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Atlantic Subpolar Gyre Warming – Impacts on Greenland Offshore Waters?

by

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Abstract

Sea surface temperature anomalies in the region of the North Atlantic Subpolar Gyre indicate cold conditions in the 1980s and warming from the mid-1990s onwards. Peak warming was observed during October 2003. This is consistent with air temperature measurements from Nuuk/Greenland which document that 2003 was the warmest year since 1950. The sub-surface ocean hydrographic properties off West Greenland follow the observed warming of the Subpolar Gyre, and show a significant upward trend which is considerably higher than the mean warming trend as documented for the North Atlantic basin. Warming of the West Greenland Current amounted to 0.096°C/year during 1983-2004. Long-term observations from Fyllas Bank/West Greenland (1964-2004) reveal that during the 1960s similar warm sub-surface conditions were present in the West Greenland Current system, however the recent years of the new century indicate record warming which exceeds the autumn observations during those times. Data from a newly formed oceanographic section across Davis Strait and the West Greenland shelf, show increased transport of the West Greenland Current through the 330m km wide passage between Holsteinsborg/West Greenland and Baffin Island/Canada. Ocean properties during 2004 were more saline and up to 2K warmer-than-normal during autumn. Volume transports across this passage, computed for the 2004 data and compared to historic Canadian data, reveal that the transports based on the geostrophic method alone are + 2.4 *S*verdrup ($1\ Sv = 10^6 m^3 sec^{-1}$) in the core of the West Greenland Current, + 0.5 *Sv* on the West Greenland shelf, and – 1.9 *Sv* in the Baffin Island Current. While the northward (+) transport figures are in the range of the mean October and November transport values (+ 1.6 *Sv* to + 3.0 *Sv*), the southward (-) transport figures are considerably smaller than those values given in the literature (– 3.1 *Sv* to – 4.6 *Sv*). The increased baroclinic transport to the north is a consequence of warmer-than-normal temperatures and more saline conditions in the West Greenland offshore waters.

Keywords: Davis Strait, volume transports, Baffin Island Current, West Greenland Current

Introduction

As an extension of the Gulf Stream, warm subtropical waters enter the north-eastern Atlantic with the North Atlantic Current and circulate northward and westward in a broad anticlockwise gyre - the Subpolar Gyre (Fig. 1a). The heat flow accompanied with these waters is responsible for the mild climate of northern and north-western Europe which is warmer than the average for these latitudes. A southward flow of cooler waters counterbalances the warm water flow. Along the Subpolar Gyre pathway modification and cooling occurs, and Labrador Sea Water flows back to the subtropical gyre in the west 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 through the passage of the about 300 km wide Davis Strait (Fig. 1a, b), should carry warming/cooling signals to the Baffin Bay area which is located to the north of the Davis Strait. Via the cold Baffin Island Current cold, arctic waters flow through the Strait southward (Fig. 1b).

Davis Strait is a passage which allows estimating volume fluxes of these main currents which link the Arctic and the North Atlantic Subpolar Gyre west off Greenland.

During recent decades, climatic conditions in Greenland's air temperatures and offshore waters were characterized by tremendous variation. After the warmer-than-normal 1950s and 1960s, the 1970s, 1980s and early-1990s experienced a series of anomalous cold years (Buch, 2000; Buch *et al*., 2004; Drinkwater, 2004; Stein, 2004). In contrast to the last three decades, the early years of the new century did not experience the extremely cold years similar to 1972, 1983, 1984, 1992 and 1993. All comparable years during the 2000s were warmer-than-normal, and 2003 was the warmest year during the past 50 years (Stein, MS 2005). Is this warming part of the "global warming" as encountered for the world ocean basins in a recent paper by Levitus *et al.* (2005), or is the record warming a more regional feature of the Northwest Atlantic and its Subpolar Gyre (Häkkinen and Rhines, 2004)? While the first authors reveal that a large part of the change in the ocean heat content during the past 50 years (1955-2003) has occurred in the upper 700 m of the world ocean, and maximum warming is found in the upper 300 m of the North Atlantic basin (0.354°C during 1955-2003; Levitus *et al*., 2005), Häkkinen and Rhines (2004) conclude from TOPEX/Poseidon altimeter data that subpolar sea surface height increased during the 1990s, and the geostrophic velocity derived from altimeter data exhibits declining subpolar gyre circulation. Recent oceanographic observations in the West Greenland Current system (Stein, 2004; Stein, MS 2005) point at record warming in the upper layer of this part of the North Atlantic Subpolar Gyre.

The present contribution deals with climatic changes during 1950 to 2004. After discussing the data and methods, the monthly mean sea surface temperature anomaly data history for the region of the Northwest Atlantic during the past 23 years is outlined. Air temperature anomalies from Nuuk (1950-2004) as proxy for West Greenland climatology (Stein, 2004) are analyzed in a next section. This is followed by a discussion of sub-surface oceanographic conditions in the West Greenland Current domain. In a final section, our recent measurements of Davis Strait temperature and salinity properties, and volume fluxes are compared to mean autumn conditions and to historic data from the 1960s and 1980s.

Data and Methods

Monthly Mean Sea Surface Temperature Anomaly (SSTA) data (Fig. 2a to c) for the region of the Northwest Atlantic (40°N-80°N, 70°W-10°W) were taken from the IGOSS Data Base http://ingrid.ldgo.columbia.edu/SOURCES/.IGOSS. Isothermal contours are given in 0.5°C intervals. At present, SSTA data for the 1-degree resolution are available for the period Dec 1981 to Dec 2004. The climatology is adjusted to the 1950-79 base period. Sea surface temperature fields are blended from ship, buoy and bias-corrected satellite data (Reynolds and Smith, 1994).

Data on the atmospheric climate of West Greenland were sampled by the Danish Meteorological Institute at Nuuk (64°11'N, 51°44.5'W). The data set was mutually supplied by the Danish Meteorological Institute in Copenhagen and the Seewetteramt in Hamburg. The climatic mean which the air temperature anomalies are referenced to is 1961-1990. The presentation of decadal air temperature anomalies of Nuuk was used to better discriminate the characteristic features of the decades from the 1950s to 2000s (Fig. 3). This method was recently published by Stein (2004).

