HIGH-LATITUDE PROCESSES AND THE ICE COVERED OCEAN

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1 – INTRODUCTION

The high latitude oceans form an important component of the total climate system, not least because the polar and sub polar seas of both hemispheres are the formation regions for the deep water of the world's oceans. They thereby play a key role in the thermohaline circulation. The vertical overturning which regulates the thermohaline circulation is crucially affected by the buoyancy of the upper ocean layers. Atmospheric exchanges of heat and freshwater at the ocean have a direct influence on this though other factors are also involved, including advection of relatively saline water from the south by the Atlantic Ocean circulation in the northern hemisphere, ice shelf processes in the southern hemisphere and the role and influence of the high latitude hydrological cycle, especially the extent to which hydrological changes can influence thermohaline overturning in the context of climate change. Particular high latitude processes involved in this context include sea ice formation and melt, iceberg discharge, and northern hemisphere riverine input.

In this paper we consider the needs for sustained observations of the high latitude oceans, in particular the ice covered seas. In a companion paper Rintoul et al. (this volume), consider observational requirements for monitoring and understanding southern ocean variability so that, emphasis is mainly given here to the northern high latitudes, though in section 4 we give some complementary consideration to southern ocean issues from the perspective of the ice covered ocean. In the next section we consider recent evidence for ocean climate variability and change in northern high latitudes, identifying specific needs for sustained oceanic observations in this region

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in section 3. Sea ice is given explicit consideration in section 5. National and international programme aspects are touched on in section 6.

2 – RECENT CLIMATIC TRENDS AND VARIABILITY IN NORTHERN HIGH LATITUDES AND THEIR GLOBAL SIGNIFICANCE

2.1 – Recent evidence of Arctic change

For some time now, we have known or supposed that variability in the Arctic has some special role to play in the processes of global change. Polar amplification and feedback are recurrent themes in numerical climate modelling (e.g Manabe and Stouffer, 1993). However we have hitherto lacked many of the ocean time-series needed to demonstrate the basic features of long term hydrographic change within the Arctic Ocean.

This situation improved dramatically during the 1990s. First, there was a major increase in the ship-based ocean-observing effort, contributed both by surface ships. (Polarstern and Oden in 1987 and 1991, the first US/Canadian Trans-Arctic Section in the summer of 1994 aboard Polar Sea and Louis St Laurent, and three further Polarstern cruises in 1993, '95 and '96 were highlights), and by the almost-annual submarine surveys of the US SCICEX Program (1993-99) (http://www.ldeo.columbia.edu/SCICEX/) which has involved dedicated use of a U.S Sturgeon-class nuclear submarine for unclassified reseach in the Arctic ocean, including oceanographic and sea ice research. Second, the release of a vast military archive of ocean data supplied the improved ocean "climatology" (Environmental Working Group, 1997) against which the new data-sets might be compared for evidence of change. Third, whether we use the newly-described Arctic Oscillation (AO; Thompson and Wallace, 1998) or the North Atlantic Oscillation (NAO; Dickson et al, in press) as the more-appropriate index of Arctic climate, it seems clear that winter climatic forcing over the Arctic and its subjacent seas was at a century-long extreme state during the 1990s (Walsh, Chapman and Shy, 1996). This meant that when data and climatology were compared, the changes identified were spectacular and of a large-enough amplitude to be traceable through a gappy observing system and stand out against a still-shaky climatology. Three main changes in particular have characterised the period of the 1990s.

The first was a more intense and more widespread influence of Atlantic water than previously observed, with a warming and spreading of the Atlantic-derived sublayer across the Eurasian Basin (Quadfasel et al 1991; Anderson et al. (1994); Carmack et al 1995; Aagaard et al, 1996; Swift et al, 1997; Carmack et al, 1997; Morison et al, 1998 a,b and in press; Mikhalevsky et al. (1999); see also McLaughlin et al, 1996; Kolatschek et al, 1996). The inflow of Atlantic Water into the Arctic Ocean represents the northernmost extension of the poleward flow of warm waters within the Atlantic Ocean. During that northward flow, the warm waters are continually modified - transformed to colder, denser water masses - as they are exposed to the atmosphere. This heat in turn helps drive the atmosphere. The Atlantic waters entering the Arctic represent the main heat source for the Arctic Ocean (Aagaard and Greisman, 1975; Vowinckel and Orvig; 1970). The budget is closed by export of colder waters and sea ice back south to the North Atlantic, by loss of heat to the atmosphere, and by the change of heat storage in the Arctic water column and volume of sea ice.

The increasingly anomalous southerly airflow over Nordic seas that accompanied this change is held responsible for a progressive warming and perhaps a strengthening of the two streams of Atlantic water that enter the Arctic Ocean, across the Barents Sea shelf and along the Arctic Slope west of Spitsbergen. This is reflected in the winter NAO Index which increased from its lowest values of record (generally) in the 1960s to its highest-recorded values during the early 1990's (Dickson et al submitted). By the late-80s-early 90s, when the NAO reached its interannual and interdecadal maximum, the superposition of a short-term warming event on a long-term warming trend meant that both Atlantic-inflow streams were running between 1 and 2°C warmer than normal (Dickson et al in press; Grotefendt et al 1998). Adlandsvik's barotropic transport model (Adlandsvik, 1989; Adlandsvik and Loeng, 1991; Loeng, Ozhigin and Adlandsvik, 1997) suggests that the transport through the Barents Sea pathway may have increased by around a quarter at this time. We also have possible proxy evidence from sea-level records to suggest that the West Spitsbergen Current was similarly boosted. From an annual standard section across the West Spitsbergen Current at 76° 20' N, the warming of the inflow through Fram Strait is seen to be accompanied by a progressive freshening and decrease in density in the upper 500m since the 1960s. The indications are that freshening also affected the Barents Sea branch of the Atlantic Current (Dickson et al in press). Since the increasing NAO is associated both with a major increase in precipitation along the length of the Norwegian Atlantic, and with decreased winter production of sea-ice (Deser, Walsh and Timlin, 1999), a broadscale freshening throughout the Atlantic water domain is not unexpected. Entering the Eurasian Basin, Morison's comparison of SCICEX data with "climatology" (Figure 1, from Morison et al in press) showed that the Atlantic sublayer had shoaled and warmed by up to 2°C and extended in distribution by about 20% (Morison, Aagaard and Steele, 1998), so that the mutual front between waters of Pacific and Atlantic origin had shifted from the Lomonosov to the Alpha-Mendeleev Ridge.

