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Present oceanographic conditions in Greenland Waters

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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 marine environment and ocean circulation in the Greenland territorial waters is highly dominated by the large scale circulation of the North Atlantic Ocean and thereby also by the variability of this circulation generated by climate fluctuations. Only the near-shore areas and the fjords are dominated by local conditions such as river runoff, ice formation etc. The dominant ocean water components in the Greenland waters originates either from the warm, saline North Atlantic Current or from the cold, low saline Arctic Ocean.

The first knowledge of the ocean circulation near Greenland was attained when Erik the Red discovered Greenland in year 982, but it should last almost 900 years before the first nearly right current map were published by the Danish naval officer C. Irminger in 1854. The majority of the oceanographic knowledge about the Greenland waters has however been obtained since World War II. A large percentage of the observations are made off West Greenland after 1950, when the newly founded Greenland Fisheries Research Institute[1] started their oceanographic monitoring programme on a net of standard sections defined by the International Commission for Northwest Atlantic Fisheries (ICNAF)[2]. In 1963 a major international co-operative research programme - NORWESTLANT - was carried out. NORWESTLANT was divided up into three field phases each covering a net of section on the eastern and western side of Greenland south of approximately 66^{o}N. In the recent decade much international research attention has been devoted to study the deep convection processes in the Greenland Sea due to its importance to the regional as well as the global climate. Additionally the World Ocean Circulation Experiment (WOCE) has added valuable information to the understanding southern Greenland oceanography.

Buch (1990; reissued in 2000) gave a detailed discussion of the oceanographic conditions in the Greenland Waters. The present report will, therefore, focus on updating our present understanding of the oceanographic conditions of the Greenland waters and their variability as an effect of variations in the North Atlantic climate system. It is the purpose thereby to describe the present physical environmental conditions of importance to marine ecosystem, which shall form the basis for analysis and interpretation of climate forecasting results for the Greenland area.

The focus of the report will be on the waters off West Greenland, since this area is of highest economical importance to the Greenlandic society due to its relative high biological productivity.

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[1] The Greenland Fisheries Research Institute was in 1996 renamed to The Greenland Insistute for Natural Ressources after being moved to Greenland.
[2] ICNAF is renamed to NAFO (Northwest Atlantic Fisheries Organisation)

2. Oceanographic conditions

General circulation

The ocean currents around Greenland is an integral part of the circulation and water mass balance of the North Atlantic and the arctic regions, where the bottom topography is of vital importance to the circulation and the distribution of water masses.

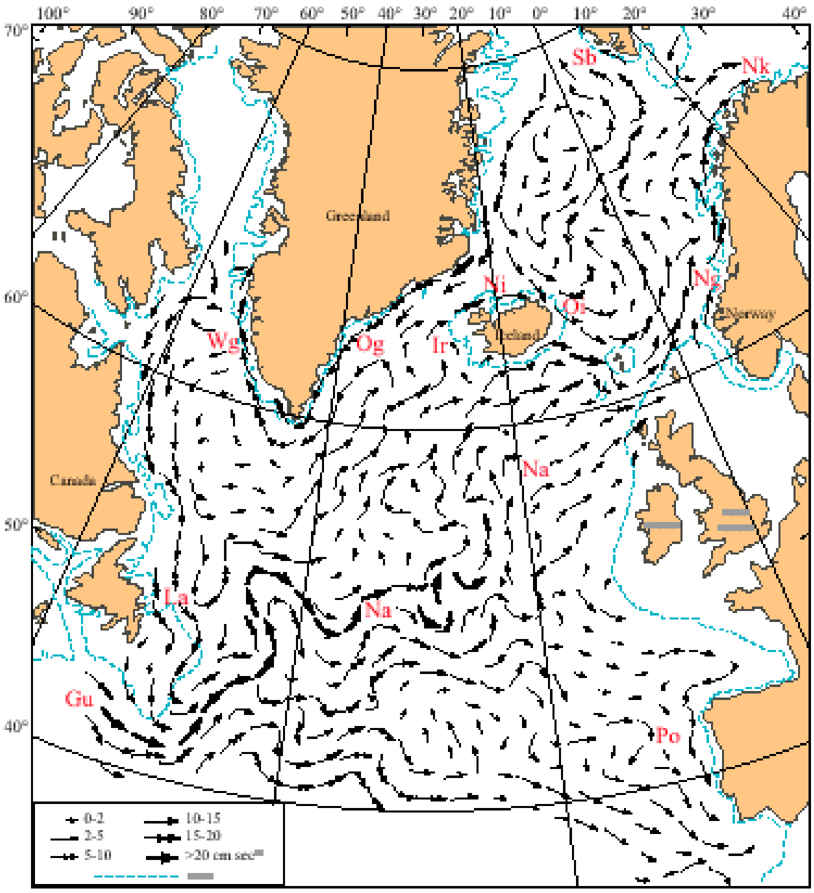


Fig.1. *Surface currents in the northern North Atlantic, after Dietrich et al., 1975.*
Gu = Gulf Stream; Na = North Atlantic Current
Ir = Irminger Current; Og = East Greenland Current
Wg = West Greenland Current; La = Labrador Current
Sb = Spitsbergen Current; Oi = East Iceland Current

From west, the North Atlantic Current, which is a continuation of the Gulf Stream, enters the area. It flows northward along the west coast of Great Britain, through the Faroe-Shetland Channel, and continues along the continental slope off Norway. At around 70^{o}N the current splits up into two components, one continuing along the west coast of Norway into the Barents Sea, and the other following the continental slope northwards to the Spitsbergen region, where it converges with the colder, less saline arctic surface water, sinks and continues as a subsurface current into the Arctic Ocean. Part of the North Atlantic Current branches off westwards, before entering the Arctic Ocean, into the East Greenland Current, where it underlies the Polar Water from 150 m to approximately 800 m.

Before entering the Faroe-Shetland Channel, part of the North Atlantic Current turns westward as the Irminger Current, which occupies the ocean area south of Iceland. Part of this current follows the Icelandic coastline to the north through the Denmark Strait and continues along the north coast of Iceland, where it meets the cold, less saline East Icelandic Current. The other part of the Irminger Current turns towards Greenland south of the Denmarks Strait, where it flows southward along the east coast of Greenland. Some of this water continues to Cape Farewell, which it rounds, while a second portion remains within the Irminger Sea, where it recirculates in a cyclonical gyre.

Turning our attention to the cold water, it originates from the Arctic Ocean, which throughout the year is supplied with fresh water primarily from the large Russian rivers. This surplus of water leaves the area mainly at two locations:

a. Through the Fram Strait i.e. the area between Greenland and Spitsbergen.

b. Through the Canadian Arctic Archipelago i.e. the area between Greenland and Canada.

The Fram Strait is by far the most important of the two outflow regions, making up about 75% of the water outflow from the Arctic basin. This water is transported southward along the east coast of Greenland and constitutes the East Greenland Current. This current flows on top of the Greenlandic shelf from the Fram Strait to Cape Farewell, rounds the Cape and continues northward along the west coast of Greenland up to a latitude of about 65-66^{o}N, where it turns westward and unites with the south flowing current off the Canadian east coast. This current, called the Baffin Current, also transports water from the Arctic Ocean, leaving the area through the second major outflow region, the Canadian Arctic archipelago. It follows the Canadian coast, continues into the Labrador Current, which meets the North Atlantic Current at around 40 - 45^{o}N.

The water in Subpolar Gyre south of Cape Farewell is relatively stagnant. In the southern part the North Atlantic Current sweeps water from the Labrador Current east- to northeast. It flows side by side and gradually mixing with the North Atlantic Current and later the Irminger Current in the Irminger Sea, and returns to the area south of Cape Farewell. Therefore the current system in this area can be regarded as a great cyclonic gyre, in which the velocities are relatively small.

Along the West Greenland fishing banks two current components are dominating. Closest to the shore the East Greenland Current component is found bringing the water of polar origin northward along the West Greenland coast. On it’s way this water is diluted by run-off water from the various fjord system. The East Greenland Current component looses its momentum on the way northward and at the latitude of Fylla Bank it turns westward towards Canada where it joins the Labrador Current. West and below the Polar Water a current component originating from the Irminger Sea and the North Atlantic Current is found. This relatively warm and salty water can be traced all the way along West Greenland from Cape Farewell to Thule.

It has recently been shown (Pickart et al., 2001) that the East Greenland Current component undergoes a major change from one side of Greenland to the other. On the eastern side the current is tightly trapped to the shelf break, while it on the western side extends far offshore over the deep basin, Fig. 2. This is a year-round phenomenon.

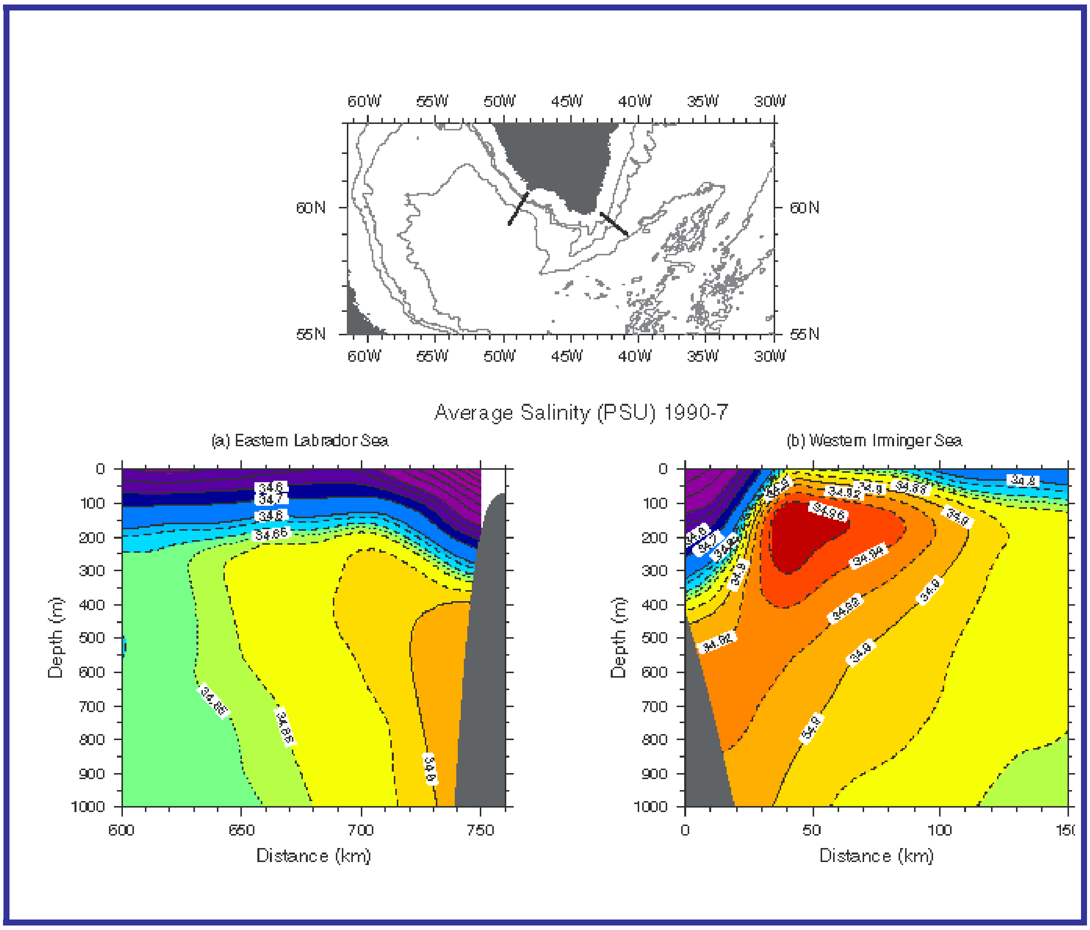


Fig. 2. Mean upper-layer salinity for the period 1990-97.
a) Eastern Labrador Sea b) Western Irminger Sea, (source: Pickart et al., 2001)

Several processes could explain this phenomenon:

- The East Greenland Current has trouble negotiating the "sharp corner" of Cape Farewell.
- Winds, which is predominantly north-westerly in this region. This implies onshore Ekman transport on the east side of Greenland and offshore on the west side.
- Fluctuations in the Irminger Current component.

The first two are not regarded as likely explanations, since annual oceanographic surveys show that polar water still is close to the coast just west of Cape Farewell (Buch, 2001) and the wind influence has large annual variations.

The most likely candidate therefore is fluctuations in the Irminger Current. Recent analysis of Topex-Poseidon altimetry data (Prater, 2000) as well as data from surface drifters and subsurface floats (Fratantoni et al., 1999; Lavander, 2000; Cuny et al., 2001) has revealed interesting support for this theory, all showing the presence of a localized source of high eddy variability off West Greenland, Fig.3.

The reason for the formation of eddies in this particular region is believed to be due to baroclinic instability of the Irminger Current as a result of the underlying bathymetry, with the continental slope being particularly steep in this area.

