Northwest Atlantic Fisheries Organization

Serial No. N4946 **NAFO SCR Doc. 04/4**

SCIENTIFIC COUNCIL MEETING – JUNE 2004

Transport of Juvenile Cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) from Iceland to Greenland – Is there Environmental Forcing?

by

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Abstract

The first observations of Atlantic cod (*Gadus morhua*) in East and West Greenland waters date back to the 16th century. This paper analyses interactions of 0-group cod and one-year old cod with environmental data. The biological and oceanographic data sets used for the analysis were obtained during annual surveys of RV "Walther Herwig" to East and West Greenland waters (1982-2003). A negative significant correlation exists between one-year old cod, NAO index and the mean baroclinic flows of the cold polar component of the West Greenland Current. By means of the distribution and abundance of 0-group haddock (*Melanogrammus aeglefinus*) it is demonstrated that the penetration of demersal fish is dependant on warming effects in the marine ecosystems of West and East Greenland. It is suggested that the advection of warm, saline water masses to banks and slopes off West Greenland favoured environmental conditions under which gadoids, such as cod and haddock live in these waters. The paper concludes that the concurrent warming trends observed in air temperatures and ocean temperature since 1993 off West Greenland have led to temperatures exceeding 6°C in the bottom water layers off West Greenland, temperatures which appear to be suitable especially for haddock. The temperature at 200 m depth at Fyllas Bank section station 4 as observed during autumn 2003, was the warmest on record. Warming in West Greenland waters is suggested to be the environmental variable responsible for the present high abundance of young gadoids around East and West Greenland.

Introduction

First observations of cod (*Gadus morhua*) were reported from East and West Greenland during the 16th century. Cod appeared to be abundant at certain periods of the last 450 years, such as around 1590 in the Angmagssalik region, around 1820, 1845 and from 1920 to the mid-1970s (Schmidt, 1931; Jensen and Hansen, 1931; Horsted, 2000). Cod abundance was low in other periods (Rätz *et al*., 1999; Wieland and Hovgard, 2002; Stein and Borovkov, 2004).

First research on the distribution of cod fry and eggs at West Greenland were done by Denmark (e.g. Jensen, 1926), or most recently by Wieland and Hovgard (2002).

First observations on cod fry off East Greenland were done by the former governor of Angmagssalik, A. Hedegaard, and *personally communicated* to Schmidt (1931). He revealed that from autumn 1926 onwards "cod is now found throughout the year, the large quantities of large cod mainly from May to July" and that "numbers of small cod also occur, even those down to 5-6 cm in length (observed in July 1930). Schmidt (1931) concluded that it does not seem unreasonable to believe, that there is a close connection between the cod of Iceland and this part of East Greenland.

Main spawning grounds of Icelandic cod are located to the southwest and west off Iceland. Those cod found off the southwest coast hatch around mid-May, while those further north and east of Iceland hatch progressively later throughout May, June and early-July (Begg and Marteinsdottir, 2000). Concentrations of pelagic, juvenile cod are entrained in the main Irminger Current system (Valdimarsson and Malmberg, 1999), and thus transported to the bank and slope regions off East Greenland. In some years (1973, 1978, 1981, 1984, 1985, 1987, 1990; see Fig. 6 in: Begg and Marteinsdottir, 2000) large concentrations are found in East Greenland waters, generally distributed along the 500 m isobath. Further research, focussing on the "Transport of fish larvae between Iceland and West Greenland waters – Hydrography and biology" is presently done in a multi-national project (funded by the "Vestnordisk Oceanklima Forskningsprogram"). Based on drift modelling of pelagic stages of fish in the East Greenland/Iceland area with special emphasis on cod larvae, there are promising results to be expected (Harms, *pers. comm.;* Ribergaard, *pers. comm.*).

Haddock (*Melanogrammus aeglefinus*) is usually found at temperatures between 4° and 10°C. This species has been rarely seen in West Greenland waters. Historically, the first specimen of haddock were caught in the Cape Farewell region in 1929 (Jensen, 1948; Hansen, 1949; Hovgard and Messtorff, 1987). Spawning areas of haddock found in Greenland waters are believed to be in Southwest Iceland (Wieland and Hovgård, 2002), in the area around the Reykjanes peninsula (Olafsson, 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). Focussing on Greenland cod and his potential recruitment from Icelandic waters, Hovgård and Messtorff (1987) used juvenile haddock as indicator for larval drift. They concluded that data on young cod and haddock distribution and abundance indicate that a larval drift of these species from Iceland to Greenland has occurred only infrequently during the 1970s and 1980s. According to their findings 0-group haddock have only rarely been seen in East Greenland waters (1974, 1979, 1980, 1984 and 1985) and when so, always in very small quantities. The same authors 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.

The present paper considers oceanographic and biological data sampled annually since 1982 during the German groundfish surveys to East and West Greenland waters. Following the model assumption as given in Anon. (2002) and by Stein and Borovkov (2004) on the transport mechanisms in the 'Iceland-Greenland System', interactions between juvenile cod, 0-group haddock, and the underlying current and temperature fields are analysed. By means of climatic data (air pressure, NAO-index) the climatic background during the years 1973, 1984, 1985 and 1999 is presented.

Data and Methods

Biological and oceanographic data were obtained during annual groundfish surveys by Germany from 1982 to 2003. They formed the basis for the analysis of the oceanographic situation and the abundance and biomass of 0-group and one-year old cod in East and West Greenland waters, as well as the abundance and biomass of 0-group haddock. The oceanographic data are accessible through the Ocean Data View (ODV; Schlitzer, 2003) data base of the Institute for Seafisheries, Hamburg. The biological data are deposited in the format of an ACCESS Data bank. To scrutinize identify 0-group and one-year old cod from length frequency compositions during the years 1982-2003, a fish length filter was set to < 14cm, and 16-24cm respectively. Haddock 0-group was selected as fish lengths <19 cm.

