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Climatic Overview of NAFO Subarea 1, 1991–2000

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Abstract

Based on climatological data on air temperatures, sea ice cover, as well as on subsurface oceanographic time series and historic data from World Ocean Data Centre A (WDC-A), this paper analyses the climatic conditions off West Greenland during the decade of the 1990s and compares them with previous decades. The 1990s was a decade of extremes. The North Atlantic Oscillation (NAO) index flipped from one of its most positive values in winter 1995 to one of its most negative the following winter and reached a high level again during the last winter of the decade. Air temperatures at Nuuk tended to follow these extremes, e.g. during the high NAO Index in the early-1990s, there were very cold air temperatures at West Greenland. Approximately 50% of the variance in winter temperatures at Nuuk can be explained by air pressure changes over the North Atlantic. Nuuk air temperatures are shown to be representative of the climatic variability over the west coast of West Greenland from Cape Farewell in the south to Egedesminde in the Disko Bight area. There is significant correlation between the area-weighted mean bottom water temperature index for the German groundfish survey area off East and West Greenland and the autumn time series data from Fyllas Bank station 4 for the corresponding depth layers 0–200 m and 200–400 m. Accordingly, the subsurface oceanic variability measured at this slope station can be used as proxy for subsurface ocean variability off West Greenland. Surface layer cooling during the early-1990s was accompanied by decreasing salinities in the upper 400 m at the slope of Fyllas Bank, perhaps due to the heavy sea-ice conditions during 1992–93. There is evidence of low surface salinities (<33.0) during summer and autumn at Fyllas Bank station 4. These low salinities are not found during spring. This low saline water during summer and autumn off West Greenland is possibly derived from the Arctic freshwater supply that passes along East Greenland. The presence of Irminger Water ($4°C < \theta < 6°C$, $34.95 < S < 35.1$) at the slope off Fyllas Bank is mapped using WDC-A data from 1946 to 1999. It is shown that this water mass, mostly found at depths between 400 and 800 m, arrives in pulses and was present during several years in the second half of the 20th century. There were, however, major periods (1955–62 and 1973–81) when Irminger Water was not observed at Fyllas Bank station 4.

Keywords: North Atlantic Oscillation (NAO index), air temperatures, ocean temperatures, salinity, Irminger Water.

Introduction

Quests for causes of climate change are centuries long. The effects of sunspot solar cycles on climate date back to 1801, when astronomer Sir William Herschel suggested a possible correlation between the number of sunspots and the market price of wheat; his proposal has remained a controversial topic ever since (Currie *et al*., 1993; Meadows, 1975).

The climate system exhibits considerable natural variability on decadal time scales (Latif, 1998). This variability is important for three reasons:

- A better understanding of the mechanisms generating decadal climate variability might open the possibility to make predictions at decadal time scales.
- The detection of anthropogenic climate change requires information about natural variability to separate the anthropogenic signal from the natural background noise.
- Long-term changes in the climate state might influence short-term climate fluctuations. A better knowledge of the slowly evolving background state can improve the prediction of the faster climate variations substantially.

NAFO through its Standing Committee on Fisheries and Environment (STACFEN) encouraged research scientists to continue sampling of oceanographic data whenever there is research activity in the NAFO Convention Area. This lead to the existence of some long-term time series of NAFO Oceanographic Standard Stations (Stein, MS 1988). Publications, which were initiated during STACFEN or its predecessor, the Subcommittee on Environmental Research meetings, are numerous.

Buch (2000) concludes that the most significant oceanographic events in off Southwest Greenland since 1980 were closely related to the very cold atmospheric conditions in 1982–84 and 1989–94. Buch and Stein (1989) show that the cold atmospheric conditions during 1982–84 led to an above normal generation of winter ice in the Davis Strait area, and that 1982 was also characterized by a greater than normal inflow of cold Arctic water from the East Greenland current. Drinkwater (1996) considered the influence of the NAO Index on the variance in winter temperatures at different sites around the Labrador Sea, and revealed that approximately 50% (e.g. r = -0.72 at Nuuk) can be explained by air pressure changes over the North Atlantic. Stein (2000) reports that all subsurface observations at Fyllas Bank station 4 reveal an overall warming during 1998. Record warming was observed in the water layer 200–300 m with a mean temperature of 6.4°C, a value that had not previously been observed since the autumn time series began at Fyllas Bank in 1963.

The present contribution deals with climatic changes during 1991–2000 in NAFO Subarea 1. After discussing the data and methods, the West Greenland climatology of the 1990s is outlined and compared to the long-term climatic changes in the area. Nuuk air temperatures as proxy for West Greenland climatology are analyzed in a next section. This is followed by a description of the low and high frequency changes in the West Greenland climate system and the NAO Index. Sub-surface observations off West Greenland and considerations on the Irminger Water mass constitute the final sections.

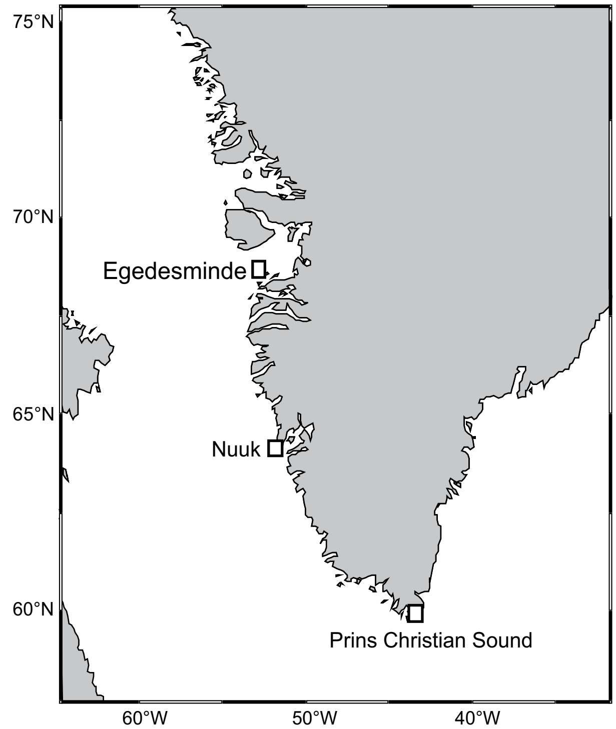

Fig. 1. Locations of air temperature sites in West Greenland.

Data and Methods

The long-term air temperature data were taken from NASA Goddard Institute for Space Studies http://www.giss.nasa.gov/data/update/gistemp/station_data/ for the following sites around Greenland (Fig. 1, Table 1): Egedesminde, Godthaab/Nuuk, Prins Christian Sound. These data are referenced to the climatic mean (1961–90, see Table 1). The temperature reference level (1961–90) is indicated by the zero-line in each figure. Although outside NAFO Subarea 1, the station at Prins Christian Sound was taken to show climatic conditions at the southern tip of Greenland, mainly due to the lack of long-term time series near Cape Farewell.

