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Oceanographic Investigations in West Greenland Waters, 1981-1997

by

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Abstract

The oceanography of the NAFO subarea 1 - along the Southwest Greenland fishing banks is highly dominated by the inflow of water masses originating from various regions in the North Atlantic and Arctic Ocean carried to the area by the East Greenland Current, the Irminger Current and a side-branch of the North Atlantic Current. The existence of the latter transport has only recently been discovered (Buch, 1990) and led to the introduction of a new water mass in the Southwest Greenland area: ***the Sub-Atlantic Water.***

During the 1980 - 1997 period Greenland has experienced great fluctuations in its climate. The North Atlantic Oscillation (NAO) index has since the early 1980'ies been in a persistent and exceptionally strong positive phase which means cold and dry conditions over Greenland. Greenland has been characterised by very cold conditions since 1980 especially in the 1982 - 1984 period, where record cold winters was experienced, but also the 1989 - 1994 period was extremely cold. These cold atmospheric conditions was reflected in the waters off Southwest Greenland by temperatures well below normal in the upper 400 m as well as in an increase in the formation of "Westice" moving the ice limit so far south that the seldom situation of "Westice" and "Storis" joining each other in the Julianehaab Bight during the winter months has been experienced several times during the recent 15 years.

1. Introduction

Knowledge of the oceanographic conditions in an ocean area and in particular their variability is extremely important to the assessment of:

- climate variability
- environmental impact on living resources (primary production, fish stocks, marine mammals)
- possibilities for exploitation of the living and non-living resources of the sea.
- possibilities for the establishment of an operational oceanographic service.

The oceanographic conditions of the Greenland waters are generally well-known and have been thoroughly discussed in Buch (1990). The seasonal and interannual variability can however be substantial reflecting climatic signals transferred to the area by the atmosphere and/or the ocean currents influencing Greenland waters i.e. the East Greenland Current, and a couple of sidebrances of the North Atlantic Current of which the Irminger Current is one.

The Greenland area has during the 1981-1997 period been characterised by dramatic climatic variability, where especially two extremely cold periods - 1982-84 and 1989-1994 - are remarkable. The winters 1983 and 1984 were the coldest ever recorded at Greenland since regular meteorological observations started in 1884. The cold atmospheric conditions were reflected to the surface layer of the ocean having severe impact on the living conditions for the economically important fish stocks primarily the cod stock.

The goal of the present report is to give an overview of the most important events in the oceanographic conditions in the Greenland Waters in the 1981 - 1997 period. The report will especially focus on the waters off Southwest Greenland from Cape Farewell to the Disko Bay (NAFO Subarea 1) due to the economic importance of this ocean area to the Greenland society

2. Oceanographic observations, 1981 - 1997

Greenland Fisheries Research Institute

The Greenland Fisheries Research Institute has since its foundation in 1947 tried to operate all the NAFO sections in NAFO Subarea 1 at least once a year and especially the Fylla Bank section several times per year. In 1980 the institute decided to upgrade their oceanographic observation programme and a oceanographer was employed. In addition to the NAFO standard sections a new set of sections were defined for the Disko Bay area, Fig. 1. All sections north of the Fylla Bank Section were covered twice a year (June-July and November) while the southernmost sections were occupied only once (March-April). In 1990 the oceanographer left the Greenland Fisheries Research Institute, for which reason the work on the standard sections was cancelled in 1991. Since 1992 one annual cruise to the NAFO standard sections was performed by the Royal Danish Administration of Navigation and Hydrography on a contract with the Greenland Fisheries Research Institute.

In connection with trawl surveys oceanographic observations have been carried out on the trawl sites i.e. away from the NAFO standard sections.

The Greenland Fisheries Research Institute used the Nansen Bottles equipped with reversing thermometers for their oceanographic observations until 1989 when a SEABIRD SBE 9-01 CTD was introduced in the work. The same type of CTD has been used by the Royal Danish Administration of Navigation and Hydrography. The maximum depth of observation have always been 1000 m.

Calibration of the CTD sensors has been done in vitro at the manufacturers calibration facilities an in situ by taking near bottom water samples at the deepest stations.

The water samples collected for salinity analysis when using Nansen Bottles and those taken for CTD calibration purpose were analysed using a Guildline Autosal 8400 or a Guildline Portosal 8410.

In addition to the traditional observations of temperature and salinity observations of oxygen and nutrients were introduced in 1982. The nutrient observations were stopped after a few years while the oxygen observations were performed up until 1990.

Observations by other nations

Since 1963 the German Institute für Seefischerei, Hamburg have during late autumn conducted an annual groundfish survey on the fishing banks off East- and West Greenland. Associated with these trawl survey oceanographic observations have been carried out on standard sections along the east coast of Greenland south of the Denmark Strait and on the NAFO standard sections off West Greenland.

International Projects

The Greenland Fisheries Research Institute participated actively in the Greenland Sea Project together with the Marine Research Institute of Iceland. The two institutes contributed to the Greenland Sea Project by performing oceanographic measurements in the East Greenland Current between 72°30 N and the Denmark Strait.

The Nordic contribution to the World Ocean Circulation Experiment - NORDIC WOCE - carried out observations in the Denmark Strait, while Germany, Canada and the Netherlands occupied the WOCE sections approaching Greenland near Cape Farewell.

In recent years much attention is being paid to the deep and intermediate water formation processes north of the Denmark Strait due to its importance to the global thermohaline circulation. Several nations are engaged in research projects in this area of which the biggest projects are the EU MAST programmes European Subpolar ocean Project (ESOP) and Variability of Exchanges in the Northern Seas (VEINS).

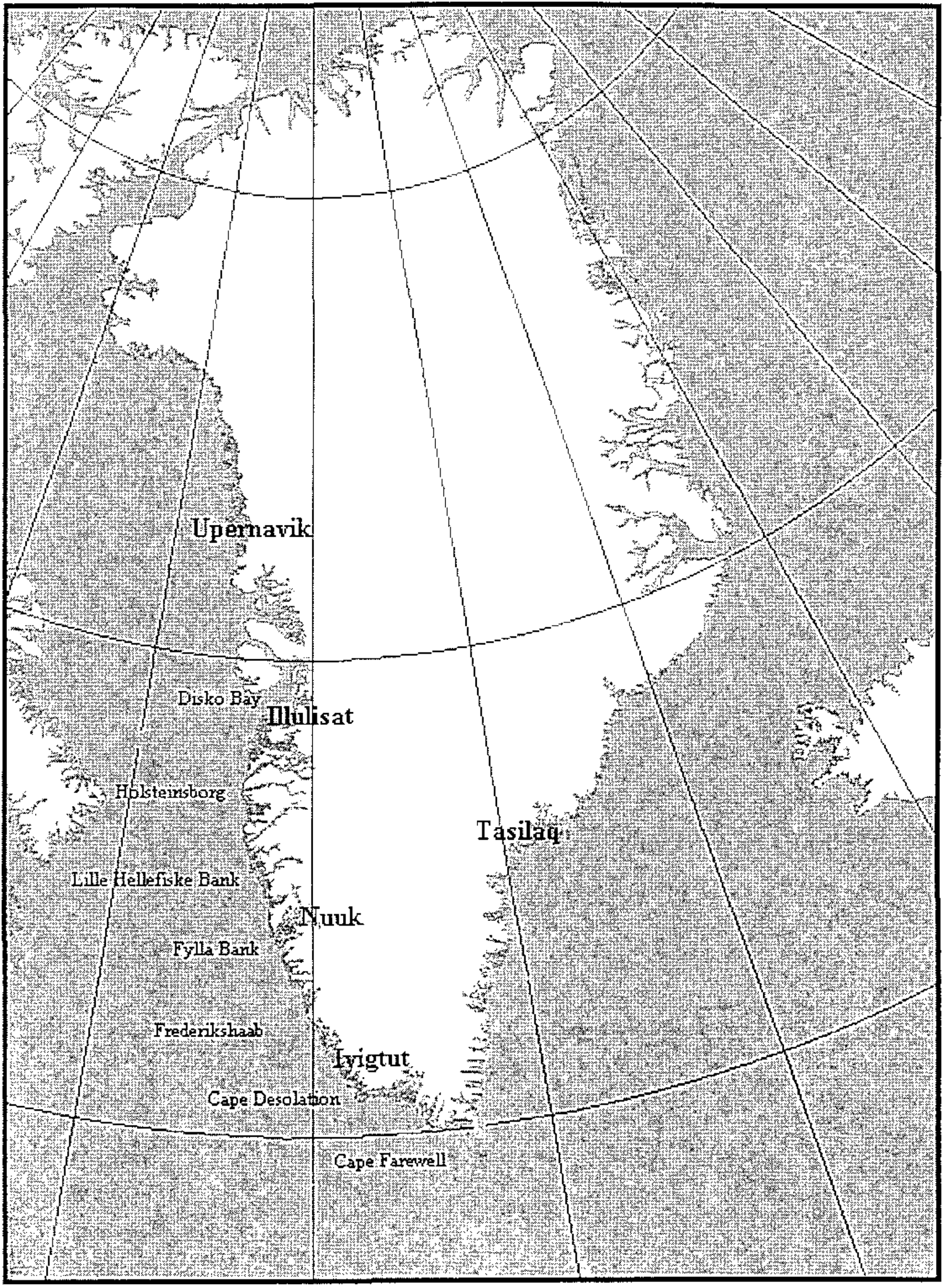


Fig.1. Area of investigation.

3. Atmospheric conditions

General aspects and the NAO index

Recent climatic research has demonstrated that the North Atlantic Oscillation (NAO) and the El Niño-Southern Oscillation (ENSO) together is the major source of interannual variability of weather and climate around the world. While there has been a major public interest and awareness of the El Niño event in 1997-98 and its many climatic consequences, the NAO is a relatively unknown phenomenon; but there are close correlation between NAO and the climate in the North Atlantic region, Greenland and Europe.

The NAO, which is associated with changes in the surface westerlies across the Atlantic onto Europe, refers to a meridional oscillation in the atmospheric mass with centres of action near the Iceland Low and the Azores High (van Loon and Rogers, 1978). Although it is evident throughout the year, it is most pronounced during winter and accounts for more than one-third of the total variance of the Sea Level Pressure (SLP) field over the North Atlantic. Because the signature of the NAO is strongly regional, a simple index of NAO was defined by Hurrell (1995) as the difference between the normalised mean winter (December-March) SLP anomalies at Lisbon, Portugal and Stykkisholmur, Iceland. The SLP anomalies at each station were normalised by dividing each seasonal pressure by the long-term mean (1964 - 1995) standard deviation. The variability of the NAO index since 1864 is shown in Figure 2 (Hurrell and van Loon, 1997), where the heavy solid line represents the low pass filtered meridional pressure gradient. Positive values of the index indicate stronger than average westerlies over the middle latitudes associated with low pressure anomalies over the region of the Icelandic Low and anomalous high pressures across the subtropical Atlantic.

In addition to a large amount of interannual variability, there have been several periods when the NAO index persisted in one phase over many winters, van Loon and Rogers, 1978, Barnett 1985, Hurrell and van Loon, 1997. Over the region of the Icelandic Low, seasonal pressures were anomalously low during winter from the turn of the century until about 1930 (with exception of the 1916-1919 winters), while pressures were higher than average at lower latitudes. Consequently, the wind onto Europe had a strong westerly component and the moderating influence of the ocean contributed to higher than normal temperatures over much of Europe (Parker and Folland, 1988). From the early 1940s until the early 1970s, the NAO index exhibited a downward trend and this period was marked by European wintertime temperatures that were frequently lower than normal (van Loon and Williams, 1976, Moses et al., 1987). A sharp reversal has occurred over the past 25 years and, since 1980, the NAO has remained in a highly positive phase with SLP anomalies of more than 3 mb in magnitude over both the subpolar and the subtropical Atlantic. The 1983, 1989 and 1990 winters were marked by the highest positive values of the NAO index recorded since 1864 (Fig. 2).

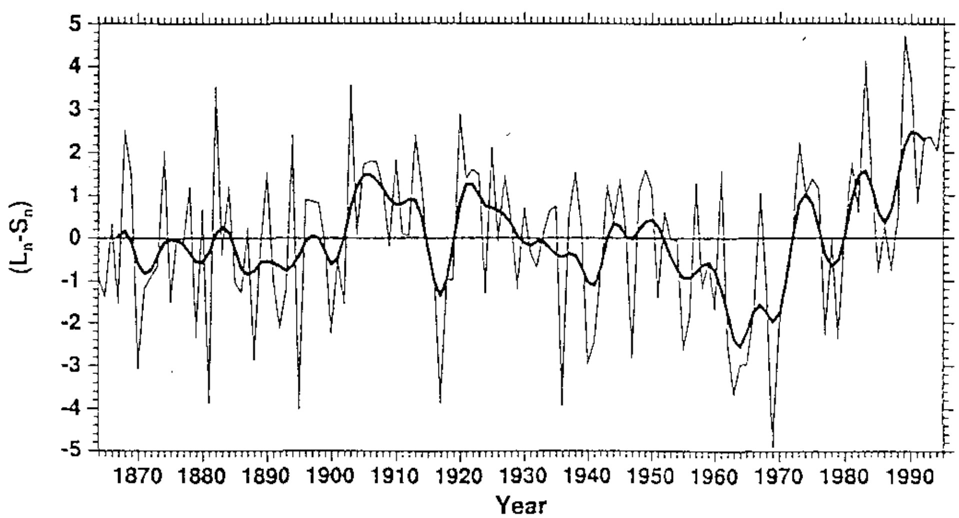


Fig. 2 Time series of the winter (December - March) index of the NAO (as defined in the text) from 1864-1995. The heavy solid line represents the meridional pressure gradient smoothed with low pass filter to remove fluctuations with periods less than 4 years. (After Hurrell and van Loon, 1997).

