On the coupling between Climate, Hydrography and Recruitment variability of Fishery Resources off West Greenland

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Abstract

A review of the past 50 years of climatic conditions off West Greenland is given. We find large variability in the atmospheric and oceanographic conditions as well as in the fish stocks. A positive relationship is found between the hydrographic conditions expressed by the water temperature and the fish recruitment of cod and redfish whereas the recruitment of shrimp and halibut seems to react positively to lower temperatures. Observed shifts in the hydrographic conditions during the second half of the 1990s indicate that a change in the fish stock environment may be expected in the coming years. Relationships between the past variations in fisheries resources, hydrographic conditions, and the large-scale climatic conditions, expressed by the North Atlantic Oscillation (NAO), strongly supports the incorporation of environmental variability in prediction models for fish stock recruitment and thereby in the assessment of the fisheries resources.

Keywords: biomass, climate, cod, shrimp, fishery, Greenland, salinity, temperature, variability

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1. Introduction

In the 20th century Greenland experienced two great transitions, from seal hunting to cod fishery, then from cod to shrimp fishery, both affecting the human population centres of West Greenland and the economy (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 the temperate water masses of the Atlantic Ocean. They are important fishing grounds and are characterised by relatively few dominant species, which interact strongly (Pedersen and Kanneworff, 1995; Rätz, 1999; Pedersen and Zeller, 2001). Ocean currents that transport water from the polar and temperate regions affect the marine productivity in the Greenland shelf areas, and changes in the North Atlantic circulation system therefore have major impacts on the distribution of species and fisheries yield (Pedersen and Smidt, 2000; Pedersen and Rice, 2001).

Greenland climate has undergone some drastic changes throughout the 20th century. The period 1920-1970 was generally warm while the subsequent 30 years have been dominated by three extreme cold periods around 1970, the early 1980’s and the early 1990’s. These atmospheric changes are also reflected in the oceanographic conditions of Greenland waters (Buch, 2000 a,b).

In the assessments of fishery resources, information on how climate changes will affect the fish species composition and future fisheries in Greenland waters will be extremely valuable.

In the present paper we describe the recent development in the West Greenland fishery, climate and hydrography using available time-series, indices of biological and climatic variability, and discuss possible relations.

2. Biological variability

A rich Atlantic cod (*Gadus morhua*) fishery started off West Greenland in the 1920s after a general warming of the Northern Hemisphere (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 as did the catches of other commercially important fish species - redfish (*Sebastes marinus and S. mentella*), Atlantic halibut (*Hippoglossus hippoglossus*) and wolffish (Atlantic wolffish, *Anarhichas lupus*, and spotted wolffish, *A. minor*) - mainly taken as by-catch in the fishery for cod. After 1969, catches of cod and redfish fluctuated around a much lower mean than prior to the late 1960s (Fig. 1).