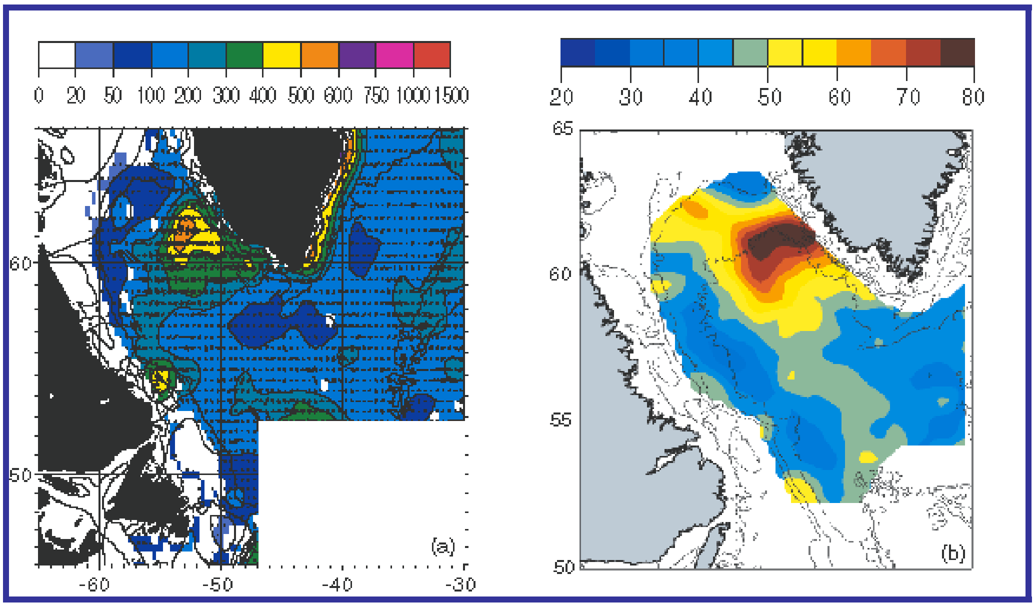


Fig. 3 a) EKE from WOCE surface drifters (from Fratantoni et al., 1999;
b) Sea-surface height variability from POPEX (from Prater, 2000)

This picture of the surface circulation in the ocean off Greenland only reflects the average condition, and great seasonal and inter-annual variations do, however, occur. Recent research has demonstrated that the North Atlantic Oscillation (NAO) is the major source of interannual variability of weather and climate in the North Atlantic region and thereby also to variations in the ocean circulation and the oceanic environment (see Section 3).

Tides

The tide is the name given to the alternate rise and fall of sea level with an average period of 12.4h (24.8h in some places). Locally, the period varies by an hour or so on either side of the average figure and the rise and fall sequence shows an almost infinite variety around the globe. Tides are a consequence of the simultaneous action of the moon's, sun's and earth's gravitational forces and the revolution about one another of the earth-moon and the earth-sun. The fact that the paths of the rotation of the sun and the moon about the earth are not circles but ellipses, and that the planes of rotation are not always in the equatorial plane but move north and south with the annual cycle for the sun and a monthly cycle for the moon add further complications to the resultant tide producing forces. The motions of the sun and moon are known very exactly and it is possible to express the resultant tide producing forces as the sum of a number of simple harmonic constituents, each of which has its own characteristic period, phase and amplitude - the most important is given in Table 1.

The most important tidal constituent in the Davis Strait- Baffin Bay area is the semidiurnal M_2 with a amphidromic[3] point at about 70°N almost in the middle of the Baffin Bay, Fig. 4. Along West Greenland the greatest amplitude (120 cm) is found in the Nuuk area, decreasing to around 40 cm north of Disko Island.

Name	Symbol	Period (solar hours)	Relative size
Semi-diurnal			
• Principal lunar	M_2	12.42	100
• Principal solar	S_2	12.00	47
• Large lunar elliptic	N_2	12.66	19
• Luni-solar	K_2	11.97	13
Diurnal			
• Luni-solar	K_1	23.93	58
• Principal lunar	O_1	25.82	42
• Principal solar	P_1	24.07	19
• Larger lunar elliptic	Q_1	26.87	8
Long period			
• Lunar fortnightly	M_f	327.9	17
• Lunar monthly	M_m	661.3	9
• Solar semi-annual	S_{sa}	4383	8

Tabel 1. Most important tidal constituents

The strongest tidal signal - *Spring tide* - is experienced when the Sun, Earth and Moon are on lying on a line, which happens every 14 days at new Moon and full Moon. The lowest tidal signal - *Nip tide* - is experienced 7 days after Spring tide at half moon (when the line between the Moon and Earth is perpendicular to the line between the Sun and Earth). The difference between High and low water at a few location along the west coast of Greenland at Spring tide and Nip tide are given in the table below.

	Difference in water level between high- and low water	
Location	Spring tide	Nip tide
Nanortalik	2.7 m	0.9 m
Paamiut	3.3 m	1.0 m
Nuuk	4.6 m	1.5 m
Maniitsoq	4.3 m	1.2 m
Sisimiut	4.3 m	1.2 m
Asiaat	2.5 m	0.8 m

[3] Amphidromic Point = point with no tidal amplitude around which cotidal lines rotate in anti-clockwise

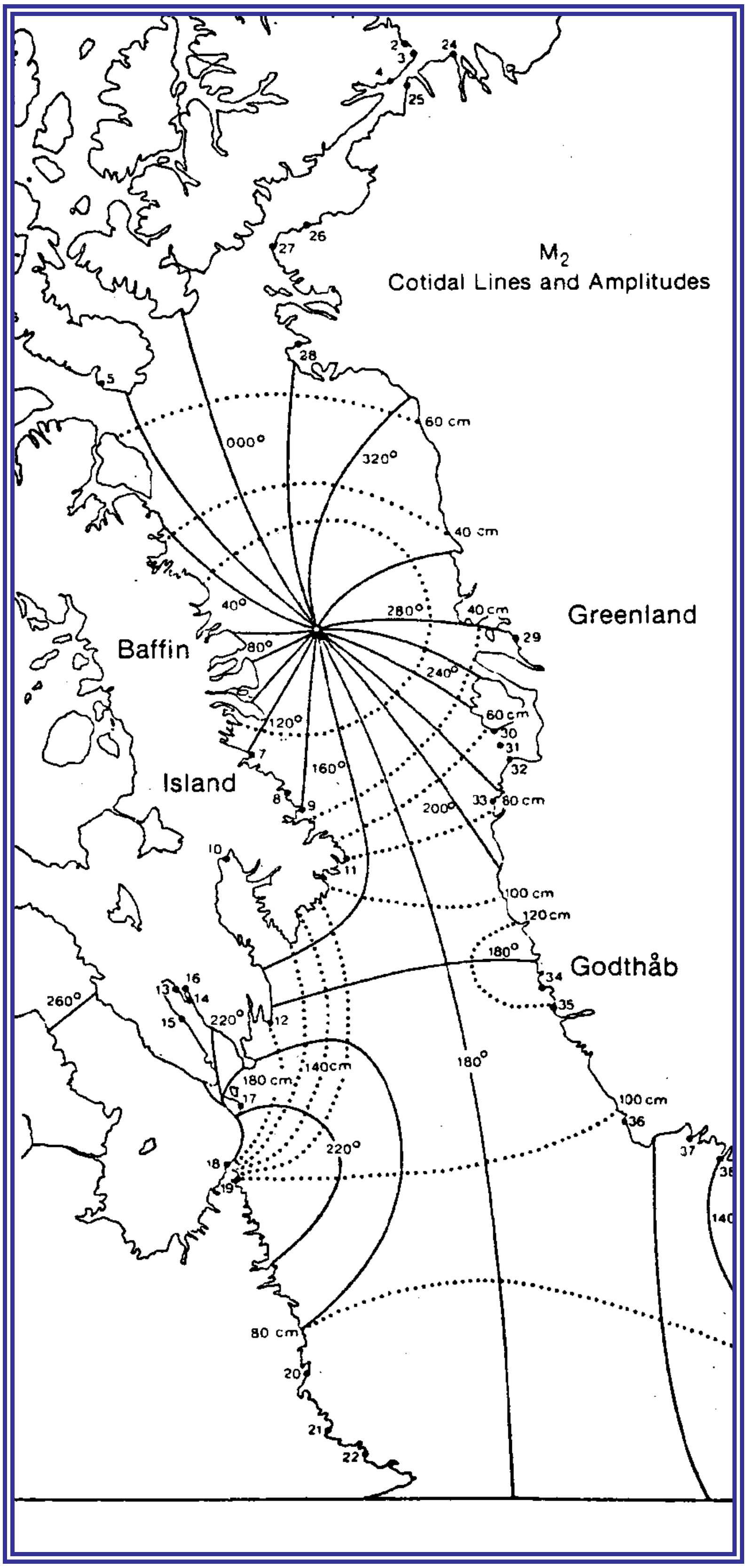


Fig.8. M_2-cotidal lines and amplitudes based on coastal observations

Sea ice

Sea ice is an important parameter in Greenland waters and the West 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.

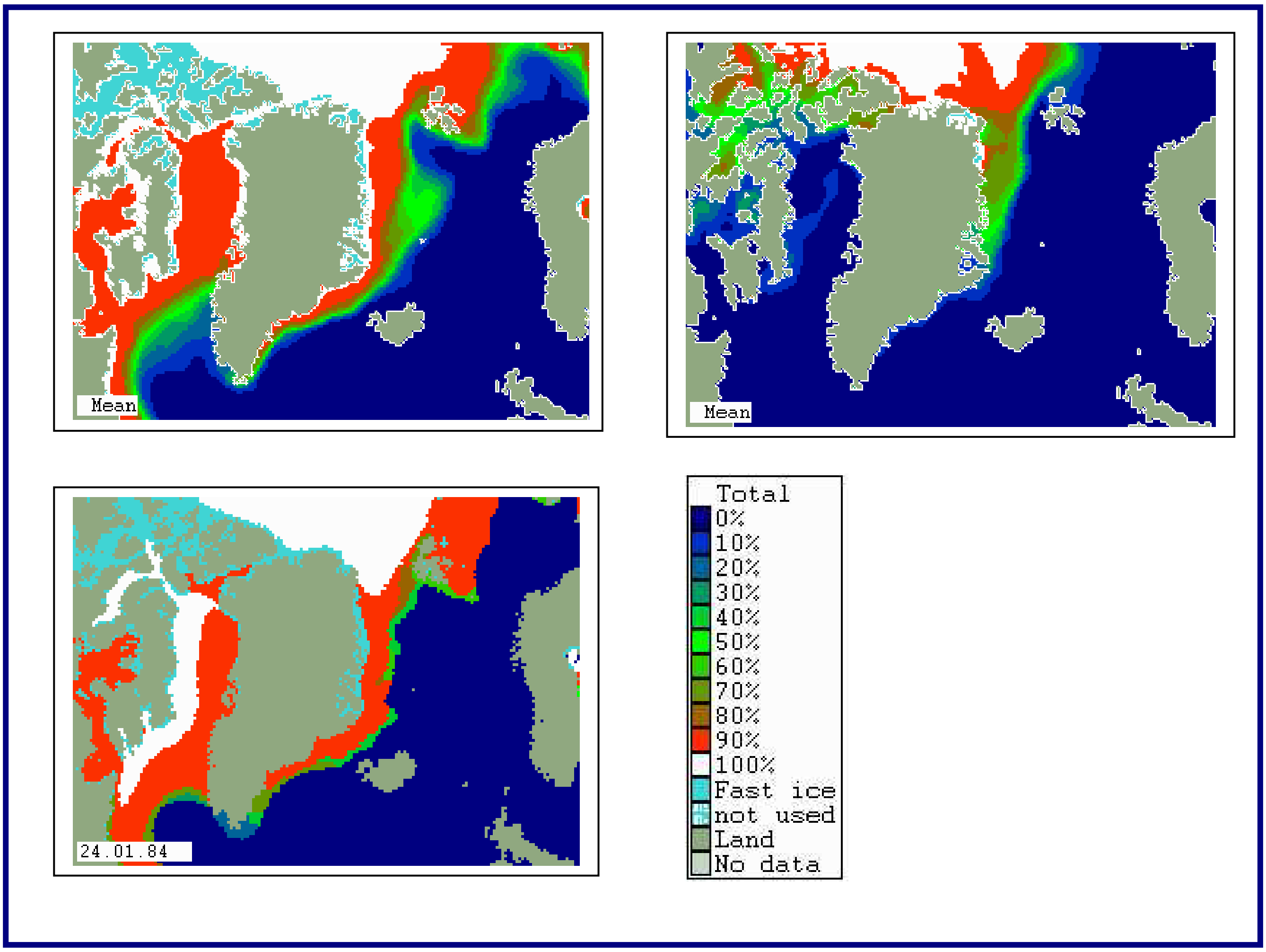


Fig. 5 Mean distribution of sea ice around Greenland in the month of February (maximum distribution) and September (minimum distribution).
The Ice map from January 24, 1984 shows the rare situation where westice and storice meets in West Greenland.
(source: Global Digital Sea Ice Data Bank (http://web.dmi.dk/pub/GDSIDB_mirror/content.html))

The West Greenland waters, primarily the Julianehaab Bight, are covered 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 West 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 - 1995 period extreme amounts of “Storis” entered West Greenland water in 1982, 1984, 1989, 1990 and 1993 (Greenland Ice Service, pers. Comm.).

The formation of “Westice” starts in the northern Baffin Bay in September and in the succeeding months it continues to block larger and larger areas along the Northwest Greenland coast. In most years the ice limit reaches Aasiat in December - January. The waters of West Greenland are normally not affected by “Westice” because the inflow of warm water of Atlantic origin has its maximum during autumn and early winter, Buch (1990/2000).

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 1980-95 period.

Fjord oceanography

Most fjords in West Greenland are sill fjords i.e. resulting in strong limitations to the exchange of water between the deeper parts of the fjord and the open, Fig.9.

