes of the arctic system variability. These regimes not only cause changes in the ice drift and ocean surface currents, but are also responsible for the major changes in the thermohaline structure of the upper ocean. During the anticyclonic regime, the "winter" conditions— cold and dry atmosphere, increased ice thickness and ice concentration, increased water salinity, and decreased water temperature—prevail over the seasonal cycle. During the cyclonic regime, the "summer" arctic conditions—warm and wet atmosphere, decreased ice thickness and ice concentration, decreased water salinity, and increased water temperature—prevail.

Here we tested only wind-driven effects influencing the Arctic Ocean. It is also necessary to take into account changes in atmospheric climatology. Additionally, the values of salt, heat, and mass transport through the open boundaries of the Arctic Ocean are different for the years with a cyclonic and anticyclonic circulation. We continue to investigate the role of these factors in ocean and ice dynamics and thermodynamics. There is a significant lack of data for the years with a cyclonic regime of circulation and for summer in the central Arctic. High-resolution modeling and special field observations designed for model experiments are needed in the Arctic.

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Recent Environmental Change in the Russian Maritime Arctic

Lawson W. Brigham

Scott Polar Research Institute, University of Cambridge

The deep waters and shallow coastal seas of the Arctic Ocean are undergoing significant environmental changes. Satellite passive microwave (PMW) data have already shown that the extent and total area of sea ice in the Arctic Ocean have been decreasing since 1978. A recent analysis by Cavalieri et al. (1997) of PMW data for November 1978 through December 1996 showed the areal extent of Arctic sea ice decreased by 2.9 ± 0.4 percent per decade. Record or near-record minimum areas of Arctic sea ice have been observed in 1990, 1991, 1993, 1995, and 1997. These changes have also been observed on a regional scale in discharge data for the Siberian rivers and sea ice conditions for the Russian Arctic coastal seas.

Historical analysis of mean monthly discharges from the Lena River (1935–1990) shows maximum flows in June and July with discharges decreasing through October. Discharges from November through May are characteristically minimal. However, a review of Lena River data (1935–1990) for May-June-July reveals large discharges in May in the late 1980s. These anomalous flows have also been detected in PMW data for sea ice conditions in the Laptev Sea.

The PMW record (sea ice concentration maps) for mid-May in the Laptev Sea (1979–1995) provides a glimpse of the size of the Great Siberian Polynya. In 7 of the 9 years from 1979–1987, the polynya was less than $60,000$ km^2 in size. In all but one year from 1988–1995, the size of the polynya was greater than $60,000$ km^2. U.S. National Ice Center (NIC) sea ice data (1972–1994) show no overall trend in the extent of sea ice in the Laptev Sea. However, the data for the East Siberian Sea show a significant reduction in sea ice extent and coverage since 1987.

These changes in the environment of the Russian maritime Arctic are consistent with other recent changes

throughout the Arctic Basin. The shallow shelf seas of the Russian Arctic can provide visible evidence of global and regional change, primarily through the use of satellite passive and active microwave systems.

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Observational Evidence of Recent Changes in the Northern High Latitude Environment

(From a paper in preparation by Serreze et al.)

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Results from numerous observational studies indicate change in the northern high-latitude environment over the past several decades. Prompted by concern over anthropogenic influences on global climate and model predictions that indicate an amplified response of northern high latitudes to increased concentrations of greenhouse gases, we present a synthesis of these observations.

Land station records for 1966–1996 show air temperature increases over northwest North America and Eurasia, largest for winter and spring, with compensating cooling over eastern Canada and southern Greenland. Arctic Ocean records (1961–1990) from the Russian "North Pole" (NP) drifting ice stations show significant warming trends for the months May and June and for summer as a whole. Warming is also observed in records for 1979–1995 that combine the NP data with observations from drifting buoys and coastal stations. Reconstructions from proxy sources imply that 20th century Arctic temperatures are the highest over the past 400 years.

Satellite records available since 1979 indicate a slight but significant downward trend in sea ice extent, dominated by late summer ice reductions along the Eurasian coast in the 1990s. Results from oceanographic cruises indicate warming and increased areal extent of the Arctic Ocean's Atlantic layer (200–400 m depth). Negative snow cover anomalies have characterized both North America and Eurasia since the late 1980s. Precipitation has increased over northern high latitudes since 1900, especially during autumn and winter. On the basis of records since the mid 1940s, the mass balance of small Arctic glaciers has been generally negative, paralleling a global tendency. Observations point to increased permafrost temperatures in Alaska and Russia

but lower temperatures over eastern Canada. Satellite data (1981–1991) indicate increased plant growth in the Northern Hemisphere, largest from 45–70°N. Alaskan records also reveal that because of warming and drying, the tundra has changed from a net sink of atmospheric carbon dioxide to a net source. These changes are paralleled by a northward migration of the tree line.

