
Appendix A

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Ecosystem Variability in West Greenland Waters

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Abstract

A review of the climate conditions off West Greenland during the past 50 years shows large variability in the atmospheric, oceanographic and sea-ice variables, as well as in fish stocks. A positive relationship is found between water temperature and the recruitment of cod and redfish, whereas the recruitment of shrimp and halibut is negatively related to temperature. Observed shifts in the hydrographic conditions during the second half of the 1990s indicate that some changes in the environment may be expected in the coming years. Relationships between the past variations in fish resources, hydrographic conditions, and the large-scale climatic conditions, as expressed by the North Atlantic Oscillation (NAO), strongly support the incorporation of environmental variability into prediction models for fish recruitment and therefore into the assessment of the fish resources.

Key words: biomass, climate, cod, fishery, West Greenland, salinity, shrimp, temperature, variability, NAO

Introduction

In the 20th century Greenland experienced two great transitions, the first from seal hunting to a cod fishery, and then from cod to a shrimp fishery. Both affected the human population centres and the economy of West Greenland (Hamilton *et al.*, 2000). The economic transitions reflected large-scale shifts in the underlying marine ecosystems, driven by interactions between climate and human resource use.

The marine shelf ecosystems off East and West Greenland are intermediate between the cold Polar water masses of the Arctic region and temperate water masses of the Atlantic Ocean. They are important fishing grounds and are characterized by relatively few dominant species, which interact strongly (Pedersen and Kannevorff, 1995; Rätz and Stransky, MS 1999; Pedersen and Zeller, 2001). Ocean currents, that transport water from the polar and temperate regions, affect the marine productivity on the Greenland shelves and changes in the North Atlantic circulation system therefore have major impacts on the distribution of fish species and fishery yields (Pedersen and Smidt, 2000; Pedersen and Rice, 2002).

Greenland climate has undergone some dramatic changes through the 20th century. The period 1920–70 generally experienced warm air temperatures while the subsequent 30 years have been dominated by three extreme cold periods around 1970, the early 1980s and the early 1990s. These atmospheric changes have also been reflected in the oceanographic conditions of the Greenland waters (Buch, 2000 a, b).

In the present paper we describe recent developments in the fishery, the atmospheric climate and ocean hydrography off the West Greenland and discuss possible relationships between climate variability and the fish stocks.

Data

The fisheries and fish stock data have been retrieved from a number of assessment documents available from the Northwest Atlantic Fisheries Organization (NAFO; www.nafo.int), the International Council for the Exploration of the Seas (ICES; MS 2000), and the Greenland Institute of Natural Resources.

The Greenland Fisheries Research Institute (GFRI), since it was founded in 1947, has tried to occupy all the

NAFO (formerly, the International Commission for North Atlantic Fisheries (ICNAF)) standard sections (Fig.1) along the west coast of Greenland at least once per year and the Fylla Bank section several times per year. All sections north of the Fylla Bank section have generally been covered twice a year (June–July and November) while the southernmost sections have been occupied only once (March–April). In 1990, the oceanographic activity was reduced due to reorganisation of the GFRI, resulting in the standard sections being cancelled in 1991. From 1992 to 1997, one annual survey to the NAFO standard sections was performed by the Royal Danish Administration of Navigation and Hydrography on contract to the Greenland Fisheries Research Institute, and since 1998 the Danish Meteorological Institute (DMI) has undertaken this task. In addition, oceanographic observations have been carried out during the fish trawl surveys.

The DMI has obtained meteorological observations in Greenland since 1873 and, for almost the same period, has collected information on the distribution of sea ice in Greenland waters.

Atmospheric sea level pressures from Ponta Delgada, in the Azores, and Reykjavik, Iceland, were obtained from the Climate Research Unit (www.cru.uea.ac.uk/cru/data/nao.htm) and updated to 2002. For a description of these data see Jones *et al.* (1997) and Jones (1984).

Biological Variability

A rich Atlantic cod (*Gadus morhua*) fishery started off West Greenland in the 1920s after a general warming of the Northern Hemisphere (Jensen, 1939; Dickson *et al.*, 1994; Buch *et al.*, 1994; Horsted, 2000). The West Greenland cod fishery peaked in the 1960s at annual catches between 400 000 and 500 000 tons. During the late 1960s, the cod catches declined drastically along with the catches of other commercially important fish species, including redfish (*Sebastes marinus* and *S. mentella*), Atlantic halibut (*Hippoglossus hippoglossus*) and wolffish (Atlantic wolffish, *Anarhichas lupus*, and spotted wolffish, *Anarhichas minor*), that were mainly taken as by-catch in the cod fishery. After 1969, catches of cod and redfish fluctuated around a much lower mean level (Fig. 2).

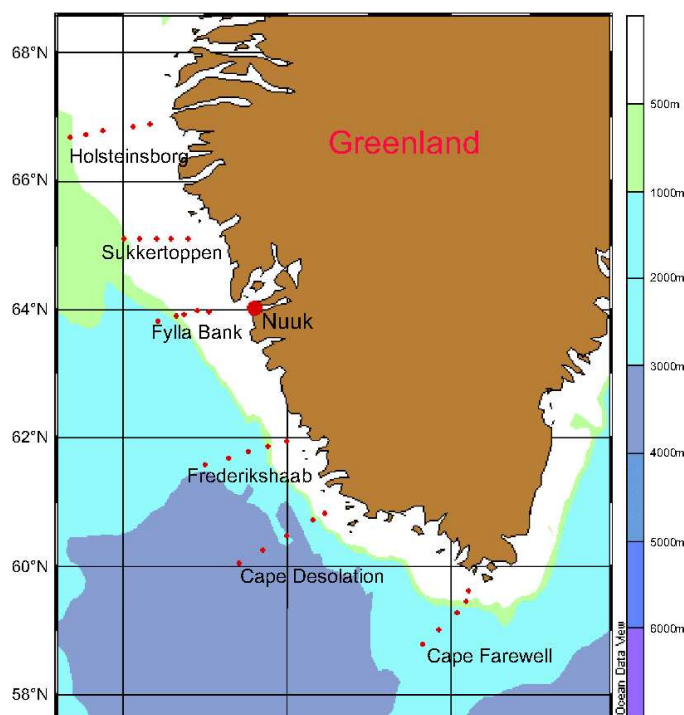


Fig. 1. NAFO standard oceanographic sections off West Greenland. Note that for each section Station 1 is closest to land.

