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# Oceanic Interdecadal Climate Variability

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Climate Variability

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# PREFACE

Evidence of Interdecadal Climate Variability (ICV) within the global climate system has focussed the attention of researchers from the physical, chemical and biological disciplines. At its Twelfth Session, Woods Hole, 4-8 June 1991, the SCOR-IOC Committee on Climatic Changes and the Ocean (CCCO) concluded that there was an emerging need for a coherent multidisciplinary research programme examining the interdecadal time scales of ocean climate. Accordingly, the Committee established an *Ad Hoc* Study Group on Interdecadal Climate Variability which reviewed (Honolulu, 18-20 February 1992) the status of knowledge and existing activity in ocean research as it relates interdecadal variability in global climate, with specific reference to thermohaline circulation, fresh water, air-sea interaction, and the carbon cycle.

This report provides background material for a proposed interdisciplinary research programme aimed at a better understanding and modelling capability of oceanic interdecadal climate variability. To this end, evidence of ICV within the global climate system is documented and two relatively recent examples relating to large scale shifts in atmospheric circulation, ocean temperature distribution, and fisheries in the Pacific and North Atlantic regions are highlighted. The working group recommended that an international workshop be organized to review decadal/interdecadal scale variability and to design an appropriate observing, modelling and research strategy for development of an international interdisciplinary interdecadal climate variability science programme.

Prof J.J. O'Brien
Chairman, SCOR-IOC Committee on
Climatic Changes and the Ocean

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## INTRODUCTION

Although there are many important examples of climate fluctuations with quasi-periods of 10-30 years, such interdecadal climate variability (ICV) has received relatively little attention by the scientific community, particularly in comparison with the 3-5 year time scales associated with the El Niño Southern Oscillation (ENSO). Instances of ICV are found in many physical and biological systems and can be discerned in high-resolution proxy records that are unlikely to have been affected by humankind. The genesis of such variability is not yet clearly established but because of the large heat and moisture storage capacity of the oceans as compared to the atmosphere, and their ability to transport heat and salt over large distances, the oceans are likely to play a key role in setting the time scale for ICVs. Besides having important socio-economic effects, an understanding of natural decadal-scale climate variations is crucial to differentiating natural climate changes from those due to anthropogenic forcing (e.g., greenhouse warming). This class of interdecadal variations is particularly challenging because as well as the oceans, it centrally involves interactions between the atmosphere, ocean and cryosphere, and is probably also related to biogeochemical processes.

Observations of global mean air temperatures (Figure 1, from Nitta and Yoshimura, 1992) reveal year-to-year variations superposed upon a long-term trend throughout the twentieth century. However, there are also important decadal-scale variations in the record. The warmest temperatures occurred in the 1980s and 1990s, but prior to that, the warmest period was in the 1930s to 1950s, with a cooler period in the 1960s and 1970s. Is the warmth of the past decade part of a long-term trend of global warming associated with the observed greenhouse gas increases in the atmosphere (IPCC, 1990), or is it due to natural decadal-scale fluctuations? Only by obtaining a better understanding of climate variations on the decadal time-scale can we place anthropogenic changes in proper perspective.

Some of the greatest climate impacts occur over the ICV time scale. Beginning in 1976, a series of harsh winters gripped the central and eastern United States, a factor which helped plunge the nation into an oil shortage and may have contributed to climatic changes in the North Atlantic as discussed below. At the same time, in the eastern North Pacific, a substantial portion of the sockeye salmon fishery eluded the fishing community by changing their long-standing return migration route to the mouth of the Fraser River from the south end of Vancouver Island to the north end. Seemingly independent, hindsight now binds these disparate events as related symptoms of a large scale shift in the atmospheric circulation and ocean temperature distribution across the North Pacific/North American region. Other connections range from an increase in the chlorophyll concentration of the surface waters over the North Pacific gyre, a wholesale increase in sea and air temperature along the eastern North Pacific margin, and a series of dry years that affected the northwest United States.

Another recent example of ICV has come from the North Atlantic. Now known as the "Great Salinity Anomaly" (or GSA), this event involves a freshening of the surface waters of the northern North Atlantic during the 1960s and 1970s. Scrutiny of available hydrographic

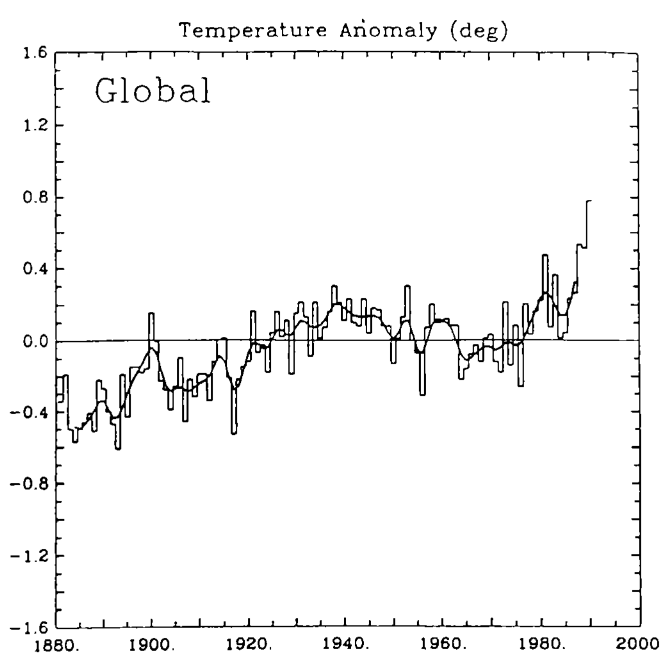



**Figure 1.**
Global mean land air temperature anomalies relative to 1951–1980 (Annual values and smoothed curves) (from Nitta and Yoshimura, 1992).

data reveals that this large scale event began with an increased profusion of low salinity sea-ice melt water east of Greenland in the mid to late 1960s which then made a slow cyclonic transit around the North Atlantic gyre returning to the east Greenland Sea in 1982. While the salinity anomaly is partially detectable from sporadic historical samples, oceanographers find the movement of the anomaly with time a particular revealing event. This is because it is one of the few occasions when the rate of gyre circulation has been observed.

Deep water masses of the World Ocean form at both polar extremes of the Atlantic, which can be characterized as an overturning ocean. In contrast, the Pacific has a circulation more constrained to horizontal layers. From a climate standpoint, a freshening such as the GSA may interrupt the northward transport of heat in the Atlantic because the lighter, less saline surface water cannot attain the extremely high density during winter cooling that is necessary to drive it to the abyss. A breakdown in convection and deepwater formation in the northern North Atlantic would reduce the poleward heat transport by the thermohaline circulation that normally flows north and then ventilates to replace the sinking deep water.

Aside from redistributing the earth's heat and salt, the thermohaline circulation mixes water mass properties (including contaminants). Convective water mass formation regions are also important in providing a sink for atmospheric carbon dioxide, and thus plays a role in the global carbon budget. Improved understanding of this process will require a multi-disciplinary approach.

Other recent examples of ICV include decade-long droughts over the African Sahel, modulation of the Asian monsoon, wet spells and drought over the western United States and associated hydrological changes (Figure 2 from Cayan *et al.*, 1989), changes in frequency of occurrence of hurricanes in the tropical Atlantic, 20-30 year temperature cycles in the Southern Ocean (Cook *et al.*, 1991) and decadal-scale fluctuations in Arctic Ocean ice cover (Mysak *et al.*, 1990). For virtually all of these phenomena, our understanding is limited because instrumental records are short and all the physical mechanisms are not known. Some important clues can be garnered from longer paleoclimate evidence, however. For example, a 1500 year ice core taken in the Peruvian Andes (Thompson and Mosley-Thompson, 1989) shows a high-resolution record of ICV deposition that is larger than that seen in the modern instrumental record. A notable finding from this tropical site is evidence of anomalously high dust deposition and changes in other properties during the Little Ice Age. This episode previously was viewed principally as a North Atlantic regional phenomenon. This facet of the Peruvian glacial record indicates that many prominent examples of low frequency climate variation can have global ramifications and that they usually encompass many interwoven physical variables which affect terrestrial and oceanic systems. Further, the striking variability preserved by this record suggests that the ICV scale is a prominent feature of the climate system that has not attracted much attention because human experience and instrumental records are short.

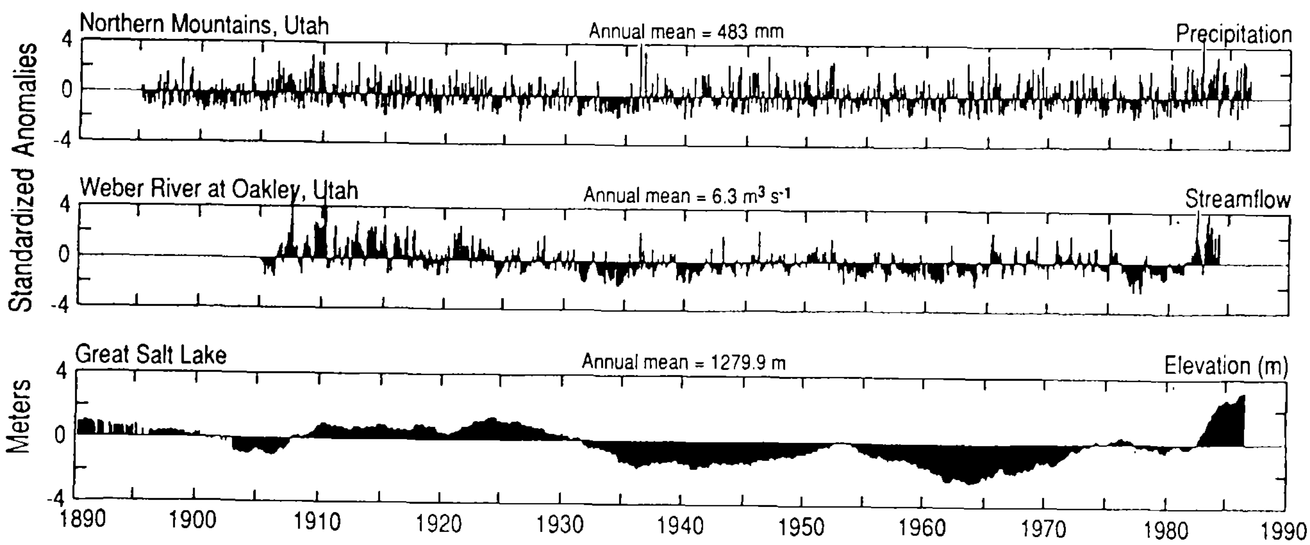



**Figure 2.**
Monthly time series of regional mean precipitation at Northern Mountains Division (compiled by National Climatic Data Center, NOAA), streamflow in Weber River at Oakley, Utah (obtained from U.S. Geological Survey), and elevation of Great Salt Lake (obtained from U.S. Geological Survey). The precipitation and streamflow values are anomalies from the annual cycle that have been standardized by dividing by the appropriate monthly standard deviation. Great Salt Lake elevation is in meters. Annual mean values for the three variables are indicated on plots. The successively lower frequency nature of the effects of a watershed from the precipitation to runoff to storage in a lake is clearly seen, as the time scales of the precipitation, streamflow, and Great Salt Lake elevation anomalies is about one month, about 20 months, and several years, respectively (from Cayan, Gardiner, Landwehr, Namias and Peterson, 1989).

Information on changes below the ocean surface is scarce. In the North Pacific, however, there is evidence (Figure 3) that the cooling in SSTs over the recent

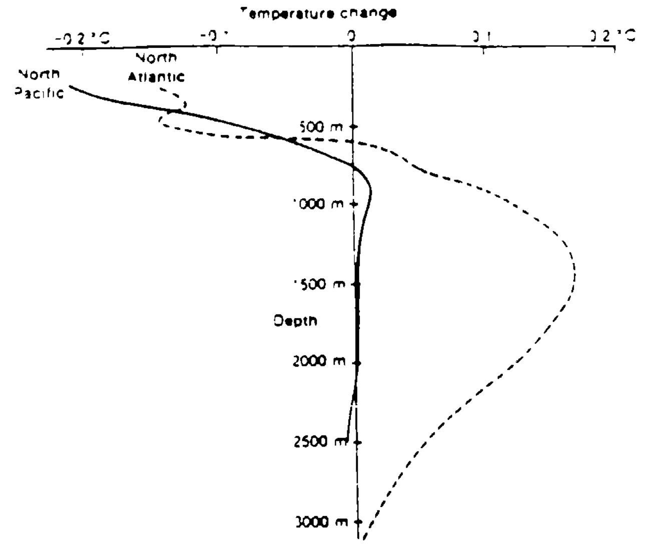



**Figure 3.**
Sub–surface ocean temperature changes at depth between 1957 and 1981 in the North Atlantic and North Pacific (adapted from Antonov, 1990, from IPCC, 1990).

decades extends to well below 500m in depth, and so involves a considerable amount of heat capacity of the ocean. The large variability emphasizes the critical need for data. All time series which describe the ocean's properties and its biomass are important. Because of the sustained effort required to build consistent data sets over long periods of time, funding becomes a constraint. The range of available platforms has diminished, through the reduction of the merchant fleet, the paring-down of their crews, the increasing expense of research vessel time and the loss of much of the Ocean Weather Station (OWS) network. Consequently, questions of which time series to continue arise with increasing frequency.

It is vital then to establish some sort of rational basis for choice if we are to focus our resources on the survival of what is important to measure for detection of ICVs rather than what is merely interesting. Ultimately this choice hinges on the question of impact, whether we are talking about the effect of a particular change on the environment, or via such changes, on humankind. The underlying aim here is to develop sufficient understanding to partition the changes we observe into the processes and effects of climate (including Global Warming) and those associated with more direct anthropogenic impacts, because these have the greatest potential to affect humankind and restrict or restrain their activities.

In the remainder of this report we focus upon two of the above mentioned examples of interdecadal climate variability (the mid-1970s North Pacific climate shift and decadal variations in the North Atlantic basin) to give a perspective of what is known and what is unknown about this important class of climate variability. Climate variability is a global issue, and because of improved observations and modelling capabilities, we are in a position to take a fresh and productive look at this problem. Newly emerging techniques in the simulation of chemical and biological systems, and the recovery of more and better paleoclimatic records, offer opportunities for worthwhile interdisciplinary studies and better insight into the working of the global climate system on decadal time scales.

## THE NORTH PACIFIC

### OBSERVATIONS

Reliable analyses of regional patterns of sea surface temperature (SST) anomalies for decades over the globe can only be carried out for the period after 1946 because SSTs were not well monitored prior to then and the method of measurement has changed. From the available data, it is clear that climate warming in recent years has not been uniform. The most striking and largest amplitude anomalies of decadal-mean temperature in the Northern Hemisphere are found for 1977-1986 (Figure 4). In that decade, substantially cooler (>0.5°C) than normal conditions (relative to the 1951-80 mean) occurred in central North Pacific SST. There was a large warming (>1.5°C) over Alaska and SST increased along the west coast of North America, while cooling occurred over eastern North America.

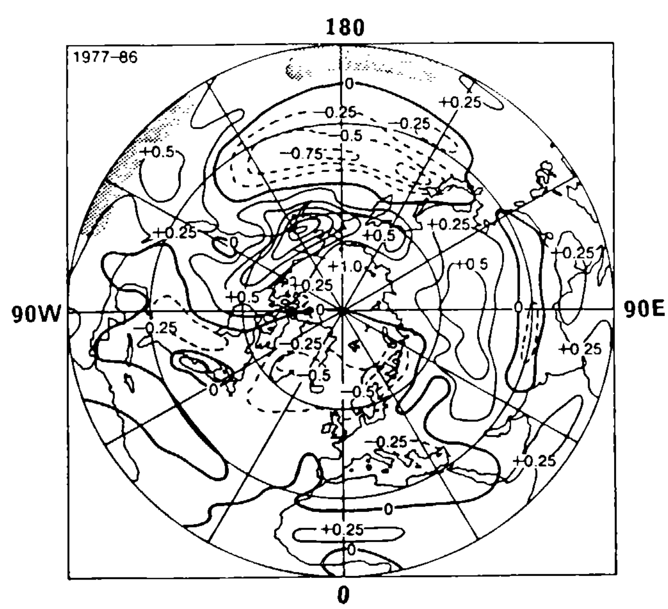



**Figure 4.**
Decadal average air surface–temperature or sea surface temperature anomalies as departures from the 1951–80 mean, for 1977–86. Contours every 0.25°C (from Trenberth, 1990).

This distinctive pattern of surface temperature anomalies for 1977-86 is linked to changes in many other climate variables. Several studies have examined its linkage to other parts of the atmosphere and ocean and postulated about the physical processes involved. What has emerged is a physically consistent and coherent picture of decadal-scale climate change. The North Pacific/North American atmospheric circulation has changed throughout the troposphere. At the North Pacific surface, the wind stress and wind stress curl changed, and by implication so did the Ekman pumping in the ocean and the Sverdrup transport and ocean currents. Sea surface temperatures, surface air temperatures, sea-ice, and streamflow in coastal regions all changed. Other evidence suggests pronounced changes in phytoplankton and ocean biology, and fishstock in the North Pacific. The changes appear to be closely linked with low frequency variability in the tropical Pacific and Indian Oceans, and the El Niño Southern Oscillation (ENSO) phenomenon. The following documents these aspects in more detail.

Examination of numerous time series have shown that the decadal-timescale changes in the North Pacific have occurred primarily in the winter half year, and particularly from November to March. The particular regime seen in Figure 5 (Graham, Submitted) appears to have lasted for 12 years from the winter of 1976-77 to 1987-88 (although the perspective may change as the recent record is extended further). This is shown by anomalies in sea level pressure (Figure 6 from Trenberth, 1990) and associated time series of the area average over a region of the North Pacific (Figure 7 from Trenberth, 1990). At the ocean surface, the wind

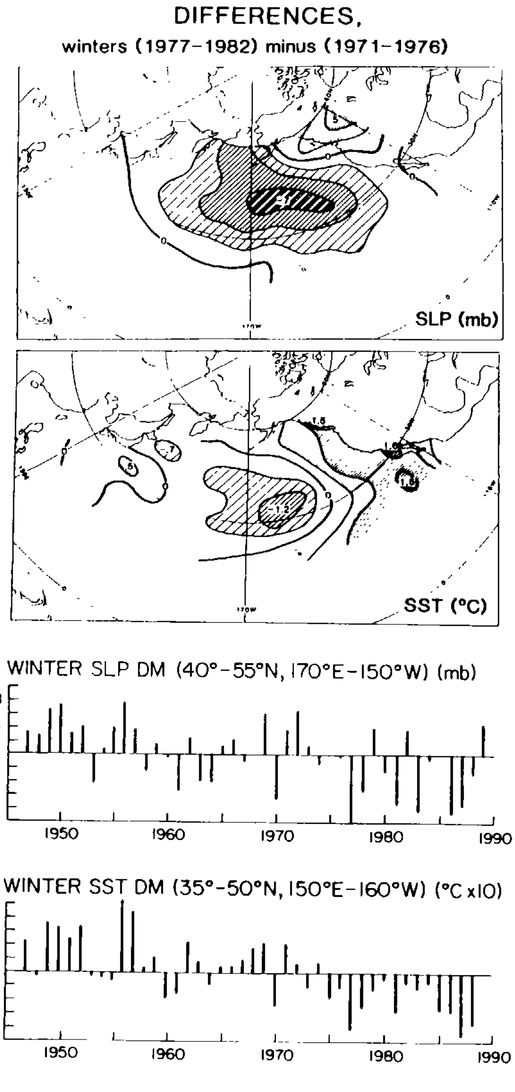



**Figure 5.**
Upper panels – Differences in boreal winter averages for North Pacific SLP (contour interval 2mb) and SST (contour interval 0.5°C); winters (1977–78 to 1981–82) less (1970–71 to 1976–77). Lower panels – time series of boreal winter area averages; SLP for 40°N to 55°N and 170°E to 150°W, SST for 35°N to 50°N and 1150°E to 160°W (from Graham, 1992).