Subsurface oceanographic observations off West Greenland were taken from two sources:

- The first was the oceanographic database of the Institut für Seefischerei, Hamburg. This dataset starts in autumn 1963 (Fyllas Bank) when the annual groundfish surveys off West Greenland were initiated. For climatic considerations temperature and salinity data from Fyllas Bank standard oceanographic station 4 were taken (Stein, MS 1988).
- The second was World Ocean Database (WOD98, WOD01) and the World Ocean Atlas 1994. Data from Fyllas Bank/West Greenland were mainly sampled by Denmark and Germany. For this site there is also information measured by vessels from Canada, USA, Norway, UK and Russia. The time period covered in this paper is 1946–2000.

The NAO Index refers to the mean December, January, and February (DJF) sea level pressure (SLP) from the Azores (Ponta Delgada, PD) and from Iceland (Akureyri, A). The individual SLPs are standardized to the 1961–90 base period and calculated using:

$$NAO_i = \frac{P_i - \bar{P}}{\sigma}\Big| PD - \frac{P_i - \bar{P}}{\sigma}\Big| A$$

with $_i$ = year, P_i = SLP from PD or A, σ = standard deviation of the 1961–90 base period.

DJF pressures for 1998/99 and 1999/2000 for Ponta Delgada were defined by regression with neighbouring stations (Loewe and Koslowski, 1998).

Time series analysis of sub-surface data was carried out using Ocean Data View (Version 5.7). Water mass

TABLE 1. Climatic means (°C) given by month and annually for 1961–90 for air temperature sites (see Fig. 1 for locations). (DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November).

Site	Lat./Long.	DJF	MAM	JJA	SON	Annual	Data
Egedesminde	68.7N, 52.8W	-12.95	-9.25	4.58	-1.90	-4.88	1949–2000
Godthaab/Nuuk	64.2N, 51.8W	-7.14	-3.76	5.51	-0.23	-1.41	1866–2000
Prins Chr.Sound	60.0N, 43.2W	-3.71	-0.98	5.75	1.49	0.63	1949–2000

analysis was performed using the "patch" option in Ocean Data View for Irminger Water (4°C < θ <6°C, 34.95 <S <35.1) (Fig. 16, 17).

Results

Climatology of West Greenland

Mean annual air temperatures at Egedesminde (Fig. 2) show large variation during the last fifty years of the 20th century. Cold events in the beginning of the 1970s and especially during 1982 and 1983 are salient features of the time series. Record low mean monthly temperatures were encountered at Egedesminde during March 1972 (-20.3°C) and February 1984 (-31.3°C). The anomalies given in Fig. 2 are referenced to the climatic mean 1961–90. The cold events are 1972 (-2.7°C), 1983 (-4.2°C), and 1984 (-4.0°C). The 1990s reveal a warming trend. Coldest conditions were encountered during 1993, mainly due to the extreme cold air temperatures in February (-22.1°C) and March (-25.3°C). Record cold temperatures during this decade were observed during February 1992 (-26.3°C) and March 1993 (-25.3°C).

Figure 3, which gives decadal air temperature anomalies at Egedesminde as a function of the year of the decade for the last five decades of the 20th century, reveals that the 1990s is a decade of extreme climatic conditions, similar to the previous two decades. Rather cold conditions were present during 1990 to 1995. The amount of cooling, however, was not as large as during the 1980s. Intermediate warming was observed during the second half of the 1990s and most of the previous decades, except for 1989, which was very cold.

The climatology of Nuuk (Fig. 4) yields similar conditions during the 1990s as encountered for Egedesminde, i.e. coldest temperatures were found during 1993 due to the extremely cold air temperatures in January (-15.2°C), February (-13.5°C) and March (-14.3°C). Compared to previous decades, mean annual air temperatures during the 1990s were similar to the 1980s, when 1983 and 1984 were the coldest years. In the early years of the time series,

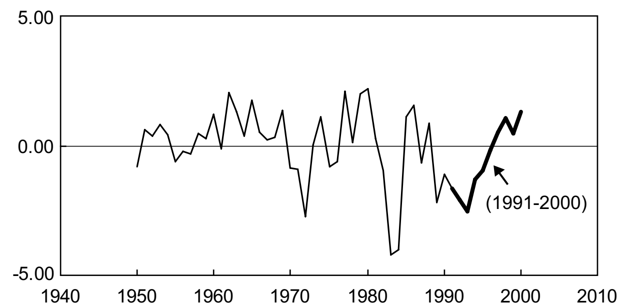

Fig. 2. Mean annual air temperature anomaly (°C) at Egedesminde (referenced to climatic mean as given in Table 1).

cold events were present in 1884 (-3.4°C), 1894 (-2.3°C) and 1998 (-2.6°C), a feature that will be dealt with in more detail later.

The composite of decadal air temperature anomalies at Nuuk as given in Fig. 5 reveals a similar structure as in Fig. 3. The 1970s, 1980s and 1990s were considerably cold during the first years of the decade, indicating maximum cooling during years 2, 3 and 4 of each decade. Warmer than normal air temperatures were observed for most years of the second half of the decades, except for 1989 which was a very cold year at Nuuk, similar to Egedesminde.

Although outside NAFO Subarea 1, the station Prins Christian Sound (Fig. 6) was taken to show climatic conditions at the southern tip of Greenland, mainly due to the lack of long-term time series closer to Cape Farewell. A warming trend for the 1990s was observed, similar to Egedesminde and Nuuk. In relation to previous decades, however, climatic conditions resembled the 1970s. Also similar to the two more northern sites, 1993 was the coldest year on record with monthly mean temperatures of -8.1°C in January and -7.4°C in February.

Nuuk air temperatures as proxy for West Greenland climatology

Long-term time series of air temperatures are scarce for Greenland. Only three time series are available which

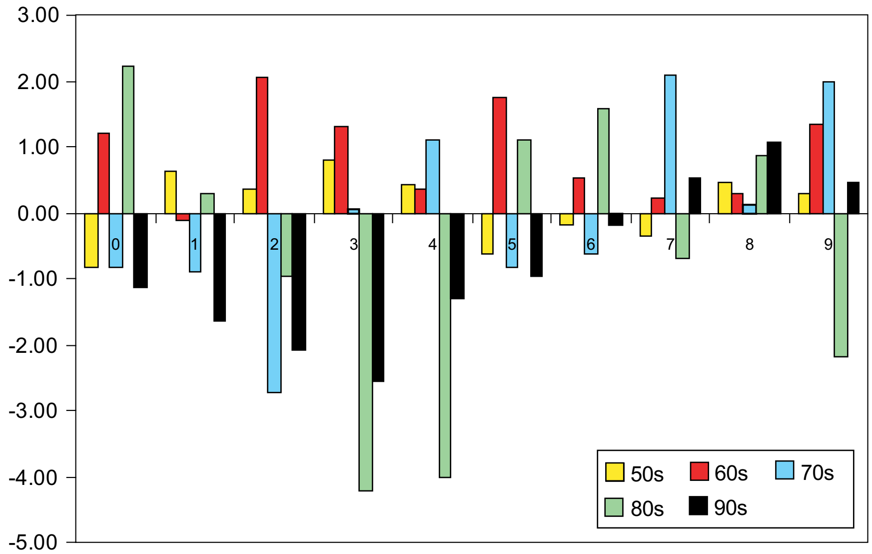

Fig. 3. Decadal air temperature anomalies (°C) relative to the mean of 1961–90 at Egedesminde for the decades from the 1950s to the 1990s plotted as a function of the year of the decade.

