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On the coupling between climate, hydrography, and recruitment variability of fishery resources off West Greenland

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In this article we review the past 50 years of climatic conditions off West Greenland, where there has been large variability in the atmospheric and oceanographic conditions as well as in 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 support the incorporation of environmental variability in prediction models for fish stock recruitment and thereby in the assessment of fisheries resources.

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

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Introduction

In the 20th century, Greenland experienced two great transitions, one from seal hunting to cod fishery, the other 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 characterized 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).

The climate around Greenland has undergone major changes during the 20th century. The period 1920–1970 was generally warm, while the subsequent 30 years were dominated by three extremely cold periods: around 1970, the early 1980s, and the early 1990s. These atmospheric changes are also reflected in the oceanographic conditions of Greenland waters (Buch, 2000a, b).

In 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 this article 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 relationships.

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

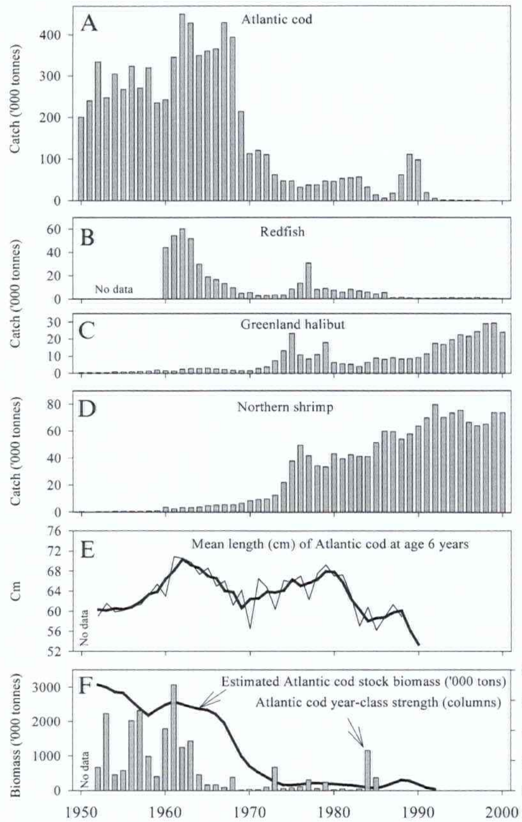

Figure 1. (A–D) Catches of the four major commercial fish species off West Greenland (NAFO Subarea 1, inshore and offshore combined) from Horsted (2000) and NAFO Scientific Council Meeting Reports and Documents for 2001 at www.nafo.ca. (E) The mean length of age 6 West Greenland cod from Riget and Engelstoft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

Greenland cod fishery peaked in the 1960s at annual catches of between 400 000 and 500 000 t. During the late 1960s, the cod catches declined dramatically, as did the catches of other commercially important fish species – redfish (*Sebastes marinus* and *S. mentella*), Atlantic halibut (*Hippoglossus hippoglossus*), and wolffish (Atlantic wolfish (*Anarhichas lupus*) and spotted wolffish (*A. minor*)) – mainly taken as bycatch in the fishery for cod. After 1969, catches of cod and redfish fluctuated around a much lower mean than prior to the late 1960s (Figure 1).

With the exception of a temporary improvement of the cod abundance during 1988–1990, due to the strong 1984 year-class recruited from Iceland, data from the annual groundfish survey for cod on the West Greenland shelf (0–400 m depth) conducted 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 centre of the cod fishery moved south during the 1980s, and the sizes of fish at age also declined (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 (Figure 1). In recent years a new fishery for snow crab (*Chionoectes opilio*) shows a steep increasing trend from a few hundred tonnes in 1994 to close to 5000 t in 1999.

During the past two decades, northern shrimp has been by far the most important fishery resource in Greenland. The 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 to 73°N. There is no evidence of distinct subpopulations 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 increased thereafter (see Figure 1).