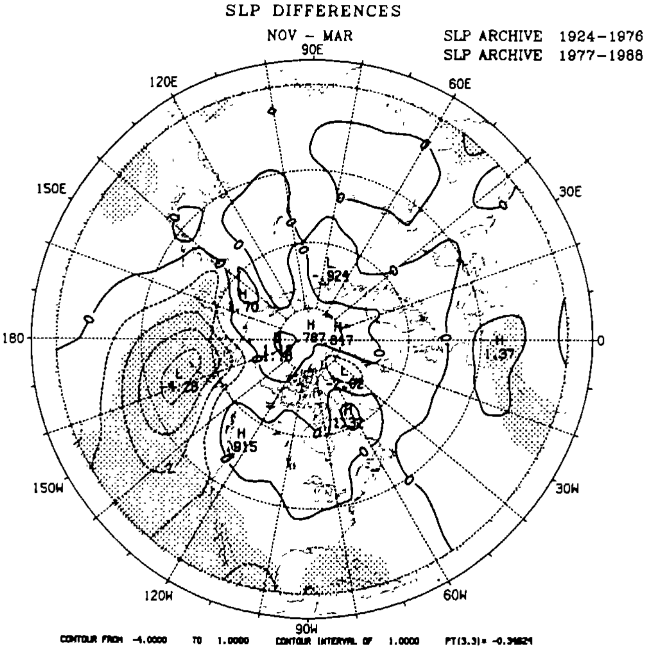



**Figure 6.**
The difference in mean sea-level pressures from 1977–88 for November–March versus 1924–76 (mb) (from Trenberth, 1990). Stippling indicates statistical significance at 5%.

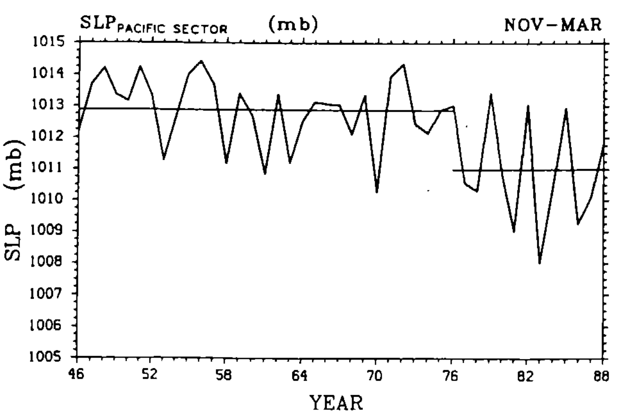



**Figure 7.**
Time series of mean North Pacific sea-level pressures averaged over 27.5° to 72.5°N, 147°E to 122.5°W for the months November–March (from Trenberth, 1990). Means for 1946–76 and 1977–87 are indicated.

changes drive variations in surfaces fluxes, ocean mixing and ocean currents. In the Sea of Okhotsk, sea-ice cover often shows a reverse tendency with greater than normal values after about 1976 (Sekine, 1991). Large changes are also found throughout the troposphere (Figure 8 from Nitta and Yamada, 1989), which have

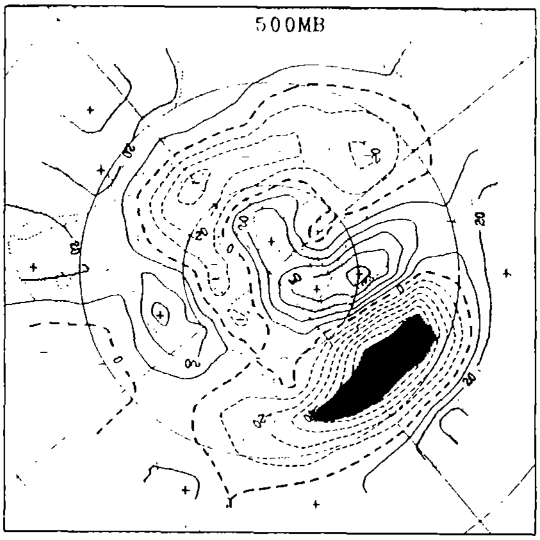



**Figure 8.**
Differences of the 500-mb geopotential height during winter between a 10-year average for 1977-86 and for 1967-76 (from Nitta and Yamada, 1989). Contour intervals are 10 gpm and negative contours are dashed. The 95% level of significance is shaded.

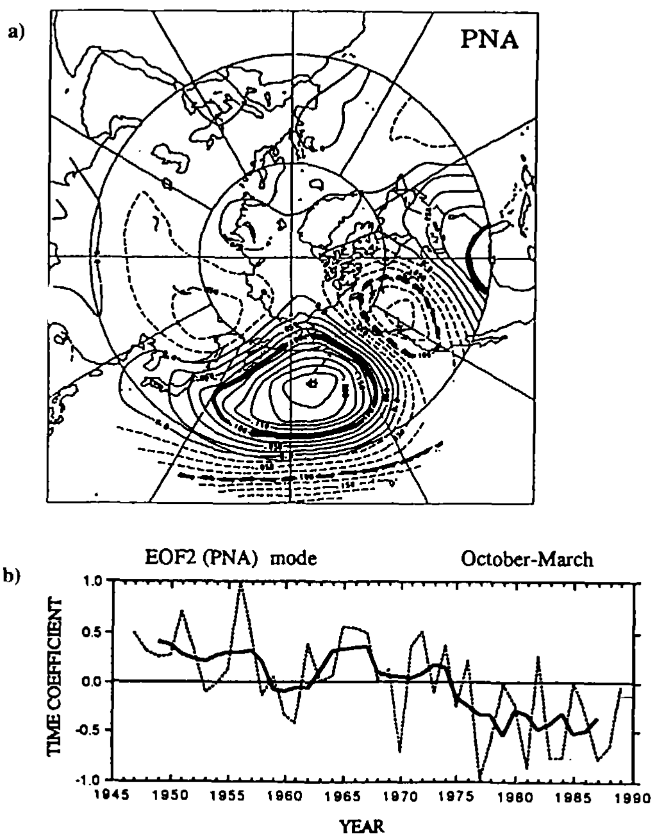



**Figure 9.**
a) 500mb height winter 5-days varimax rotated eof factor-2 PNA;
b) EOF2 (PNA) mode October-March (from Kawamoura and Nishimori, 1992).

been documented further using an empirical orthogonal function (EOF) analysis (Figure 9 from Kawamura and Nishimori, 1992).

The latter pattern was associated with strong changes downstream over North America. This "Pacific-North American" teleconnection pattern and its time series is closely linked to the changes in surface temperatures of Figure 5 primarily through advection of temperature and moisture, and possibly involving changes in cloudiness as well. Over the Pacific Northwest, the shift to a stronger high pressure ridge over western Canada provided changes in both temperature and precipitation. Examples of the changes along the coast of Alaska can be seen in the surface temperatures at Sitka (57°N 135°W) shown in Figure 10 (Salmon, 1992) - note the consistently above normal values in the smoothed curve after 1976 - and the below normal sea-ice cover in the Bering Sea. Streamflow in many rivers along coastal Alaska increased, while that in others, in the northwestern United States was substantially reduced (Figure 11 from Cayan *et al.* 1991).

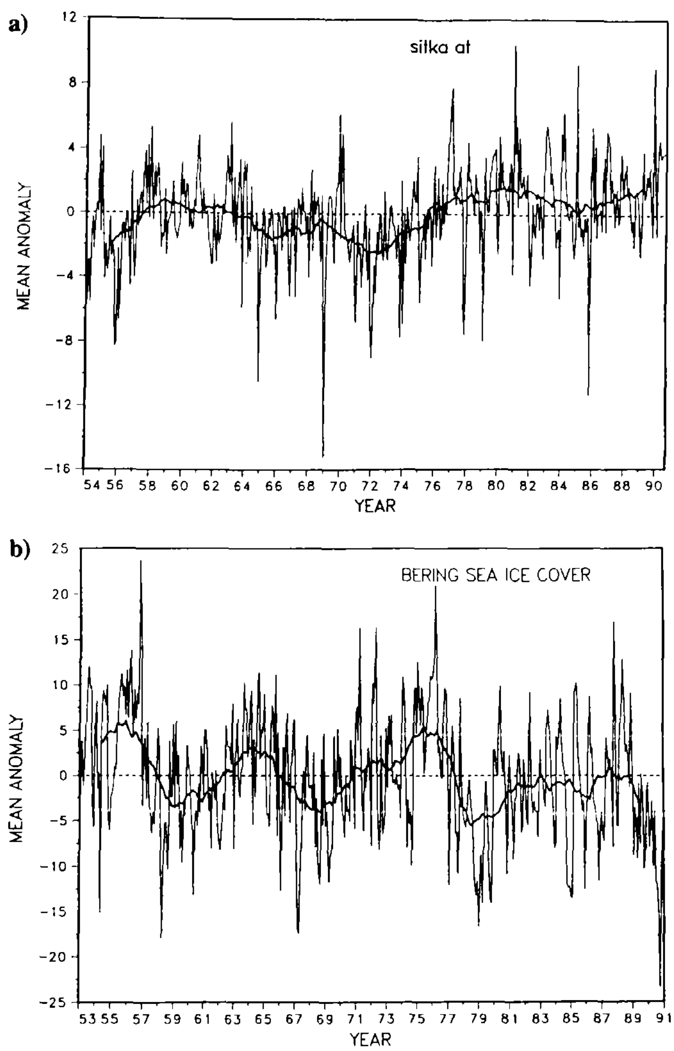
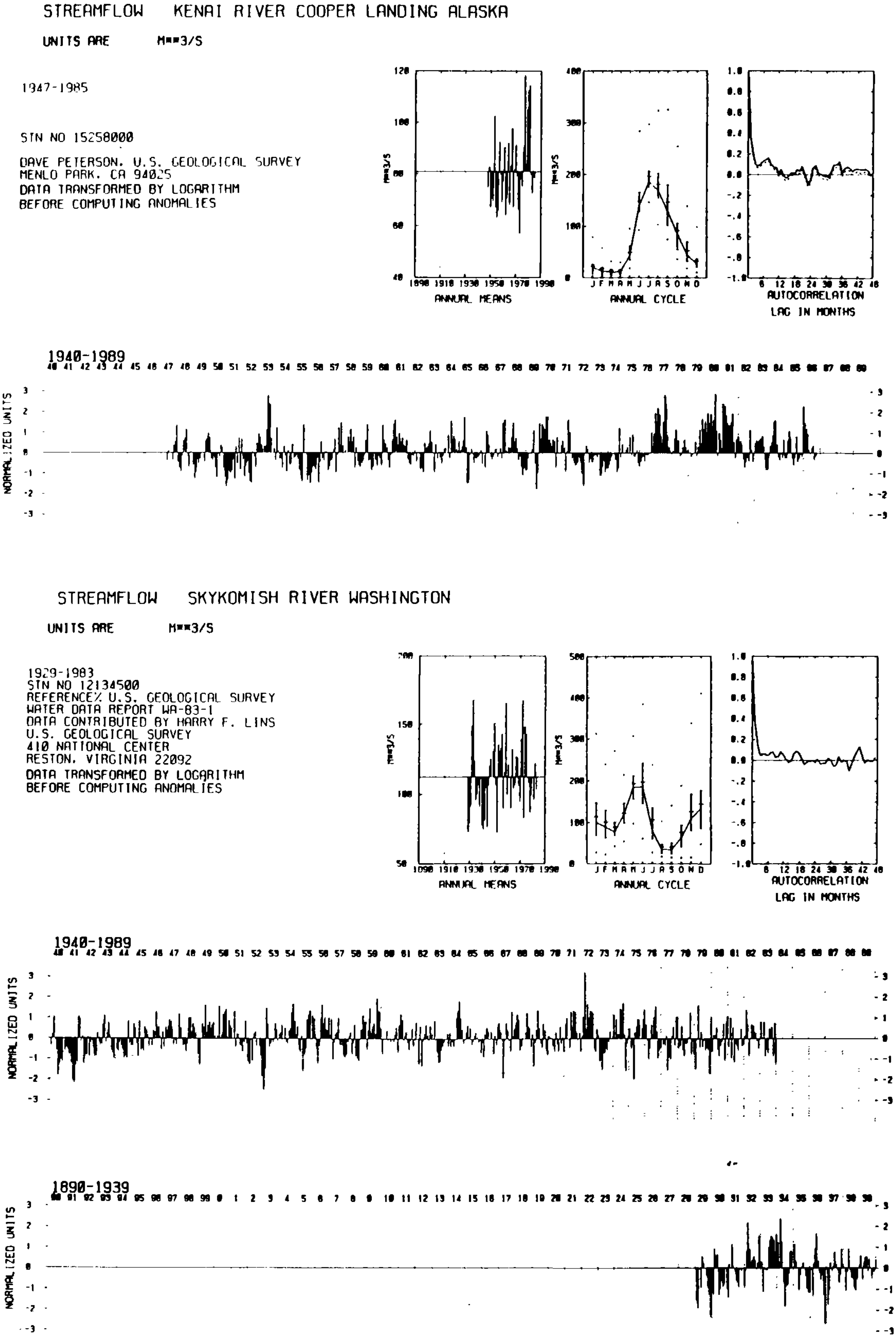



**Figure 10.**
a) Surface air temperature at Sitka, Alaska 1953-1991;
b) Sea Ice Cover in the Bering Sea 1952-1991 (from Salmon, 1992). The solid line is a 12-month running average. Both records show considerable 5-10 year variability.

**Figure 11.**
Standardized monthly streamflow anomalies and selected statistics from Kenai River (Coastal Alaska) and Skyomish River (Western Washington). Note shift to high streamflow in Alaska and low streamflow in Washington in 1977 (from Cayan, McClain and Nichols, 1991).



The effects on SST are more readily seen in Figure 12 (Salmon, 1992) which shows the first EOF pattern of SST over the North Pacific and time series of area averages from the central and eastern North Pacific that have opposite signs in the EOF pattern. The warming after 1976 in the eastern region and the approximately coincidental cooling in the central region can be clearly seen.

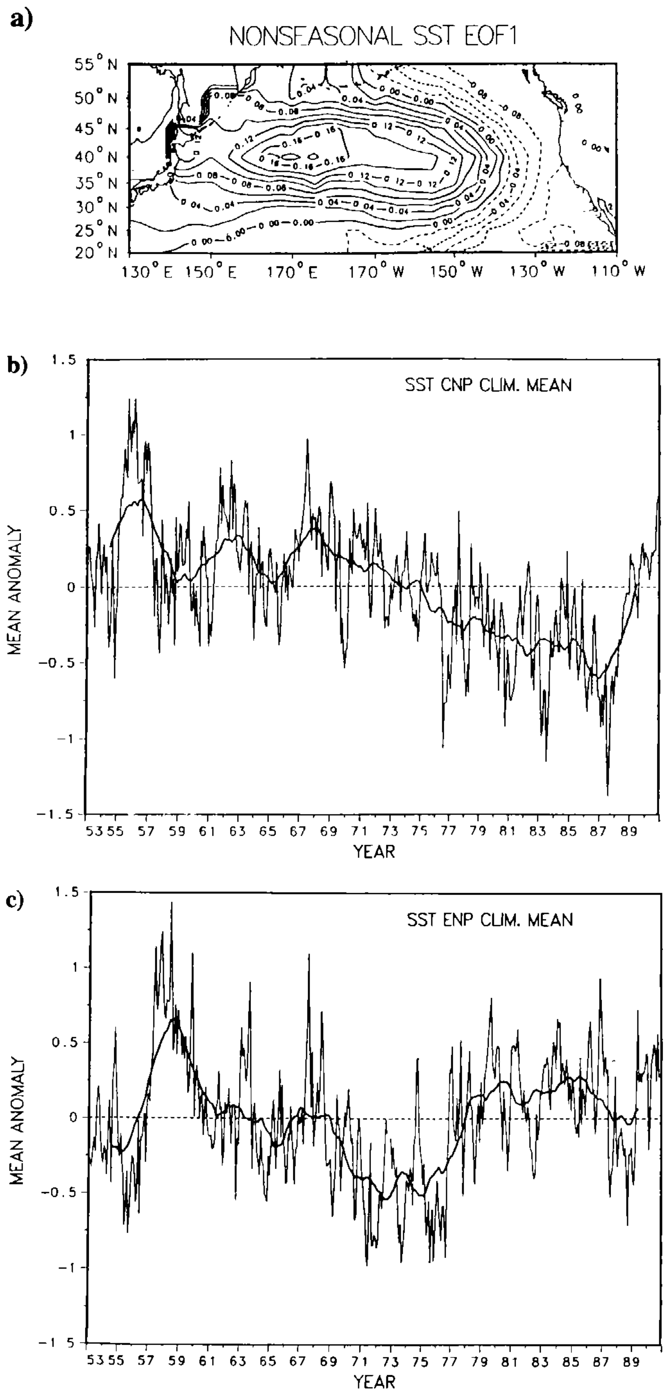



**Figure 12.**
a) First EOF pattern (units are dimensionless) of SST over the North Pacific;
b) time series of area means (units of degrees Celsius) from to the central North Pacific;
c) eastern North Pacific (from Salmon, 1992).

The changes in the atmospheric circulation alter the sensible and latent heat fluxes from the ocean surface into the atmosphere. The flux changes observed during the 1970s-1980s are consistent with changes in the observed SST pattern (Cayan, 1992 a,b,c). A basin wide change in winds is apparent in the difference between pseudo-wind stress (1977-1982) vs. (1971-1976) (Figure 13 from D. R. Cayan, N. Graham and J. Ritchie, personal communication), with stronger cyclonic circulation south of the Aleutian Islands after 1976. Stronger westerlies also occur from 30°N to 45°N, and weakened trade winds from 10°N to 20°N. Yamagata and Masumoto (1992) describe the implications for changes in the winter Asian monsoon (e.g., near 20°N 130°E). In the North Pacific these changes imply changes in the curl of the wind stress (Figure 14 from Salmon, 1992), which has implications for the Ekman pumping and Sverdrup transport. Indeed, Trenberth (1991) used surface wind observations to calculate significant changes in the Sverdrup transport amounting to over 5 Sv in the central Pacific-Kuroshio gyre and over 15 Sv in the subpolar gyre, both in the sense of stronger currents after 1977. Sekine (1988) has examined the Oyashio from 1960-87 and finds a stronger subpolar gyre transport of over 20 Sv in 1977, 78, 81, 83 and 84 compared with other years from 1961 to 1984, and also the penetration of the Oyashio farther south by 1 to 2 degrees of latitude from 1980-87.

The decadal changes during the mid-1970s also had profound effects on the central and eastern Pacific epipelagic ecosystem (Ebbesmeyer *et al.*, 1991). To begin with, measurements north of Hawaii suggest an increase in total chlorophyll in the water column and thus in phytoplankton (Venrick *et al.*, 1987). The changes in ocean currents and temperatures around 1976 have also evidently altered the migration patterns of fish, in particular tuna and salmon, in the Northeast Pacific (Figure 15 from T. Barnett, personal communication; and Mysak, 1986). The space-time scales of the dominant ENSO climatic signal in the Pacific has been associated with a greatly reduced phytoplankton biomass in both the western (Dandonneau, 1986) and eastern (Barber and Chavez, 1983) Pacific and is linked to radical changes in the pelagic ecosystem of the California Current (Chelton,1981; Bernal, 1981).