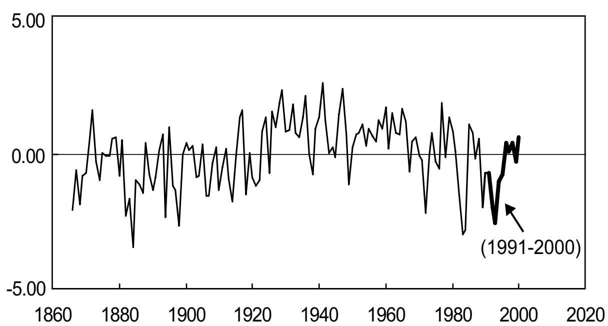

Fig. 4. Mean annual air temperature anomaly (°C) at Nuuk (referenced to climatic mean as given in Table 1).

have data through to the present, two of them starting in 1949 (see Table 1). Examination of long-term trends and variations in climatic time series off West Greenland can thus only be based on the Nuuk data. It therefore seems appropriate to determine how representative the Nuuk air temperature time series is of climatic changes in the West Greenland area, from the Cape Farewell region to the Disko Island region. The mean annual air temperatures of the three sites Egedesminde, Nuuk and Prins Christian Sound, from 1950 to 2000 are shown in Fig. 7. Although the latter site does not fall within the NAFO Convention area, being just east of Cape Farewell, it is used for statistical testing of Nuuk as climatology proxy for West Greenland. The observed time series at the three sites reveal synchronous changes over the past fifty years. Amplitudes of thermal changes decrease from north to south (bottom to top in Fig. 7). Correlation analysis yields highly significant coherence of the time series (Nuuk/Prins Christian Sound, $r = 0.84$; Nuuk/Egedesminde $r = 0.86$). Nuuk air temperatures were therefore used for further analysis of climatological changes during the past 125 years in the West Greenland region.

Low and high frequent changes in the West Greenland climate system

Stein (1995) showed that a low frequency model might explain the long-term warming and cooling cycles observed from the 19th century onwards (Fig. 8). The basic assumptions of the harmonic model, which is based on a period of 108 years, consisting of warmer-than-normal conditions in 1923–76 and colder-than-normal conditions before and after. According to the model, the present downward trend will be maintained until approximately (2003/2004). The long-term climatic signal is modulated by high frequency events, which occur at different periodicities (Stein, 1995).

Cold events are particularly evident at the beginning of the decades of the 1970s, 1980s and 1990s (Fig. 5). The years 1972, 1982 and 1992 were extremely cold years both at Egedesminde and at Nuuk. Even colder were the years 1983 and 1993 at both locations. Stein (1995) showed that the characteristic frequency of these cold events is approximately 12.5 years (peak to peak). Whether the present observed warming is "intermediate"

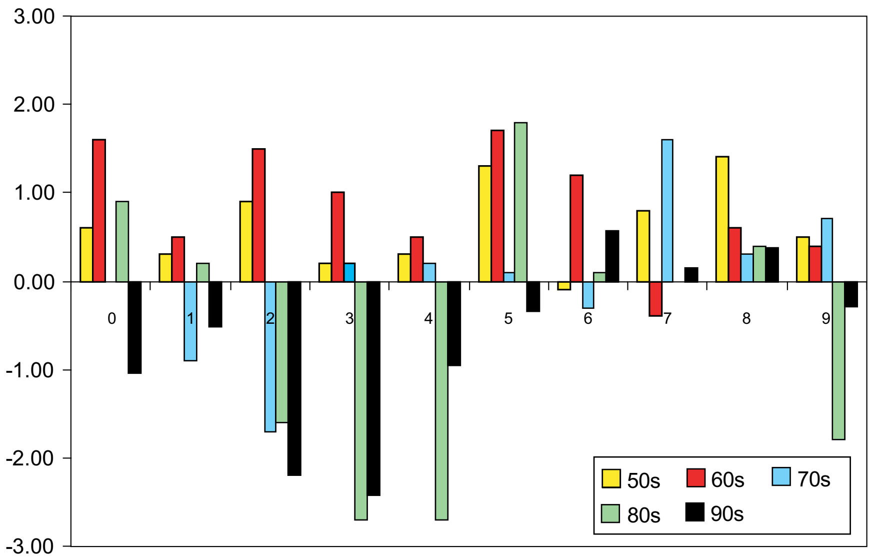

Fig. 5. Decadal air temperature anomalies (°C) relative to the mean of 1961–90 at Nuuk for the decades from the 1950s to the 1990s plotted as a function of the year of the decade.

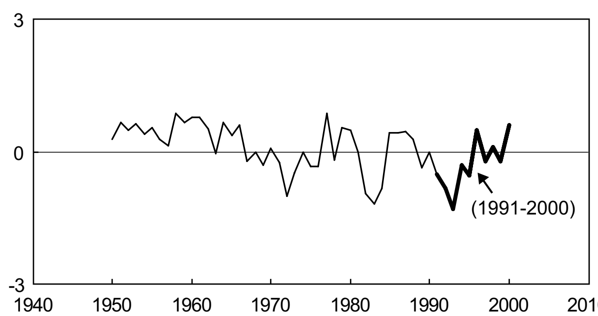

Fig. 6. Mean annual air temperature anomaly (°C) at Prins Christian Sound (referenced to climatic mean as given in Table 1).

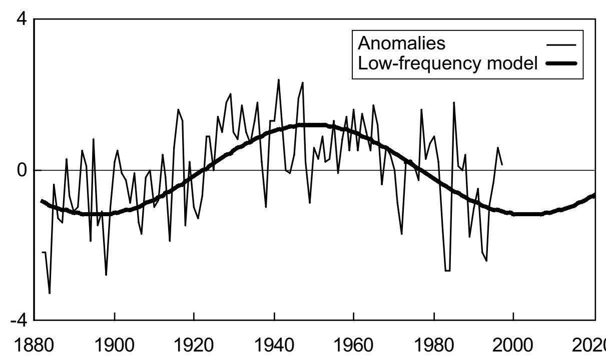

Fig. 8. Annual Nuuk air temperature anomalies (°C) and the low-frequency model taken from Stein, 1995.

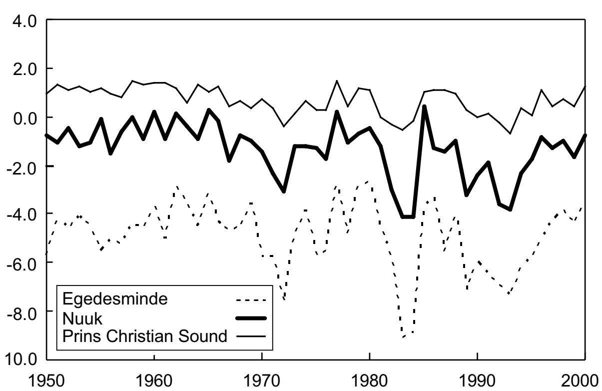

Fig. 7. Mean annual air temperatures (°C) at Egedesminde, Nuuk and Prins Christian Sound, 1950–2000. For location of sites see Fig. 1.

or a trend reversal from cooling to warming was analyzed by Stein (1999). He found that the model curve (dashed line in Fig. 9, period 3.8 years) correlates fairly well with the year mean curve, and the mid-1990s peak could be explained as intermediate warming and not as a return to warm conditions.