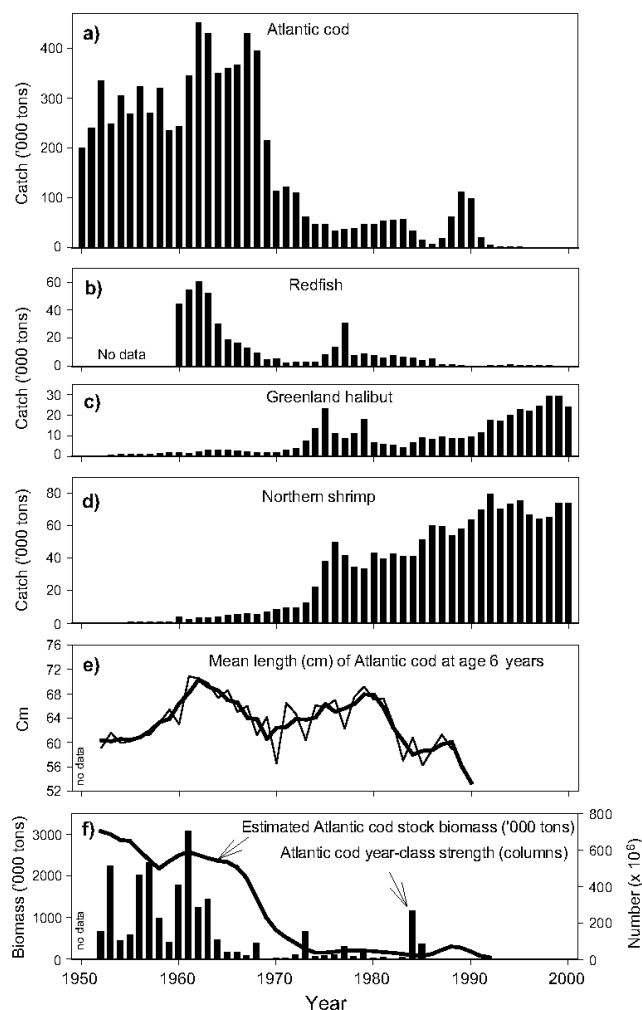


Fig. 2. (a–d) Annual catches of four important commercial fish species off West Greenland (NAFO Subarea 1, inshore and offshore combined). (e) Mean length-at-age 6 of cod (heavy line is the 3-year running mean). (f) Estimated stock biomass and year-class strength of West Greenland cod. Data from: (a–d) Horsted (2000), NAFO Scientific Council Meeting Reports and Documents for 2001; (e) Riget and Engelstoft (1998); (f) ICES (MS 1996, 2000).

Except for a temporary improvement of cod during 1988–90 due to a strong 1984 year-class recruited from Iceland, annual groundfish surveys on the West Greenland Shelf (0–400 m depth), undertaken by Germany since 1982, show a dramatic decline in overall biomass and mean individual weight of the demersal fishes (Rätz and Stransky, MS 1999).

The decline in the cod catches is believed, in large part, to be a response to climate variability. Climate is thought to have led to both the center of the cod fishery moving south during the 1980s and the decrease in size-at-age (Hovgård and Buch, 1990; Riget and Engelstoft, 1998; Rätz *et al.*, 1999; Horsted, 2000). At the same time catches of two other commercially important species,

northern shrimp (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*) increased (Fig. 2). In recent years a new fishery for snow crab (*Chionoectes opilio*) shows a steep increasing trend from a few hundred tons in 1994 to 15000 tons in 2001.

During the last two decades, northern shrimp has been the most important fishery resource in Greenland by far. Export of shrimp to Japan, has provided a high-value economic alternative to cod, and by 1995 comprised 73% of Greenland's total exports. The shrimp stock off West Greenland is distributed in NAFO Div. 0A and Subarea 1 (see Fig. 3). There is no evidence of distinct sub-populations and the entire shrimp stock is assessed as a single population. The Greenland fishery exploits the stock in Subarea 1 (Div. 1A to 1F) in offshore and inshore areas (primarily Disko Bay) (Fig. 3). Overall shrimp catches increased until 1992, varied at lower levels from 1993 to 1997 and increased thereafter (see Fig. 2).

From 1975 to 1984 the annual effort in the shrimp fishery showed a slightly increasing trend from about 75 000 hr to about 93 000 hr of fishing. In subsequent years the offshore fleet increased and effort rose to 250 000 hr in 1991–92 (Fig. 4). Thereafter effort decreased as a result of management measures, reduced activity in Div. 0A and a higher fishing efficiency of the participating vessels.

The catch-per-unit-effort (CPUE) for the West Greenland shrimp fishery can be used as a stock biomass index (Fig. 4). The spike in 1987 is likely the result of some very strong year-classes produced in the early 1980s. From 1990 to 2000 the CPUE index has shown an increasing trend suggesting an increasing shrimp stock biomass (Fig. 4).

The GFRI has conducted annual stratified-random shrimp trawl surveys since 1988 in the main West Greenland shrimp distribution area (Carlsson and Kannevorff, MS 2000). For the period 1988–97, biomass indices of the fishable shrimp stock in the offshore areas were stable at a level of about 250 000 tons (Fig. 5a). From 1998 the biomass indices show a significant increase to a record high biomass estimate in 2000 of 350 000 tons.

A change in geographical distribution of the commercial fishing effort for shrimp has been observed since the late 1980s (Hvingel, MS 2000). Initially, Div. 1A and 1B contained the most important fishing grounds, but from the late 1980s the fishery has gradually moved southward as indicated by the mean latitude of effort allocation (Fig. 5b). At the same time, the highest shrimp catches in the annual shrimp survey showed a movement

towards shallower depths (Fig. 5c). The change in shrimp catch distributions both geographically and in depth observed during the survey period may indicate stock migration towards preferable temperature habitat due to the lower temperatures in the late-1980s and early-1990s (described in a later section). However, from 1995 to 1999, the average bottom temperature during the shrimp survey (July–August) showed a clear increasing trend (Fig. 5d) and this has not yet resulted in a movement of the center of the main fishing effort northward again (Fig. 5b).