## PHYSICAL PROCESSES

Unlike the North Atlantic, deep convection is not present in the North Pacific and changes in the thermohaline circulation are not expected to be a major factor in decadal-scale climate variations there. Instead it appears that the changes in the ocean are strongly linked to changes in the overlying atmospheric circulation, and there remains a question as to how much the changes in SST locally may feed back on the circulation.

**Figure 13.**
Pseudo wind stress is in units of $m^2/s^2$, from COADS and Florida State University data sets. Differences in winter (December, January, February) mean pseudo-wind stress over the Pacific (1977–1982) minus (1971–1976) (from Cayan, Graham and Ritchie, personal communication).

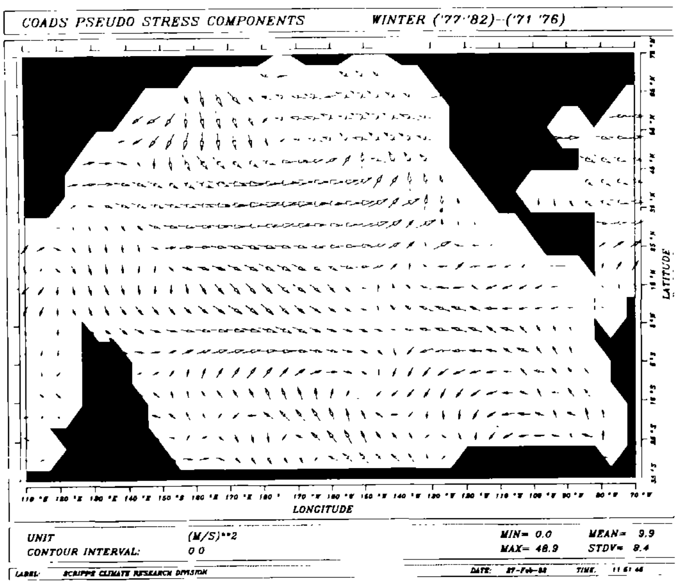



**Figure 14.**
Wind stress curl in units of $10^{-7}$ Newtons/$m^3$ in the NE Aleutian Low for 45°–60°N across the basin from 1946–91 (from Salmon, 1992).

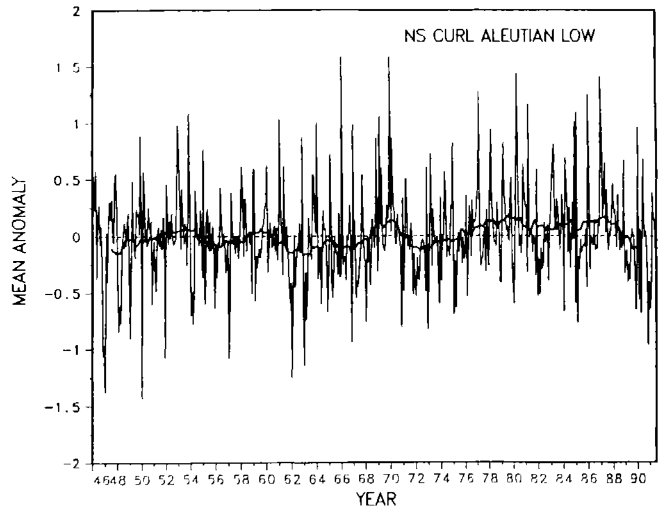
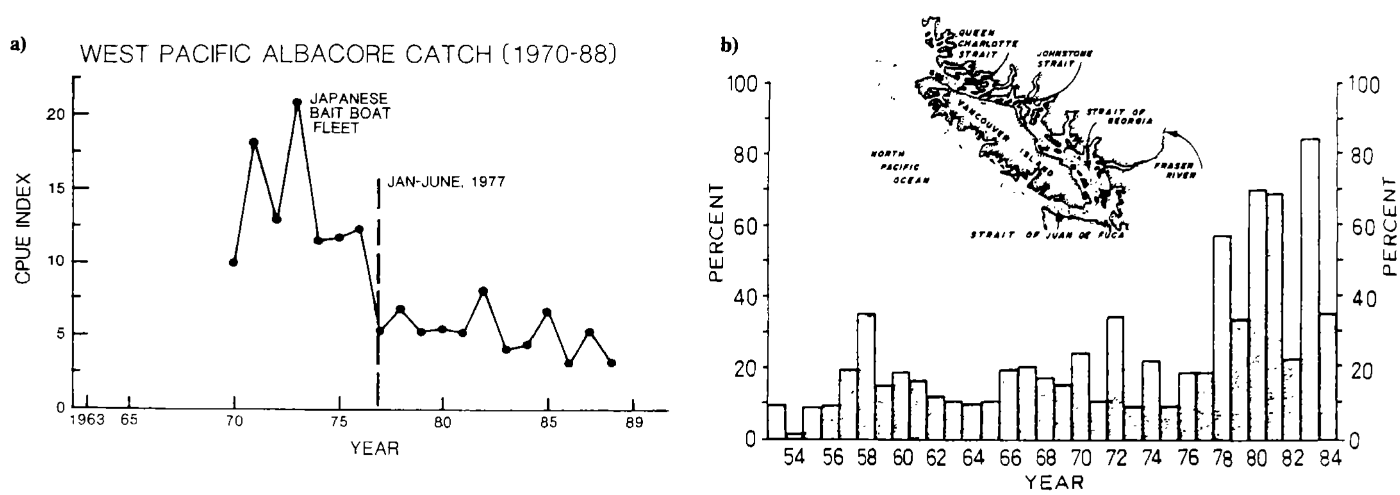



**Figure 15.**
a) Time series of catch per unit effort (CPUE) index for Albacore in the western North Pacific (Kuroshio Extension) (Japanese bait boat fleet data) (from T. Barnett, personal communication);
b) Inset: migratory routes of adult sockeye salmon on their way to the Fraser River and other southern British Columbia and Washington State spawning grounds. Histogram: percentage of sockeye salmon approaching the Fraser River through the northern passage during 1953–84 (from Mysak, 1986).




Moreover, it seems unlikely that the deeper-than-normal Aleutian low arises from changes in land-sea contrast in the Northern extratropics. Instead, the changes appear to be strongly linked to those in the tropics. Bjerknes (1966) was the first to note the association between a deeper-than-normal Aleutian low in the North Pacific and ENSO events in the tropical Pacific. Modelling studies (Shukla and Wallace, 1983; Blackmon *et al.*, 1983) with specified tropical SSTs corresponding to ENSO events indicate that the North Pacific atmospheric circulation responds to heating and convection in the tropical Pacific.

In the 1977-88 period noted as an example of interdecadal variability in the North Pacific, there were three ENSO events (1976-77, 1982-83, and 1986-87), (see Figure 16), and the winter of 1977-78 was also under the influence of the tail end of the 1976-77 ENSO. However, there were no cold events (La Niñas) during this interval. As a result tropical Pacific SSTs averaged above normal while the reverse is the case for anomalies of heat content in the western tropical Pacific (Figure 17). In the North Pacific, exceptionally deep Aleutian lows formed in all four winters and contributed strongly to the regime (Figure 6). However, the winter of 1980-81, which was not an ENSO year, also exhibited a very deep Aleutian low (Figure 6), and even in the intervening years from 1977-88 the Aleutian low did not recover to such high values as found in previous decades.

The imbalance between warm and cold events in the Pacific from 1977-88 was but part of the anomalously warm conditions that extended to the Indian Ocean (Nitta and Yamada, 1989). Both Nitta and Yamada and Graham (1992) have noted corresponding changes in the outgoing longwave radiation (OLR). Although Chelliah and Arkin (1992) have shown that some of the apparent trends in OLR are due to changes in instruments and satellite equator crossing times, Graham (1992) analysis of Highly Reflective Cloud data and moisture convergence strongly support the idea of a mid-1970s increase in convection over the west-central equatorial Pacific. These aspects can be tested more thoroughly in modelling studies, as described next.

## MODELLING

The interdecadal atmospheric variability found in the 1970s and 1980s has been simulated by several modelling groups using specified observed monthly mean SSTs over the globe, and subregions of the globe.

Graham (1992) describes results from a simulation using the ECMWF-MPI AGCM when forced with observed global SSTs for the period 1970-1985. The results show the model is capable of qualitatively reproducing several important aspects of the interdecadal variability over the Northern Hemisphere. For example, Figure 18 shows the first mode from a canonical

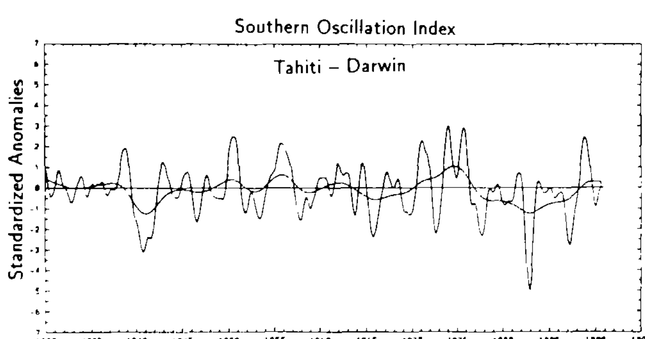



Figure 16.
Southern Oscillation Index, standardized anomalies (1930–1990).

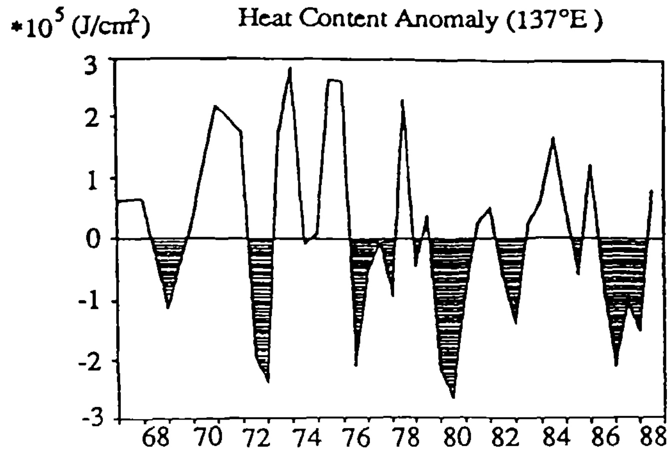



**Figure 17.**
Observed time series of heat content anomalies (above a depth of 300 m averaged between 2°N and 10°N along 137°E) (from Yamagata and Masumoto, 1992).

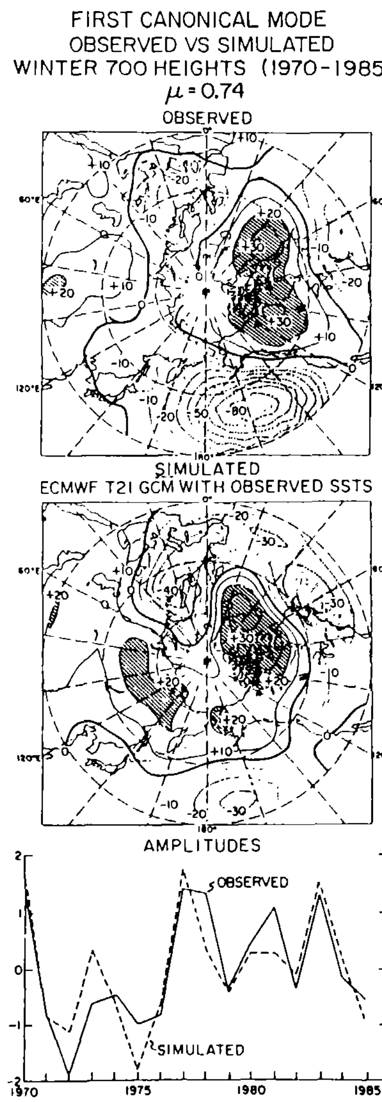
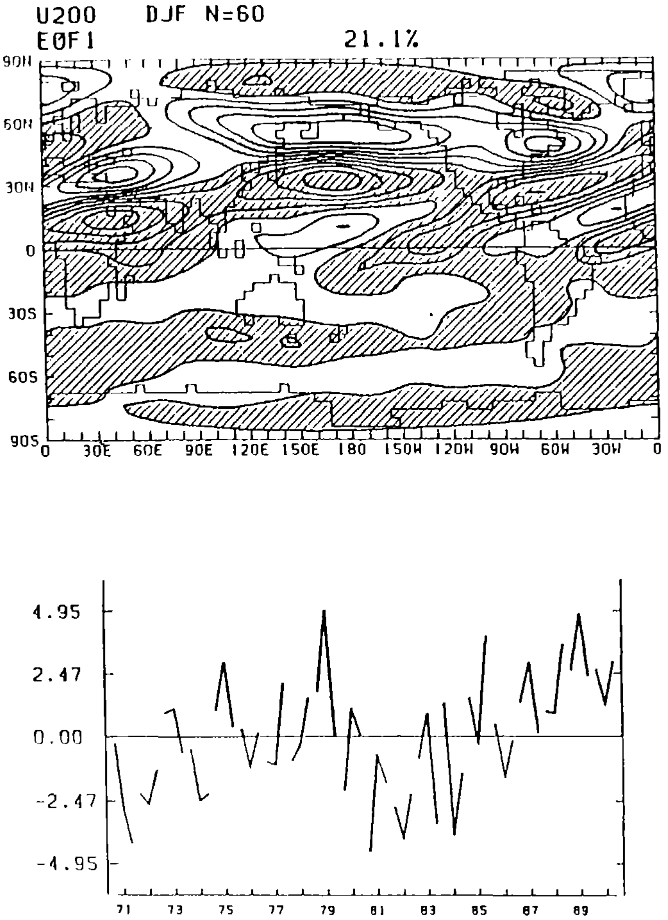



**Figure 18.**
First Canonical Mode observed vs simulated (ECMWF–MPI GCM) boreal winter 700 mb height, 1969–70 through 1985–86. Spatial patterns are shown in upper (observed) and middle (simulated) panels: stippling (hatching)shows large negative (positive) values; zero contour is heavy. Bottom panel shows temporal amplitudes (from Graham, 1992).

**Figure 19.**
First EOF of the zonal wind at 200 mb (from Kitoh, 1991).




correlation analysis of observed and simulated boreal winter 700 mb heights from 1969-70 to 1985-86. The pattern of negative height anomalies (cf also Figure 8) over the central North Pacific, the eastern U.S., western Europe and eastern Asia is well reproduced, as well as its temporal characteristics associated with the change around 1976.

Kitoh (1991) has integrated the Marine Research Institute's Atmospheric General Circulation Model (MRI-AGCM) using observed SST (40°S to 60°N) during the period 1969 to 1990. The first EOF of the zonal wind at 200 mb is characterized by the meridional migration of the jet stream over the North Pacific with a time scale of about 10 years (Figure 19). The pattern of the correlation coefficients between SST and the first EOF suggests that the tropical Pacific SST east of New Guinea is a key region for the interdecadal variation of the midlatitude jet stream (Figure 20). The importance of tropical SSTs on midlatitude atmospheric variability has also been suggested in studies by Geisler *et al.* (1985), Palmer and Mansfield (1986) and Graham (1992), and it appears that an inherent extratropical mode may be excited. Lau and Nath (1990) have suggested that the midlatitude SSTs may also be important.

In addition to the influence of SSTs on the atmosphere, it is also apparent that atmospheric variability may influence the ocean, especially in the tropics. Using a tropical ocean model forced by FSU winds, Inoue and O'Brien (1987) suggested that a long-term trend in the sea level records observed in the tropical western Pacific from 1974-81 is related to the observed weakening of the tradewinds in the central Pacific. Kitamura (1990) also showed a similar trend in the dynamic height field using an ocean GCM forced by the same wind data (see Figure 21). Away from the equator the decadal-scale response of the Pacific Ocean has also been well simulated (Miller *et al.*, 1992).

Although the AGCMs and OGCMs with the fixed boundary conditions are qualitatively successful in simulating overall features of certain types of interdecadal variations, interdecadal climate variability is likely a consequence of the coupled ocean-atmosphere interaction. A fully coupled ocean-atmosphere-ice model focusing on this important natural variability is needed to understand the physical mechanisms of the complicated interactive processes (see also **The Atlantic Modelling** section below).

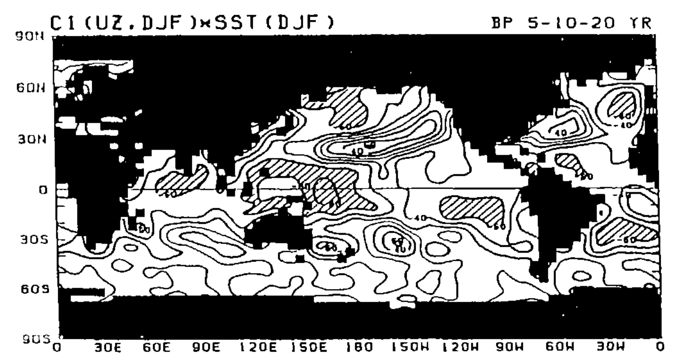



**Figure 20.**
Correlations between the filtered $C_1^{GCM}(U)$ and the filtered SST (from Kitoh, 1991). The filter has a 1.0 response at 10 years and a 0.5 response at 5 and 20 years. Values less than –60% are hatched.

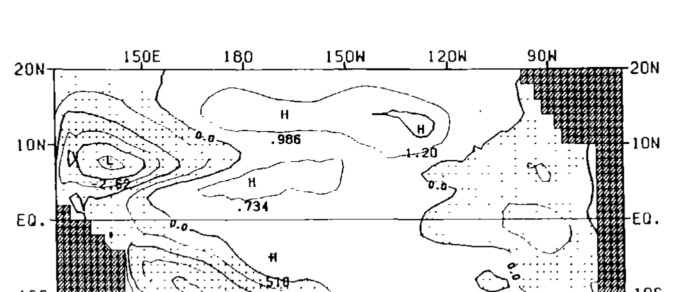


**Figure 21.**
Linear trend in the dynamic height determined by least square regression of a straight line to a time series for the 1975–1981 period (from Kitamura, 1990). Contour interval is 0.5 dyn.cm/year. Shaded area indicates the negative sense (decreasing with time).

# THE ATLANTIC

It becomes quickly apparent in reviewing available time series from the Atlantic region that the dominant processes of decadal-scale change are quite specific to the Atlantic sector, and that in many cases the decadal-scale is selected out of the expected continuum in the physical and biological changes that are observed. Thus, in contrast to a recent statement of Wunsch (1991), the frequency/wave number spectrum of the Atlantic Ocean variability is **not** "almost surely everywhere filled".

Within the constraints imposed by the time series, we first identify a number of the key elements of change specific to the Atlantic sector. As mentioned above, the Atlantic is quite distinct from the Pacific in that it contains the world's main regions of deep water formation, a process which drives the global thermohaline circulation. Since this meridional overturning circulation is forced by surface buoyancy fluxes, the processes of evaporation and precipitation, heating and cooling, runoff, and sea-ice formation and melting are particularly important.

## OBSERVATIONS AND PROCESSES

### Hemispheric versus Regional Temperature Changes

Compared with the annual mean surface temperature fluctuations for the northern hemisphere for the period 1861-1984, carefully weighted and adjusted to reflect time variation in data-type and quality (Figure 22a), temperature anomalies for the North Atlantic show a different pattern of change in the area 40-70°N, 10-60°W (Figure 22b). Following a generally warm period in 1950s and early 1960s, a cooling of the North Atlantic occurred in recent years, which contrasts with warming hemispheric air temperatures (Figure 22a, from Ellett and Blindheim, 1991).