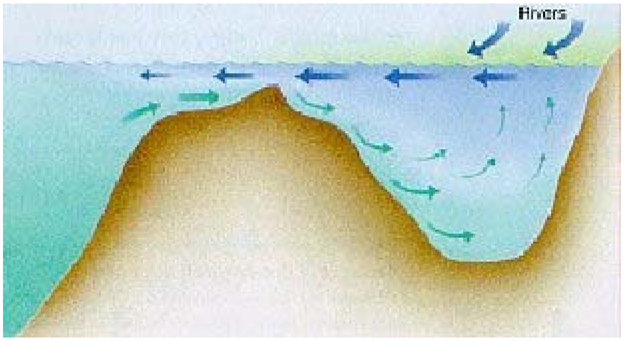


Fig.6 Large-scale fjord circulation

The large scale circulation in a fjord depends on three factors: bottom conditions, water exchange with the open ocean and the supply of fresh water from land. Schematically, the circulation consists of a surface current with brackish water which flows out of the fjord, and a current in deeper layers with more saline water going in the opposite direction, Fig. 6. The fresh water largely comes from rivers in the drainage area, an area which normally is several times larger than the fjord itself. Direct precipitation/evaporation at the sea surface is of minor importance.

The inflow of fresh water to the fjord may be described as the engine which drives the large scale circulation. The inflow generally causes a higher water level in the fjord than outside. This difference in water level forces the brackish surface water out of the fjord. On its way to the mouth of the fjord the brackish water becomes increasingly saline since the surface water mixes with the underlying water. In order to replace the water entrained into the surface current an undercurrent of more saline water is flowing into the fjord at intermediate depth levels. During the winter the fresh water inflow to Greenland fjords are reduced to almost zero because lakes and rivers freeze and the precipitation on land falls as snow. The surface salinity in the fjords will thereby increase to the level found in the coastal waters outside the fjord, and the circulation in the fjord will decrease to a minimum. These conditions will facilitate convection in the fjord.

The deep water in West Greenland fjords are renewed through two different mechanisms:

- Inflow of water from the open ocean with higher density than the deep water of the fjord. This process normally requires strong northerly winds along the west coast of Greenland, which will cause high density water to rise above sill level outside the fjord.
- Vertical convection during autumn and winter cooling and freezing of the surface water causing salt rejection from the freezing water.

The latter mechanism is functioning every winter and it is therefore seldom to observe anoxic conditions in the deep water of Greenland fjord

3. Climate variability

North Atlantic Oscillation (NAO)

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 Fig. 7 (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.

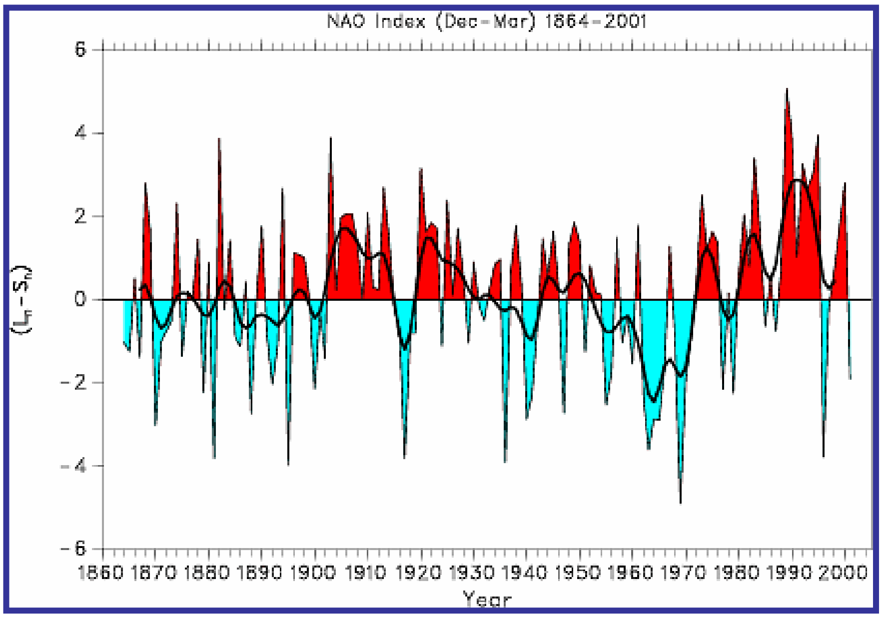


Fig. 7 Time series of the winter (December - March) index of the NAO (as defined in the text) from 1864-1995. The heavy solid line represents the meridional pressure gradient smoothed with low pass filter to remove fluctuations with periods less than 4 years. (Update from Hurrell and van Loon, 1997).

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 30 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 and 1989-1995 winters were marked by some the highest positive values of the NAO index recorded since 1864 (Fig. 7).

A detailed analysis by Hurrell, 2000 shows, that the NAO exerts a dominant influence on wintertime temperatures across much of the Northern Hemisphere. Surface air temperature and sea surface temperature (SST) across wide regions of the North Atlantic Ocean, North America, the Arctic, Eurasia and the Mediterranean are significantly correlated with NAO variability. Such changes in surface temperature (and related changes in rainfall and storminess) can have significant impacts on a wide range of human activities as well as on marine and terrestrial ecosystems.

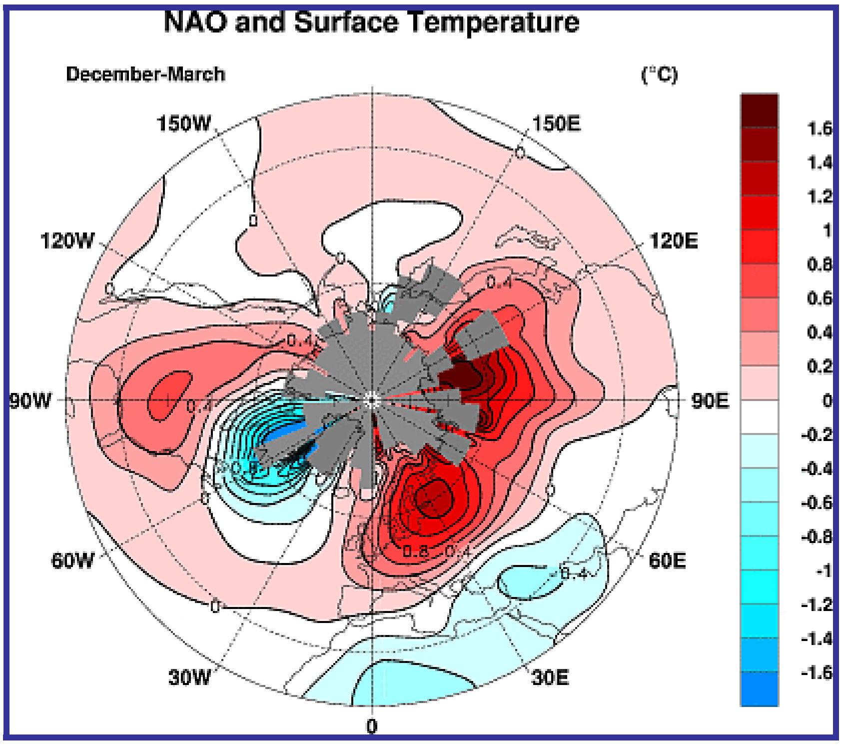


Fig. 8. Changes in land surface and sea surface temperatures (°C) corresponding to a unit deviations of the NAO index for the winter months (December-March) from 1935-1999. The contour increment is 0.2°C. Regions of insufficient data are not contoured. . (After Hurrell, 2000).

When the NAO index is positive, enhanced westerly flow across the North Atlantic during winter moves relatively warm (and moist) maritime air over much of Europe and far downstream across Asia, while stronger northerlies over Greenland and northeastern Canada carry cold air southward and decrease land temperatures and SST over the northwest Atlantic (Fig. 8). Temperature variations over North Africa and the Middle East (cooling), as well as North America (warming), associated with the stronger clockwise flow around the subtropical Atlantic high-pressure center are also notable.

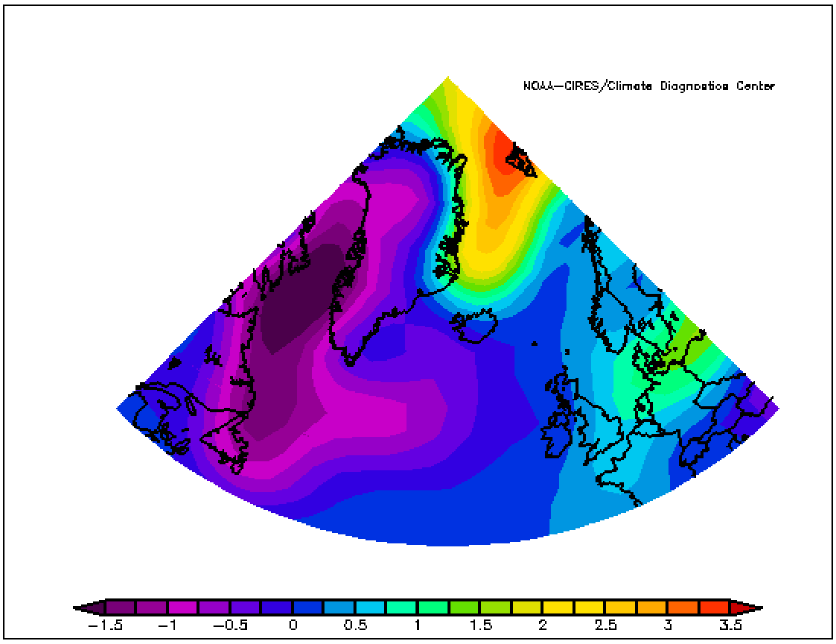


Fig. 9. Difference in air temperatures at the 1000 mb level between 1990-90 and 1960-69. Calculated using the NCEP/NCAR reanalysis database.

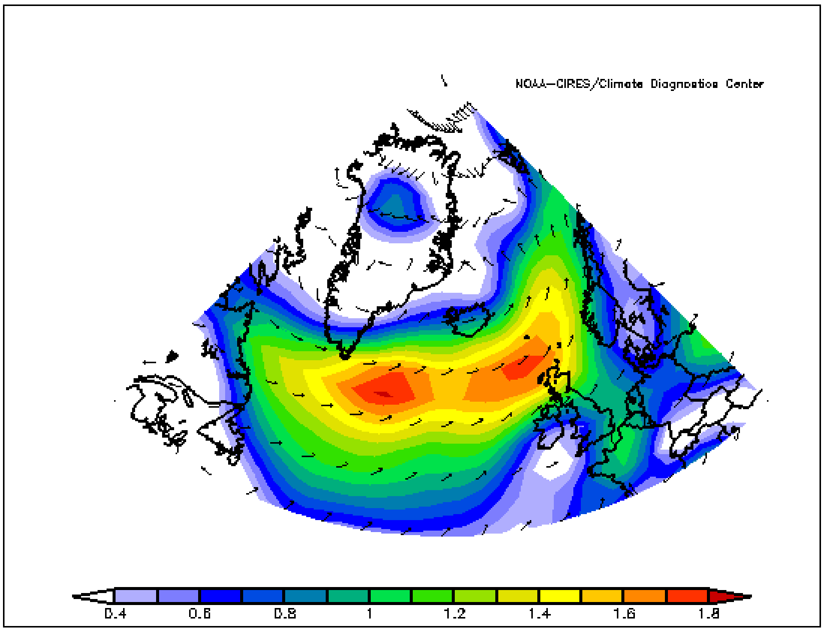


Fig. 10. Changes in the 1000 mb winds between the 1990-99 and 1960-69. Calculated using the NCEP/NCAR reanalysis database.

This can be illustrated further by comparing the temperatures over Greenland from a low NAO period (1960-69) to a high NAO period (1990-99), Fig. 9. It noticed that especially offshore West Greenland it was significantly warmer in the 1960s than in the 1990s.

Changes in the wind pattern in the Greenland area are minor as illustrated in Fig. 10. A more detailed analysis using wind observations (6 hour intervals) from a number of observation sites in Greenland confirms this statement.

The influence of the changing NAO-index on the atmosphere naturally is reflected to the ocean and the ocean circulation. In Fig. 9 the general ocean circulation of the North Atlantic is show under NAO^{+} and NAO^{-} - conditions.