The changes in local land- and sea surface temperatures based on linear regression with the NAO index are shown in Fig.3 (Hurrell and van Loon, 1997). Changes of more than 1°C associated with a one standard deviation change in the NAO index occur over the Northwest Atlantic and extend from northern Europe across Eurasia. Changes in temperatures over northern Africa and Southeast United States are also noticeable.

The surface temperature anomalies for the North Atlantic and surrounding land masses for the 1980 - 1994 period is shown in Fig. 4, Hurrell and van Loon, 1997. The similarity between the departure pattern of temperature (Fig. 3) and the 1980 - 1994 conditions is striking and suggests that the recent temperature anomalies over these regions are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980's.

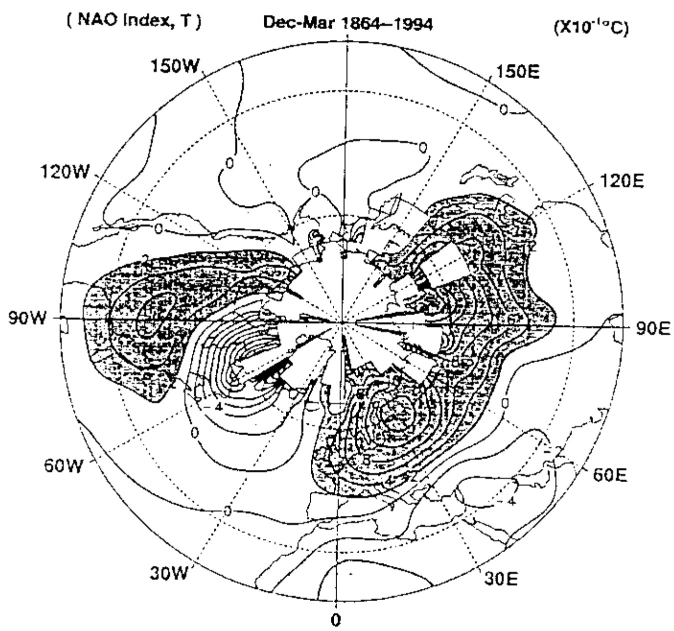


Fig. 3. Changes in temperature (x 10^{-1} ° C) corresponding to a unit deviation of the NAO index computed over the winters from 1864 through 1994. The contour increments is 0.2°C. Temperature departures > 0.2°C are indicated by dark shading and those < -0.2°C are indicated by light shading. Regions of insufficient data are not contoured. (After Hurrell and van Loon, 1997).

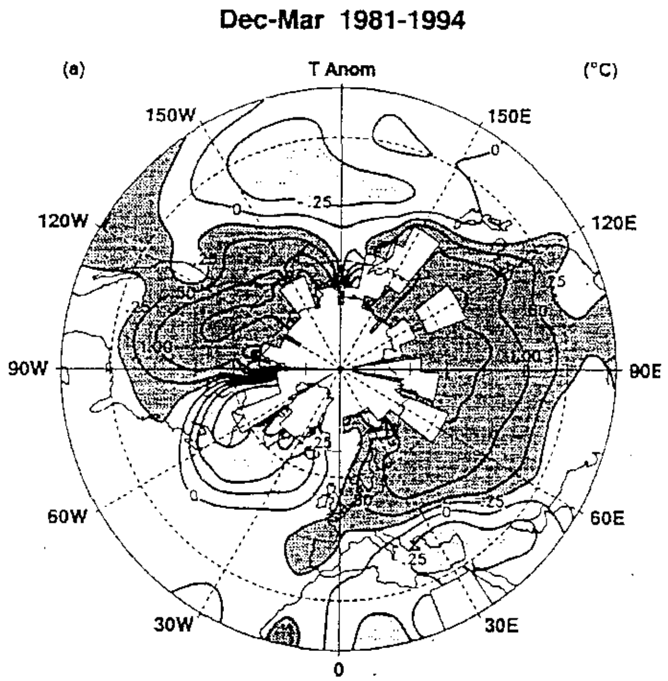


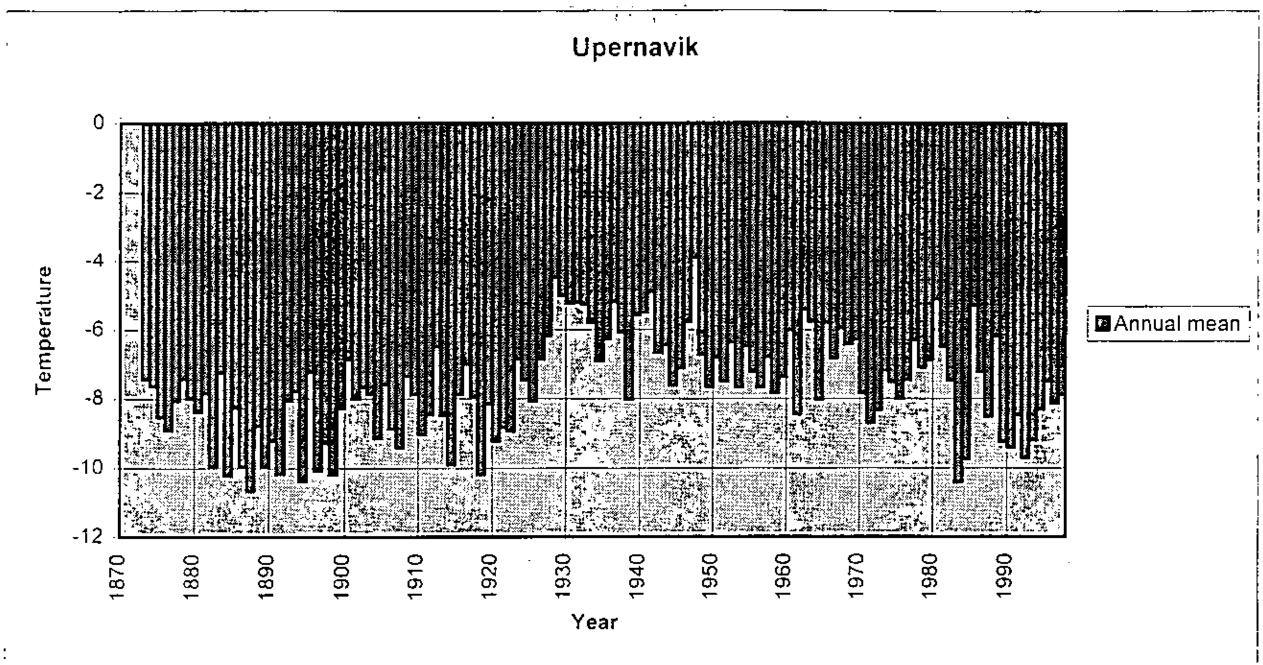
Fig. 4. Fourteen winters(1981 - 1994) average surface temperature and SST anomalies. Temperature anomalies > 0.25°C are indicated by dark shading and those < -0.25 are indicated by light shading. Regions of insufficient data coverage are not contoured.

Analysis (Hurrel and van Loon, 1997) of the relations between NAO and precipitation shows that during times of a high NAO index, the axis of maximum moisture transport shifts to a more Southwest-to-Northeast orientation across the Atlantic and extends much farther north and east onto northern Europe and Scandinavia. A significant reduction of the total atmospheric moisture transport occurs over parts of southern Europe. Analysis of evaporation minus precipitation (E - P) (Hurrel and van Loon, 1997), computed as a residual of the atmospheric moisture budget, show that E exceeds P over much of Greenland during high NAO index winters, a result that is consistent with other observational and modelling studies that indicate a declining precipitation rate over much of the Greenland Ice Sheet over the past two decades (Bromwich et al., 1993).The above given description of the NAO index clearly illustrates the strong correlation between the strength of the westerlies across the North Atlantic - the NAO index - and the climate in Greenland and Europe. It also shows that the climate in Greenland and Europe are negatively correlated to each other, a phenomenon named Seesaw in the literature.

Conditions over Greenland

Meteorological observations has been carried out at several locations in Greenland by the Danish Meteorological Institute since 1873. In Fig. 5 is shown timeseries of annual mean air temperatures from Upernavik, Illulisat, Nuuk, Ivigtut from West Greenland and Tasiilaq from East Greenland. In addition to the interannual variability all stations reflects the general picture of variability outlined above in the description of the NAO index (Fig.2).

a)


Upernavik
0
-2
-4
-6
-8
-10
-12
Temperature
1870
1880
1890
1900
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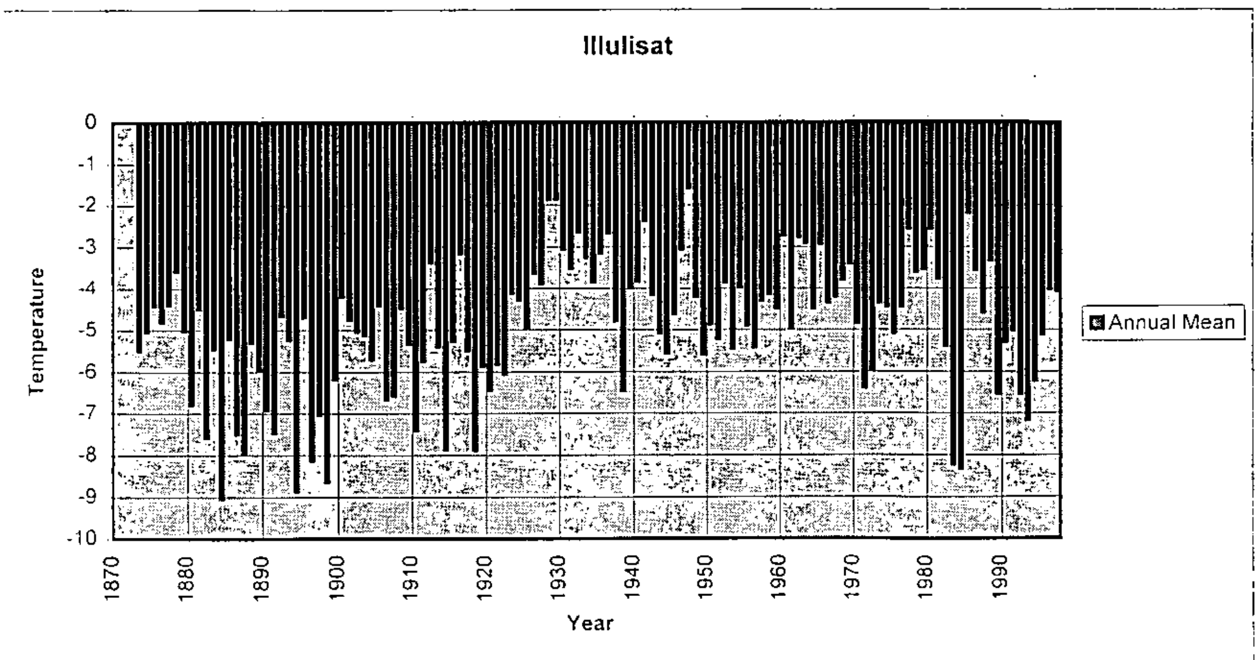
1960
1970
1980
1990
Year
Annual mean

b)


Illulisat
0
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-10
Temperature
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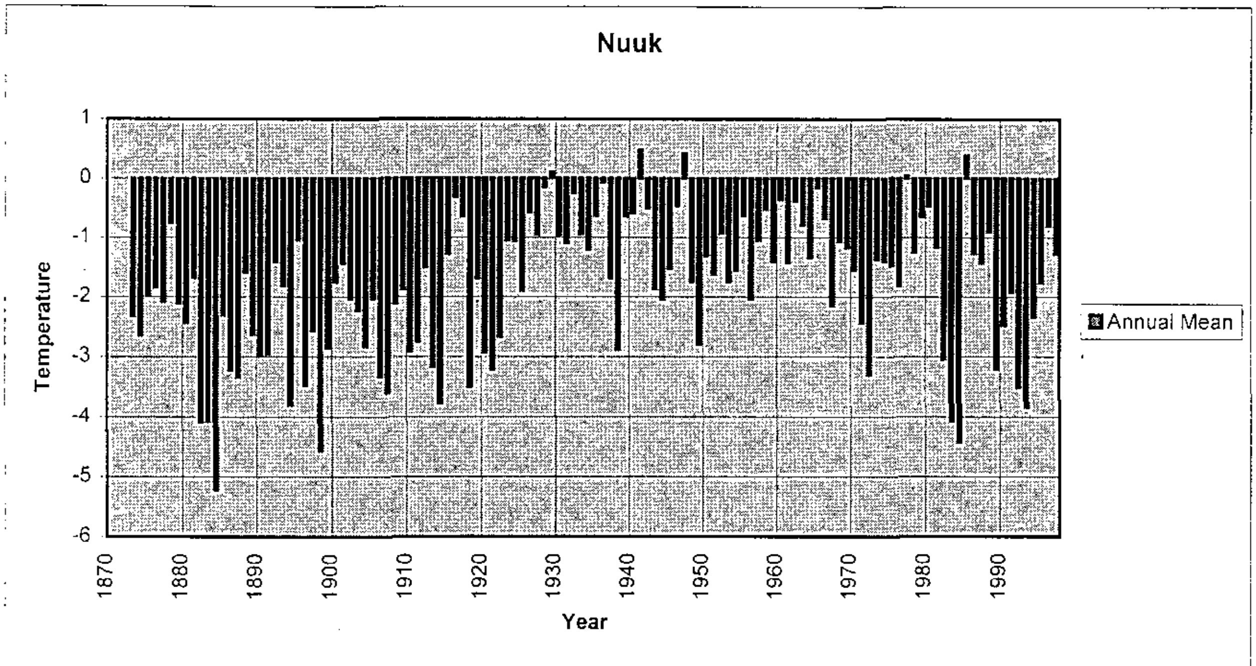
Year
Annual Mean

c)