### Thermohaline Circulation (THC)

The northern North Atlantic is of global importance for climate as in this region the Greenland Sea is the site of a deep convection center which drives the THC. The warm salty waters which circulate to high latitudes via the Atlantic and Norwegian currents are cooled during winter to form a range of intermediate and deep watermasses of moderate-to-high density; associated with this cooling process is the release of a large amount of heat to the atmosphere. The Denmark Strait and Faroe Bank Channels in the Greenland-Scotland Ridge allow these dense watermasses to overflow back to the North Atlantic, where they deepen to form (with Weddell Sea Bottom Water) the abyssal limb of the global thermohaline circulation. While the time scales of this interhemispheric circulation are significantly longer than decadal, the convection processes involved are relevant to the decadal-scale. In part, the outflows are responsible for drawing in the northward flux of heat and salt through the Norwegian Sea which supports the convection process. This inflow is of great climatic significance to northern Europe (see Figure 23).

### Deep Convection

The large volume of the Greenland Sea (500 000 km$^3$ below a depth of 1500 m) in relation to the annual deep water formation rate (0.5 Sv; Heinze *et al.*, 1986) means that the rate of deep water renewal and T-S properties of

a) b)

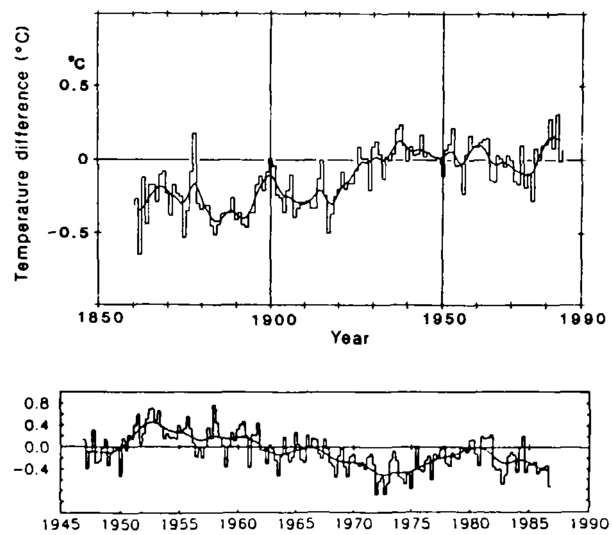



**Figure 22.**
a) Northern Hemisphere annual mean temperature variations (from Jones *et al.*, 1986). Smooth curves show 10–yr gaussian filtered values.
b) Seasonal temperature anomalies from 1951–1980 means for the N. Atlantic (40–70°N, 10–60°W), 1947–86 formed from SSTs and land data weighted by area (from Jones *et al.*, 1987). Smooth curves show 5–yr gaussian filtered values.

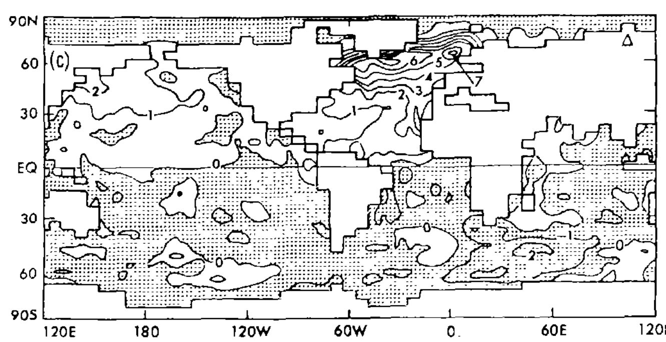
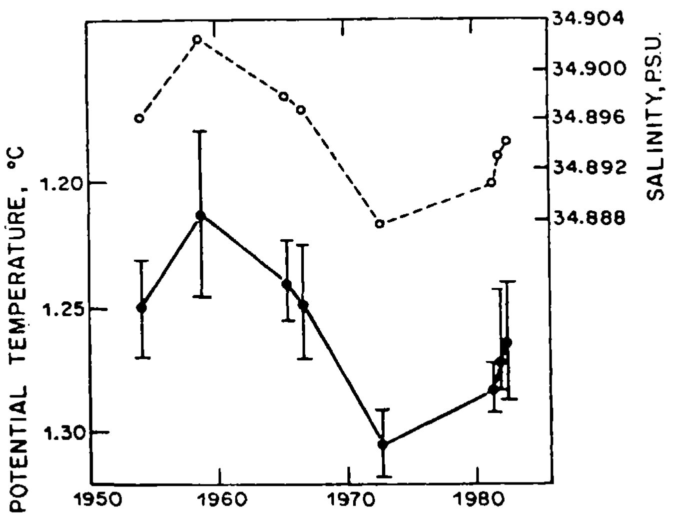



**Figure 23.**
The difference in SST patterns between the climate states obtained by Manabe and Stouffer (1988) in a coupled model of the ocean and atmosphere. The SST associated with an active Atlantic conveyor belt has been subtracted from the case with little thermohaline circulation, in degrees Centigrade.

the overflow waters change relatively slowly, on the time scale of decades. However, Greenland Sea deep convection is sensitively balanced. Aagaard and Carmack (1989) show that of the approximately 100 000 $km^3$ of fresh water that is stored within the Arctic/subarctic, the addition/relocation of only 100 $km^3$ to the deep part of the Greenland Sea would completely shut down deep convection.

From the ICES Deep Water Project we now have evidence that the properties of Greenland Sea Deep Water do indeed vary slowly with time. Figure 24 demonstrates that decadal-scale changes in temperature and salinity below 2000 m occur in the central Greenland Sea, implying a reduction of deep convection in recent years. This slowdown in the renewal of the Greenland Sea Deep Water has since been confirmed by Meincke *et al.* (1992), and has also been inferred from tracer data by Schlosser *et al.* (1991).

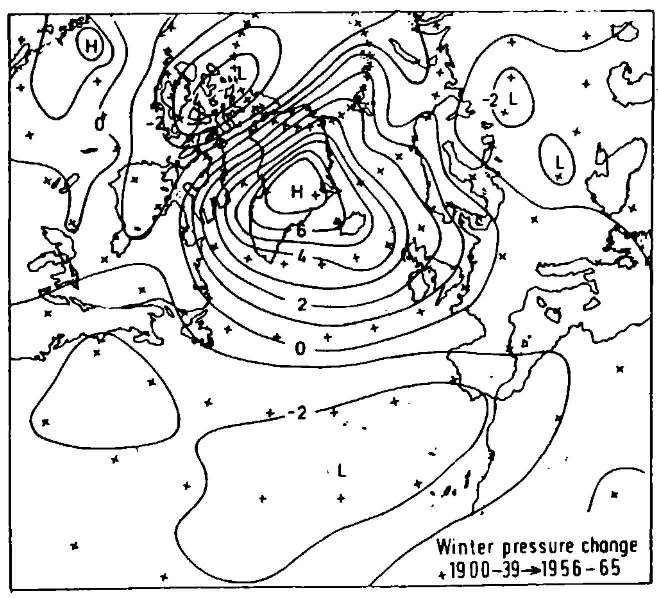
**Figure 24.**
Temperature and salinity changes below 2000m in the Greenland Basin (from Clarke *et al.*, 1990).




## Great Salinity Anomaly (GSA)

The surface export of fresh water and sea-ice from the Arctic Ocean to the Atlantic via Fram Strait is also sensitively balanced and subject to radical change, with widespread and long lasting effects on the circulation and properties of the subpolar (northern) gyre (Dickson *et al.* 1988a). The 'Great Salinity Anomaly' that resulted from an extreme perturbation of this freshwater/ice system in the mid 1960s represents the largest decadal-scale change known in the ocean climate of the northern gyre. Establishment of an intense and persistent high pressure anomaly cell over Greenland during a series of winters in the 1960s promoted anomalously strong northerly air flow over the Greenland Sea at that time (Figure 25). This brought sufficient fresh water south into the Icelandic Basin to reduce the surface salinities there below the critical value (34.7) for suppression of convection (Figure 26). Thus

**Figure 25.**
Mean change of winter sea level pressure (mb) between 1900–1939 and 1956–1965 (from Dickson, Lamb, Malmberg and Colebrook, 1975).



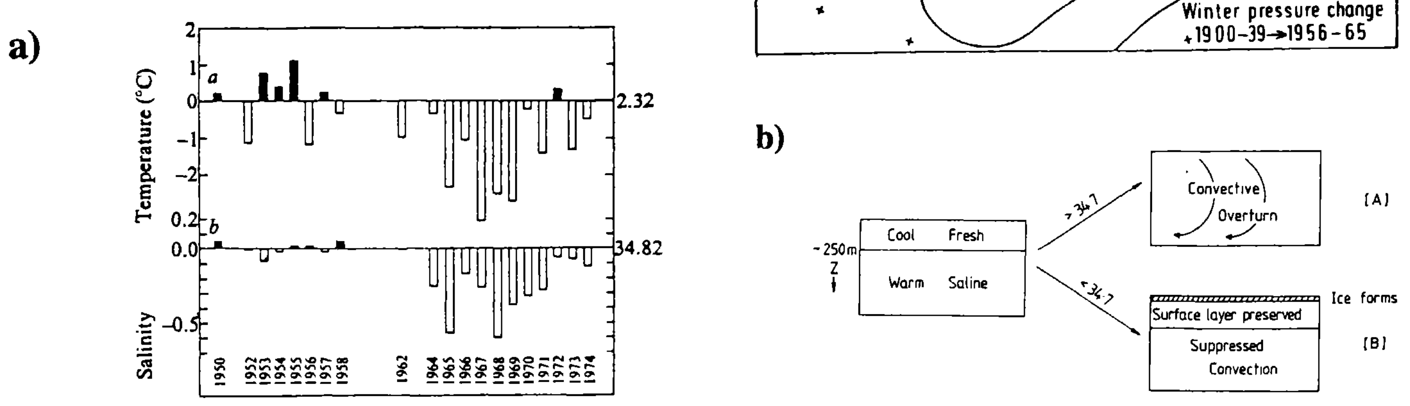




**Figure 26.**
a) Anomaly of (a) temperature and (b) salinity in June at 25m depth in a study area between Iceland and Jan Mayen (67–69°N, 11–15°W) (from Malmberg, 1973). The long-term means 1950–1958 are also shown.
b) Schematic diagram illustrating the suppression of convection north of Iceland as upper-ocean salinities decrease below 34.7.

the surface fresh water layer was not mixed out, but was exported to the North Atlantic via the subpolar gyre. High runoff from Arctic Canada to the western Arctic Basin in antecedent years may have enhanced the freshwater supply in the Arctic (Mysak *et al.*, 1990) and helped generate large positive sea-ice anomalies in the Arctic Ocean which propagated southward via Fram Strait into the Greenland Sea and subsequently into the Labrador Sea during 1968-73, contemporaneous with the GSA (Mysak and Manak, 1989; Mysak *et al.*, 1990). Walsh and Chapman (1990) have argued that anomalous winds north of Fram Strait prior to 1968 may have also contributed to the formation of the GSA.

Mysak *et al.* (1990) propose that a 10-component negative feedback loop (a simplified version of this is given in Figure 27) connects the processes of Arctic cyclogenesis, runoff, surface salinity, sea-ice, Arctic Ocean advection and Greenland Sea convection. A sufficiently strong perturbation in this loop could result in self-sustained climate oscillations in the Arctic and Greenland Sea with an estimated cycle period of 15-20 years. It is also suggested (Mysak *et al.*, 1990; Mysak and Power, 1991) that earlier and later observations of sea-ice anomalies in the Greenland Sea support the idea of such a cycle and the rapid-onset/slow-recovery characteristics that are associated with it. Certainly the time series resulting from the long-term monitoring of the salt supply to the Greenland and Norwegian Seas through the Faroe Shetland Channel since 1900 identifies more than one of these negative salinity anomalies (Figure 28).

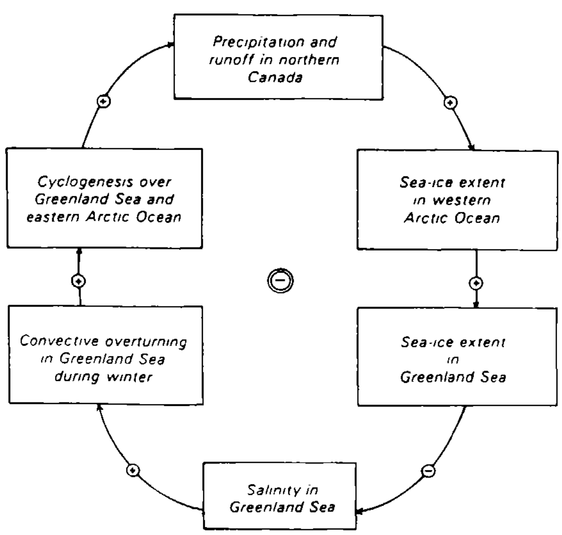



**Figure 27.**
Simplified version of the Mysak *et al.* (1990) negative feedback loop which implies the existence of an interdecadal climate cycle in the Arctic and Greenland Sea (from Mysak *et al.*, 1990). In this cycle, convection in the Greenland Sea alternates between a strong and a weak state, according to whether the surface salinity there has climatological or well–below climatological values.


**Figure 28.**
Salinity time–series for North Atlantic and Arctic Intermediate Water masses in the Faroe–Shetland Channel, 1902–1982 (from Dooley, Martin and Ellett, 1984).

## Gyre Circulation Rates and Scales

The propagation of the GSA (Dickson *et al.*, 1988a) and the accompanying heavy ice anomaly (Mysak and Manak, 1989) in the Greenland and Labrador seas give a first direct measure of mean speeds around the northern gyre (the gyre scale represents one more reason to expect a decadal-scale response in what we observe). From a carefully pieced together surface salinity record for the Rockall Channel, Ellett and Blindheim (1991) noted the arrival of the GSA signal there in late 1975 (Figure 29), some 3-4 years after it passed south along the Labrador slope. Spreading of an earlier high salinity extreme can be traced through parts of the subpolar gyre in the 1930s, though generally the series are too patchy to allow any but the most extreme signals to be traced.

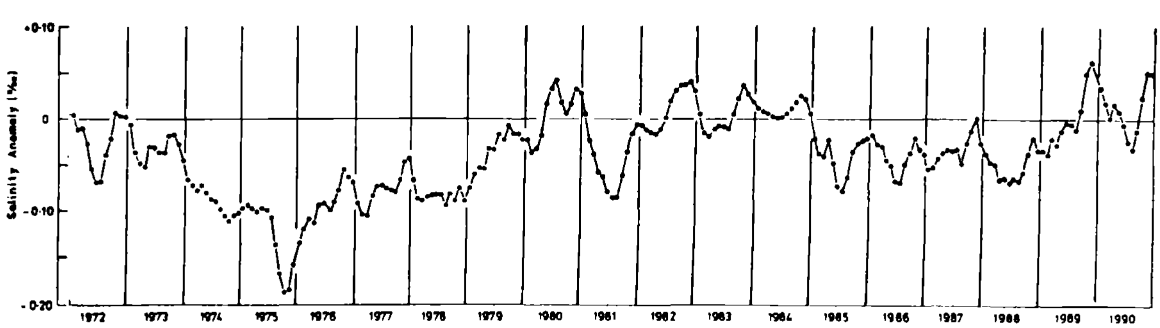
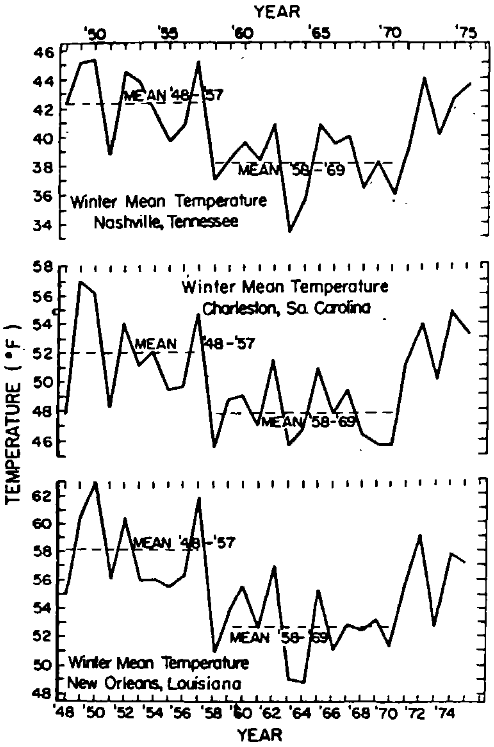



**Figure 29.**
3-month running mean of monthly salinity anomalies from 1961-70 means for the central Rockall Trough, 1972-1990 (from Ellettand Blindheim, 1991).

## Possible Influences on GSA Generation from Climatic Changes over North America

The relatively narrow width of the North Atlantic as compared with that of the Pacific may help explain the persistence of the Greenland high pressure anomaly cell (Figure 25) which partly initiated the GSA. Specifically, the decadal-scale cold regime of winter air temperature over North America, which was particularly intense over the southeastern USA during the 1960s (Figure 30), gave rise to an enhanced baroclinic contrast at the U.S. eastern seaboard that resulted in more frequent and more intense development of cyclogenesis there (Figure 31). As a consequence the Greenland ridge intensified half a wavelength downstream (Figure 32).

**Figure 30.**
Winter mean temperatures at Nashville, Charleston and New Orleans from 1947–1948 (labeled "48") to 1974–1975 (labeled "75") (from Dickson and Namias, 1976).



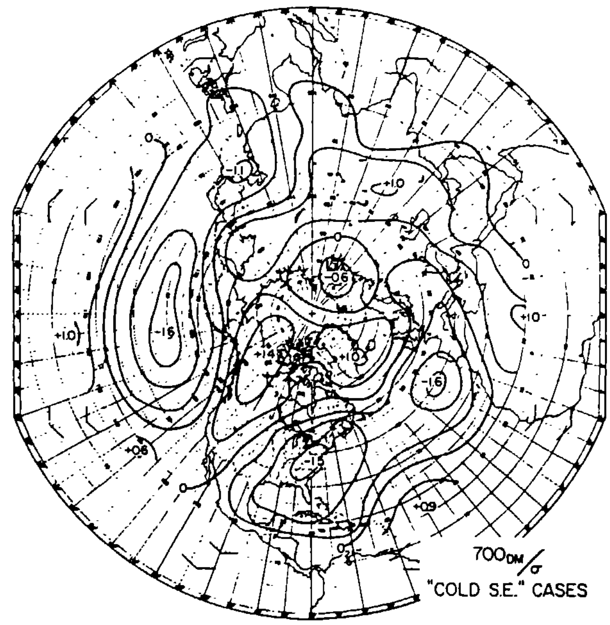




**Figure 32.**
Mean distribution of standardized 700 mb height anomaly for the cold SE group of winter months (from Dickson and Namias, 1976). The terms "anomaly" or "DM" refer to the departure from the long term mean; σ is the standard deviation.