During autumn cruises in West Greenland waters, performed by the Institut für Seefischerei in Hamburg, Germany since 1963, temperature and salinity profiles were taken at ICNAF/NAFO[1] Standard Oceanographic Stations (Stein, 1988). Data from these cruises were taken from the oceanographic database of the institute to analyse sub-surface temperature changes at station 4 of the Fyllas Bank Section, and at station 3 of the Cape Desolation Section (Fig. 4 to 6). A new oceanographic section line between Greenland and Canada was formed during the autumn 2004 cruise of FRV "*Walther Herwig III*" to measure the flow of water masses across the Davis Strait sill and the West Greenland shelf which is a 330 km wide gap between West Greenland and Baffin Island/Canada (for positions of the section stations see Table 1; for location of transect see insert map in Fig. 7). Leaving the port of

[1] ICNAF = International Commission for the Northwest Atlantic Fisheries (1950-1978); NAFO = Northwest Atlantic Fisheries Organization (1979-)

Holsteinsborg/Sisimiut on 31 October, FRV "*Walther Herwig III*" followed five NAFO Standard Stations of the Holsteinsborg Section (N1, … , N5; Stein, 1988) and, after reaching the 200 nm EEZ of Canada, continued with five stations following historic Canadian RV "*Hudson*" positions along 66°30'N (5, … , 1). The section was completed on 1 November in the vicinity of Cape Dyer/Baffin Island, Canada. All profiles were obtained with a CTD (SeaBird 911+), salinity readings were adjusted to water samples derived by Rosette water sampler, temperature was checked against electronic reversing thermometers.

Isopleth diagrams of temperature for Fyllas Bank section station 4 and of potential temperature (θ for Cape Desolation Section station 3 are given in Fig. 4 and 5. Time series of temperature anomaly at station 3 is given in Fig. 6. The vertical distribution of temperature, salinity and geostrophic currents along the Holsteinsborg-Baffin Island Section is given in Fig. 7 and 8.

Historic data from the Davis Strait passage were downloaded from World Data Centre A (http://www.nodc.noaa.gov/OC5/indprod.html) and analysed in the same way as our data (temperature, salinity, geostrophic currents, volume transports across the section). To enable comparison with our data, Canadian bottle/CTD-data obtained during October 1963, 1965 and 1988 were selected. The years comprise warm periods (1960s) and cold periods (1980s). Results on volume transport calculations are given in Table 2.

Data analysis, including the geostrophic option, and presentation (Fig. 4, 5, 7, 8) was done using the most recent version of Ocean Data View (Version 2.1, 2004; Schlitzer, 2004). Accordingly, "geostrophic velocities are derived from dynamic height differences between two hydrographic stations (Schlitzer, 2004). Because, in general, the observed depths for the two stations do not match, in a first step the measurements have to be mapped to a set of common depths (ODV uses piecewise linear least squares for the interpolation on a predefined set of standard depths). Then dynamic heights at the standard depths are calculated for both stations, and the geostrophic velocities for the station pair (at the standard depths) are obtained from the dynamic height differences. ODV also calculates average values for all variables in the collection (pair-averages). Both, the pair-averages and the geostrophic velocities are representative for the mid-point between the two stations involved."

Results

Monthly Mean Sea-surface Temperature Anomaly (SSTA) data

SSTA data as given in Fig. 2a to c for the Northwest Atlantic region (40°N-80°N, 70°W-10°W) for the month of October, reveal much variation during the 1980s, 1990s and 2000s. A pool of colder-than-normal surface water is dominating the area south and southwest off Greenland during the early-1980s (Fig. 2a), indicating cold conditions in the Labrador Sea. The years 1985-1988 are characterized by intermediate warming in Greenland offshore waters. During 1989 and the early-1990s, there are colder-than-normal SST's off Greenland while warmer-than-normal surface waters are observed in the southern region. From 1997 onwards, warming of the Subpolar Gyre region becomes more and more evident, and the October 2003 conditions seem to represent record high warming of surface waters (Fig. 2c, lower right panel). During this time, warming exceeded 3K in the southwest Greenland region. According to Häkkinen and Rhines (2004) the interpretation of satellite derived sea surface height variations depends on the relative contribution of dynamics and local heat flux to heat storage in the Subpolar Gyre, and strong surface cooling, as observed during the early-1980s and early-1990s in the Labrador Sea, can modify the stratification down to the deepest water masses. During the 1990s, *in situ* data from the Labrador Sea show decreased convection since 1996 (Häkkinen and Rhines, 2004).

Air Temperature Anomalies from Nuuk

Decadal Nuuk air temperature anomalies during the years 1950-2004 (Fig. 3) indicate that the 1950s (yellow) and 1960s (red) were generally warmer-than-normal decades. The 1970s (green), 1980s (blue) and 1990s (black) were characterized by very cold years in the first part of the decade (1971, 1972, 1982-84, 1990-94). During this century, all years were warmer-than-normal (pink columns in Fig. 3). This trend coincides with the SSTA's discussed above.

Sub-surface Oceanographic Conditions

Fyllas Bank Station 4

The autumn temperature time series at Fyllas Bank station 4 (Fig. 4) reveals considerable variation during the past decades. Located at the slope of the bank at about 900 m depth, the thermal properties below 150 m depth at this site are mostly governed by the warm component of the West Greenland Current. The warm water is covered at the surface by colder water, and there are years when polar water normally covering the bank region, extended far to the west and influenced the thermal conditions at station 4 (polar events: 1983, 1992 and 2002). During 2003, record warming was observed which amounted to 2.69 K (rel. to climatic mean 1963-90). The isopleth diagram of potential temperature is based on standard depth data from Fyllas Bank station 4 (Fig. 4), sampled during autumn. It indicates that during the 1960s sub-surface temperatures were warmer than 5.5°C. The 1970s - except for the late-1970s - and 1980s revealed sub-surface temperatures around 5°C, and from the mid-1990s onwards sub-surface warming increased and showed a maximum of warming during autumn 2003 when temperature above 7°C were observed at about 200 m depth. The depth range of warming increased considerably, from about 400 m depth to about 700 m depth (5.5°C contour).