During the 1990s there was a slight increase in catches of striped pink shrimp (*Pandalus montagui*) in local commercial fishing areas and during the annual shrimp survey (Fig. 5e). This shrimp species is well adapted to cold conditions and the increased catches may indicate a positive biological effect on this species of the cold sea climate from the late 1980s to the mid-1990s. The peaks in the abundance indices from the shrimp survey in 1995 and 1998 are unexplained (Kannevorff, MS 2000), but a lag between increased larval production and recruitment to the catchable stock should be expected.

From 1950 to 1984, GFRI annually collected zooplankton samples from West Greenland waters. The zooplankton displacement volume and most of the zooplankton taxa showed higher abundance indices in the generally warmer period 1950–68 compared to the colder period 1969–84 (Pedersen and Smidt, 2000). However, abundance indices of sandeel larvae were negatively correlated with sea temperature. Historical sandeel and shrimp larvae abundance indices (1950–84, in Pedersen and Rice, 2002), updated with abundance indices from zooplankton samples collected in 1996, 1999 and 2000, showed similar trends (Fig. 6) and are positively correlated ($r = 0.48$, $p < 0.05$, $n = 23$; Spearman rank correlation).

Climate Variability

Over the last fifty years of the 20th century, the West Greenland area has experienced some rather dramatic fluctuations in climate, which have influenced the living conditions for all species on land, as well as in the ocean. These fluctuations may therefore be regarded as one of the reasons for the observed variability in the various fish stocks described in the previous section.

Atmospheric conditions

Over the past decade, several papers have dealt with the importance of the North Atlantic Oscillation (NAO) Index on the climate in the North Atlantic region (Dickson *et al.*, 2000; Blindheim *et al.*, 2000; Dickson *et al.*, 1996;

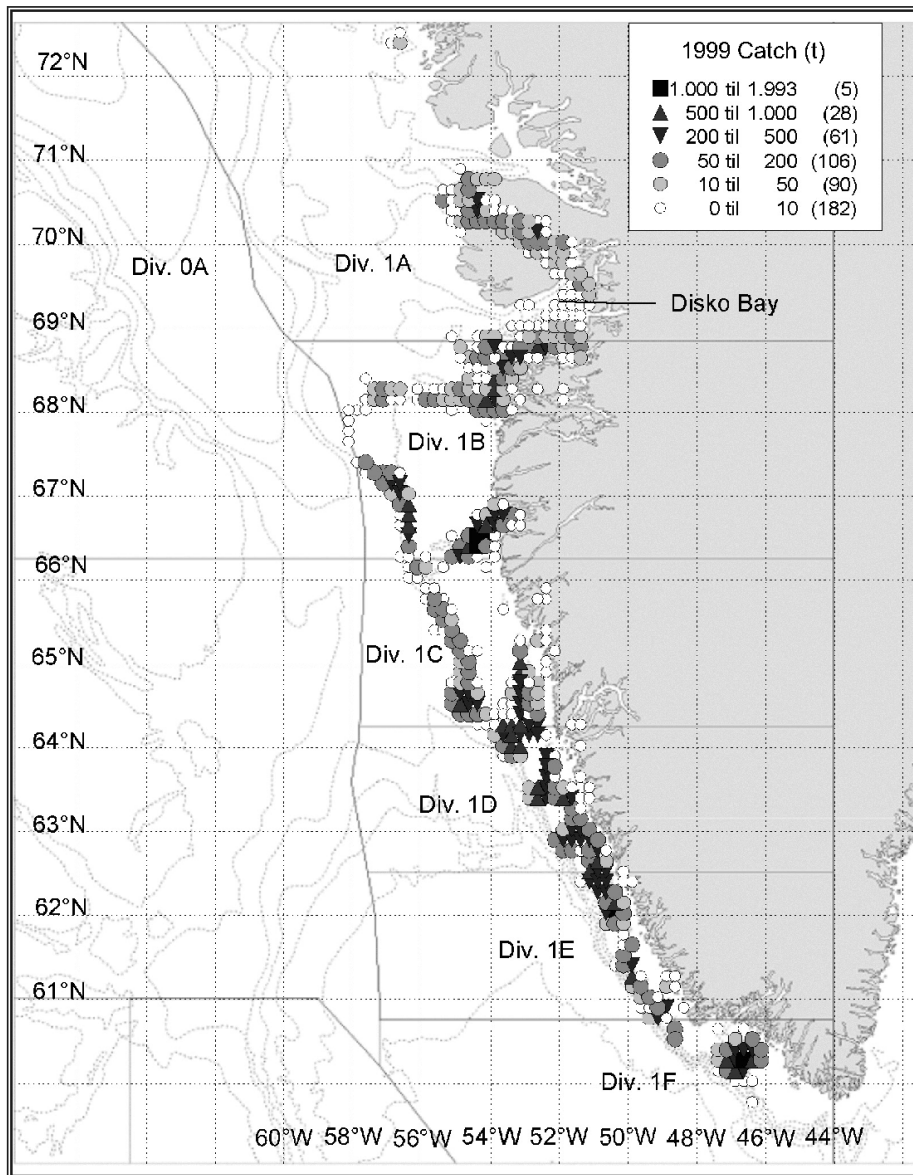


Fig. 3. Spatial distribution of the Greenland commercial shrimp catches in NAFO Subarea 1 (Div. A–F) in 1999 from Hvingel (2000).

Seager *et al.*, 2002) and thereby also in the West Greenland area (Buch, 2000b). 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). Because the signature of the NAO is strongly regional,

a simple index of NAO was defined as the difference between the normalised SLP anomalies at the Azores and Iceland (detailed discussion about the historical literature can be found in van Loon and Rogers, 1978). In order to extend the NAO index back in time, measurements from Lisbon or Gibraltar are commonly used instead of the Azores (e.g. Hurrell, 1995 and Jones *et al.*, 1997).

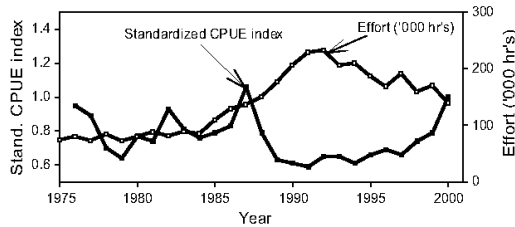


Fig. 4. Effort and standardized CPUE index of the West Greenland shrimp fishery, 1975–2000. Data from Siegstad (2000).