Taken together, these results paint a reasonably coherent picture of change, but their interpretation as "fingerprints" of greenhouse warming presents a number of problems. Although the general spatial pattern of temperature change agrees with model results, predictions that the maximum warming will occur in autumn and winter contrast with the observations showing that the largest changes occur in winter and spring (summer for the Arctic Ocean). Furthermore, much of the observed warming in recent decades (hence changes in many other variables) can be explained in terms of atmospheric circulation. This includes a generally positive phase of the North Atlantic Oscillation, increased cyclone activity over the central Arctic Ocean, and extratropical responses to tropical sea surface temperature forcing. Increasing solar insolation and decreased volcanic activity have also played roles.

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"Arctic Warming" During 1920–1940: A Brief Review of Old Russian Publications

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1. The idea of Arctic Warming during 1920–40 is supported in Russian publications by the following facts:

   - retreating of glaciers, melting of sea islands, and retreat of permafrost
   - decrease of sea ice amounts
   - acceleration of ice drift
   - change of cyclone paths
   - increase of air temperature
   - biological indications of Arctic warming
   - ease of navigation
   - increase in temperature and heat content of Atlantic Waters, entering Arctic Basin.

2. The reasons of Arctic Warming (according to old Russian publications).

3. Cooling in 1950–1960.

Rretreating of glaciers, melting of islands, and retreat of permafrost

During the *Persey* cruise in 1934 Zubov noticed that the glaciers of Jan-Mayen and Spitsbergen were considerably reduced, relative to their sizes adduced in British sailing directions of 1911. Retreat of glaciers was observed also at Spitsbergen, Franz-Joseph Land, and Novaya Zemlya. The ice bridges between some of Franz-Joseph islands melted.

Alman explored the glaciers of Spitsbergen in 1934 and came to the conclusion that they were melting. The observations of 1935–1938 showed that Iceland glaciers were melting too.

According to Sumgin, the south boundary of permafrost shifted to the north by 40 km during 1905–1933.

The disappearance of Vasilievsky Island in the Laptev Sea and washing away of the Lyakhovsky islands were phenomena of the same type.

The decrease of sea ice amounts in 1920–1940

The area of ice in the Greenland Sea in April–August of 1921–1939 was 15–20% less than in 1898–1920 (data of Karelin).

In the Barents Sea the area of ice was 12% less in 1920–1933 than in 1898–1920 (data of Zubov).

Vise pointed out that since 1929 the south part of the Kara Sea in September was free of ice, while in 1869–1928 the possibility of meeting ice there in September was about 30%.

The polar ice very often came close to the coast of Iceland in the last century and in the beginning of this century. During 1915–1940 the situation changed: no ice was observed in that region; negligible amounts of polar ice were noticed there only in 1929.

The thickness of ice determined during the *Fram* cruise was 655 cm; during the *Sedov* cruise it decreased to 220 cm (the reason for this was more intensive summer melting of ice).

Before Arctic warming, the strait of Jugorsky Shar froze near the 24th of November, but in 1920–1937 it became frozen two months later—in January.

According to Vise, near Dicson and Franz-Joseph Land the amplitudes of tides increased by 20–30% as a result of a decreasing amount of ice.

The acceleration of ice drift

In spite of the fact that the amount of Arctic ice transported to the Greenland sea increased (established by Soviet expeditions in 1920–1940), the amounts of ice in that sea decreased because of the influence of factors promoting destruction and melting of ice:

- an increase in the velocity and temperature of the Norway and Spitsbergen currents

- an increase in the velocity of winds, connected with common intensification of atmospheric and hydrospheric circulation.

The velocity of the drift of North Pole station in 1937 was 2.4 times greater than the velocity of *Fram*'s drift.

Change of cyclone paths

Vise noticed that cyclones' paths changed. They moved significantly northward from their paths before the Arctic warming and so the wind regime changed: After 1920 the prevailing winds in Jugorsky Shar changed from cold east winds to warm southwest winds.

The increase of air temperature

According to Vise, in Varde (northeast of Norway) since 1918 the average annual air temperatures were higher than the average air temperature of the previous century (the exception was 1926, when the average temperature was lower by 0.2°C).