Cape Desolation Station 3

Located further offshore than Fyllas Bank station 4, Cape Desolation station 3 is 3 000 m deep and the obtained CTD profiles cross different water masses when descending from top to bottom of the water column. In the context of this paper, only the upper 0-700 m layer is considered. The isopleth diagram of potential temperature shows a layer of warm water (>4.0°C) in the upper 600-700 m (Fig. 5). Within this layer, temperatures are changing considerably during the 22 years of observation: temperatures exceed 6°C (2nd half of 1990s), and 6.5°C during 2003 and 2004, and the vertical extension of the warm water increases from the mid-1990s onwards.

Mean temperatures for the 0-300 m and the 0-700 m layers were calculated and plotted against time (Fig. 6). The vertical dimensions of the layers were chosen in analogy to the Levitus *et al.* (2005) publication. Our data yield a significant warming trend for the time period 1983-2004 which amounts to 0.096°C (0-300 m) and 0.062°C (0-700 m). The data also show more variability from 1998 onwards. Based on a much longer time series Levitus *et al.* (2005) calculate a warming of 0.354°C during 1955-2003 for the North Atlantic basin depth layer 0-300 m. This would compare to 0.007°C/year, a value which is a magnitude lower than our 0.096°C/year warming during 1983-2004. The difference in warming trends may be explained by (a) the thermal history of the region, and (b) by the Subpolar Gyre regional warming from the mid-1990s onwards: (a) as shown for the Fyllas Bank station 4 there was warm sub-surface conditions during the 1960s in the West Greenland Current domain (see above). Applying a linear trend to both the long (1955-2003) and the short (1983-2004) time series will result in a shallower trend when going from "warm through cold to warm" conditions, instead of going from "cold to warm" conditions. And (b): both time series, the Fyllas Bank station 4 data and the Cape Desolation station 3 data (Fig. 4, 5), indicate tremendous warming of the West Greenland Current from the mid-1990s onwards. This will influence the computation of temperature trends incorporated in these data.

The annual warming coefficients, as given for the 0-300 m and the 0-700 m depth layers at Cape Desolation station 3 (see Fig. 6), thus might point at the impact of the Subpolar Gyre regional warming on the warming of West Greenlands offshore waters.

Davis Strait temperature and salinity

There are two salient features in the vertical distribution of temperature (upper panel in Fig. 7) which characterize the hydrographic properties between Greenland and Baffin Island, the Baffin Island Current and the core of the West Greenland Current (WGC). The Baffin Island Current is a broad current band which exports cold water (core temperatures <-1.64°C) from Baffin Bay southwards. On the eastern side of the section, the West Greenland Current flows along the shelf break and transports heat (core temperatures >5.9°C) into the Baffin Bay. During the 2004 observations, both currents meet and mix intensively between the two innermost stations of the section (for positions of stations NAFO5 and HUDSON5 see Table 1). There is a sub-surface tongue of warm West Greenland Current water (>3°C) located under the cold Baffin Island Current which extends westward from the WGC-core. Further west, at station HUDSON 3, a remnant of 2°C warm water is visible (Fig. 7). A month prior to our observations, RV

"*KNORR*" of the US observed a sub-surface patch of warm water at this location which had thermohaline properties of WGC-water (Petrie, *pers. comm.*). Salinity (lower right panel of Fig. 7) reveals a near-surface thin layer of low saline water (<32 psu) on the western side of the section, and <33 psu water on the eastern side. In the WGC-core at the West Greenland slope, salinities are around 34.94 psu. Similar to the vertical temperature distribution along this section there is a remnant of saline water (>34.5 psu) below the Baffin Island Current water.

Compared to mean autumn conditions, the temperatures in the WGC-core and on the West Greenland shelf as measured during autumn 2004, are up to 2K warmer than normal.

Davis Strait geostrophic velocities

For the geostrophic velocity profiles a level of no motion at the bottom was assumed for all analysed data sets (1963, 1965, 1988 and 2004). The vertical distribution of relative current speeds along the section across Davis Strait and the West Greenland shelf is given in Fig. 8 for the October 2004 measurements. The Baffin Island Current has surface speeds ranging from 10-16 cm sec^{-1} during the analysed years, whereas the West Greenland Current reveals surface velocities of 10-36 cm sec^{-1}. About 180 km of the Baffin Island/Holsteinsborg section (330 km) is dominated by the Baffin Island Current (≤12 cm sec^{-1}) during 2004, while the West Greenland Current (≤36 cm sec^{-1}) is concentrated at the shelf break off West Greenland (Fig. 8). On the West Greenland shelf, current velocities amount to about 10 cm sec^{-1} during 2004.

The warm West Greenland Current water located under the cold Baffin Island Current (>3°C, >34.5 psu; see above) flows southwards at speeds between 0.3 cm sec^{-1} and 1 cm sec^{-1}, a feature which might point at a return flow of modified WGC water.

