http://journal.nafo.int

J. Northw. Atl. Fish. Sci., Vol. 39: 1-20 Publication (Upload) date: 23 Mar 2007

Warming Periods off Greenland during 1800–2005: Their Potential Influence on the Abundance of Cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) in Greenlandic Waters

M. Stein
Institut für Seefischerei, Palmaille 9
D-22767 Hamburg, Federal Republic of Germany

Stein, M. 2007. Warming Periods off Greenland during 1800–2005: Their Potential Influence on the Abundance of Cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) in Greenlandic Waters. *J. Northw. Atl. Fish. Sci*., **39**: 1–20. doi:10.2960/J.v39.m580

Abstract

Greenland and its adjacent waters are located at the northern boundary of the Subpolar Gyre and thus subject to climatic variations within this gyre. It is suggested that periods characterized by regional shrinkage of warm water masses within the Gyre adversely affect the propagation of gadids from upstream Icelandic waters to Greenlandic waters, and periods of regional dilatation of warm water masses within the Gyre are favourable for developing gadid stocks in Greenlandic waters. Recent observations of the sea surface temperature anomalies in the North Atlantic Subpolar Gyre indicate cold conditions in the 1980s and warming from the mid-1990s onwards, with maximum temperatures observed during October 2003. This is consistent with air temperatures at Nuuk, Greenland, which document that 2003 was the warmest year since 1950. Ocean temperatures off West Greenland show a significant upward trend, which is considerably higher than that for the North Atlantic Basin. Ocean properties off West Greenland during recent times were more saline and up to 2°C warmer-than-normal. Sub-surface oceanographic observations of the advection of warm Irminger Mode water masses indicate that during the 20th century and the early-2000s pulses of this water arrived at depths of 400 m–800 m off West Greenland. Long-term climate "proxy" data, which cover the period 1800–1982, were used for comparison with instrumental records of atmospheric data (Nuuk mean annual air temperatures), and of annual mean sea surface temperature data for West Greenland area A_1. These data were compared to historic reports on the existence of cod in Greenland waters during the pre-1920s, and during the times of the Greenland cod fishery of the 1930s–1960s. Similar to the data on biomass and abundance of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), as obtained during German bottom trawl surveys between 1982 and 2005, these data suggested coupling of warming periods with the abundance of gadids in Greenland waters. By means of sea surface temperature anomalies for the North Atlantic Ocean it is shown that the regional extent of warm water masses within the North Atlantic Subpolar Gyre varies significantly during the 1850s to early-2000s.

Key words: cod, Greenland, haddock, recruitment, warm periods

Introduction

General Oceanographic Structure of the Area

The North Atlantic Current, an extension of the Gulf Stream, carries warm subtropical waters towards the Northeast Atlantic and circulates northward and eventually westward forming a broad anticlockwise gyre – the Subpolar Gyre (Stein, 2005). The northward heat transport accompanying these waters is partly responsible for the mild climate of northern and northwestern Europe, which is much warmer than the average for these latitudes. A southward flow of cooler waters counterbalances this warm water flow. Along the Subpolar Gyre, pathway modification and cooling of the warm water occurs, and in the west, Labrador Sea Water flows back towards the subtropical gyre as an intermediate depth current.

Greenland and its adjacent waters are located at the northern boundary of the Subpolar Gyre and thus subject to climatic variations within this gyre. Accordingly, the West Greenland Current, which follows the continental slope off West Greenland and travels northward through

Davis Strait, carries the warming or cooling signals into Baffin Bay to the north of Davis Strait. Cold Arctic waters flow southward through the Strait via the Baffin Island Current (Fig. 1).

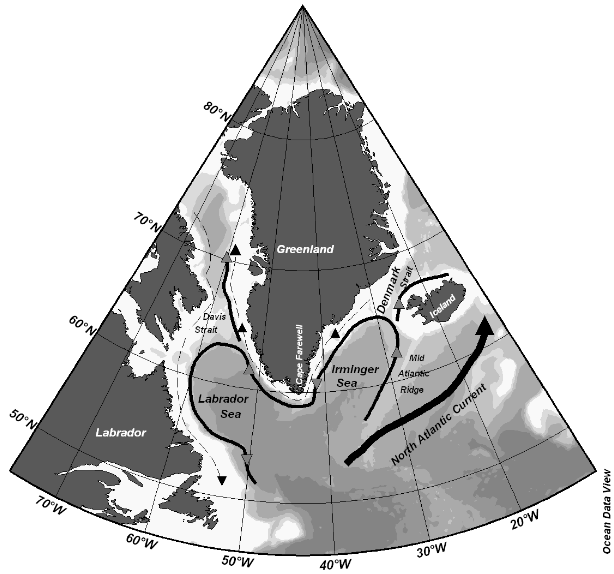

Fig. 1. Schematic of the subpolar gyre (white area: 0–500 m depth). Bold: warm currents; dashed: cold currents (Figure taken from Stein, 2005).

Historic Perspective

The environmental history of Greenland and its adjacent waters, climatic impacts on human settlements and living marine resources are subject of many fold scientific publications. In relation to marine fish stocks of the area, first observations on cod (*Gadus morhua*) in Greenland waters derive from the 16th century from East Greenland sites (Schmidt, 1931). Accordingly, an Icelander named Clemens from Látrum in Aðalvík in Iceland sailed on board an English vessel to the Angmagssalik region, presumably between 1586 and 1596. "The crew intended to go on land to shoot birds but noticed that the bay was full of cod. They made the boat fast and loaded it full with cod, just as a sample of what the bay held". Schmidt (1931) continues that "as this is reported by an Icelander who in his homeland was extremely well acquainted with the cod, there seems no doubt, that the fish discovered filling the bay at Angmagssalik about 1590 was really the cod (*G. callarias*)". *G. callarias* is a synonym of *G. morhua*. Buch *et al.* (1994) argue that in historical times cod has probably always been present in Greenland waters, but its abundance and spatial distribution have varied greatly as a result of variations in the marine environment. In the cited publication the occurrence of cod and cod fisheries at West Greenland in the 17th to 19th centuries is discussed in relation to proxy temperature time series derived from Greenland ice cores. A correlation between the occurrence of cod and the warm periods prior to the 20th century, could not be shown.

Jensen and Hansen (1931) in a historical overview on the "History of the Greenland Cod Fisheries" report on the rise and fall of the West Greenland cod fishery during the 19th century. Accordingly, the first period fell in the years around 1820, and the second period began around the middle of the century in 1845 and lasted until 1851. During the early-20th century, in 1906, experimental cod fishery off West Greenland was very disappointing and the Faeroese ship owner Napoleon Andreasen stated "If I were asked to express my opinion of the cod fishery at Greenland, then using the experience gained during the summer as guide, I should most sympathetically endeavour to dissuade any outsider from going to Greenland with the sole object of catching cod, for he will here assuredly, like myself in many cases, be painfully disappointed." The first scientific fisheries investigations were carried out by the famous Danish scientist Ad. S. Jensen – on board the brig "Tjalfe" in 1908–09 (Hansen, 1949). Hansen (1949) continues that "cod increased in numbers due to more favourable hydrographical conditions and extended northwards along the coast of West Greenland". At those times it was not "known to what extent the Greenland cod was connected with the American or the Icelandic stocks". In the early-1920s cod fishery initiated again on the West Greenland banks (Horsted, 2000), and cod catches increased to more than 400 000 t during the 1960s. In a "Laboratory Leaflet" of the Fisheries Laboratory, Lowestoft (Anon., 1965), it was stated in those times that "the major fishable stocks of cod in all parts of the North Atlantic occur in areas where water of around 2°C covers the sea bed at depths of less than 300 fathoms. On the Greenland banks this temperature is maintained by the interaction of two oceanic currents, one very cold current travelling south down the coast of East Greenland from the Polar Sea, and the other a warm offshoot of the Gulf Stream, the Irminger Current, which flows south-westward from Iceland. This interaction of cold and warm currents" – which is common in the Arctic – "means that small changes in the strength of either current can have a marked effect on the area suitable for cod. In general warm years are likely to be more favourable for cod, the increased temperature enabling them to disperse over a wider area of the banks. The physical conditions at Greenland thus seem to be more delicately balanced than in most of our cod fisheries, and in fact fishable concentrations have not always been present off Greenland. Cod were fished here around 1840–1850 but thereafter became extremely sparse until about 1916."

In many publications on the history of West Greenland cod stocks the evident increase of the cod stock and its spatial distribution at West Greenland was explained by Jensen (1939) as one of the biological consequences of the general warming of the Arctic and Subarctic regions in the 1920s (Horsted, 2000). Buch *et al.* (1994) find correlation between the occurrence of cod and the warm period starting around 1920.

Haddock (*Melanogrammus aeglefinus*) is usually found at temperatures between 4° and 10°C. This species is rarely seen in West Greenland waters. Historically, the first specimens of haddock were caught in the Cape Farewell region in 1929 (Jensen, 1948; Hansen, 1949; Hovgård and Messtorff, MS 1987). Spawning areas of haddock found in Greenland are believed to be in Southwest Iceland (Wieland and Hovgård, 2002), in the area around the Reykjanes peninsula (Olafsson, MS 1985), and spawning takes place in May–June. With the main water masses in the area, 0-group haddock is carried to Icelandic/East Greenland waters where it was found in August during the pelagic trawl surveys made by Iceland (Vilhjalmsson and Fridgeirsson, 1976). Hovgård and Messtorff (MS 1987) suggest that findings of haddock off West Greenland in the 1930s and 1940s may be explained by improvement in environmental conditions during the same period of time which was characterized by frequent and large drifts of young cod and haddock from Iceland to West Greenland. Due to the close interactions between the marine ecosystems of Iceland and Greenland, and the linkage by one of the main ocean currents in the area – the Irminger Current – it is suitable to speak of the "Iceland-Greenland-System" (Stein and Borovkov, 2004).

Meanwhile, decades have passed, commercial fishery of Greenland cod on the West Greenland banks and unfavourable environmental conditions led to near extinction of these cod stocks, and after the 1960s recruitment from the Icelandic cod stock was the only available source for replenishment of the Greenland cod stocks, because cod recruitment in Greenland waters was negligible (Rätz *et al.*, 1999; Wieland and Hovgård, 2002).

Environmental parameters are considered by several authors to contribute significantly to cod recruitment success (Lear and Parsons, 1993; deYoung and Rose, 1993). Evidence of biotic and physical influences on Northeast Arctic cod recruitment was documented by Ottersen and Sundby (1995) and Nilssen *et al.* (1994). They identified positive effects of spawning stock biomass (*SSB*) and temperature on year-class strength of cod.

Stein and Borovkov (2004) used two approaches to model the observed variability in Greenland cod (*Gadus morhua*) recruitment during the second half of the 20th century. The first model incorporated air temperature variations and zonal winds in the Denmark Strait, meridional winds in Southwest Greenland, and the linear trend observed in the Greenland cod recruitment time series. This model explained 79% of the inter-annual variation in cod recruitment off Greenland.