Nuuk
Temperature
Year
Annual Mean
1
0
-1
-2
-3
-4
-5
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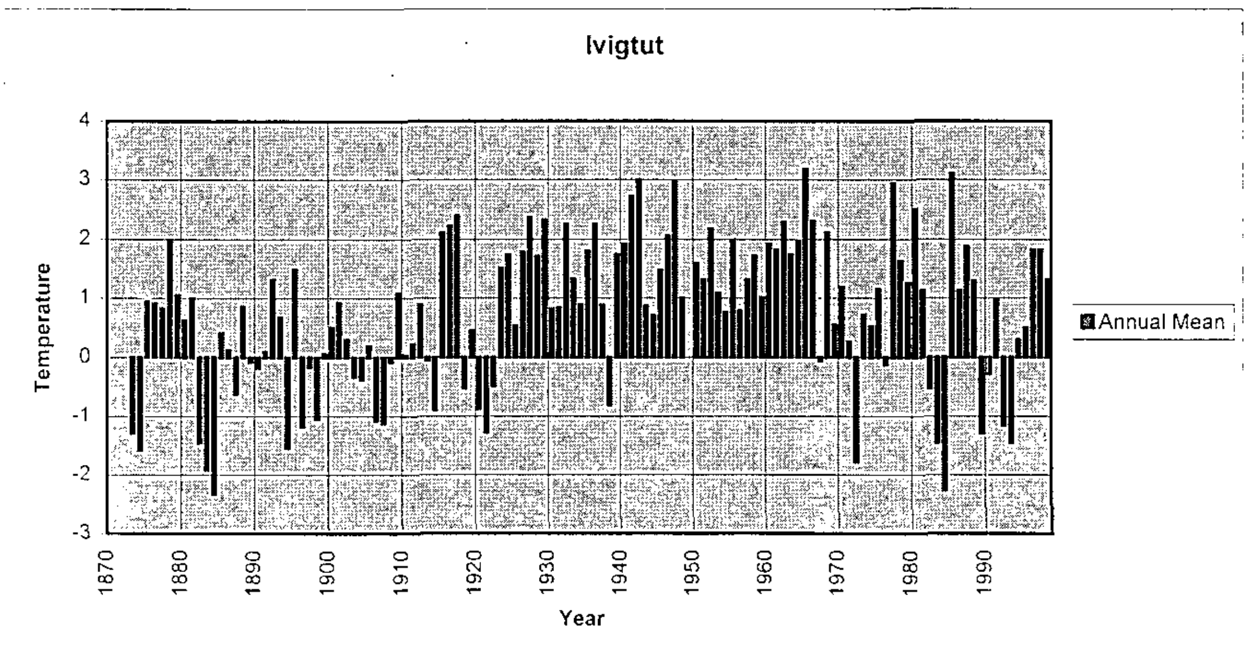
d)


Ivigtut
Temperature
Year
Annual Mean
4
3
2
1
0
-1
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1870
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e)

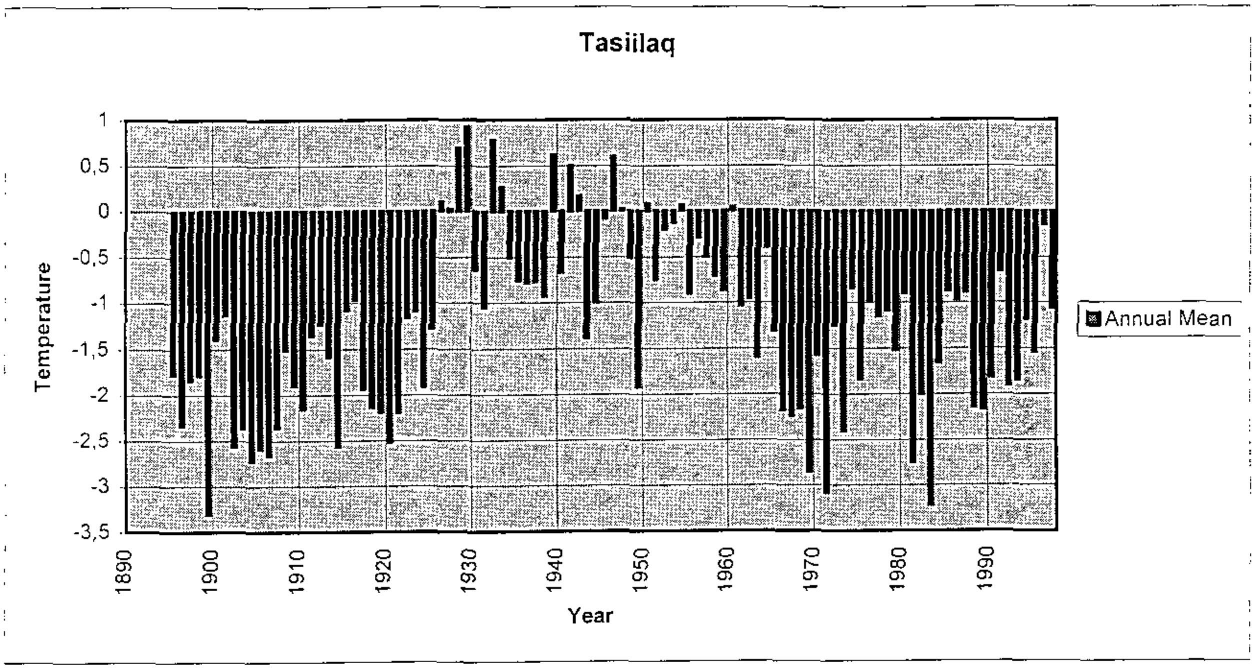


Fig. 5. Annual mean temperatures from
a) Upernavik
b) Illulisat
c) Nuuk
d) Ivigtut
e) Tasiilaq

Some geographical differences can be recognised of which one of the most significant is the relatively long cold period experienced in Tasiilaq, East Greenland in the late 1960'es and early 1970's. These cold conditions can also be traced at the southernmost West Greenland stations around 1970. The cause for the cold conditions at East- and Southwest Greenland around 1970 has been thoroughly discussed in the literature because the well known "Mid-seventies anomaly" or the "Great salinity anomaly", which was traced all over the North Atlantic area during the 1970'es and early 1980'es, was another result of a period of extremely high frequency of northerly winds over the Arctic Ocean and northern North Atlantic in the 1960'es, Dickson et al (1988). The northerly winds caused a greater than normal outflow of cold and relatively fresh polar water from the Arctic Ocean. This water together large amounts of polar ice was carried along the east coast of Greenland to the West Greenland area by the East Greenland Current. It is therefore logical that the most extreme air temperature conditions was experienced at Tasiilaq.

Focusing on the 1981 - 1997 period attention must be paid to two remarkably cold periods: 1982 - 1984 and 1989 - 1994. These two cold periods coincide well in time with the occurrence of the highest positive values of NAO index (1983, 1989,1990) as shown in Fig.2.

The 1982 - 1984 has been discussed by Rosenoern et al (1985) who showed that the cold conditions was due to the inflow of an extremely cold air mass from arctic Canada to the Davis Strait region with the centre in the vicinity of Aasiat, Fig. 6.

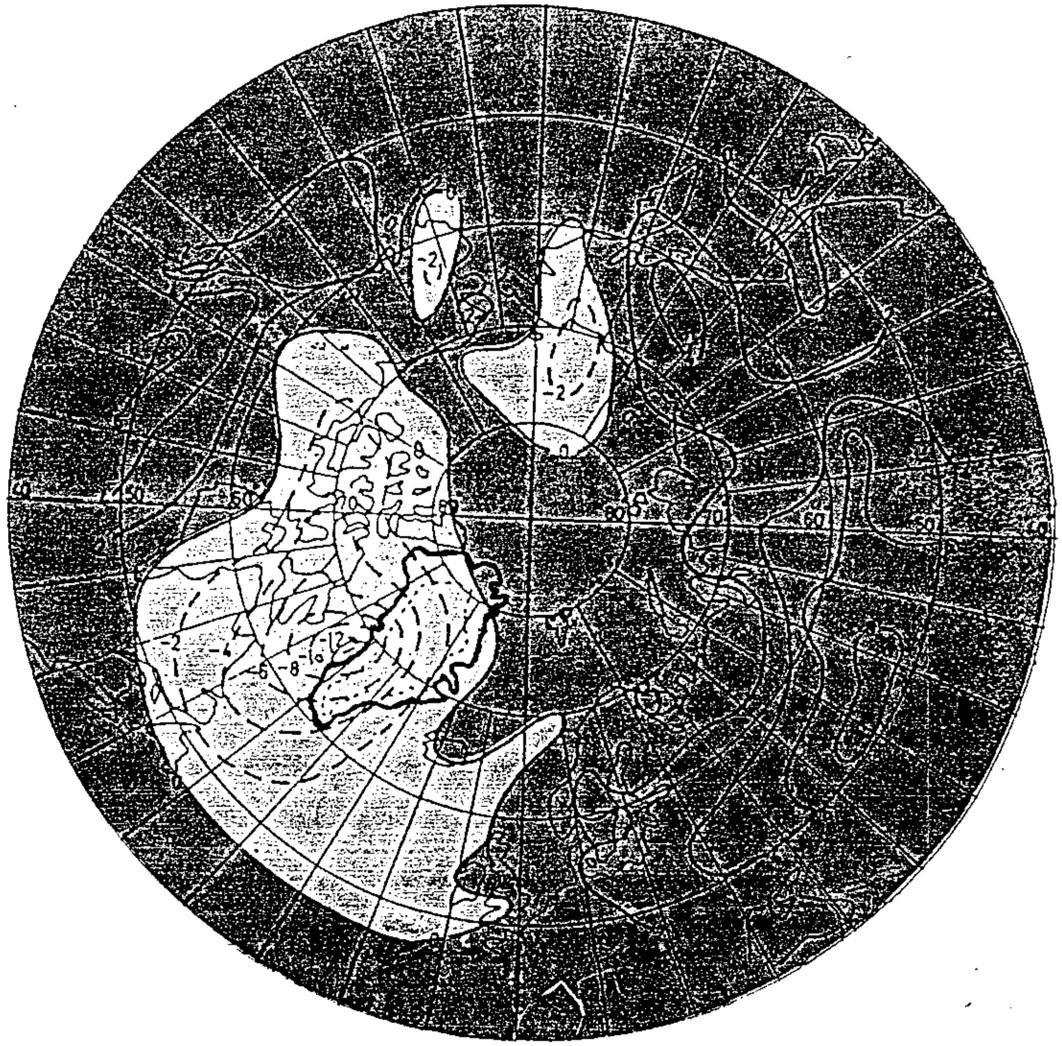


Fig. 6. Anomalies of the mean air temperature of January and February 1983 in the Arctic region. After Rosenoern et al. (1985).

Judging from the annual mean temperatures given in Fig. 5, it is seen that the 1982 - 1984 period is one of the coldest ever recorded at Greenland although not the coldest. Rosenoern et al. (1985) showed that negative temperature anomalies were observed every month from February 1982 to November 1984, but especially the winter months were extremely cold. The mean temperatures for the winter months -December, January and February- from Nuuk is shown in Fig. 7, and it is seen that the 1984 winter was the coldest ever recorded at this location (-15,2°C) and that we shall 99 years back in time to find similar conditions, -15,1°C in 1885. The monthly mean temperatures for January and February 1984 observed at the Nuuk station was by far the coldest ever recorded at this station, -19.1°C and -19.7°C respectively.

The cold period 1989 - 1994 was, like the 1982 - 1984 period, caused by the inflow of an cold arctic air mass to the Davis Strait area. The temperatures were, however, not so extreme during this period.

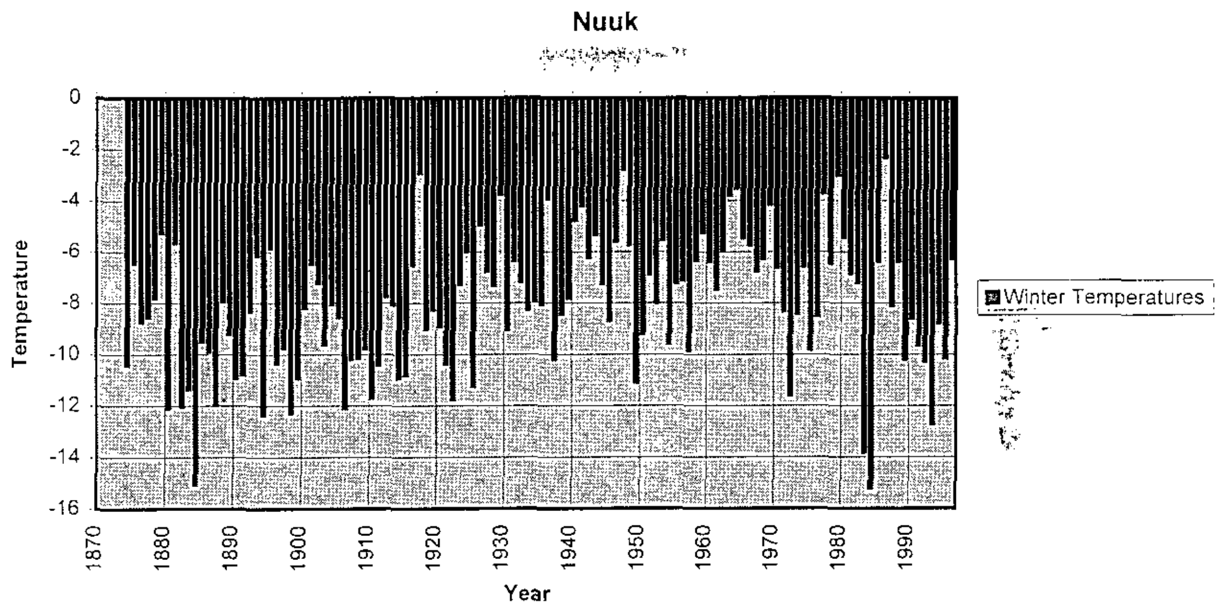


Fig. 7. Winter temperatures (December, January and February) at Nuuk.