Davis Strait volume fluxes

The geostrophic velocity profiles as discussed above, form the basis for the volume transport computations. Table 2 gives the CTD-based volume transports for October 1963, 1965, 1988 and 2004. Time series of temperature from Fyllas Bank (Fig. 4) indicate that the 1960s were among the warmer years off West Greenland. Sub-surface thermal conditions revealed similar warm conditions as observed during the period starting after the mid-1990s. The sub-surface temperatures during the 1970s and 1980s were colder than the 1960s or the recent period of the 2000s. The data on volume fluxes through Davis Strait thus cover warmer-than-normal, colder-than-normal and "much" warmer-than-normal situations, e.g. the 2004 observations. The "northward" volume transports as given in Table 2 indicate maximum values for 2004, both in the core of the West Greenland Current and on the West Greenland shelf, amounting to +2.9 *Sv* ($1\ Sv = 10^6\ m^3 sec^{-1}$). During 1963 and 1965, both warmer-than-normal years in the air temperatures and in the subsurface ocean temperature conditions (Buch *et. al*, 2004), the northward flow was +2.2 *Sv* and +1.9 *Sv* and there was +0.2 *Sv* northward transport on the West Greenland shelf during 1963. The 1988 data show an unusually low northward transport figure and there is a counter flow eastwards of the West Greenland Current core which amounts to –0.3 *Sv*. The southward flow ranges from –1.9 *Sv* during 2004 to –2.5 *Sv* during 1965.

Summary and Discussion

Using monthly mean sea surface temperature anomaly data for the Northwest Atlantic, recent own observations from NAFO Standard Stations Fyllas Bank 4 and Cape Desolation 3, as well as recent own data from a newly formed hydrographic section across Davis Strait passage, and historic data from Davis Strait it is shown that the observed warming of the North Atlantic Subpolar Gyre had a tremendous impact on West Greenland shelf and off-slope waters. While sea surface temperature warming and sub-surface ocean temperature warming seem to have peaked during 2003, the year with warmest mean annual air temperatures at Nuuk since 1950, the trend as observed in the temperature time series of the upper 300 m of the ocean off southwest Greenland points at further warming.

As a result of Subpolar Gyre warming the West Greenland Current transported more heat northward than usually. The volume transport figures (Table 2) indicate that the baroclinic part of the northward transport through Davis Strait increased considerably and is in the upper range of the monthly mean volume transport values as deduced from mooring data (Cuny *et al.*, *in press*) for October (+ 1.6 *Sv*) and November (+ 3.0 *Sv*). The current speeds obtained for the West Greenland shelf amount to 10 cm sec^{-1}, a value which agrees well with surface drifter measurements (Cuny *et al*., 2002).

All data on southward transports, the historic data from 1963, 1965 and 1988, as well as our recent measurements during autumn 2004 (see Table 2) are considerably lower than those published in literature for mean annual transports for Davis Strait, excluding the West Greenland shelf: - 4.6 ± 1.1 *Sv* (Cuny *et al*., *in press*), - 3.3 *Sv* (Loder *et al*., 1998), - 3.1 *Sv* (Ross, 1992).

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TABLE 1: Location of CTD stations along the Holsteinsborg/Baffin Island Section

Station number	Latitude	Longitude
NAFO 1	66°53‘N	54°10‘W
NAFO 2	66°50‘N	54°42‘W
NAFO 3	66°46‘N	55°36‘W
NAFO 4	66°43‘N	56°07‘W
NAFO 5	66°41‘N	56°38’W
HUDSON 5	66°30‘N	57°40’W
HUDSON 4	66°30‘N	58°19’W
HUDSON 3	66°30‘N	59°33’W
HUDSON 2	66°30‘N	60°16’W
HUDSON 1	66°30‘N	60°50’W

TABLE 2. Volume transport estimates from CTD section Holsteinsborg/Baffin Island during October given in Sverdrup (*1 Sv =* 10^6 m^3sec^{-1}; *- southward, + northward*)

Year	Southward flow	Northward flow	Flow on WG shelf
1963	-2,3	+2,2	+0,2
1965	-2,5	+1,9	no obs.
1988	-2,0	+0,5	no obs.
2004	-1,9	+2,4	+0,5

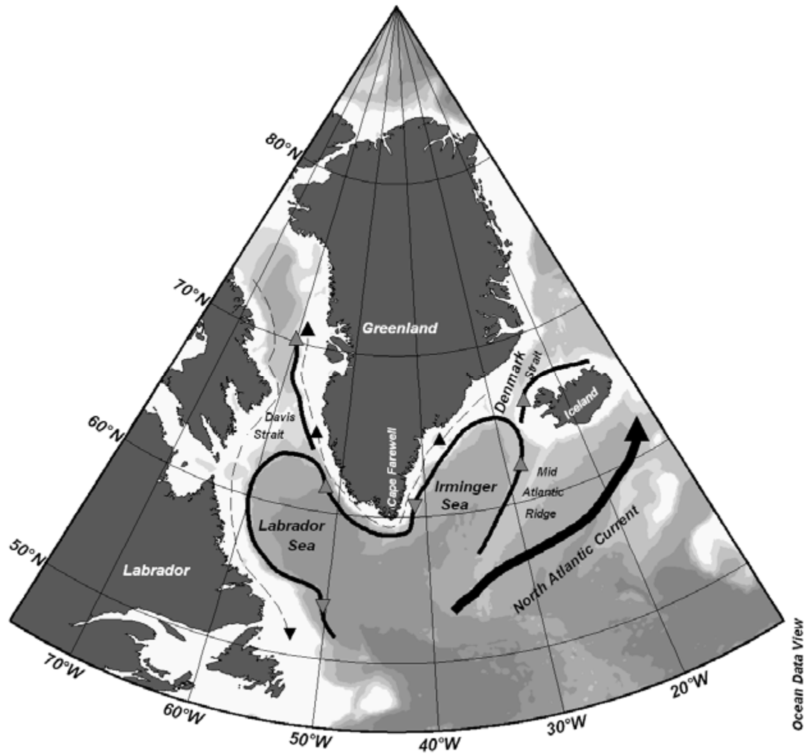

Fig. 1a. Schematic of the Subpolar Gyre (white area: 0-500 m depth). Bold: warm currents; dashed: cold currents.