Mean current speeds of the cold polar component of the West Greenland Current were obtained by the "geostrophic flows method", incorporated in the ODV-software. Mean bottom water temperatures (1989-2003) were obtained by means of the ODV-software. The North Atlantic Oscillation (NAO) Index as provided in Fig. 5 refers to the mean December, January, February (DJF) sea level pressure (SLP) from the Azores (Ponta Delgada, PD) and from Iceland (Akureyri, A). The individual SLP's are standardized to 1961-90 base period, and calculated using:

$$\mathrm{NAO_i} = \frac{p_i - \overline{p}}{\sigma}\Big|PD - \frac{p_i - \overline{p}}{\sigma}\Big|A$$

with $_i$ = year, p_i = SLP of the given year from *PD* or *A*, p = mean SLP of the 1961-90 base period from *PD* or *A*, σ =

standard deviation of the 1961-90 base period. DJF pressures for 1998/99 and 1999/2000 for Ponta Delgada were defined by regression (Loewe and Koslowski, 1998).

Data on the atmospheric climate of Greenland are obtained 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 modelling work referred to in this paper, was recently published by Stein and Borovkov (2004). Climatic data used in this publication are available on a website of NOAA-CIRES Climate Diagnostics Centre, Boulder, CO, USA.

Results

The survey area covered during the period 1982-2003 is given in Fig. 1. The abundance of cod in Greenland waters during 2002 and 2003 (Fig. 2), clearly reveals the incoming "new generations" of 0-group and year-class-1 cod observed during the 2003 autumn survey of RV "Walther Herwig III". 0-group cod as found in the bottom trawl during 1982-2003 is given in Table 1, the respective numbers for 0-group haddock are displayed in Table 2. The years 1984 and 1985 clearly show the majority of young cod found in West Greenland waters, strata 2.1, 3.1, 4.1 to enumerate the maxima in 1985. During the early- to mid-1990s no 0-group cod was found during the surveys. During 2003, most 0-group cod was found in the East Greenland/Dohrn Bank region. It must be noted that stratum 1 was not sampled during all years.

Numbers of 0-group haddock [numbers given in brackets] found in big quantities during 1985 (344), 2002 (228) and 2003 (2107), correlate significantly (41%) with the numbers of 0-group cod (Fig. 3). The correlation between one-year old cod numbers (Fig. 4) is significant but weak concerning 0-group cod (27%) and 0-group haddock (21%). It is suggested here that selectivity of the used bottom trawl (140' bottom trawl) plays a decisive role in catching especially 0-group cod.

Currents and NAO_{DJF} index

Mean geostrophic current velocities of the West Greenland Current crossing the line of the Cape Desolation section (Fig. 5) reveal considerable changes during 1982-2003. There are gaps of observations (1984, 1985, 1992, 2000). The NAO index plotted in the same figure seems to be useful as a proxy for changes in the speeds. There is a positive, highly significant correlation (Fig. 6) between the strength of the baroclinic mean values of the cold polar component of the West Greenland Current and the NAO winter index (69%). This suggests that the air pressure anomaly over the North Atlantic Ocean, nine months prior to measuring the thermohaline fields along the Cape Desolation Section (Stein, 1988), appear to affect the dynamic properties of the mean ocean currents off West Greenland. This indicates that high NAO indices cause high baroclinic flows/transports and low NAO indices lead to reduced current flows/transports in the polar component of the West Greenland Current system. NAO+ years are characterized by strong westerlies bringing warm air masses to Europe, whereas during NAO- years warmer-than-normal air temperatures are prevailing in the Iceland/Greenland/Labrador Sea region. The NAO index given in Fig. 5, demonstrates that 1984 and 1999 were NAO+ years and the index was high in contrast to 1985 which was a NAO- year with a low index. Current observations are only available for the year 1999.

Analysis on the correlation between geostrophic currents, NAO winter indices and 0-group cod, 0-group haddock and one-year old cod, provides significant negative but weak correlation results only for the latter. Accordingly, the variation in the one-year old cod abundance in Greenland waters may be explained to a minor degree by geostrophic currents (20%), and the NAO winter index (16%).

Temperature

The long-term air temperature variation at Nuuk showed colder-than-normal and warmer-than-normal periods (bold line in Fig. 7). Going back in history to the times of first reporting of cod in the Angmagssalik fjord around 1590, information on air temperatures derived from the ice core data (Crowley and Kim, 1993) - the stable isotopes of oxygen and hydrogen atoms in the water molecule are typically used to infer paleoclimate, particularly paleotemperature (Oeschger, 1991) - may be taken as a relative measure (Fig. 8). When comparing the data from 1800 onwards, with directly measured air temperatures from Nuuk (Fig. 9), it would appear that the relative temperature time series has revealed the climatic trends fairly well. Accordingly, the findings of cod in the 16th century were done in an intermediate warming period during the "Little Ice Age" (1450 AD to about 1850 AD). The relatively low temperatures in the area at the time, thus suggests that climatic cooling did not seem to have had adverse affects on the fish stocks.

Based on instrumental temperature records, the 19th century and the early-1900s saw colder-than-normal air temperatures at Nuuk. Warmer-than-normal conditions were encountered during the 1920s to mid-1970s, and colder-than-normal conditions thereafter. From the mid-1990s onwards, temperatures seem to increase. Stein (1995) showed that a low frequency model might explain the long-term warming and cooling cycles observed from the 19th century onwards. The basic assumptions of the harmonic model, which is based on a period of 108 years, consisted of warmer-than-normal conditions in 1923-1976 and colder-than-normal conditions before and after. The long-term climatic signal is modulated by high frequency events, which occur at different periodicities (Stein, 1995). Cold events are particularly evident at the beginning of the 1970s, 1980s and 1990s (Fig. 7). The years 1972, 1982 and 1992 were extremely cold years. Even colder were the years 1983 and 1993. Stein (1995) showed that the characteristic frequency of these cold events is approximately 12.5 years (peak to peak). Future will show whether the present observed warming is "intermediate" or a trend reversal from cooling to warming (Stein, 2004).