Accompanying this change at shallower depths, Steele and Boyd (1998) reveal that the cold halocline layer, which acts to insulate the sea-ice from the warm Atlantic layer below, had dwindled away in the Eurasian Basin with profound effects on the surface energy- and mass-balance of sea-ice in that region. Hydrography, tracers and modelling all suggest that this change stemmed from the eastward diversion of Russian river input in response to the altered atmospheric circulation (see Maslowski's model output, in Dickson, 1999). Arctic-wide, the whole pattern of atmospheric pressure and ice drift appears to have shifted counterclockwise in a similar sense. A record extent of open water was recorded in the eastern Arctic in the early 1990s (Serreze et al 1995; Maslanik et al 1996; McPhee et al 1998).

The third new feature to emerge during the 1990s was the evidence to link this long-term variability of the Arctic Ocean with seas further south. A combination of current measurements, upward looking sonar and satellite imagery show that the amplifying NAO was accompanied by an increased annual efflux of ice through the western Fram Strait. A record volume-flux of 4687 km^3 yr^{-1} in 1994-95 was deduced by Vinje, Nordlund and Kvambekk, 1998; see also Kwok and Rothrock, 1999). The southward recirculation of extreme warmth from the eastern Fram Strait (see above) was also observed to affect the Denmark Strait Overflow, some 2500km further south (Dickson et al 1999).

2.2 - Arctic links to global change and a previous Arctic warming

While these regional events seem unambiguous, they do beg the larger question of whether such changes in the ocean-atmosphere system of the Arctic have global change implications. We cannot yet answer this effectively. We can identify a range of potential effects of course. These may be local, through the effect of a changing ocean-stratification and ice cover (Steele and Boyd, 1998; McPhee et al 1998) on surface heat flux or air-sea carbon dioxide flux, or remote, through the variable export of fresh waters and heat to the headwaters of the global thermohaline circulation for example. But we continue to lack knowledge of the mechanisms that are supposed to underpin these links to "global change", and while we may have confidence that our observations have qualitatively captured the essence of recent Arctic variability, we are a long way short of being able to quantify these changes.

Thus, en route to answering the global change question, the priority issues would seem to be " how does the Arctic Ocean circulation work and what are the inputs and outputs. In particular what do we have to do to improve our estimates of: the heat flux from lower latitudes to the Arctic Ocean, the freshwater flux from the Arctic to lower latitudes, and the feedback in the carbon dioxide cycle?" Having said that, variability itself prompts another question, namely that even if we are correct in attributing the recent episode of "Arctic warming" to extreme (positive) behaviour of the North Atlantic Oscillation, there was a previous and even greater warming episode at high latitudes of the Atlantic sector between the 1920s and 1950s (Dickson and Brander, 1993; Loeng, 1991) for which the NAO offers little explanation. Certainly, in studies of historic temperature change in the Barents Sea (Anon 1996), the 0-200m temperature on the Kola Section appears to bear little relation to either the NAO Index or to the Bear Island-Fugloya atmospheric pressure gradient prior to 1960, despite the robustness of these relationships thereafter. If a warmer inflow to the Arctic is of global significance now, it must have been then. So what caused the earlier episode(s) of Arctic warming?

In many ways, the earlier episode of Arctic warming in the middle decades of this century was more amplified, more protracted and more extensive than the relatively restricted spreading of subsurface warmth that has attracted our attention in the 1990s. To revisit and continue the early steps by ICES toward understanding the warm decade of the 1930s (Anon, 1948), a first step is to reassemble the relevant record of hydrography, meteorology, sea ice and hydrology for the Arctic for the period 1922-1958. This roughly spans the period from the Maud Expedition to the IGY, a period of active scientific research throughout the Arctic which included the Second International Polar Year. The geographical region involved extends from the Bering Sea, throughout the Arctic Ocean and marginal seas and into the Nordic Seas. The International Arctic Research Center, University of Alaska, has already begun the task of assembling these data sets, promoting data-archaeology and data-rescue activities where necessary, and anticipates that the bulk of the useful information will be in the hands of the research community by mid-2001.

3. PRIORITY REQUIREMENTS FOR NORTHERN HIGH LATITUDE OCEANOGRAPHIC DATA: WHAT AND WHERE?

3.1. Open Arctic Ocean

The dramatic temperature increase in the Arctic's Atlantic Water layer over the last decade outlined in section 2 above and thinning of the sea ice cover (McPhee et al.,1998) hint of major climate change. But lacking detailed knowledge of the causes and amplitude of the changes, no definitive statements or predictions of the future climatic state are yet possible beyond what can be achieved with coupled ocean-atmosphere models. These however need to be complemented with an integrated long-term observational programme enabling continued monitoring of changes in the Arctic interior. Possible elements of such a monitoring network are discussed below. A clear requirement is to monitor changes in the sea ice distribution - coverage, thickness and total amount. These are addressed in section 5. Here we deal with monitoring of the ocean beneath the sea ice cover, remembering that these need to be considered in tandem, both from a logistical and scientific point of view.

3.1.1 - Monitoring changes in the Arctic water masses and circulation

The observations of recent changes emphasise the need to consider the full 3-D Arctic Ocean in order to quantify them and understand what causes them. 3-D coverage is made difficult by the inaccessibility for regular ship access and efforts need to be continually made to ensure continued high quality hydrographic measurements from ice breakers/ice-strengthened vessels, both to fill in data-sparse regions and to enable repeat hydrography to be made (Figure 1). In terms of

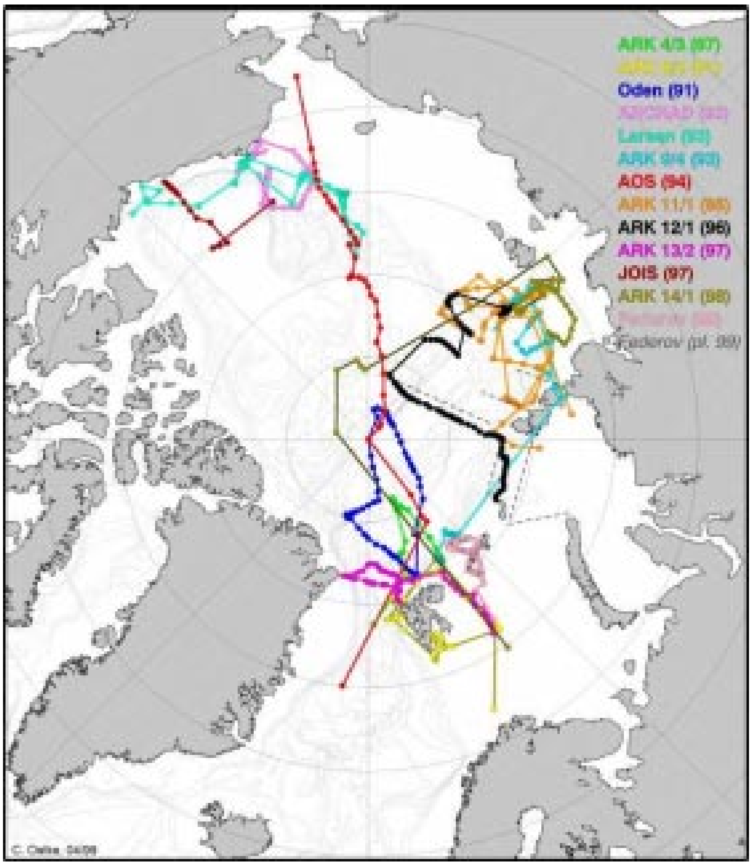

Figure 1 - Summary of major Arctic cruises since 1987 (courtesy C. Oelke, International ACSYS Project Office)