Although the NAO signal 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 (references in Hurrell, 1995). We use wintertime (December–March) SLP difference between Ponta Delgada, Azores, and Reykjavik, Iceland, and subtract the mean SLP difference for the period 1961–90 to construct the NAO anomaly.

The variability of the NAO index since 1865 is shown in Fig. 7, 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 mid-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 for many winters, (van Loon and Rogers, 1978, Barnett 1985, Hurrell and van Loon, 1997). Over the region of the Icelandic Low, the seasonal pressures were anomalously low during winter from the turn of the century until about 1930 (with exception of the 1916–19 winters), while pressures were higher than average at lower latitudes. Consequently, the wind over 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 into the extreme low NAO of the sixties 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 occurred after the early-1970s and, since the 1980s, the NAO has remained in a highly positive phase with SLP anomalies of more than 10 hPa in magnitude over both the subpolar and the subtropical Atlantic. The 1989, 1990, 1994 and 1995 winters were marked by some of the highest positive values of the NAO index recorded since 1865 (Fig. 7).

A detailed analysis by Hurrell and van Loon (1997) suggests that the temperature anomalies for the North Atlantic and surrounding land masses for the 1980–94 period are strongly related to the persistent and exceptionally strong positive phase of the NAO index (their Fig. 1a is reproduced in Fig. 8 using NCEP/NCAR reanalysis data). This clearly illustrates a strong correlation between the strength of the westerlies across the North Atlantic – (the NAO index) and the air temperatures in Greenland and Europe. It also shows that the air temperatures in Greenland and Europe are negatively correlated, a phenomenon referred to as a seesaw effect (e.g. van Loon and Rogers, 1978).

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). Note that especially offshore of West Greenland, it was significantly warmer in the 1960s than in the 1990s.

A time series of annual mean air temperatures from Nuuk, West Greenland for the period 1873–2002 is shown in Fig. 10. In addition to the interannual variability, it reflects the general picture of variability outlined above in the description of the NAO index (Fig. 7), i.e. high NAO conditions are normally reflected in cold conditions in Greenland (Fig. 9). The late-1990s 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, 2001, 2002).

A detailed analysis using 6 hr winds from a number of observation sites in Greenland show that the changes in the wind pattern in the Greenland area are generally minor, in large part because of the dominating influence by the local orography.

Hydrographic conditions

The waters off West Greenland are dominated by water masses advected into the region from outside (Buch, 2000a,b):

- In the surface layer close to the coast, cold and low saline Polar Water originates from the East Greenland Current.
- Water below and to the west of the Polar Water derives from the North Atlantic Current.

The changes in the atmospheric conditions caused by the shift from low NAO to high NAO conditions affect the ocean circulation and ocean conditions in the North Atlantic (Dickson *et al.*, 1996, Dickson *et al.*, 2000). The

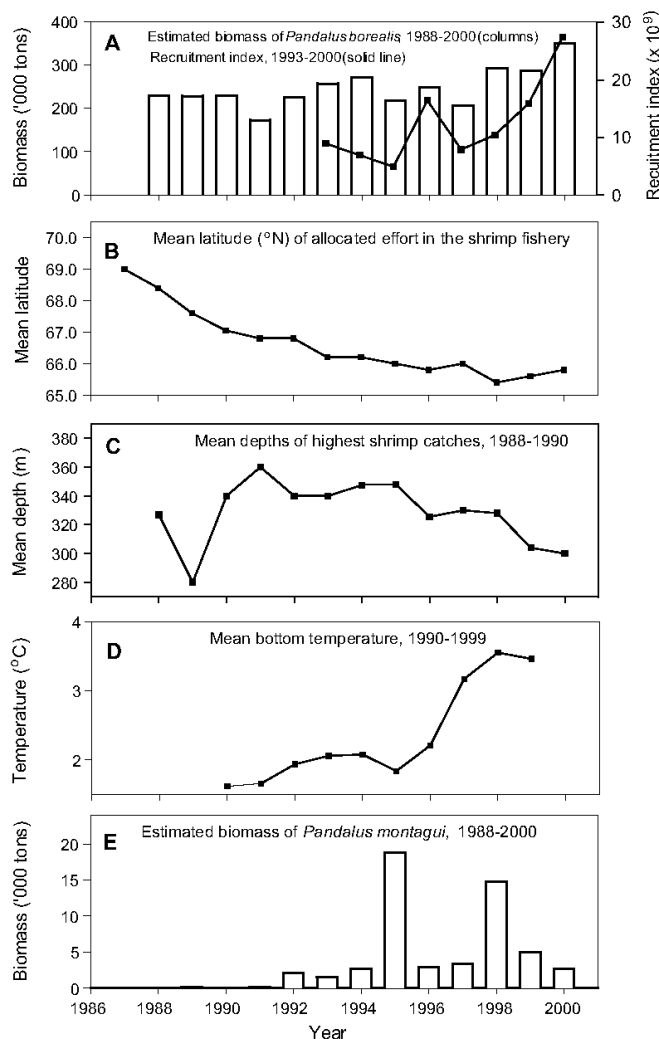


Fig. 5. (a) Northern shrimp biomass indices from the annual shrimp survey and (b) the mean latitude of the effort in the commercial fishery. (c) Mean depths of highest shrimp catches and (d) mean bottom temperature during the survey. (e) The annual biomass indices of *Pandalus montagui* during the survey. Data from (a–b) Siegstad (MS 2000); (c) Carlsson and Kanneworff (MS 2000); (d) Carlsson and Kanneworff (MS1999); (e) Kanneworff (MS 2000).

oceanographic conditions off West Greenland are also directly and indirectly affected by climate variability related to the changes in NAO.

The most well-known oceanographic time series from West Greenland is the mid-June mean temperature on top of Fylla Bank (Station 2, 0–40 m; Fig. 11), which

the GFRI has maintained due to its importance to the cod stock assessment. These temperatures can 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 3-year running means naturally smooth out the high-frequency variations and better reflect the large-scale climatic variability.