Sea ice.

Sea ice is an important parameter in Greenland waters and the Southwest Greenland area is mainly dominated by two types of sea ice:

1. "Storis", multiyear ice of polar origin carried to Southwest Greenland by the East Greenland Current.
2. "Westice", first-year ice formed in the Baffin Bay and Davis Strait.

The Southwest Greenland, primarily the Julianehaab Bight, is cover with "Storis" 8-9 months of the year. The leading edge of the "Storis" normally passes Cape Farewell in December or January, but can vary several months from year to year. The amount of "Storis" entering Southwest Greenland waters show great interannual variability and is governed by several factors such as the outflow of sea ice from the Arctic Ocean, the formation of sea ice in the Greenland Sea, wind conditions in the Greenland -, Iceland - and the Irminger Sea. In the 1981 - 1997 period extremely great amounts of "Storis" entered Southwest Greenland water in 1982, 1984, 1989,1990 and 1993.

The formation of "Westice" starts in the northern Baffin Bay in September and in the succeeding months it continues to block larger areas along the Northwest Greenland coast. In most years the ice limit reaches Aasiat in December - January. The waters of Southwest Greenland is normally not affected by "Westice" because the inflow of warm water of Atlantic origin has its maximum during autumn and early winter, Buch (1990).

The presence of extremely cold air masses over the Davis Strait in 1983 -1984 and 1989 - 1994 naturally resulted in the formation of extraordinary large amounts of "Westice", whereby the ice limit was moved so far south that the seldom situation of the "Westice" and the "Storis" joining each other in the Julianehaab Bight has been experienced several times during the recent 15 years.

4. Oceanographic conditions

4.1. Water masses

The waters off Southwest Greenland are dominated by four water masses all formed outside the Davis Strait (Buch, 1990):

- In the surface layer close to the coast cold and low saline water Polar Water is found. It is carried to Southwest Greenland by the East Greenland Current.
- Below and west of the polar Water we find water originating from the North Atlantic Current
- At great depths North East Atlantic Deep Water and Northwest Atlantic Bottom Water are found.

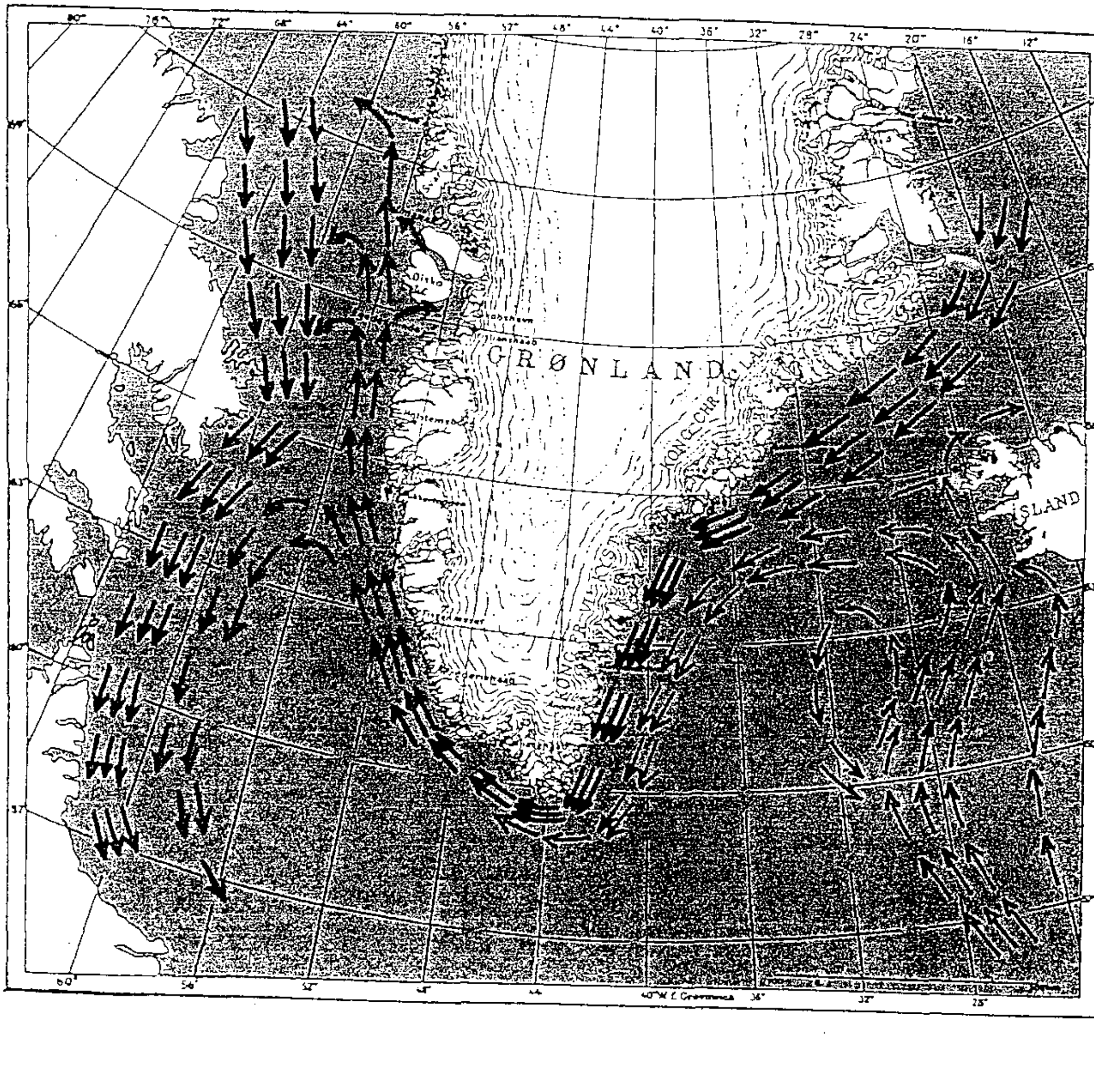


Fig. 8. Surface currents around Greenland.

The two deep water masses are not discussed in the present paper since they are found at depths greater than the maximum depth of observation - 1000 m - used by the Greenland Fisheries Research Institute in their observation programme.

The general picture of the ocean circulation east and west of South Greenland - with the East Greenland Current and the Irminger Current meeting south of the Denmark Strait flowing southward side by side, rounding Cape Farewell entering the Southwest Greenland area (Fig.8) - is well known and described in detail by Buch (1990).

The T/S-characteristics of Polar Water as it is found in the East Greenland Current are temperatures generally below 0°C but they may rise to 3-5°C in the surface layer during the summer. Salinity is below 34.4 psu. Buch (1990) however showed that the T/S-characteristics of Polar Water are altered on its way to Southwest Greenland due to mixing with surrounding water masses. Along the Southwest Greenland Fishing banks Polar Water therefore is characterised by temperatures below 1°C which may rise to 3-5°C during summer, salinity's are below 33.75 -34.0 psu. This classification is quite similar to the one given by Kiilerich (1943).

The Atlantic water component has until recently been referred to as Irminger Water, but the analysis of old data by Buch (1990) questions this statement.

Killerich (1943) summarised the oceanographic observations made in the Southwest Greenland area prior to World War II and defined Irminger water as water with temperatures between 3.5 and 5°C and salinity's above 34.75 psu. Lee (1968) and Clarke (1984) have defined Irminger Water as a mixture of Irminger Sea Water, formed in the Irminger Sea during winter, and North Atlantic Water and they characterised Irminger Water to have temperatures between 4 and 6°C and salinity's between 34.95 and 35.1 psu.

The discrepancy between the two definitions of Irminger water, especially the rise of the lower salinity limit to 34.95 psu gives reason to revalidate the presence of Irminger Water off Southwest Greenland and therefore to raise the following questions:

- Is Irminger Water the only water mass of Atlantic origin present off Southwest Greenland?
- Is Irminger Water at all present in the area?

Buch (1990) addressed these questions by using the extensive data set collected by the Greenland Fisheries Research Institute together with data collected during the NORWESTLANT programme in 1963.

A way of illustrating the presence of different water masses of Atlantic origin is by constructing T/S-diagrams. Due to the seasonal variability of the inflow of Atlantic water plots have been prepared for each of the four seasons using observations from Fylla Bank st.4 and 5 from the years 1950 - 1988 (all bottle data). (Fig. 9. a-d, surface data (S<34.0 psu) have disregarded).

These T/S-diagrams clearly indicate the presence of Irminger Water (T around 4.5°C, S>34.95) during all seasons. It is, however, striking to see how few observations of salinity's above 34.95psu that are actually made over a almost forty year long observation period. This is partly due to the fact that the vertical spacing between the observation points during bottle casts was 100 - 200 m in the depth interval where Irminger Water is found. Another possible explanation could be that Irminger Water does not reach the latitude of Fylla Bank every year. Buch (1982, 1984 and 1985) has shown that salinity's above 34.95 psu is observed at Fylla Bank only in certain years. It is possible that Irminger Water in some years can have reached Fylla Bank without being observed since the observation intensity has not been the same each year. On the other hand, it is also possible that Irminger Water only occasionally enters the Southwest Greenland area.

Fig. 9 shows that throughout the year there is a body of water in the Southwest Greenland area with salinity's above 34.85 and temperatures around 4°C. This body of water may have been formed by the Irminger water mixing with the surrounding water as it flows towards Southwest Greenland resulting in a decrease in temperature and salinity. We may therefore see the Irminger component of the Southwest Greenland Current as a tongue-like flow of water an impression confirmed by the vertical section given in Fig.10. In the core of this body of water, temperatures are close to 4.5°C and salinity's above 34.95, but at the outer limit the temperature is reduced to around 4°C and salinity to about 34.85. The core do apparently seldom reaches far beyond Cape Farewell.

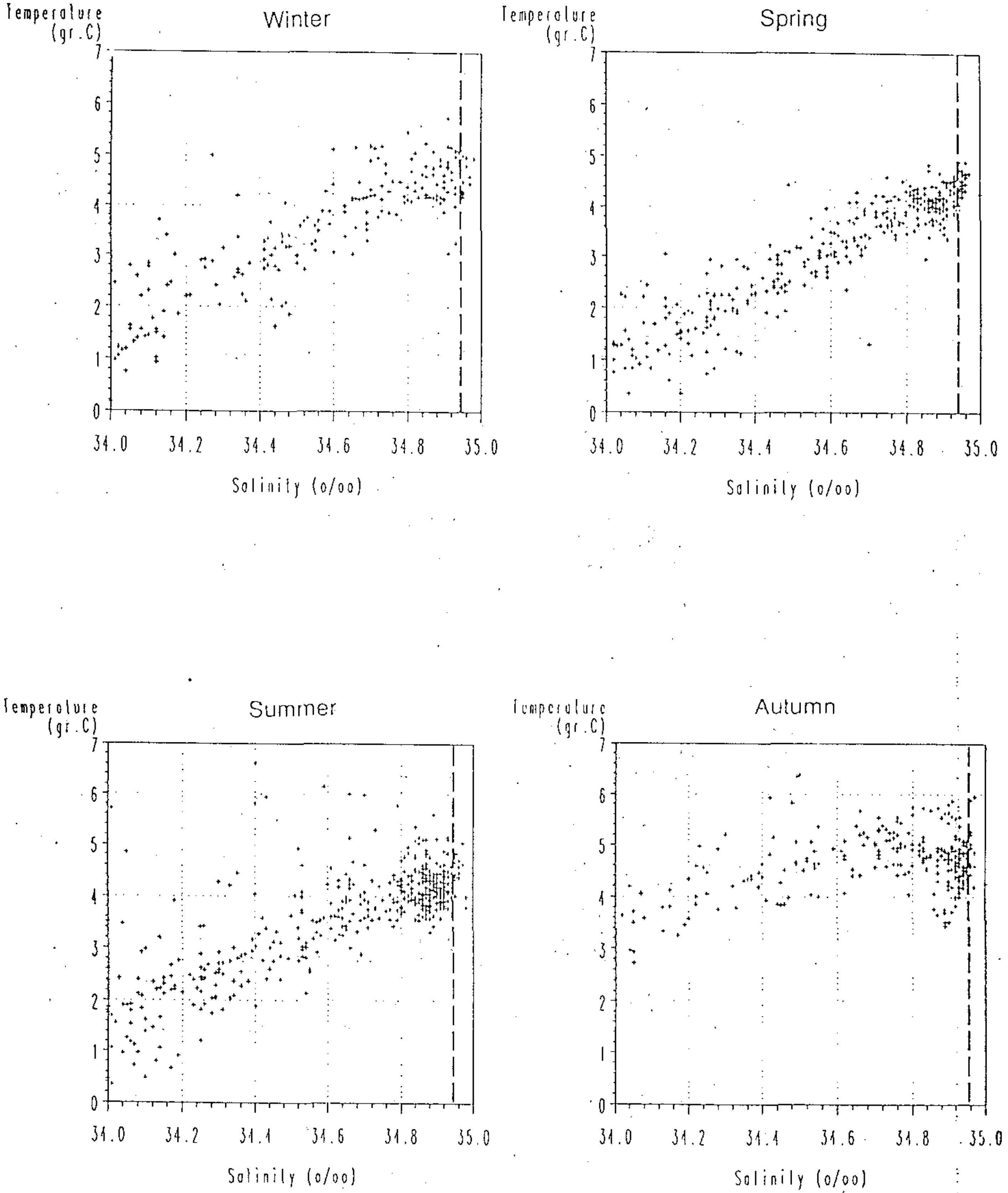


Fig. 9. Seasonal T-S plots using data from Fylla Bank st.4 and 5 from 1950 - 1998.