Beginning with 1930, not one negative anomaly of average yearly or monthly temperature was observed in the whole Arctic sector from Greenland to Cape Tcheluskin, and during the same time the positive anomalies reached significant values: 1934/35 ± (4–10)°C, November in Spitsbergen ± 10°C.

Vise noticed, that the average annual temperatures observed during the *Fram* cruise (for the period of November 1893–August 1895) were lower by 4.1°C than those observed during the *Sedov* cruise (for the period of November 1937–August 1939), although the *Fram* and *Sedov* locations more or less coincided

(*Fram*, 81°59'/113°26'; *Sedov*, 82°43'/121°30).

At the station Tikhaya (Franz-Joseph Land), temperatures below 40°C were never observed after 1929. But 10 expeditions in the archipelago before 1929 observed such temperatures every winter, except 1896.

Biological indications of Arctic warming

Knipovich, in 1921, was the first who paid attention to the changes of Arctic fauna. Marketable species of fish spread to the north after the beginning of the 20th century and fisheries in the north became more intensive.

Some benthos species spread to the north.

The ornitofauna of the Arctic region changed: some species of birds (White Gulls) left their places of habitation, and some southern species were noticed in the far north (swans in Iceland).

Uspensky stated that 40–50 species of birds moved to the North during 1890–1930.

Ease of navigation

The sailing conditions in the Arctic region became much more favorable in 1920–1940. This can be proved by the following cruises:

- *Knipovich*, 1932 (round Franz-Joseph Land)

- *Sibiryak*, 1932 (round Severnaya Zemlya)

- sailing of non-icebreaking ships along North Sea Route in 193—no ice met

- possibility for non-icebreaking ships to double Novaya Zemlya every year since 1930.

The severe conditions of navigation in previous years can be proved by the following cruises:

- In 1912, the ship *Foka*, a member of the Sedov expedition, could not reach Franz-Joseph Land.

- In 1912, the ship *St. Anna*, a member of the Brusilov expedition, was trapped in ice near Yamal and carried out with the ice to the central Arctic.

- In 1901, the icebreaker *Ermak* failed to double Novaya Zemlya.

Increase of temperature and heat content of Atlantic Waters entering the Arctic Basin

The waters of Nordcape Current (Zubov) became warmer by approximately 0.7°C in 1940–45 compared to the beginning of this century.

In the regions adjacent to Spitsbergen and Franz-Joseph Land, the lower boundary of the cold intermediate layer rose from 150–200 m in the beginning of the century to 75–100 m in 1940–45.

Not one station made during the *Fram* cruise showed Atlantic Waters exceeding a temperature of 1.13°C, but in 1935 (*Sadko* cruise) Zubov observed Atlantic Water temperatures reaching 2.68°C, and in 1938 (*Sedov* cruise) even in the places situated to the north and east of *Fram*'s drift (it must be colder there) the temperatures reached 1.8°C.

According to Shokalsky, "the temperature of surface waters of the Gulfstream steadily rises from the beginning of our century." The increase of surface waters' temperature can also be seen (Shokalsky) in the

other regions of the ocean subjected to the influence of the Gulfstream and the Atlantic Current.

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Variability in Deep Exchange Between Eurasian and Greenland Basins: Evidence from Stable Tritium

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Stable tritium (tritium + radiogenic helium-3) concentrations estimated from seven stations occupied between 1979 and 1993 in deep waters in the Eurasian Basin and northern Fram Strait indicate a significant decrease in 1993. A box model, on the other hand, predicts a slow and steady decline with time owing to deep mixing and diffusion. Model results simulate the Greenland Sea and Eurasian Basin deep water observations reasonably closely up to the early 1990s. When the exchange parameters are readjusted to simulate the decrease in stable tritium in deep Eurasian Basin water, the deep exchange between the Greenland Sea and Eurasian Basin is enhanced, i.e., occurs over a shorter time scale. This is most likely in response to the reduced/ceased deep water formation in the Greenland Sea in the early 1980s. The model also predicts a trend in which the stable tritium concentration in the deep Eurasian Basin mimics that in the Greenland Sea with a time lag of 8 years. These time periods are very close to those indicated by actual tritium/helium-3 dating.