Mean bottom water temperatures off West Greenland were estimated from the temperatures measured at each fishing station close to the sea floor (1989-2003, Fig. 10). The linear trend incorporated in the temperature time series, is highly significant and explains 82% of variation. Correlation with Nuuk mean annual air temperature anomalies is positive and highly significant (72%). However, de-trending the time series shows that correlation is mainly (54%) based on the linear trend incorporated in both data sets.

Analysis on the correlation between air temperatures, bottom water temperatures and the abundance of 0-group cod and one-year old cod yields **no** significant correlation results.

0-group haddock and bottom water temperatures (Fig. 11) correlate significantly (40%). The correlation is, however, entirely based on the linear trend present in both data sets.

A recent example for considerable warming of the West Greenland Current is given in Fig. 12 which compares temperature, salinity and density at Cape Desolation section station 3 during autumn 2002 and 2003. In autumn 2003, the top 1 500 m were more than 1°C warmer and more saline than in the year before. A water mass with salinities exceeding 35.0 PSU in the core of the West Greenland current was recorded.

Abundance and biomass of haddock (Fig. 13) as observed during the 2003 autumn survey of RV "Walther Herwig III" are pointing at an unusual situation in the waters around Greenland. The number of haddock found in individual strata (Table 2) during 1982-2003 show that starting in the second half of the 1990s, the numbers increased and peak during the 2003 observations. This trend correlates significantly with the warming found in the bottom waters off West Greenland (Fig. 11). The temperature at 200 m depth at Fyllas Bank section station 4 (Stein, 1988) as observed during autumn 2003, was the warmest on record (Fig. 14; 7.18°C). The temperature curve as given in Fig. 14 documents the continuous warming since 1993 at Fyllas Bank. There is **no** indication for increased current flow in the West Greenland Current (Fig. 5). Since 2001, the calculated mean flow speeds are below the mean (123 cm/sec). Since 1998, 0-group cod and 0-group haddock numbers start to show some minor increase (Table 1, 2; Fig. 4).

Discussion

During the 20th century, the period of more than 50 years of warmer-than-normal air temperatures, from the 1920s to mid-1970s, might have favoured the abundance of cod in Greenland waters. First observations of adult and 0-group cod in East Greenland waters made during 1926 (Schmidt, 1931), correlate with our observations during the 2003 autumn survey of RV "Walther Herwig III" off East Greenland, when abundance of 0-group cod peaked in the Dohrn Bank region (c.f. stratum 7.2 in Table 1). This may point at the close link to the Icelandic cod stocks and the supply of the Greenland stocks from Iceland via the Denmark Strait.

The close connection between the North Atlantic Oscillation (NAO) index during winter and the strength of the cold polar component of the West Greenland current system fosters the question whether this has an impact on the advection and survival of fish larvae, i.e. whether NAO influences the transport of cod larvae from Icelandic waters to Greenlandic waters. Modelling recruitment variation of Greenland cod (*Gadus morhua*) during the second half of the 20th century, Stein and Borovkov (2004) reveals 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, and that they indicate for the years 1997, 1998 and 1999 high recruitment levels, similar to the years 1983, 1984 and 1985. Statistical analysis on correlations between the cold polar current component of the West Greenland Current and 0-group cod and haddock abundance, as well as NAO index and 0-group cod and haddock yields **no** significant results. Correlation between current component, NAO winter index and one-year old cod, provides, however, significant negative but weak correlation results: Currents (20%), NAO winter index (16%). Although statistically not significant, it is noteworthy that high abundance of 0-group haddock and cod are observed during NAO - years (warmer-than-normal air temperatures are prevailing in the Iceland/Greenland/Labrador Sea region) and low transport conditions. This is the case in 1985 (cod, haddock), 1986 (haddock), 2002 (haddock), and 2003 (cod, haddock), (Table 1, 2; Fig. 5). Low abundance of 0-group haddock and cod are found during NAO + years (colder-than-normal air temperatures are prevailing in the Iceland/Greenland/Labrador Sea region) and high transport conditions. This was the case during most of the years between 1989 and 1998 (Fig. 5). High transport conditions along the bank/slope region off West Greenland represent increased inflow of cold polar water of East Greenland Current origin. These cold water masses seem to be unfavourable for juvenile gadoids like cod and haddock.

It would appear that advection of warm, saline water to the banks and slopes off West Greenland favoured environmental conditions under which demersal fish live in these waters. Comparing the numbers of haddock found during the mid-1980s (Hovgård and Messtorff, 1987) and the recent findings (Table 2), the conclusion may be drawn that the environmental conditions of the East and West Greenland waters provide ambient temperatures which are favourable for haddock. This interpretation is supported by the significant correlation between 0-group haddock and bottom water temperatures in West Greenland waters.

It is assumed here that the properties of the advected water masses – warmer than normal – are influential to the abundance of juvenile cod and haddock. These properties constitute suitable and “attractive” ambient conditions, maybe also through better food supply throughout the warming period (from 1993 onwards). Thus, 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.

Warming over time, not the inter-annual variations seem to be relevant for the abundance of juvenile fish in Greenland waters, cod and haddock.

Acknowledgements

I thank Dr. Karl-Hermann Kock, Institut für Seefischerei, Hamburg, Germany for discussions and critically reading the manuscript.

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Table 1. Number of 0-group cod (*Gadus morhua*), per stratum off East and West Greenland (1982-2003); for strata definition see Fig. 1.