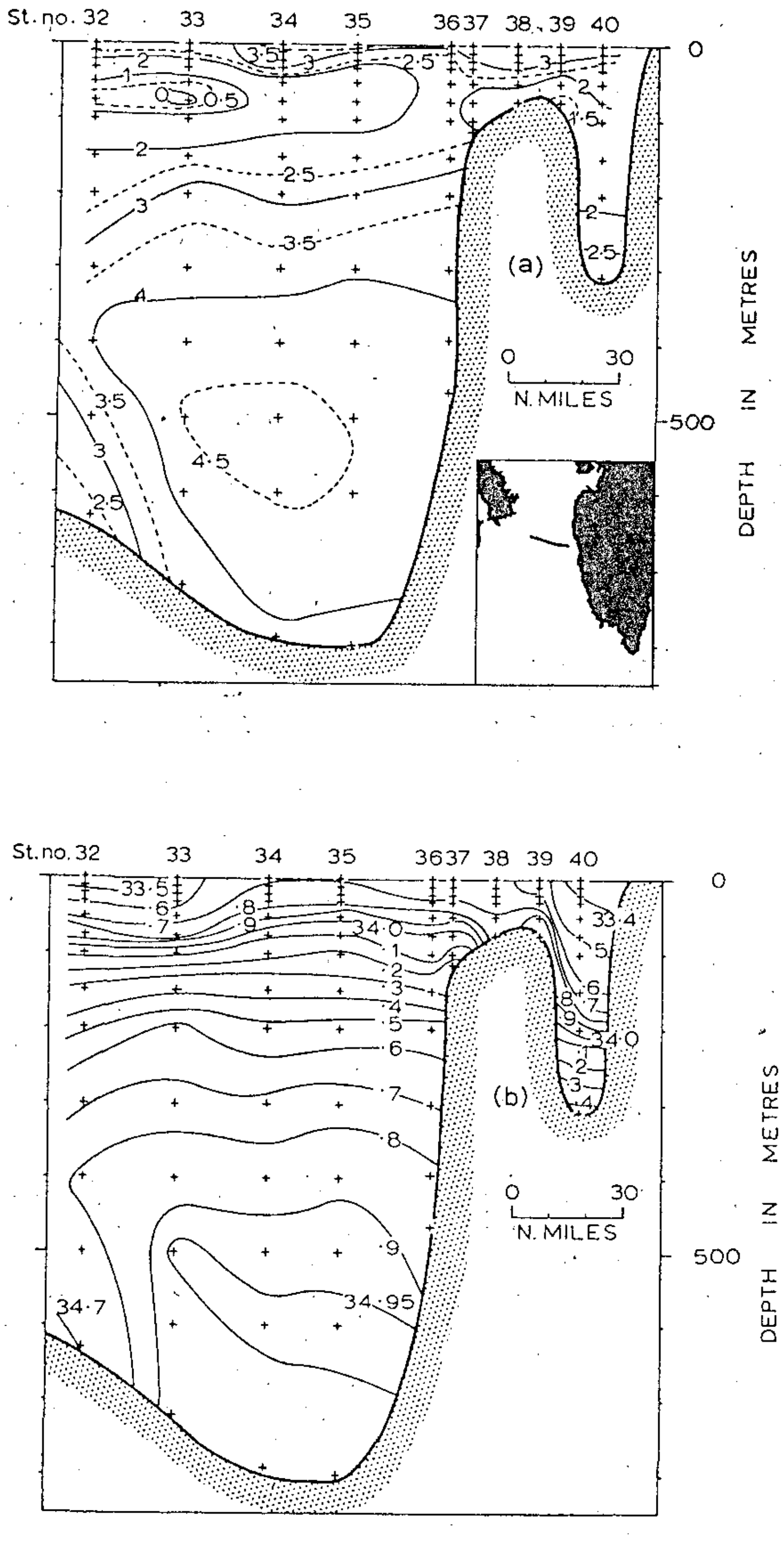


Fig. 10. Vertical temperature and salinity distribution at NORWESTLANT 3 section 13. After Lee (1968).

Fig.10. Vertical temperature and salinity distribution at NORWESTLANT 3 section 13. After Lee (1968).

In Fig. 9 the temperature is seen to increase during autumn, but the rise happens in a water mass now believed not to be Irminger Water. Water with salinity's above 34.5 is found at depths excluding the possibility of a temperature rise due to atmospheric heating. The high temperatures, especially during autumn, supports the assumption that the water with salinity's in the interval 34.5 - 34.85 is originating from the North Atlantic Current. This water mass will be called "**SUB-ATLANTIC WATER**".

The question hereafter is: "From where does Sub-Atlantic Water enter the Southwest Greenland area?"

The following hypothesis is proposed:

> ***The warm water with salinity's in the interval 34.5 - 34.85 observed along the continental slope off Southwest Greenland at depths between 200 - 600 m originates from the area South - Southwest of Cape Farewell where water with the true T/S characteristics are observed (Lee, 1968). It branches off towards the west in the area Southeast - East of Cape Farewell, rounds Cape Farewell and enters the Davis Strait.***

Based on the analysis of Buch (1990) it can be concluded:

- Irminger Water enters the Southwest Greenland area in a tongue-like fashion. Temperatures are above 4°C and salinity's above 34.85 psu. In the core of the inflow temperature are around 4.5°C and salinity's above 34.95. The core of the inflow has been observed as far north as the submarine ridge between the Davis Strait and Baffin Bay (66°N) at depths of 500 - 1100 m. The normal situation, however, seems to be that the core of the inflow seldom passes far beyond Cape Farewell.
- The inflow of Irminger Water has previously been highly overestimated, because a strong inflow of warm water (T>5°C) taking place every autumn has up to now been classified as Irminger Water. The major part, however, of this inflow of warm water has salinity's between 34.5 and 34.85 psu and thus does not meet the T/S specifications for Irminger Water.
- The high temperatures indicate that this water must originate from the North Atlantic Current. Water from the northern limit of the North Atlantic Current has the right T/S-characteristics and it branches off towards the west in the area Southeast - East of Cape Farewell, rounds Cape Farewell and enters the Davis Strait.
- This water mass, called **Sub-Atlantic Water,** is probably formed through mixing between water from the North Atlantic- and the Labrador Currents, occurring South - Southwest of Cape Farewell where the two currents meet.
- The Sub-Atlantic Water are believed to enter the Southwest Greenland area throughout the year because water with salinity's in the given interval and temperatures above 2.5°C dominates at all seasons. The rise in temperatures late in the year may be due to solar heating of the surface layer in the area of formation, higher temperatures and less sea ice in the Labrador Current during summer.

The presence of Sub-Atlantic Water along the Southwest Greenland continental slope can be considered a fact but its formation and it flow pattern towards Southwest Greenland is of a more speculative nature based only on NORWESTLANT data. There is, therefore, a need for further investigation and understanding of this matter. An immediate sources of information for this purpose may be the data collected on the three WOCE sections approaching Cape Farewell.

Oxygen

Since 1982 observations of the oxygen content have been carried out regularly at the sections along Southwest Greenland 1-3 times per year.

The oxygen concentration of the different water masses found off Southwest Greenland are relatively high i.e. the majority of observations are within the interval 6-9 ml/l; which gives a saturation in most cases above 80%. The concentrations are generally decreasing from surface to bottom.

The T/S - characteristics of water masses of different origin are often so identical that additional parameters are needed for identification. In the Southwest Greenland area the need for other parameters is not urgent in order to distinguish the water masses, but taking into account the problem concerning the origin of the water masses, especially those having their source in the North Atlantic Current as discussed above a further tracer is needed oxygen being a possible candidate. For this reason the oxygen concentration versus temperature and salinity, respectively, is plotted for the sections along Southwest Greenland, examples from the Fylla Bank Section are shown in Fig. 11.

The data shown in Fig. 11 confirm that the concentration interval is 6-9 ml/l, decreasing with depth i.e. with increasing salinity.

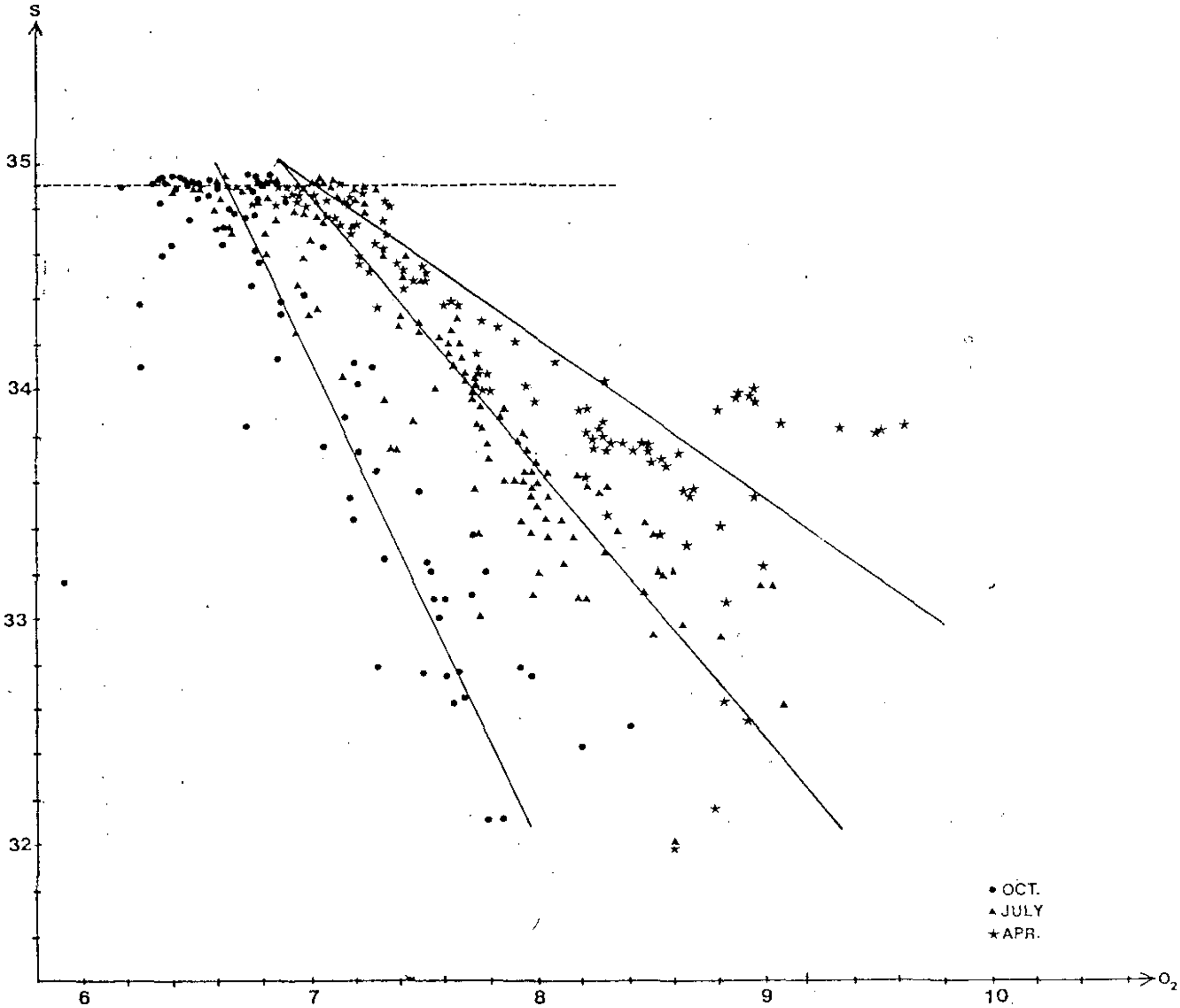


Fig. 11. Oxygen concentrations versus salinity at the Fylla Bank st. 4 and 5 in 1983 - 1988 at three different seasons.

Apart from these more general results the following characteristics are noticed:

1. The oxygen concentration is inversely proportional to the salinity, which of course is due to the observed decrease in oxygen concentration with depth, but the oxygen-salinity relationship reveals a seasonal dependence, with decreasing oxygen content from spring to autumn.
2. The oxygen concentration is inversely proportional to the temperature, generally independent of season except for some high oxygen concentrations at high temperatures observed in July, which may be attributed to the rise in surface temperatures during summer due to solar heating.
3. The East Greenland Water has a high oxygen content, generally above 7.6 ml/l.
4. Concentrations above 8.5 ml/l are observed in the surface layer in spring and summer, and this is most likely due to wind forced mixing, plankton blooming or vertical convection. The highest concentrations 8.8 - 9.6 ml/l shown in Fig. 11 are observed in a 75 metre thick surface layer in April 1984 in water with temperatures below -1°C and salinity's in the interval 33.8 - 34.0 psu. This cold, oxygen rich surface layer is most likely formed by vertical convection during the very cold winter 1983-84.
5. The water with salinity's between 34.5 and 34.9 has oxygen concentrations between 6.3 and 7.4 ml/l, but all data from spring and summer lie in the interval 6.8 - 7.4 ml/l, while the autumn observations, i.e. at the time when the inflow of the very warm water T > 4.5°C takes place, show distinct lower oxygen concentrations, 6.3 - 6.9 ml/l.
6. The Irminger water, S > 34.95, reveals oxygen concentrations between 6.8 and 7.3 ml/l. This is not very clearly illustrated in Fig. 11, but is observed at other sections.

It must be stressed that these oxygen concentrations are all solely from Fylla Bank, but observations made at the other Southwest Greenland hydrographic sections show similar results.