From 1975 to 1984, the annual effort in the shrimp fishery showed a slightly increasing trend from about 75 000 to about 93 000 h. In the subsequent years a considerable enlargement of the offshore fleet took place and effort went up by a factor of almost 3, reaching 250 000 h in 1991–1992 (Figure 2). Thereafter effort decreased as a result of management measures and a general increased fishing efficiency of the participating vessels. The

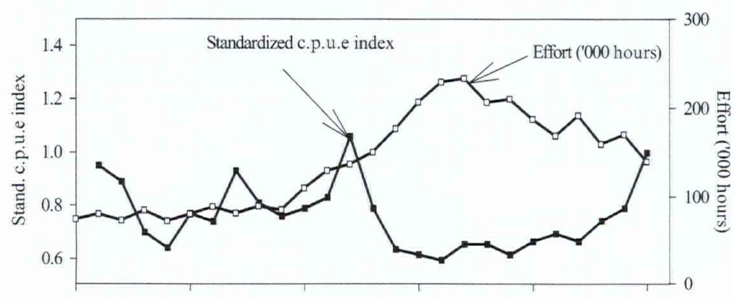

Figure 2. Effort and standardized c.p.u.e. index of the West Greenland shrimp fishery 1975–2000 from Siegstad (2000).

catch per unit effort (c.p.u.e.) time-series for the West Greenland shrimp fishery can be used as a stock biomass index (Figure 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 c.p.u.e. indices show an increasing trend indicating an increasing shrimp stock biomass.

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 250 000 t (Figure 3A). From 1998 the biomass indices show a significant increase to a record high biomass estimate in the year 2000 of 350 000 t.

A change in geographical distribution of the commercial fishing effort has been observed since the late 1980s (Hvingel, 2000). Up through the 1990s

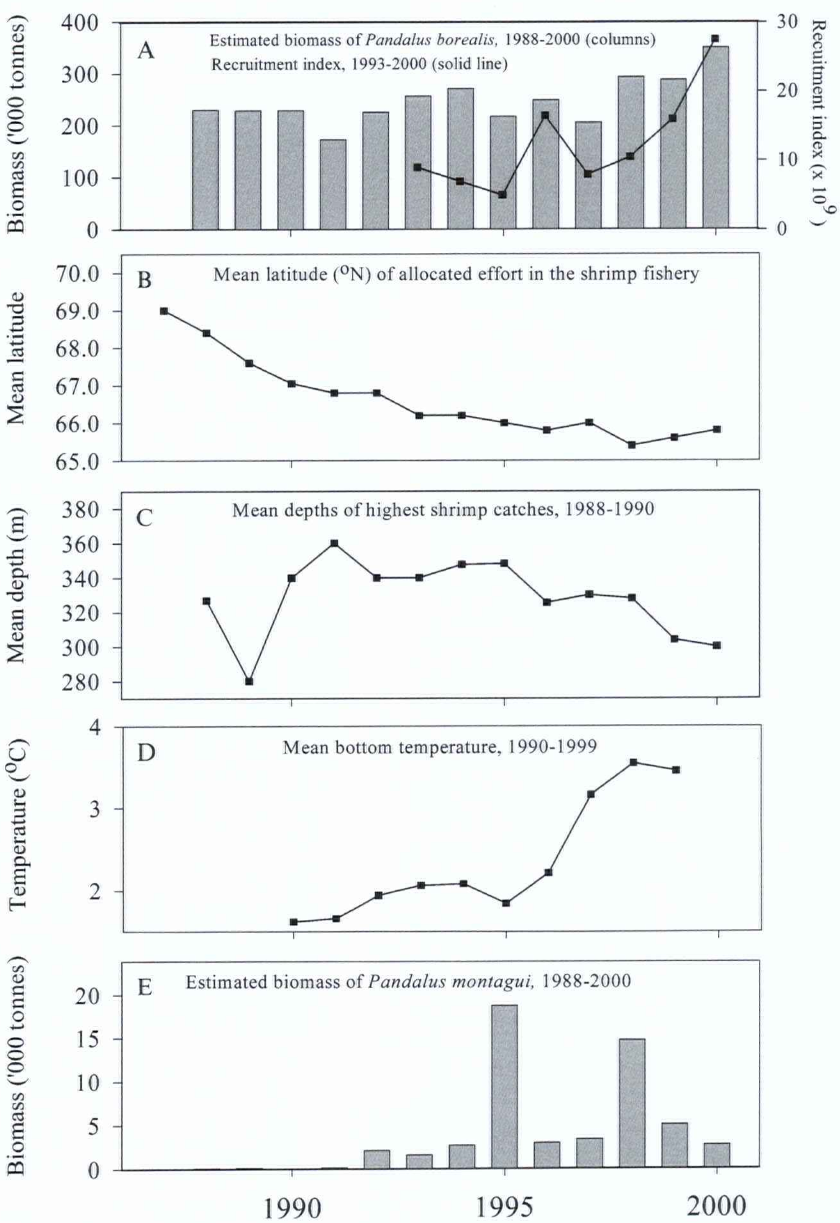

Figure 3. (A) Northern shrimp biomass indices from the annual shrimp survey and (B) the mean latitude of the effort in the commercial fishery from Siegstad (2000). (C) Mean depths of highest shrimp catches and (D) mean bottom temperature during the survey from Carlsson and Kanneworff (2000, 1999), respectively. (E) The annual biomass indices of *Pandalus montagui* during the survey from Kanneworff (2000).