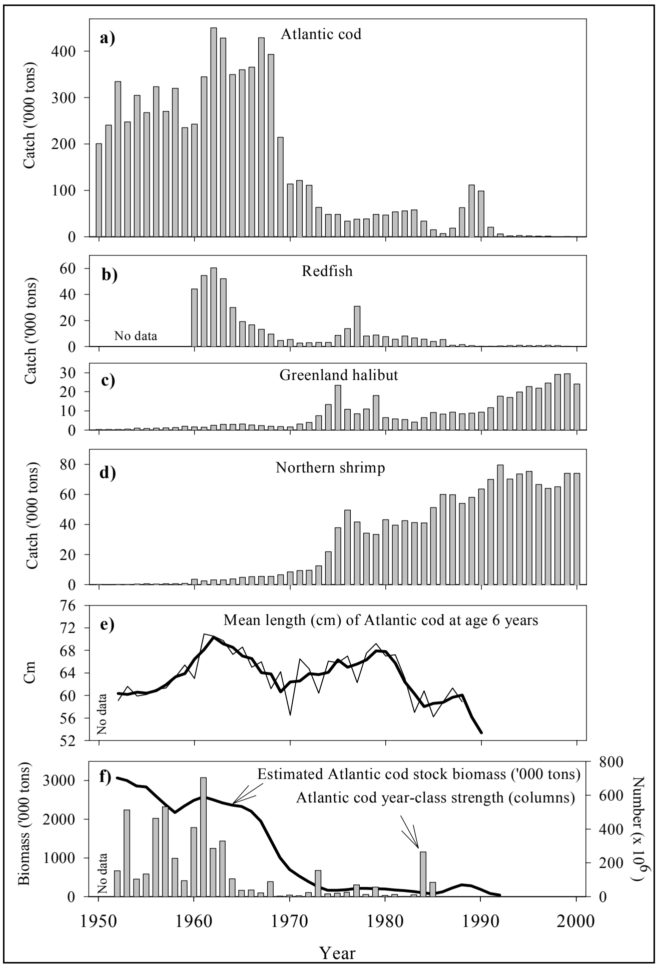

Fig. 1. (a-d) Catches of the four major commercial fish species off West Greenland (NAFO Subarea 1, inshore and offshore combined) from Horsted (2000) and NAFO Scientific Council Meeting Reports and Documents for 2001 at www.nafo.ca. (e) The mean length of age 6 West Greenland cod from Riget and Engelstoft, (1998) (where the heavy line is the 3-year running mean) and (f) their year-class strength from Anon (1996, 2000).

Except for a temporary improvement of the cod abundance during 1988-1990, due to the strong 1984 year-class recruited from Iceland, data from annual groundfish survey for cod on the West Greenland shelf (0-400 m depth) performed by Germany since 1982 show a dramatic decline in overall biomass and size (mean individual weight) of fish (Rätz, 1999).

The decline in the amount caught is not the only supposed effect of climate change on the Greenland cod. The center of the cod fishery moved south during the 1980s, and the sizes of fish at age dropped as well (Hovgård and Buch, 1990; Riget and Engelstoft, 1998; Horsted, 2000). At the same time catches of two other commercially important species northern shrimp (*Pandalus borealis*), and Greenland halibut (*Reinhardtius hippoglossoides*), increased (Fig. 1). In recent years a new fishery for snow crab (*Chionoectes opilio*) shows a steep increasing trend from a few hundred tons in 1994 to close to 5000 tons in 1999.

During the last two decades northern shrimp has by far been the most important fishery resource in Greenland. Export of shrimp to Japan has provided a high-value economic alternative to cod, comprising 73% of Greenland's total exports in 1995. The shrimp stock off West Greenland is distributed from 60 – 73°N. There is no evidence of distinct sub-populations and the entire shrimp stock is assessed as a single population. Overall shrimp catches increased until 1992, varied at slightly lower levels from 1993 to 1998 and increase thereafter (see Fig. 1).

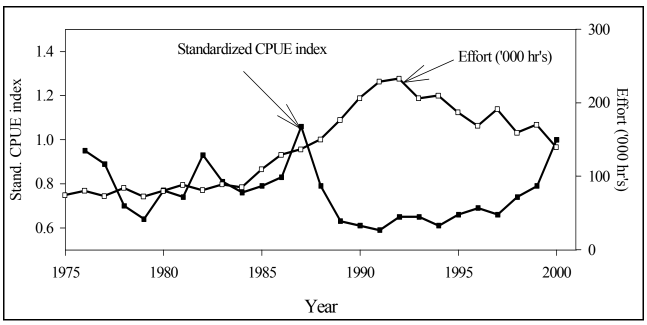

Fig. 2 Effort and standardized CPUE index of the West Greenland shrimp fishery 1975-2000 from Siegstad (2000).