No. of 0-group cod per stratum

	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2	5.1	5.2	6.1	6.2	7.1	7.2
1982			3											
1983											1			
1984	6	1	14	5	3		8							
1985	4	1	47	8	16	3	104		2		8	15		8
1986	2			1	1		5		1					
1987	5				1									
1988	5		1	1	1				1					1
1989	3						3							
1990	1		4				38							
1991	2		4		1									
1992														4
1993														
1994							3							1
1995														
1996														
1997											2			
1998	1						5					1		2
1999					3		1		6		7	1		1
2000			1		4									
2001			2											
2002							1		7					
2003					2		3		4		3	1		99

Table 2. Number of 0-group haddock (*Melanogrammus aeglefinus*), per stratum off East and West Greenland (1982-2003); for strata definition see Fig. 1.

No. of 0-group haddock per stratum

	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2	5.1	5.2	6.1	6.2	7.1	7.2
1982														
1983														
1984												1		
1985	1		18	2	33	17	44		20	1	118	88		2
1986	2		1				2		27	3	4	23		
1987				4					3			2		
1988	1		1		2				1		1			
1989														
1990					1		3	1	3					
1991							1		4		2			
1992								1						
1993									1		12			
1994														
1995							1				1			
1996														
1997									2					
1998							2		5		39			1
1999			4		11		19		51	1	11	3		1
2000					11				29		4	1		
2001									2		1			
2002			1		19		2	2	99		1	95		9
2003			153	3	164		191		1159		6	131		300

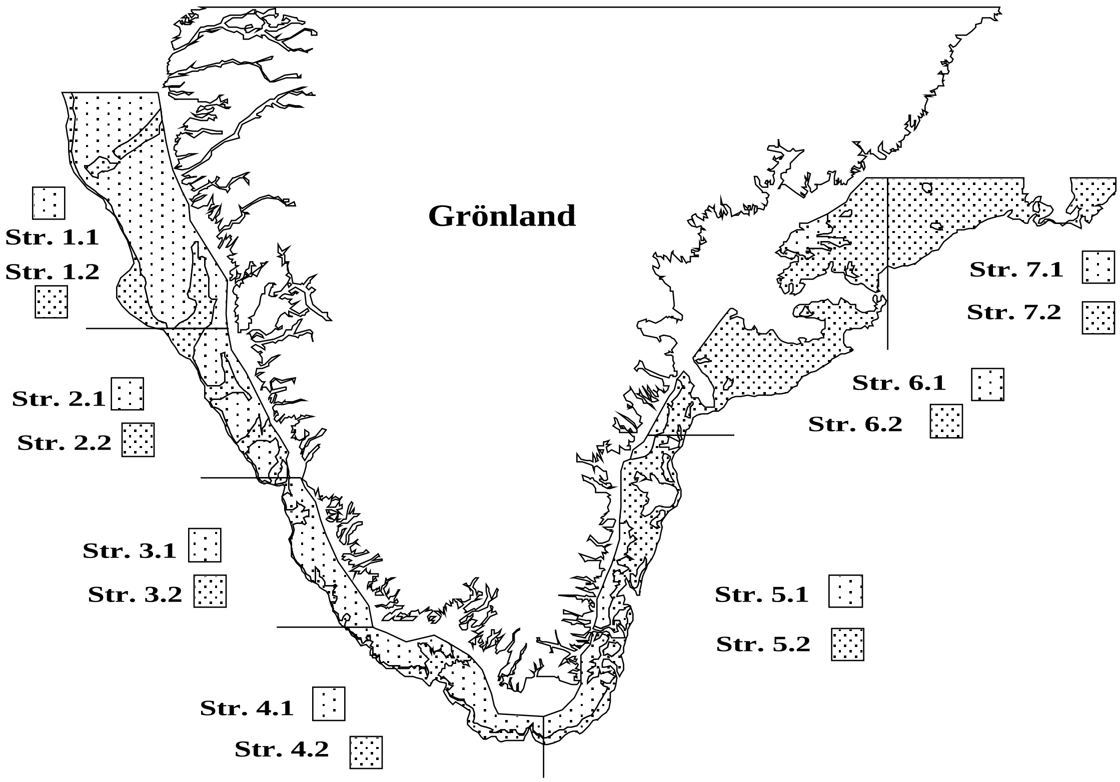

Fig. 1. Area of investigation during the German bottom trawl surveys (1982-2003) with RV "Walther Herwig II and III" and individual survey strata; strata 0-200 m: 1.1, 2.1, 3.1, 4.1, 5.1, 6.1 and 7.1, and 200-400 m: 1.2,2.2,3.2,4.2, 5.2, 6.2 and 7.2 around Greenland

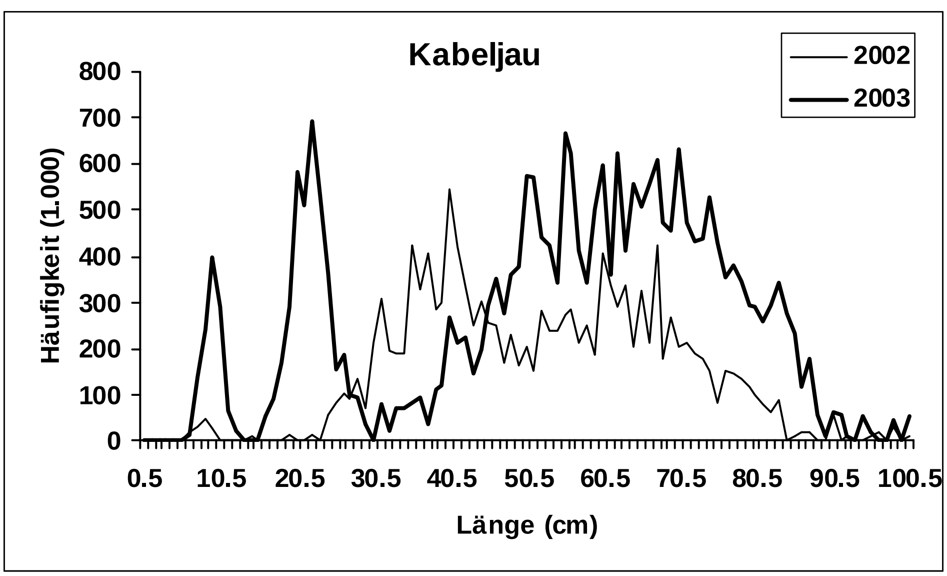

Fig. 2. Length frequencies of Atlantic cod (*Gadus morhua*) during the German autumn bottom trawl survey to East and West Greenland waters, 2002-2003