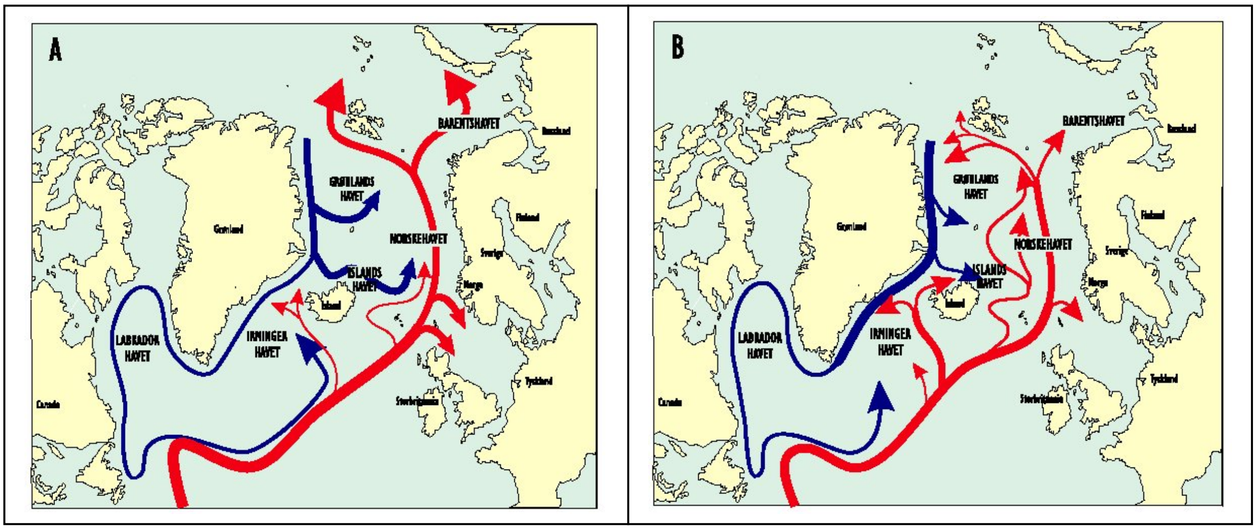


Fig. 11. Ocean circulation under high (A) and low (B) NAO-index conditions. (after Blindheim et al., 2001)

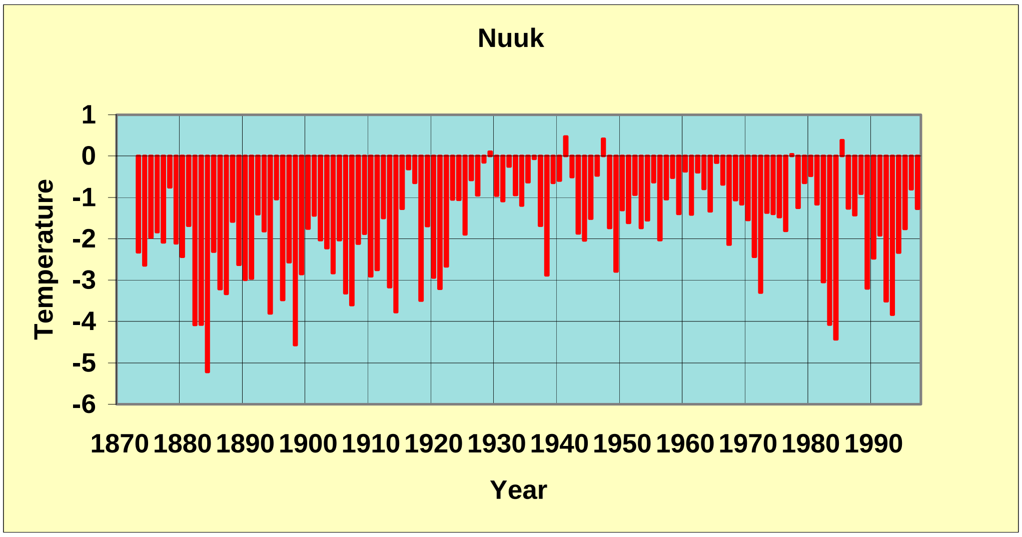
Positive values of NAO result in an intensification of the North Atlantic Current, which is deflected towards the east having the result that the Irminger Current has low intensity, while the inflow to the North Sea and the Arctic Ocean are strong. This results in warm conditions in Europe and the Arctic region. The East Greenland Current has high intensity north of the Denmark's Strait but low south of the strait, because water is flowing into the Greenland Sea and the Iceland Sea via the Jan Mayen- and the East Icelandic Currents.

During negative NAO conditions the intensity of the North Atlantic ocean circulation is almost quite opposite. The intensity of the North Atlantic Current is weaker resulting in several side branches, strong Irminger Current, reduced inflow to the North Sea and the Arctic Ocean. The East Greenland Current has a high intensity all the way to Cape Farewell with weak inflows to the Greenland- and Iceland Seas.

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

Timeseries of annual mean air temperatures from Nuuk, West Greenland and Tasiilaq, East Greenland is shown in Fig. 12. In addition to the interannual variability all stations reflects the general picture of variability outlined above in the description of the NAO index (Fig.7), i.e. high NAO conditions is normally reflected in cold condition in Greenland. The late 1990'es are however an exception from this pattern, since both NAO and Nuuk air temperatures show relatively high values. This was due to a slight displacement of the NAO pattern towards the East or Northeast, ICES, 2000.



b)

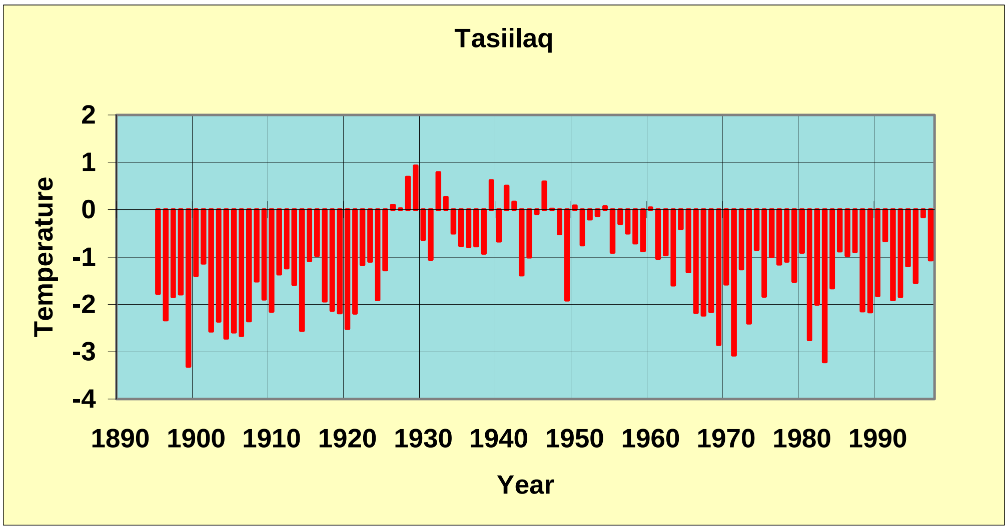


Fig. 12. Annual mean air temperatures from: a) Nuuk; b)Tasiilaq

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 West 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. It was a 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 with 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 - 1995 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 Rosenørn 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. Judging from the annual mean temperatures given in Fig. 12, it is seen that the 1982 - 1984 period is one of the coldest ever recorded at Greenland although not the coldest. Rosenørn 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- was in 1984 the coldest ever recorded (-15,2^{o}C in Nuuk) and that we shall 99 years back in time to find similar conditions (-15,1^{o}C in 1885).

4. Water masses

The water masses around Greenland (definition, distribution, formation etc.) have been discussed in great detail by Buch, 1990/2000. The present report will, therefore, concentrate on updating our knowledge on the water mass characteristic, distribution and variability off West Greenland the area of the highest economical importance to Greenland due to its rich shrimp fishery. The analysis is primarily based on the monitoring data collected annually by the Greenland Institute for Natural Resources on the NAFO standard sections.

The waters off West Greenland are dominated by water masses all formed outside the Davis Strait (Buch, 1990/2000):

- In the surface layer close to the coast cold and low saline Polar Water is found. The East Greenland Current carries it to West Greenland.
- Below and west of the Polar Water we find water originating from the North Atlantic Current.

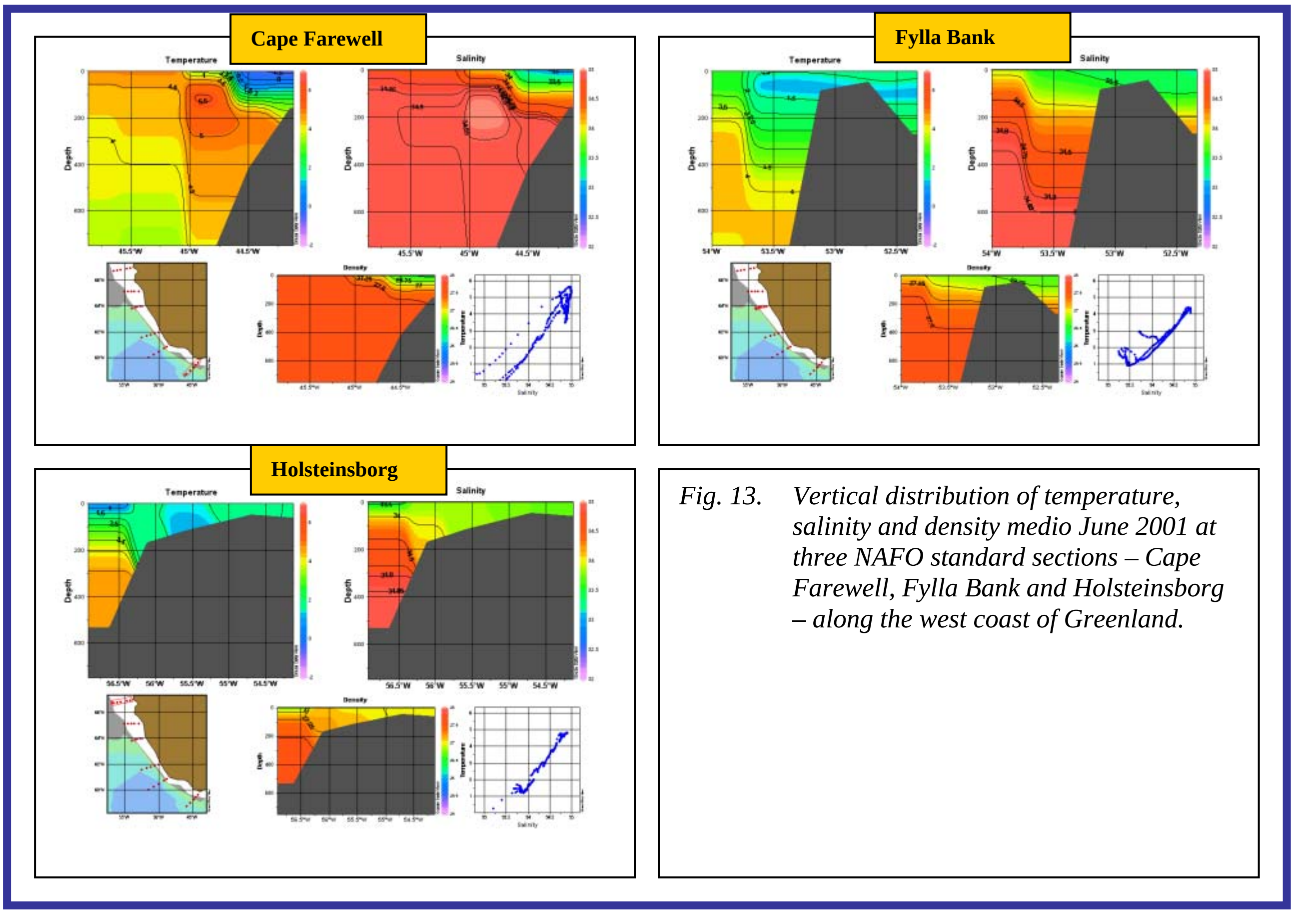


Fig. 13. Vertical distribution of temperature, salinity and density medio June 2001 at three NAFO standard sections – Cape Farewell, Fylla Bank and Holsteinsborg – along the west coast of Greenland.

In Fig. 13 the vertical distribution of temperature, salinity and density is shown on three NAFO standard sections off West Greenland. At the southernmost section at Cape Farewell the front between the Polar Water and the Atlantic Water is clear and sharp. Further north the front is much more diffuse - as discussed in section 2 – and the core of the polar water is here located at a depth of around 100m.

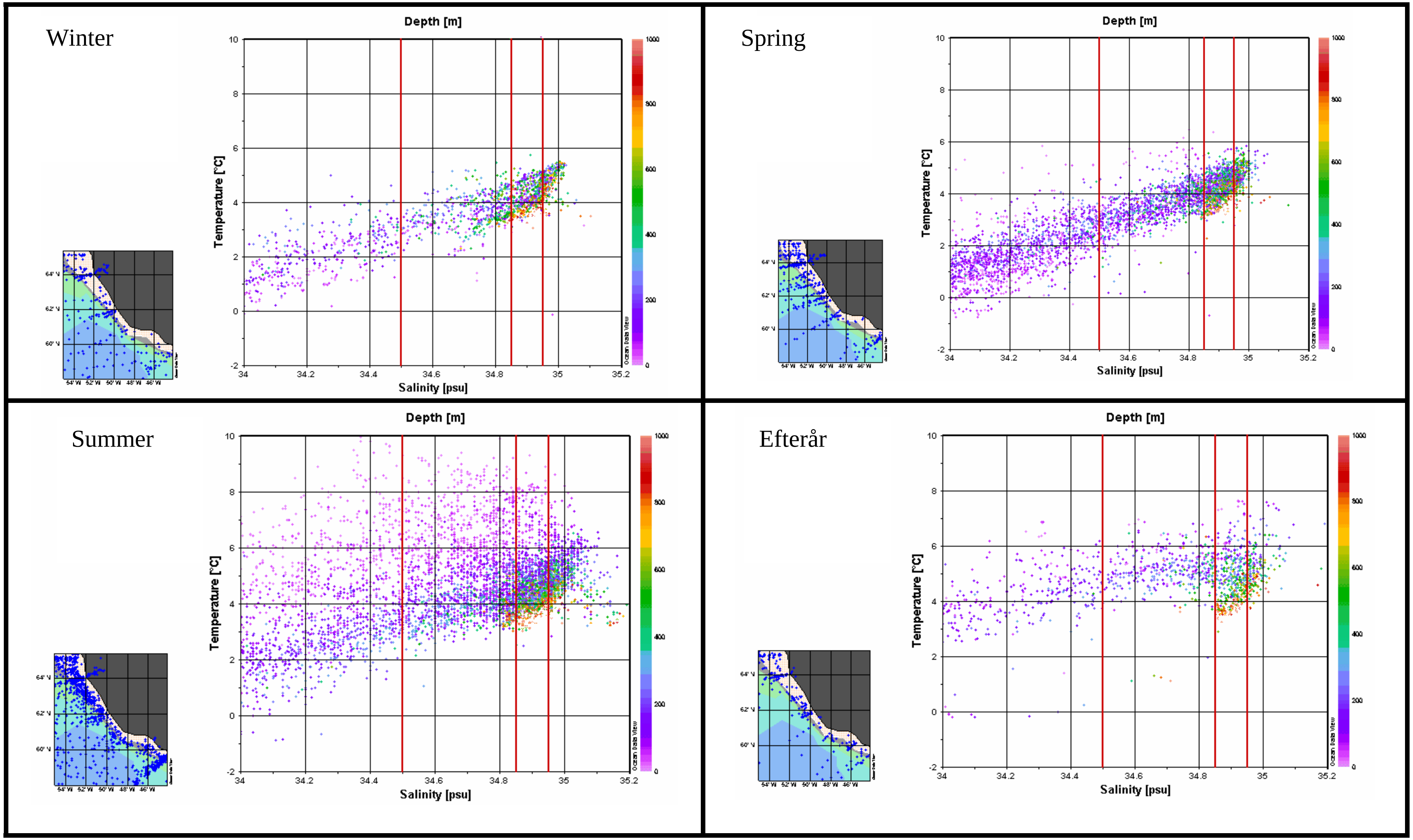


Fig. 14. Seasonal T-S plots from the West Greenland area using all available data in the World Ocean Atlas 1994. The colour indicates the observation depth.