In a second step, multiple linear regression models were used to explain the inter-annual variability in cod recruitment off Greenland. Model input data included: time series of cod recruitment and spawning stock biomass from Iceland and Greenland, sea surface temperatures and air temperatures around Greenland, and zonal wind components between Iceland and Greenland. Model results indicated that, during the decades between 1950 and 1990, there were three different cause-effect regimes which significantly influenced the variability of cod recruitment. The three regimes included:

(a) During the 1950s and 1960s, a regime with favourable sea surface temperatures and a self-sustaining cod stock off Greenland with high spawning stock biomass that produced a series of above-average strong year-classes,
(b) during the 1970s and 1980s, a regime of declining spawning stock biomass and recruitment, with recruitment dependent on advection from Iceland, and
(c) during the 1990s, when the advective potential for recruitment from the Icelandic cod stock was the only available source for replenishment of the Greenland cod stocks, because cod recruitment in Greenland waters was almost nonexistent.

The three models explained 76% to 77% of the observed inter-annual variation in cod recruitment off Greenland.

Both modeling methods suggested that advective factors dominated the "Iceland-Greenland-System" significantly. Biological advective influences were documented in the "regime-oriented" analysis where the Icelandic cod recruitment played a major role in all model results as well as in the negative trend apparent in the *SSB* time series. The advective influence of the climatic parameters was evident in the detrended model which consisted of the linear trend present in the Greenland cod recruitment time series, and environmental variables (*e.g.* air temperature and wind conditions in the

Iceland-Greenland-System). Zonal winds played a particularly important role in the Denmark Strait region, whereas meridional winds were essential in the Cape Farewell region.

Sea-surface temperature anomalies in the North Atlantic Subpolar Gyre indicate cold conditions in the 1980s and warming from the mid-1990s onwards, with maximum temperatures observed during October 2003 (Stein, 2005). The latter is consistent with air temperatures at Nuuk, Greenland, which document that 2003 was the warmest year since 1950. Ocean temperatures off West Greenland show a significant upward trend, which is considerably higher than that for the North Atlantic Basin. Long-term (1964–2004) observations from Fyllas Bank off West Greenland also reveal warm conditions during the 1960s, although the highest temperatures on record are from the recent years of the present century. Geostrophic transports estimated from autumn 2004 hydrographic data between Greenland and Baffin Island suggest increased northward transport of the West Greenland Current. Ocean properties at this time were more saline and up to 2°C warmer-than-normal.

Recent observations made during the German bottom trawl surveys around Greenland (Anon., 2006) reveal that the 2003 year-class of cod is more abundant than other recent year classes, possibly similar to the 1984 year-class, but the distribution of the 2003 year-class is more easterly than those in the 1980s. Haddock off Iceland also indicates increasing *SSB* from 2001 to 2005 due to several strong year-classes. All indications are that the current *SSB* is the highest in 25 years or more. Since 1998, most year-classes have been well above average, and the 2003 year-class is the strongest in the observed time series. The 2004 and 2005 year-classes appear to be average (Anon., 2006).

The present paper considers biological data on cod and haddock sampled annually since 1982 during the German groundfish surveys to East and West Greenland waters, and historic reports on the abundance of cod and haddock in Greenland waters. It is assumed here that interactions between temperature and the success of year-classes of the considered gadids are most sensitive during the months of May–August – the time of the pelagic phase of 0-group cod and haddock (Marteinsdottir *et al.*, 2000; Olafsson, MS 1985). Accordingly, historic air temperature data during May–August are used to estimate climatic changes in the Subpolar Gyre adjacent to Greenland between the middle of the 19th century and present. Instrumental records on air temperatures and sea surface temperatures form the basis for modelling the climatic environment (West Greenland sea surface temperatures and Nuuk air temperatures) during pre-instrumental times. Sub-surface oceanographic data from two West Greenland sites – Fyllas Bank and Cape Desolation Section – are used to show the temporal variation of temperature and salinity at depths, and the advection of warm water masses to West Greenland within the domain of the North Atlantic Subpolar Gyre. Based on these historic and modelled data the assumption is tested whether the abundance of cod and haddock in Greenland waters can be linked with warming periods in the oceanic and atmospheric climate off Greenland.

Data and Methods

The evaluation of climatic changes in the atmosphere and ocean adjacent to Greenland is performed by using air temperature anomalies and sea surface temperature anomalies which are based on instrumental records, climate "proxy" data based on stacked ice core oxygen isotope records from West Greenland, and sea surface temperature anomaly data which are extended back to 1854. Short-term variability of the oceanic climate off West Greenland is given in a chapter on the advection of Irminger Water to West Greenland waters during the 20th century and the present century. The instrumental climatic time series, as well as the high-resolution climate "proxy" data are given as five-year mean values to better discriminate warm and cold periods, warming and cooling scenarios.

Data on the atmospheric climate of Greenland were sampled by the Danish Meteorological Institute at Nuuk (64°11' N, 51°44.5' W). This data set was mutually supplied by the Danish Meteorological Institute in Copenhagen and the Seewetteramt, Hamburg. The climatic mean which the air temperature anomalies are referenced to is 1961–1990. The variation of West Greenland's climate during 1876–2005 is given in five-year running means (1880–2005). Another source of information on climatic temperatures is derived from the NOAA Extended Sea Surface Temperatures (SSTs) data set (http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl). The 95% confidence uncertainty for the near-global average of these data is 0.4°C or more in the 19th century, near 0.2°C for the first half of the 20th century, and 0.1°C or less after 1950 (Smith and Reynolds, 2004). Mean SSTs for the months of May–August during five-year periods (1855–1859, … , 2000–2004) are plotted to indicate changes of the thermal properties within the North Atlantic Subpolar Gyre during the 19th to 21st century.

High-resolution climate "proxy" data for the past two centuries (1800–1970) were taken from Jones and Mann (2004). They are based on stacked ice core oxygen isotope records from West Greenland, and date back to AD 553.

During cruises of the Federal Research Centre for Fisheries, Hamburg to West Greenland waters, oceanographic data were sampled at ICNAF/NAFO Standard Oceanographic Stations (Stein, MS 1988). These data are available from the oceanographic data base of the Institut für Seefischerei, Hamburg, and from international data archives (*e.g.* ICES, MEDS, WOD-2001).

Oceanographic observations used in the present publication were taken along the Cape Desolation Section and the Fyllas Bank Section. Due to the historic analysis, the data are derived from reversing thermometers and bottle samples as well as CTDs. For the more recent CTD data (Kiel-Multisonde and SeaBird 911+; 1983 onwards) salinities were calibrated from water samples taken using a Rosette water sampler. The precision of the derived salinities allows water mass analysis to discriminate between Irminger Water (>34.95 psu) and Modified Irminger Water (>34.88 psu). Water mass analysis and presentation of isopleth diagrams was done using the most recent version of Ocean Data View (ODV, Version 3.1.0; Schlitzer, 2006).

The second instrumental oceanographic data set used in the present analysis, was made available to the author by the former ICES Hydrographer Jens Smed. It comprises SST anomaly data for areas in the North Atlantic, of which the West Greenland data set for area A_1 (60–70°N, 50–58°W) was considered. Annual mean temperature anomaly data (1876–1975) of area A_1 were used. The reference period for the SST anomaly data is 1876–1915 (Smed, 1975). To reveal potential climatic variations in historic times prior to the instrumental records, a harmonic model was applied to the SST data of area A_1.

$$\zeta(t) = A\sin(2\pi/\tau + \varphi) + \text{linear trend}$$

The derived model was used to extrapolate data back to 1800. The same procedure was applied to the air temperature anomalies of Nuuk.

Cod and haddock time series data were taken from the data base of the Institut für Seefischerei. The data were obtained during the annual cruises to Greenland waters. They cover the period 1982–2005, and show abundance and biomass of cod and haddock. Information on cod in Greenland waters during historic times was adopted from Buch *et al.* (1994).

Data on zonal and meridional wind components between Iceland and Greenland were taken from the climatic data sets of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl).

Results

Nuuk air temperature anomalies

Presentation of Nuuk/West Greenland air temperature anomalies time series is given in five-year running means (Fig. 2a). Accordingly, climatic conditions varied during the late 1800s to early-2000s with a low frequency period (Stein, 1995; Stein, MS 2004). Very cold conditions were seen during the 1880s to 1910s. Warming began around 1920, and it remained warmer than normal until about 1970. Thereafter, with the exception of the period 1976–80, it became colder in Nuuk/West Greenland until the mid-1990s. From the 1996–2000 period onwards, climatic conditions changed again for warmer-than-normal conditions, and Nuuk presently enjoys warm conditions as during the 1926–30 period.

For further analysis of climatic features contained in the time series, and for an assessment of climatic changes in air temperatures prior to the instrumental records, a harmonic model was adjusted to the time series given in Fig. 2a. The harmonic model as given in Fig. 2b reveals a period of colder-than-normal air temperatures which came to an end around 1920, a warm period thereafter which ended in the early-1970s, and another colder-than-the reference period which ends about 1996. The linear trend incorporated in the harmonic model time series is significant and explains 13% of variation.

Extrapolation of the model data to pre-1880 periods (Fig. 2c) indicate that most of the 19th century was colder-than-normal. There were warmer-than-normal conditions off West Greenland only around 1850.

Sea surface temperature (SST) data area A_1 (West Greenland)

The sea surface temperature anomaly data show the variation of SSTs for areas in the North Atlantic (Smed, 1975). Annual mean values (1876–1975) for A_1 were reduced to five-year running means (Fig. 3a).

The harmonic model as given in Fig. 3b reveals a period of warmer-than-normal SSTs prior to 1890, a colder-than-normal period which ends between 1910

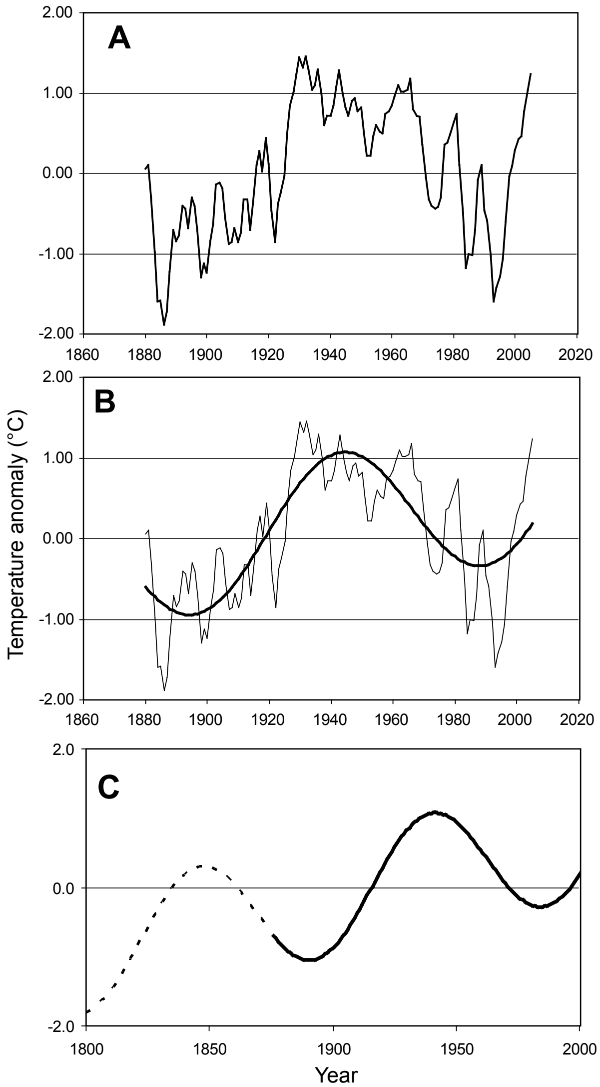

Fig. 2. (**A**) Nuuk/West Greenland's air temperature anomalies in terms of five-year running means; (**B**) harmonic model adjusted to the data ($r^2 = 0.62$); (**C**) Modelled West Greenland's air temperature anomalies based upon harmonic model and extended to 1800 (dashed); data: 1880–2005.