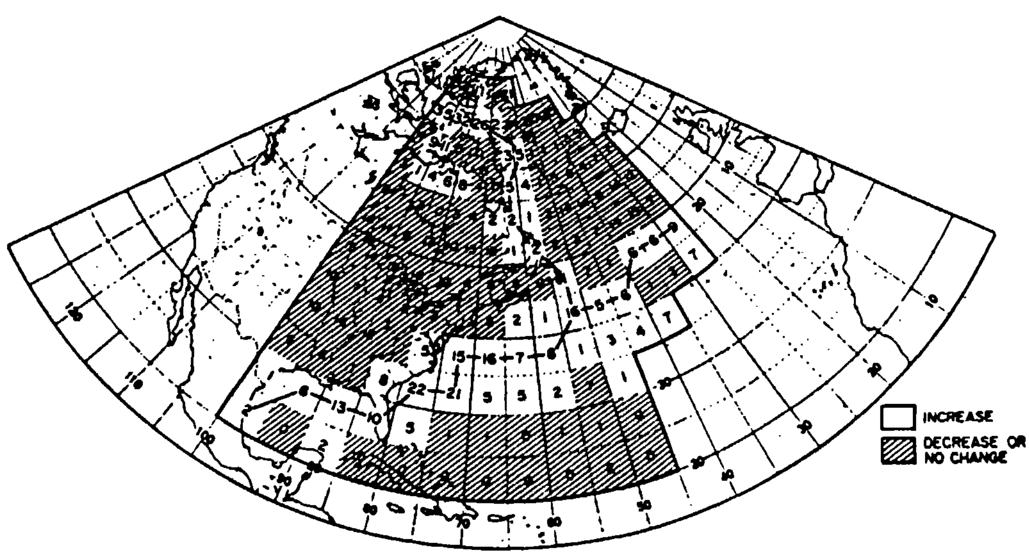



**Figure 31.**
Change in the (7–month) total number of cyclones (by 5° squares) between the warm SE and cold SE groups of winter months; areas of decreasing or unchanging cyclone frequency are hatched (from Dickson and Namias, 1976)

## Watermass Changes: Labrador Sea and Subpolar Gyre

The propagation of the GSA signal around the margins of the Labrador Sea was accompanied by a capping (or severe reduction) of winter convection at OWS BRAVO in the central Labrador Sea in the early 1970s (Lazier, 1980). This was caused by the cooling and freshening of the surface waters there (Figure 33), which may have been partly due to large sea-ice anomalies (Marsden *et al.*, 1991) that were associated with the GSA. In winter 1972, deep winter convection was renewed at OWS BRAVO (Myers *et al.*, 1990), and continued throughout the 1970s and into the 1980s (Read, 1992). Although CFC data hint at some suppression of convection again in the early 1980s, Wallace and Lazier (1988) report that a renewal of deep convection in the Labrador Sea water had certainly developed by 1986.

There seems little reason to doubt that a downstream effect of the GSA was the arrival in the eastern Atlantic of a sudden unprecedented cooling and freshening by up to 7 standard deviations from the long-term mean in the appropriate (1600 m) layer of the ANTON DOHRN seamount section of the Rockall Channel in 1990 (Figure 34). This event provides the first direct evidence of spreading rates at intermediate depths in the northern gyre.

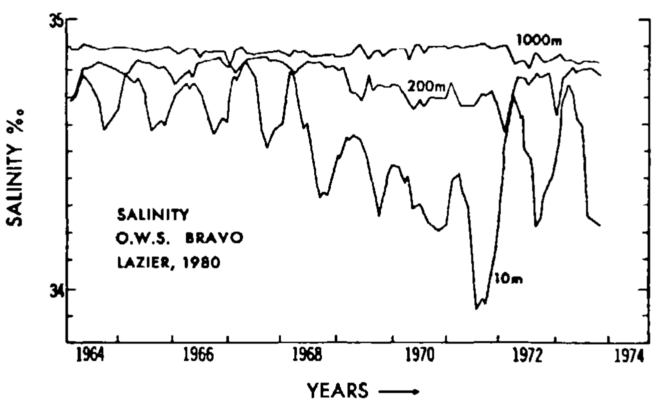



**Figure 33.**
Salinity as a function of time at 10, 100, and 1000 m depth at OWS BRAVO in the Labrador Sea, from Lazier (1980).

## Watermass Changes: Barents Sea

Ådlandsvik and Loeng (1991) propose a feedback system for the Barents Sea climatic system in which variations in Atlantic inflow determine the position of the Barents Sea polar front, which in turn influences the winter ice coverage and hence the heat flux to the atmosphere. Figure 35 shows a close agreement

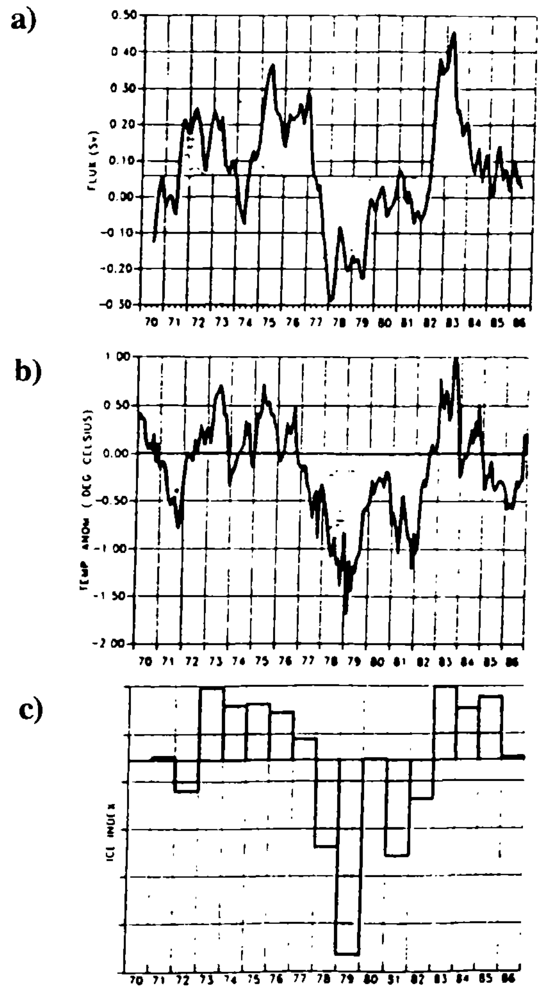


**Figure 35.**
a) Moving 1-yr means of modelled monthly flux through the Fugløya–Bjørnøya section;
b) Monthly temperatures from the Kola section from Bochov (1982); and c) Barents Sea winter ice index (from Ådlandsvik and Loeng, In press).

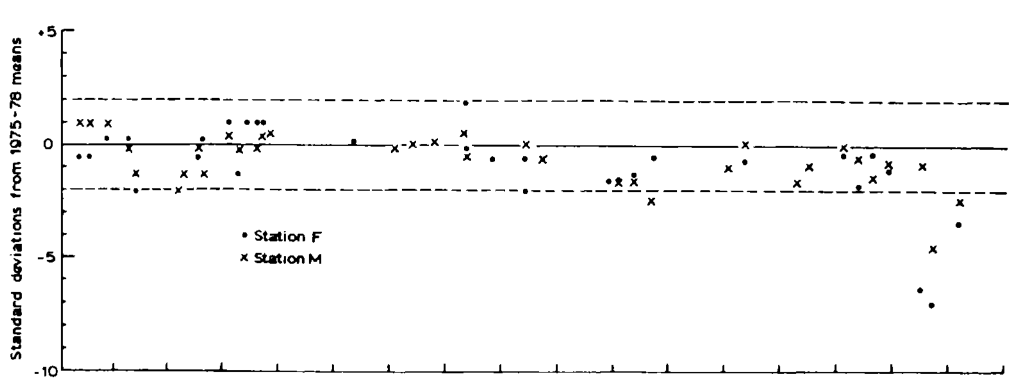



**Figure 34.**
Salinity variations at 1600m depth, Anton Dohrn Seamon section along approximately 57°25'N, Northern Rockall Trough (unpublished data from D.J.Ellett, SMBA, personal communication).

between modelled monthly mass fluxes through the Fugløya-Bjørnøya section, the observed temperatures along the Kola section and the Barents Sea winter ice index over the period 1970-86. Thus these authors suggest that the Barents Sea climate oscillates on a decadal time scale between a warm and a cold state through the feedback mechanism (further evidence of this oscillation is given in Figure 36) and that the formation of bottom water on the Barents Sea shelf is important in determining that state. (Either dense bottom water drains from the shelf allowing Atlantic water to enter, or Atlantic water inflow displaces bottom water.)

### Watermass Changes: West Atlantic

A changing frequency of cold air outbreaks from the North American continent is regarded by Worthington (1977) as responsible for corresponding changes in the formation rate of 18°C mode water and for increases in Gulf Stream transport after the winter of 1976/77. The "18C" mode water history at the Panulirus site (32°10'N, 64°30'W) has been reconstructed after 1954, and shows changes that are coherent with the winds in the Gulf Stream sector. There, the upper water column was denser and colder from 1964 to 1975 than before and after (Talley and Raymer, 1982), and the density of the mode layer increased, although its ventilation rate did not change (Figure 37 from Jenkins, 1982). Changes in other mode waters and other water masses have been found in the eastern Atlantic (Pollard and Pu, 1985), but time series for this region are more difficult to construct.

### Midlatitudes and Tropics

In large areas of the tropics, sub-tropics and mid-latitudes of the Atlantic Ocean, sea surface temperature exhibits a significant variability at decadal and interdecadal periods of a magnitude comparable to the annual fluctuations (though there is little sign of a systematic El Niño response) (Folland and Parker, 1990). These variations are coherent over a larger zonal than meridional domain (Lau and Nath, 1990). Whether they occur simultaneously for the different latitudes is a matter of debate, depending to some extent on the length of the time series analyzed. Simultaneously, large fluctuations of Sahel rainfall have been observed, with lower rainfall between the late sixties and the mid eighties than in the fifties (Figure 38;

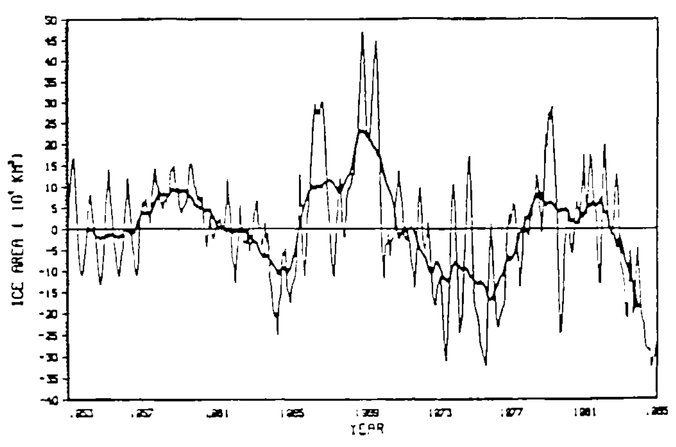


**Figure 36.**
Smoothed time series of monthly anomalies of areal sea–ice extent in the Barents Sea clearly showing a decadal–scale oscillation (from Mysak and Manak, 1989). Light and dark curves correspond to 3– and 25–month running means, respectively.

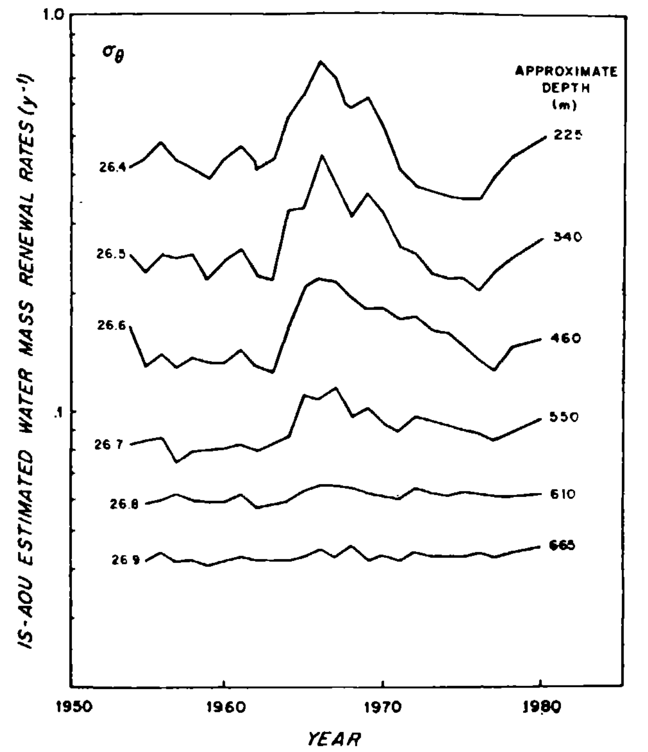



**Figure 37.**
Watermass renewal rate ($y^{-1}$) as a function of time for $26.4<\sigma_\theta<26.8$ (from Jenkins, 1982). The renewal (or ventilation) rate was estimated using the IS computed AOU and the oxygen utilization rates obtained from $^3H-^3He$ dating. Note the logarithmic scale and the alteration of relative amplitude with depth. Note also the increasing relaxation time with depth.

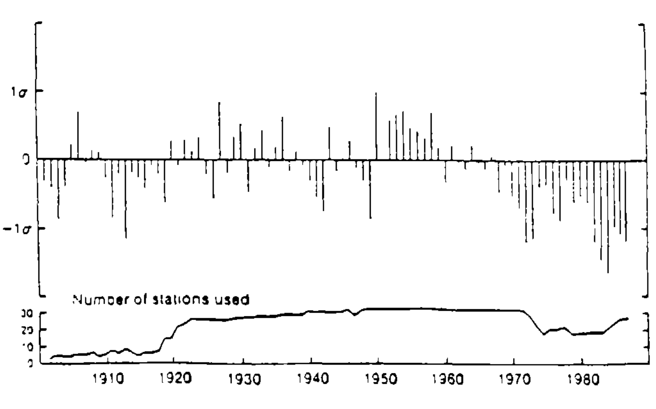



**Figure 38.**
Standardized annual rainfall anomalies for the Sahel, 1901–1987 (upper panel). Values to 1984 are from Nicholson (1985); 1985–1987 values are based on CLIMAT reports. The lower panel gives the number of stations used.

see also Nicholson (1985); Folland *et al.* (1991). Interestingly enough, similar decadal-scale variations in rainfall are not so prominent in nearby continental regions such as northeast Brazil, where interannual fluctuations are more evident (Hastenrath, 1984).

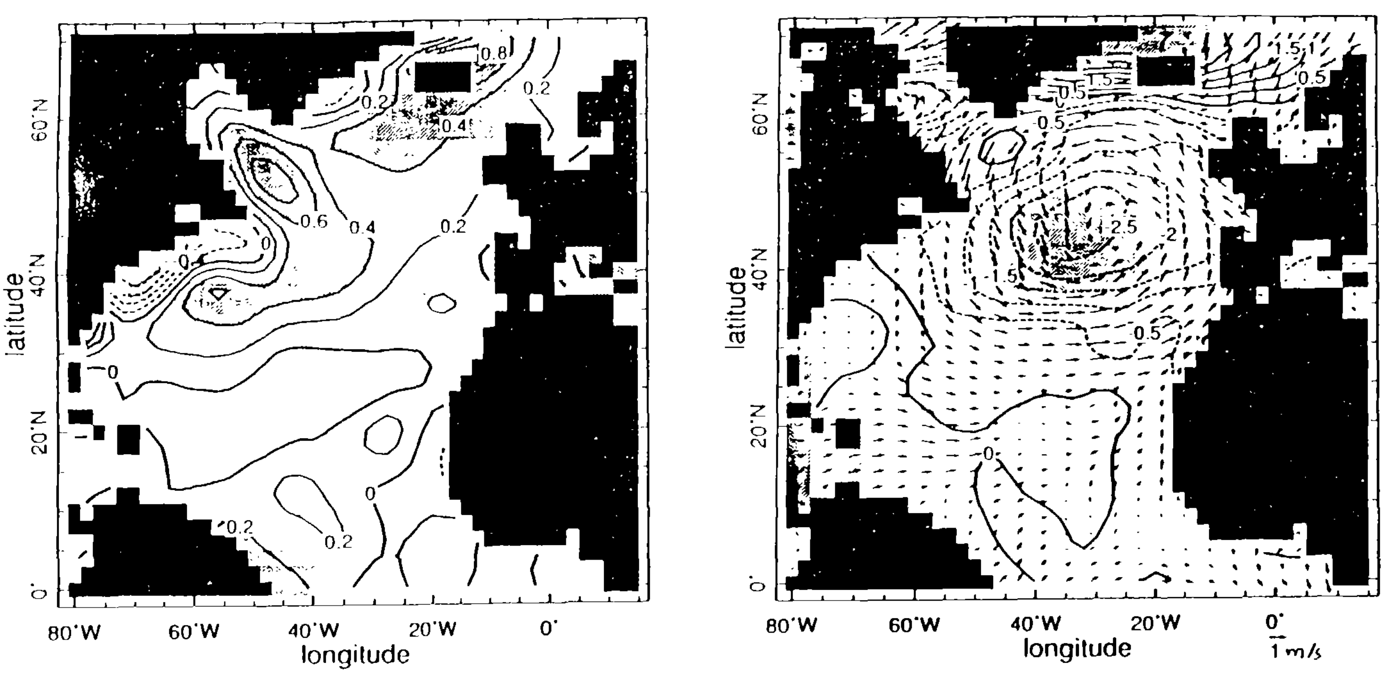
Hitherto, the examples of decadal-scale change quoted have been exclusively concerned with the physical environment. While useful in themselves in providing direct measurements of circulation processes and other oceanic features which can be used for the improvement and testing of models, they largely ignore the question of ecosystem impacts. The involvement of the ecosystem in Atlantic change is described below under four main headings: wind and coastal upwelling, $CO_2$ drawdown and global warming, changes in fisheries and the planktonic ecosystem, and warming in the subarctic.

## Wind and Coastal Upwelling

Quite apart from any future effect which global warming may exert, we have already observed since the mid-1950s an increase in alongshore windspeeds over the eastern Atlantic which is puzzling in its persistence over several decades (Bakun, 1990). This change is part of a large-scale variation of the surface atmospheric circulation over the North Atlantic, together with a change in winter SST (Figure 39). Compared to the recent decades, the northwest Atlantic was much warmer during the 1950s and early 1960s (Figure 39a), and the westerlies were usually found further south (Figure 39b). Also during those earlier years, the winds were less upwelling-favorable along the coasts of northwest Africa and Iberian Peninsula (Figure 39b).

These wind changes, documented also from ship reports of various quality, receive additional support from two independent sources: first, the frequency of watches in North Sea Light Vessels with winds of force 8 or greater (Lamb and Weiss, 1979) has itself shown a sustained increase, and second, the measurements of significant wave height at the Seven Stones Light Vessel (Western Channel) appears to have undergone a long-period increase (Carter and Draper, 1988).

The "depth of mixing" is an important control on the time-of-initiation, and subsequent development rate of the spring phytoplankton bloom. This is to say, a deeper mixed layer caused by increased winds say, has associated with it larger eddies which transport the phytoplankton to greater depths and hence keep them removed from the surface light source for longer periods of time. Thus Dickson *et al.* (1988b) regard the aforementioned sustained increase in meridional windspeed as responsible for the long-term decreasing trends in both phytoplankton and zooplankton standing




**a)** Sea Surface Temperature
Positive events: Winter 1950-64

**b)** Sea Level Pressure and Winds
Positive events: Winter 1950-64

**Figure 39.**
a) Composite winter SST for the period 1950–64 minus the period 1970–84 as derived from COADS. Shaded area indicates where the differences are significantly nonzero (at the 95% confidence level) (Y. Kushnir, pers. comm., 1992);
b) Same as a) except for sea level pressure and winds.

**Figure 40.**
Trends of zooplankton abundance in 12 CPR Standard Areas around the British Isles (from Dickson *et al.*, 1988b).