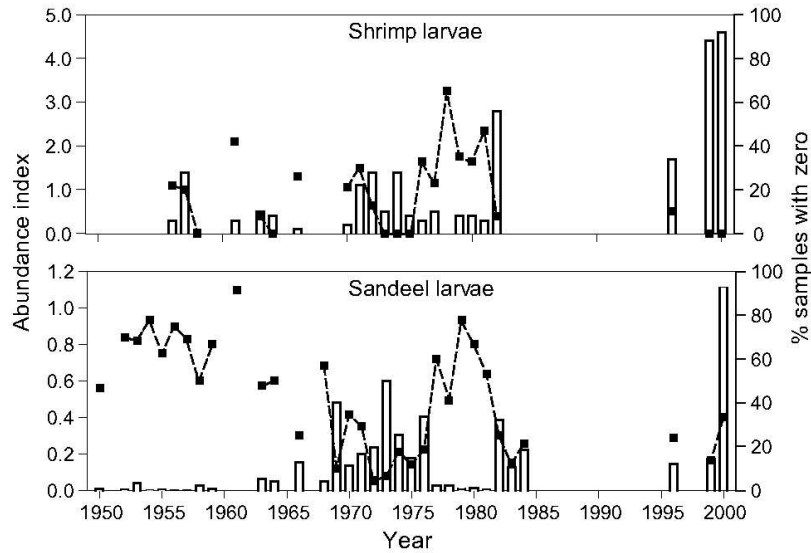


Fig. 6. Shrimp and sandeel larvae abundance indices (columns) and percentage of samples with zero catch (squares), 1950–2000. Years with data are indicated by the squares.

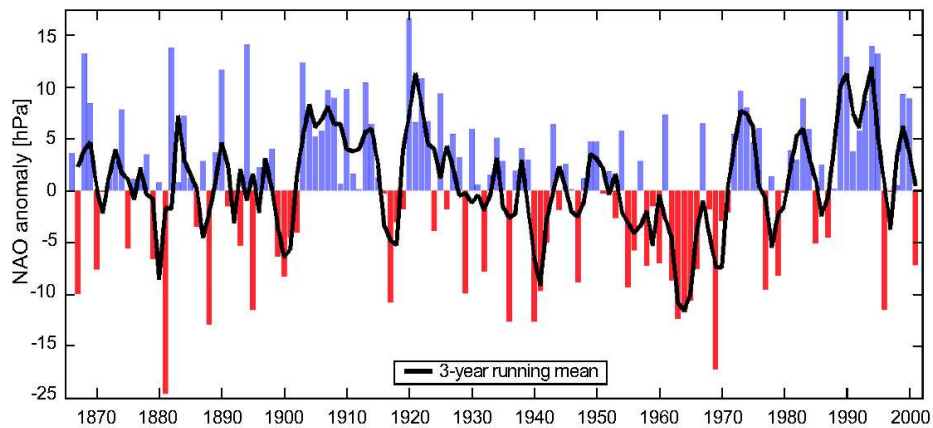


Fig. 7. Time series of the winter (December–March) index of the NAO (as defined in the text) from 1865–2002. The heavy solid line represents the meridional pressure gradient smoothed with a 3-year running mean filter (data updated from www.cru.uea.ac.uk/cru/data/nao.htm).

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

- The 1950–68 period generally showed high temperatures around 2°C.
- Around 1970 the coldest period was experienced. The cold temperatures of this period were due to an anomalous high inflow of Polar Water, which was closely linked to the "Great Salinity Anomaly"

(Dickson *et al.*, 1988, Belkin *et al.*, 1998). At the same time, the NAO index changed from negative to positive causing a shift from warm to cold atmospheric conditions off West Greenland.

- In the early 1980s and early 1990s two extremely cold periods were observed reflecting the cold atmospheric conditions associated with the high NAO indices during these years.

- Low ocean temperatures were observed in 1997 although the atmospheric conditions were quite warm. Together with low salinity measurements (Fig. 10) they suggest a high inflow of Polar Water.
- During the late-1990s, temperatures have been rather high despite high NAO values. This was due to a displacement of the NAO pattern towards the east or northeast (ICES, 2000, 2001, 2002).

Figure 12 shows the time-series of the mid-June salinity observed on top of Fylla Bank. The "Great Salinity Anomaly" around 1970 is clearly evident in this data set, as well as in the temperature data (Fig. 11). The cold ocean temperatures in the early-1980s and early-1990s are not reflected in the surface salinities at Fylla Bank supporting that these cold periods were due to atmospheric cooling. Relatively low salinities were observed in 1996 and 1997 indicating that the inflow of Polar Water was above normal in these two years and most likely contributed to the lower temperatures as well.

At greater depth, there are three water masses of Atlantic origin (Buch, 2000b):

- **Irminger Water** – temperature around 4.5°C and salinity above 34.95.
- **Irminger Mode Water** – Irminger Water mixes with surrounding water masses on its way towards southwest Greenland – temperature around 4°C and salinities between 34.85 and 34.95.
- **Northwest Atlantic Mode Water** – temperature above 2°C and salinities between 34.5 and 34.85. In late autumn, the temperature rises to above 5°C.

Time series plots of temperature and salinity from stations just west of the shelf along the Cape Farewell and Fylla Bank sections are shown in Fig. 13. Changes in the inflow of water of Atlantic origin can be seen. Before the 1970s, pure Irminger Water ($S > 34.95$) was present at the Cape Farewell Station 3 in large quantities at depths greater than 100–400 m, although the inflow appeared to

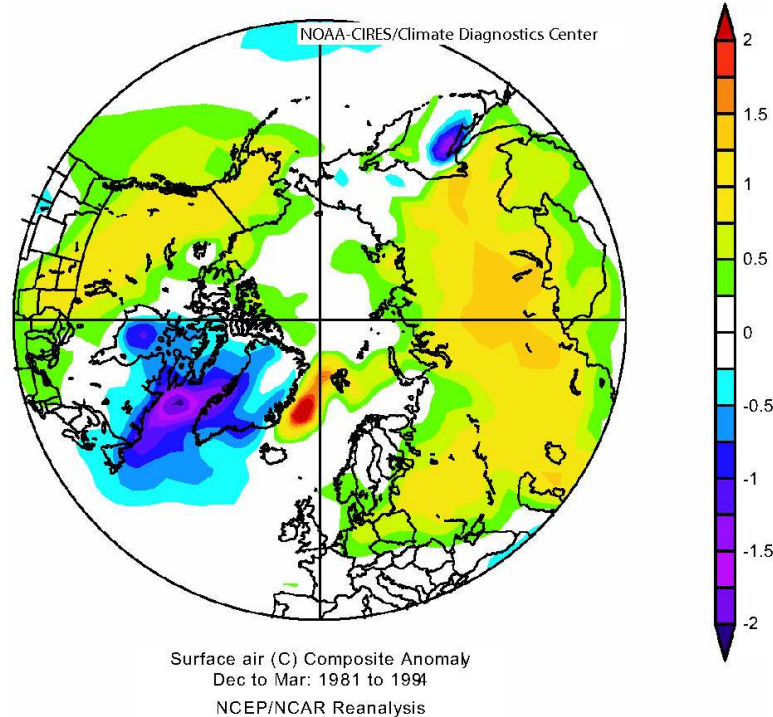


Fig. 8. Fourteen winters (December–March, 1981–94) average surface temperature anomalies relative to the period 1968–96 calculated using the NCEP/NCAR reanalysis database. (www.cdc.noaa.gov).