the fishery has gradually moved southward, as indicated by the mean latitude of effort allocation (Figure 3B). At the same time the highest shrimp catches in the annual shrimp survey showed a trend of moving towards shallower depths (Figure 3C). The changes in shrimp catch distributions observed during the survey period, both geographical and over depth, 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 (Figure 3D). However, the increasing bottom temperature has not yet moved the mean latitude of the commercial fishery northward again (Figure 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 (Figure 3E). This shrimp species is well adapted to cold conditions and the increased catches may indicate a positive biological effect on this cold ocean climate species from the late 1980s to the mid-1990s. The peaks in 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 1950–1968 compared to the colder period 1969–1984 (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 ($r = 0.48$, $p < 0.05$, $n = 23$; Spearman rank correlation).

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 for 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 experienced some fairly dramatic fluctuations in climate over the past 50 years, which have influenced the living conditions of 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 paragraph.

Several articles over the past decade have dealt with the importance of the North Atlantic Oscillation Index (NAO index) in forming the climate in the North Atlantic region (Dickson *et al.*, 1996, 2000; Blindheim *et al.*, 2000) and thereby also in the West Greenland area (Buch, 2000b). A simple NAO index was defined by Hurrell (1995) as the difference between the normalized mean winter (December–March) SLP anomalies at Lisbon, Portugal, and Stykkisholmur, Iceland. The SLP anomalies at each station were normalized by dividing each seasonal pressure by the long-term mean (1964–1995) standard deviation.

The variability in the NAO index since 1864 is shown in Figure 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 winters from the turn of the century until about 1930 (with the

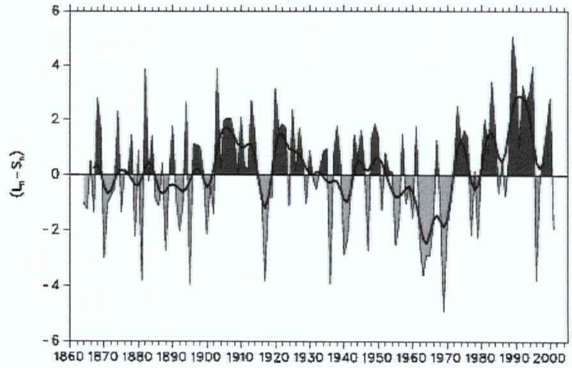

Figure 4. Time-series of the winter (December–March) index of the NAO (as defined in the text) from 1864–2001. The heavy solid line represents the meridional pressure gradient smoothed with low-pass filter to remove fluctuations with periods less than 4 years. (Updated from Hurrell and van Loon, 1997).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

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, the NAO index exhibited a downward trend into the extremely 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 (Figure 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 (Figure 4).

A detailed analysis suggests that the recent temperature anomalies of the North Atlantic and surrounding land masses have been 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 the climate in Europe are negatively correlated (Figure 5). West Greenland offshore air masses were significantly warmer in the 1960s than in the 1990s. A detailed analysis using wind observations (6-h intervals) from a number of observation sites in Greenland shows that changes in the wind pattern in the Greenland area are minor because of the large influence of the local orography.

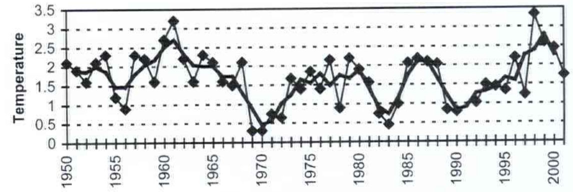

Figure 6. Mean sea temperatures of the upper 40 m on Fylla Bank Stn 2, medio June, 1950–2001. Dots = observations; heavy line = 3-year running mean.

The waters off West Greenland are dominated by the 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, 2000). These in turn have affected 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 Stn 2, 0–40 m; Figure 6), which the Greenland Fisheries Research Institute has carefully maintained.