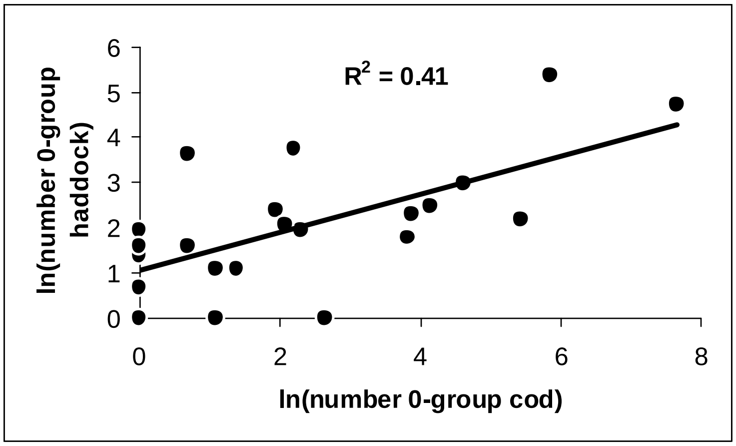

Fig. 3. Correlation of 0-group Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*).

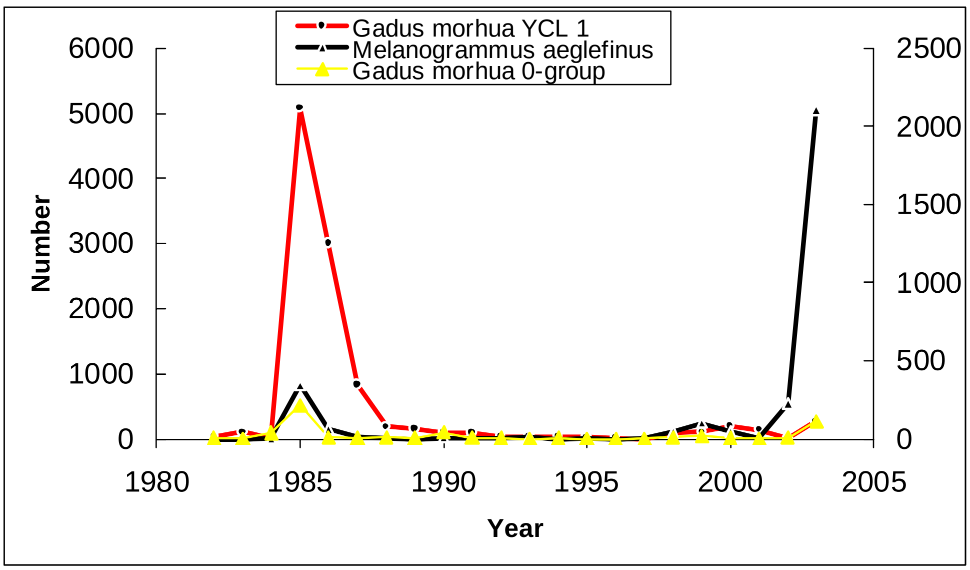

Fig. 4. Number of juvenile Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*).

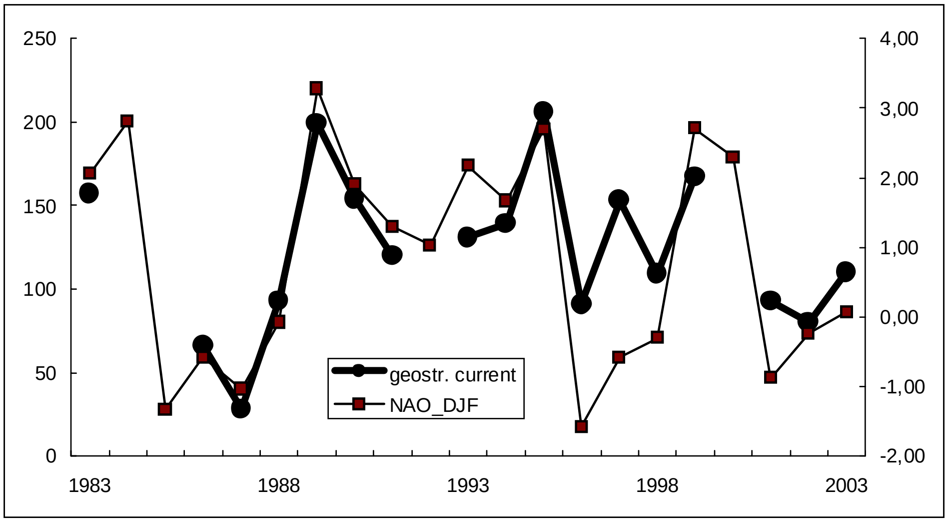

Fig. 5. Mean geostrophic current velocities of the West Greenland Current crossing the line of the Cape Desolation section and NAO_{DJF} index.