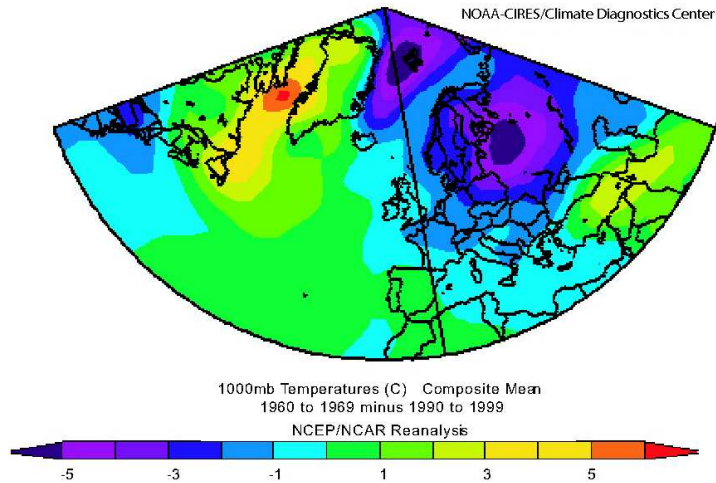


Fig. 9. Difference in air temperatures at the 1000 hPa level between 1960–69 and 1990–90 calculated using the NCEP/NCAR reanalysis database (www.cdc.noaa.gov).

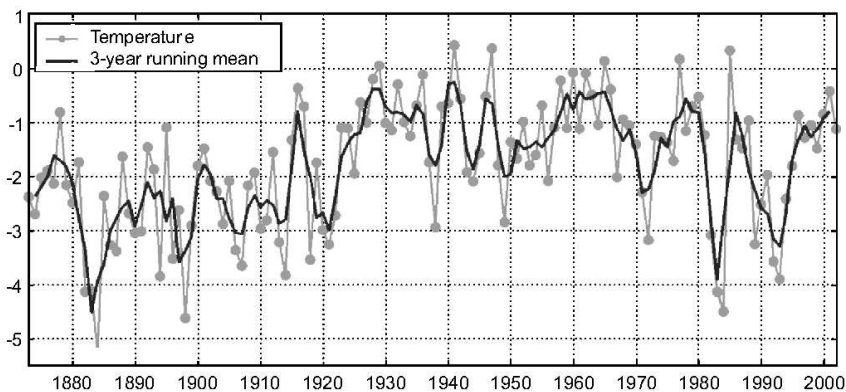


Fig. 10. Annual mean air temperatures at Nuuk, 1873–2002. The red curve represents a 3-year running mean. See Fig. 1 for location.

be gradually decreasing. The heat content was markedly greater at that time with temperatures above 4.5°C in most of the upper 600 m of the water column, with the upper 200 m having temperatures above 5.5°C . The dominant water mass between 1970–95 seems to be the Irminger Mode Water; however, note that no data were available from the mid-1970s to the early-1990s. From 1995, Irminger Water is again observed but in smaller quantities than prior to 1970. The apparent increased activity in the circulation of Irminger Water after 1995 relative to previous years was also observed in the interior of the Irminger Sea (Mortensen and Valdimarsson, 1999).

At Fylla Bank Station 4, there is a similar apparent reduction in the inflow of salt and heat. The Irminger Mode Water was present in much higher quantities before the mid-1970s than after, and 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 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 was also observed in the Irminger Water component north of Iceland (Malmberg, 1985), indicating a reduction of the strength of the Irminger Current after

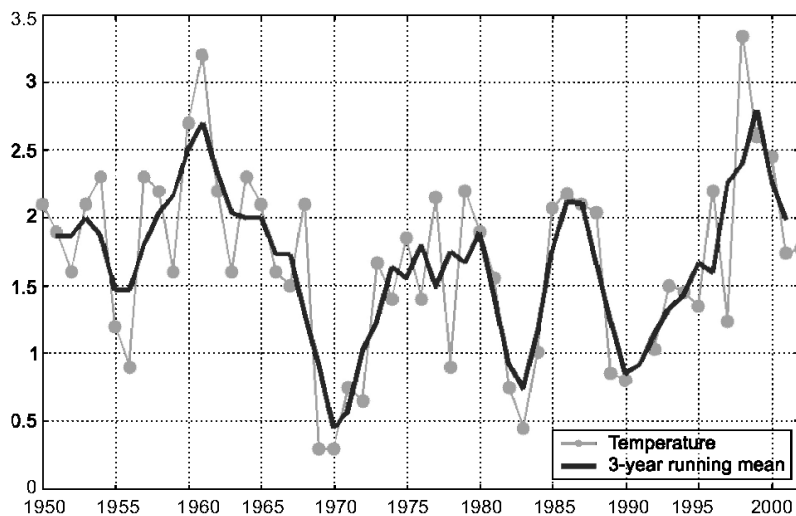


Fig. 11. Mean sea temperatures of the upper 40 m on Fylla Bank Station 2, mid-June, 1950–2002.

1965 and/or a more dominant influence of Polar Water. From the mid-1960s to the early-1970s, 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 by the increased windstress forcing of the North Atlantic Current eastward.

Ice conditions

Two main types of sea ice dominate in West Greenland waters:

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

The southwest 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 the timing can vary from year to year by several months. 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, and wind conditions in the Greenland, Iceland and the Irminger seas. Extremely large amounts of "Storis"

entered southwest Greenland waters in 1968–70, 1982, 1984, 1989, 1990 and 1993 (person's name, Greenland Ice Service, pers. comm.).