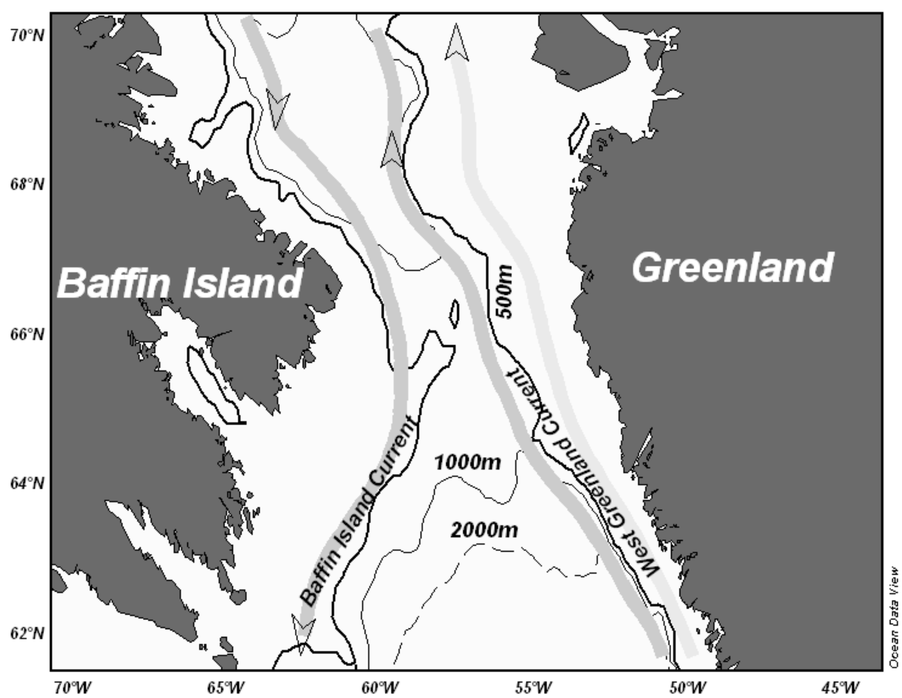

Fig. 1b. Circulation diagram for the Davis Strait region; West Greenland Current: shelf break component (grey), shelf component (light grey); depth contours for 500 m (bold), 1 000 m (thin) and 2 000 m (dashed) are given.