The changes in the atmospheric conditions caused by the shift from low NAO to high NAO conditions have affected the ocean circulation and ocean conditions in the North Atlantic (Dickson et al, 1996, Dickson et al., 2000). The oceanographic conditions off West Greenland will therefore be directly and indirectly affected by climate variability related to the changes in NAO.

The T/S-characteristics of Polar Water as it is found in the East Greenland Current are temperatures generally below 0^{o}C but they may rise to 3-5^{o}C in the surface layer during the summer. Salinity is below 34.4. Buch (1990/2000) however showed that the T/S-characteristics of Polar Water are altered on its way to West Greenland due to mixing with surrounding water masses. Along the West Greenland fishing banks Polar Water therefore is characterised by temperatures below 1^{o}C which may rise to 3-5^{o}C during summer, salinities are below 33.75 -34.0. 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 a more detailed analysis questions this statement. 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^{o}C and salinities between 34.95 and 35.1.

In order to study the water masses of Atlantic origin in more detail, all available observational data from West Greenland as published in World Ocean Atlas 1994 are used for a T/S-plot analysis. Due to the seasonal variability of the inflow of Atlantic water T/S-diagrams have been prepared using the Ocean Data View Software for each of the four seasons (Fig. 14. a-d, S<34.0 have disregarded).

These T/S-diagrams clearly indicate the presence of Irminger Water (T~4.5^{o}C, S>34.95) during all seasons. A more detailed analysis producing T/S-plot for each decade shows great decadal variability in the inflow of Irminger Water to the West Greenland area, it can for instance be seen in Fig.15 that the inflows during the 1960'ies were much higher than during the 1980'ies.

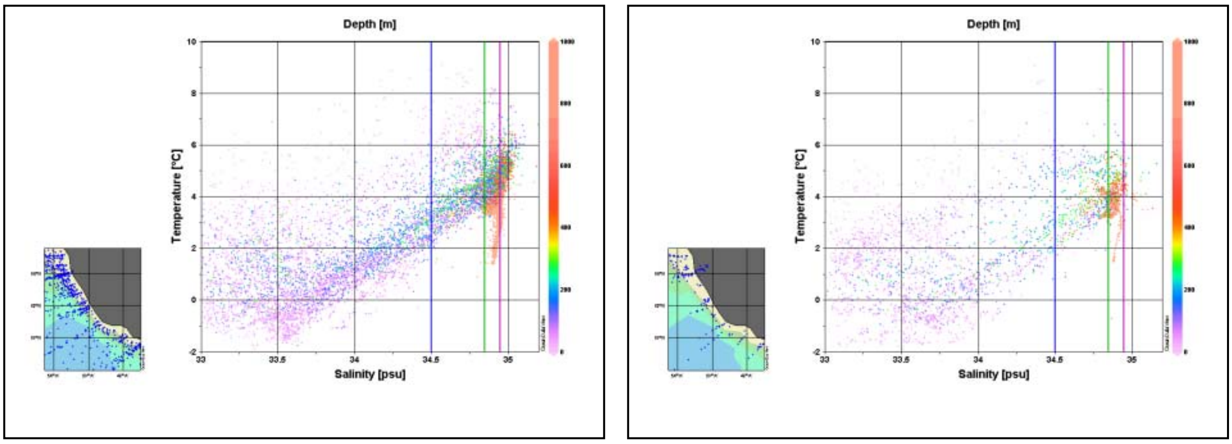


Fig. 15. TS-plots from the West Greenland area using all available data in the World Ocean Atlas 1994 for the 1960'ies (left) and the 1980'ies (right).

Fig. 14 additionally shows that throughout the year there is a body of water in the West Greenland area with salinities above 34.85 and temperatures around 4^{o}C. This body of water most likely have been formed by the Irminger Water mixing with the surrounding water as it flows towards West Greenland resulting in a decrease in temperature and salinity. Water off West Greenland with temperatures above

4°C and salinities between 34.85 and 34.95 is therefore named ***Irminger Mode Water***, and this water mass can always be observed off West Greenland, while pure Irminger Water (T around 4.5°C; S>34.95) only occasionally is observed in the area and then primarily in the southernmost part.

The T/S plots in Fig. 14 and the example of a vertical temperature and salinity distribution plot in Fig. 8 show that there exists a huge volume of water with temperatures above 2.5°C and salinities in the interval 34.50 - 34.85. Additionally it is seen in Fig. 14 that the temperature increases during autumn. Water with salinities above 34.5 is found at depths excluding the possibility of a temperature rise due to atmospheric heating (see Fig.14 where the colour coding indicates the observation depth). The high temperatures, especially during autumn, support the assumption that water with salinities in the interval 34.5 - 34.85 is originating from the North Atlantic Current.

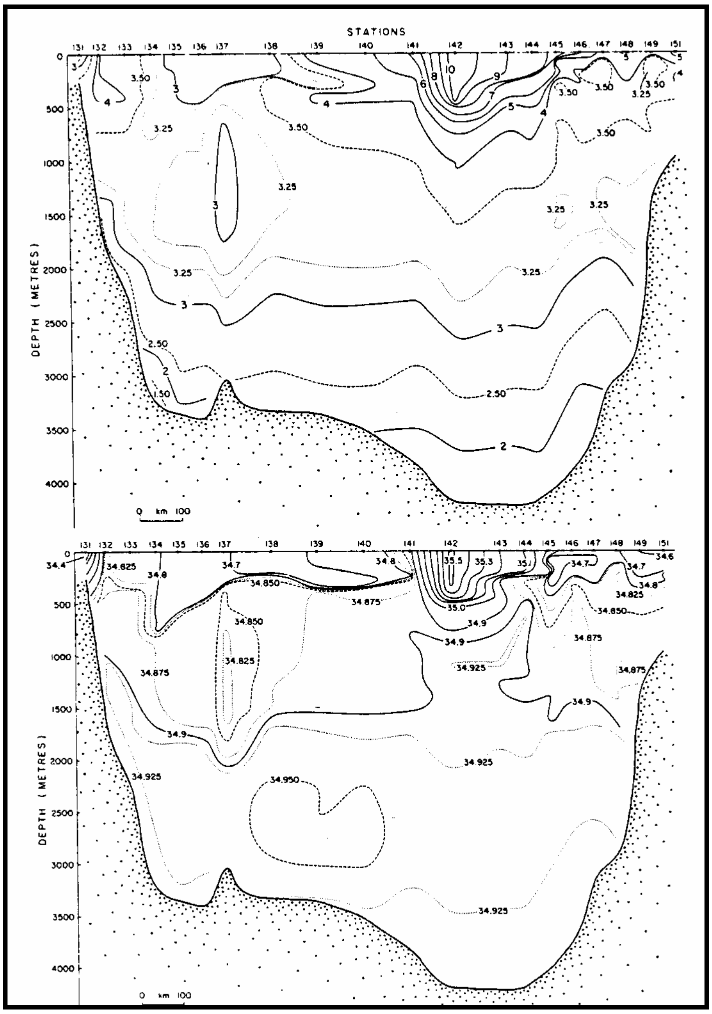


Fig. 16. Potential temperature and salinity fields along the Cape Farewell to Flemish Cap Section, 1978. After Clarke (1984).

Along the Cape Farewell sections of the NORWESTLANT surveys (Lee, 1968) a rather thick layer (200 to 250 metres) with salinities between 34.6 - 34.85 was observed at a distance of around 100 nm south of Cape Farewell. The temperatures were around 2.5°C during the first two NORWESTLANT surveys and increased to above 4.5°C during the third survey. Clarke (1984) reported observations from a section between Cape Farewell and Flemish Cap taken in early 1978. North of the North Atlantic Current to about 100nm south of Cape Farewell a 200-300 thick layer with temperatures above 2.5°C and salinities below 34.85 was observed, Fig.16.

There is therefore reason to believe that the water mass observed off West Greenland characterised by salinities between 34.5 and 34.85 and temperatures above 2°C - late in the year often above 5°C, has its origin in the northern part of the North Atlantic Current. The relatively low salinities most likely is due to influence from the Labrador Current. This water mass was named "***Northwest Atlantic Mode Water*",** by Buch (2000). A possible path towards West Greenland can be seen in Fig. 1, where water from the northern rim of North Atlantic Current turns north at around 40°W flowing towards the area off Southeast Greenland. Here it turns southward flowing towards the Cape Farewell area, where it turns northward again. In the Davis Strait at around 63-65°N the water flows towards west until it reaches the Labrador Current.

Fronts

Along the westcoast of Greenland a front between the low saline Polar Water (mixed with fresh water from land runoff) and the saline water of Atlantic origin is found in the surface layer just west of the West Greenland fishing banks.

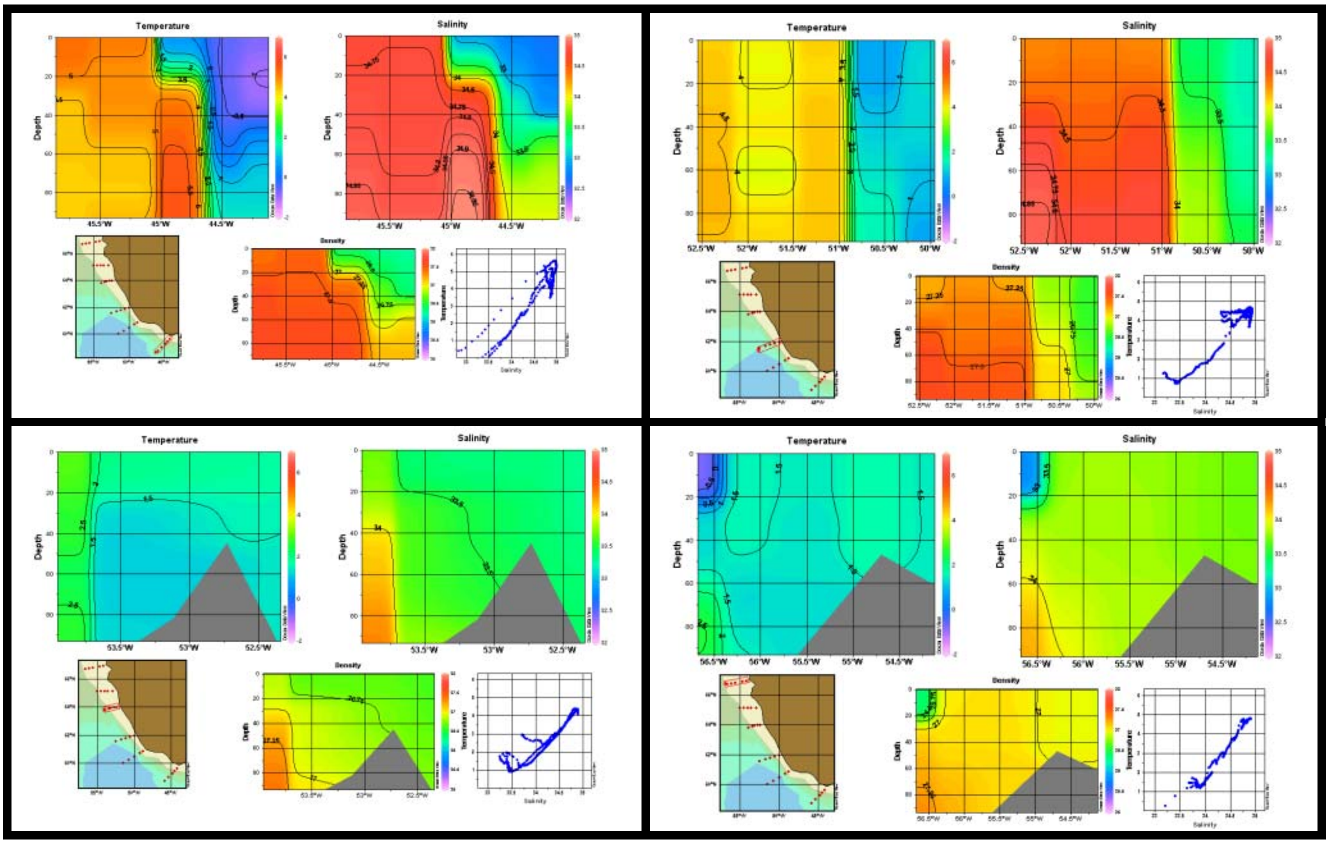


Fig. 17. Vertical distribution of temperature, salinity and density in June 2001 in the upper100 m at the NAFO standard sections Cape Farewell, Frederikahaab, Fylla Bank and Holsteinsborg.

In Fig. 17 it is seen that the front is very sharp at the southernmost sections and becoming increasingly diffuse further north. At the Holsteinsborg section the front seen further south has almost vanished, while another front at the westernmost part of the section has revealed itself reflecting the presence of newly melted Westice.