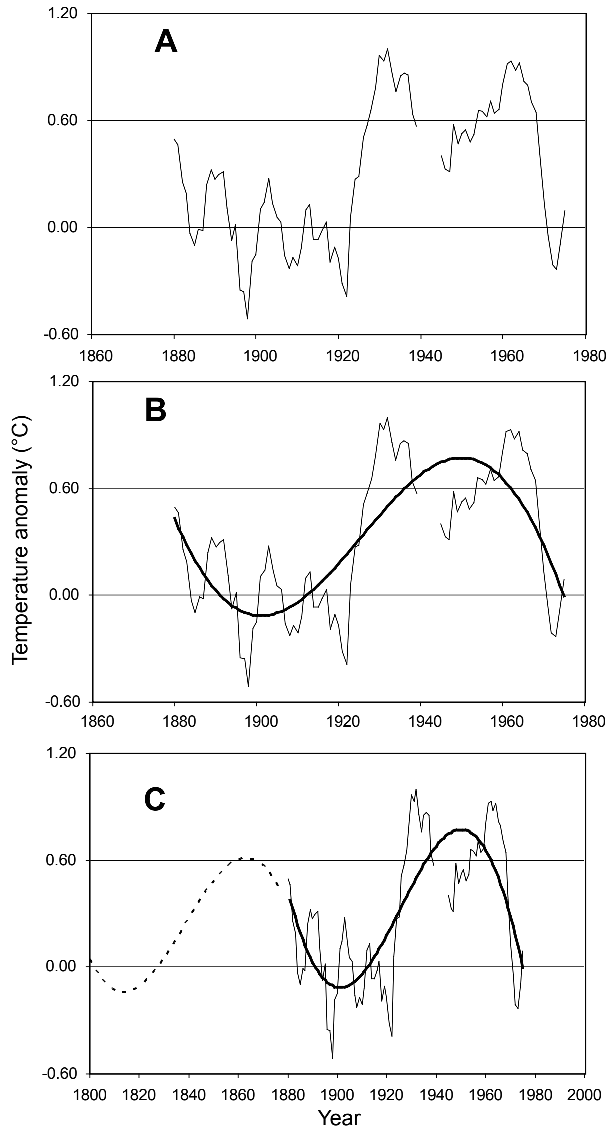

Fig. 3. (**A**) Sea surface temperature anomalies in area A_1 (West Greenland) in terms of five-year running means; (**B**) harmonic model adjusted to the data ($r^2 = 0.58$); (**C**) Modelled West Greenland's sea surface temperature anomalies based upon harmonic model and extended to 1800 (dashed); data: 1880–1975, no data 1940–1944.

and 1920, and a warm period thereafter which ends in the late-1970s. The linear trend incorporated in the SST time series is significant and explains 40% of variation.

Extrapolation of the model data to pre-1880 periods (Fig. 3c) suggest that most of the 19th century experienced warmer-than-normal SSTs off West Greenland. Only around 1820 there were colder-than-normal conditions off West Greenland. These results are significantly different from the model results obtained from air temperature anomalies.

Nuuk air temperature anomalies and SST data area A_1 (West Greenland)

Correlation between Nuuk air temperature anomalies and SST data area A_1 (West Greenland) is tested on the basis of five-year mean anomaly data (Fig. 4). Both time series indicate covariance as concerns timing of events, however, there is tremendous difference as concerns amplitudes of these variations. Large deviation is

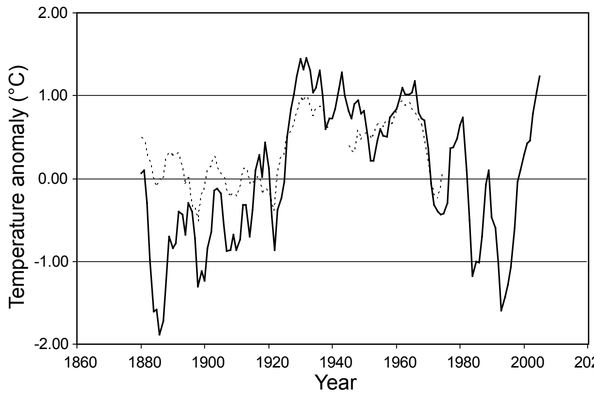

Fig. 4. Nuuk/West Greenland's air temperature anomalies in terms of five-year running means; data: 1880–2005 (solid line), and sea surface temperature anomalies in area A_1 (West Greenland); data: 1880–1975 (dashed line), in terms of five-year running means; no data 1940–1944.

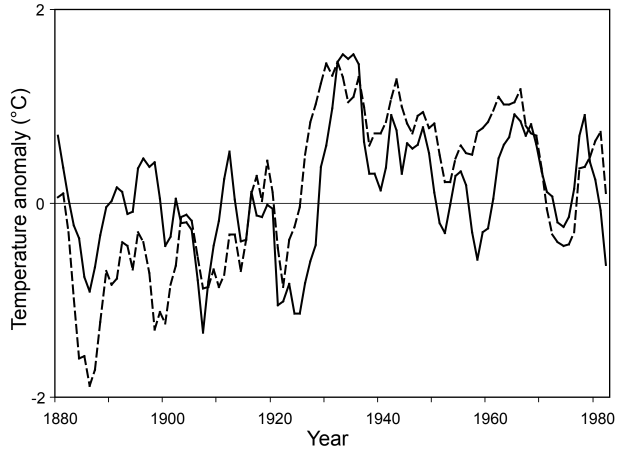

Fig. 5. West Greenland Climate Ice Core (solid line)/Nuuk mean annual air temperature anomalies (dashed line); $r^2 = 0.26$, $p<0.001$; data in terms of five-year running means.

encountered during the 1880s (-1.88°C and -0.01°C), around 1900 (-1.30°C and -0.51°C), and around 1930 (1.44°C and 0.97°C, for Nuuk and SST, respectively). The correlation between both time series is highly significant ($r^2 = 0.68$, $p<0.001$).

High-resolution "proxy" temperature data

Long-term unsmoothed climate "proxy" data were made available by Jones and Mann (2004). The data are based on stacked ice core oxygen isotope records from West Greenland and date back to AD 553.

Of this data set, "proxy" temperatures for the period 1880–1982 were used for comparison with instrumental records of atmospheric data (Fig. 5, Nuuk mean annual air temperatures), and of sea surface temperature data taken from Smed (1975) as annual mean data of area A_1 (Fig. 6, West Greenland).

In both cases, there are considerable differences in terms of the timing of climatic events. Warming as seen in the climatic time series of Nuuk mean annual air temperature anomalies, initiated around 1920. The same timing is visible in the SST data. The climate "proxy" data indicate this event began about five years later. As concerns the co-variation of air temperature time series and "proxy" temperature time series, there are periods of fairly good correlation except for a period after 1950 (Fig. 5). Statistical analysis indicates significant fit which, however, only explains 26% of the variation contained in the time series. Comparison of SST time series and "proxy" temperature time series shows remarkable

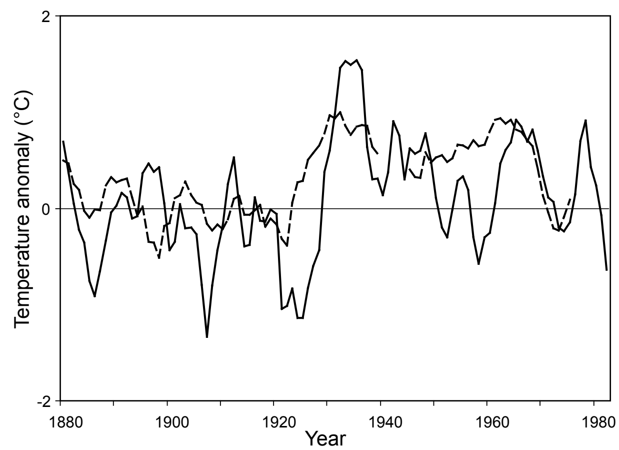

Fig. 6. West Greenland Climate Ice Core (solid line)/SST's area A_1 (West Greenland, dashed line); $r^2 = 0.11$, $p<0.001$; data in terms of five-year running means.

differences as concerns the period after 1950 (Fig. 6). The "ice core" derived temperature data indicate cooling after 1950 which came to an end after 1960. Both time series correlate significantly, but only with $r^2 = 0.11$.

As can be seen from Fig. 5, there is much deviation between measured air temperatures and "proxy" temperatures prior to 1920. Deviations are largest around 1900 and in the 1880s, where differences amounted to -0.9°C. This implies that difficulties will arise when using "proxy" temperatures for describing climatic variations during pre-instrumental times. The warmer-than-normal periods as displayed in Fig. 7 for the period 1800–1880,

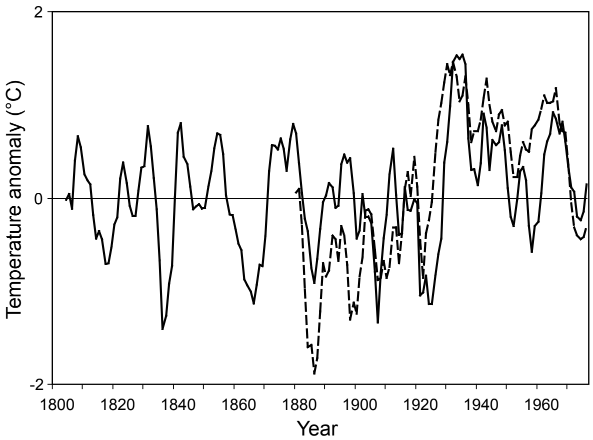

Fig. 7. West Greenland Climate Ice Core (solid line)/Nuuk mean annual air temperature anomalies (dashed line); data in terms of five-year running means.

will be changed to colder-than-normal periods when adjusting the "proxy" temperature time series to the cold events as measured in the 1880s around 1900.

NOAA Extended Sea Surface Temperature Anomalies

During the second part of the 1850s (Fig. 8), warming was encountered in the waters adjacent to Greenland during May-August. Warming was also apparent to the southeast off Greenland. It would appear that the domain of the North Atlantic Subpolar Gyre (NASG) waters had warmed by up to 0.4°C during these years (see chapter on data and methods for data accuracy during these times). After that, in the 1860s, the NASG shrunk in its regional extension and cooled. The center of warming had moved to mid-latitudes during these times (1860–64). During the 1870s, there was a tremendous increase in regional extension of the NASG, covering the "Greenland-Iceland System with warm water of more than 1.0°C above the climatic mean. There existed warm water regions in near-coastal areas of East Greenland, Southeast Greenland, and to the west off Greenland (1870–74). In the 1880s, there was cooling of the NASG during the first half of the decade, but warming in the second half. The center of warming had, however, moved southwards.