From 1975 to 1984 the annual effort in the shrimp fishery showed a slightly increasing trend from about 75 000 to about 93 000 hr. In the subsequent years a considerable enlargement of the offshore fleet took place and effort went up by almost a factor of three reaching 250 000 hr in 1991-1992 (Fig 2). Thereafter effort decreased as a result of management measures and a general increased fishing efficiency of the participating vessels. The catch-per-unit-effort (CPUE) time-series for the West Greenland shrimp fishery can be used as a stock biomass index (Fig. 2). The marked spike in 1987 is likely to be the result of some very strong year classes produced in the early 1980s. From 1990 to 2000 the CPUE indices show an increasing trend indicating an increasing shrimp stock biomass.

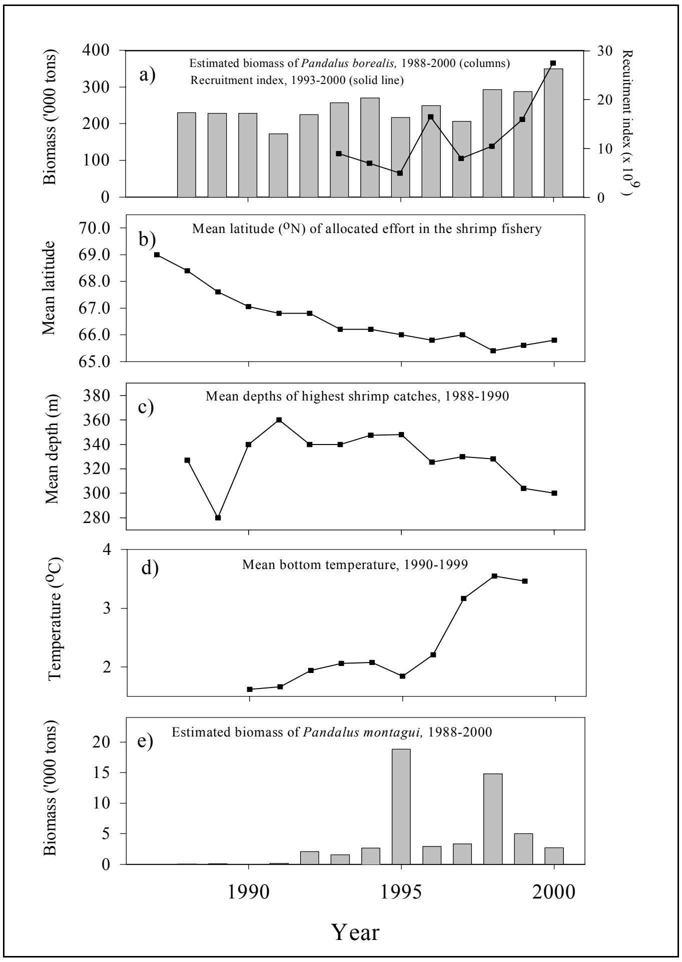

Fig. 3 (a) Northern shrimp biomass indices from the annual shrimp survey and (b) the mean latitude of the effort in the commercial fishery from Siegstad (2000). (c) Mean depths of highest shrimp catches and (d) mean bottom temperature during the survey from Carlsson and Kanneworff (2000, 1999) respectively. (e) The annual biomass indices of *Pandalus montagui* during the surveyfrom Kanneworff (2000).

The Greenland Fisheries Research Institute (GFRI) has conducted annual stratified-random shrimp trawl surveys since 1988 in the main West Greenland shrimp distribution area (Carlsson and Kanneworff, 2000). For the period 1988-1997 biomass indices of the fishable shrimp stock in the offshore areas were stable at a level of about 250 thousand tons (Fig. 3a). From 1998 the biomass indices show a significant increase to a record high biomass estimate in year 2000 of 350 thousand tons.

A change in geographical distribution of the commercial fishing effort has been observed since the late 1980's (Hvingel, 2000). Up through the 1990s the fishery has gradually moved southward as indicated by the mean latitude of effort allocation (Fig. 3b). At the same time the highest shrimp catches in the annual shrimp survey showed a trend of moving towards shallower depths (Fig. 3c). The changes in shrimp catch distributions both geographical and over depth observed during the survey period may indicate stock migrations towards preferable habitat temperatures due to changes in the ocean climate in the same period. From 1995 to 1999 the average sea bottom temperature during shrimp surveys (July-August) show a clear increasing trend (Fig. 3d). However, the increasing bottom temperature has not yet moved the mean latitude of the commercial fishery northward again (Fig. 3b).