regular monitoring, particularly of short timescale variability, however the use of moored thermistor chains and current meters (coupled with upward looking sonar to measure ice thickness) at selected locations remain crucial. A future goal is the deployment of subsurface profiling floats (the cornerstone of Argo) in the under-ice environment, both in the Arctic and the Antarctic. However, there are two problems with using them include the lack of a mid-depth sound channel for tracking and the difficulty of penetrating the ice in order to transmit data, though technical developments are underway to overcome these difficulties.

Another promising avenue is the Moored Profiler (MP), which can be equipped with a CTD sensor as well as a 3-axis acoustic-travel-time current meter to measure, autonomously and long-term, the vertical structure of the ocean currents (see Doherty el al 1999, Toole et al, 1999, as well as http://www.whoi.edu/PO). One can envision anchoring these moorings to the sea ice at selected sites, letting them drift slowly towards the Fram Strait, picking them up and redeploying upstream. The Moored Profiler yields very high vertical resolution and enables, for instance, calculation of vertical heat fluxes, a crucial parameter in connecting changes (warming) of water masses to changes (melting) in ice cover.

3.1.2 Monitoring changes in Arctic heat storage

The importance of changes in heat storage for the Arctic heat budget has been highlighted through the 1990's by observations of pronounced warming at the level of the Atlantic Water. Acoustic tomography and thermometry, pioneered by Munk and Wunsch (1979) are ideal remote sensing tools for determining path averaged vertical temperature profiles and heat content in high latitude regions. The 1994 Trans-Arctic Acoustic Propagation experiment (Mikhalevsky et al., 1999) transmitted sound across the entire Arctic Ocean, and made one of the first measurements of the warming of the Atlantic Water layer in the Arctic. Comparisons were made with more standard oceanographic observations, and the acoustics-based results were found to be accord with them, giving confidence in using acoustic techniques in the Arctic.

Together with long-term measurements of the heat, salt and volume fluxes into and out of the Arctic, discussed below, future use of such an integrated monitoring network would yield an unprecedented level of detail, both in time and in horizontal and vertical space. It yields the promise of a better understanding of the Arctic climate system.

3.2 Monitoring the exchange with subarctic seas

Figure 2 shows the distribution of key sites for the long-term monitoring of Arctic-subarctic

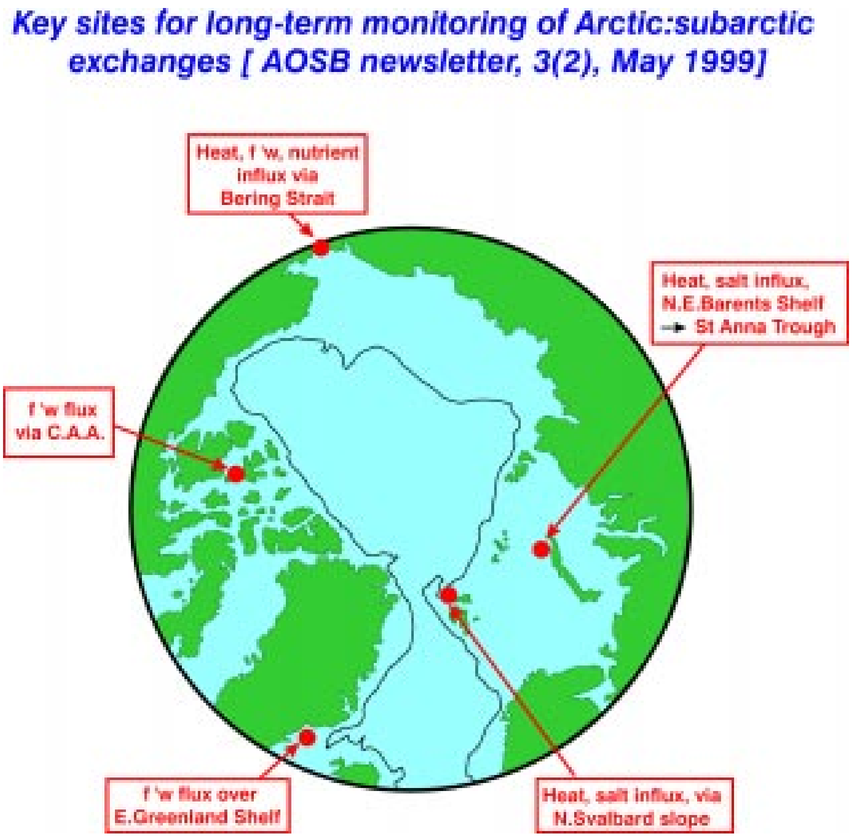

Fig 2: Key Arctic exchange monitoring sites

exchanges. It is based on the following needs:

3.2.1 - Improved estimate of heat and salt fluxes to the Arctic

(a) **via Fram Strait.** The first perceived gap is the need to quantify the heat input contributed by the western (warmer, more saline) branch of Atlantic inflow to the Arctic. The present EC-VEINS investigation of the Fram Strait throughflow needs supplementary measurements if we are to identify that part of the flow which will enter the Arctic Ocean from that which will recirculate southwards without ever entering the Arctic. A suggested moored array site is northwards across the Slope from the NW tip of Spitzbergen to cross the warm, saline Atlantic inflow at the earliest point after it has actually entered the Arctic Ocean, where the ice cover is likely to be less problematic than further east and where the warm, saline current core is still well confined against the upper Slope. There, both the baroclinic and barotropic components of inflow to the Arctic could be monitored with a limited array of bottom-mounted instruments. A long term sea level station nearby at Barentsberg is already available to help with the barotropic transport estimate.