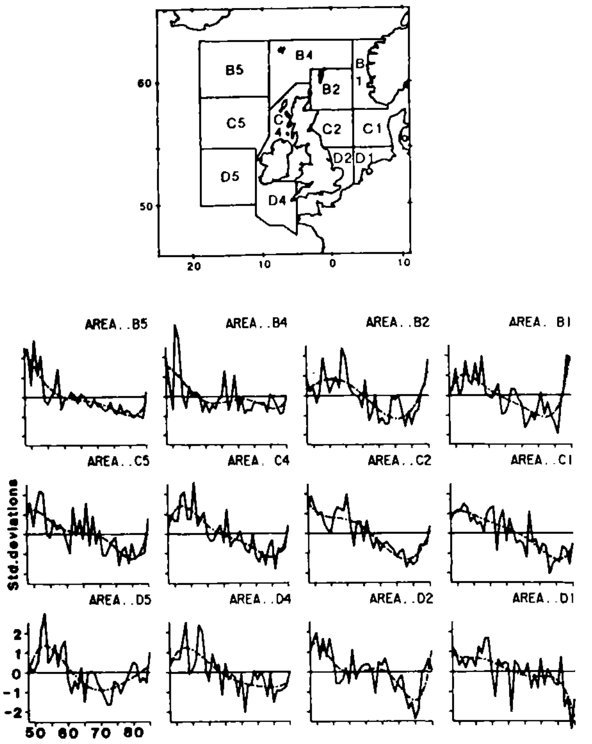
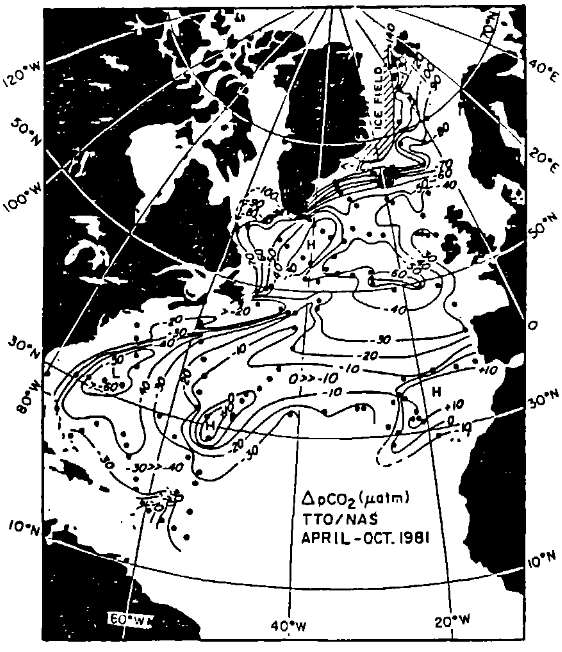



**Figure 41.**
Distribution of the sea–air $pCO_2$ difference observed during the TTO/North Atlantic Study Programme in April through October, 1981 (from Takahashi, personal communication). Note that the proposed 20°W JGOFS section passes through one of the most prominent low $pCO_2$ areas centered around 50°N and 20°W. The data are listed in Takahashi *et al.* (1982).




stock (Figure 40) in seas around Britain (including the eastern Atlantic).

## $CO_2$ Drawdown and Global Warming

Since the 1981 Transient Tracers in the Ocean (TTO) Expedition, it has been known that the largest sea-air $pCO_2$ difference in the North Atlantic (and, we suspect, one of the largest on earth) lies in a relatively narrow band (300 km wide or so) along the eastern margin of the East Greenland sea-ice from Cape Farewell to Spitsbergen. There, Takahashi *et al.* (1982) show $\Delta pCO_2$ values as low as 140 $\mu$atm in summer (Figure 41). The annual mean $\Delta pCO_2$ values estimated for this zone are naturally lower (-37 in the large region which includes this zone) but are nevertheless of Atlantic - and therefore of global significance, since much of the hemispheric drawdown of $CO_2$ occurs in the North Atlantic.

These TTO estimates may well underestimate the importance of this zone. $\Delta pCO_2$ values of -230 units have since been encountered along the ice edge north-west of Iceland, the largest difference from atmospheric concentrations (implying the largest $CO_2$ drawdown) yet observed anywhere.

The factors which promote such a radical drawdown (e.g., the abrupt onset of biological spring as the ice cover melts back, the sluggishness of the grazer response to such an abrupt onset, and the chemical pump through rapid cooling of surface waters as they circulate in towards the ice margin) are all particular to the marginal ice zone. The strip of thin sea-ice bordering East Greenland must be more sensitive to global warming than the bulk of the Arctic or Antarctic ice sheets, but short of its removal, interdecadal changes in the effectiveness of the subarctic seas as a $CO_2$ sink must result from decadal-scale changes in sea-ice extent, which have certainly been observed in the past (Mysak *et al.*, 1990).

In the North Atlantic sector, we have the promising beginnings of a time series to describe atmospheric $CO_2$ in the Norwegian records from OWS M (Figure 42).

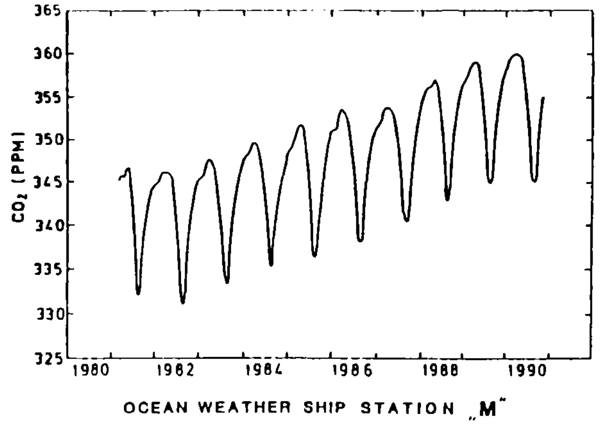



**Figure 42.**
Atmospheric $CO_2$ concentrations observed at Station "Mike" during the last decade NOAA (Conway *et al.* 1990). The observations compare well with the famous series from Hawaii (from Gammelsrod *et al.*, 1991).

These observations exhibit similarities but also seasonal differences from equivalent records elsewhere, yet being weather-ship based, are extremely vulnerable to vagaries of funding despite the global significance of $CO_2$ climatology in this sector and the vulnerability to climatic perturbation.

There is a role for plankton ecosystem monitoring in observing the effects of anthropogenic eutrophication. Continuous Plankton Recorder time series of many decades duration in the North Atlantic sector provide abundant evidence of interdecadal shifts in plankton community structure (Dickson *et al.*, 1988b). The biggest test with greatest economic repercussions lies in developing the existing system to inform us objectively and quantitatively of changes in toxic bloom prevalence, since the same relative shift in the community structure of the summer plankton is expected, for both natural climatic and anthropogenic reasons, in temperate waters.

### Warming in the Subarctic

As already stated, the main warming episode in the North Atlantic (40 - 70°N) during the present century occurred in the 1950s or 1960s, according to region. In most areas this peak was the culmination of a steady warming since the 1920s or 30s and was followed by sustained cooling (see Ellett and Blindheim, 1991). The ecological and socio-economic consequences of this warming episode in the subarctic were dramatic, especially along the West Greenland Banks.

In the early years of the warming trend between 1925 and 1934, a number of fish species including salmon, haddock, coalfish, spurdog, ling and dealfish appeared off West Greenland for the first time. The amelioration of conditions there led to the dramatic rise of the West Greenland cod stock through a variety of causes; it supported a succession of good year classes there (the first in 1917, 1922 and 1924, 5 even stronger year classes in succession in 1931-5, and the strongest of all in 1942 and 1945), it permitted the northward colonization of the Banks from Julienhaab in 1917 to Disko in 1936, and aided by the changing windfield, supported the exchange of fry and eggs with Iceland via the Irminger Currents (Cushing, 1982). By the time of peak warmth, the international cod catch at West Greenland had grown by 3 orders of magnitude from ~ 400 tonnes/a around 1920 to >450,000 tonnes/a in the early 1960s; in the late 1960s, however, there was a rapid decline (Figure 43).

Since there is evidence that the Icelandic cod stock was also partly sustained by these great year classes and by immigrant fish from Greenland, and since the fishery for cod in the Barents Sea also began in the late 1920s, these decadal-scale changes associated with the subarctic warming are justifiably described as of fundamental socio-economic importance. [Similar events may have happened in the past. Taning (1953) notes that cod were abundant as far north as Disko between 1840 and 1850.]

## MODELLING

Modelling work which simulates some of the decadal-scale North Atlantic climate variations described above has only recently begun and is an active area of research today. We shall now give examples of a few such modelling efforts which employ both GCMs as well as simpler models. The presentation will be divided into four parts: atmospheric GCMs, thermohaline and other ocean circulation models, coupled GCMs and simple models of the GSA.

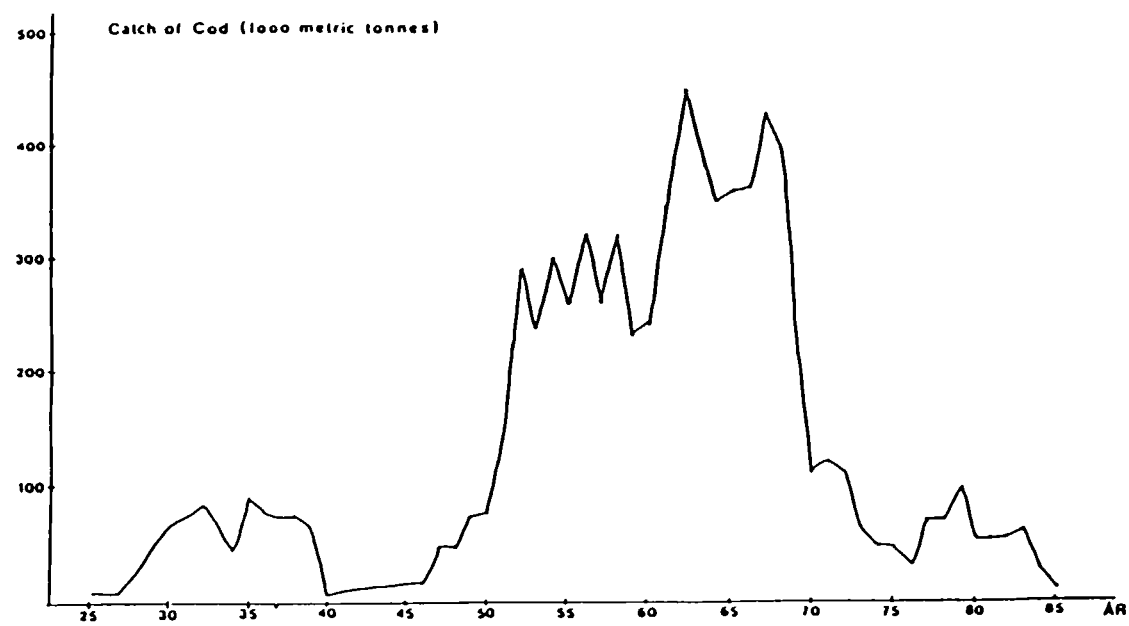



**Figure 43.**
Catches of cod off West Greenland 1925–1985 (from Buch and Hansen, 1988).

### Atmospheric GCMs

The response of atmospheric GCMs to specified extratropical SST anomalies in the North Atlantic has been calculated by Palmer and Sun (1985), Lau and Nath (1990) and others. Palmer and Sun also compared their simulations with observed atmospheric circulation anomalies. According to whether the winter SST anomalies over several years are warm or cold, different simulated and observed teleconnection patterns (at both 500 mb and sea level) which extend over Europe and Siberia are found. (An example of one of these patterns, a high-low-high pattern over the North Atlantic-Eurasian sector, can also be seen in Figure 18. The above results suggest that substantial shifts in the storm tracks over Eurasia occur in response to long-term SST anomalies. A consequence of the former could be the different patterns of precipitation that are observed over central Europe and western Siberia during the 1950s and 1970s (Figure 44).

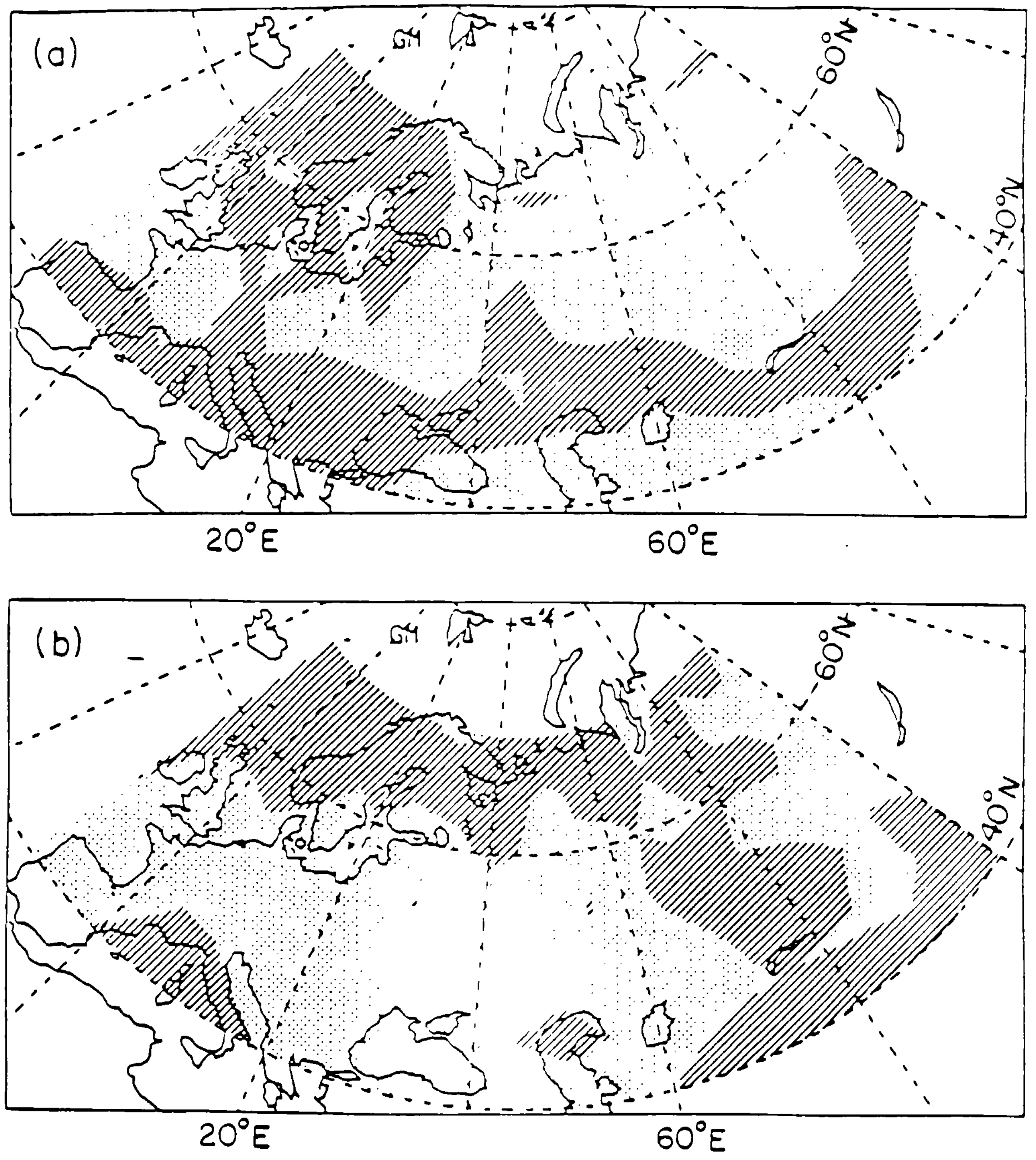



**Figure 44.**
a) Observed winter precipitation anomalies averaged over 1951–56 (a period of positive SST anomalies in the North Atlantic). Hatching indicates a positive anomaly and stippling indicates a negative anomaly. The anomalies are in the range of –30 to 40 mm (from Peng and Mysak, 1991);
b) As in a) but for 1971–76 (a period of negative SST anomalies in the North Atlantic).

The influence of observed SST variations on the Sahel rainfall has been investigated by the U.K. Meteorological Office (e.g., see Folland *et al.*, 1986; 1991) using their AGCM. In particular, Folland *et al.* (1991) found that observed rainfall anomalies for both the "wet" years in the 1950s and the "dry" years in the 1970s and 1980s (Figure 38), can be reasonably well simulated (Figure 45) and appear to be mainly due to SST anomalies in the tropical oceans. However, the agreement between the observations and the model results did improve when worldwide SST anomalies were included in the surface forcing fields.

### Thermohaline and other Ocean Models

The modelling of air-sea and air-ice-sea interactions which may support decadal (and longer-period) oscillations in the ocean began with the development of simple box models of the thermohaline circulation (THC) (Stommel, 1961; for a review, see Welander, 1986). This modelling approach to the study of internal variability in the deep ocean circulation is still an active area of research today (e.g., Marotzke, 1990; Joyce, 1991). In parallel with this recent work, however, there have been a number of ocean GCM studies which show that the THC may exhibit decadal-scale, self-sustained oscillations. (It was suggested some time ago by Bjerknes (1964) that such THC variability may cause decadal-scale climate fluctuations in the North Atlantic.) Weaver and Sarachik (1991a, 1991b) show that under mixed surface boundary conditions (i.e., a Newtowian restoring boundary condition on temperature and a specified flux condition on salinity), the Bryan-Cox ocean GCM can support internal, decadal oscillations for hundreds of years (Figure 46), which turn out to be confined to the convection region of the model domain. These fluctuations are associated with the advection of salinity anomalies into the region of deep water formation from the mid-ocean region between the subtropical and subpolar gyres. Because of the close link between observed salinity and sea-ice anomalies (Marsden, *et al.*, 1991), this type of oscillation may partly explain the well-defined decadal fluctuations that have been observed in the sea-ice cover of the Barents Sea (Figure 36). A particularly noteworthy result of the modelling work is that the existence of the oscillations is crucially dependent on an accurate prescription of the E-P forcing field (Weaver *et al.*, 1991).

In addition to the above THC modelling work, there have also been other theoretical studies to try and understand the nature and causes of decadal-scale variability in the North and tropical Atlantic. For example, in order to determine the consequences of the observed changes in the thermohaline structure of the North Atlantic between the two pentads 1955-59 and 1970-74 (see Levitus, 1990, and the papers quoted therein), Greatbatch *et al.* (1991) used the model of Mellor *et al.* (1982) to diagnose the change in the transport of the subtropical and subpolar gyres between the two pentads. The calculations suggest that the transport of the Gulf Stream was about 30 Sv weaker in the early 1970s than in the late 1950s, which is about one-third of the estimated long-term time-averaged transport. To study interannual and longer-term variability of the tropical Atlantic, an ocean GCM has been developed by French scientists (Morliere, Pers. comm., 1992) in which the forcing consists of monthly winds from ship reports and wind- and SST-dependent heat fluxes. While the model does exhibit decadal-scale changes, these do not agree well with the observations, possibly because of certain limitations associated with the meridional boundary condition and heat fluxes.