A more detailed study of temperature and salinity observations throughout the year shows that the front between the two water masses is weak from January to May, and relatively strong the remaining part of the year with maximum strength in September and October, see Fig. 18.

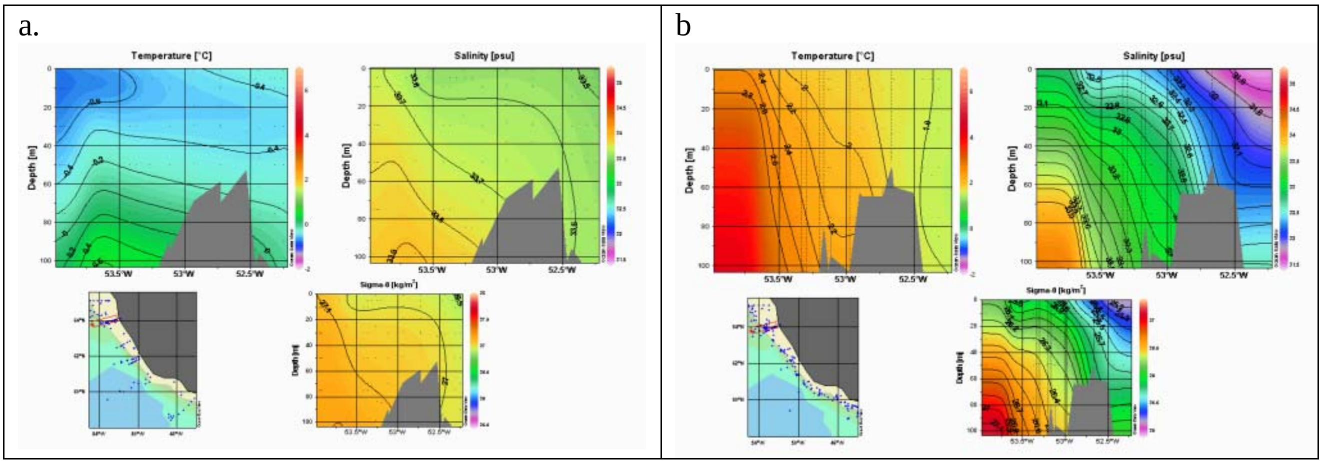


Fig. 18. Vertical distribution of temperature, salinity and density in the upper100 m at Fylla Bank in a) March and b) October. Mean Values for the period 1950-1999.

The weak stratification during the winter months is a combined effect of the upper layer being homogenised by vertical overturning due to atmospheric cooling and the fact that the inflow of Polar Water is relative low in this part of the year.

In the autumn the inflow of both Polar and Atlantic Water is high, and a strong gradient between the two water masses is observed.

It shall also be noticed that strength of the front is primarily governed by the differences in salinity.

From the perspective of biological productivity the vertical velocities across the front transporting nutrient rich water from greater depth to the surface layer is of interest. Using model calculations it is seen that the vertical velocity can reach values of $7 x 10^{-5}$ m/s, Fig. 19. It is additionally seen that there is – as could be expected – good correlation between northerly winds and positive (upward) vertical velocities.

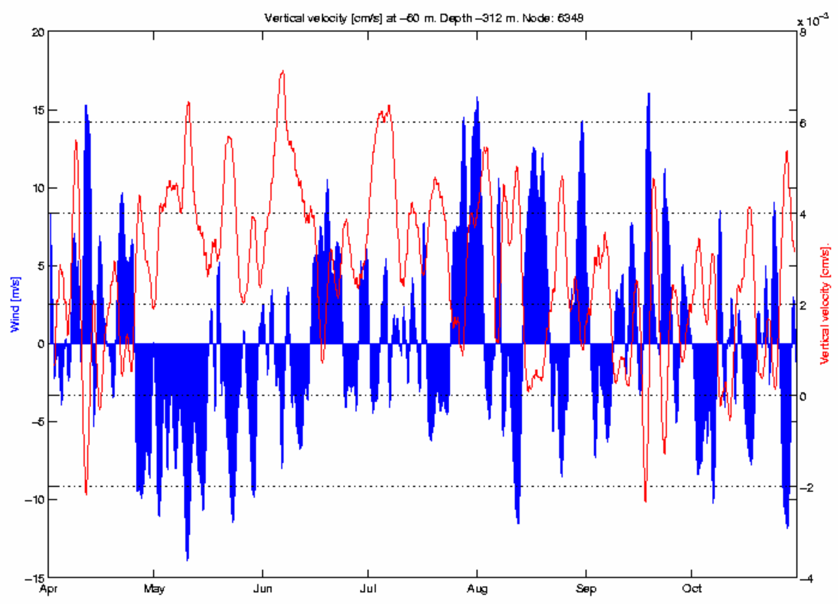


Fig. 19. Model calculation of the vertical velocity at 60 m's depth just west of Fylla Bank (red line). The blue columns show daily mean values of north-south wind directions (positive values means winds from the south)

5. Interannual variability

Surface conditions

The most well known oceanographic time series from West Greenland is the mid-June mean temperature on top of Fylla Bank (Fylla Bank st.2, 0 - 40 m), Fig. 20.

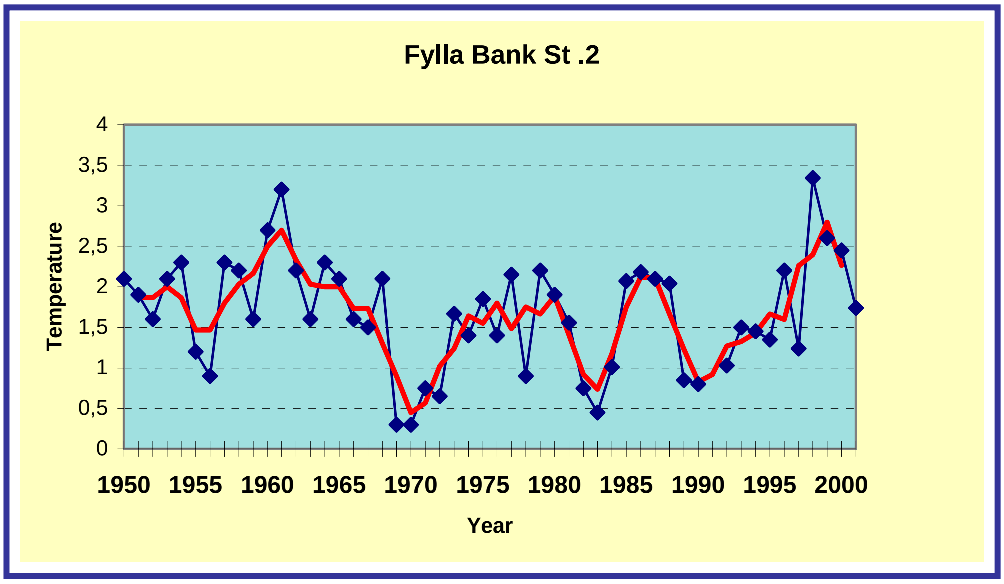


Fig. 20. Mean temperatures of the upper 40 m on Fylla Bank St. 2, medio June 1950 - 1997. Blue line = observations; red line = 3 year running mean

The temperature may vary quite drastically from one year to the next, often more than 1^{o}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^{o}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, 1990/2000), 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. 12, which could indicate a high inflow of Polar Water.
- During recent years temperatures have been rather high most likely due to increased inflow of Irminger Water, se below.

Fig. 21 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 salinities at Fylla Bank, which off course was not to be expected because these cold periods was due to atmospheric cooling.

Relatively low salinities 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 West 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 salinities were observed only at the Cape Farewell section in 1996.

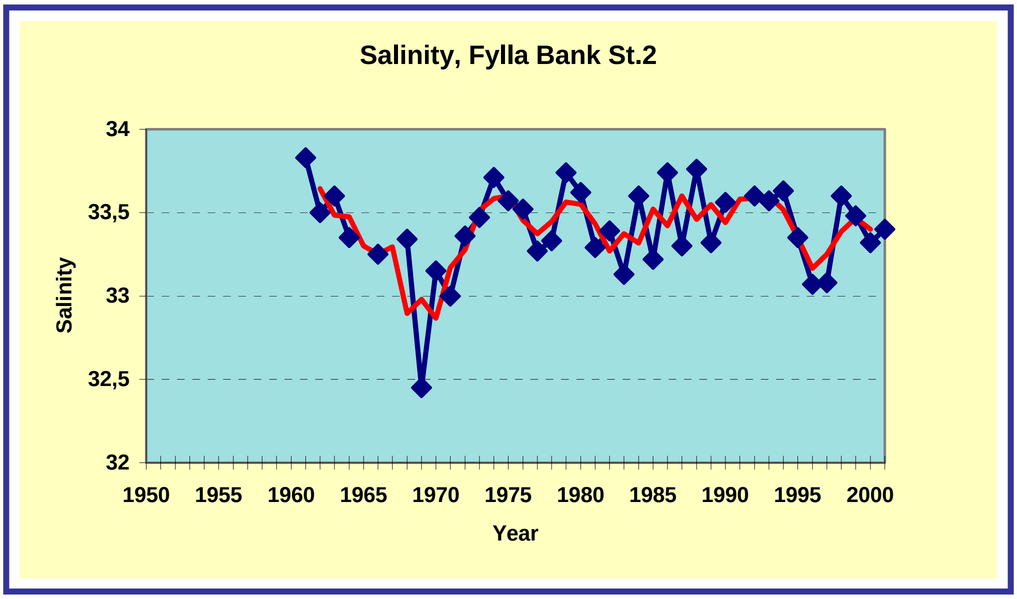


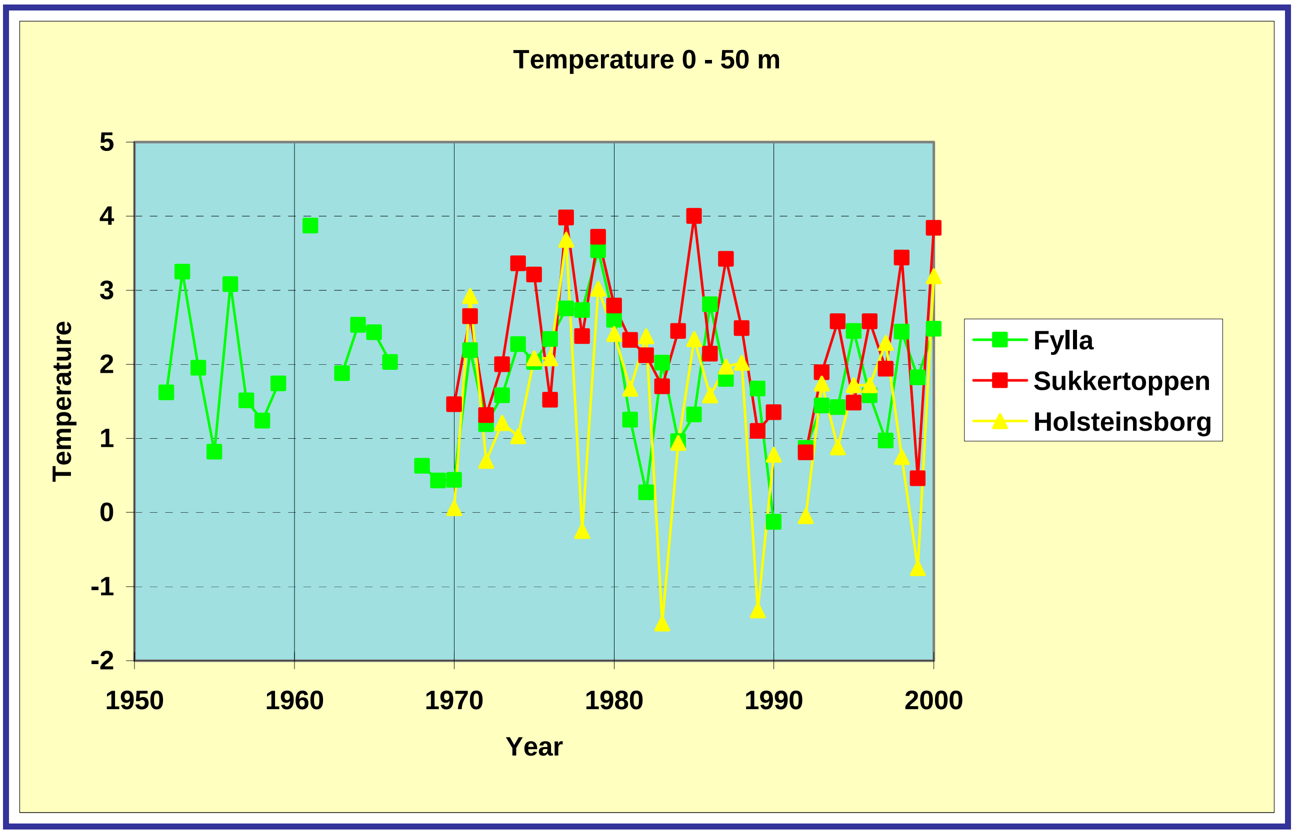
Fig. 21. Mean salinity of the upper 40 m on Fylla Bank st. 2, medio June 1961 - 1997.
Blue line = observations; red line = 3 year running mean

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

Further offshore - just west of the fishing banks there exists relatively long time series of July temperatures and salinities 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 salinities of the upper 50 metres from the three stations is shown in Fig. 22.