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 3e). 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 ocean 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 (Kanneworff, 2000), but a lag between increased larval production and recruitment to the catchable stock should be expected.

From 1950 to 1984, GFRI collected annual zooplankton samples in June-July 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. Historic sandeel and shrimp larvae abundance indices (1950-1984, in Pedersen and Rice, 2001) updated with abundance indices from zooplankton samples collected in 1996, 1999 and 2000 showed similar trends and correlated positively (r=0.48, p<0.05, n=23; Spearmann rank correlation).

3. Climate variability

Oceanographic measurements have been made at least once a year by the GFRI, since its foundation in 1947, along the NAFO (earlier International Commission for North Atlantic Fisheries) standard sections off the west coast of Greenland, The Fylla Bank section was in many years occupied several times per year. Additional observations were collected at trawl sites during fisheries surveys. The Danish Meteorological Institute (DMI) has carried out meteorological observations in Greenland since 1873 and has for almost the same period collected information on the distribution of sea ice in Greenland waters.The West Greenland area has over the past fifty years 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 chapter.

Several papers have over the past decade dealt with the importance of the North Atlantic Oscillation Index (NAO-index) in forming the climate in the North Atlantic region (Dickson et al., 2000; Blindheim et al., 2000; Dickson et al., 1996) and thereby also in the West Greenland area (Buch, 2000b). 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.

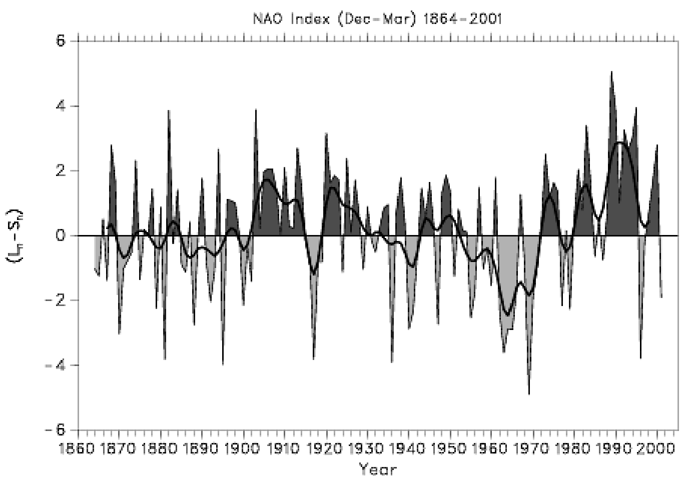

Fig.4. Time series of the winter (December - March) index of the NAO (as defined in the text) from 1864-2001. The heavy solid line represents the meridional pressure gradient smoothed with low pass filter to remove fluctuations with periods less than 4 years. (Updated from Hurrell and van Loon, 1997). (www.cru.uea.ac.uk/cru/data/nao.htm)

The variability of the NAO index since 1864 is shown in Fig. 4, 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, (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 1916-1919 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 1960s s , the NAO index exhibited a downward trend into the extreme low NAO of the 1960s and this period was marked by European wintertime temperatures that were frequently lower than normal (Moses et al., 1987). A sharp reversal has occurred over the past 30 years and, since 1970, 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 (Fig. 5). The 1983, 1989, 1990, 1994 and 1995 winters were marked by some of the highest positive values of the NAO index recorded since 1864 (Fig. 4).