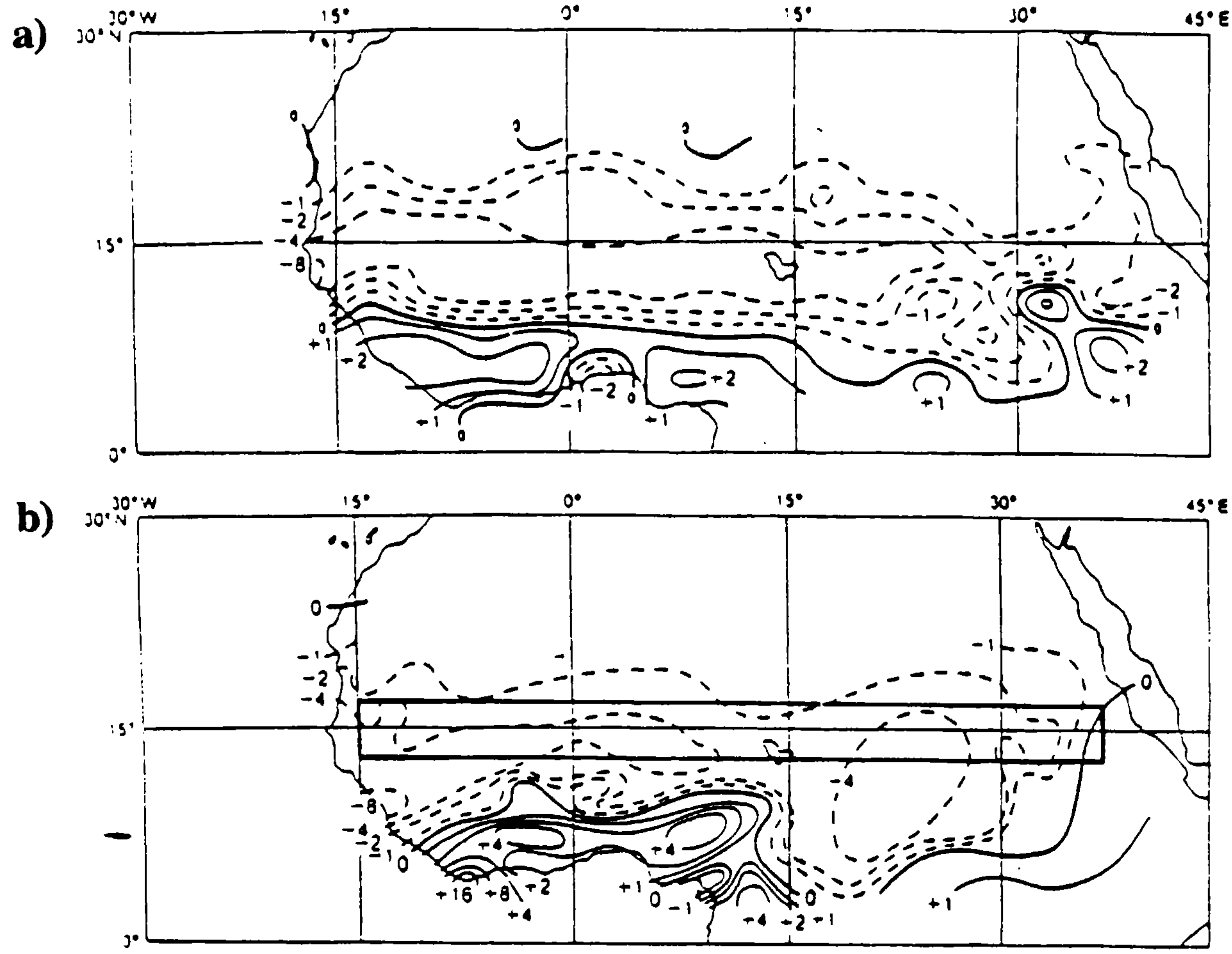
### Coupled Atmosphere-Ocean GCMs

The occurrence of internal interdecadal variability in climate simulations from various coupled atmosphere-ocean GCMs has recently been noted by several investigators (Manabe *et al.*, 1991; Von Storch *et al.*, 1992; W. Washington, 1992, pers. comm.). For example, Figure 47 shows that the global-mean and hemispheric-mean air temperatures undergo interdecadal fluctuations of several tenths of a degree celsius. In these calculations, adjustments (which vary spatially, but not in time) are added to the surface fluxes of heat and water in order to compensate for inherent biases in the model, and to yield an improved simulation of the mean climate. In more recent studies (T. Delworth, Pers. comm., 1992), it has been found that the northern hemisphere fluctuations seen in Figure 47 are due mainly to marked fluctuations in the intensity of the THC in the North Atlantic, which have an approximate period of 30 - 50 years and an amplitude of 1 to 2 Sv. Changes in the large-scale density field lead the fluctuations in the THC intensity by several years. Such density changes are also associated with in-phase changes of surface salinity and surface temperature, which are reminiscent of observed interdecadal fluctuations (Levitus, 1990). There are also clear relationships between these fluctuations and anomalies of salinity and temperature at depth, as well as with several atmospheric fields. A more complete analysis of the mechanism and significance of these model fluctuations is under current investigation.

### Simple Models of the Great Salinity Anomaly (GSA)

In addition to local atmospheric forcing as a mechanism for generating the GSA (e.g., see Figure 25), there were also non-local processes at work in the Arctic which may have contributed to the formation of the GSA: a) a strengthening of the winds over the Arctic Transpolar Drift Stream which transports ice into the Greenland Sea (Walsh and Chapman, 1990); b) a large increase in runoff into the western Arctic (Mysak *et al.*, 1990) which led to a large positive ice anomaly there in

**Figure 45.**
a) Modelled North African rainfall rate: difference between an experiment using 1984 SST and a similar experiment for 1950 averaged over July to September. Contours are 0, ±1, 2, 4, 8 and 16 mm/day, with negative contours dashed (from Folland *et al.*, 1991);
b) Observed North African rainfall rate: difference between 1984 and 1950 for July to September. Contours as in a).



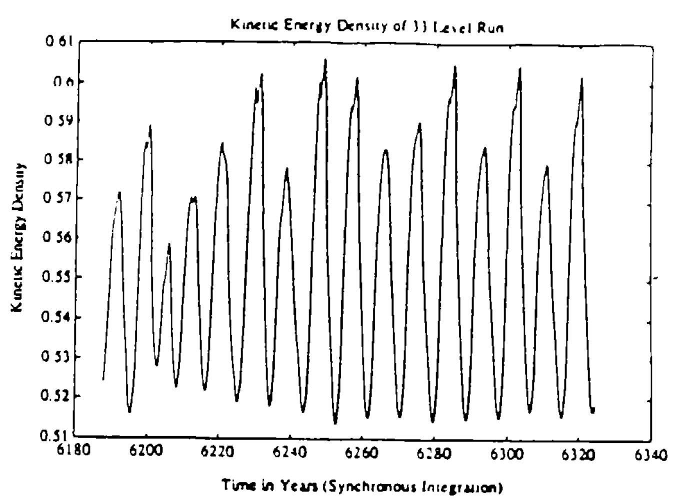




**Figure 46.**
Kinetic energy density ($10^{-1}$ kg m$^{-1}$ s$^{-2}$) for the 33-level synchronous integration run showing a 8.6-year period oscillation (from Weaver and Sarachik, 1991b).

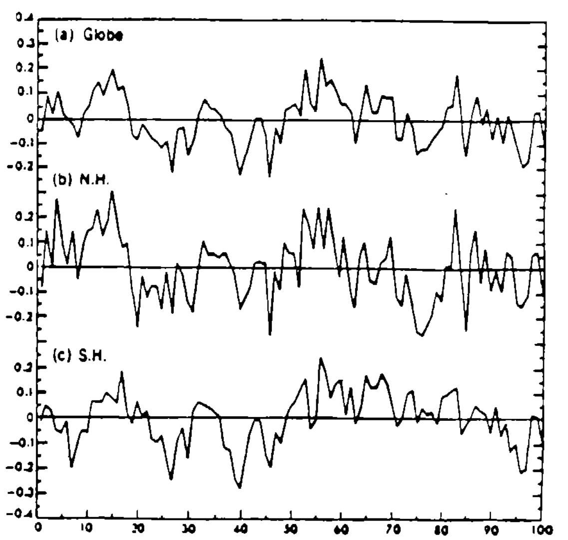



**Figure 47.**
The temporal variations of area-averaged deviation of annual mean surface air temperature (°C) from the 100-year mean temperature produced by an integration of a couple atmosphere-ocean GCM with present-day concentration of atmospheric carbon dioxide for a) globe, b) Northern Hemisphere, c) Southern Hemisphere (from Manabe *et al.*, 1991).

the mid-sixties (Mysak and Manak, 1989) that was subsequently transported into the Greenland Sea. The above processes, along with convection in the Greenland Sea and cyclogenesis in the Arctic and subarctic may be linked together by a negative feedback loop (Figure 27), which implies the existence of an interdecadal Arctic climate cycle. Darby and Mysak (1992) have recently used this loop as a framework to develop a Boolean delay equation model of interdecadal climate oscillations in the Arctic Ocean and Greenland Sea which includes the generation, evolution and disappearance of GSA-like events. Among other things, the model shows that the advection of both ice and salinity anomalies from the Arctic into the Greenland Sea are necessary to simulate a realistic time history of the GSA.

The advection and evolution of the GSA in the Greenland and Norwegian seas and in the Greenland and Barents seas has been modeled by Legutke (1991) and by Ikeda (1990), respectively. However, both of these studies use an atmospherically forced, limited-area ocean circulation model **without** an ice component. Thus they are not able to simulate important ice-ocean processes that are associated with the GSA. Nevertheless, in the Norwegian Sea (i.e., away from the marginal ice zone), Legutke's simulation of the spread of the GSA below the surface is quite successful (Figure 48). However, the fact that the modeled anomaly is only about half the strength of the observed anomaly in that region indicates that some important processes are missing in her ocean-only model.

To model the complete cycle of the GSA, from its possible origin in the western Arctic, to its near demise in the northern part of the Norwegian Sea (Dickson *et al.*, 1988a), a fully coupled ice-ocean circulation model needs to be used. Work is currently underway (D. Holland, 1992, pers. comm.) to simulate these aspects of the GSA as well as other features of interdecadal variability in the Arctic and North Atlantic oceans. In this study the ocean component of the model consists of the recently developed isopycnal ocean circulation model of Oberhuber (1992).

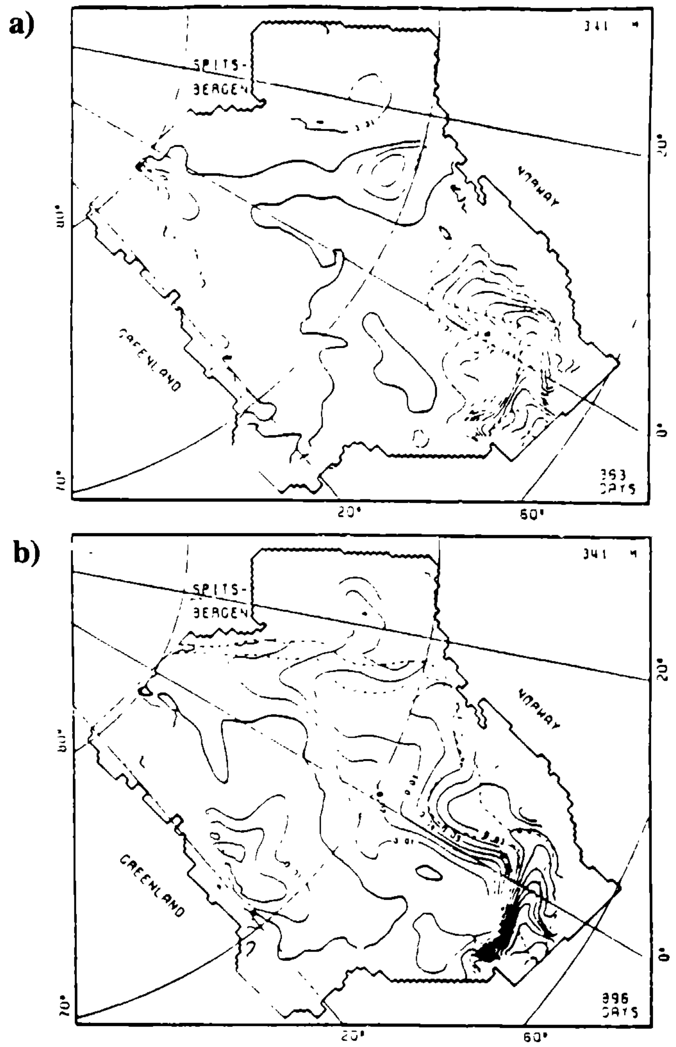



**Figure 48.**
Horizontal distribution of salinity differences at 341 m (8th level) between the model results of two experiments (from Legutke, 1991). These differed only in the salinity specified at the southern boundary (across the Faroe–Shetland Channel): in one experiment the climatological salinity distribution is specified, and in the other, a negative salinity anomaly is imposed. a) Simulation after running the model for one year; b) simulation after 30 months. The dashed lines are isobaths. The stippled area has water depths below 341 m. The contour intervals are 0.01.

# II. SUMMARY AND RECOMMENDATIONS

**What is known?**

* Decadal time scale climate variability is prominent in the North Pacific, North Atlantic and adjacent land areas.

* There is clear evidence that decadal-scale changes over the North Pacific are linked to those in the tropics.

* In the North Atlantic, decadal-scale variability does not appear to be strongly linked to the tropics. Rather it seems likely that it involves the linked processes of deep convection, fresh water flux, and ice formation.

* In both oceans there is a recognizable ecosystem response to the decadal-scale variability in the ocean and atmosphere.

**What is not known?**

* What factors are driving the changes?

* Are the changes merely part of a red spectrum or is there a fundamental time scale in the system helping to organize the variability? Are there important forcing mechanisms external to the climate system (e.g., solar activity)?

* To what extent are the variations part of the natural climate system and to what extent are they anthropogenically induced (e.g., by greenhouse gases, carbon and sulfur cycles etc.)?

**What is being done?**

* There are some national research programmes (e.g., NOAA Atlantic Climate Change Programme) that make important contributions to studies of certain aspects of ICV. Recently a number of fresh ideas, observations and modelling results have emerged which warrant an internationally organized programme to understand and elucidate this overlooked climate time scale.

* The Global Climate Observing System (GCOS) of WMO, IOC, UNEP and ICSU has been established to provide comprehensive information on the total climate system, involving multi-disciplinary range of physical, chemical and biological properties and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. The Global Ocean Observing System (GOOS) of IOC has also been established and will provide the ocean related observations for GCOS. The climate component of GOOS will include observations needed to monitor, describe and understand the physical and biogeochemical properties that determine ocean circulation and the seasonal to decadal climatic changes in the ocean.

* The emergence of several major science programmes of global scope and decadal duration give the prospect of interpreting the changes observed; to the established WOCE and JGOFS have recently been added the international Global Ocean Ecosystems Dynamics (GLOBEC) initiative on zooplankton dynamics, the Commission of the European Community (CEC) Ocean Margin Exchange Experiment (OMEX) which will represent the most intensive study to date of physical, biological and sedimentological transfers across an ocean boundary, and the Large Marine Ecosystem concept, which intends to develop a knowledge of entire ecosystems and the principal forces that drive them in different ocean regions.

* Technological advances are in prospect of presenting us with the tools needed to reduce costly dependence on an intermittent "going and fetching" observing system and to supplement it to form something more continuous and more global. These tools include inexpensive reliable telemetry, unmanned sampling and profiling

devices, satellites (including active and passive microwave devices), acoustics and faster, more comprehensive models. A flexible mix of methods and techniques, and a varying sampling strategy to the differing anthropogenic problems and climatic impacts of individual ocean regions should be possible.

**What is required?**

* A solid commitment to sustained monitoring of the oceans, as envisioned under the GOOS. Also required is a corresponding long-term monitoring programme for land surface, atmospheric and ecological processes as described under the Global Climate Observing System (GCOS).

* A collection of high-resolution paleoclimate records and continued archaeology and reanalysis of instrumental data.

* A series of suitable studies designed to elucidate key processes in interdecadal climate variability.

* A comprehensive modelling programme of the complete climate system to explore natural and anthropogenical induced climate variability at decadal time scales.

* An international scientific workshop (1993 time frame) to review decadal/interdecadal scale variability, asses its importance and design an appropriate observing, modelling and research strategy for development of an international interdisciplinary science programme.

# REFERENCES


Ådlandsvik, B. and H. Loeng (1991). A study of the climatic system in the Barents Sea. *Polar Res.*, **10(1)**, 45-49.

Aagard, K. and E.C. Carmack (1989). The role of sea-ice and other fresh water in the Arctic circulation. *J. Geophys. Res.*, **94**, 14485-14498.

Antonov, J.I. (1990). Recent climatic changes of vertical thermal structure of the North Atlantic and North Pacific Oceans. *Meteorol. i Gidrolog.*, **4**.

Bakun, A. (1990). Global climate change and intensification of coastal ocean upwelling. *Science*, **247**, 198-201.

Bakun, A. (1991). Global greenhouse effects, multi-decadal wind trends and potential impacts on coastal pelagic fish populations. *ICES 1991 Var. Symp.*, **22**, 10 pp + 8 figs.

Barber, R. T. and F. P. Chavez (1983). Biological consequences of the 1982-83 El Niño. *Science*, **222**, 1203-1210.

Bernal, P. A. (1981). A review of the low frequency response of the pelagic ecosystem in the California current. *CalCOFI Rep.*, **22**, 49-62.

Bjerknes, J. (1964). Atlantic air-sea interactions. Adv. Geophys **10**, 1-82.

Bjerknes, J. (1966). A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*, **18**, 820-829.

Blackmon, M. L., J.G. Geisler and G. J. Pitcher (1983). A general circulation model study of January climate anomaly patterns associated with interannual variation of equatorial Pacific sea surface temperatures. *J. Atmos. Sci.*, **40**, 1410-1425.

Bochkov, Yu A. (1982). Retrospective survey of water temperature in the 0-200 m layer in the "Kol'skii meridian" section in the Barents Sea (1900-1981). pp. 113-122. In: *Ecology and Catches of Deep Sea Fish in the North European Basin.* Murmansk, PINRO.

Buch, E. and H. H. Hansen (1988). Climate and cod fishery at West Greenland. pp. 345-364. In Wyatt and Larreneta (Eds.), Long-term Changes in Marine Fish Populations, Proc. Vigo Symposium, November 1986.

Carter, D.J.T. and L. Draper (1988). Has the North-East Atlantic become rougher? *Nature*, **332**, 494.

Cayan, D.R., J.V. Gardiner, J.M. Landwehr, J. Namias, and D.H. Peterson (1989). "Introduction". In: *Geophysical Monograph 55: Aspects of Climate Variability in the Pacific and the Western Americas*, D.H. Peterson (ed.). American Geophysical Union, Washington DC, USA. pp. xi-xvi.

Cayan, D.R., D.R. McLain and W.D. Nichols (1991). Monthly Climatic Time Series Data for the Pacific Ocean and Western Americas, U.S. Geological Survey. *Open File Report 91-92*, 380 pp.

Cayan, D.R. (1992a). Variability of latent and sensible heat fluxes estimated using bulk formulae. *Atmosphere-Ocean*, **30**, 1-42.

Cayan, D.R. (1992b). Latent and sensible heat flux anomalies over the northern oceans: The connection to monthly atmospheric circulation. *Journal of Climate*. In press.

Cayan, D.R. (1992c). Latent and sensible heat flux anomalies over the northern oceans: Driving the sea surface temperature. *Journal of Physical Oceanography*, **22**, 859-881.

Chelliah, M. and P. Arkin 1992). Large-scale interannual variability of monthly outgoing longwave radiation anomalies over the global tropics. *J. Climate*, **5**, 371-389.

Chelton, D. B. (1981). Interannual variability of the California current -physical factors. *CalCOFI Rep.*, **22**, 34-48.

Clarke, R.A., J.H. Swift, J.L. Reid and P.K. Koltermann (1990). The formation of Greenland Sea deep water: double diffusion or deep convection? *Deep Sea Res.*, **37(9)**, 1385-1424.

Cook, E., T. Bird, M. Peterson, M. Barbeth, B. Buckley, R. D'Arrigo, R. Francey and P. Tans (1991). Climatic change in Tasmania inferred from a 1089-year tree-ring chronology of Huon pine. *Science*, **253**, 1266-1268.

Cushing, D.H. (1982). *Climate and Fisheries*. Academic Press, London. 373 pp.

Dandonneau, Y. (1986). Monitoring the sea surface chlorophyll concentration in the tropical Pacific: Consequences of the 1982-1983 El Niño. *Fish. Bull.*, **84(3)**, 687-695.

Darby and Mysak (1992). A Boolean delay equation model of an interdecadal Arctic climate cycle. Climate Dynamics. In press.