The 1890s (Figs. 8 and 9) appeared as a decade with warm SSTs in the NASG, the center of which had moved to the east and southeast off Greenland. The first decade of the new century showed shrinkage of the Gyre, and only East Greenland waters were warmer than normal during those times. From 1915 onwards, warming increased in the NASG. A warm Gyre was seen in the second part of the 1920s, when the entire Irminger Sea, Labrador Sea and the waters to the south of Greenland had warmed by 0.8°C and more. During the 1930s, the Gyre reached one of its largest areal extensions during the covered time series, and warmer-than-normal sea surface temperatures were seen in wide parts of the Northwest and West Atlantic. Also during the second part of the 1930s (Fig. 10) general warming of North Atlantic surface waters was the prominent feature of the SSTs between Europe, Iceland-Greenland and Canada. The center of warming had moved south, and temperature anomalies amounted to more than 1.2°C. The second half of the 1940s indicated some shrinkage of the Gyre, however, May–August temperature anomalies during the early-1950 showed widely distributed warmer-than-normal SST, with prominent warming in areas off West Greenland. During the second half of the 1960s, the NASG still indicated warming, especially in the region of the Irminger Sea. The coastal areas off East Greenland indicate, however, colder-than-normal conditions.

The 1970s through to the early-1990s (Figs. 10 and 11) reveal tremendous cooling, especially during the first half of the 1980s (Fig. 11, upper right panel), and the early-1990s were characterized by colder-than-normal sea surface temperatures which were seen from Atlantic Canada to the southwest off Iceland.

From 1995 onwards, the SST anomalies show a completely different structure than encountered during the decades of the previous centuries: Warmer-than-normal conditions are seen to cover the whole of the North Atlantic Ocean as displayed in Fig. 11. Except for a small area east off the US-American seaboard, the SST-anomalies are mostly positive during these times.

Advective processes in West Greenland off-shore waters

Advection of Irminger Water, Temperature and Salinity. Figs. 12 and 13 outline the vertical variation in time of temperature and salinity at Cape Desolation Station 3 and Fyllas Bank Station 4 for the upper 1000 m. From the mid-1990s onwards, water temperatures increase in the upper 400 m and record high values of >7°C are encountered (Fig. 12). Parallel to the warming features, salinities increased in the upper layers, and water of Irminger Mode characteristics (>34.95 psu) is found off West Greenland. Clarke (1984) gives a definition for the Irminger Current flowing into the Labrador Sea with the following water mass characteristics:as water of 4–6°C, 34.95–35.1 psu. In the present paper this definition is taken for Irminger water in the water mass analysis. Since this water mass obtains its characteristics

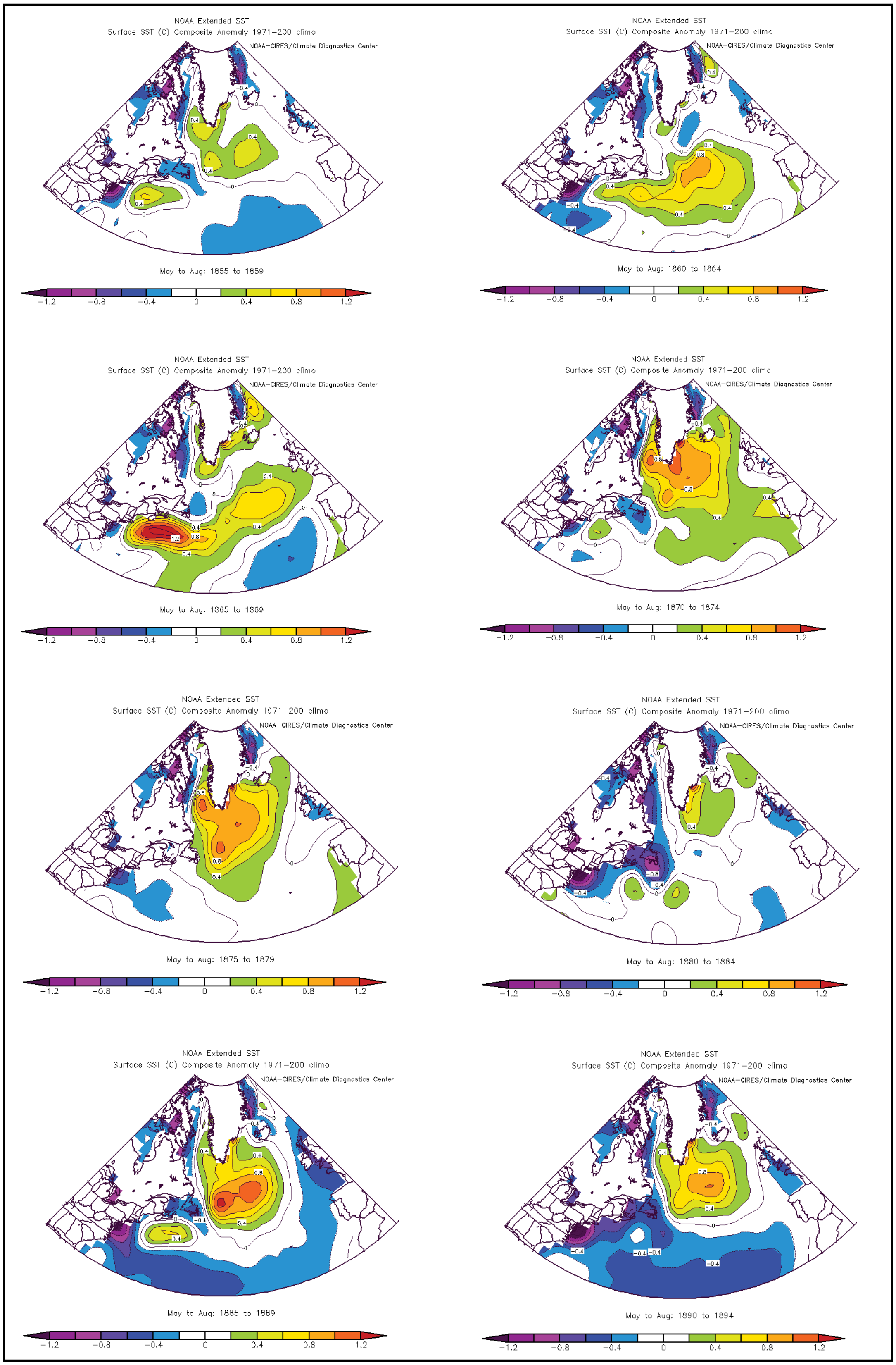

Fig. 8. NOAA Extended Sea Surface Temperature anomaly data during May–August 1855–1894; data are given in five-year means relative to the 1971–2000 climatic mean.

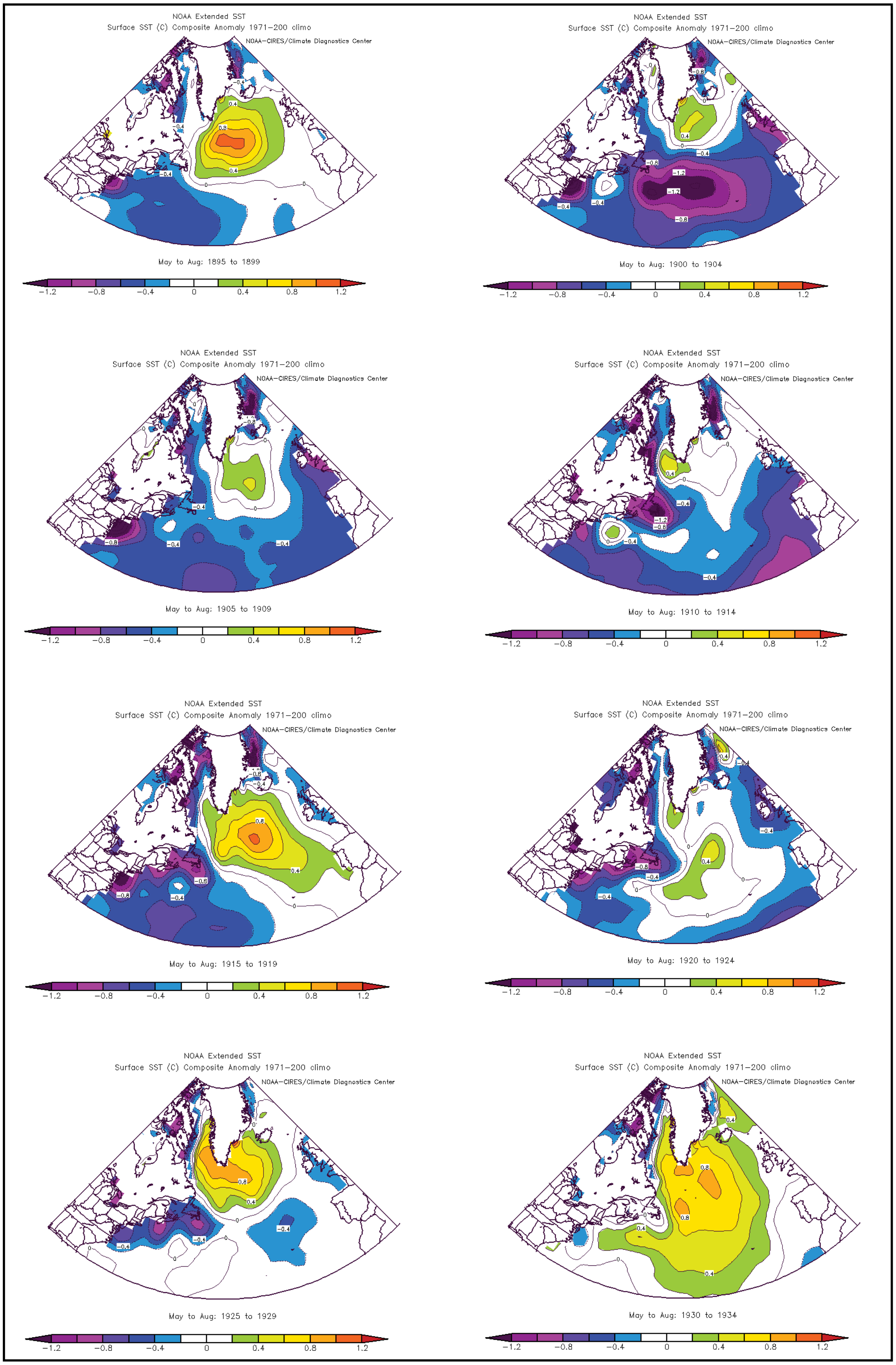

Fig. 9. NOAA Extended Sea Surface Temperature anomaly data during May–August 1895–1934; data are given in five-year means relative to the 1971–2000 climatic mean.