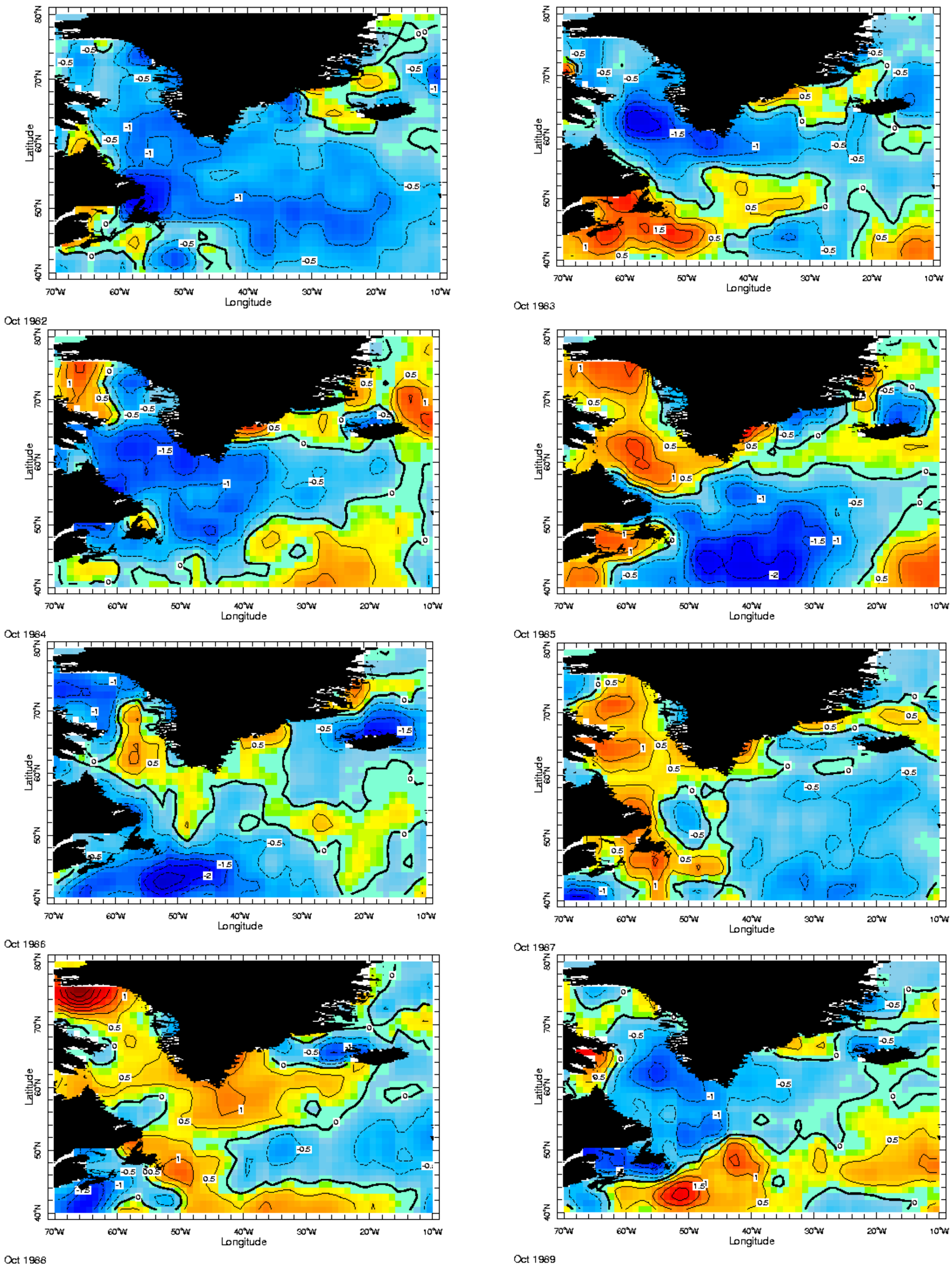

Fig. 2a. Sea-surface temperature anomalies during October 1982-1989

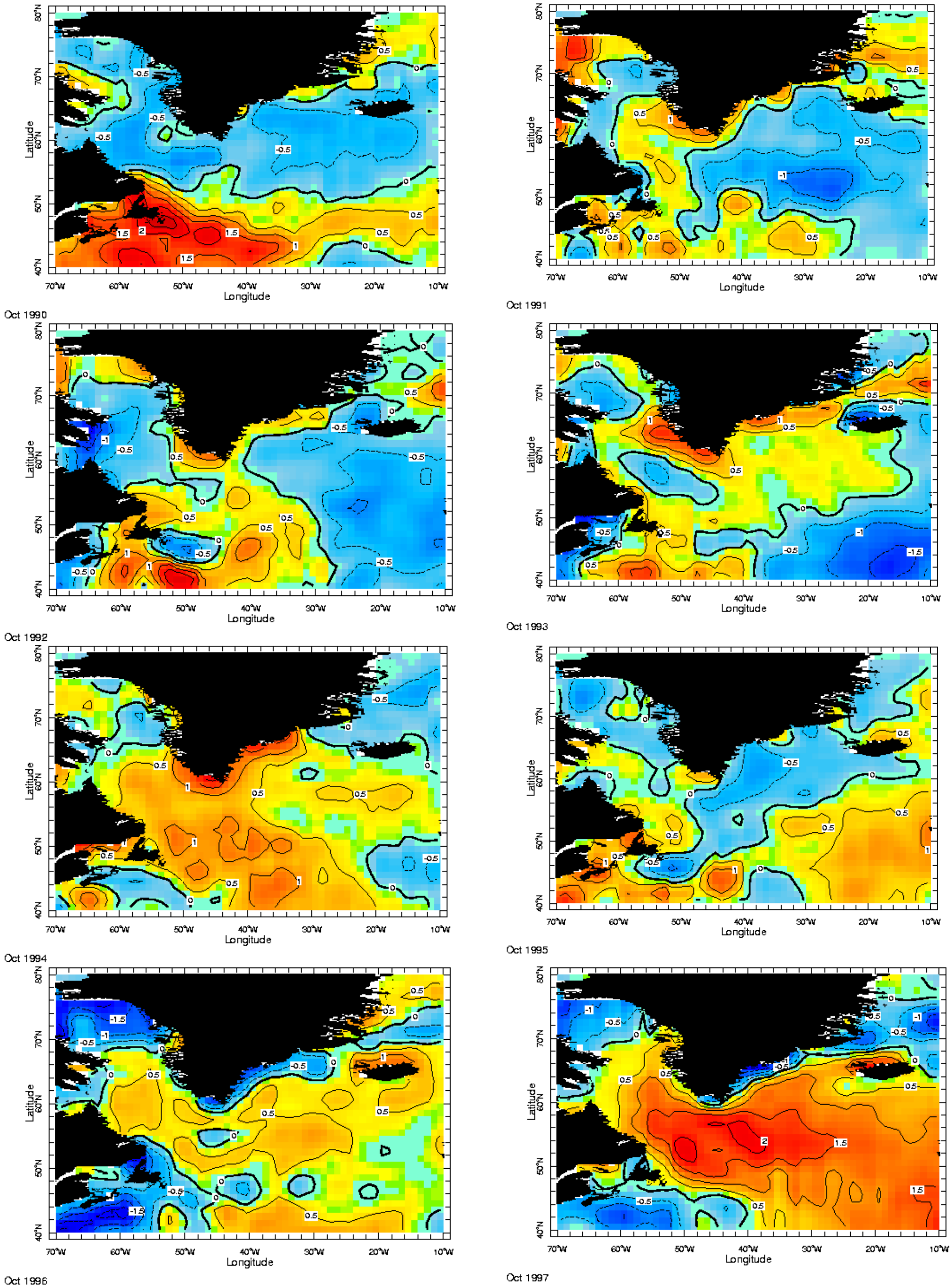

Fig. 2b. Sea-surface temperature anomalies during October 1990-1997

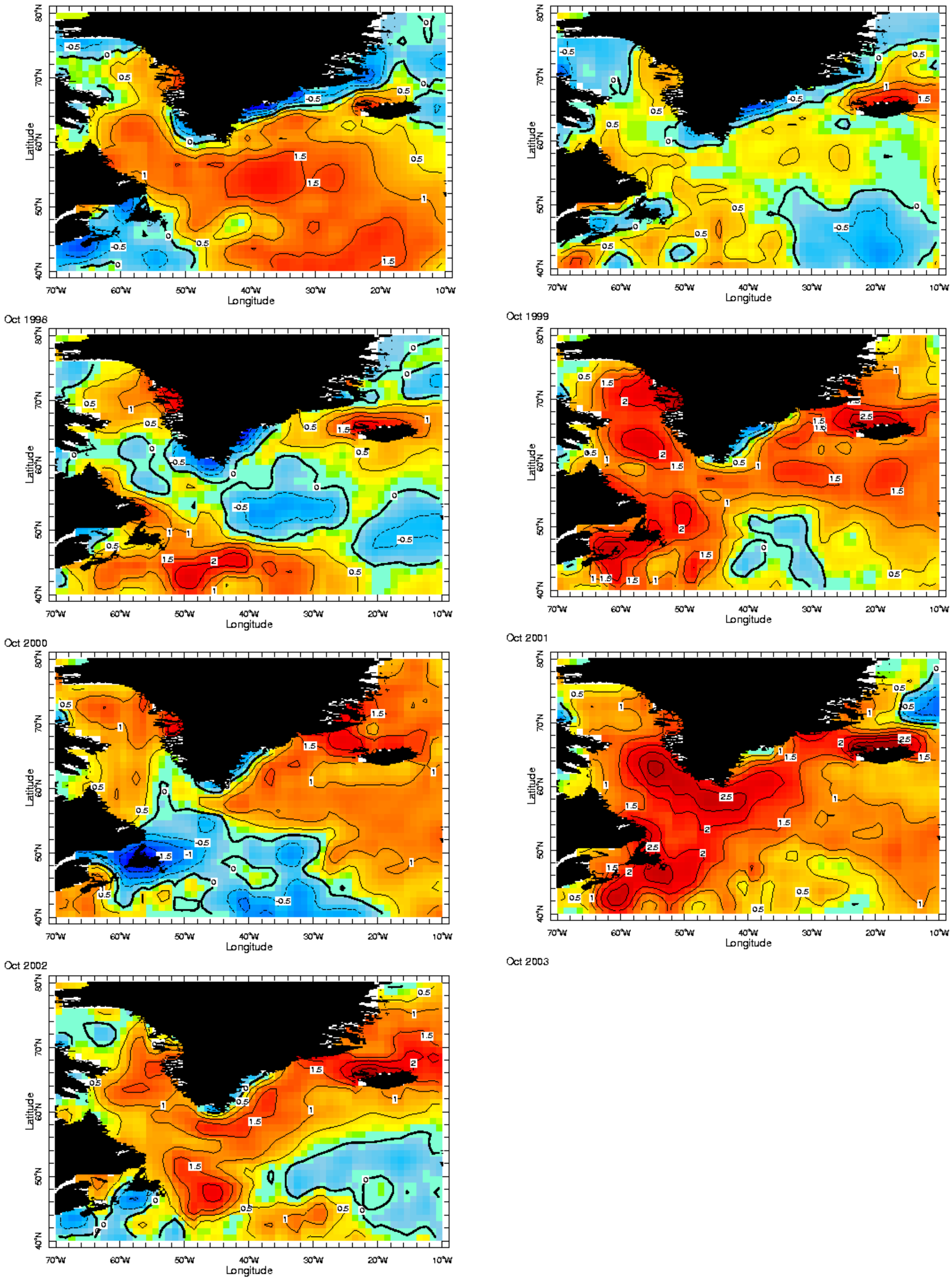

Fig. 2c. Sea-surface temperature anomalies during October 1998-2004