(b) via the Barents Sea. Our measurements of heat and salt input to the Arctic via this cooler fresher branch of the circulation have largely been made in the western Barents Sea, where the estimation of the fluxes to the Arctic Ocean will be obscured by an unknown component of westward recirculation. A Norwegian/Russian team has already shown that it is possible to monitor this branch close to its point of entry to the Arctic Ocean (St Anna's Trough) in their successful recovery of a pioneering long-term current meter array from waters between Franz Josef Land and Novaya Zemlya (Loeng et al 1997). The location of the inflow core was clearly demonstrated in the strong, steady flows towards the south side of this passage. Thus the array itself is practicable in technique, location and physical access.

(c) **via the Bering Strait.** Inflow from the Pacific is a critically important source of low-salinity water and nutrients to the Arctic system. The former is a major component of the Arctic's freshwater budget and halocline, while the latter is key to supporting carbon fixation, particularly on adjacent shelf regions. Modelling efforts suggest that variability in the flow through Bering Strait reflects fluctuations in the balance between the hydraulic head (northward) and an opposing wind stress. Monitoring such flows has been an ongoing effort of oceanographers at the University of Washington since the 1960's, and in recent years this effort has been joined by oceanographers from Canada's Department of Fisheries and Oceans. Recent observations show a remarkable freshening of the Pacific's inflow, a full unit (psu) in salinity during the present decade.

3.2.2 - Improved measurement of the freshwater flux from the Arctic.

Achieving a better measure of freshwater flux from the Arctic is justified by the global importance that coupled models currently assign to relatively minor changes in freshwater distribution at high latitudes (e.g. Rahmstorf and Ganopolski, 1999) Hitherto, the important component of freshwater flux under the East Greenland ice-pack has proved elusive and this may be the major component of the southward flux. The southward flux of ice from the Arctic through western Fram Strait is now well monitored by Norway and in that location, the ratio of ice to liquid freshwater is approximately known (about 50:50). However this flux is only of global importance once it passes south of Denmark Strait to affect the global thermohaline circulation, and we have evidence from EC-VEINS that much can recirculate back into the Nordic Seas en route. The East Greenland Shelf south of Denmark Strait is therefore the critical location for monitoring the net transport and phase of the freshwater flux, and is an area where both are almost totally unknown. A new array designed to provide such a measure under the ice of the SE Greenland shelf is needed. Basing the sensor deployment on summer and winter salinity transects during the IGY, the suggestion is that this could be achieved using two moorings each equipped with multiple salinity sensors focussed on the freshest layers of the upper water-column and with current meters to provide the necessary detail on the vertical current structure. It may be desirable to supplement these with ice-drifting buoys to give Lagrangian information on the near-surface vertical salinity structure immediately beneath the East Greenland marginal sea-ice, if possible from Fram Strait to SE Greenland. Since recent transects and moored arrays in Barrow Strait (Canada/US JOIS cruise, 1997) have successfully shown the way in measuring the freshwater flux through the Canadian Arctic Archipelago, it makes good sense also to make coordinated measurements of both components of the freshwater flux at the same time, particularly since the most advanced Arctic ocean models now anticipate that their time-dependence may be linked.

3.2.3 - What is the sensitivity of the carbon cycle to Arctic variability?

Arctic change may achieve global impact through marine biogeochemical processes. The rationale is that much of the water which enters the Arctic Ocean does so across extensive shelves, the Atlantic inflow through the Barents Sea, and the fresher Pacific inflow which enters across both the

Bering Sea and Chukchi Sea shelves. An extensive heat loss takes place during both of these inflows which, together with a substantial primary production, drives an air-sea flux of carbon dioxide. In the present context, the question is how sensitive this air-sea flux is to climate variability and hydrographic change. Some elements of this response are known. Warming the inflowing water will decrease the solubility and thus the air-sea flux. Changes in the volume flux will affect the air-sea gas exchange by changing both the inventory of dissolved inorganic carbon, and the supply of nutrients. Increased melting of sea ice can affect summer primary production by increased stratification and through the effect of stratification changes on light- and nutrient-supply. An increased summer melt-back of ice will increase the heat loss during the winter season and increase brine production, with consequent effects on ventilation and the sequestration of anthropogenic carbon dioxide. The difficulty is to evaluate the relative importance of these processes in order to incorporate their net effect in climate models. As we move towards the period of peak anthropogenic carbon dioxide release (Rahmstorf and Ganopolski, 1999), the importance of being able to do so becomes a priority for the Arctic.

4 – THE SOUTHERN OCEAN

The remoteness and environment of Antarctica has severely hampered data collection in the Southern Ocean. However, the sparse in situ data (Olbers et al. 1992) and that obtained from satellite-borne sensors (Gloersen et al. 1992) have lead to an appreciation of the unique and complex role the Southern Ocean plays in the global ocean and climate system (Gordon,1991a), including the cryospheric component.

In winter, seasonal ice cover stretches from the continental margins northward, reaching half way to the ACC, covering approximately 20 million square kilometers. In summer, the ice cover retreats to just a few regions of perennial ice, with an areal coverage of about 4 million square kilometers. This seasonal pulsation of the sea ice is strongly responsive and interactive with the ocean/atmosphere heat and freshwater fluxes and associated ocean overturning. The Southern Ocean sea ice is not as thick as in the Arctic, as vigorous upward flux of oceanic heat limits its growth (Gordon and Huber, 1990; Martinson, 1993; McPhee and Martinson, 1994). Models, however, suggest that the southern sea ice fields are important in governing the average global air temperature (Rind et al. 1997). For both this reason and because sea ice plays a key role in production of dense shelf waters that ultimately lead to deep and bottom ocean ventilation, it is important that we understand the ocean and atmosphere forces that control sea ice distribution, and that they are properly simulated in global climate models. Thus at least one model (Manabe et al., 1992) has suggested that anthropogenically-induced warming due to greenhouse gas concentrations may strengthen the pycnocline stability of the seas around Antarctica through increased precipitation, resulting in turn in a thicker and more durable sea ice cover, at least until global warming overwhelms the ice production. Other models, particularly those which include representation of fractional sea ice cover, contradict this result.

Warming of the deep water within the Weddell Sea in recent decades, may indicate less heat loss to the atmosphere which may be linked to variability in sea ice thickness, though the needed data are not available to confirm this. In the mid-970s in the region of the Greenwich meridian and 65°S a large winter polynya formed over a 300,000-km^2 region. Associated with the Weddell Polynya ocean stratification was removed and strong convection cooled the ocean to nearly 3000 m (Gordon, 1982). The fact that the Weddell polynya occurred at all makes us question the stability of the Southern Ocean's present mode of stratification and deep ocean ventilation (Gordon, 1991b).