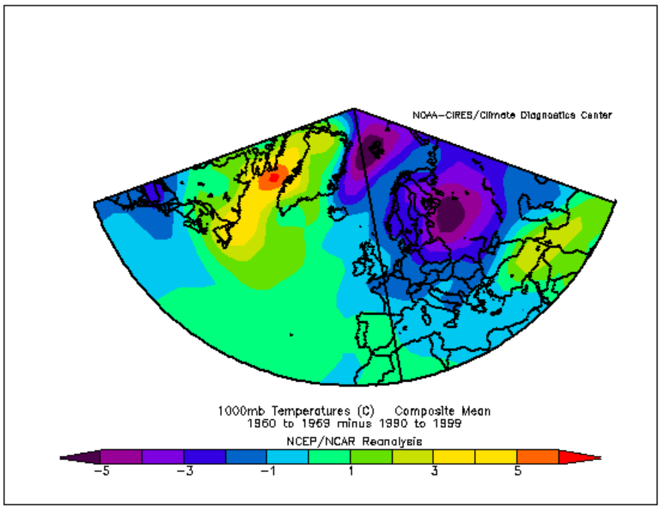

Fig. 5. Difference in air temperatures at the 1000 mb level between 1960-69 and 1990-99 , calculated using the NCEP/NCAR reanalysis database (www.cdc.noaa.gov).

A detailed analysis suggests that the recent temperature anomalies for the North Atlantic and surrounding land masses are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s (Hurrell and van Loon, 1997). This clearly illustrates a 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 (Fig . 5). Offshore West Greenland were air masses were significantly warmer in the 1960s than in the 1990s.

A detailed analysis using wind observations (6 hour intervals) from a number of observation sites in Greenland show that the changes in the wind pattern in the Greenland area are minor because of the large influence by the local orography.

The waters off West Greenland are dominated by advection of water masses (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 have affected the ocean circulation and ocean conditions in the North Atlantic (Dickson et al, 1996, Dickson et al., 2000). These in turn affect the oceanographic conditions off West Greenland. The most complete 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. 6), which the Greenland Fisheries Research Institute has carefully maintained.

The temperature can vary drastically from one year to the next, often more than 1°C, reflecting the variability of both the atmospheric forcing and the inflow of Polar Water. The curve showing the 3-year running mean values smooth the variations and better reflects the large scale climatic variability.

The 50y temperature time-series reveals some very distinct climatic events:

- The 1950 - 1968 period generally showed high temperatures around 2°C above normal.
- Around 1970 the coldest period was experienced. The cold climate of this period was 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). In the same period the NAO negative index changing to positive indices reflecting in a shift from warm to cold atmospheric conditions.
- 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.
- A remarkably low temperature was observed in 1997 although the atmospheric conditions were quite warm. Together with low salinity measurements (Fig. 7) this indicates a high inflow of Polar Water.
- During recent years 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).

Fig. 7 shows the time-series of the Mid-June salinity on top of Fylla Bank (actual observations as well as a 3y running mean). The “Great Salinity Anomaly” around 1970 is clearly reflected in this data set, while the high NAO indices in the early 1980s and 1990s do not show up in any significant way in the surface salinities at Fylla Bank, which of course was not to be expected because these cold periods were due to atmospheric cooling.

Relatively low salinities were observed in 1996 and 1997 indicating that the inflow of Polar Water were above normal in these years.

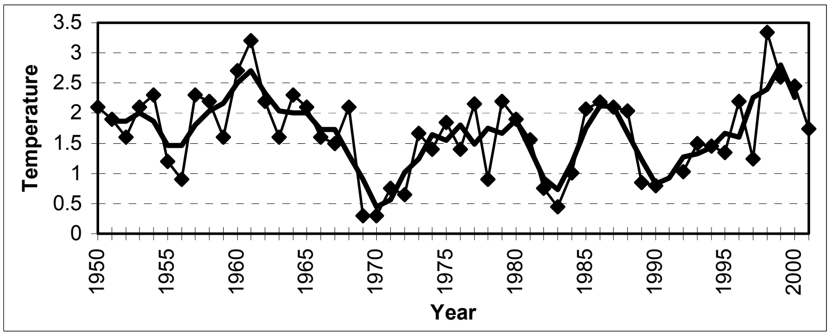

Fig. 6. Mean sea temperatures of the upper 40m on Fylla Bank St. 2, medio June, 1950 - 2001.
Dots = observations
Heavy line = 3-year running mean