It is clearly demonstrated that the various water masses found in the Southwest Greenland area have distinct levels of oxygen content, and that the water of polar origin can be distinguished from water of North Atlantic origin.

The seasonal variability observed in the oxygen - salinity relationship can in the case of surface layer be explained by physical - and biological processes and the fact that during spring and summer the oxygen rich East Greenland polar water is present in far greater quantities than later in the year.

The observed seasonal variability in the oxygen content of the S = 34.5 - 34.9 water, especially the very distinct difference in oxygen content between spring/summer and autumn which is identical to the observed seasonal variability in the T/S-characteristics discussed previously, may prove to be valuable to future research concerning the origin of this or these water masses. It seems evident that the rise in temperature and decrease in oxygen concentrations observed during autumn reflects either an inflow of a water mass of different origin or changes in the area of formation. The former of these explanations is probably the most likely one.

It has also been demonstrated that the warm water entering the Southwest Greenland area during autumn has different and lower oxygen concentrations than the more saline Irminger Water, which also enters the area late in the year. This excludes the possibility that the warm water is a mixing product of the Irminger Water and some less saline water mass since they both will have higher oxygen concentrations than the observed warm water.

It is concluded that measurements of oxygen can add valuable in formation to the oceanographic research in the Southwest Greenland area.

4.2. Interannual variability

As mentioned above the Greenland Fisheries Research Institute has carried out oceanographic observations at the standard sections along Southwest Greenland since 1948. The observations have, especially during the early years, been disseminated in time and space for which reason it is impossible to establish long time series for all the standard sections. The Fylla Bank Section is, however, an exception because due to its close vicinity to Nuuk, where the research ships of the Greenland Fisheries Research Institute is stationed, this section has been observed several times a year.

Surface conditions

The most well known oceanographic time series from Southwest Greenland is the Mid-June mean temperature on top of Fylla Bank (Fylla Bank st.2, 0 - 40 m), Fig. 12, which the Greenland Fisheries Research Institute carefully has maintained due to its importance to the cod stock assessment.

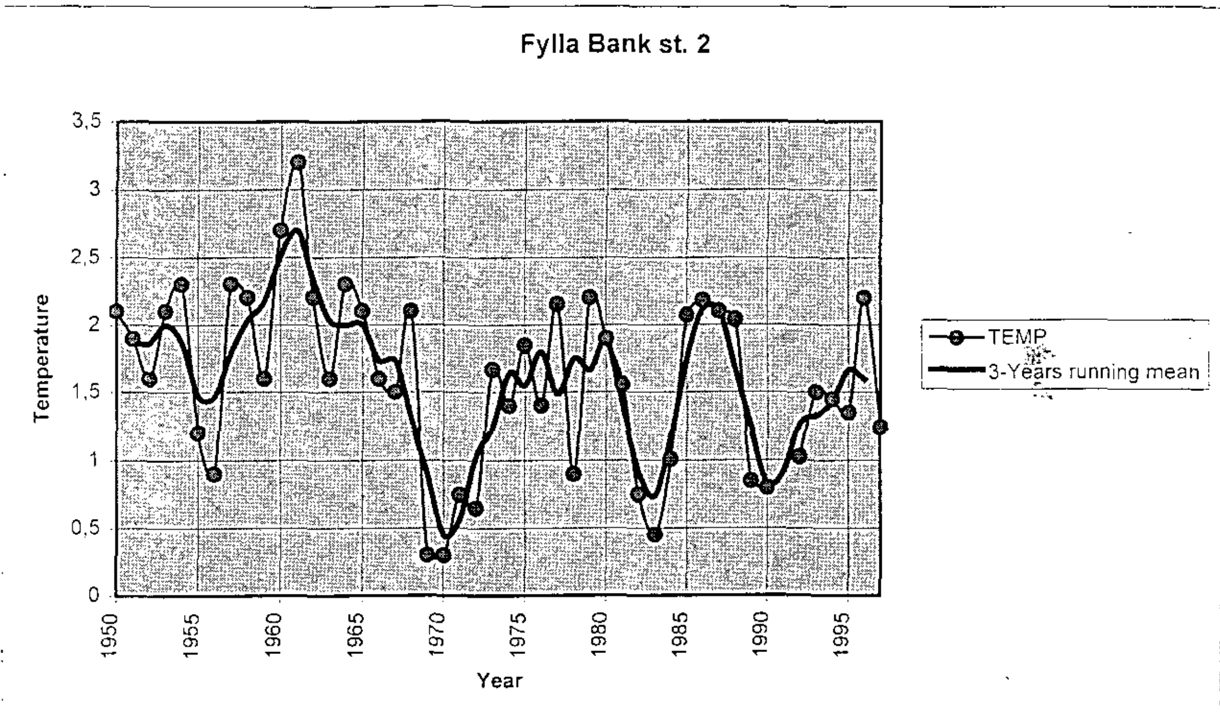


Fig. 12. Mean temperatures of the upper 40 m on Fylla Bank St. 2, medio June 1950 - 1997.

The temperature may vary quite drastically from one year to the next, often more than 1°C, reflecting the variability of both the atmospheric influence and the inflow of Polar Water. The curve showing the 3 year running mean values naturally smoothens out the variations and reflects therefore better the large scale climatic variability.

The almost 50 year long temperature time-series reveal some very distinct climatic events:

- The 1950 - 1968 period generally showed high temperatures around 2°C.
- Around 1970 a cold period - the coldest - was experienced. The cold climate of this period was due to a anomalous high inflow of Polar Water (Buch, 1990), which was closely linked to the "Great Salinity Anomaly", Dickson et al. (1988).
- The early 1980'es and early 1990'es two extremely cold periods were observed reflecting the cold atmospheric conditions in the Davis Strait area as discussed in section 3.
- A remarkably low temperature was observed in 1997 although the atmospheric conditions were quite warm, Fig. 5 and 7, which could indicate a high inflow of Polar Water.

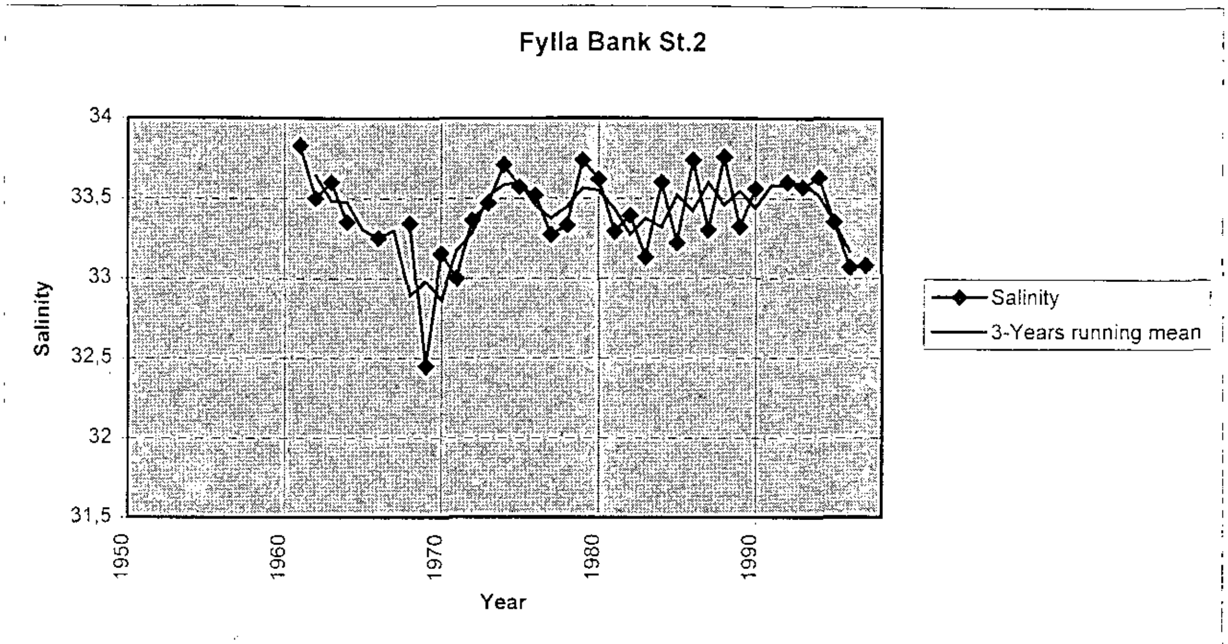


Fig. 13. Mean salinity of the upper 40 m on Fylla Bank st. 2, medio June 1961 - 1997.

Fig. 13 shows the time-series of the Mid-June salinity on top of Fylla Bank (actual observations as well as a 3 years running mean). The "Great Salinity Anomaly" around 1970 is clearly reflected in this data set, while the climatic anomalies in the early 1980'es and 1990'es do not expose themselves in any significant way in the surface salinity's at Fylla Bank, which off course was not to be expected because these cold periods was due to atmospheric cooling.

Relatively low salinity's were observed in 1996 and 1997 indicating that the inflow of Polar Water have been above normal in these years. This could be a sign of a new "Salinity Anomaly" although not yet of the same dimension as the one experienced around 1970. Analysis of data from the other Southwest Greenland sections show extremely low salinity values at the sections north of Fylla Bank (station 2 on the Lille Hellefiske Bank - and Holsteinsborg sections) in 1996, comparable to the low values observed in the late 1960'ies. At the southernmost sections - Cape Farewell to Frederikshaab - no real time series exists, but judged from the observations made in June-July since 1992 abnormally low salinity's were observed only at the Cape Farewell section in 1996.

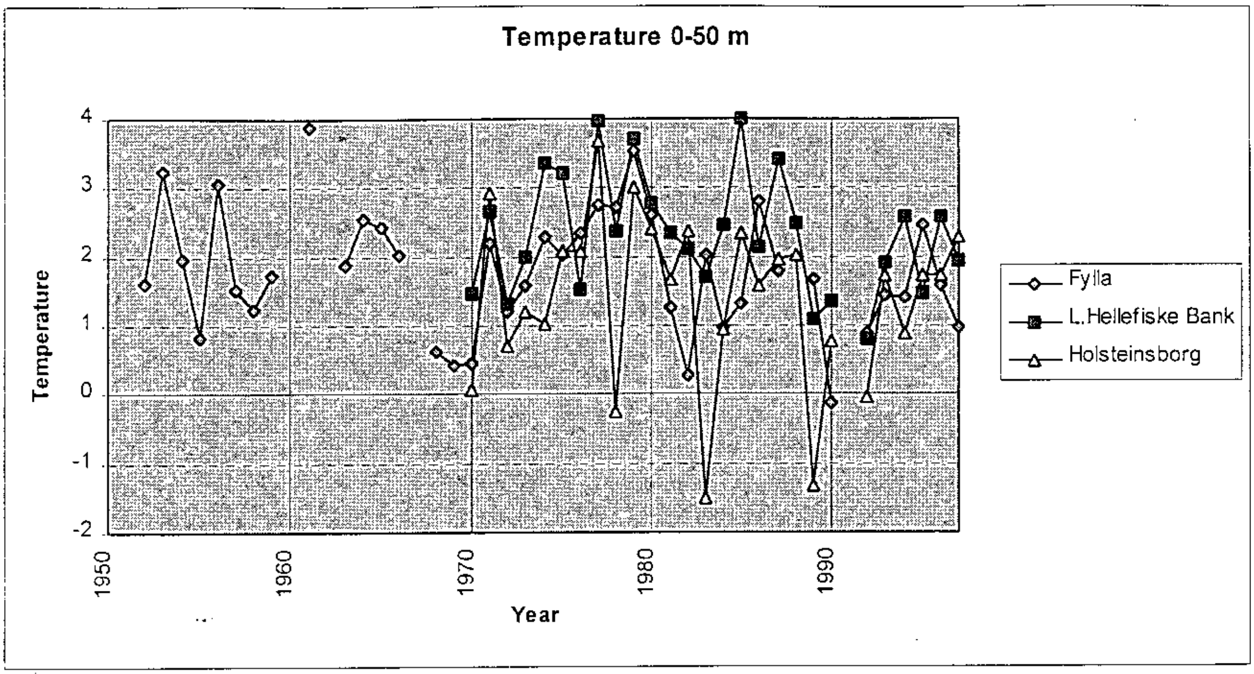
It may therefore be concluded that in 1996 a "low salinity signal" was observed in the Polar Water component off Southwest Greenland at most sections.

1996 and 1997 was additionally characterised by a high inflow of Atlantic Water (Irminger- as well as Sub-Atlantic Water) in the southern part of Southwest Greenland physically evidenced by surface temperatures well above 6°C, in 1996 even above 7°C, at the outermost stations at the Cape Farewell Section.

Further offshore - just west of the fishing banks there exists relatively long time series of July temperatures and salinity's from the following sections and stations:

- Fylla Bank st.4, start 1952
- Lille Hellefiske Bank st.5, start 1970
- Holsteinsborg st.5, start 1970

The mean temperatures and salinity's of the upper 50 metres from the three stations is shown in Fig. 14.