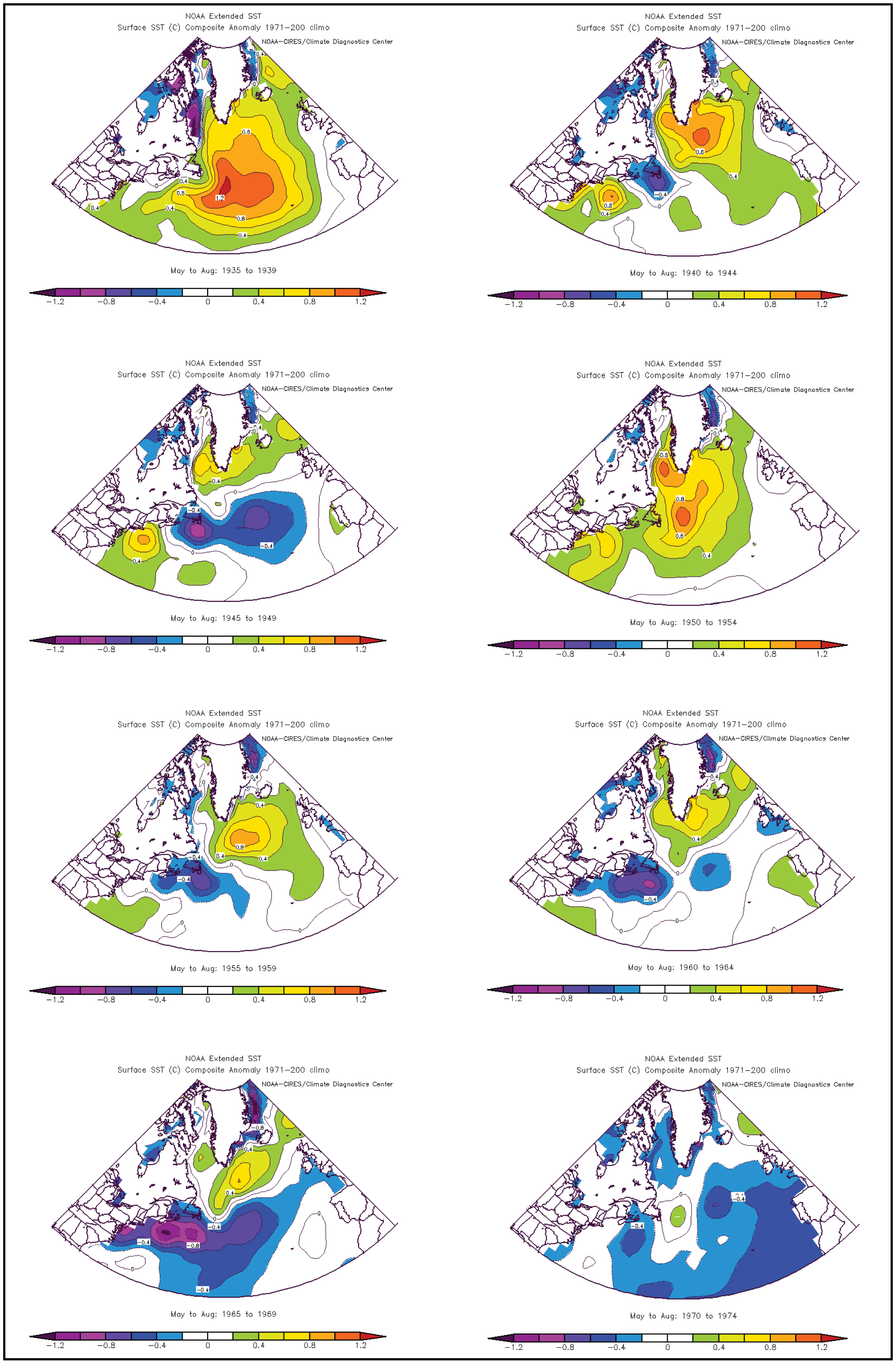

Fig. 10. NOAA Extended Sea Surface Temperature anomaly data during May–August 1935–1974; data are given in five-year means relative to the 1971–2000 climatic mean.

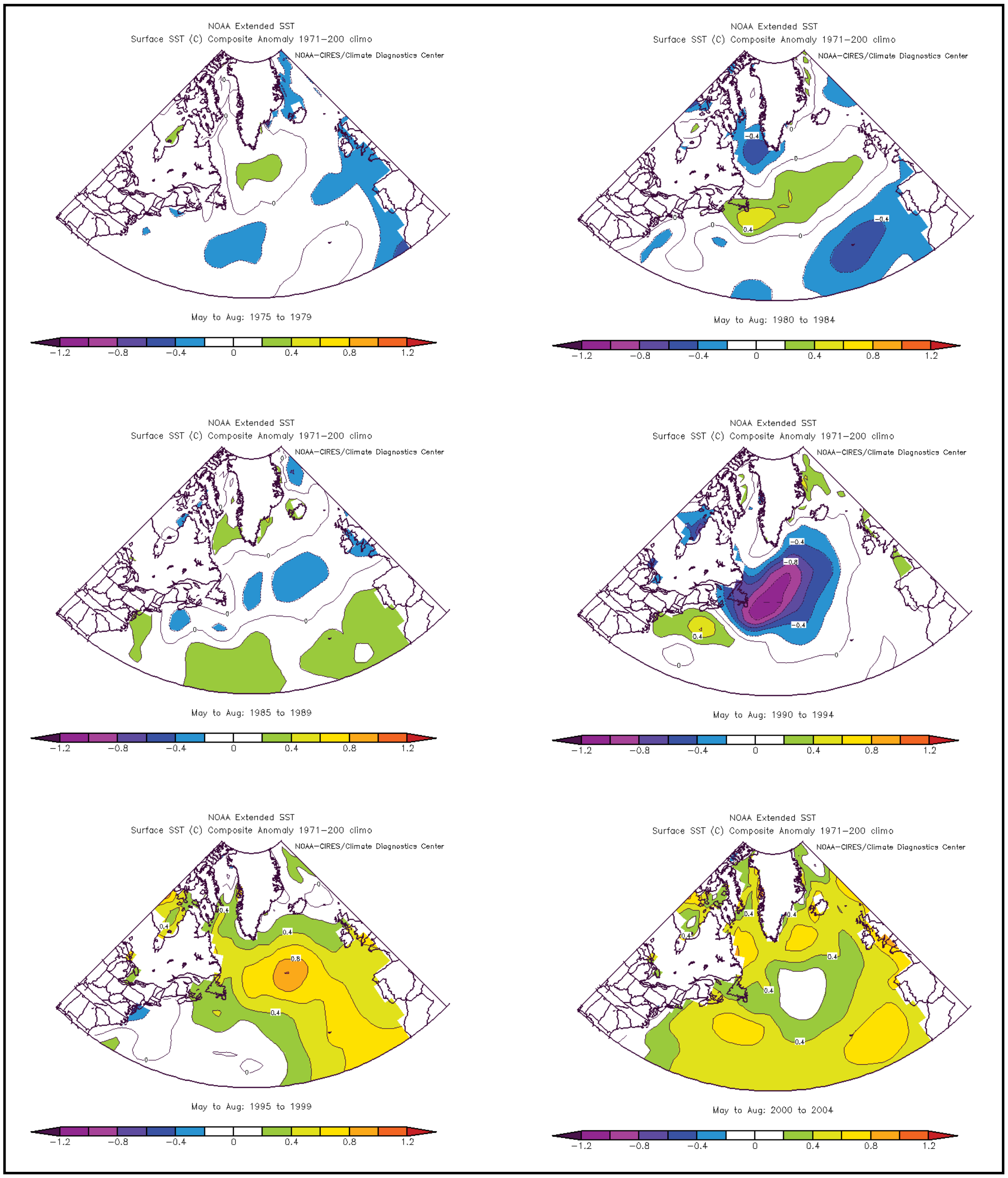

Fig. 11. NOAA Extended Sea Surface Temperature anomaly data during May–August 1975–2004; data are given in five-year means relative to the 1971–2000 climatic mean.

upstream in the Irminger Sea, the increasing temperatures and salinities at Cape Desolation Station 3 point at advective processes.

Presence of Irminger Mode Water at Fyllas Bank. Further north, at Fyllas Bank Station 4 (Fig. 13), Irminger Mode Water is found at deeper layers at about 400 m depth and beyond. Our time series reveals that also during the 1960s this warm and saline water mass was found off Fyllas Bank. Maximum temperatures were observed during autumn 2003, the year of record warm air temperatures at Nuuk (see Introduction).

The presence of Irminger Water at the shelf break of Fyllas Bank during the 20th century and this century is documented in Fig. 14. The data set derived from the

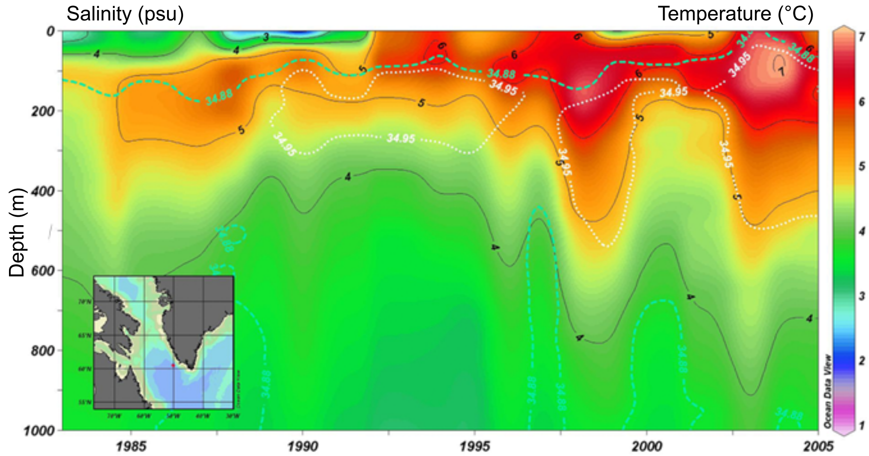

Fig. 12. Cape Desolation Station 3: Temperature of upper 1000 m over time (1983–2005); overlays: isohalines of pure Irminger Water (34.95 psu) and of Modified Irminger Water (34.88 psu).

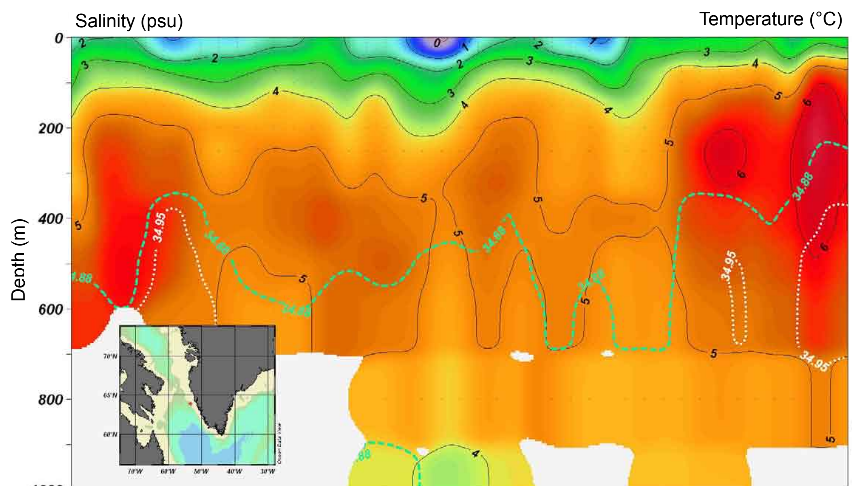

Fig. 13. Fyllas Bank Station 4: Temperature of upper 1000 m over time (1963–2005); overlays: isohalines of pure Irminger Water (34.95 psu) and of Modified Irminger Water (34.88 psu).

World Data Centre archives suggests periods when this water mass reached Station 4 of the Fyllas Bank Section (Stein, MS 1988), and periods when it did not. Irminger Water at Station 4 appeared during the late-1930s, the late-1940s and in the 1960s. During the 1980s and 1990s there were few occasions when Irminger Water was present off Fyllas Bank, however, during the present century, this water mass is again observed off the bank.

Potential Impacts on Gadid Stocks in Greenlandic Waters

Cod and Haddock. The well known catch figure of cod in Greenland waters during the 20th century (Fig. 15) was published by Horsted (2000). Starting during the 1920s with less than 30 000 t, total catches increased to more than 100 000 t during the 1930s, and reached record high values during the 1960s (1967: 429 479 t). After this decade, catches decreased to about 50 000 t. 1989 was the last year when catches increased the 100 000 t level. During the 1990s only marginal catches were reported, and 1995 which is the final year in the cited statistic, nominal catches of cod were only 1 710 t.