At many sites along the continental margin of Antarctica, deep reaching plumes drive mixtures of dense shelf and slope water into the deep ocean (Gordon, 1998; Rintoul, 1998). They, together with less dense plumes reaching only to intermediate levels, ventilate a thick layer of the adjacent ocean and eventually cool the lower two kilometers of the world ocean (Orsi and Bullister 1999). These plumes form over small spatial and temporal scales along specific sections of the continental margin. This, plus the presence of ice, makes Antarctic Bottom Water (AABW) formation processes very difficult both to observe and model; advancement of AABW research represents a significant technological challenge to field oceanographers and numerical modellers alike.

Glacial ice and the ocean meet at the shores of Antarctica. This occurs not only at the northern face of the ice cap, but also at hundreds of meters depth along the bases of floating ice shelves. Such ocean-ice interaction is believed to be a key factor in controlling glacial ice mass balance and stability; it provides extremely cold (<-2°C) glacial ice melt water, key in the formation of AABW, to the ocean's shelf regime (Foster and Carmack, 1976; Schlosser et al. 1990).

The northern limits of sea ice-and perhaps convection at the continental margins and polar front-vary on interannual scales. These changes appear to be linked to the variability of the ACC and the wind field in the Antarctic Circumpolar Wave (ACW), as described by White and Peterson (1996). They suggest a link of the ACW with lower latitude climate phenomena.

While major strides have been made in the last 10 years, at present we have only a "glimpse" of the mean state and variability of the Southern Ocean, its coupling with the atmosphere and cryosphere, and the zonal and meridional fluxes. Observations are incomplete in space and time; our models do not properly simulate ventilation processes, and thus provide an incomplete picture of the Southern Ocean's impact on climate. To advance the field, we must develop targeted CLIVAR-related process experiments and establish sustained measurement programs.

Within the ice covered southern ocean there is a need for:

- Establishing time series measurements within the sea ice covered Southern Ocean, which include: ocean thermohaline and tracer stratification within the full water column; outflow of the dense water products from the continental margins; sea ice distribution and thickness; glacial ice melt water distribution.

- Quantifying the ocean processes and their climate consequences, that govern the distribution of sea ice, including polynyas over deep water and coastal regions.

- Quantifying the processes that govern the formation of dense shelf waters and associated deep reaching convective plumes along the margins of Antarctica.

5 - SEA ICE

5.1 - Background

A unique characteristic of the high latitude oceans is its sea ice cover which itself forms an interactive component of the total climate system. Freezing and melting of sea ice are controlled in the main by the surface radiation balance and the vertical oceanic heat flux. Sea ice responds to both atmospheric and oceanic forcing, and changes in the sea ice distribution affect the atmosphere-ice-ocean system in several ways. The air-sea heat fluxes depend crucially on whether there is an ice cover or not, leading, in the short run, to radically different water mass distribution under ice and in open ocean, as well as radically different atmospheric conditions (milder) near open ocean. How the Arctic system responds in the long run to a vanishing ice cover is not clear. Numerical simulations can help build intuition on this issue.

Both ice motion and ice freeze and melt control the geographical distribution of ice thickness and extent. In turn a number of parameters and processes are influenced by sea ice. For example sea ice to a large extent isolates the ocean from direct contact with the atmosphere above making dramatic changes to the surface temperature in autumn,winter, and spring the surface albedo and radiative balance and the surface turbulent exchanges. In addition, sea ice influences the dynamics of the upper mixed layer of the ocean and the formation of deep water masses. This occurs through “keel stirring” and the processes of sea ice formation and melt which change the density of the upper ocean layers through brine rejection during freezing and deposition of fresh water during melting. These, coupled with heat exchange through leads, directly affect the mixing of the upper ocean layers and the fluxes of salt and freshwater into the ocean, and thus the buoyancy of the upper ocean layers. An important consequence of ice dynamics is that ice freeze and melt may occur in totally different locations as the ice is transported from one place to another with consequences for the ocean density structure and deep water formation regions.

Sea ice is known to impact on ocean and atmosphere on a wide variety of timescales. On short timescales (days to weeks) sea ice fluctuations are of most importance regionally. On longer timescales sea ice can have a wider infuence on the climate system overall , in particular through the important mechanism of ice-albedo feedback which models show will enable polar amplification of greenhouse gas-induced warming over the high latitudes in winter. Changes in the total volume of sea ice has implications for the Arctic fresh water budget, fresh water being stored in the ice during high-volume periods. This has implications for the water mass distribution beneath, and is also in some way related to changes in the amount of ice exported through the Fram Strait and Denmark Strait, which in turn may effect dense water formation further south, as well as the strength of the meridional overturning rate.

5.2 - Remote sensing of sea ice from satellites

5.2.1 - Passive imaging from satellites

Satellite observations have recently revealed significant trends in sea ice extent, particularly in the northern hemisphere and it is important that such time series are continued and maintained. Sea ice time series derived from multi-channel passive microwave data are among the longest continuous satellite-derived geophysical records, extending over two decades. The Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) provided data from 1978-87, and the follow-up Special Sensor Microwave Imager (SSM/I) onboard Defense Meteorological Satellite Program (DMSP) satellites has provided data since 1987. The 25 x 25 km gridded data sets are issued by the National Snow and Ice Data Center (USA). The brightness temperature data are used to calculate total ice concentration (the percent of ice-covered ocean within an image pixel), from which total ice area (the area of ice-covered ocean) and total ice extent (the area within the ice-ocean margin) are derived. Analysis of SMMR and SSM/I records taken separately revealed a greater reduction in Arctic sea ice area and extent during the SSM/I period. The decreases from 1987-94 were ~4% per decade compared to ~2.5% per decade from 1978-87 (Johannessen et al., 1995), with no significant trends found in the Antarctic. Since then, merged SMMR-SSM/I time series have been produced and analyzed, establishing the trends more firmly. Bj›rgo et al. (1997) established the trend in Arctic ice area and extent (1978-95) to be about -0.3 x 106 km2 per decade (Figure 1), corresponding to ~3% per decade, with no significant change in the Antarctic. The 3% per decade decrease in the Arctic ice extent (1978-97) was subsequently corroborated in a separate analysis (Cavalieri et al., 1997) that also confirmed the hemispheric asymmetry seen earlier (Johannessen et al., 1995; Bj›rgo et al., 1997). Cavalieri et al. (1997) found a slight (~1.5%) increase in the Antarctic, which may be considered significant. The hemispheric ice covers fluctuate quasi-periodically, with predominant periods between 3-5 years, though their variability is apparently not correlated (Cavalieri et al., 1997).