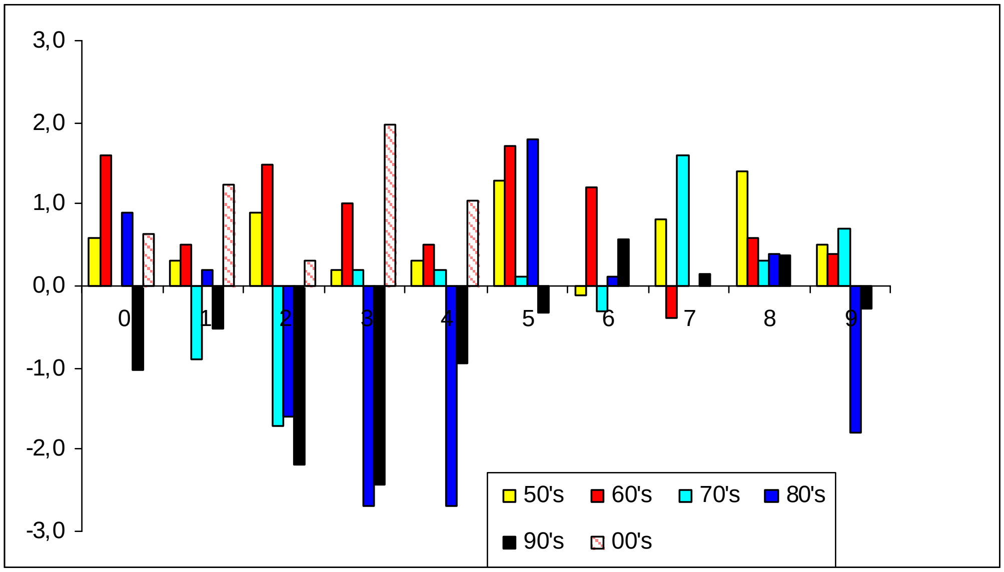

Fig. 3. Decadal air temperature anomalies (K) relative to the mean of 1961-90 at Nuuk for the decades from the 1950s to the 2000s plotted as function of the year of the decade; data: 1950-2004

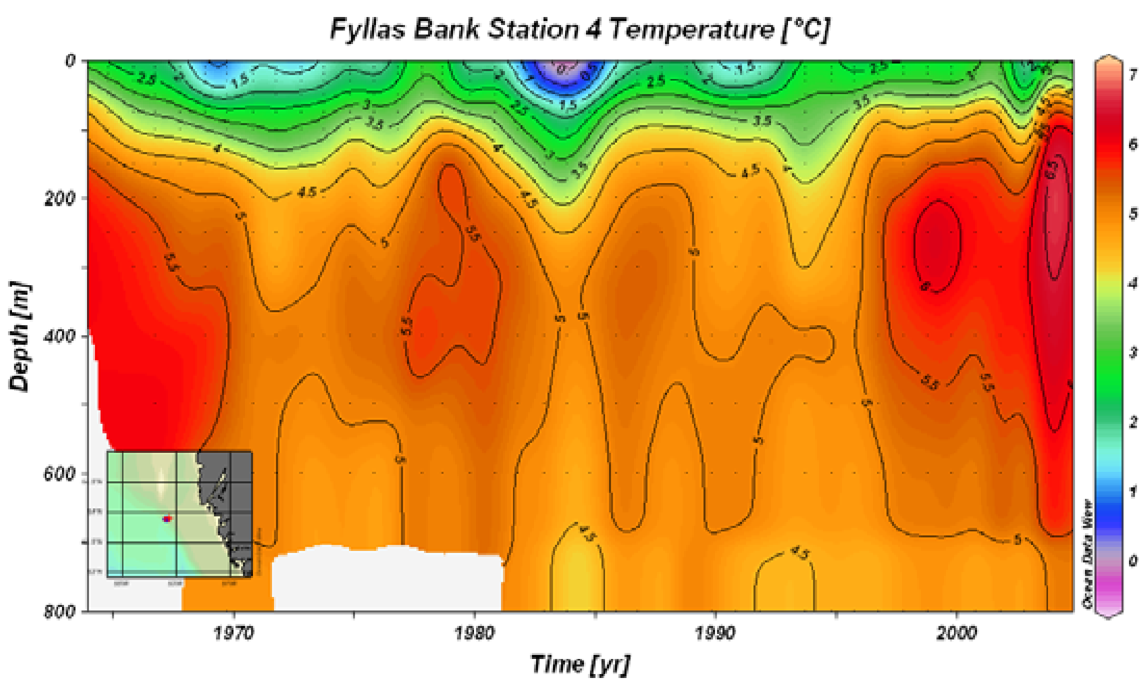

Fig. 4. Isopleth diagram of temperature at Fyllas Bank Station 4; autumn data: 1964-2004