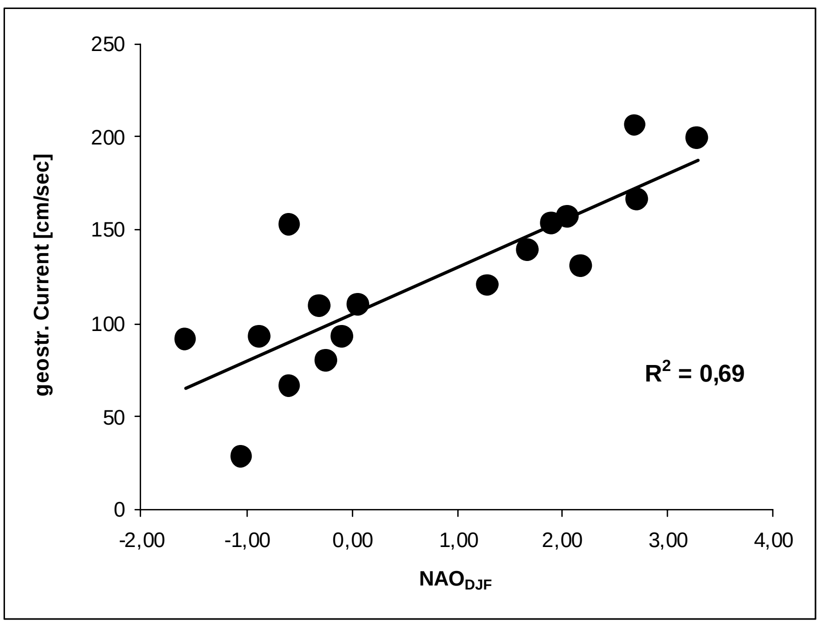

Fig. 6. Correlation of mean geostrophic current velocities of the West Greenland Current crossing the line of the Cape Desolation section and NAO_{DJF} index.

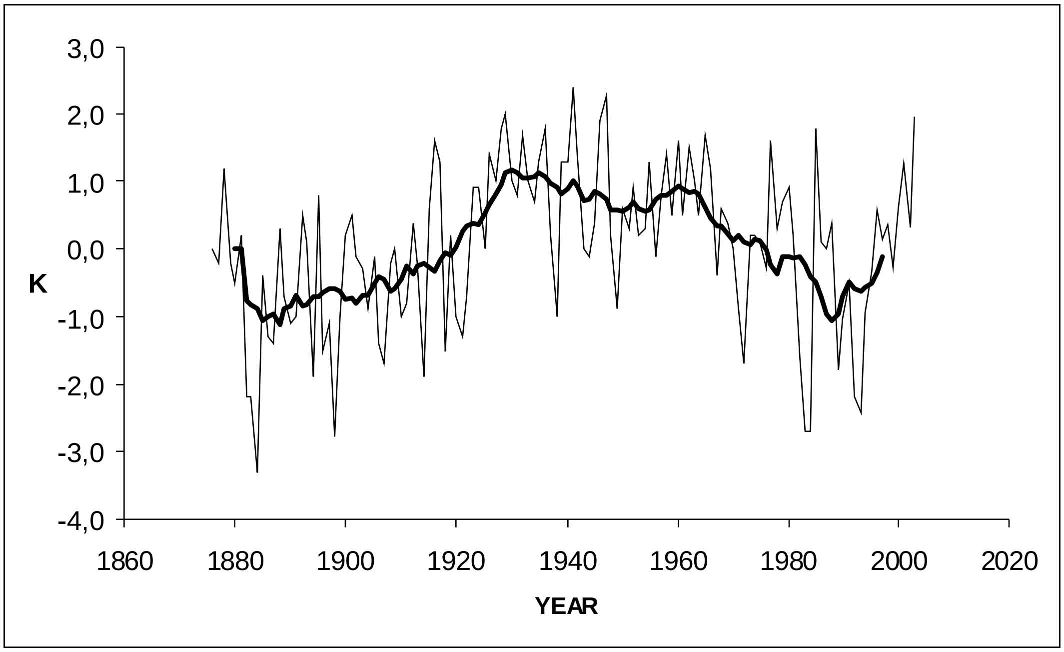

Fig. 7. Air temperature anomalies (rel. 1961- 1990) at Nuuk (1876-2003); bold: 13 year mean.

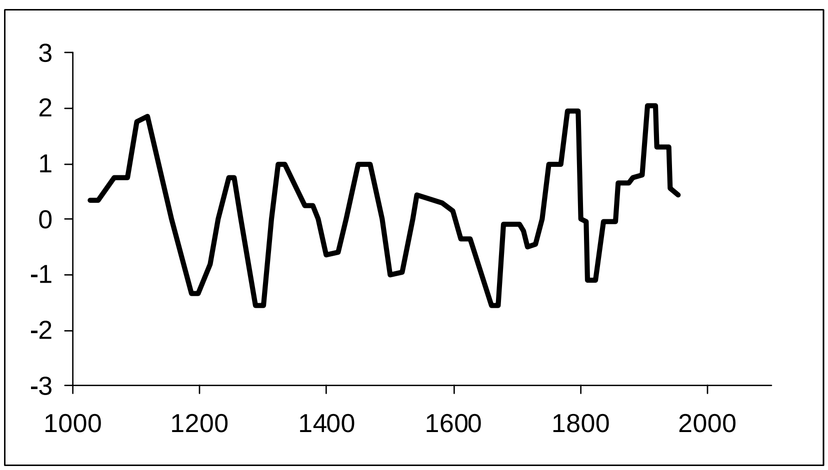

Fig. 8. Greenland air temperature time series derived from ice core data (adopted from Crowley and Kim, 1993); relative temperature scale.