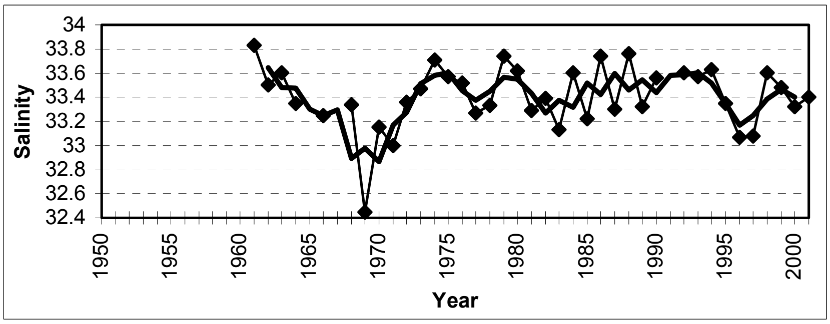

Fig. 7. Mean salinity of the upper 40m on Fylla Bank st. 2, medio June 1961 - 2001.
Dots = observations
Heavy line = 3-year running mean

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

- *Irminger Water* - temperature around 4.5°C and salinity above 34.95.
- *Irminger Mode Water* - Irminger Water mixed with surrounding water masses on it way to 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 temperatures rise to above 5°C.

Analysis of temperature and salinity data collected off West Greenland over the past 6-7 decades are given in Fig. 8 showing timeseries 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 1970s 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. Since 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).

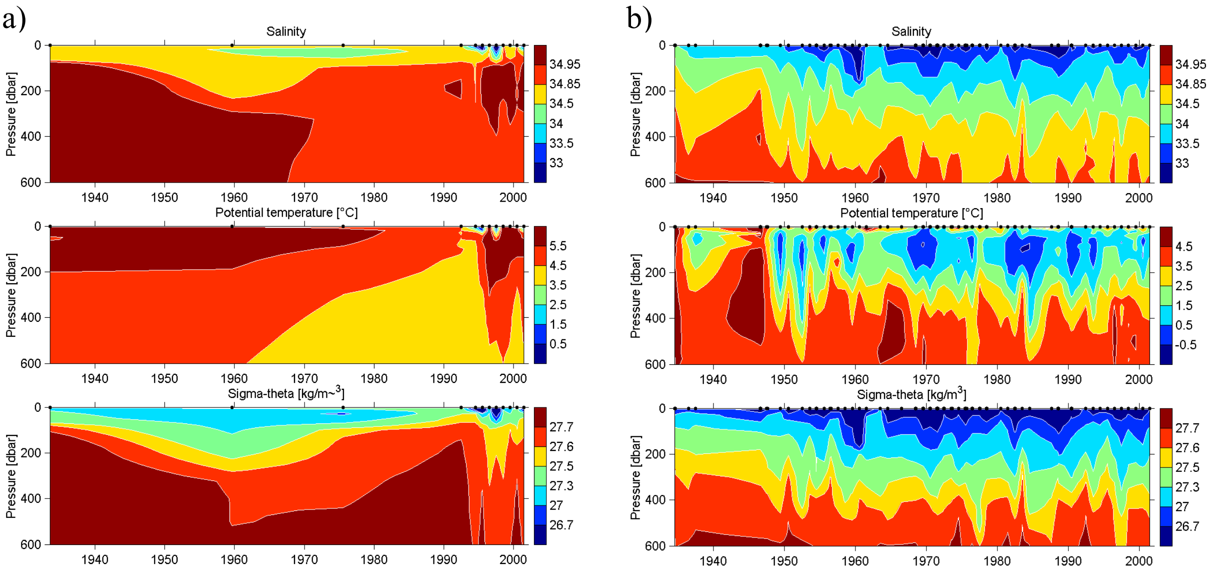

Fig. 8. Timeseries of summer (June to August) salinity, temperature and density at:

a. Cape Farewell st.3
b. Fylla Bank st.4

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 1970s than after and we notice 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 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 both directly by the increased windstress forcing the North Atlantic Current towards east and indirectly by spinning up the Irminger gyre resulting in an increasing surface Ekman transport out from the center.