Dickson, R.R. and J. Namias (1976). North American influences on the circulation and climate of the North Atlantic sector. *Monthly Weather R.*, **104(10)**, 1255-1265.

Dickson, R.R., H.H. Lamb, S.A. Malmberg, and J.M. Colebrook (1975). Climatic reversal in the northern North Atlantic. *Nature*, **256**, 479-482.

Dickson, R.R., J. Meincke, S.A. Malmberg and A.J. Lee (1988a). The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. *Prog. Oceanogr.*, **20**, 103-151.

Dickson, R.R., P.M. Kelly, J.M. Colebrook, W.S. Wooster and D.H. Cushing (1988b). North winds and production in the eastern North Atlantic. *J. Plankton Res.*, **10(1)**, 151-169.

Dooley, H.D., J.H.A. Martin and D.J. Ellett (1984). Abnormal hydrographic conditions in the Northeast Atlantic during the 1970s. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer*, **185**, 179-187.

Ebbesmeyer, D., D. Cayan, D. McClain, W.D. Nichols, D.H. Peterson and K. Redmond (1991). Sensitivity of marine biology to climate change in a North Pacific Swath. Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, Asilomar, California, April 10-13, 1990.

Ellett, D.J. and J. Blindheim (1991). Climate and hydrographic variability in the ICES area during the 1980s. *ICES 1991 Var. Symp. No. 1*, 12 pp. + 23 figs.

Folland, C.K. and D.E. Parker (1990). Observed variations of sea surface temperature. In: *Climate-Ocean Interaction*. M. Schlesinger (ed.). Kluwer Academic Publishers, 21-52.

Folland, C.K., T.N. Palmer and D.E. Parker (1986). Sahel rainfall and worldwide sea temperatures, 1901-1985. *Nature*, **320**, 602-607.

Folland, C.K., J. Owen, M.N. Ward and A. Colman (1991). Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. *J. Forecasting*, **10**, 21-56.

Gammelsrod, T., S. Osterhus and O. Godoy (1991). Forty years of hydrographic observations at weather ship station 'MIKE' (66°N, 2°E). *ICES 1991 Var. Symp.*, **P5**, 2 pp. + 6 figs.

Geisler, J.E., M.L. Blackmon, G.T. Bates and S. Munoz, (1985). Sensitivity of January climate response to the magnitude and position of equatorial sea surface temperature anomalies. *J. Atmos. Sci.*, **42**, 1037-1049.

Graham, N.E. 1992. Decadal scale climate variability in the 1970s and 1980s: Observations and model results; N.E. Graham in "Decade-to-century time scales of climate variability". Academic Press, submitted.

Greatbatch, R.J., A.F. Fanning and A.D. Goulding (1991). A diagnosis of interpentadal circulation changes in the North Atlantic. *J. Geophys. Res.*, **96**, 22009-22023.

Hastenrath, S. (1984). Interannual variability and the annual cycle: Mechanisms of circulation and climate in the tropical Atlantic sector. *Mon. Wea. Rev.*, **112**, 1097-1107.

Heinze, Ch.P., P. Schlosser and K.P. Koltermann (1986). Deep water renewal in the European Polar Seas as derived from a multi-tracer approach. *ICES CM 1986/C:17*, 8 pp. + 4 figs.

Ikeda, M. (1990). Decadal oscillations of the air-ice-ocean system. *Atmos.-Ocean*, **28**, 106-139.

Inoue, M. and J.J. O'Brien (1987). Trends in sea level in the western and central equatorial Pacific during 1974-75 to 1981. *J. Geophys. Res.*, **92, C5**, 5045-5051.

IPCC (1990). Climate Change : The IPCC Scientific Assessment. University Press, 365 pp.

Jenkins, W.J. (1982). On the climate of a subtropical ocean gyre: decade timescale variations in water mass renewal in the Sargasso Sea. *J. Mar. Res.*, **40** (Suppl.), 265-290.

Jones, P.D., T.M.L. Wigley and P.B. Wright (1986). Global temperature variations between 1861 and 1984. *Nature*, **322**, 430-434.

Jones, P.D., T.M.L. Wigley, C.K. Folland and D.E. Parker (1987). Spatial patterns in recent worldwide temperature trends. *Climate Monitor*, **16(5)**, 175-185.

Joyce, T.M. (1991). Thermohaline catastrophe in a simple four-box model of the ocean climate. *J. Geophys. Res.*, **96**, 20393-20402.

Kawamura, R. and M. Nishimori (1992). Climatology of teleconnections with intramonthly to interdecadal time scales observed in the 500 mb height field during the northern hemisphere winter. *Tenki*, **39**. In press.

Kitamura, Y. (1990). Simulation of the annual and interannual variation of the tropical Pacific Ocean. *J. Mar. Systems*, **1**, 169-181.

Kitoh, A. (1991). Interannual variations in an atmospheric GCM forced by the 1970-1989 SST. Part II: Low frequency variability of the wintertime northern hemisphere extratropics. *J. Meteor. Soc. Japan*, **69**, 271-291.

Lamb, H.H. and I. Weiss (1979). On recent changes of the wind and wave regime of the North Sea and the outlook. *Fache. Mitt. Amtl. Wehrgeophys.*, **194**, 1-108.

Lau, N.G. and M.J. Nath (1990). A general circulation model study of the atmospheric response to extratropical SST anomalies observed in 1950-1979. *J. Climate*, **3**, 965-989.

Lazier, J. (1980). Oceanic conditions at Ocean Weather Ship BRAVO; 1964-1974. *Atmos.-Ocean*, **18**, 227-238.

Lazier, J. (1988). Temperature and salinity changes in the deep Labrador Sea 1962-86. *Deep Sea Res.*, **35**, 1247-1253.

Legutke, S. (1991). Numerical experiments relation to the "Great Salinity Anomaly" of the seventies in the Greenland Norwegian seas. *Prog. Oceanog.*, **27**, 341-363.

Levitus, S. (1990). Interpentadal variability of steric sea level and geopotential thickness of the North Atlantic Ocean, 1970-1974 versus 1955-1959. *J. Geophys. Res.*, **95**, 5233-5238.

Malmberg, S. -A. (1973). Astand sjavar milli Islands og Jan Mayen 1950-72. *Aegir*, **66**, 146-148.

Manabe, S. and R. Stouffer (1988). Two stable equilibria of a coupled ocean-atmosphere model. *J. of Climate*, **1**, 841-866.

Manabe, S., R.J. Stouffer, M.J. Spelman and K. Bryan (1991). Transient esponses of a coupled ocean-atmosphere model to gradual changes of Atmospheric $CO_2$. Part I: Annual mean response. *J. Climate*, **4**, 758-818.

Marotzke, J. (1990). Instabilities and multiple equilibria of the thermohaline circulation. Ph.D. thesis. Inst. für Meerskd., Univ. Kiel, Kiel, Germany, 126 pp.

Marsden, R.F., L.A. Mysak and R.A. Myers (1991). Evidence for stability enhancement of sea-ice in the Greenland and Labrador Seas. *JGR*, **96**, 4783-4789.

Meincke, J., S. Jonsson and J.H. Swift (1992). Variability of convective conditions in the Greenland Sea. *ICES Mar. Sci. Symp.*, **195**. In press.

Miller, A.J., D. R. Cayan, T.P. Barnett, N.E. Graham, and J.M. Oberhuber (1992). Interdecadal variability of the Pacific Ocean: Model response to observed heat flux and wind stress anomalies, submitted to Climate Dynamics.

Mellor, G.L., C.R. Mechoso and E. Keto (1982). A diagnostic model of the general circulation of the Atlantic Ocean. *Deep Sea Res.* **29**, 1171-1192.

Myers, R.A., G. Mertz and J.A. Helbig (1990). Long period changes in the Salinity of Labrador Sea Water. *ICES CM 1990/C:21*, 8 pp.

Mysak, L.A. (1986). El Niño, Interannual variability and fisheries in the Northeast Pacific Ocean. *Can. J. of Fish. and Aquat. Sci.*, **43**, 464-497.

Mysak, L.A. and D.K. Manak (1989). Arctic sea-ice extent and anomalies, 1953-1984. *Atmosphere-Ocean*, **27**, 376-405.

Mysak, L.A., D.K. Manak and R.F. Marsden (1990). Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an interdecadal Arctic climate cycle. *Climate Dynamics*, **5**, 111-133.

Mysak, L.A. and S.B. Power (1991). Greenland Sea-ice and salinity anomalies and interdecadal climate variability. *Clim. Bull.*, **25 (2)**, 81-91.

Mysak, L.A. and S. B. Power (1992). Sea-ice anomalies in the Western Arctic and Greenland Sea and their relation to an interdecadal climate cycle. Climatological Bulletin, submitted.

Nicholson, S.E. (1985). Sub-Saharan rainfall 1981-84. *J. Clim. Appl. Met.*, **24**, 1388-1391.

Nitta, T. and S. Yamada (1989). Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. *J. Meteor. Soc. Japan*, **67**, 375-382.

Nitta, T. and J. Yoshimura (1992). Interannual and interdecadal variations of global surface air temperature. U/M.

Oberhuber, J.M. (1992). Simulation of the Atlantic circulation with a coupled sea-ice mixed layer-isopycnal general circulation model. Part I: Model description. *J. Phys. Oceanogr.* In press. (Also available as MPI Rep. 59.)

Palmer, T.N. and D.A. Mansfield (1986). A study of wintertime circulation anomalies during past El Niño events using a high-resolution general circulation model. II: Variability of the seasonal mean response. *Quart. J. R. Met. Soc.*, **112**, 639-660.

Palmer, T.N. and Z. Sun (1985). A modelling and observational study of the relationship between sea surface temperature in the north-west Atlantic and the atmospheric general circulation. *Quart. J. R. Met. Soc.*, **111**, 947-975.

Peng, S. and L.A. Mysak (1991). A teleconnection study of interannual sea surface temperature fluctuations in the northern North Atlantic and precipitation and runoff over western USSR. Centre for Climate and Global Change Research Rep. 91-13. McGill University, Montreal.

Pollard, R.T. S. and Pu (1985). Structure and circulation of the Upper Atlantic Ocean north-east of the Azores. *Prog. Oceanogr.*, **14**, 443-462.

Read, J. (1992). Decadal changes in Labrador sea water. *SIGMA, UK WOCE Newsletter*, **6**, 6.

Rogers, J.C. (1990). Patterns of low frequency monthly sea level pressure variability (1899-1986) and associated wave cyclone frequencies. *J. Climate*, **3**, 1364-1379.

Salmon, D. (1992). On interannual variability and climate change in the North Pacific. Ph.D thesis. Univ. of Alaska.

Schlosser, P., G. Bönisch, M. Rhein and R. Bayer (1991). Reduction of deepwater formation in the Greenland Sea during the 1980s: Evidence from tracer data. *Science*, **251**, 1054-1058.

Sekine, Y. (1988). Anomalous southward intrusion of the Oyashio east of Japan I. Influence of the interannual and seasonal variations in the wind stress over the North Pacific. *J. Geophys. Res.*, **93(C3)**, 2247-2255.

Sekine, Y. (1991). Sea-ice coverage in the Sea of Okhotsk. Proceedings of the 1991 fall meeting of the Oceanographic Society of Japan.

Shukla J. and J.M. Wallace (1983). Numerical simulation of the atmospheric response to equatorial sea surface temperature anomalies. *J. Atmos. Sci.*, **40**, 1613-1630.

Soutar, A. and J.D. Isaacs (1969). History of fish populations inferred from fish scales in anaerobic sediments of California. *Calif. Mar. Res. Comm. CalCOFI*, **13**, 63-70.

Soutar, A. and J.D. Isaacs (1974). Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediments off California. *Fish. Bull. US Fish. Wildlife Serv.*, **72**, 257-75.

Stommel, H. (1961). Thermohaline convection with two stable regimes of flow. *Tellus*, **13**, 224-230.

Takahashi, T., D. Chipman, N.Schechtman, J. Goddard and R. Wanninkof (1982). Measurements of the partial pressure of CO2 in discrete water samples during the North Atlantic Expedition, The Transient Tracers of Oceans Project, report, 269 pp., Lamont-Doherty Geol. Observ., Palisades, N.Y.

Talley, L.D. and M.E. Raymer (1982). Eighteen degree water variability. *J. Mar. Res.*, **40** (Suppl.), 757-775.

Taning, A. V. (1953). Long term changes in hydrography and fluctuations in fish stocks. *Ann. Proc. Intern. Commn. NW Atlant. Fish*, **3**, 69-77.

Thompson, L.G. and E. Mosley-Thompson (1989). One-half millenia of tropical climate variability as recorded in the stratigraphy of the Quelccaya ice cap, Peru. In: *Geophysical Monograph 55: Aspects of Climate Variability in the Pacific and the Western Americas*. D.H. Peterson (ed.). American Geophysical Union, Wash., DC, USA, pp. xi-xvi.

Trenberth, K.E. (1990). Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of the Amer. Meteor. Soc.*, **71**, 988-993.

Trenberth, K.E. (1991). Recent climate changes in the Northern Hemisphere. In: *Greenhouse-gas induced climatic change: a critical appraisal of simulations and observations*. M.E. Schesinger (ed.). Elsevier Publishers.

Venrick, E.L., J.A. McGowan, D.R. Cayan and T.L. Hayward (1987). Climate and chlorophyll a: long-term trends in the central North Pacific Ocean. *Science*, **238**, 70-72.

Villemarque, J-H. de L. (1991). The French cod fishery from the 16th to 18th century in the north-west Atlantic. *ICES CM 1991/G:67*, 19 pp. + 6 figs.

Von Storch, H., E. Zorita and U. Cubasch (1992). Downscaling of global climate estimates to regional scales: an application to Iberian rainfall in wintertime. *J. Climate*. In press. (Also available as MPI Rep. 64).

Wallace, D.W.R. and J.R.N. Lazier (1988). Anthropogenic chlorofluoromethanes in newly formed Labrador sea water. *Nature*, **323(3)**, 61-63.

Walsh, J.E. and W.L. Chapman (1990). Arctic contribution to upper-ocean variability in the North Atlantic. *J. Climate*, **3**, 1462-1473.

Weaver, A.J. And E.S. Sarachik (1991a). The role of mixed boundary conditions in numerical models of the ocean's climate. *J. Phys. Oceangr.*, **21**, 1470-1493.

Weaver, A.J. and E.S. Sarachik (1991b). Evidence for decadal variability in an ocean general circulation model: an advective mechanism. *Atmos.-Ocean*, **29**, 197-231.

Weaver, A.J., E.S. Sarachik and J. Marotzke (1991). Freshwater flux forcing of decadal and interdecadal oceanic variability. *Nature*, **353**, 836-838.

Welander, P. (1986). Thermohaline effects in the ocean circulation and related simple models. Large-scale Transport Processes in Oceans and Atmosphere, J. Willebrand and D. L. T. Anderson, Eds., NATO ASI series, D. Reidel Publishing, pp. 163-200.

Worthington, L.V. (1977). Intensification of the Gulf Stream after the winter of 1976-77. *Nature*, **270**, 415-417.

Wunsch, C. (1991). Decade-to-Century changes in the ocean. Unpub. M/S.

Yamagata, T. and Y. Masumoto (1992). Interdecadal natural climate variability in the western Pacific and its implication in global warming. *J. Meteor. Soc. Japan.*, **70**, 167-175.

# Appendix I

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# Appendix II

## GLOSSARY OF ACRONYMS AND SPECIAL TERMS

| | |
|---|---|
| AGCM | Atmospheric General Circulation Model |
| CCCO | Committee on Climatic Changes and the Ocean (SCOR-IOC) |
| CEC | Commision of the European Communities |
| CFC | Chlorofluorocarbon |
| CLIMAT | WMO Programme for Monthly Climate Data Transmission |
| COADS | Comprehensive Ocean Atmosphere Data Set |
| CPR | Continuous Plankton Recorder |
| CPUE | Catch Per Unit Effort |
| DM | Departure from the long-term Mean |
| ECMWF | European Centre for Medium Range Weather Forecasts |
| ENSO | El Niño Southern Oscillation |
| EOF | Empirical Orthogonal Function |
| FSU | Florida State University |
| GCM | General Circulation Model |
| GCOS | Global Climate Observing System |
| GLOBEC | Global Ocean Ecosystems Dynamics |
| GOOS | Global Ocean Observing System |
| GSA | Great Salinity Anomaly |
| ICES | International Council for the Exploration of the Sea |
| ICSU | International Council of Scientific Unions |
| ICV | Interdecadal Climate Variability |
| IOC | Intergovernmental Oceanographic Commission (of UNESCO) |
| IPCC | Intergovernmental Panel on Climate Change (UNEP-WMO) |
| JGOFS | Joint Global Ocean Flux Study (SCOR) |
| JMA | Japan Meteorological Agency |
| MPI | Max-Planck Institut (Germany) |
| MRI | Meteorological Research Institute (JMA) |
| NOAA | National Oceanic and Atmospheric Administration (USA) |
| OGCM | Ocean General Circulation Model |
| OLR | Outgoing Longwave Radiation |
| OMEX | Ocean Margin Exchange Experiment (CEC) |
| OWS | Ocean Weather Station |
| PNA | Pacific and North America |
| SCOR | Scientific Committee on Oceanic Research (ICSU) |
| SLP | Sea Level Pressure |
| SST | Sea Surface Temperature |
| THC | Thermohaline Circulation |
| TTO | Transient Tracers in the Ocean |
| UNEP | United Nations Environment Programme |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| WCRP | World Climate Research Programme |
| WMO | World Meteorological Organization |
| WOCE | World Ocean Circulation Experiment (WCRP) |

| | | |
|---|---|---|
| 20 | A Focus for Ocean Research : The Intergovernmental Oceanographic Commission - History, Functions, Achievements | E,F,S,R |
| 21 | Bruun Memorial Lectures, 1979 : Marine Environment and Ocean Resources | E,F,S,R |
| 22 | Scientific Report of the Intercalibration Exercise of the IOC-WMO-UNEP Pilot Project on Monitoring Background Levels of Selected Pollutants in Open Ocean Waters *(out of stock)* | E only |
| 23 | Operational Sea-Level Stations | E,F,S,R |
| 24 | Time-Series of Ocean Measurements. Vol. 1 | E,F,S,R |
| 25 | A Framework for the Implementation of the Comprehensive Plan for the Global Investigation of Pollution in the Marine Environment *(out of stock)* | E,F,S,R |
| 26 | The Determination of Polychlorinated Biphenyls in Open-ocean Waters | E only |
| 27 | Ocean Observing System Development Programme | E,F,S,R |
| 28 | Bruun Memorial Lectures, 1982 : Ocean Science for the Year 2000 | E,F,S,R |
| 29 | Catalogue of Tide Gauges in the Pacific | E only |
| 30 | Time-Series of Ocean Measurements. Vol. 2 | E only |
| 31 | Time-Series of Ocean Measurements. Vol. 3 | E only |
| 32 | Summary of Radiometric Ages from the Pacific | E only |
| 33 | Time-Series of Ocean Measurements. Vol. 4 | E only |
| 34 | Bruun Memorial Lectures, 1987 : Recent Advances in Selected Areas in the Regions of the Caribbean, Indian Ocean and the Western Pacific | Composite E,F,S |
| 35 | Global Sea-Level Observing System (GLOSS) Implementation Plan | E only |
| 36 | Bruun Memorial Lectures 1989 : Impact of New Technology on Marine Scientific Research | Composite E,F,S |
| 37 | Tsunami Glossary - A Glossary of terms and Acronyms Used in the Tsunami Literature | E only |
| 38 | The Oceans and Climate : A Guide to Present Needs | E only |
| 39 | Bruun Memorial Lectures, 1991 : Modelling and Prediction in Marine Science | E only |