Maslanik et al. (1996) analyzed the seasonality and forcing mechanisms behind the decreases in Arctic ice extent in the 1990s, using SMMR-SSM/I data (1979-95) together with meteorological data. The ice reductions were found to be most pronounced in the Siberian sector in the summer, with record low Arctic ice minima in 1990, 1993 and 1995, apparently linked to atmospheric circulation anomalies. The summer reductions suggest consequential changes in other aspects (e.g., perennial ice thickness) of the ice cover. Perennial, multi-year ice (i.e., having survived the summer melt) ice is ~3 times thicker than first-year or seasonal ice (~1-2 m), such that changes in their distribution could also both reflect and effect climate change. The capability to monitor interannual variations in multi-year ice area from SMMR and SSM/I data has recently been exploited using winter data, when first-year and multi-year ice signatures permit their distinction. The analysis revealed a relatively large (~7% per decade) reduction in the multi-year ice area 1978-98 (Figure 2), compared with an ~2% per decade decrease in the total ice area in winter (Johannessen et al., 1999). This finding is supported by a SMMR-SSM/I data analysis that found an 8% increase (5.3 days) in the length of the sea ice melt season in the Arctic from 1978-96 (Smith, 1998). It is also corroborated by spatially- and temporally-fragmentary observations (from submarine sonar transects) of ice thickness decreases, as well as oceanographic data that have revealed changes in Arctic water masses since the 1970s that are reasoned to stem from a substantial (~2 m) melting of perennial MY ice. If this trend were to continue, it could eventually lead to a markedly different sea ice regime in the Arctic, altering heat and mass exchanges as well as ocean stratification.

5.2.2 - Active sensing from satellites

The variability of several sea ice parameters can be studies using data from satellite-borne active mictrowave imaging sensors. Since 1991, Synthetic Aperture radar (SAR) data have been aquired from the European Space Agency's European Remote Sensing satellites (ERS-1 and ERS-2). These high resolution (~25 m) backscatter data are aquired along 100 km swathes, which is a limiting factor for regional and larger-sclae studies. Since 1995, the Canadian Radarsat has generated SAR datasets including wide-swath (500 km) images with similar spatial resolution to ERS-SAR. Satellite SAR data are complementary to passive microwave data, as both the spatial-temporal sampling and imaging mechanisms are completely different. Sea ice phenomena and parameters that can be Sea ice phenomena and parameters that can be studied from SAR backscatter data include open and refrozen leads and polynyas, sea ice roughness (and type), and sea ice motion, at scales two orders of magnitude smaller than passive microwave data. SAR data can serve as independent observations for comparison with sea ice parameters derived from passive microwave or visible- and thermal-band imagery. Sea ice parameter retrieval, and hence product generation, from SAR data remains a research topic (e.g., Sandven et al., 1999), though some applications such as sea ice motion fields (and thereby derived parameters such as divergence/convergence and shear) are relatively well developed (e.g., Kwok et al., 1998). As yet, however, there are no generally-available SAR-derived cryospheric data products of the magnitude of those derived from NOAA or SMMR- SSM/I data

5.2.3 - Innovative satellite-based techniques, present and future

a) Present: Several innovative techniques have recently begun providing cryospheric datasets from presently available satellite data. For example, large-scale cryospheric features may be studied using 50km resolution data from the ERS wind scatterometer. The backscatter data provide the basis to study ice motion from changes in the patterns of spatially-averaged surface roughness, which can potentially be related to ice deformation and ice type [Gohin and Cavanie, 1994]. There have also some very promising analyses of sea ice motion from passive microwave data [e.g. Emery et al., 1997; Kwok and Rothrock, 1999], incorporating data from the relatively high frequency (thereby higher spatial resolution) 85 Ghz channel. These passive microwave-derived estimates may be combined with AVHRR- and SAR-derived estimates to produce ice motion fields back to 1979. The accuracy of the displacement fields may approach that of those derived from Arctic Buoy Programme data (see below), but with greater spatial coverage [Schmidt and Hansen, 1999]. Innovative methods to estimate spatially-averaged sea ice thickness using spaceborne altimetry also appear promising [Peacock et al., 1998] and may be applied to continuous ERS altimeter datasets since 1991.

b) Future: Several future techniques remote sensing systems, datasets and methodologies for cryospheric studies may be realized within the coming decade. ESA has already approved one such dedicated system, CRYOSAT, as part of their Earth Explorer Program. The goals of CRYOSAT are to measure fluctuations in sea ice and land ice masses (thickness) at large space and time scales, in order to determine their fluctuations to within the limit set by natural variability [Wingham et al., 1998]. The technical concept is to use synthetic aperture radar and interferometric techniques in synergy with satellite radar altimetry. Satellite laser altimetry (e.g., NASA's planned Geoscience Laser Altimeter (GLAS)) may also provide valuable data to map sea ice (and land ice) elevations.

5.3 - Acoustic tomography

The potential to synoptically monitor not only ocean temperature and perhaps sea ice thickness in the Arctic Ocean may be also realized using a proposed network of undersea acoustic sensors. Acoustic techniques have been used in other oceans, and a pilot experiment has shown that transmission across the Arctic basin is possible. Moreover, because sea ice has a dampening effect on acoustic waves, this attenuation may contain information about the sea ice cover, including its thickness [Mikhalevsky et al., 1999].

5.4 - Sea ice monitoring by submarine

Extensive historical datasets on sea ice characteristics, including ice concentration, draft (from which thickness can be deduced and data on pressure ridge characteristics are available from past nuclear submarine cruises, largely made for military purposes. Many of these data have now been declassified and efforts are being made to bring them into a coordinated dataset. The SCICEX programme has provided valuable additional data in recent years Given the key role but limited lifetime of SCICEX, consideration urgently needs to be given to the possibility of continued future submarine access. The U.S-led Surface Heat Budget of the Arctic Ocean (SHEBA) programme is a continuing key activity on process studies of atmosphere-ice-ocean interactions. SHEBA (http://sheba.apl.washington.edu/) was coordinated with a SCICEX cruise in its field phase, which consisted of an extensive 1-year long ice camp in the Beaufort Sea lasting from October 1997-October 1998.

5.5 - In-situ monitoring of sea ice

A number of in situ observational initiatives and platforms for study of sea ice are in place. These include:

- the International Arctic Ocean Buoy programme (IABP) (http://iabp.apl.washington.edu/)
- the the WCRP International Programme for Antarctic Buoys (IPAB) (http://www.antcrc.utas.edu.au/antcrc/buoys/buoys.html),

providing data on ice drift, mean sea level pressure and in some cases temperature.