The formation of "Westice" starts in northern Baffin Bay in September and in the succeeding months it spreads along the northwest Greenland coast. In most years the ice limit reaches Aasiat (southern entrance to Disko Bay) in December or January. The waters of southwest 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, 2000a).

The presence of extremely cold air masses over the Davis Strait in 1983–84 and 1989–94 (Fig. 14) resulted in the formation of extraordinary large amounts of "Westice", which moved so far south it resulted in the unusual situation that the "Westice" and the "Storis" met in the vicinity of Julianehaab Bight. This occurred several times during these periods.

Discussion

The shift in community structure and landing composition of fish in Greenland during the second half of the 20th century coincides in time with the large climatic changes observed in the Greenland area. It is therefore believed that the observed changes in recruitment patterns are largely driven by changes in ocean climate. In terms of mechanisms linking oceanographic factors to recruitment

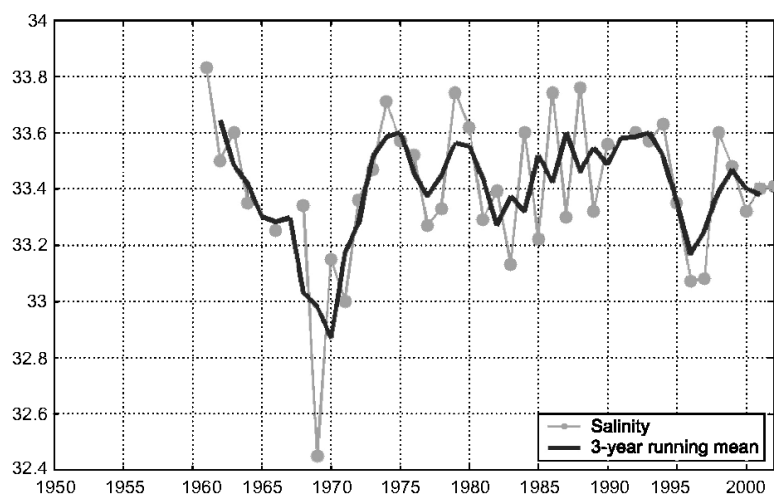


Fig. 12. Mean salinity of the upper 40 m on Fylla Bank Station 2, mid-June, 1961–2002.

of fish and shellfish in West Greenland, sea temperature, drift of larvae by surface currents, and stability of the water masses (oceanographic fronts) have been proposed (Pedersen and Rice, 2002). Variability in these factors is related in turn to the inflow of water from other parts of the North Atlantic, which is strongly related to NAO variations. The individual strengths of the East Greenland Current and the Irminger Current have a dominating effect on the physical environment of the shelf areas around southern Greenland.

Based on changes in hydrographic observations, the ocean transport of salt and heat towards West Greenland appears to have decreased drastically after 1970. This occurred at the same time as the reduced heat flux into the ocean from the atmosphere. These climate changes seem to have had a negative effect on the recruitment success of the West Greenland cod stock, and a number of other boreal fish stocks, and a positive effect on the production of northern shrimp and Greenland halibut.

The drastic reduction (almost disappearance) in the West Greenland cod fishery is believed to have two causes:

- **Reduction in the West Greenland spawning stock.** The number of cod recruited at age 3 years have been documented to be significantly correlated with the spawning stock biomass and June water temperature on top of Fylla Bank (Hansen and Buch, 1986; Hovgård and Buch, 1990). Both factors positively affected the number of offspring and explained 51% of the observed variation in recruitment (Rätz *et al.*, 1999).

- **Reduced inflow of cod larvae from Icelandic spawning grounds.** The inflow of cod larvae occurred almost every year in the 1950s and early-1960s, (Fig. 2 in Hansen and Buch, 1986) but since then has been negligible except for the 1973 and 1984 year-classes.

Changes in the thermal regime can have a considerable impact on the abundance of groundfish and pandalid shrimps (Anderson 2000; Koeller, 2000; Stein, 2000). In the summer of 1982, cod larvae were abundant in West Greenland, but the following extremely cold winter was assumed to lead to a dramatic reduction in this year-class (Pedersen and Smidt, 2000).

Northern shrimp prefer relatively cold temperatures in the range of 1–6°C and their larvae are less vulnerable to low temperatures compared to cod (Shumway *et al.*, 1985). This may partly explain the positive reaction of the West Greenland shrimp stock to the changed climatic conditions. However, the shift in the underlying marine ecosystem at West Greenland may have been amplified by the declining cod stock due to a release in predation pressure on e.g. sandeel and northern shrimp (Koeller, 2000; Lilly *et al.*, 2000). Additionally, by-catches in the steady growing fishery for northern shrimp during the last part of the 20th century may have played a role in reducing and keeping the mean trophic level low (Kingsley *et al.* MS 1999; Pauly *et al.*, 2001).

The observed increase in the shrimp biomass during recent years is related to both increasing growth (decrease in mean length at sex change) and recruitment (Carlsson