The North Atlantic Oscillation (NAO) Index

The NAO is a large-scale alternation of atmospheric mass with centres near the Icelandic Low and the Azores High. It is most pronounced during winter. A "high-index" pattern, indicating strong mid-latitude westerlies, is characterized by an intense Iceland Low, with a strong Azores Ridge to the south. In the "low-index" case, the westerlies are weak. The NAO Index as given for the decade of the 1990s shows mostly positive values (Fig. 10). There was a major exception to this pattern occurring between the winters of 1994/1995 and 1995/1996 when the index flipped from being one of its most positive values to one of its most negative value during last century. The different patterns of winter sea level pressure anomalies of the North Atlantic Ocean for a "high-index" case and a "low-index" case are shown in Fig. 11a and b, respectively. Nuuk winter mean air temperatures tend to be out of phase with the NAO (Fig. 10). Indeed, the correlation between both time series is significant (r = -0.73, P << 0.001).

Sea Ice Conditions off West Greenland

Among the West Greenland bank areas, Fyllas Bank is probably least affected by sea ice. There are two sources of sea ice relevant for the bank and slope areas off West Greenland. Multi-year sea ice, coming from the Arctic Ocean *via* the East Greenland current to the Cape Farewell area, is called "Storis" (which translated means 'Great Ice') because of its thickness (Anon., 1998).

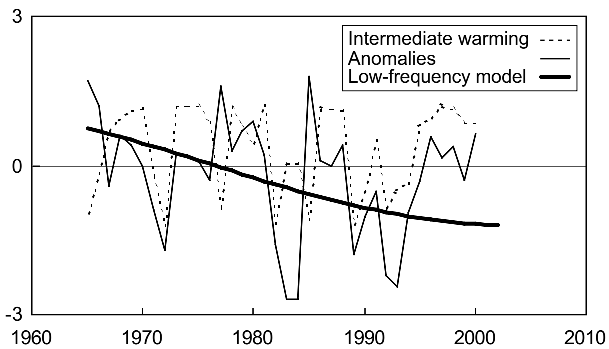

Fig. 9. Analysis of "Intermediate warming", annual mean air temperature anomalies (°C) at Nuuk and the low-frequency model of Stein (1999).

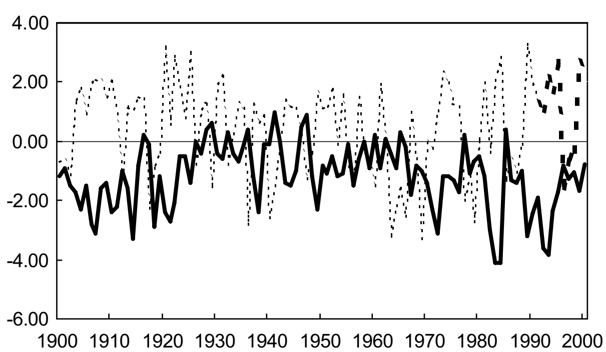

Fig. 10. NAO index and annual mean air temperature (°C) at Nuuk.

During winter, southeasterly winds favour the transport of "Storis" northward along the West Greenland coast. It drifts north of 63°N (into the Fyllas Bank area) every second year on average (Mosbech *et al*., 2000). Since 1958, Fyllas Bank has been completely free of sea ice from mid-August until mid-December. In January 1982, multi-year ice drifted north of 63°N due to extreme wind conditions in the last months of 1981. With the exception of 1982, "Storis" has not been observed north of 63°N earlier than late February during the period 1958–99. Due to the relatively warm north-going West Greenland Current, the eastern parts of Davis Strait are navigable in winter as far north as Sisimiut.

The second source of ice derives from Baffin Bay and is called "West Ice". Sea ice normally covers Davis Strait only during the last half of very cold winters. Buch and Stein (1989) and Buch (2000) indicate that the presence of extremely cold air masses over Davis Strait led to the exceptional situation when "West Ice" and "Storis" met off southwest Greenland.

Some examples of extreme sea ice cover off West Greenland during the early-1990s are given in Fig. 12. The upper left panel of Fig. 12 shows the unusual situation when "West Ice" and "Storis" met on the 26 February 1992 and Greenland was completely surrounded by sea ice. Ice again surrounded Greenland in 1993. During 10 March 1993 (upper right panel of Fig. 12) the southward extension of the "West Ice" reached the southwestern bight of West Greenland and a tongue of "Storis" was visible in the Cape Farewell region. A fortnight later, the ice edge moved further south off West Greenland, however, the "Storis" retreated on 24 March 1993 (lower left panel of Fig. 12). Another example of "Storis" is given in the lower right panel of Fig. 12. During 23 February 1994 "Storis" was present in the Cape Farewell area and in the Julianehaab Bight.

Oceanographic Observations off West Greenland

Oceanographic observations from Fyllas Bank are given in Fig. 13 to 17 and autumn climatic means of temperatures and salinities are displayed in Table 2. The near-surface thermal conditions reveal extreme cooling during 1992 (Fig. 13, 0–50 m) and warming thereafter. Similar cooling was observed during the early-1970s and early-1980s. These phenomena are coherent with atmospheric cooling at West Greenland sites of Egedesminde (Fig. 2), Nuuk (Fig. 4) and Prins Christian Sound (Fig. 6) during the same periods. Present thermal conditions of the upper 50 m water layer are near record highs.

The top 200 m of the water column at station 4 of Fyllas Bank was also considerably warmer during the