Ice thickness monitoring programmes based on moored upward looking sonars to produce ice thicknessare coordinated through:

- the WCRP/ACSYS Arctic Ice Thickness Monitoring Programme (AITMP) and its associated data centre (http://www.lby.npolar.no/ADACIT)
- the Antarctic Sea Ice Thickness Project (AITP)

(http://www.ifm.uni-kiel.de/me/research/Projekte/ANSITP/ANSITP.html).

It is essential that these in-situ monitoring efforts not only continue but are also are built on in the future.

6 – NATIONAL AND INTERNATIONAL PROGRAMME ASPECTS

As well as those explicitly mentioned above, many of the measurement needs discussed have been identified in a number of national and international programmes. A number of these are aimed at addressing the important unknowns in identifying how Arctic variability feeds through to lower latitudes and contributes to global change. Examples include those of the Arctic Ocean Sciences Board, the International Arctic Science Committee, the WRCP Arctic Climate System Study (and its likely successor study on Climate and Cryosphere), the Japanese Frontier Research System for Global Change, the US-NOAA Global Change Research Program, the US-NSF Arctic System Science Study, and the specified priority interests of the upcoming EC Framework-V Key Action on "Global change, Climate and Biodiversity". These all express an implicit or explicit need to link Arctic Ocean variability with climate change and its societal impacts in the region, the adjacent subarctic, and the Hemisphere. Identifying the varied strands of funding will be important to the desirable aim of achieving a pan-Arctic coordination in these studies.

For the Antarctic, relevent programmes include those of the International Antarctic Zone programme (iAnZone) and the Scientific Committee for Antarctic Research (SCAR), in particular the SCAR Global Change and the Antarctic (GLOCHANT) Antarctic Sea-Ice Processes and Climate Programme (ASPeCt).

7 - REFERENCES

Anon, 1948. Climatic Changes in the Arctic in relation to plants and animals. ICES Rapp. et P-V, 125, 1-52

Anon. 1996. Report of the Cod and Climate Backward-Facing Workshop, IMR,Bergen , 21-23 March 1996. ICES CM 1996/A:9, 20 pp + 28 figs.

Aagaard K., L. A. Barrie, E. C. Carmack, C. Garrity, E. P. Jones, D. Lubin, R. W. Macdonald, J. H. Swift, W. B. Tucker, P. A. Wheeler and R. H. Whritner 1996. US, Canadian researchers explore Arctic Ocean. EOS, 77 (22), 209 and 213.

Aagaard, K. and P. Greisman, 1975. Toward new mass and heat budgets for the Arctic Ocean. Journal of Geophysical Research, 80(27), 3821-3827, 1975.

Adlandsvik, B., 1989. Wind-driven variations in the Atlantic Inflow to the Barents Sea. ICES CM 1989/C:18 13 pp (mimeo).

Adlandsvik, B., and H. Loeng, 1991. A study of the climate system in the Barents Sea. Polar Res., 10, 45-49.

Anderson, L. G., G. Bjork, O. Holby, E.P. Jones, G. Kattner, K.P. Koltermann, B. Liljeblad, R. Lindegren, B. Rudels and J. Swift, 1994. Water masses and circulation in the Eurasian Basin: Results from the Oden 91 expedition. Journal of Geophysical Research, 99, pp.3273-3283.

Carmack, E. C., R. W. Macdonald, R. G. Perkin, F. A. McLaughlin and R. Pearson, 1995. Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 Expedition, Geophys. Res. Lttrs., 22(9), 1061-1064.

Carmack, E. C., K. Aagaard, J. H. Swift, R. W. Macdonald, F. A. McLaughlin, E. P. Jones, R. G. Perkin, J. N. Smith, K. M. Ellis and L. R. Kilius, 1997. Changes in Temperature and Tracer Distributions within the Arctic Ocean: Results from the 1994 Arctic Ocean Section. Deep-Sea Res. II 44 (8) 1487-1502.

Deser, C., J. E. Walsh and M. S. Timlin, 1999. Arctic Sea Ice Variability in the Context of recent Wintertime Atmospheric Circulation Trends. J. Clim. (in press).

Dickson, RR and KM Brander, 1993. Effects of a changing windfield on cod stocks of the North Atlantic. Fish. Oceanogr, 2, 3/4, 124-153

Dickson, R. R., J. Meincke, I. M. Vassie, J. Jungclaus and S. Osterhus. 1999. Possible predictability in overflow from the Denmark Strait. Nature lond., 397, 243-246.

Dickson, R. R., 1999. All Change in the Arctic. Nature Lond., 397, 389-391.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vigne, G. Alekseev, and W. Maslowski. The Arctic Ocean Response to the North Atlantic Oscillation. J. Clim. (in press)

Dickson, RR., N Bindoff, A. Wong, B. Arbic, B. Owens, S. Imawaki and JW Hurrell. (submitted) The World during WOCE. Proc. Int. WOCE Conf. Halifax, Academic Press

Doherty, K.W., D.E. Frye, S.P. Liberatore and J.M. Toole, 1999. A moored profiling instrument. J. Atmos. Oceanic Tech., in press.

Environmental Working Group. 1997. Joint US-Russian Atlas of the Arctic Ocean, Oceanography Atlas for the Winter Period. CD-ROM, NODC.

Foster, T.D., and E.C. Carmack, 1976. Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea, Deep-Sea Res., 23, 301-317.

Gloersen P., W. Campbell, D. Cavalieri, J. Comiso, C. Parkinson, and H.J. Zwally, 1992. Arctic and Antarctic Sea Ice, 1978-1987: Satellite Passive Microwave Observations and Analysis, NASA Spec. Publ. 511.

Gordon, A. L., and B. A. Huber, 1990. Southern Ocean winter mixed layer, Journal of Geophysical Res., 95(C7), 11,655-11,672.

Gordon, A.L., 1991a. The Southern Ocean - its involvement in global change. In: Proc. Conf. on Role of The Polar Regions in Global Change, edited by G. Weller, p. 249-255, Univ. of Alaska, Fairbanks.

Gordon, A.L. 1991b Two stable modes of Southern Ocean winter stratification. In: "Deep Convection and Water Mass Formation in the Ocean", Edited by Gascard, J. and P. Chu. Elsiver Publisher, pp. 17-35.

Gordon, A.L.,1998. Western Weddell Sea Thermohaline Stratification, in: Ocean, Ice and Atmosphere:Interactions at the Antarctic Continental Margin" edited by S.S. Jacobs and R. Weiss, Antarctic Research Series , AGU, Washington, D.C., Vol. 75, pp. 215-240.

Gordon, A.L., 1982. Weddell deep water variability, J. Mar. Res., 40(suppl), 199-217.