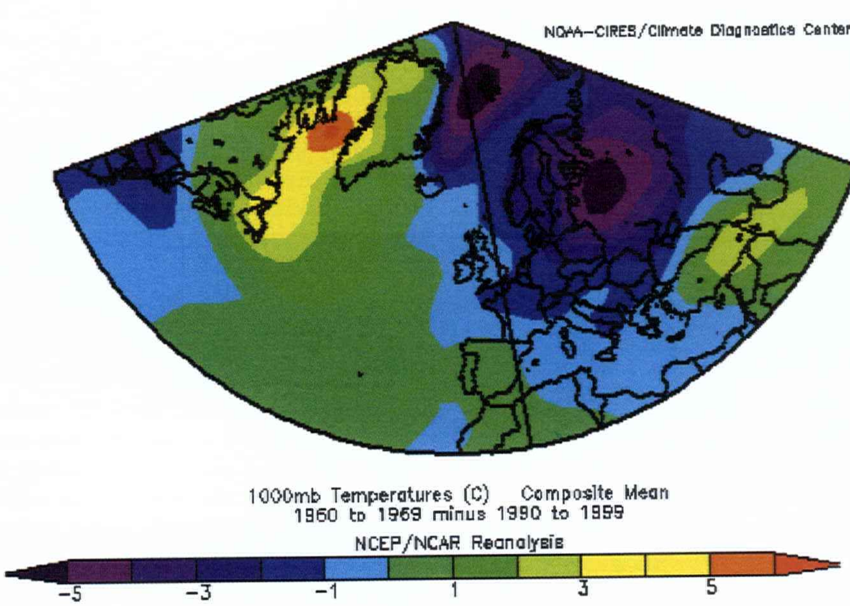

Figure 5. Difference in air temperatures at the 1000 mb level between 1960–1969 and 1990–1999, calculated using the NCEP/NCAR re-analysis database (www.cdc.noaa.gov).

The temperature can vary dramatically from one year to the next, often by 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 smoothes the variations and better reflects the large-scale climatic variability.

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

- The 1950–1968 period generally showed high temperatures around 2°C above normal.
- The coldest period was experienced around 1970. 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 reflected in a shift from warm to cold atmospheric conditions.
- 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.
- A remarkably low temperature was observed in 1997, although the atmospheric conditions were quite warm. Along with low salinity measurements (Figure 7), this indicates a high inflow of Polar Water.
- During recent years, temperatures have been fairly high despite high NAO values. This was due to a displacement of the NAO pattern towards the east or northeast (ICES, 2000a).

Figure 7 shows the time-series of the mid-June salinity on top of Fylla Bank (actual observations as well as a 3-year 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 was above normal in these years.

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

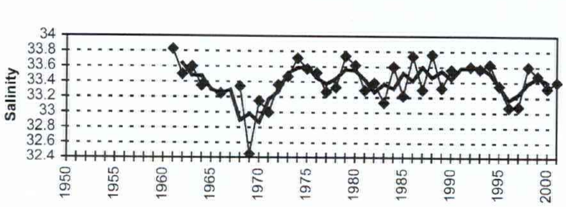

Figure 7. Mean salinity of the upper 40 m on Fylla Bank Stn 2, medio June 1961–2001. Dots = observations; heavy line = 3-year running mean.

- *Irminger Water* – temperature around 4.5°C and salinity above 34.95.
- *Irminger Mode Water* – Irminger Water mixed with surrounding water masses on its 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 six to seven decades are given in Figure 8 showing time-series 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 Stn 3 in large quantities at depths greater than 100–400 m, although the inflow was gradually decreasing. It was 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 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).

At the Fylla Bank Stn 4 we observed a similar trend in reduced inflow of salt and heat. The Irminger Mode Water was present in much higher quantities before the 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 has additionally been 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 in the strength of the Irminger Current after 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 have been 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 centre.