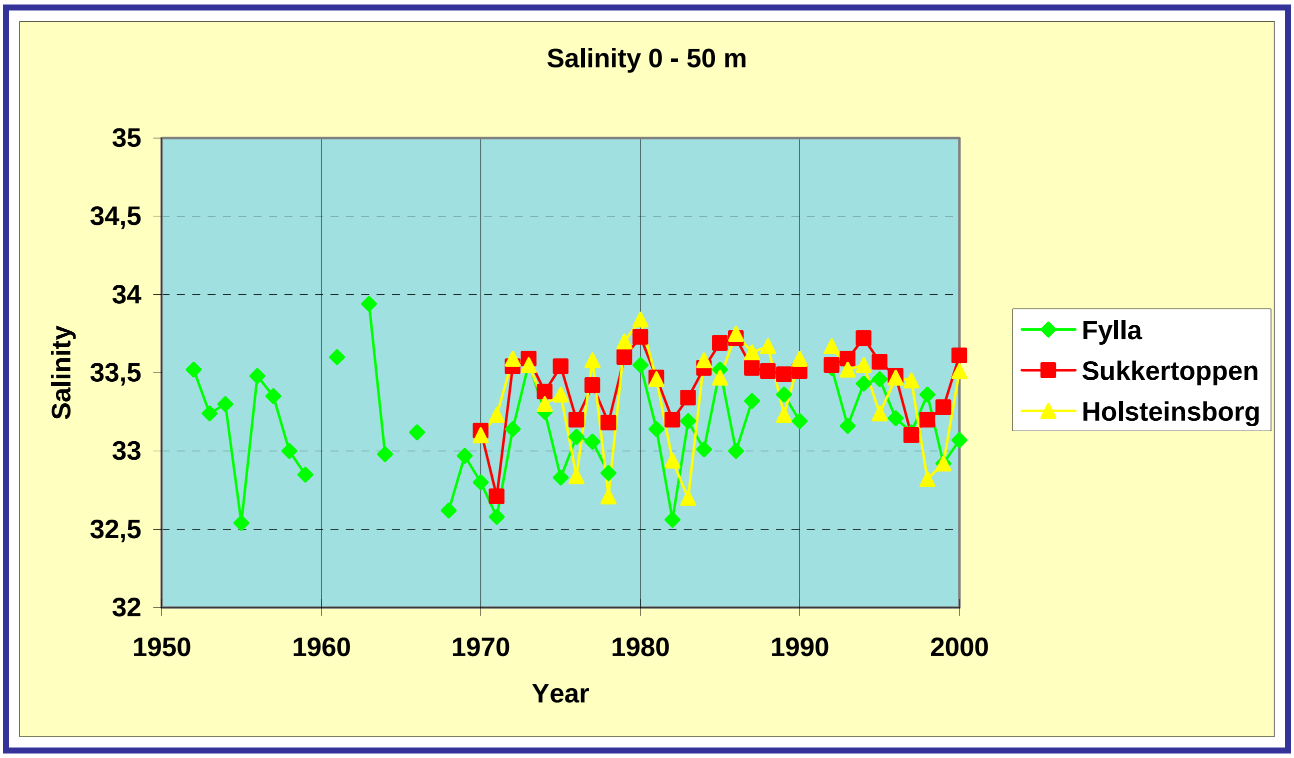


Fig. 22. Mean temperature and salinity in the upper 50m at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5

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 salinities are observed at the Lille Hellefiske Bank, while the lowest salinities 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 West 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.

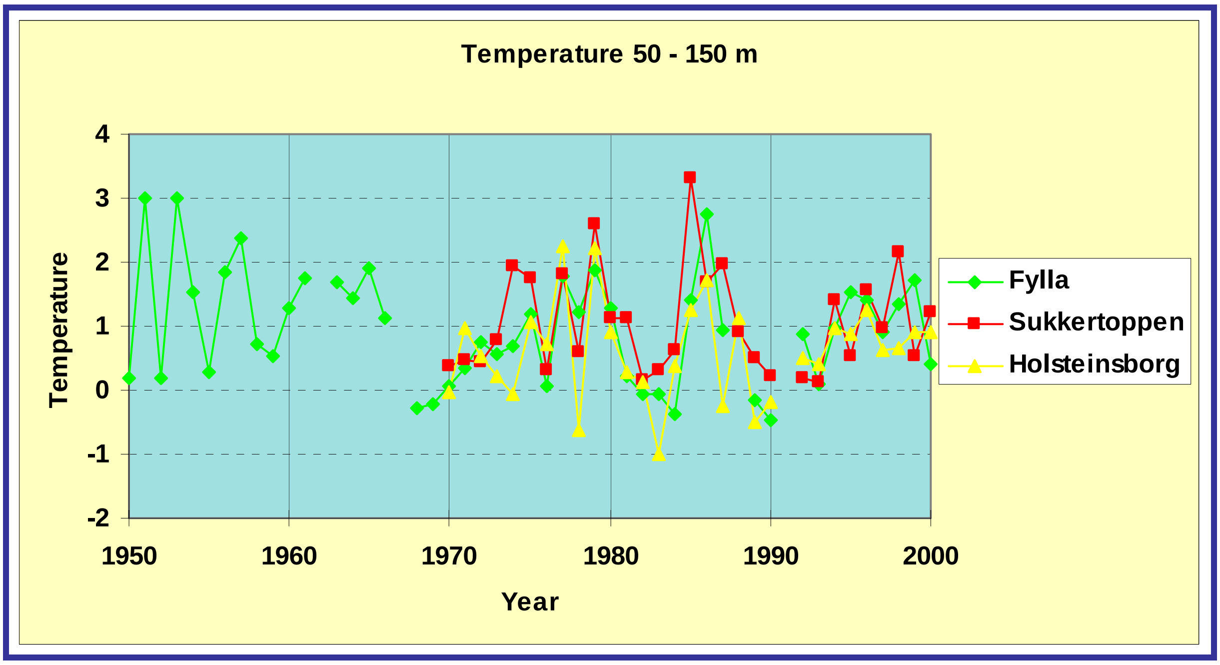
Deeper layers

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 - 150m, 150 - 400m and 400 - 600m water column. This layering has been chosen for the following reason:

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

It is seen from the three figures that there is great inter-annual 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 West 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 West 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 have, 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 West Greenland area, which is a clear reflection 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 salinities 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.



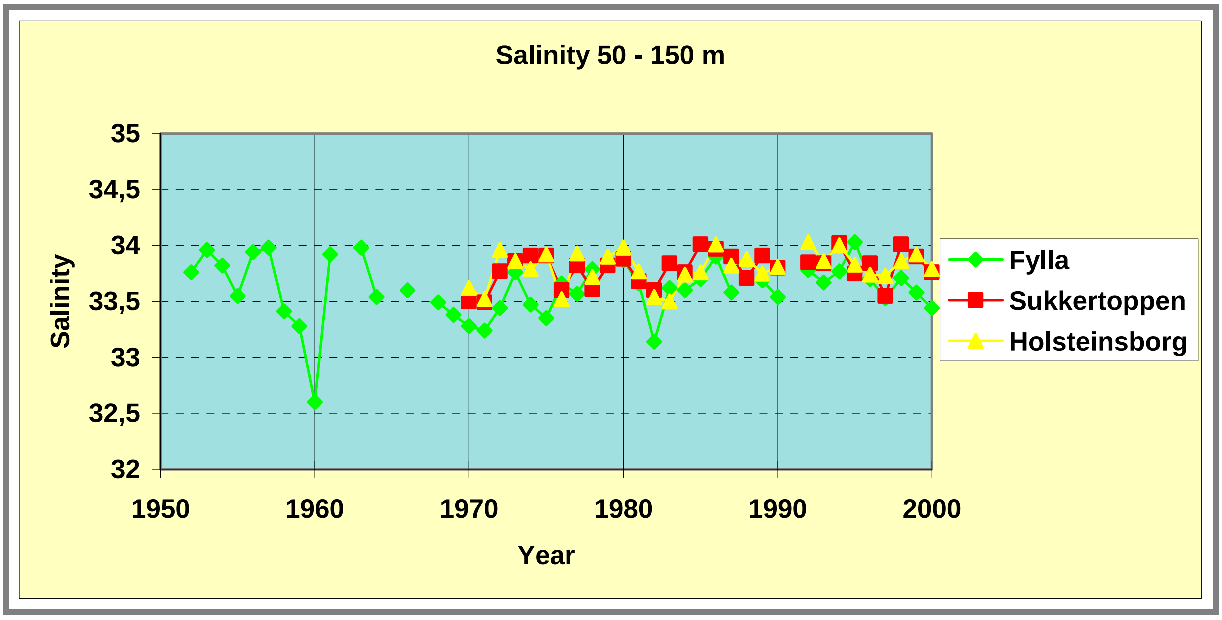
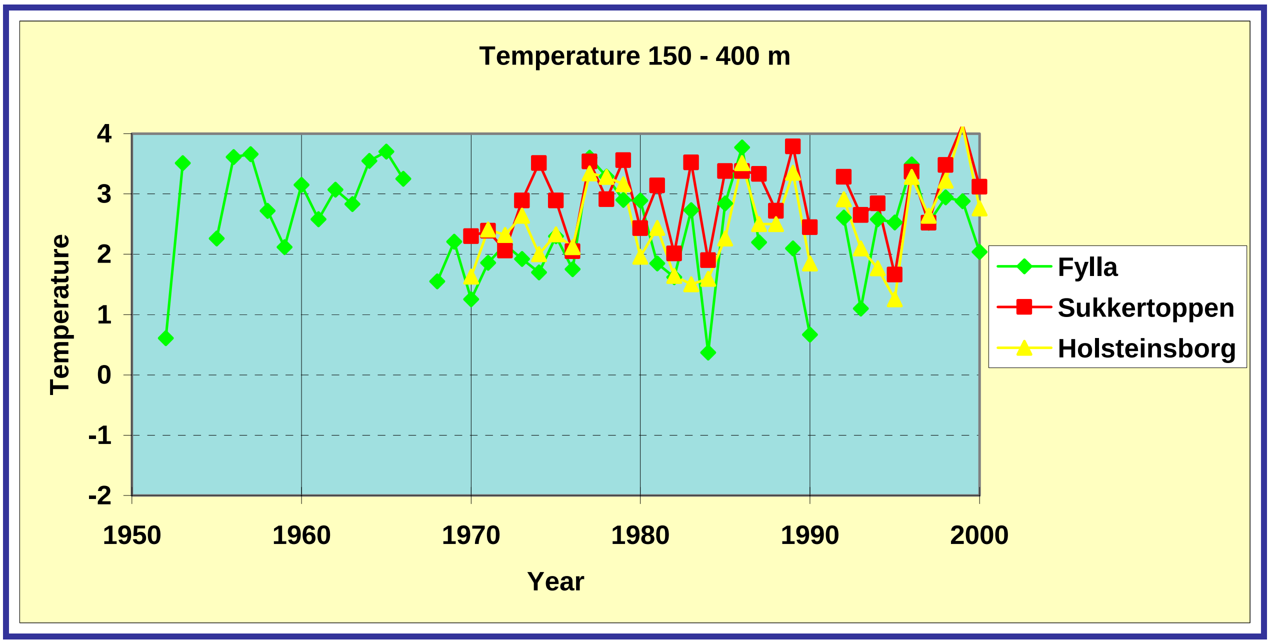


Fig. 23. Mean temperature and salinity in the 50 - 150 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5

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.