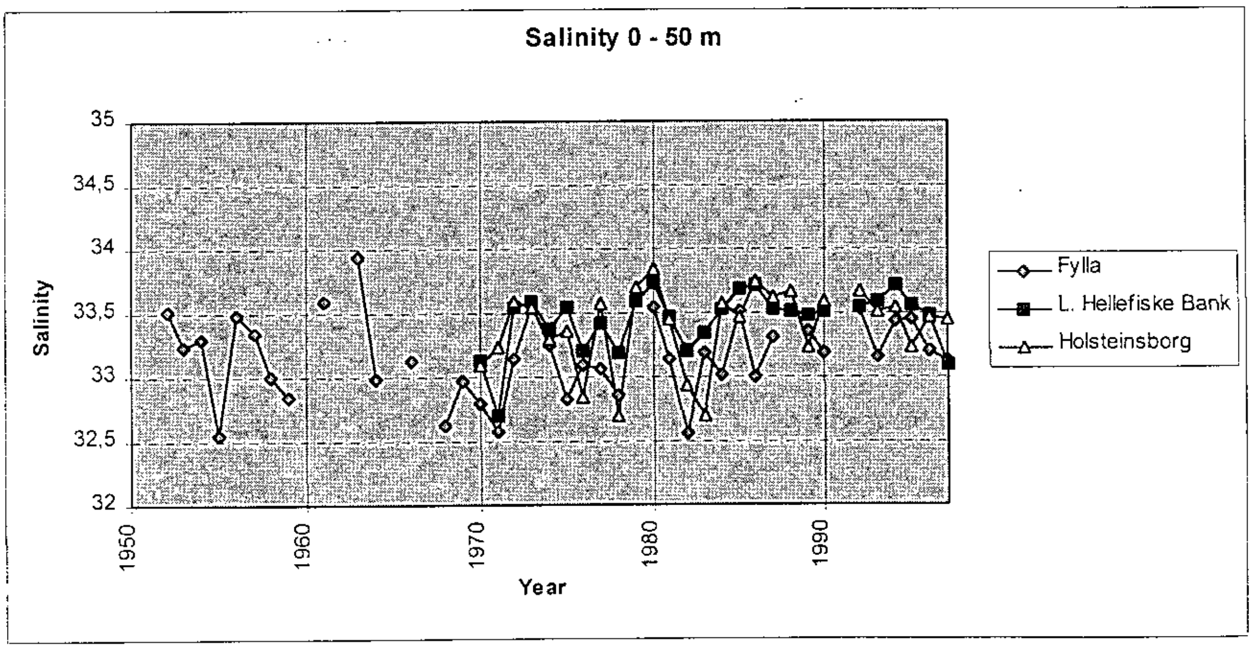


Fig. 14. Mean temperature and salinity in the upper 50m at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5

The time series reveal that

- The overall tendency in the interannual variability at the three stations are comparable although individual years may show large differences in temperature and salinity as well as opposite signs in the development from the preceding year.
- Generally the highest temperatures and salinity's are observed at the Lille Hellefiske Bank, while the lowest salinity's most often are observed at Fylla Bank. This is due to the fact that the Fylla Bank area is influenced by Polar Water and the Holsteinsborg station at this time of the year often is influenced by melting west ice and possibly also by cold, relatively fresh water of Polar origin flowing southward on the Canadian side of the Davis Strait; but none of these reach the Lille Hellefiske Bank area.
- The three cold periods mentioned above is also reflected in these time series. Opposite to the conditions at Fylla Bank St.2 a significant decrease in salinity was observed at all three stations during the 1982 - 1984 period, especially in 1982 which properly was caused by a high inflow of polar ice to the Southwest Greenland area in 1982 combined with the heavy formation of ice in the Davis Strait during the extremely cold winters in 1983 and 1984.
- Relatively warm and saline conditions were experienced in 1979-80.
- Some years extremely cold and low saline conditions were observed at the Holsteinsborg station, which is due to the presence of ice at the time of observation.

Deeper layers

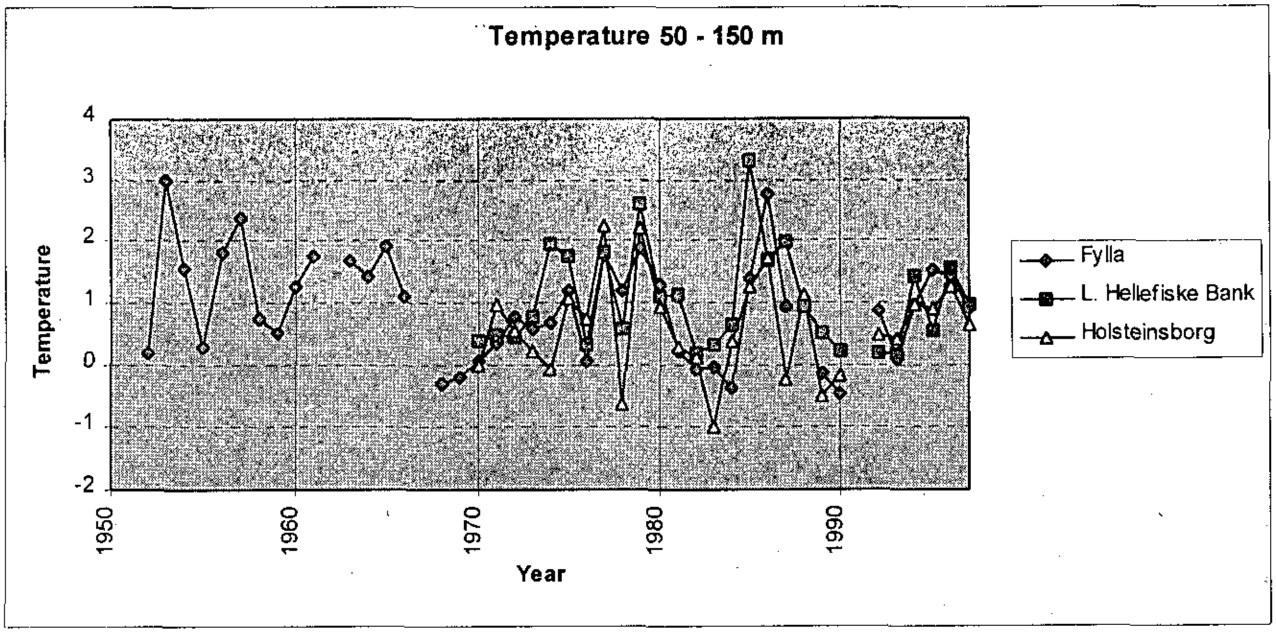
The variability in the deeper layers are illustrated by the July time series of temperature and salinity from the same three stations just west of the fishing banks that were used above. In Figs. 17, 18 and 19 the mean values of temperature and salinity is given for the 50 - 150 m, 150 - 400 m and 400 - 600 m water column. This layering has been chosen for the following reason:

I. The 50 - 150 m layer is mainly influenced by Polar Water
II. The 150 - 400 m layer is the transition zone between Polar Water and water of Atlantic Origin
III. The 400 - 600 m layer is occupied by Atlantic water masses.

It is seen from the three figures that there is great interannual variability at all depth levels, although the amplitude of the fluctuations naturally decreases with depth. This is a clear indication of the fact that the Southwest Greenland waters are influenced by the dynamics of several currents having their origin in different parts of the North Atlantic. The variability of the oceanographic conditions in the Southwest Greenland area therefore reflects the individual strengths of the various currents the particular year but also the climatic signal that the currents carry with them from their respective area of formation.

In the 50 - 150 m layer the temperature fluctuations in general follows the same pattern as was observed in the surface layer i.e. the cold periods are clearly seen also in this layer, because vertical convection caused by the extreme atmospheric cooling during wintertime creates cold conditions in this layer and superimposed on this is the inflow of cold Polar Water. The fluctuations in the salinity signal has, as expected, decreased compared to the surface layer. In 1982 the salinity was extremely low at the Fylla Bank station, actually it was even lower than during the period with the "Great Salinity Anomaly" around 1970. This is a clear sign of a great inflow of Polar Water and as mentioned above 1982 was a year with a great inflow of Polar Ice to the Southwest Greenland area, which is a clear refection of a high transport rate in the East Greenland Current. In 1997 both the Fylla Bank and the Lille Hellefiske Bank station showed relatively low salinity's as well as relatively low temperatures which could be a sign of a new salinity anomaly as discussed earlier in connection with the surface conditions, although the negative trend in 1997 is not comparable with the conditions around 1970 or 1982.

In the 150 - 400 m layer the temperature fluctuations still are sizeable. The cold periods still can be recognised but it is evident that other signals play a dominant role in this layer, which off course was to be expected in a layer forming the transition between two different current regimes.



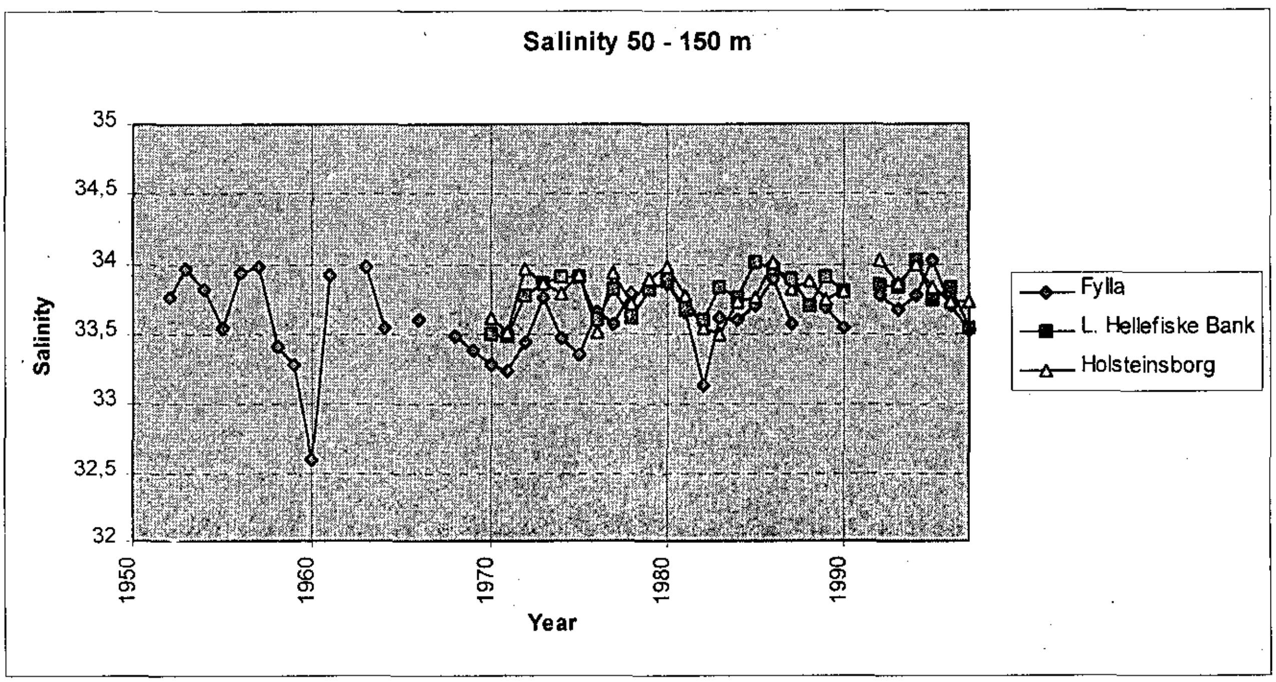
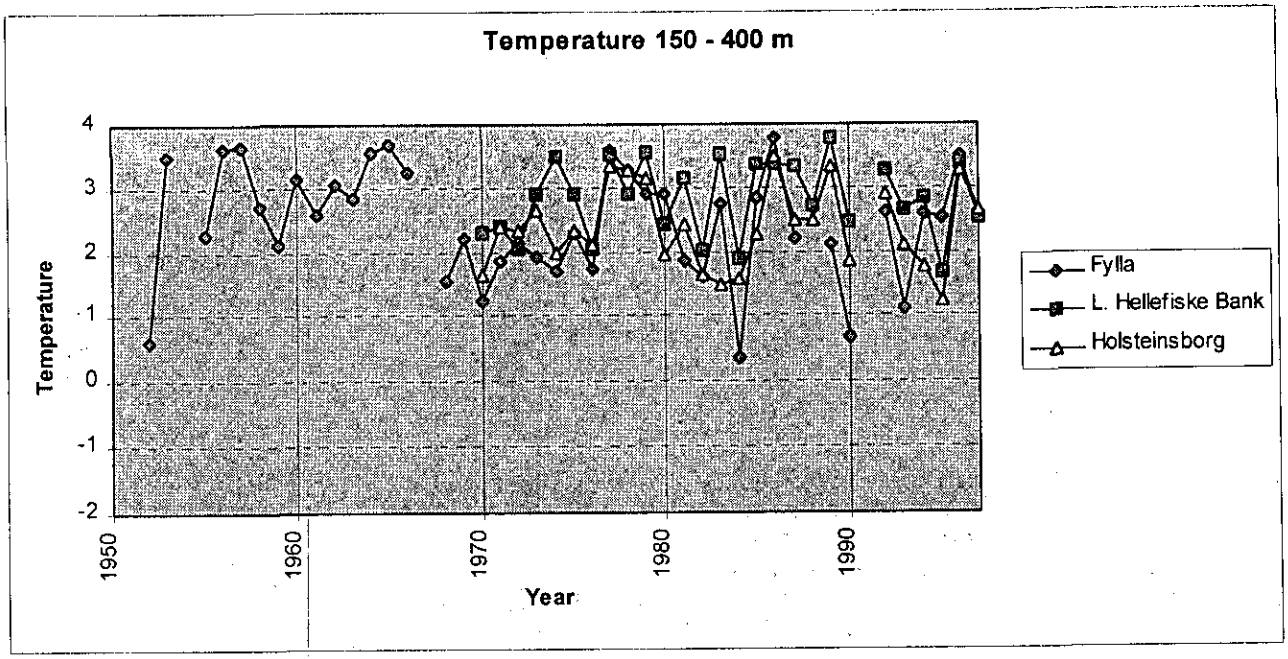


Fig. 15. Mean temperature and salinity in the 50 - 150 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5