Grotefendt K., K. Logemann, D. Quadfasel, and S. Ronski, 1998. Is the Arctic Ocean warming? J. Geophys. Res. 103, 27,679-27,687

Kolatschek, J., H. Eicken, V. Yu. Alexandrov and M. Kreyscher, 1996. The sea-ice cover of the Arctic Ocean and the Eurasian marginal seas: A brief overview of present day patterns and variability. Pp. 2-18 in: R. Stein, G. I. Ivanov, M. A. Levitan and K. Fahl (Eds), Berichte zur Polarforschung, 212, Alfred-Wegener Instute fur Polar und Meeresforschung, Bremerhaven, Germany.

Kwok, R., and D.A. Rothrock, 1999. Variability of Fram Strait Ice Flux and the North Atlantic Oscillation. JGR-Oceans, 104, 5177-5189.

Loeng H. 1991. Features of the physical oceanographic conditions of the Barents Sea. Proc. Pro Mare Symp on Polar Marine Ecol., Polar Res., 10 (1) 5-18

Loeng, H., V. Ozhigin and B. Adlandsvik, 1997. Water fluxes through the Barents Sea. ICES J. Mar. Sci., 54, 310-317.

Manabe, S., Spelman, M.J.,and Stouffer, R.J., 1992. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part II: Seasonal response. J. Climate, 5, 105-126.

Manabe, S. and R. J. Stouffer, 1993. Century-scale effects of increased atmospheric CO2 on the ocean-atmosphere system. Nature, 364, 215-218.

Martinson, D. G., 1993. Ocean heat and seasonal sea ice thickness in the Southern Ocean. In W. R. Peltier (Ed.), Ice in the Climate System, (Vol. I, pp. 597-609). Berlin: Springer-Verlag.

Maslanik, J. A., M. C. Serreze and R. G. Barry, 1996. Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. Geophys. Res. Lttrs., 23, 13, 1677-1680.

McLaughlin, F. A., E. C. Carmack, R. W. Macdonald and J. K. B. Bishop, 1996. Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin, J Geophys. Res., 101 (C1), 1183-1197.

McPhee, M., and D. Martinson, 1994. Turbulent mixing under drifting pack ice in the Weddell Sea. Science, 263, 219-220.

McPhee, M. G., T. P. Stanton, J. H. Morison and D. G. Martinson. 1998. Freshening of the Upper Ocean in the Central Arctic: is Perennial Sea Ice Disappearing? Geophys Res. Lttrs, 25, 10, 1729-1732.

Mikhalevsky, P.N., A.N. Gavrilov, and A.B. Baggeroer, 1999. The Trans-Arctic Acoustic Propagation Experiment and Climate Monitoring in the Arctic. IEEE J. Ocean. Eng. V.24, no.2, pp.183-201.

Morison, J., M. Steele and R. Anderson, 1998a. Hydrography of the upper Arctic Ocean measured from the Nuclear Submarine, USS PARGO. Deep-Sea Res., I 45 (1) 15-38.

Morison, J, K. Aagaard, and M. Steele, 1998b. Report on the Study of the Arctic Change Workshop, November 10-12, 1997, Univ. of Washington, ARCSS Rept No. 8. 63 pp.

Morison, J, K. Aagaard, and M. Steele, in press. Recent changes in the Arctic: a review. Arctic. (submitted).

Munk, W. and C. Wunsch, 1979. Ocean acoustic tomography: A scheme for large scale monitoring. Deep-Sea Res., 26, 123-161.

Olbers, D., V. Guretski, G. Seiss, and J. Schroter, Hydrographic Atlas of the Southern Ocean, Bremerhaven, Alfred-Wegener Institute, 1992.

Orsi and Bullister, 1999. Progress in Oceanography.

Quadfasel, D., A. Sy, D. Wells, and A. Tunik, 1991. Warming in the Arctic. Nature 350, 385.

Rahmstorf, S and A. Ganopolski. in press 1999. Long-term Global Warming Scenarios Computed with an Efficient Coupled Climate Model. Climate change.

Rind, D., Healy, R., Parkinson, C., & Martinson, D., 1997. The role of sea ice in 2xCO2 climate model sensitivity, 2, Hemispheric dependencies [2xCO_2]. Geophys. Res. Lett., 24(12), 1491-1494.

Rintoul, S., On the origin and influence of the Antarctic Bottom Water of the southeast Indian Ocean, in: Ocean, Ice and Atmosphere:Interactions at the Antarctic Continental Margin" edited by S.S. Jacobs and R. Weiss, Antarctic Research Series , AGU, Washington, D.C., Vol. 75.

Schlosser, P. R.Bayer, A. Foldvik, T. Gammelsrød, G. Rohardt, and K.Münnich, Oxygen-18 and helium as tracers if Ice Shelf Water and water/ice interaction in the Weddell Sea, J. Geophys. Res. 95, 3253-3263.

Serreze, M. C., J. A. Maslanik, J. R. Key, R. F.Kokaly and D. A. Robinson, 1995. Diagnosis of the record minimum in Arctic sea-ice area during 1990 and associated snow cover extremes. Geophys. Res. Lttrs., 22 (16), 2183-2186.

Steele, M. and T. Boyd, 1998. Retreat of the cold halocline layer in the Arctic Ocean. J. Geophys Res, 103, 10419-10435.

Swift, J. H., E. P. Jones, K. Aagaard, E. C. Carmack, M. Hingston, R. W. Macdonald, F. A. McLaughlin, and R. G. Perkin. 1997. Waters of the Makarov and Canada Basins, Deep-Sea Res. 44 (8), 1503-1529.

Thompson, D. W. J., and J. M. Wallace, 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters, 25,1297-1300.

Toole, J.M., K.W Doherty, D.E. Frye, and S.P. Liberatore, 1999. Velocity measurements from a moored profiling instrument. Proceedings of the IEEE Sixth Working Conference on Current Measurement, March 11-13, 1999, San Diego, 144-149.

Vinje, T., N. Nordlund, and A. Kvambekk, 1998. Monitoring Ice Thickness in Fram Strait. J. Geophys. Res., 103, 10437-10449.

Vowinckel, E. and S. Orvig, 1970. The climate of the North Polar Basin. In: Climates of the Polar Regions, ed. S. Orvig, 14, pp. 129-225. Elsevier.

Walsh, J. E., W. L. Chapman, and T. L. Shy, 1996. Recent decrease of sea level pressure in the central Arctic. Journal of Climate, 9, 480-486.

White, W.B. and R.G. Peterson, 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature, and sea-ice extent, Nature, 380, 699-702.