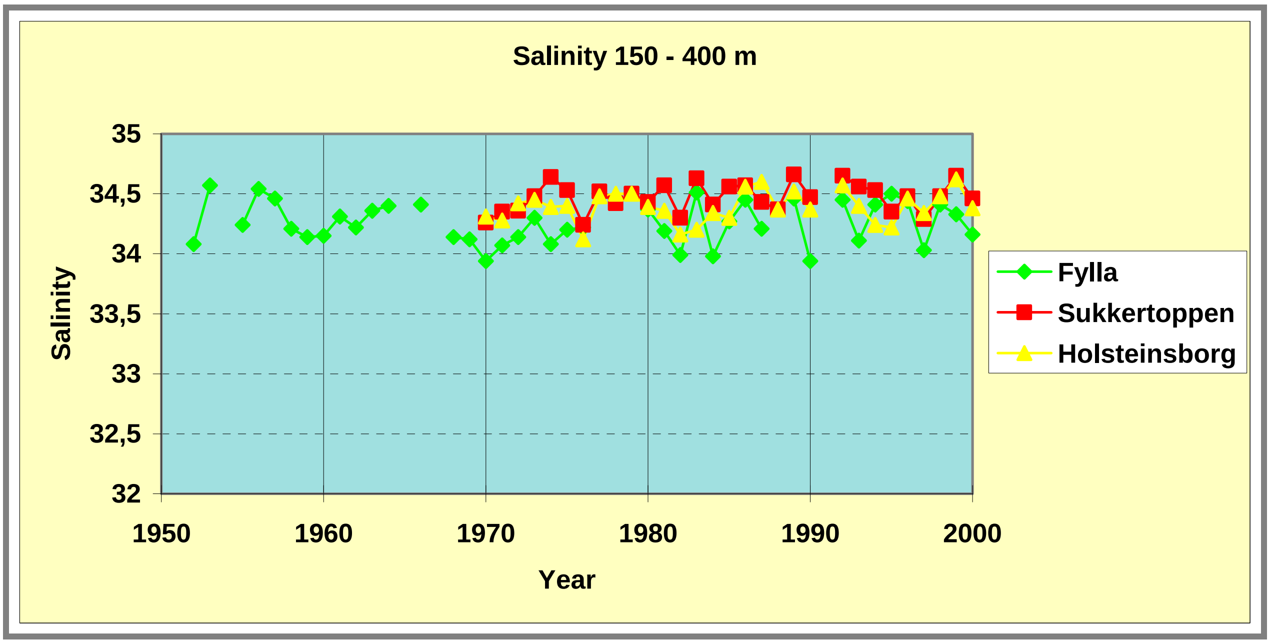
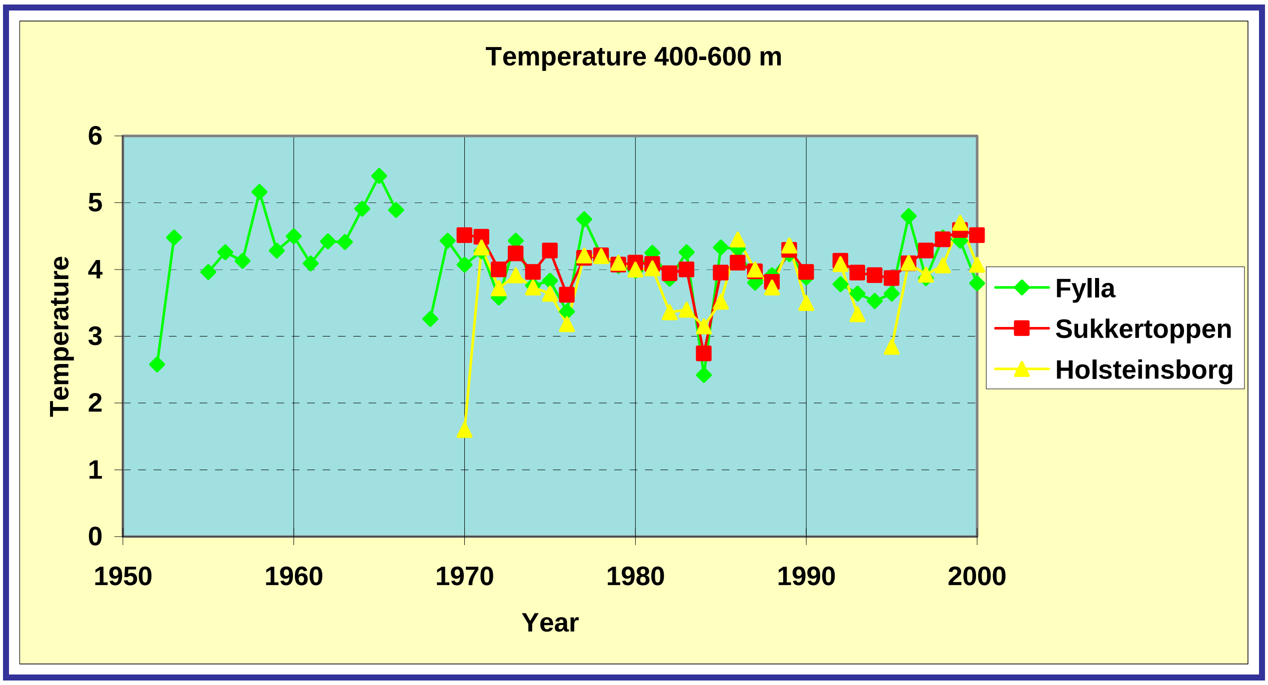


Fig. 24. Mean temperature and salinity in the150 - 400 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5



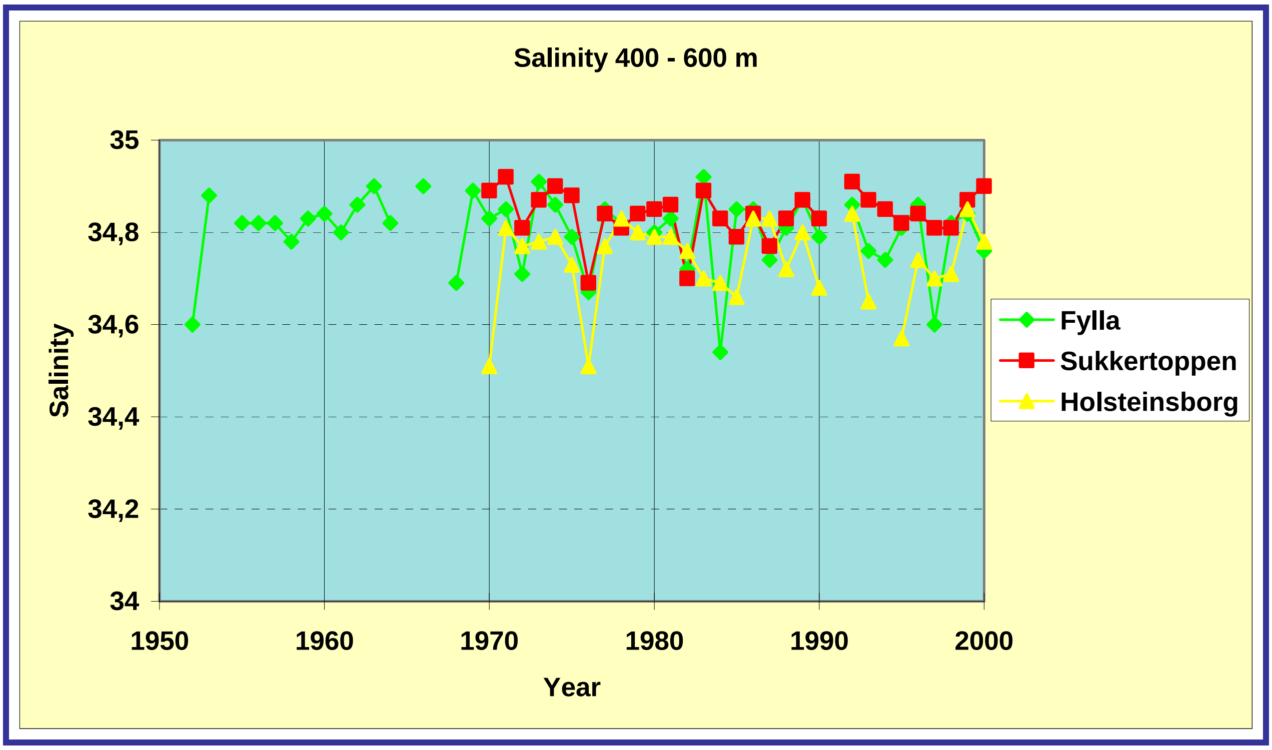


Fig. 25. Mean temperature and salinity in the 400 - 600 m layer at Fylla Bank st.4, Lille Hellefiske Bank st.5 and Holsteinsborg st.5

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, 1990/2000, 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 West Greenland preventing inflow of Sub-Atlantic Water at normal rates.

The 400 - 600 m layer is characterised by temperatures around 4°C and salinities around 34.8. Salinities higher than 34.8, and especially values close to 34.9, 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 the late 1990'ies were characterised by a higher than normal inflow of Irminger Water. 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 salinities above 35 was observed at the Cape Farewell section.

Analysis of temperature and salinity data collected off West Greenland over the past 6-7 decades (Buch el al, 2002) are given in Fig. 26 showing time series plot of temperature, salinity and density from stations just west of the shelf at the Cape Farewell- and Fylla Bank sections, respectively. It is seen that the inflow of water of Atlantic Origin has changed. Before the 1970'es pure Irminger Water ($S > 34.95$) was present at the Cape Farewell st. 3 in large quantities at depths greater than 100 – 400 m, although the inflow was gradually decreasing. It is also noticed that the heat inflow was markedly greater at that time with temperatures above 4.5°C in the entire upper 600 m water column, the upper 200 m even had temperatures above 5.5°C. After 1970 Irminger Water has only been observed in smaller quantities after 1995 and a similar statement can be given for temperatures above 5.5°C. In the intermediate period the dominant water mass was Irminger Mode Water. The increased activity in the circulation of Irminger Water has also been observed in the interior of the Irminger Sea after 1995 (Mortensen and Valdimarsson, 1999).

At the Fylla Bank st.4 we observe a similar trend in reduced inflow of salt and heat. The Irminger Mode Water was present in much higher quantities before mid 1970'es than after and it is noticed that the three cold periods are clearly reflected in the temperatures of the upper 200 m. A weak freshening in the upper 150-200 m is additionally observed since 1965 resulting in a less dense water mass within this layer. This freshening, however, is most dominant in the upper 50-100 m. A similar freshening during the same period has also been observed in the Irminger Water component north of Iceland (Malmberg, 1985), indicating a reduction of the strength of the Irminger Current after 1965 and/or a more dominant influence of Polar Water. From mid 1965'es to the early 1970'es, the freshening was caused by an anomalous high inflow of Polar Water closely linked to the "Great Salinity Anomaly", whereas afterwards it is believed to be caused by a high NAO anomaly reducing the strength of the Irminger Current.

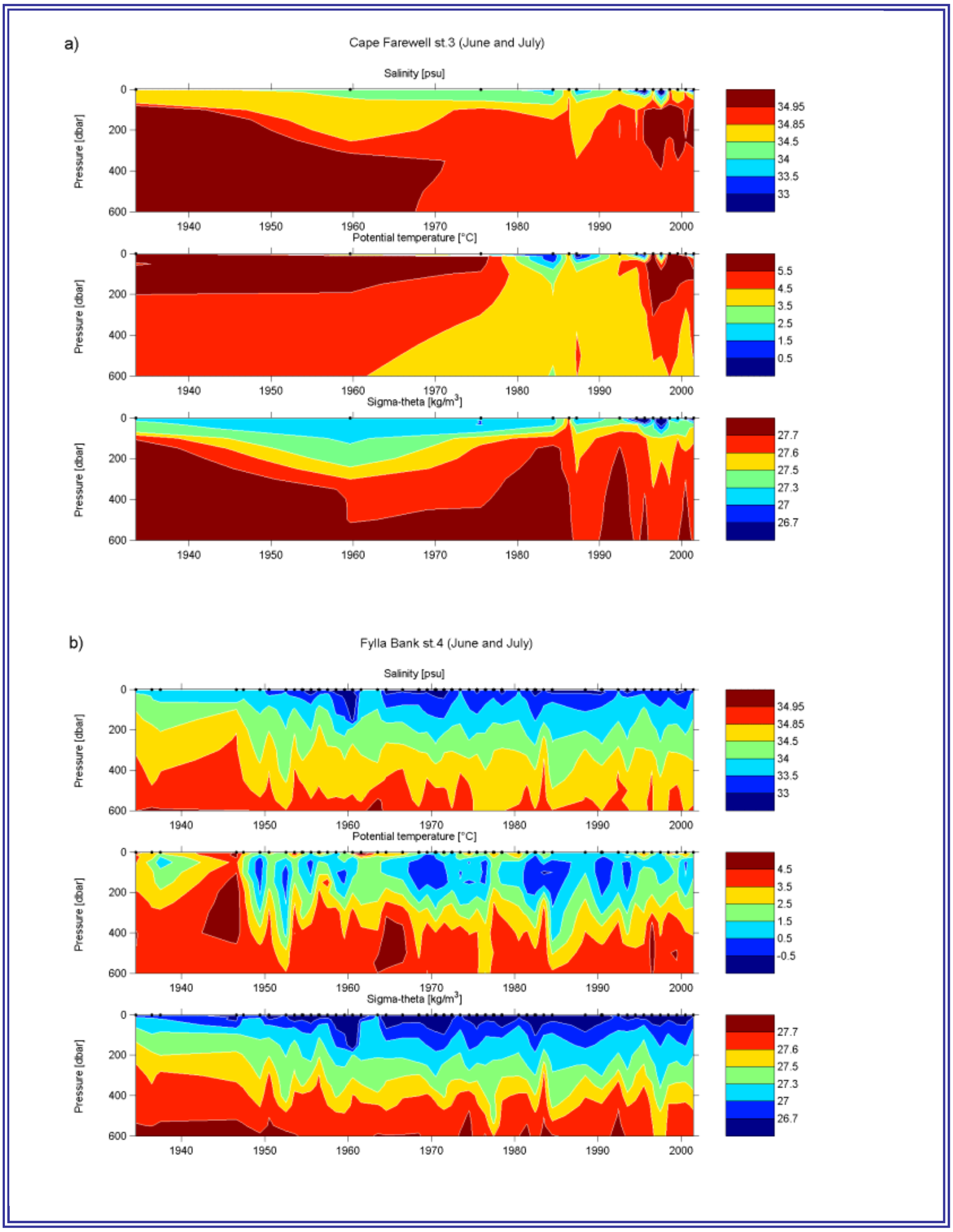


Fig 26. Timeseries of summer (June and July) salinity, temperature and density at:

a. Cape Farewell st.3

b. Fylla Bank st.4

From Buch et al, 2002.

6. Summary and conclusions

The intention of the present paper was to update our understanding of the oceanographic conditions and their variability of the Greenland Waters – especially the West Greenland waters – in relation the description given by Buch (1990/2000).

The physical environment in the waters off Greenland is highly dominated by the inflow of water masses originating from various regions in the North Atlantic and Arctic Ocean. Additionally air-sea-ice interaction processes are of great importance 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 West 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 20 years.

The interannual variability of the oceanographic conditions has been analysed using time series of temperatures and salinity's from the Fylla Bank, Lille Hellefiske Bank and Holsteinsborg. The most significant oceanographic events observed in the West 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. It has however also been demonstrated that the inflow of pure Irminger Water to the West Greenland has been highly diminished since 1970, which means that the flux of heat and salt has been reduced, which adds another dimension to the extreme marine climate experienced off West Greenland over the last 2-3 decades.

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, Buch et al. (2002). The change in the marine climate has, however, been favourable to the development of a rich shrimp fishery in Greenland, so there seem to be good correlation between the climate changes and the observed shift in the marine ecosystem. This correlation is, however, based mainly on the use of ocean temperatures as a proxy for the climate change. Scientific investigation to understand the ecological, chemical and physical processes behind changes in the marine ecosystem has almost not been performed.

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