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SHEBA'97 Mixed Layer Compared With Past Measurements

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During the initial SHEBA (Surface Heat Budget of the Arctic) deployment phase in October 1997, multiyear ice near the center of the Beaufort Gyre, an anticyclonic ocean circulation feature over the Canadian Basin of the Arctic Ocean, was anomalously thin. The upper ocean was also both warmer (relative to freezing) and substantially less saline than in previous years. The total salinity in the upper 100 m of the water column, compared with conditions observed in the same region during the Arctic Ice Dynamics Experiment (AIDJEX) in 1975, is equivalent to an excess surface input of about 2.4 m of fresh water. Heat content (relative to freezing) has increased by 67 MJ m^{-1}.

During AIDJEX the seasonal change in salinity over the melt season implied a melt equivalent to about 0.8 m of fresh water. An analogy with the seasonal progression observed during AIDJEX suggests that as much as 2 m of freshwater input may have occurred during the summer of 1997, with the most likely source being ice melt resulting from decreased ice concentration and lower aggregate albedo early in the summer in

the classic albedo-feedback scenario. The phenomenon may be associated with changes in the atmospheric circulation. Unchecked, the pattern could lead to a significantly different sea-ice regime in the central Arctic.

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Buoy Observations in the Beaufort Sea

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Features of the ocean circulation in the Beaufort Sea were investigated using ADCP data obtained from a Beaufort Gyre Ice-Ocean Environmental Buoy (BG-IOEB) during 1992–1994. There were three major results. The first was the spatial distribution of eddy kinetic energy. On the flat and deep Canadian Basin off Alaska, the circulation was governed by mesoscale eddies with their maximum activity in the cold halocline layer. In contrast, on the Northwind Ridge and Chukchi Plateau the activity of the mesoscale eddies considerably weakened, and the circulation was governed by the seafloor topography from the upper cold halocline layer to the Atlantic Layer. This implied that the eddy kinetic energy was converted into the energy of topographically trapped currents. The second was a correlation between the seafloor topography and the horizontal velocity in the Atlantic layer below the main pycnocline. Based on the first result, the eddy-topography interaction (Holloway, 1992) was considered to be an important driving force for the Atlantic Water intrusion along the shelf breaks or the rim of seamounts in the Arctic Ocean. The third was an intensification of both the barotropic and baroclinic current on the eastern slope of the Northwind Ridge. This intensification could be established through interactions between Rossby waves and seafloor topography. In addition, evidence of a current scattering around the small-scale submarine canyons and ridges on the Northwind Ridge and Chukchi Plateau was shown using the distribution topostrophy which was an indicator how the current was parallel to the bathymetry.

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Interannual Variability in the Fate of Sea Ice Exported from the Siberian Seas

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Large amounts of Arctic sea ice form over shallow shelves, are transported across the central basin, and are exported, primarily through Fram Strait and, to a lessor degree, the Barents Sea and Canadian Archipelago. Analysis of sea ice origins and fates shows that ice formed in the various seas tends to influence different areas of the perennial ice pack and marginal ice zone. Ice exported from the Kara Sea can melt in the Laptev Sea, Barents Sea, Svalbard region, or eastern parts of Fram Strait. Laptev Sea ice generally melts north of Svalbard or is advected through Fram Strait and into the East Greenland Current. Ice exported from the East Siberian Sea will be advected to the north and then continue southward with the East Greenland Current through Fram Strait or drift westward in the Beaufort Gyre along the Canadian Archipelago. But there are large seasonal and interannual variations in ice pathways. Sea ice exiting the Siberian shelf seas in 1981–1983 and 1989–1991+ tended to drift more toward the east than in other years. This easterly shift was reflected in the trajectories of East Siberian Sea ice, which is normally caught up in the Beaufort Gyre but exited through Fram Strait instead. Also, in 1989–1991 there was unusually strong advection of Kara Sea ice to the east, extending even past the New Siberian Islands. Such variations are important because they influence the fate of fresh water, organisms, carbon, nutrients, contaminants, sediments, and driftwood transported by the ice.

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Additional Pertinent Abstracts

Observed Linkages Between Eurasian Surface Air Temperature, the North Atlantic Oscillation,
Arctic Sea-Level Pressure, and the Stratospheric Polar Vortex