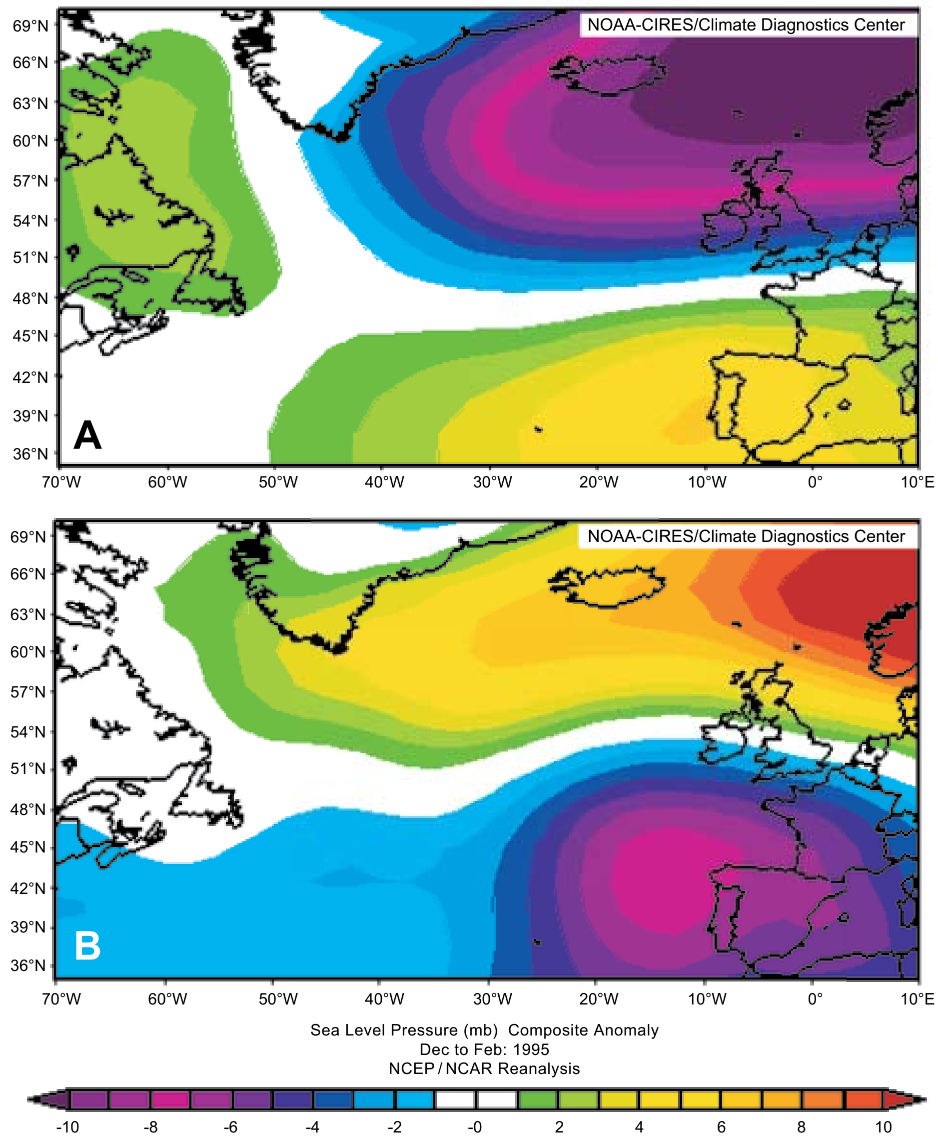

Fig. 11. The Atlantic distribution of mean sea-level pressure anomalies for (**A**) December 1994 to February 1995 (NCEP/NCAR Reanalysis data from NOAA-CIRES Climate Diagnostics Centre) and (**B**) December 1995 to February 1996 (NCEP/NCAR Reanalysis data from NOAA-CIRES Climate Diagnostics Centre).

1990s than in the previous decades. Peak warming was encountered during 1996 (Fig. 13, 0–200 m) and temperatures have remained warmer-than-normal since then. Salinities at station 4 of Fyllas Bank were mostly above normal during the 1990s (Fig. 13 lower panels).

Statistical correlations were calculated between the area-weighted mean temperature index, as calculated for the German groundfish survey areas off East and West Greenland by Rätz (1999), and the Fyllas Bank Station 4 temperatures for 1982–99. Results indicate that for the water layers 0–200 m and 200–400 m, i.e. the depth zones of the individual strata, there was significant coherence (Fig. 14, Table 3).

Isopleth diagrams were constructed from historic data provided by the World Data Centre A (WDC-A), Washington. The available data are grouped by season (spring, summer and fall) to analyze season specific changes in more detail (Fig. 15). The same dataset was used to determine the presence of Irminger Water (4°C $< \theta <$ 6°C, 34.95 $<$ S $<$ 35.1) at Fyllas Bank station 4 (Fig. 16, 17).

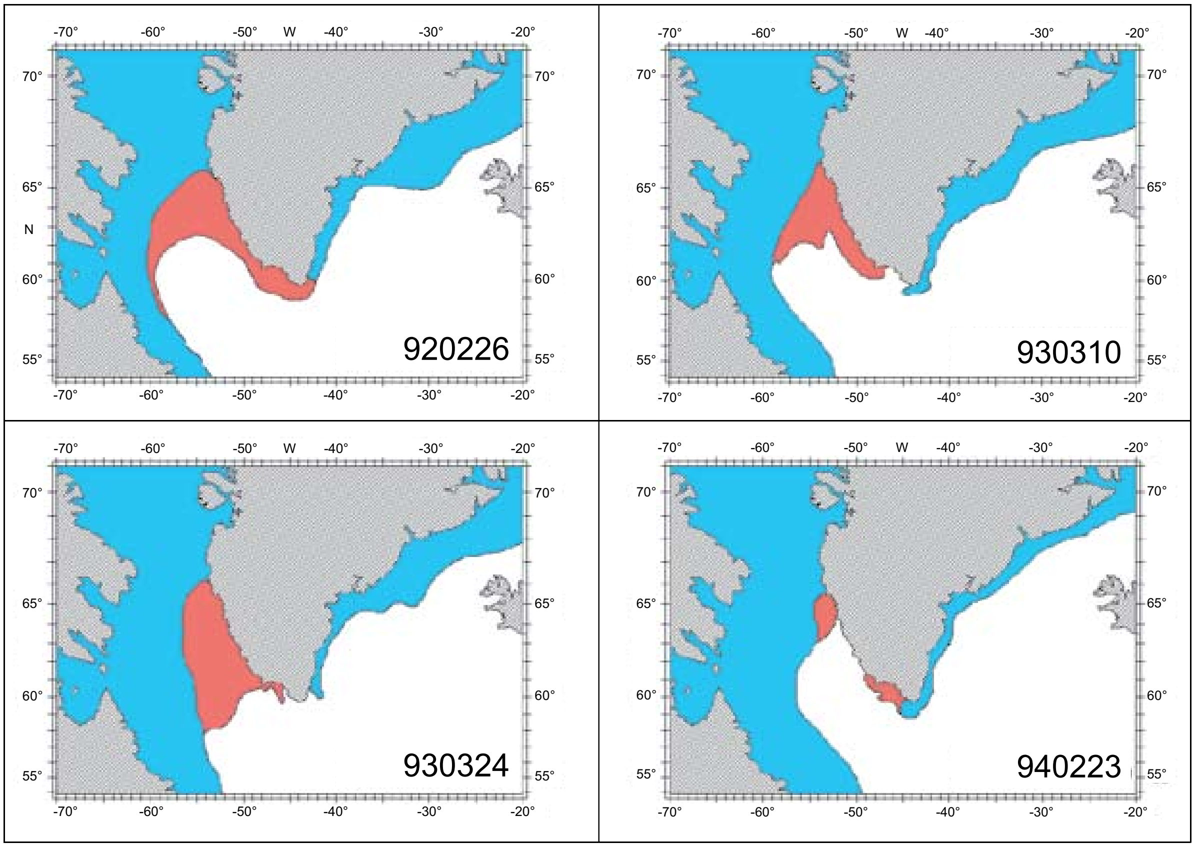

Fig. 12. The monthly mean ice area averaged by decade (top) and the time series of annual mean ice area based upon the average of the monthly means from January to April (bottom) for the Scotian Shelf. The black horizontal lines represent the decadal means.