Biomass and abundance data of cod and haddock during 1982–2005 are given in Fig. 16. The terminal years of cod fishery during the 1980s emerge clearly

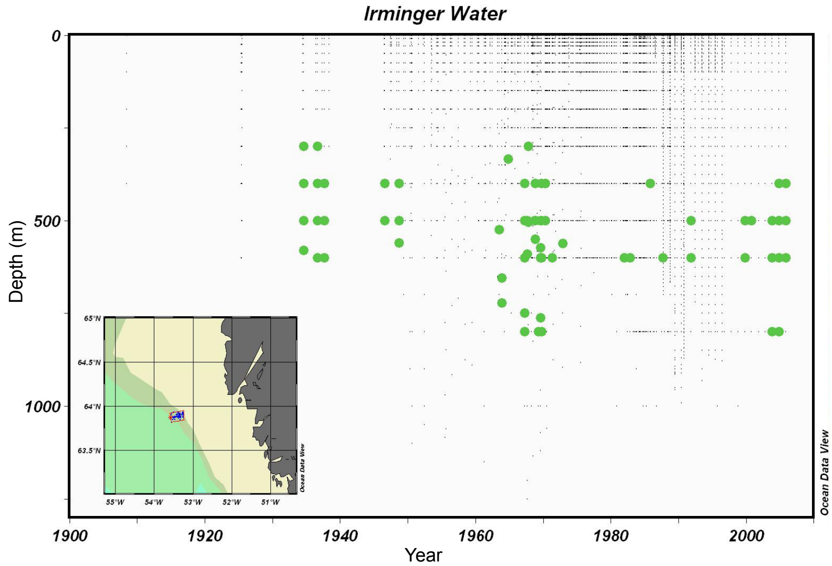

Fig. 14. Fyllas Bank Station 4: Presence (green dots) / absence (small black dots) of Irminger Water at the shelf break of Fyllas Bank (data: 1908–2005).

from Fig. 16b. Calculated biomass numbers for the years 1987–89 were in the range of 600 000–700 000 t. As mentioned by Horsted (2000) recruitment of the 1984 year-class to the fishable stock during 1987–90, led to temporary improvement in the total catch at West Greenland to levels around 100 000 t.

During most of the 1990s, biomass and abundance data of cod and haddock indicated depleted stock conditions off Greenland. Thereafter, however, abundance of haddock increased to record high levels since 1982. The haddock year-class 2003 clearly emerges from Fig. 16a. Biomass and abundance data for cod are in the range of the mid-1980s. Fig. 16d clearly shows that the year-class 2003 of cod dominates the cod stocks off Greenland. As for haddock, year-class 2005 dominated the length frequency spectrum.

Abundance of 0-group haddock and mean bottom water temperatures off West Greenland are significantly correlated (Fig. 17).

Periods during 1982–2005 where 0-group haddock was found off East and West Greenland in large numbers are clearly revealed in Fig. 18. Since the bottom trawl used during the surveys since 1982, is a 140' ground rope trawl with 10 mm liner in the cod end, this net can not catch 0-group cod (8–10 cm in length during October–November) quantitatively. However, those fish which

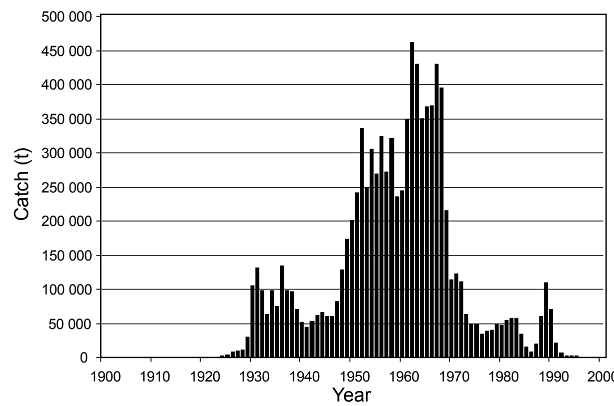

Fig. 15. Annual nominal catches of cod (*Gadus morhua*) in Greenland waters ; data: Table 6a in Horstedt (2000).

made their way into the net and further to the cod end, were kept. Fig. 18 thus might be taken as an index for the abundance of 0-group cod in Greenland waters during the past 25 years. The 1984 and 1985 year-classes which clearly emerge from Fig. 18, led to the temporary improvement in the total catch at West Greenland to levels around 100 000 t (Horsted, 2000). The 2003 year-class might be another hope for the Greenlandic fishery on cod in the near future.

For comparison with historical records on cod abundance in Greenland waters, the "proxy" temperature

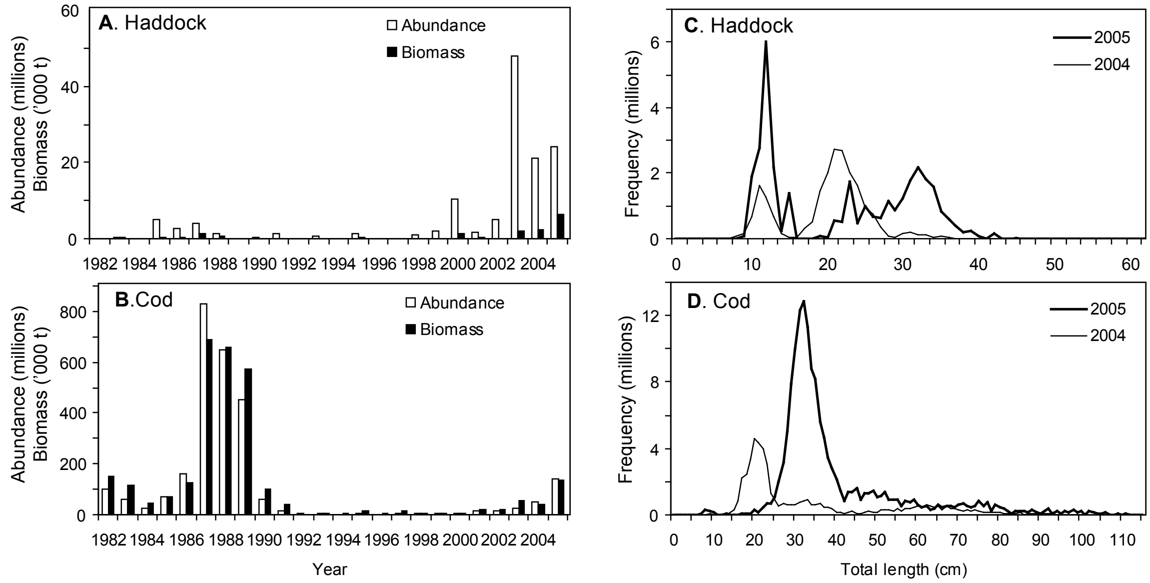

Fig. 16. Indices of abundance and biomass of (**A**) Haddock (*Melanogrammus aeglefinus*) and (**B**) Cod (*Gadus morhua*), and length frequencies for (**C**) haddock and (**D**) cod for the years 2004 and 2005; data: 1982–2005.

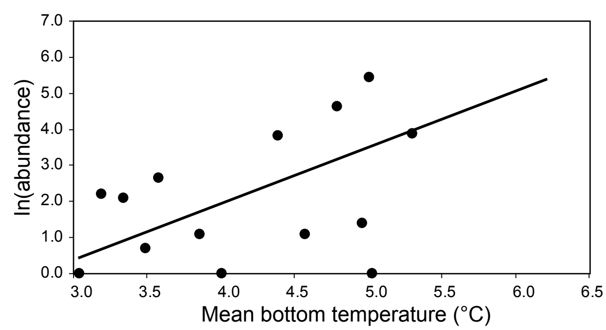

Fig. 17. Correlation of 0-group haddock (*Melanogrammus aeglefinus*) and mean bottom water temperatures off West Greenland, averaged over the number of hauls in the given year; data: 1989–2003; $r^2 = 0.40$, $p<0.05$.

time series is taken, and reports of cod catches off West Greenland (Schmidt, 1931), as well as catches during the 20th century (Horsted, 2000) are added (Fig. 19).

Cod catches in Greenland waters during the second part of the 20th century are posted in Fig. 20 until 1991, the last year with catches over 20 000 t. The triangles at the end of the time series, 2003–2005, mark the most recent increases in cod biomass and abundance in Greenland waters.

Wind Induced Transports of Gadid Larvae. Based on the results of Stein and Borovkov (2004), NCEP/

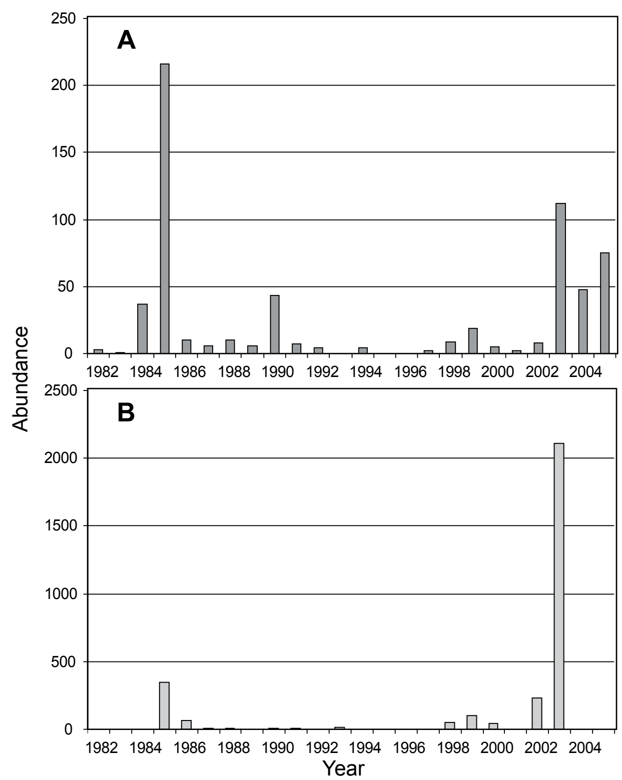

Fig. 18. Numbers of (**A**) 0-group cod (*Gadus morhua*) and (**B**) haddock (*Melanogrammus aeglefinus*), obtained during German bottom trawl surveys in Greenland waters (bottom trawl 140' ground rope with 10 mm liner); data: 1982–2005.

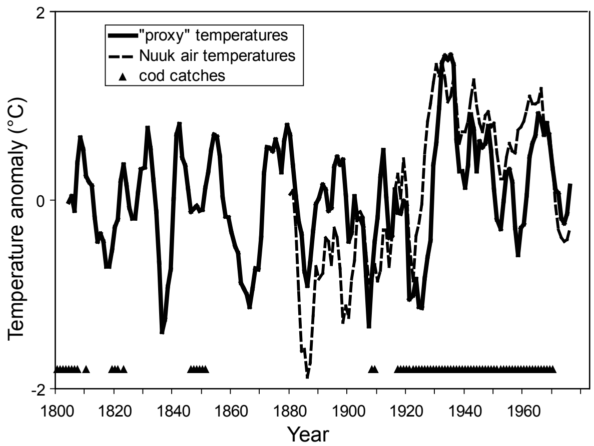

Fig. 19. Non-adjusted "proxy" temperature anomaly time series; triangles indicate reports of cod catches off West Greenland (Schmidt, 1931), and catches during the 20th century (Horsted, 2000).