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The leading empirical orthogonal function of the wintertime sea-level pressure (or 1000-hPa height) field is more strongly coupled to surface air temperature fluctuations over the Eurasian continent than to the more widely publicized North Atlantic Oscillation (NAO). It resembles the NAO in many respects, but its primary center of action covers more of the Arctic, giving it a more zonally symmetric appearance. Coupled to strong fluctuations at the 50-hPa level on the intraseasonal, interannual, and interdecadal time scales, this mode can be interpreted as an equivalent barotropic surface signature of modulations in the strength of the polar vortex aloft. It is proposed that the zonal asymmetric surface air temperature and mid-tropospheric circulation anomalies observed in association with this mode are secondary baroclinic features induced by the land-sea contrasts. The same modal structure is mirrored in the pronounced trends in winter and springtime surface air temperature, sea-level pressure, and 50-hPa height over the past 30 years: parts of Eurasia have warmed by as much as several degrees, sea-level pressure over parts of the Arctic has fallen by 4 hPa, and the core of the lower stratospheric polar vortex has cooled by several degrees. These trends are interpreted as the

development of a systematic bias in one of the atmosphere's dominant naturally occurring modes of variability.

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Preliminary Biological and Chemical Oceanographic Evidence for a Long-Term Warming Trend in the Arctic Ocean (current materials of the SHEBA Ice Camp, Beaufort Sea)

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Both current observations and historical data lead to the tentative conclusion that the region of the Beaufort Sea currently occupied by the SHEBA ice camp is and has been experiencing a period of climate warming at least since the AIDJEX expedition of 20 years ago. The warming has led to biological and chemical changes in both the euphotic zone of the water column and the sea ice ecosystem.

Between 1975 and 1981 scientists from the Former Soviet Union (FSU) occupied the Beaufort Gyre (materials of the drifting station NP-22). A comparison of sea ice and upper water column data between then and now shows the following trends: (1) a startling decrease in >20-mm-sized sea diatoms and microfauna within the ice interior; (2) a marked increase in freshwater algae within the ice interior; (3) a currently depauperate cryopelagic community at the ice-water interface; (4) lower chlorophyll and nitrate-nitrogen concentrations in the sea ice and upper water column; (5) significantly lower salinities in the sea ice and upper water column than used to be typical for this region; (6) an ice ecosystem currently dominated by a microbial community composed of large, heterotrophic bacteria and <20-mm-sized photoautotrophic and heterotrophic protists including mostly flagellates and diatoms. Such a community is typical of an oligotrophic system living on recycled nutrients with very little new production—a rather untypical situation for a multiyear, sea ice ecosystem. Among the photoautotrophs are chlorophytes which are more typical of freshwater rather than marine systems. While this group is always present in the spring-summer melt water ponds on the upper surface of the ice, it is not normally a dominant component of the primary producer community in the interior of multiyear ice as it is now.

Comparisons of SHEBA data with AIDJEX data (Miles McPhee, this workshop) also show striking changes in the past 20 years, both in the average thickness of the sea ice and in the salinity of the underlying water column. The average ice thickness has decreased by 2 m in this region of the Beaufort Sea, and the upper 30 m of the water column are 2‰ less saline than 20 years ago. Currently, the upper 50 m have no measurable standing stock concentrations of nitrate-N, which is untypical for much of the Arctic Ocean. Obviously, vertical mixing is being inhibited by the lens of low-salinity surface water which is creating a very

stable and sharp pycnocline at around 30 m. It is our guess (we hope to examine this further) that the system above the pycnocline is primarily a freshwater/brackish system living on recycled nitrogen while the system below the pycnocline is using nitrate and thus depleting this nutrient in the lower euphotic zone. Our understanding of this region of the Beaufort Sea will obviously be increased as the SHEBA year progresses.

APENDIX E
Program Description For
Canadian Archipelago Throughflow (CAT)

prepared by

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Quantifying the freshwater budget of the Arctic Ocean is key to understanding Arctic Ocean variability. It is of central importance to understanding the global thermohaline flow and global climate. Sites and rates of deep convection in the Greenland-Iceland-Norwegian Sea are strongly influenced by the freshwater flux from the Arctic through Fram Strait and the Canadian Archipelago. The objective of the Canadian Archipelago Throughflow (CAT) program, prompted by agreement among ARCSS scientists on the need for multiple-year time-series in the Arctic, is to provide multiple-year data sets of the freshwater flux (and other oceanographic properties) using current-meter moorings deployed at the three relatively narrow straits in the Canadian Archipelago. These data and their derivatives could be used to constrain Arctic models, provide data on Arctic boundary conditions, provide direct evidence of variability in the Arctic Ocean, and further quantify the global freshwater budget. The need to measure the freshwater flux through the Canadian Archipelago is recognized in national and international science plans, but most recently at the ARCSS All-hands workshop in Virginia Beach from 8–10 May 1997, where measuring the freshwater flux through the Canadian Archipelago was determined as a key science issue by the working groups on Circulation of the Arctic Ocean (Chairs: K. Aagaard and T. Weingartner) and the Hydrological Cycle of the Arctic (Chairs: K. Falkner and L. Codispoti).