4. Discussion

The shift in community structure and landing composition of fish in Greenland during the second half of the 20th century does coincide 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 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, 2001). Variability in these factors is related in turn to the inflow of water from other parts of the North Atlantic which in turn is highly related to NAO variations. The individual strengths of the East Greenland and Irminger Currents have a dominating effect on the physical environment of the shelf areas around southern Greenland.

The ocean transports of salt and heat towards West Greenland is believed to have decreased drastically after 1970, although this statement is not based on transport observations or calculation, and so did the heat exchange with the atmosphere. This seems 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 recruits at age 3 years have been documented to be significantly correlated with the spawning stock biomass and June water temperature on top of Fyllas Bank (Hansen and Buch, 1986; Hovgaard 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 was occurring almost every year in the 1950s and early 1960s, (Fig. 2 in Hansen and Buch, 1986); but have since been absent except for the 1973 and 1984 year classes.

Changes in the thermal regime can have a considerable impact on the abundance of ground fishes 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 were assumed to terminate this year-class (Pedersen and Smidt, 2000).

Northern shrimp prefer relatively cold temperatures in the range of 1-6^{o}C and especially their larvae are less vulnerable to low temperatures compared to cod (Shumway *et al*., 1985), which 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 of fish 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*., 1999; Pauly *et al*., 2001).

The observed increase in the shrimp biomass during the recent years is related to the shrimp production by increasing individual shrimp growth (decrease in mean length at sex change) and recruitment (Carlsson and Kanneworff, 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. 3a). This positive development is believed to be related to the favourable temperature conditions observed off West Greenland during this period where the increased inflow of Irminger Water (Fig. 8) has carried heat to the area.

The relative cold period during late 1980s to mid 1990s, where shrimp habitat temperatures decreased below the temperature preference (3-4^{o}C), seems to have caused a southern migration of the shrimp stock and the fishery. The warming trend from 1995 to 2000 towards the preferred habitat temperatures seems to have favoured growth and recruitment for northern shrimp, whereby an extraordinary increase in the shrimp biomass has been observed in very recent years.

Pandalid shrimps have been demonstrated to be indicator species in the cold regime community structure of the Gulf of Alaska (GOA) ecosystem (Anderson, 2000). On the Labrador Self extensive ice cover in cold years possibly contributes positively to 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 between ice cover and shrimp production 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.

5. Conclusions

From the description of the development in the West Greenland fishery and the climate variability in the area it can be concluded:

- The Greenland economy, formerly being highly dependant on a rich cod fishery, is today almost entirely dependant on the Greenland shrimp stock.
- The Greenland climate has since 1970 been considerably colder than during the 1920-1970 period, which can be related to a shift in the NAO-index from negative to positive values.
- The redistribution of the atmospheric pressure fields have altered the surface ocean currents of the North Atlantic, having had the effect that the inflow of heat, salt and cod larvae to the West Greenland area via the various current components of Atlantic origin have decreased considerably.
- There seem to be a 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 climate change. Scientific investigation to understand the ecological, chemical and physical processes behind changes in the marine ecosystem has until now almost not been performed.
- The increase in the West Greenland shrimp stock biomass can most likely not be attributed solely to the changes in climate. The almost disappearance of the cod stock has reduced the predator pressure and by-catches of the shrimp fishery contribute to keeping the predator pressure low.
- The close relationship between climate variability and the marine ecosystem off West Greenland strongly supports the incorporation of environmental variability in prediction models for fish stock recruitment and thereby in 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. These efforts must be supplemented with the development of coupled ocean and ecological models to increase our knowledge of the interacting physical and biological processes. 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.

6. Acknowledgement

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