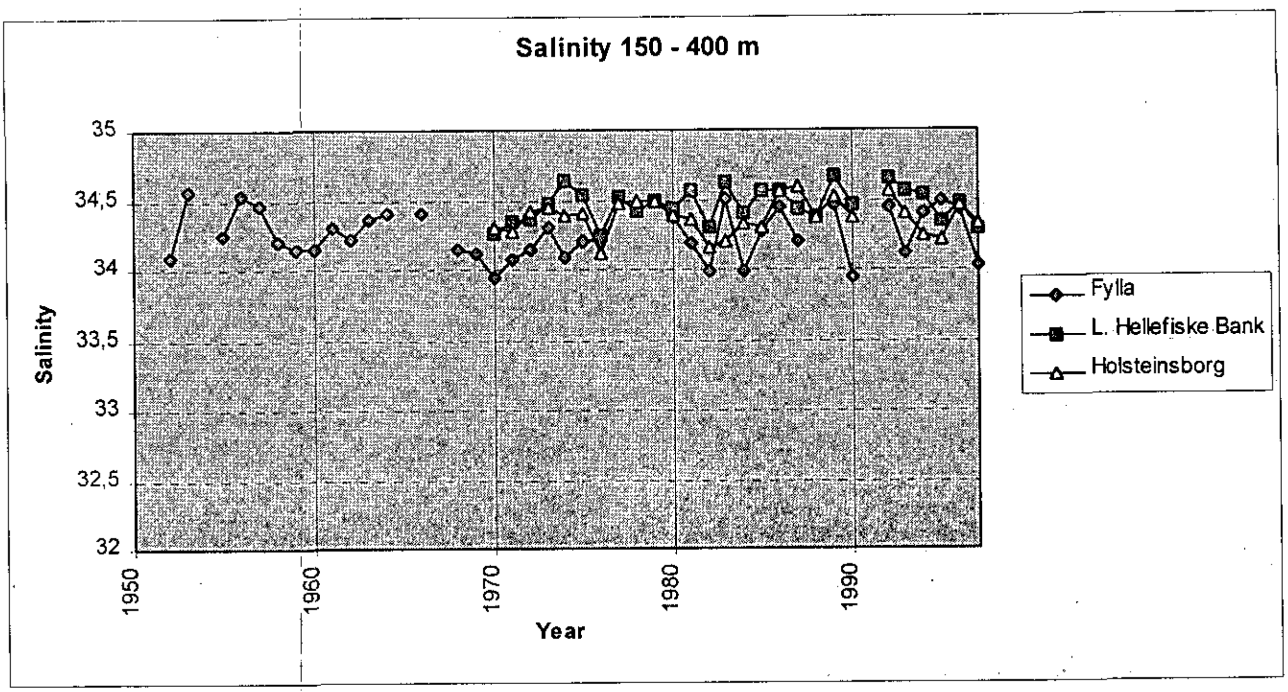
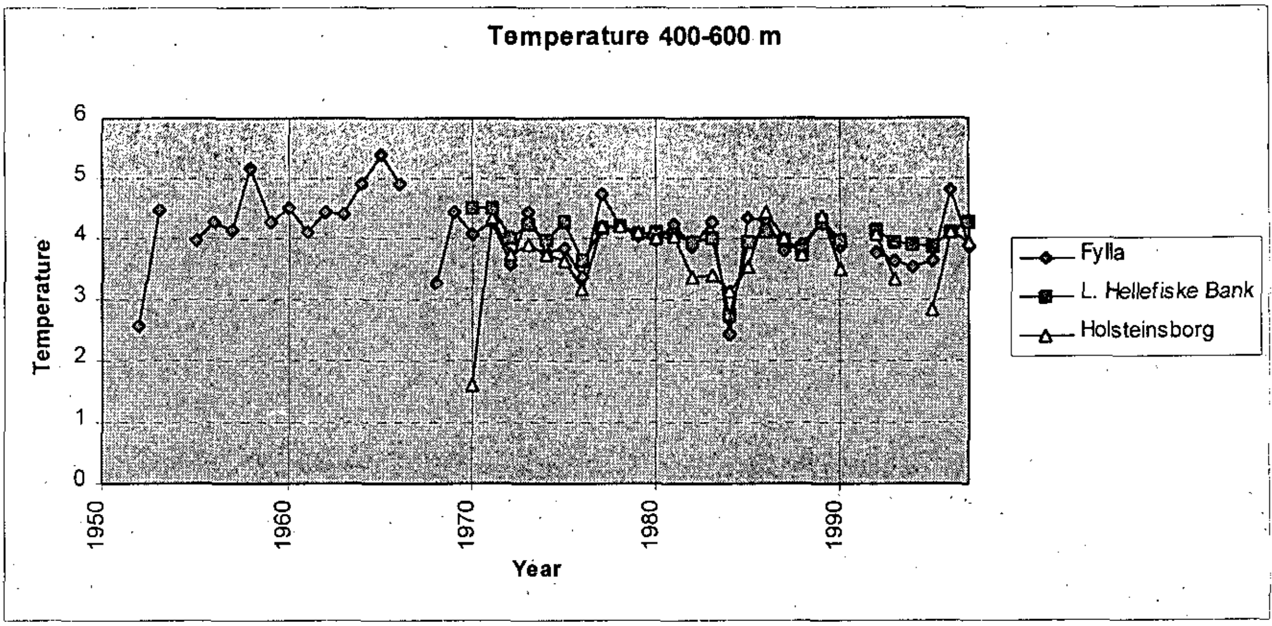


Fig. 16. Mean temperature and salinity in the150 - 400 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5



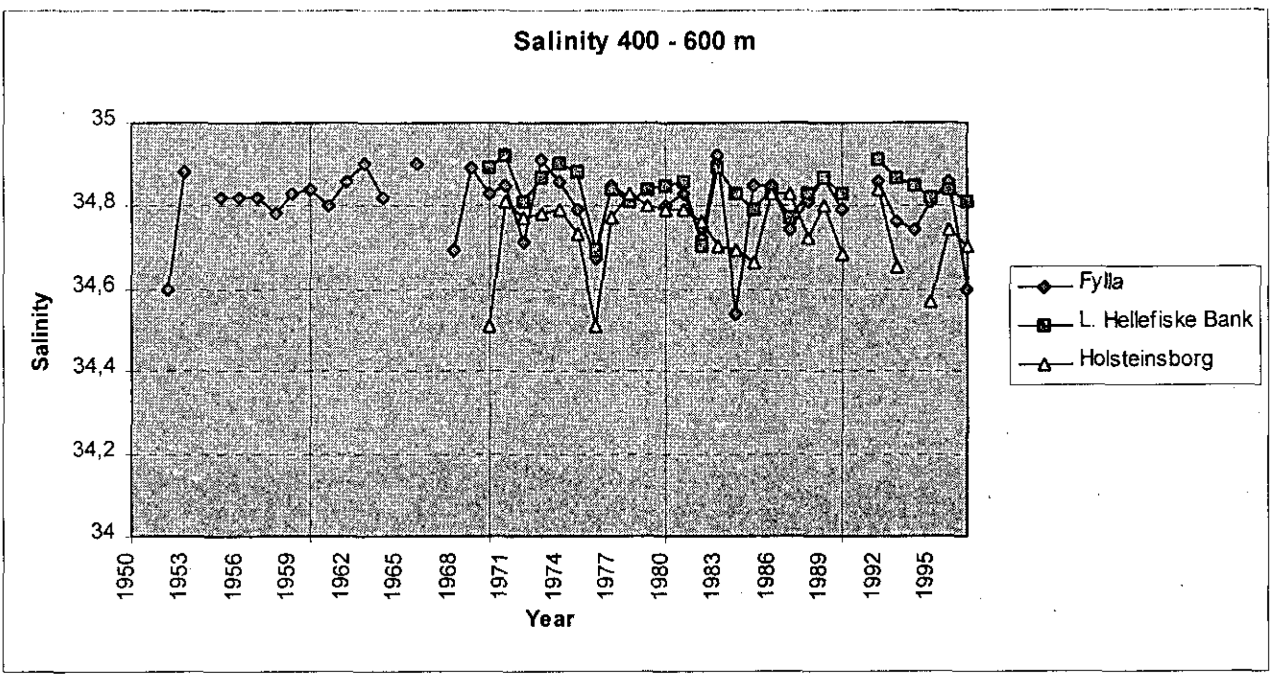


Fig. 17. Mean temperature and salinity in the400 - 600 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5

The warm conditions as experienced in the late 1970'es and late 1980'ies therefore reflects a dominance of water of Atlantic origin i.e. Sub-Atlantic Water. The salinity is generally highest at the Lille Hellefiske Bank, which properly is due to the fact that at this depth interval the Fylla Bank and the Holsteinsborg stations are more influenced by Polar Water than the Lille Hellefiske Station. Extremely low salinity values were observed at the Fylla Bank station around 1970 and in 1982, 1984, 1990 and 1997, which can be interpreted as a sign of Polar Water dominance and confirms the trends observed in the shallower layer except for the 1984 situation. The low saline conditions at Fylla Bank in 1984 was discussed by Buch, 1990, who argued that vertical convection during the previous extremely cold winter had caused huge amounts of low saline surface water to sink to great depth off Southwest Greenland preventing inflow of Sub-Atlantic Water at normal rates.

The 400 - 600 m layer is characterised by temperatures around 4°C and salinity's around 34.8 psu. Salinity's higher than 34.8, and especially values close to 34.9 psu, indicate high inflow rates of Irminger Water. The salinity at the Holsteinsborg station is at this depth interval generally lower than on the other stations, which is because the Atlantic components, especially the Irminger component, do not in full strength reach as far north as the Holsteinsborg area. The most extreme event was observed in 1984 at Fylla Bank and in the temperature signal also at Lille Hellefiske Bank. The explanation to these low temperature and salinity conditions is believed to be the same as given above for the similar observations in the 150-400 m layer.

The observations performed during the summer cruises at the southernmost sections in recent years have not been incorporated into the time series discussed above because the series still are to short; but it can briefly be mentioned that 1996 and 1997 were characterised by a higher than normal inflow of Irminger Water. Both years a tongue of high saline water ($S > 34.95$) was reaching as far north as to an area between the Frederikshaab- and the Fylla Bank sections, and in 1997 water with salinity's above 35 psu was observed at the Cape Farewell section.

5. Summary and conclusions

The intentions of the present paper was to give an overview of the oceanographic conditions in NAFO subarea 1 - along the Southwest Greenland fishing banks during the 1981 - 1997 period. The oceanography of this area is highly dominated by the inflow of water masses originating from various regions in the North Atlantic and Arctic Ocean carried to the area by the East Greenland Current, the Irminger Current and a side-branch of the North Atlantic Current. The existence of the latter transport has only recently been discovered (Buch, 1990) by a thoroughly analysis of old temperature and salinity data and using the accepted definitions of T/S-characteristics for the relevant water masses. This led to the introduction of a new water mass in the Southwest Greenland area: the Sub-Atlantic Water.

In addition to the ocean transports there is intense air-sea interaction in the area influencing primarily the temperature conditions, which subsequently influences the extent of sea ice which again has an impact on the salinity of the surface water and via vertical convection also on deeper layers.

The atmospheric conditions over the North Atlantic area is highly dominated by the NAO index, which since the early 1980'ies has been in a persistent and exceptionally strong positive phase. A high NAO index means cold and dry conditions over Greenland, and Greenland has been characterised by very cold conditions since 1980 especially in the 1982 - 1984 period, where record cold winters was experienced, but also the 1989 - 1994 period was extremely cold. These cold atmospheric conditions was reflected in the waters off Southwest Greenland by temperatures well below normal in the upper 400 m as well as in an increase in the formation of "Westice" moving the ice limit so far south that the seldom situation of "Westice" and "Storis" joining each other in the Julianehaab Bight during the winter months has been experienced several times during the recent 15 years.

The interannual variability of the oceanographic conditions in NAFO Subarea 1 has been analysed using time series of July temperatures and salinity's from the Fylla Bank -, Lille Hellefiske Bank - and Holsteinsborg sections. The time series from these sections reach back in time to 1970 - for the Fylla Bank section even to around 1950.

The time series reveals great interannual variability at all depth levels, although the amplitude of the fluctuations naturally decreases with depth. This is a clear indication of the fact that the Southwest Greenland waters are influenced by the dynamics of several currents having their origin in different parts of the North Atlantic. The variability of the oceanographic conditions in the Southwest Greenland area therefore reflects the individual strengths of the various currents the particular year but also the climatic signal that the currents carry with them from their respective area of formation.

The most significant oceanographic events observed in the Southwest Greenland area since 1980 are closely related to the two periods (1982 - 1984 and 1989 -1994) of very cold atmospheric conditions. The ocean temperature was below normal in the upper 400 m during these cold periods. Especially in 1984 the extremely cold winter caused vertical convection to penetrate to great depths (>600 m) whereby huge amounts of cold, low saline water was formed and seemingly preventing the Sub-Atlantic Water to enter the area in normal amounts.

There are some indications, but not a totally clear picture, of great amounts of Polar Water entering the area in 1996 and 1997 i.e. a new "Salinity Anomaly". The negative anomaly in temperature and salinity can be traced at most of the relevant sections, but the signal is, however, not as strong as the one observed during passage of the well known "Great Salinity Anomaly" around 1970. 1996 and 1997 have additionally been characterised by a higher than normal inflow of Irminger Water to the southernmost part of the Southwest Greenland area.

The great variability in the oceanographic conditions off Southwest Greenland do have a strong impact on the living conditions for a number of fish stocks living close to the limit of their existence in this area. The cold conditions experienced in this area during the recent two to three decades have caused a dramatic change in the ecological balance. Cod was found in great quantities from the 1920'ies up until 1970, since then only in small amount and in recent years, after the latest cold period, cod is almost absent along the Southwest Greenland fishing banks. To Greenland, being almost totally economically dependent on fishery, the disappearance of the most important fish stock is a disaster.

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