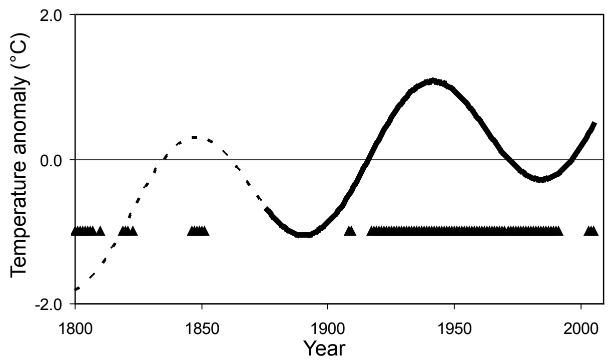

Fig. 20. Modelled West Greenland's air temperature anomalies based upon harmonic model and extended to 1800 (dashed); triangles indicate reports of cod catches off West Greenland (Schmidt, 1931), catches during the 20th century (Horsted, 2000) and the recent increase of cod biomass and abundance.

NCAR climatic data on zonal and meridional wind components were analysed for the months of May-August in 1985 and 2003, for the region between Iceland and Greenland (Fig. 21). The zonal wind component plays a significant role in the transport of cod larvae from Iceland across the Denmark Strait (Fig. 1) to Greenland (Stein and Borovkov, 2004). This hypothesis is tested here, based on the wind conditions during 1985 and 2003 (Fig. 21), and the respective 0-group indices of cod and haddock (Fig. 18).

The wind conditions were very similar during May–August in 1985 and 2003, with both years being characterized by strong negative zonal and meridional components off Iceland and Greenland. Negative zonal components represent winds blowing from the east, negative meridional components indicate winds blowing from the north. The resulting winds are thus northeasterlies which favour the transport of gadid larvae from Iceland to Greenland, and strengthen the Irminger-West Greenland Current System.

Discussion

When we attempt to characterize the atmospheric and oceanic climate off Greenland during past decades and centuries, we mostly use available instrumental records. These data cover at maximum the period 1876 to present. Statistical methods were used to extrapolate the temperature time series back to 1800. This method does, however, extrapolate the trend and periodicity of the measured time series, which might not be adequate. Another means to reveal climatic changes in pre-instrumental times are "proxy" climatic data which are derived from ice cores, tree rings, or sediments in lakes. There are several caveats when using these sources of information, and it seems suitable to compare "proxy" data time series with instrumental records time series where available.

Climatic time series based upon instrumental records, yield consistent results as regards timing of events. Nuuk air temperatures and West Greenland SSTs correlate significantly (r^2 = 0.68, p<0.001). For the period of the 1920s to the late-1960, both time series indicate warmer-than-normal conditions. Due to the larger heat storage capacity of the ocean, changes in temperature are less dramatic than those experienced in the Nuuk air temperatures during the 1880s, 1980s and 1990s.

High-resolution climate "proxy" data which are based on stacked ice core oxygen isotope records from West Greenland, correlate significantly with Nuuk air temperatures, however, only 26% of the variation are explained. The "proxy" data yield the general variation of air temperatures in time, there are, however, major deviations in timing of characteristic signals, like the onset of warming in the 1920s. During the 19th century the "proxy" data indicate considerable higher temperatures than the instrumental records. This has implications when describing climatic variations in pre-instrumental times. The "proxy" air temperature anomalies indicate warm conditions around 1810, and cooling thereafter, whereas the model curve indicates a period of cold conditions.

Comparing the modelled climatic time series of Nuuk air temperature anomalies and West Greenland

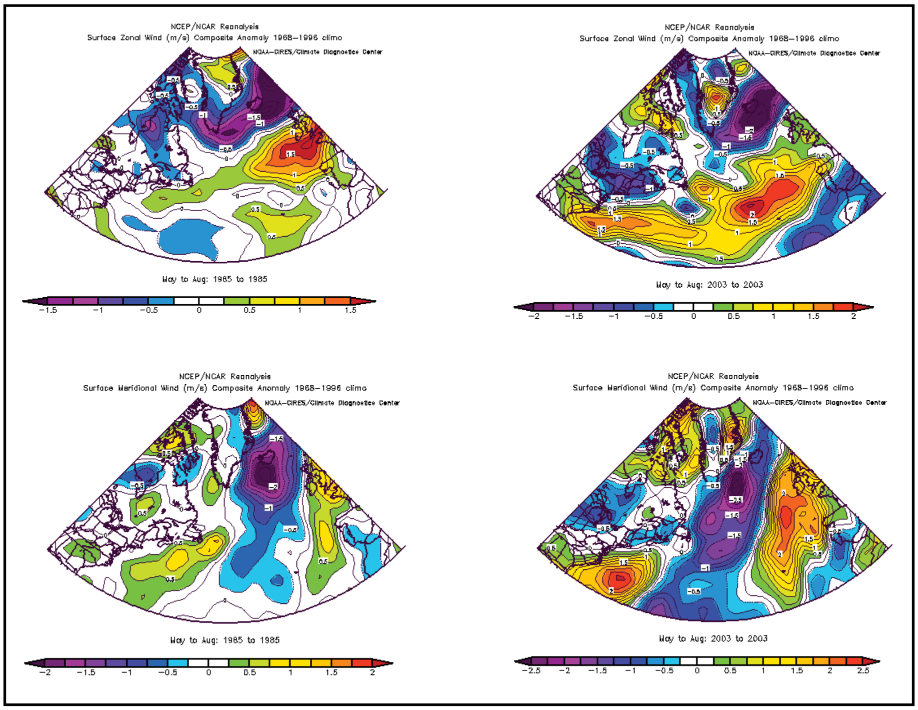

Fig. 21 NCEP/NCAR climatic data on zonal (upper panel) and meridional (lower panel) wind components for the months of May–August 1985 and 2003.

SSTs with the "proxy" temperature anomaly time series it would appear that the colder-than-normal conditions around 1820 is also revealed in the model curve of SSTs. The warmer-than-normal conditions between 1840 and 1860 are also modelled in the air temperatures and the SSTs which peak around 1860. No clear indication for the warming period around 1870 to 1880 as shown in the "proxy" time series, is visible in the two model curves, except for the initial part of both time series which show warmer-than-normal conditions around 1880, and by this reflecting parts of the 1870s, since the value for 1880 represents the mean of 1876–80.

Advective processes seem to play a decisive role in Greenland waters. This is clearly documented by oceanographic properties like temperature and salinity which indicates warming and increased salinities in the depth layers 400–800 m. This is also indicated by the presence of warm Irminger Water masses which seem to arrive in pulses off West Greenland. Observations made during the 20th century, reveal the presence of this water mass as far north as the slope station off Fyllas Bank from the 1930s onwards. Presence of Irminger Water off West Greenland is representative for warm environmental conditions. Modelling recruitment variation of Greenland cod (*Gadus morhua*) during the second half of the 20th century, Stein and Borovkov (2004) reveal that environmental parameters like air temperature, sea surface temperature and surface winds contribute significantly (79%) to the observed variation. Concerning the year classes 1973, 1984, 1985 and 1999, there is evidence that the obtained models clearly document these four year classes. Recruitment modelling (*cf.* Fig. 6 in Stein and Borovkov, 2004) indicates for the years 1997, 1998 and 1999 high recruitment levels, similar to the years 1983, 1984 and 1985.

NOAA Extended Sea Surface Temperature Anomalies reveal similar warming periods as seen in the "proxy" air temperature anomalies for the second half of the 19th century. During 1855–59, warming was encountered in the waters adjacent to Greenland during May–August. Warming was also apparent to the southeast off Greenland, and the North Atlantic Subpolar Gyre waters had warmed by up to 0.4°C during these years. After that, in the 1860s, similar to the "proxy" time series, the Gyre shrunk in its regional extension and cooled. During the 1870s, there was a tremendous increase in regional extension of the Gyre, covering the "Greenland-Iceland System with warm water of more than 1.0°C above the climatic mean. There existed warm water regions in near-coastal areas of East Greenland, Southeast Greenland, and to the west off Greenland (1870–74). This warming period is also detectable in the "proxy" time series.

There seems to be reasonable evidence that the high-resolution climate "proxy" data are able to describe the climatic variations off West Greenland in a very consistent manner. The addition of reports of cod catches off West Greenland during the 19th century, and catches during the 20th century, to the graph of the "proxy" time series (Fig. 19) reveals that the general description as given by Anon (1965) might be near to reality: "In general warm years are likely to be more favourable for cod, the increased temperature enabling them to disperse over a wider area of the banks." It is, however, not only wider dispersal, a favourable climate contributes through environmental parameters like air temperature, sea surface temperature and surface winds significantly to the observed variation in gadid recruitment. And we must not forget the consequences of favourable climatic conditions on the biota of the area.

As shown by Stein and Borovkov (2004) increases in the zonal winds in the East Greenland area during the first summer influence larval cod survival in the East Greenland Current, and meridional winds in the Southwest Greenland area play an important role during the first winter year of life for young cod.

As can be seen from Fig. 20 it is also during periods of colder-than-normal temperatures, as in the beginning of the 19th century, when cod catches were reported from West Greenland. Temperatures at the beginning of the 19th century differ considerably if we compare Figs. 19 and 20. The "proxy" air temperature anomalies (Fig. 19) indicate warm conditions around 1810, and cooling thereafter. Similar temperature conditions for the early-1800s are given by Vinther *et al.* (2003) based on GRIP (joint European Greenland Ice Core Project) ice core data from central Greenland at 72° 35' N, 37° 38' W, and temperature records obtained from coastal sites which were combined with early observational records from locations along the south and west coasts of West Greenland (Vinther *et al.*, 2006). The model curve (Fig. 20) indicates, however, a period of cold conditions, characterized by a positive temperature gradient. This concurs with Jónsson (1994) who emphasizes that a gradual, but irregular, increase in temperatures during the first half of the 19th century, was reflected in an increase of Icelandic cod landings. As mentioned below advective factors dominate the "Iceland-Greenland-System". Model results (Stein and Borovkov, 2004) suggest that, without the export of pelagic juvenile cod from Iceland to Greenland there would be no significant cod recruitment off Greenland. Accordingly, air temperatures in Iceland and Greenland, peaking in the 1820s and 1840s, and landings of Icelandic cod following this very closely could point at improvement of the state of the Icelandic cod stock – and consequently of the Greenlandic cod stock – when compared with the low state of the stock at the beginning of the 19th century (Jónsson, 1994).

Similar conclusions are drawn by Dickson *et al.* (1994) who identified three major cod periods at West Greenland: in the 1820s (–1831?), in 1845–50 and in the 1920s to 1960s. They hypothesize that the two periods in the 19th century could have been generated in the same way as the last period: wind-induced increase in the spread of warmth and larvae from Iceland *via* a strengthened Irminger-West Greenland Current System (Fig. 21). Taking the long-term minima in sea-ice extent in the Davis Strait (itself a proxy for the wind-field in the early part of the year) they see partial evidence that similar hydrobiological processes were involved.