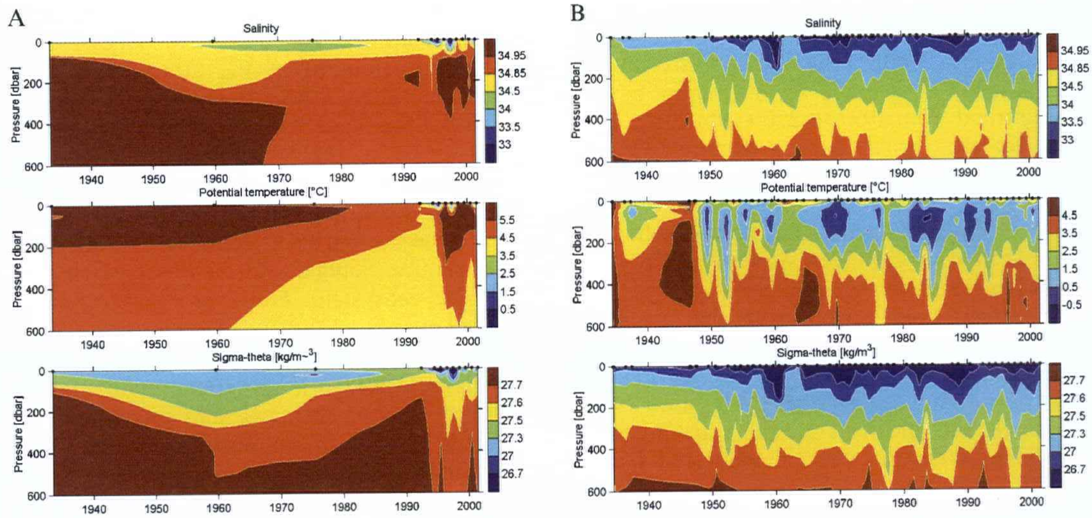

Figure 8. Time-series of summer (June to August) salinity, temperature, and density at (A) Cape Farewell Stn 3, (B) Fylla Bank Stn 4.

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 of fish and shellfish in West Greenland, sea temperature, larval drift caused by surface currents, water-mass stability (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 are believed to have decreased dramatically after 1970, as 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 massive reduction (almost disappearance) in the West Greenland cod fishery is believed to have had two causes:

- *Reduction in the West Greenland spawning stock.* The number of cod recruits at age 3 years has 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 occurred almost every year in the 1950s and early 1960s (Figure 2 in Hansen and Buch, 1986), but has 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 was assumed to have terminated this year class (Pedersen and Smidt, 2000).

Northern shrimp prefer relatively cold temperatures in the range 1–6°C, and 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 for example sandeel and northern shrimp (Koeller, 2000; Lilly *et al*, 2000). Additionally, bycatches of fish in the steadily 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 shrimp biomass during recent years is related to an increase in 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 (Figure 3A). This positive development is believed to be related to the favourable temperature conditions observed off West Greenland during this period, when the increased inflow of Irminger Water (Figure 8) has carried warm water to the area.

The relatively cold period from the late 1980s to mid-1990s, when shrimp habitat temperatures decreased below the temperature preference (3–4°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 Shelf, extensive ice cover in cold years may contribute positively to the survival of larvae and juveniles in the same year and the effect can be detected in the c.p.u.e. 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 probably plays an important role as a 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.

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 dependent on a rich cod fishery, is today almost entirely dependent on the Greenland shrimp stock.
- Since 1970, the Greenland climate has 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 has altered the surface ocean currents of the North Atlantic in that the inflow of heat, salt, and cod larvae to the West Greenland area via the various current components of Atlantic origin has decreased considerably.
- There seems to be a good correlation between the climate changes and the observed shift in the marine ecosystem. However, this correlation is based mainly on the use of ocean temperatures as a proxy for climate change. Until now there has been little scientific investigation to understand the ecological, chemical, and physical processes behind changes in the marine ecosystem.
- The increase in the West Greenland shrimp stock biomass can probably not be attributed solely to climate changes. The almost complete disappearance of the cod stock has reduced the predator pressure and bycatches 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 into prediction models for fish stock recruitment and thereby in the assessment of fisheries resources. However, this will require increased research in process studies seeking 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 Greenland society.

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References

Anderson, P. J. 2000. Pandalid shrimp as indicators of ecosystem regime shift. Journal of Northwest Atlantic Fishery Science, 27: 1–10.

Barnett, T. P. 1985. Variations in near-global sea level pressure. Journal of Atmospheric Science, 42: 478–501.

Belkin, I. M., Levitus, S., Antonov, J., and Malmberg, S. A. 1998. "Great Salinity Anomalies" in the North Atlantic. Progress in Oceanography, 41: 1–68.