Oceanographic properties have been measured in the past at both Fram Strait and Bering Strait, but to date no long-term measurements exist to describe the heat and salt exchange through the Canadian Archipelago. The three main channels of the Canadian Archipelago are Kane Basin (bounded by Greenland and Ellesmere Island), Jones Sound, and Lancaster Sound. These channels are narrow and shallow enough to allow measurements with adequate horizontal and vertical resolution. Further, measurements at these locations would provide unambiguous estimates of the freshwater flux, in contrast to hydrographic programs carried out farther south where recirculation of and variations in the West Greenland Current increase the uncertainty of freshwater flux estimates.

The CAT program recognizes new evidence for long-term variations in the Arctic [Carmack and Aagaard 1996; Morison, 1996]. These variations may be strongly linked to the existence of two regimes of Arctic Ocean circulation based on the fifty-year modeling simulations and data analyses by Proshutinsky and Johnson [1997]. They describe two regimes of circulation: the typical anti-cyclonic circulation pattern that favors flow out through Fram Strait, and a cyclonic circulation which enhances flow out through the Canadian Archipelago. Thus, these circulation regimes drive variations in the freshwater flux out of the Arctic that could be observable in data from current-meter moorings deployed in the Canadian Archipelago. Variations in the freshwater flux rate between Fram Strait and the Canadian Archipelago are therefore measurable and would provide additional evidence for the phasing of the two regimes. Understanding this process is clearly relevant to ARCSS goals.

While decade-long time-series are desirable, a reasonable beginning is a four-year measuring program using approximately fourteen current-meter moorings. These could be deployed and begin collecting data within one year of funding. Three moorings would be deployed across Smith Sound in southern Kane Basin between Cape Herschel and Cape Hatherton (30 km), four moorings across Jones Sound between Devon

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Island and Coburg Island (40 km), and seven moorings across Lancaster Sound between Borden Peninsula and Cape Warrender (140 km). All would be deployed in year one, recovered and re-deployed in years two and three, and recovered finally in year four. Moorings would be equipped with RCM9 current meters and SEACAT temperature and salinity sensors. Selected moorings would be equipped with upward-looking sonars to profile ice. Other instruments could be placed on the moorings, depending on the needs of the broader science community.

Although CAT was conceived and designed as a stand-alone program, coordinating it with other ARCSS high-latitude programs would ensure retrieval of the most complementary data possible. In fact, the CAT program can be viewed as a key component of any high-latitude program focused on changes in the Arctic.

List of Acronyms

AIDJEX - Arctic Ice Dynamics Joint Experiment
AIRS/AMSU - Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit
AMRL - Antarctic Marine Living Resources
AO - Arctic Oscillation
AOS - Arctic Ocean Section
ARCSS - Arctic System Science
ARCSS-OAII - Arctic System Science - Ocean-Atmosphere-Ice Interaction
ARCUS - Arctic Research Consortium of the United States
AUV - Autonomous Underwater Vehicle
AVHRR - Advanced Very High Resolution Radiometer
CAT - Canadian Archipelago Throughflow
DFO Canada - Department of Fisheries and Oceans, Canada
EOF - Empirical orthogonal function
EWG - Environmental Working Group
GISP - Greenland Ice Sheet Program
HARCC - Human Dimension of Arctic Climate Change
IABP - International Arctic Buoy Programme
IARC - International Arctic Research Center
JAMSTEC - Japanese Marine Science and Technology Center
MODIS - Moderate Resolution Imaging
NAO - North Atlantic Oscillation
NIC - National Ice Center
NOAA - National Oceanic and Atmospheric Administration
NODC - Naval Oceanographic Data Center
NSF - National Science Foundation
PALE - Paleontology of Arctic Lakes
POP - Parallel Ocean Program
RADARSAT - Radar Remote Sensing Satellite
RGPS - RADARSAT Geophysical Processing System Working Group
SAT - Surface air temperature
SBI - Shelf Basin Interaction
SHEBA - Surface Heat Budget of the Arctic Ocean
SLP - Surface sea level atmospheric pressure
SMM/I - Special Sensor Microwave/Imager
SMMR - Scanning Multichannel Microwave Radiometer
TOVS - Tiros Operational Vertical Sounder
ULS - Upward Looking Sonar