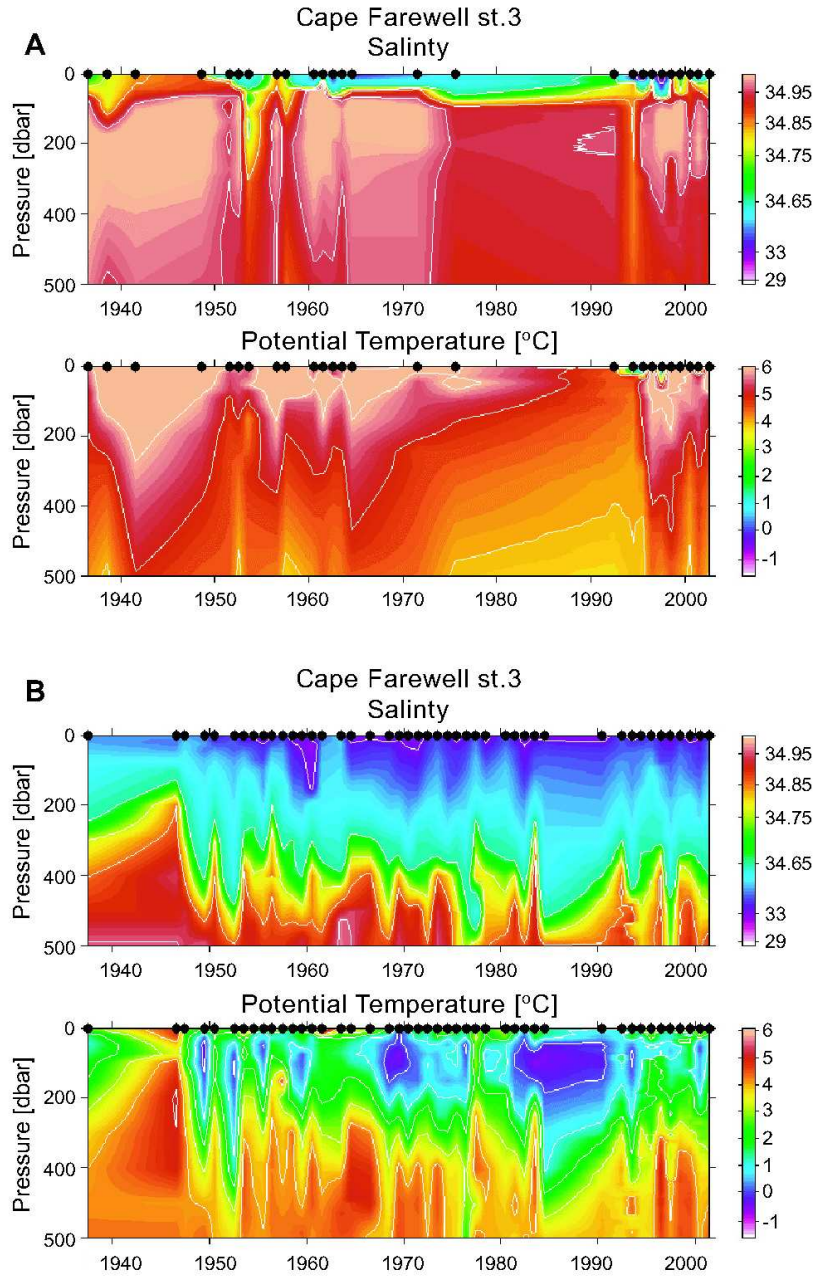


Fig 13. Time series of summer (June and July) salinity and temperature at (a) Cape Farewell Station 3 and (b) Fylla Bank Station 4 (see Fig. 1 for locations).

and Kannevorff, MS 1999; Siegstad, 2000). The shrimp recruitment indices (number of juvenile shrimp) show a steep increasing trend from 1997 to 2000, which is a good

prospect for the shrimp fishery (Fig. 5a). This positive development is believed to be related to the favourable temperature conditions observed off West Greenland

during this period, especially the increased inflow of warm Irminger Water (Fig. 14) to the area.

The relative cold period from the late-1980s to 1995, when temperatures decreased below the temperature preference of shrimp (3–4°C), seemed to have resulted in a southern migration of the shrimp stock and the fishery. The warming trend from 1995 to 2000 towards preferred temperatures seems to have favoured growth and recruitment of northern shrimp, thereby leading to an extraordinary increase in the shrimp biomass since the late-1990s.

Extensive ice cover in cold years contributes positively to the survival of larvae and juveniles in the same year and the effect can be detected in the CPUE several years later (the mean age of shrimp in the catch is about 6 years) (Parsons and Colbourne, 2000). A recent study by Ramseier *et al.* (2000) showed that the extent of localized sedimentation of particulate organic carbon (POC) can be derived from information about ice cover. POC likely plays an important role as food supply for shrimp, and it is possible that the explanation of the functional relationship is related more to nutrient supply than temperature-related phenomena. According to Parsons and Colbourne (2000) this would help explain the apparent inconsistencies between *in situ* observations, which suggest "cold conditions" are favourable for shrimp, and laboratory studies, which indicate that larval growth and survival are enhanced at higher temperatures.

Summary

- The Greenland economy, which was formerly highly dependent on a rich cod fishery, is today almost entirely dependent on the Greenland shrimp stock.
- The Greenland climate since 1970 has been considerably colder than during the 1920–70 period, which can be related to a shift in the NAO index from negative to positive values.
- The redistribution of the atmospheric pressure fields has altered the surface currents of the North Atlantic, resulting in the reduction of the inflow of heat, salt and cod larvae to the West Greenland area.
- While there are good correlations between the climate changes and the observed shift in the marine ecosystem off West Greenland, scientific investigations to understand the ecological, chemical and physical processes behind the changes in the marine ecosystem are required.
- The increase in the West Greenland shrimp stock biomass is most likely not solely attributable to the changes in climate. The near disappearance of the cod stock will have reduced shrimp predation by this species. Also by-catches in the shrimp fishery would contribute to keeping the predation pressure low.
- The close relationship between climate variability and the marine ecosystem off West Greenland strongly support the incorporation of effects of environmental fluctuations in prediction models for fish stock recruitment and the assessment of the fisheries resources. This will, however, require increased research in process studies that seek to understand the processes linking fisheries recruitment to environmental factors. Such efforts must include the development of coupled ocean and ecological models, not only to increase our understanding but also to make realistic forecasts of the ecosystem changes for use in

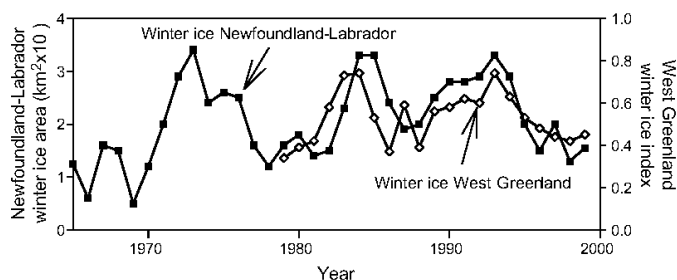


Fig. 14. Area of winter (January–March) ice cover (km²) off Newfoundland-Labrador, 1963–99 from Drinkwater *et al.* (MS 2000) and area index of winter (January–February) ice cover "Westice" off West Greenland (62°N–70°N) from Leif Toudal Pedersen, Danish Technical University.

fisheries assessment work. Models of ecosystem developments under changing climatic conditions should be considered in fishery assessments in the future and they should lead to better planning for the Greenland society.

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Appendix B

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