Blindheim, J., Borovkov, V., Hansen, B., Malmberg, S. Aa., Turrell, B., and Østerhus, S. 2000. Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing. Deep-Sea Research I, 47: 655–680.

Buch, E. 2000a. A monograph on the physical oceanography of the Greenland waters. Danish Meteorological Institute, Scientific Report, 00-12. 405 pp. (Re-issued version of a Greenland Fisheries Research Institute report from 1990 with the same title.)

Buch, E. 2000b. Air-sea-ice conditions off southwest Greenland, 1981–97. Journal of Northwest Atlantic Fishery Science, 26: 1–14.

Buch, E., Horsted, S. Aa., and Hovgård, H. 1994. Fluctuations in the occurrence of cod in Greenland waters and their possible causes. ICES Marine Science Symposia, 198: 158–174.

Carlsson, D. M., and Kanneworff, P. 1999. Bottom temperatures and possible effect on growth and size at sex reversal of northern shrimp in West Greenland. NAFO SCR Doc. 110 (Ser. no. N4190). 6 pp.

Carlsson, D. M., and Kanneworff, P. 2000. Stratified-random trawl survey for northern shrimp (*Pandalus borealis*) in NAFO Subareas 0+1, in 2000. NAFO SCR Doc. 78 (Ser. no. N4335). 27 pp.

Dickson, R. R., Briffa, K. R., and Osborn, T. J. 1994. Cod and climate: the spatial and temporal context. ICES Marine Science Symposia, 198: 280–286.

Dickson, R. R., Lazier, J. R. N., Meincke, J., Rhines, P., and Swift, J. 1996. Long-term coordinated changes in the convective activity of the North Atlantic. Progress in Oceanography, 38: 241–295.

Dickson, R. R., Meincke, J., Malmberg, S. A., and Lee, A. J. 1988. The "Great Salinity Anomaly" in the northern North Atlantic 1968–1982. Progress in Oceanography, 20: 103–151.

Dickson, R. R., Osborn, T. J., Hurrell, J. W., Meincke, J., Blindheim, J., Adlandsvik, B., Vinje, T., Alekseev, G., and Maslowski, W. 2000. The Arctic Ocean Response to the North Atlantic Oscillation. Journal of Climate (August).

Hamilton, L., Lyster, P., and Otterstad, O. 2000. Social change, ecology and climate in 20th-century Greenland. Climatic Change, 47: 193–211.

Hansen, H., and Buch, E. 1986. Prediction of year-class strength of Atlantic cod (*Gadus morhua*) off West Greenland. NAFO Science Council Studies, 10: 7–11.

Horsted, S. A. 2000. A review of the cod fisheries at Greenland, 1910–1995. Journal of Northwest Atlantic Fishery Science, 28: 1–109.

Hovgård, H., and Buch, E. 1990. Fluctuation in the cod biomass of the West Greenland Ecosystem in relation to climate. *In* Large Marine Ecosystems: Patterns, Processes, and Yields, pp. 36–43. Ed. by K. Sherman, L. M. Alexander, and B. D. Gold. AAAS Press, Washington.

Hurrell, J. W. (1995). Decadal trends in the North Atlantic oscillation regional temperatures and precipitation. Science, 269: 676–679.

Hurrell, J. W., and van Loon, H. 1997. Decadal variations in climate associated with the North Atlantic oscillation. Climate Change, 36: 301–326.

Hvingel, C. 2000. The Greenlandic fishery for northern shrimp (*Pandalus borealis*) off West Greenland, 1970–2000. NAFO SCR Doc. 81 (Ser. no. N4338). 27 pp.

ICES. 1996. Report of the North-Western Working Group. ICES CM 1998/Assess: 15. 377 pp.

ICES. 2000a. Report of the North-Western Working Group. ICES CM 2000/Assess: 15. 328 pp.

ICES. 2000b. The 1999/2000 ICES Annual Ocean Climate Status Summary. Prepared by the Working Group on Oceanic Hydrography. Editor: Bill Turrell. (http://www.ices.dk/status/clim9900/)

Kanneworff, P. 2000. Occurrence of *Pandalus montagui* in trawl survey samples from NAFO Subarea 0+1. NAFO SCR Doc. 77 (Ser. no. N4334). 6 pp.

Kingsley, M. C. S., Kanneworff, P., and Carlsson, D. M. 1999. By-catches of fish in the West Greenland Shrimp Survey: an initial analysis. NAFO SCR Doc. 111 (Ser. no. N4191). 7 pp.