Thus, as emphasized by Stein (MS 2004), warming in West Greenland waters is suggested to be the environmental forcing responsible for the high abundance of young demersal fish like juvenile cod and haddock. As documented in the analysis of water masses, the warm Irminger water mass seems to arrive in pulses off West Greenland. Increased northward transport of the West Greenland Current during 2004, with ocean properties at this time being more saline and up to 2°C warmer-than-normal (Stein, 2005) point at a warmer-than-normal North Atlantic Subpolar Gyre (Fig. 11). It is suggested that there are two modes which are characteristic for the Gyre:

· periods of regional shrinkage of warm water masses within the Gyre, being adverse for the propagation of gadids from upstream Icelandic waters to Greenlandic waters,
· and periods of regional dilatation of warm water masses within the Gyre, being favourable for developing gadid stocks in Greenlandic waters.

With regard to biological advection in the Greenland-Iceland system, it is suggested that the dynamics – as induced *e.g.* by the prevailing wind-fields during summer – and the water mass properties of this Gyre steer the variation in abundance of gadids in West Greenland waters significantly.

Results from the 2005 German bottom trawl survey in Greenland waters indicate that the positive trend as found for the Greenland cod stock in 2003, is continuing. Compared to the historical scenario, this trend can, however, only be seen as minor recovery. Recovery is based on the 2003 year-class which clearly dominates the other age groups. Additionally, the warming of water masses (as observed since the mid-1990s in the area) and no directed fishery on cod, seem to play a role.

Summary

Comparative studies on instrumental and "proxy" temperature time series were performed to arrive at the best estimate on climatic fluctuations off Greenland during more than two centuries. Modelling temperature variations during pre-instrumental time periods, *e.g.* between 1800–1876 for the West Greenland air temperatures, leads to problems when arguing on decadal scales. The warming in the beginning of the 19th century as indicated in two "proxy" temperature time series, and in temperature records obtained from coastal sites along the south and west coasts of West Greenland, is not shown in the modelled time series of Nuuk air temperature anomalies.

"Proxy" temperature time series reveal problems in timing and scaling of events when compared with measured temperatures. There seems, however, to be reasonable evidence that the high-resolution climate "proxy" data are able to describe the climatic variations off West Greenland in a very consistent manner, and they are able to resolve temperature variations on decadal scales or less. The modelling method is not able to reveal high-frequency variations due to the extrapolated linear trend and low frequency periodicity inherent in the measured time series. These data, however, merit attention when explaining characteristic multi-decadal variations in the period covered by data.

Of the physical processes involved in the variations of the oceanic environment off Greenland, advective processes seem to play a decisive role in Greenland waters. This is clearly documented by the presence of warm Irminger Water masses which seem to arrive in pulses off West Greenland during the 20th century and the beginning of this century. Warming and cooling of water masses within the North Atlantic Subpolar Gyre, *viz* periods of regional shrinkage and dilatation of warm water masses within the Gyre, seem to play a vital role in the developing of gadid stocks in Greenland waters.

Of the atmospheric forcing processes, it is the wind-induced increase in the spread of warmth and larvae from Iceland to Greenland via a strengthened Irminger-West Greenland Current System. May–August wind anomalies during two years with anomalous strong cod and haddock 0-group indices, 1985 and 2003, are in favour for this theory. Along similar processes the two periods in the 19th century, 1820s (–1831?), in 1845–50, and during the 20th century, in the 1920s to 1960s could have been generated. The most recent example of a cod year class benefiting from this warming and wind drift induced scenario, is the 2003 cod year class which dominates the Greenland cod stocks at present.

When considering the pros and cons of the used methods in detecting temperature variations off Greenland over more than two centuries, they each have their respective merits. For the discrimination of temperature scenarios during times of reports on cod catches off West Greenland, however, the "proxy" temperature data have more potential than the modelled and extrapolated temperature data. They should therefore be taken when explaining correlations between the occurrence of cod in Greenland waters, and temperature variations during pre-instrumental times.

References

ANON. 1965. The West Greenland cod fishery. Laboratory leaflet (new series) No. 7, March 1965. Fisheries Laboratory Lowestoft, Pakefield, U.K.

ANON. 2002. Report of the workshop on the transport of cod larvae. Hillerød, Denmark, 14–17 April 2002. *ICES CM Doc.,* 2002/C:13 Ref.: ACE. http://www.ices.dk/reports/occ/2002/wktcl02.pdf

ANON. 2006. Report of the North-Western Working Group (NWWG), 25 April–4 May 2006 (*ICES CM Doc.,* 2006/ACFM:26). http://www.ices.dk/committe/acfm/comwork/report/2006/may/cod-ewgr.pdf and http://www.ices.dk/committe/acfm/comwork/report/2006/may/had-iceg.pdf

BUCH, E., HORSTED, S. A., and H. HOVGÅRD. 1994. Fluctuations in the occurrence of cod in Greenland waters and their possible causes. *ICES Mar. Sci. Symp*., **198**: 158–174.

CLARKE, R. A. 1984. Transport through the Cape Farewell-Flemish Cap section. *Rapp. P.-V. Réun. Cons. Int. Explor. Mer*, **185**: 120–130.

DICKSON, R. R., K. R. BRIFFA, and T. J. OSBORN. 1994. Cod and climate: the spatial and temporal context. *ICES Mar. Sci. Symp*., **198**: 280–286.

DEYOUNG, B., and G. A. ROSE. 1993. On recruitment and distribution of Atlantic cod (*Gadus morhua*) off Newfoundland. *Can. J. Fish. Aquat. Sci.*, **50**: 2729–2741.

HANSEN, P. M. 1949. Studies on the biology of the cod in Greenland waters. *Rapp. P.-V. Réun. Cons. Int. Explor. Mer,* **123**: 1–77.

HORSTED, S. V. 2000. A review of the cod fisheries at Greenland, 1910–1995. *J. Northw. Atl. Fish. Sci.*, **28**: 1–112.

HOVGÅRD, H., and J. MESSTORFF. MS 1987. Is the West Greenland cod mainly recruited from Icelandic waters? An analysis based on the use of juvenile haddock as an indicator of larval drift. *NAFO SCR Doc*., No. 31, Serial No. N1315, 18 p.

JENSEN, A. S. 1926. Investigations of the "Dana" in West Greenland waters, 1925. *Rapp. P.-V. Réun. Cons. Int. Explor. Mer*, **39**: 85–102.

JENSEN, A. S. 1939. Concerning a change of climate during recent decades in the arctic and subarctic regions from Greenland in the west to Eurasia in the east, and contemporary biological and geophysical changes. *Det Kgl. Danske Vid. Selskab Biol. Meddr*. **XIV**, 8. København.

JENSEN, A. S. 1948. Contribution to the ichtyofauna of Greenland, 8–24. Skrifter udgivet af Universitetets zoologiske Museum København. **IX**: 1–182.

JENSEN, A. S., and P. M. HANSEN. 1931. Investigations on the Greenland cod (*Gadus callarias* L.). *Rapp. P.-V. Réun. Cons. Int. Explor. Mer*, **52**: 1–41.

JONES, P. D., and M. E. MANN. 2004. Climate over past millennia. *Rev. Geophys.,* **42**, No. 2, RG2002. doi:10.1029/2003RG000143

JÓNSSON, J. 1994. Fisheries off Iceland, 1600–1900. *ICES Mar. Sci. Symp*., **198**: 3–16.

LEAR, W. H., and L. S. PARSONS. 1993. History and management of the fishery for northern cod in NAFO Divisions 2J, 3K and 3L. *In*: Perspectives on Canadian fisheries management, L. S. Parsons and W. H. Lear (eds). *Can. Bull. Fish. Aquat. Sci*., **226**: 55–89.

MARTEINSDOTTIR, G., B. GUNNARSSON, and I. M. SUTHERS. 2000. Spatial variation in hatch date distributions and origin of pelagic juvenile cod in Icelandic waters. *ICES J. Mar. Sci.,* **57**: 1182–1195. doi:10.1006/jmsc.2000.0880

NILSSEN, E. M., C. C. E. HOPKINS, K. THYHOLDT, and J. POPE. 1994. Recruitment variability and growth of northeast arctic cod: influence of physical environment, demography, and predator-prey energetics. *ICES Mar. Sci. Symp.,* **198**: 449–470.

OLAFSSON, J. MS 1985. Recruitment of Icelandic haddock and cod in relation to the variability in the physical environment. *ICES CM Doc.,* 1985/G:59/Q (mimeo). 10 p.

OTTERSEN, G., and S. SUNDBY. 1995. Effects of temperature, wind and spawning stock biomass on recruitment of Arcto-Norwegian cod. *Fish. Oceanogr.,* **4**: 278–292.

RÄTZ, H.-J., M. STEIN, and J. LLORET. 1999. Variation in growth and recruitment of Atlantic Cod (*Gadus morhua*) off Greenland during the second half of the 20th century. *J. Northw. Atl. Fish. Sci.,* **25**: 161–170.

SCHLITZER, R. 2006. Ocean Data View. http://odv.awi.de

SCHMIDT, J. 1931. On the occurrence of the cod (*Gadus callarias* L.) at East Greenland. *Rapp. P.-V. Réun. Cons. Int. Explor. Mer*, **52**: 1–8.

SMED, J. 1975. Monthly anomalies of the sea surface temperature in areas of the northern North Atlantic in 1972. *Ann. Biol.*, **30**: 15–17.

SMITH, T. M., and R. W. REYNOLDS. 2004. Improved extended reconstruction of SST (1854–1997). *J. Clim*., **17**: 2466–2477. doi:10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2

STEIN, M. MS 1988. Revision of list of NAFO standard oceanographic sections and stations. *NAFO SCR Doc*., No. 1, Serial No. N1432, 9 p.

STEIN, M. 1995. Climatic conditions around Greenland – 1992. *NAFO Sci. Coun. Studies*, **22**: 33–41.

STEIN, M. MS 2004. Transport of juvenile cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from Iceland to Greenland – is there environmental forcing? *NAFO SCR Doc.*, No. 4, Serial No. N 4946, 15 p.

STEIN, M. 2005. North Atlantic subpolar gyre warming – impacts on Greenland offshore waters. *J. Northw. Atl. Fish. Sci.*, **36**: 43–54. doi:10.2960/J.v36.m568

STEIN, M., and V. A. BOROVKOV. 2004. Greenland cod (*Gadus morhua*): modeling recruitment variation during the second half of the 20th century. *Fish. Oceanogr.,* **13(2)**: 111–120. doi:10.1046/j.1365-2419.2003.00280.x

VILHJALMSSON, H., and E. FRIDGEIRSSON. 1976. A review of 0-group surveys in the Icelandic-East Greenland area in the years 1970–1975. *ICES Coop. Res. Rep*., No. 54.

VINTHER, B.M., S.J. JOHNSEN, K.K. ANDERSEN, H.B. CLAUSEN, and A.W. HANSEN. 2003. NAO signal recorded in the stable isotopes of Greenland ice cores. *Geophys. Res. Lett.*, **30**(7): 1387. doi:10.1029/2002GL016193.

VINTHER, B. M., K. K. ANDERSEN, P. D. JONES, K. R. BRIFFA, and J. CAPPELEN. 2006. Extending Greenland temperature records into the late eighteenth century. *J. Geophys. Res*., **111**: D11105. doi:10.1029/2005JD006810

WIELAND, K., and H. HOVGÅRD. 2002. Distribution and drift of Atlantic cod (*Gadus morhua*) eggs and larvae in Greenland offshore Waters. *J. Northw. Atl. Fish. Sci*., **30**: 61–76.