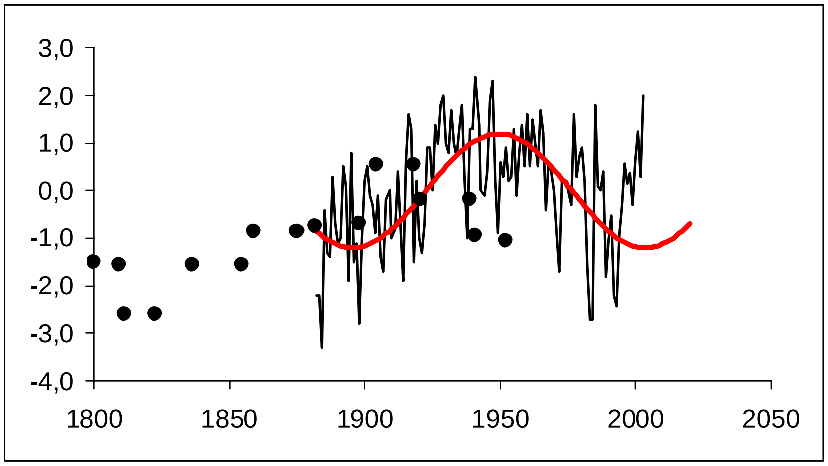

Fig. 9. Overlap of time series of annual mean air temperature anomalies (thin line) at Nuuk/West Greenland (1883-2003, rel. 1961-1990) and relative temperature as derived from ice core data (position of dots is individually adjusted to the Nuuk curve; see Fig. 9); red: harmonic model of long-term air temperature variation at Nuuk (c.f. Stein, 1995)

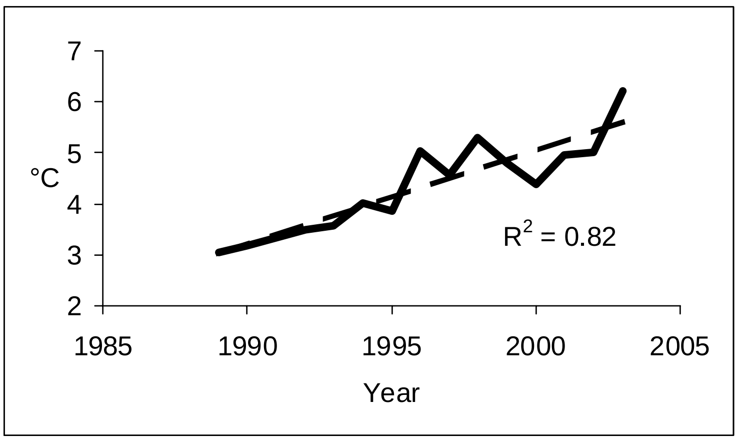

Fig. 10. Mean bottom water temperatures off West Greenland estimated from the temperatures measured at each fishing station near the sea floor (1989-2003).

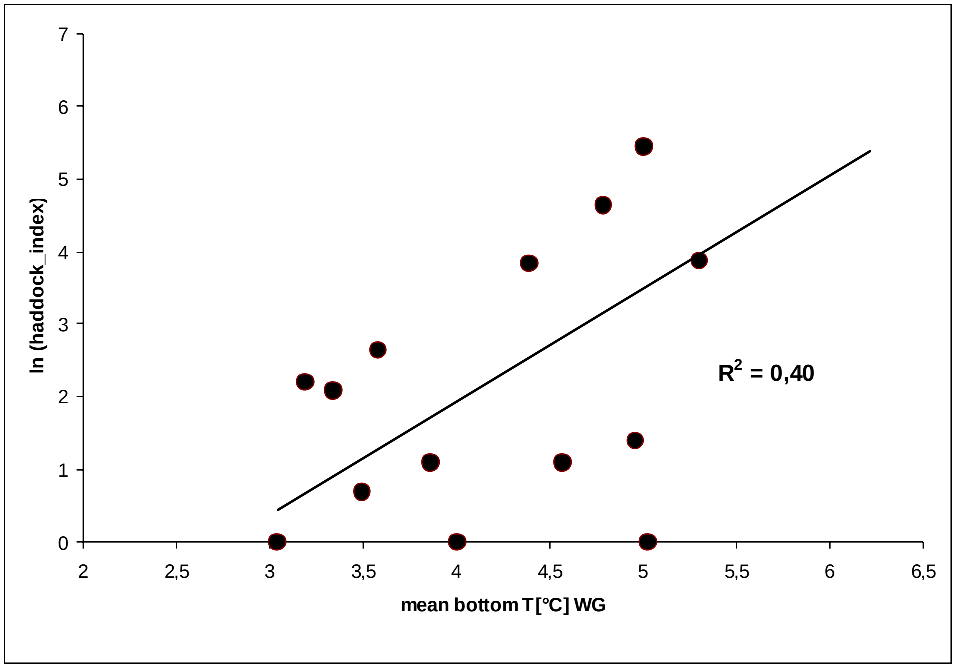

Fig. 11. Correlation of 0-group haddock (*Melanogrammus aeglefinus*) and mean bottom water temperatures off West Greenland (1989-2003).