Surface layer thermal conditions at Fyllas Bank station 4 are dominated by cold events during spring and summer (Fig. 15 left panel, top and middle). At the beginning of the 1990s, cooling was most intense during summer. At depths below 400 m, warm (>4°C), saline water (>34.75) was found during the summers of the 1950s through to the 1980s, and during the second half of the 1990s. There was a cold, intermediate period from the early-1980s to the mid-1990s in this deep layer. During autumn (Fig. 15, lower left panel), temperatures exceeded 5°C in the deep layer during the warm periods and were below this temperature during the cold period. Although the temperature's absolute values are less in the spring and summer, the warming and cooling patterns in the deep layers are again evident (Fig. 15). At the end of the 1990s, >6°C temperatures in the deep waters were observed at Fyllas Bank station 4. The top layer shows some cooling during the early-1990s with the 4°C isotherm in autumn bending downwards. This cooling was accompanied by decreasing salinities in the upper 400 m (Fig. 15, lower right panel). A common feature of the surface layers during summer and autumn are the low salinities (<33.0). The spring salinities do not fall below 33.0.

The Irminger Water mass

There is more than one definition for Irminger Water in oceanographic literature. Dietrich (1957) defines this watermass as having a temperature of 4.0°C and a salinity of 34.90. This cold and relatively low saline water receives its characteristics in the Irminger Sea by vertical convection during winter. Malmberg (1972) gives a temperature range of 3.5 to 4.0°C and a salinity of 34.92 for Irminger Sea water as one of the main water types in the Greenland-Iceland-Ridge area. Clarke and Gascard (1983) define among watermasses in the upper Labrador Sea, Irminger Water with a temperature of 5.5°C and a salinity of 35.0. Clarke (1984) gives a definition for the Irminger Current flowing into the Labrador Sea as water of 4–6°C, 34.95–35.1. In the present paper the latter definition is taken for Irminger water in the watermass analysis at Fyllas Bank, station 4 (4°C< θ <6°C, 34.95<S<35.1, Fig. 16, 17).

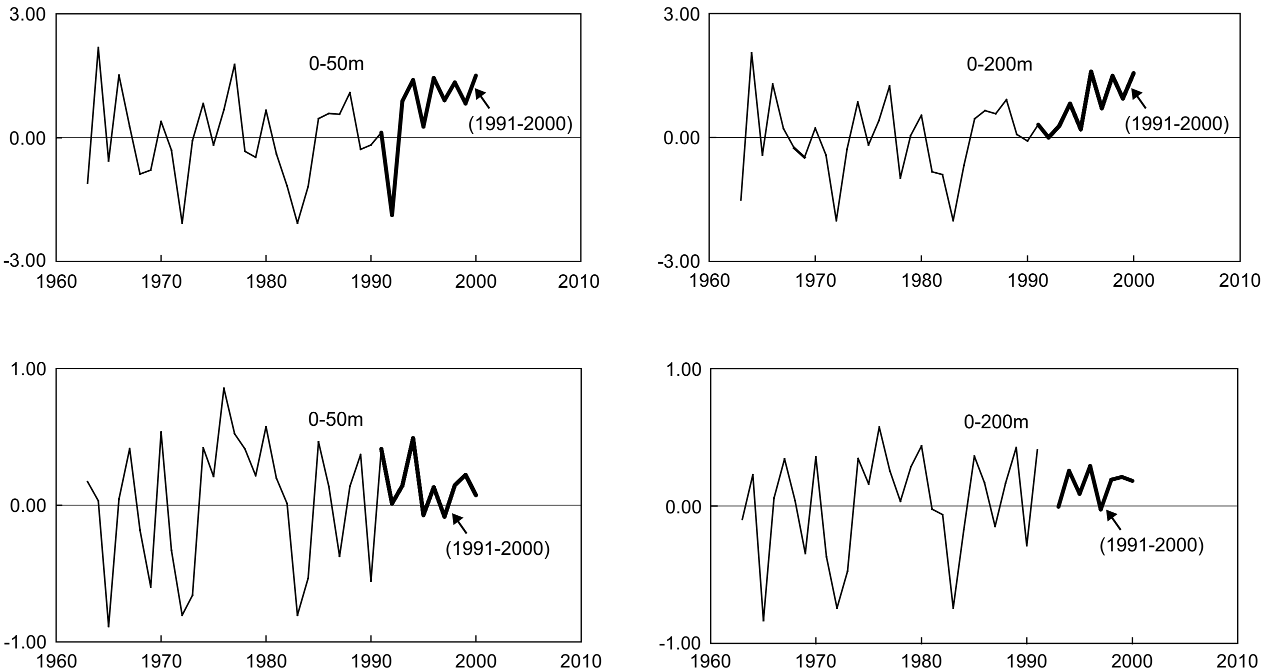

Fig. 13. The decadal means of the number of icebergs crossing south of 48°N (top) and the time series of the annual numbers (bottom). The horizontal lines in the bottom plot are the decadal means.

TABLE 2. Climatic means (°C/psu) (1963–90) for temperature and salinity by depth at Fyllas Bank Station 4.

Site	Lat./Long.	0–50 m	0–200 m	Data
Fyllas Bank temperature	63°53'N, 53°22'W	1.73	2.68	1963–2000
Fyllas Bank salinity	63°53'N, 53°22'W	33.01	33.48	1963–2000

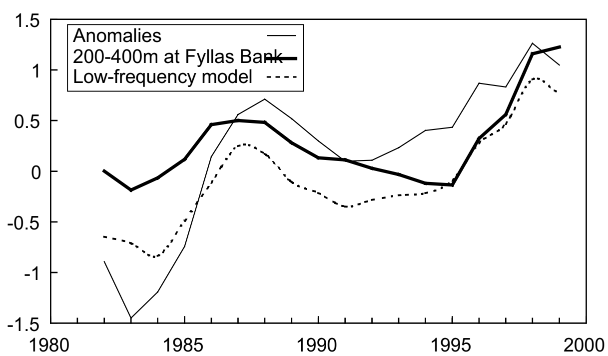

Fig. 14. Mean temperature anomalies (°C) of water layers 0–200 m, 200–400 m at Fyllas Bank Station 4 and area-weighted mean temperature index of German groundfish survey area for East and West Greenland (Rätz, 1999).

The presence of Irminger Water at Fyllas Bank station 4 between 1946 and 2000 is mostly found at depths between 400 and 800 m (Fig. 16). Irminger Water was not found during all year, however. There are clusters of Irminger Water mass presence around 1950 (1946, 1948–50, 1954), 1963 and during the second half of the 1960s (1967–70, 1972), during the 1980s (1982–83, 1985, 1987–88), and there are two events in the 1990s, 1993 and 1999. Seasonal discrimination of the presence of Irminger Water at Fyllas Bank station 4 is shown in Fig. 17 for spring, summer and autumn. Except for the 1990s, Irminger Water was present at Fyllas Bank, station 4, in all seasons during the time periods as marked by the clusters in Fig. 16. Correlation analysis between the NAO index and the presence of Irminger Water at Fyllas Bank Station 4 yielded no significant result (r_{max} = - 0.11, with time series lagged 1 year).