Koeller, P. A. 2000. Relative importance of abiotic and biotic factors to the management of the northern shrimp (*Pandalus borealis*) fishery on the Scotian Shelf. Journal of Northwest Atlantic Fishery Science, 27: 21–33.

Lilly, G. R., Parsons, D. G., and Kulka, D. W. 2000. Was the Increase in shrimp biomass on the Northeast Newfoundland Shelf a consequence of a release in predation pressure from cod? Journal of Northwest Atlantic Fishery Science, 27: 45–61.

Malmberg, S. A. 1985. The water masses between Iceland and Greenland. Rit Fiskideildar, 9, 127–140.

Mortensen, J., and Valdimarsson, H. 1999. Thermohaline changes in the Irminger Sea. ICES CM 1999/L: 16.

Moses, T., Kiladis, G. N., Diaz, H. F., and Barry, R. G. 1987. Characteristics and frequency reversals in mean sea level pressure in the North Atlantic sector and their relationships to long-term temperature trends. Journal of Climatology, 7: 13–30.

Parker, D. E., and Folland, C. K. 1988. The nature of climatic variability. Meteorological Magazine, 117: 201–210.

Parsons, D. G., and Colbourne, E. B. 2000. Forecasting fishery performance for northern shrimp (*Pandalus borealis*) on the Labrador Shelf (NAFO Divisions 2HJ). Journal of Northwest Atlantic Fishery Science, 27: 11–20.

Pauly, D., Palomares, M. L., Froese, R., *et al.* 2001. Fishing down Canadian aquatic food webs. Canadian Journal of Fisheries and Aquatic Sciences, 58: 51–62.

Pedersen, S. A., and Kanneworff, P. 1995. Fish on the West Greenland shrimp grounds, 1988–1992. ICES Journal of Marine Science 52: 165–182.

Pedersen, S. A., and Rice, J. 2001. Dynamics of fish larvae, zooplankton, and hydrographical characteristics in the West Greenland large marine ecosystem 1950–1984. *In* Changing States of the Large Marine Ecosystems of the North Atlantic. Ed. by K. S. Shermann, H.-R., and Skjoldal. Elsevier, Amsterdam.

Pedersen, S. A., and Smidt, E. L. B. 2000. Zooplankton distribution and abundance in West Greenland waters, 1950–1984. Journal of Northwest Atlantic Fishery Science, 26: 45–102.

Pedersen, S. A., and Zeller, D. 2001. A mass balance model for the West Greenland marine ecosystem. *In* Fisheries Impact on North Atlantic Ecosystems: Models and Analyses. Ed. by S. Guenette, V. Christensen, and D. Pauly. Fisheries Centre Research Reports 9(4). (In press.)

Ramseier, R. O., Garrity, C., Parsons, D. G., and Koeller, P. 2000. Influence of particle organic carbon sedimentation within the seasonal sea-ice regime on the catch distribution of northern shrimp (*Pandalus borealis*). Journal of Northwest Atlantic Fishery Science, 27: 35–44.

Rätz, H.-J. 1999. Structures and changes of the demersal fish assemblage off Greenland, 1982–96. NAFO Science Council Studies, 32: 1–15.

Rätz, H.-J., Stein, M., and Lloret, J. 1999. Variation in growth and recruitment of Atlantic cod (*Gadus morhua*) off Greenland during the second half of the twentieth century. Journal of Northwest Atlantic Fishery Science, 25: 161–170.

Riget, F., and Engelstoft, J. 1998. Size-at-age of cod (*Gadus morhua*) off West Greenland, 1952–92. NAFO Science Council Studies, 31: 1–12.

Shumway, S. E., Perkins, H. C., Shick, D. F., and Stickney, A. P. 1985. Synopsis of biological data on the pink shrimp, *Pandalus borealis* Krøyer, 1838. NOAA Technical Report NMFS 30 (FAO Fisheries Synopsis No. 144). 57 pp.

Siegstad, 2000. Preliminary assessment of shrimp (*Pandalus borealis*) in Davis Strait, 2000 (Subareas 0+1). NAFO SCR Doc. 84 (Ser. no. N4341). 22 pp.

Stein, M. 2000. Hydrographic and atmospheric conditions off East Greenland - their potential effect on the distribution of shrimp (*Pandalus borealis*). Journal of Northwest Atlantic Fishery Science, 27: 63–67.