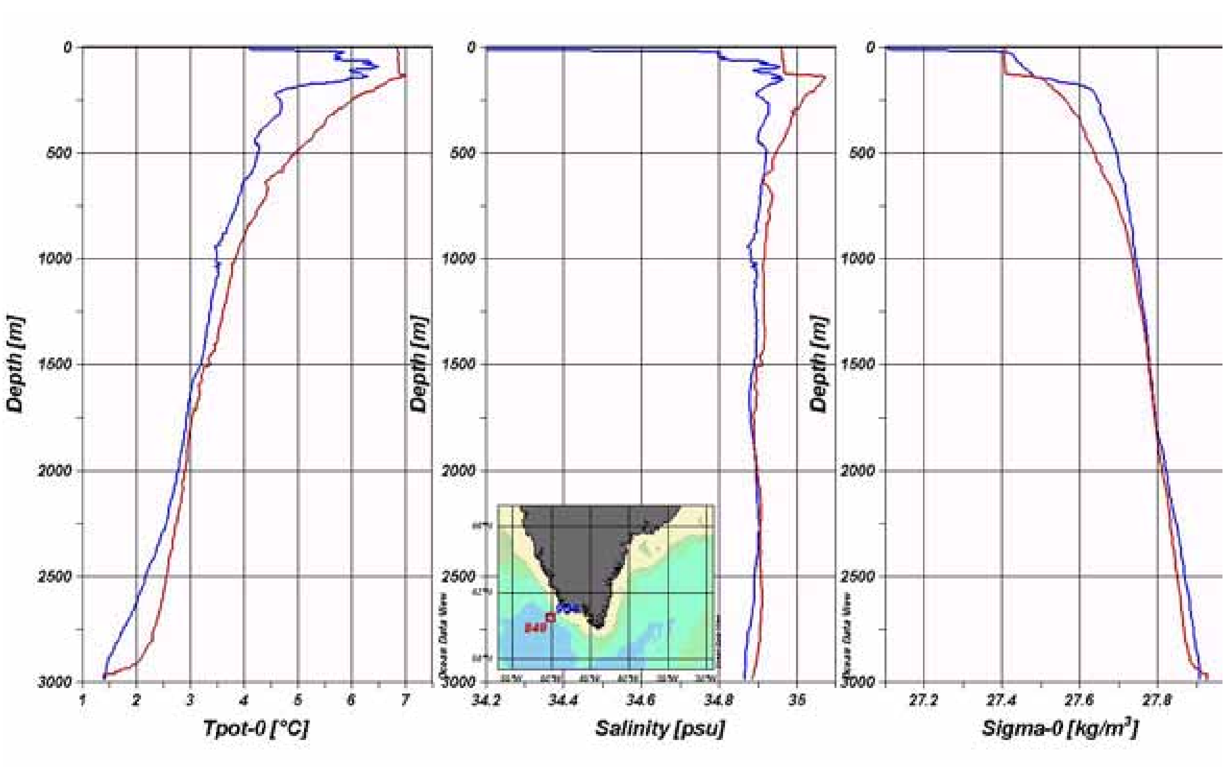

Fig. 12. Temperature, salinity and density profiles at Cape Desolation section station 3, 2002 (blue) and 2003 (red).

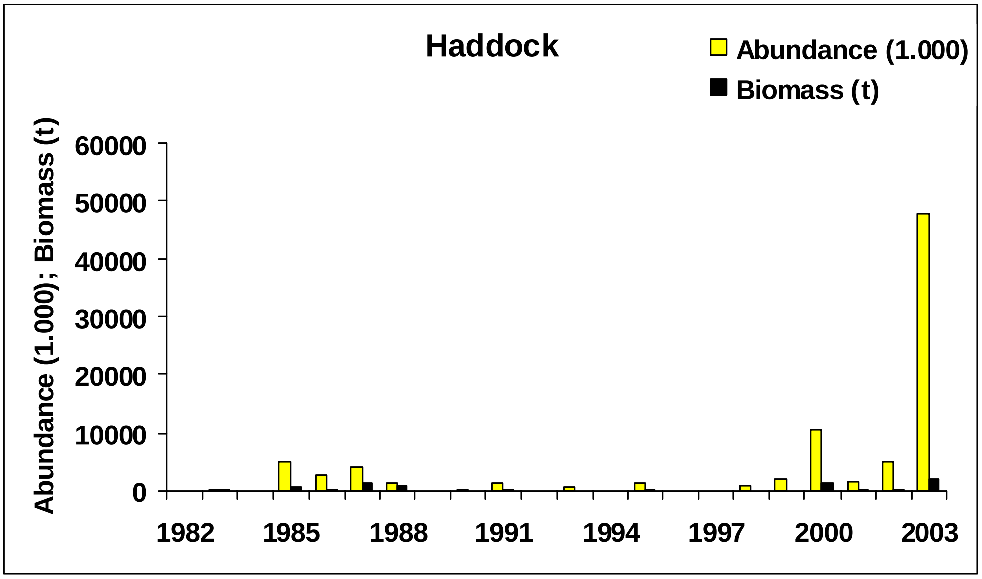

Fig. 13. Abundance and biomass of haddock (*Melanogrammus aeglefinus*) in Greenland waters (1989-2003).

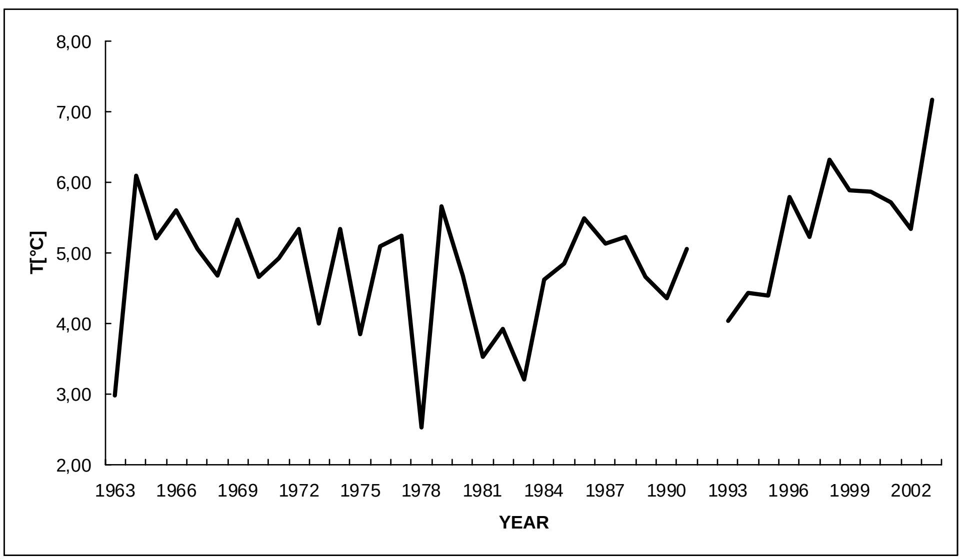

Fig. 14. Temperature measured at 200 m depth at Fyllas Bank section station 4 (1963-2003).