Discussion

Air temperature data reveal that the 1950s and 1960s were warmer-than-normal at Egedesminde, which is to the

TABLE 3. Correlations and statistical significance levels between mean temperature anomaly of water layers 0–200 m and 200–400 m at Fyllas Bank (Station 4) and area-weighted mean temperature index from German groundfish surveys off East and West Greenland (Rätz, 1999)

Water layer	r^2	Data
0–200 m	0.82 ($P << 0.001$)	1982–99
200–400 m	0.78 ($P << 0.001$)	1982–99

north of the West Greenland fishing banks, at Nuuk, which is in the vicinity of Fyllas Bank, a well known fishing ground off West Greenland, and at Prins Christian Sound, which is in the Cape Farewell region. Cold events were recorded at each of these sites, during the 1970s, 1980s and 1990s with the coldest conditions at Egedesminde during the early-1980s.

The lack of air temperature data at Egedesminde and Prins Christian Sound prior to 1949 led to the consideration

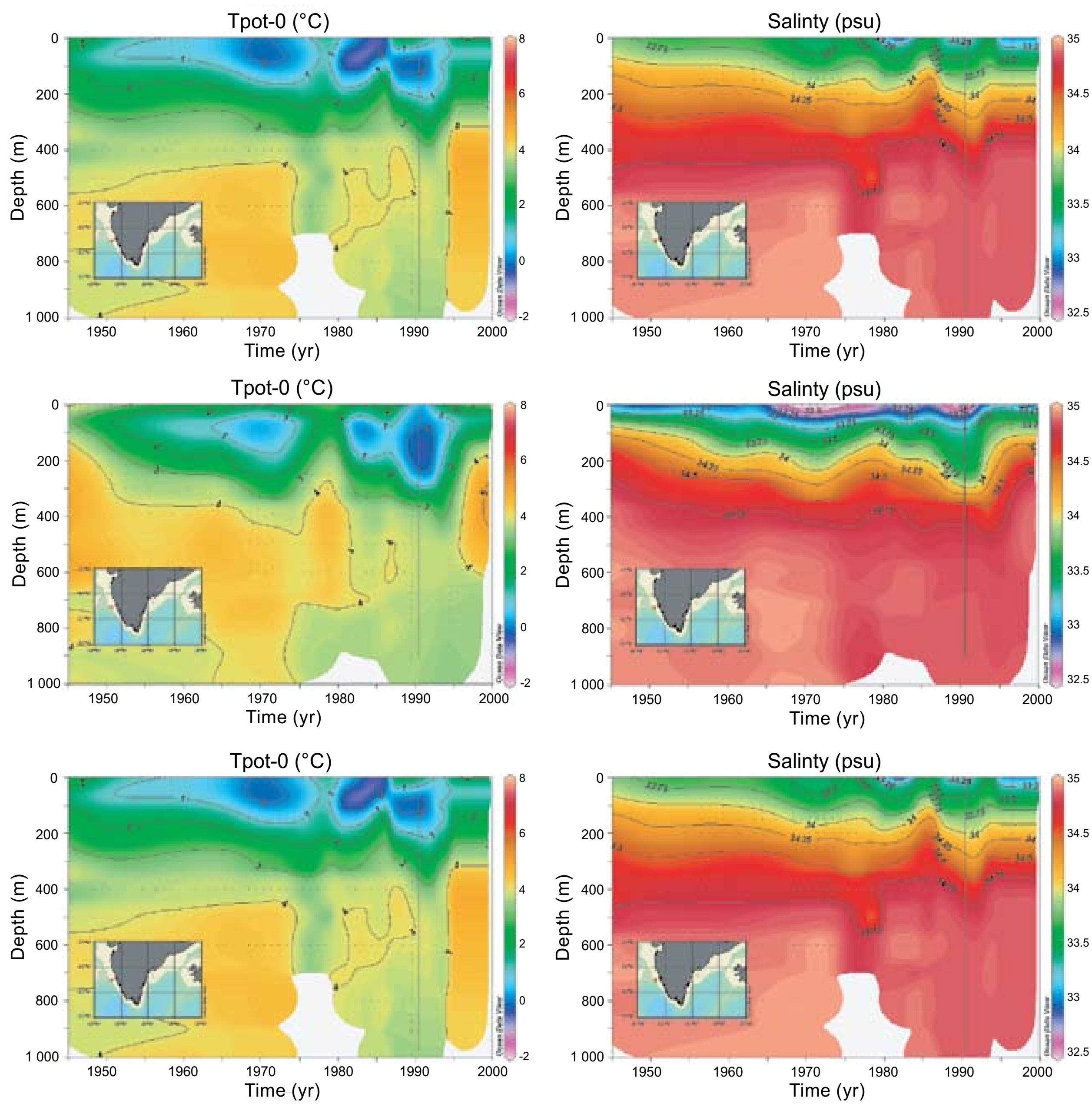

Fig. 15. Isopleth diagram of temperature (left) and salinity (right) at Fyllas Bank Station 4; spring (April–June, top panel), summer (July–September, middle panel), and autumn (October–December, lower panel).

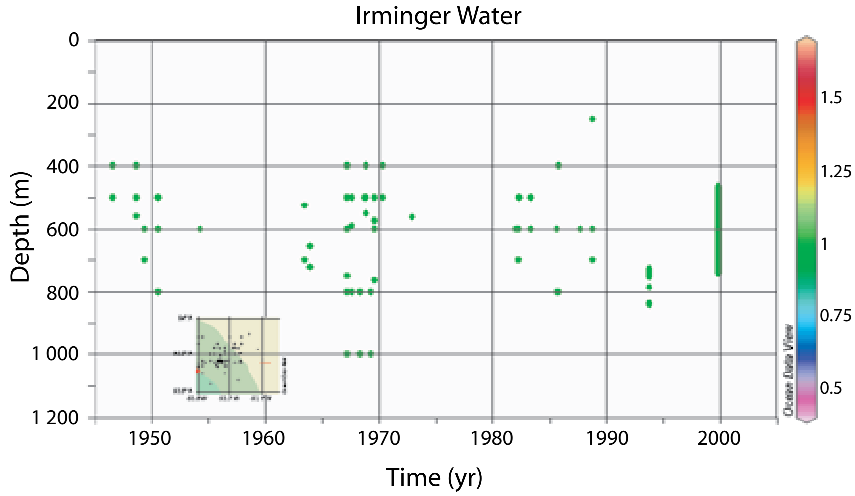

Fig. 16. Presence of Irminger Water at Fyllas Bank Station 4 during 1946–99.

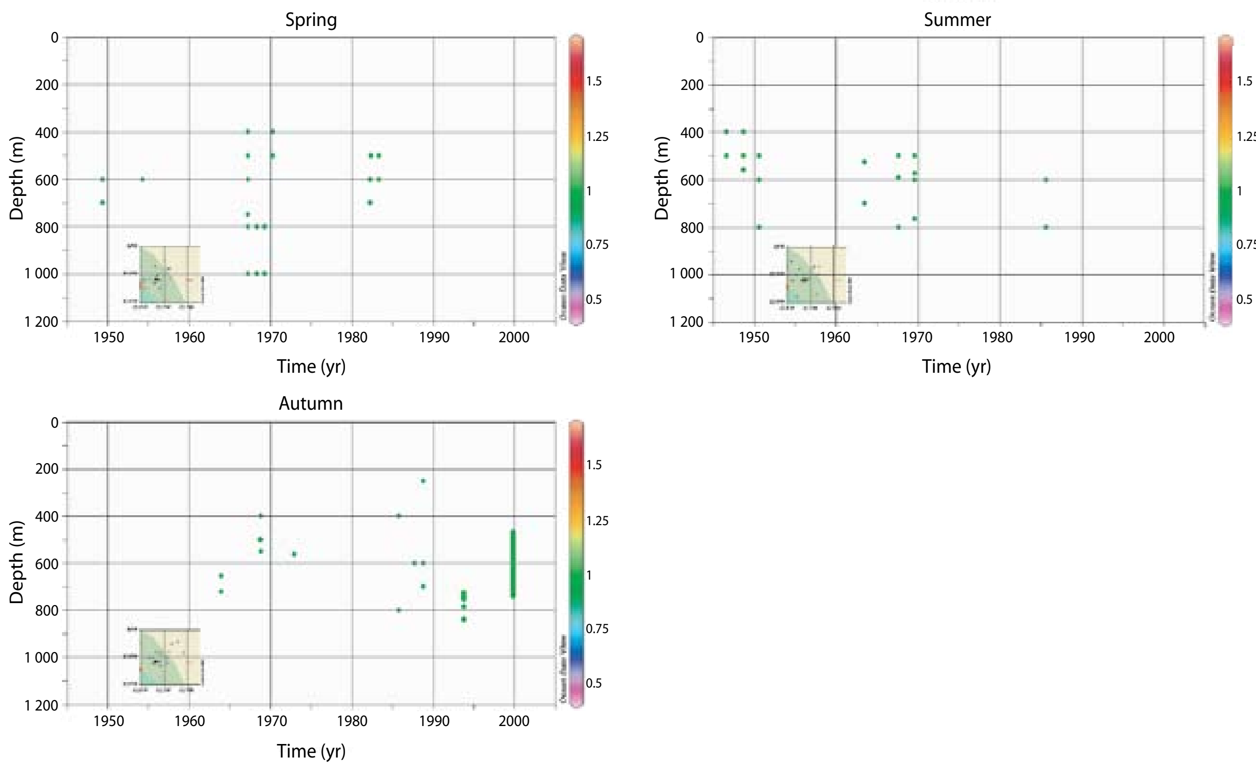

Fig. 17. Presence of Irminger Water at Fyllas Bank Station 4 during 1946–99; spring (April–June, top left panel), summer (July–September, top right panel), autumn (October–December, lower panel).

of whether Nuuk air temperature time series could be used as a proxy for the long-term climatic variability off West Greenland. Correlations between Nuuk air temperatures and those at Egedesminde and Prins Christian Sound were high and statistically significant. This led to the conclusion that the Nuuk air temperature time series may be taken as representative of climatic changes in the West Greenland region, from Cape Farewell in the south to Disko Bight in the north. The warming and cooling periods observed during the past 120 years at Nuuk seem to follow a long-term cycle that is characterized by about 54 years (Stein, 1995) of warm conditions (1923–76), with cold conditions before and after. At present the climatic system of West Greenland is in a cooling phase that is expected to continue until the early years of the 21st century. The warming that followed the short-term cold events during the decades of the 1970s, 1980s and 1990s, are indicative of quasi-decadal variability. Although the warming trend observed during the late-1990s is significant, it is not interpreted as a return to a long-term warming trend. The cold events recorded at Nuuk during 1882–84, in 1894, and 1898 seem to be common features in West Greenland climatology, and may be locally caused phenomenon as described in Buch and Stein (1989) and Rosenøn *et al*. (MS 1985).

Knowledge of the past and present behaviour of the NAO, which is known to effect or modify wind speed, air/sea heat exchange and evaporation over much of the North Atlantic region, is essential for interpreting observed climatic changes during the 1990s and previous decades (Anon., 2002). The warm 1960s in West Greenland climatology were low NAO index years. These were followed by increasingly positive NAO indices during the 1970s, 1980s and 1990s. The annual NAO Index was observed to show considerable annual variation. During the 1990s the index flipped from one of its most positive values to one of its most negative value in the 20th century. Air temperatures at West Greenland followed this annual variation inversely. Similar to Drinkwater (1996), Nuuk winter mean air temperatures were found to be negatively correlated with the NAO index during the 20th century ($r = -0.73$, $P << 0.001$).

Sea-ice conditions off West Greenland show considerable variation during the 1990s. Severest ice conditions were encountered during February and March 1992–94. In winter 1992, on 26 February, the rather seldom condition of "Storis" meeting "West Ice" in the southern bight was observed.

The two sources of information used in this paper to investigate the subsurface ocean variability during the 1990s, as well as the decades of the 1950s to 1980s, show considerable variation in the thermohaline properties off West Greenland. Cold and low saline events were observed during the early-1970s, 1980s and 1990s. The near-surface thermal conditions reveal extreme cooling during 1992, and warming thereafter. Warming was also observed in the 0–200 m layer with anomalies well above the mean value. During the second half of the 1990s, thermal conditions in West Greenland waters appeared to be in the range of the warm 1960s. Significant correlation between the area-weighted mean temperature index for the German groundfish survey area off East and West Greenland and the Fyllas Bank station 4 temperatures for the analysed time period 1982–99, were found for the water layers 0–200 m and 200–400 m. This suggests that advective processes, i.e. a close coupling between East and West Greenland by the current system plays a dominant role in ocean temperature variability at Fyllas Bank. Accordingly, it seems suitable to assume that the Fyllas Bank Station 4 temperature and salinity time series are representative of West Greenland subsurface ocean variability.

The analysis of historic WDC-A data shows that the slope region off West Greenland, as observed at Fyllas Bank station 4, is dominated by cold events during spring and summer. At the beginning of the 1990s, cooling was most intense during summer. At depths below 400 m, warm, saline water was found during most of the summers of the second half of the 20th century. There is, however, a cold period from the early-1980s to the mid-1990s in this deep layer. A similar temporal pattern in the deep layer can be seen in autumn. At the end of the 1990s, record high temperatures were observed at Fyllas Bank (Station 4). Surface layer cooling during the early-1990s was accompanied by decreasing salinities in the upper 400 m. This might be explained by the anomalous atmospheric and sea ice conditions during 1992–93. There is evidence of low surface salinities (<33.0) during summer and autumn at Fyllas Bank Station 4. These low salinities were not found during spring. This low saline water during summer and autumn is possibly derived by Arctic freshwater supply through the East Greenland Coastal Current or the East Greenland Current (Bacon *et al*., 2002).

Irminger Water was mostly found at depths between 400 and 800 m at Fyllas Bank station 4. It was, however, not found during all years. Irminger Water was present around 1950, during the second half of the 1960s, around 1970, during most of the 1980s, and there are two events in the 1990s. Major gaps in the presence of Irminger Water at the West Greenland slope off Fyllas Bank were encountered from 1955–62 and from 1973–81. These observations indicate that Irminger Water arrives in pulses at Fyllas Bank . Since the Irminger Water mass was mostly found at depths below 400 m, it seems unlikely that atmospheric processes play a steering role in the advection of this water mass to the West Greenland slopes.

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Note from Editor:
15 April 2010 Original captions to figures 12 and 13 were incorrect in the original version. They have now been changed in this pdf. An errata slip was placed in the hardcopy soon after publication.