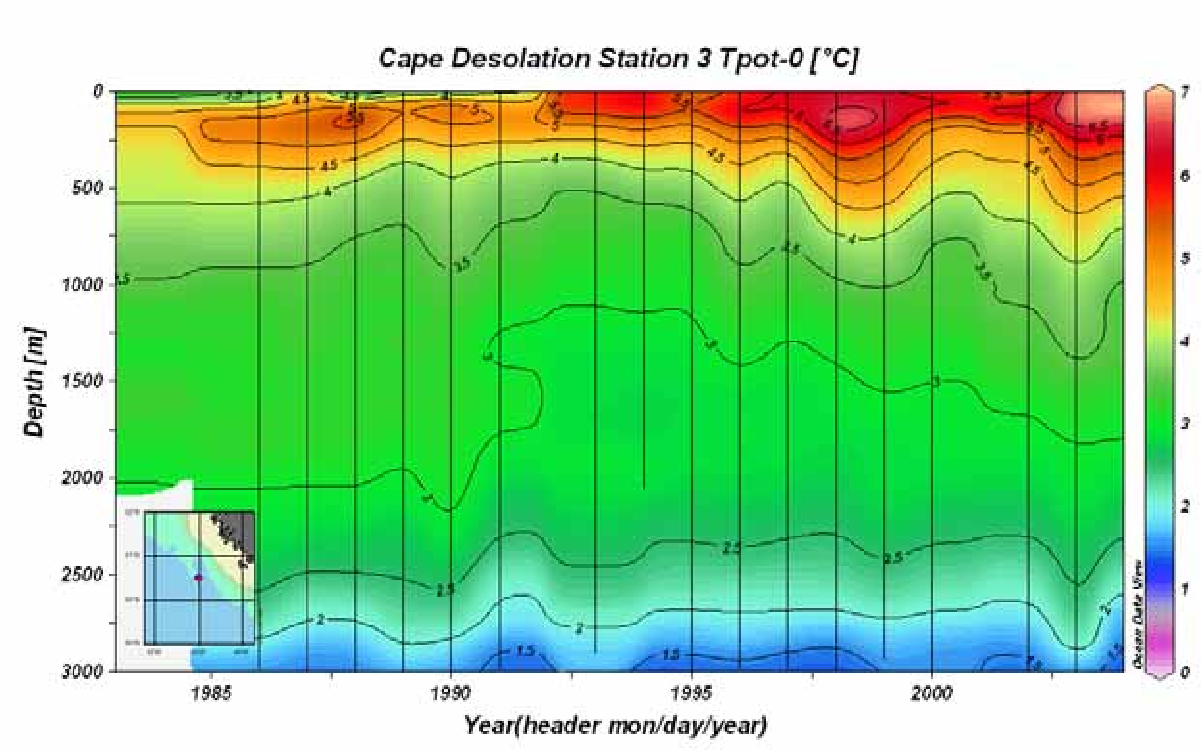

Fig. 5. Isopleth diagram of temperature at Cape Desolation Station 3; autumn data: 1983-2004.

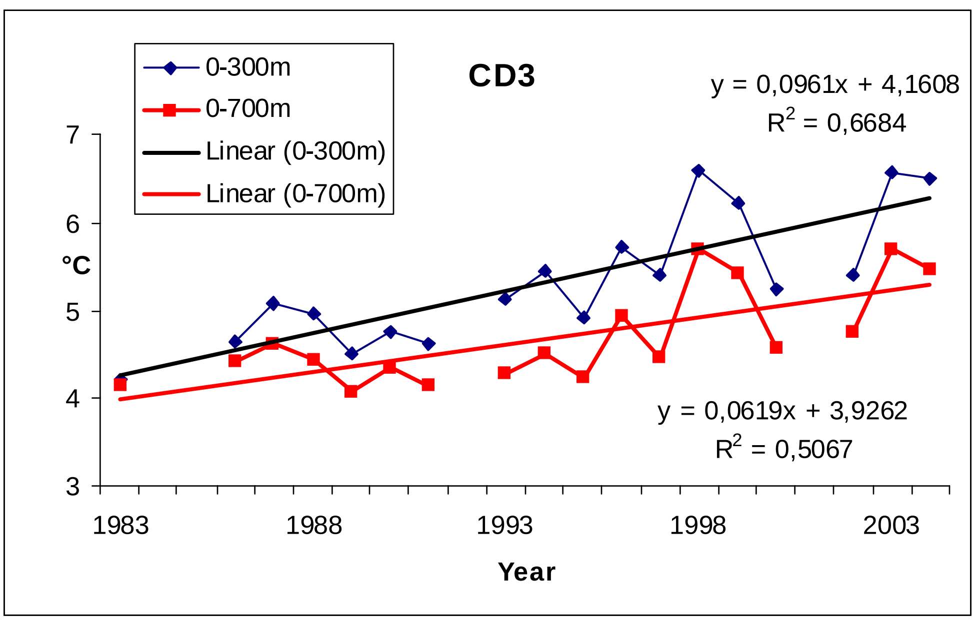

Fig. 6. Time series of temperature 0-300 m, 0-700 m and linear trend; autumn data: 1983-2004

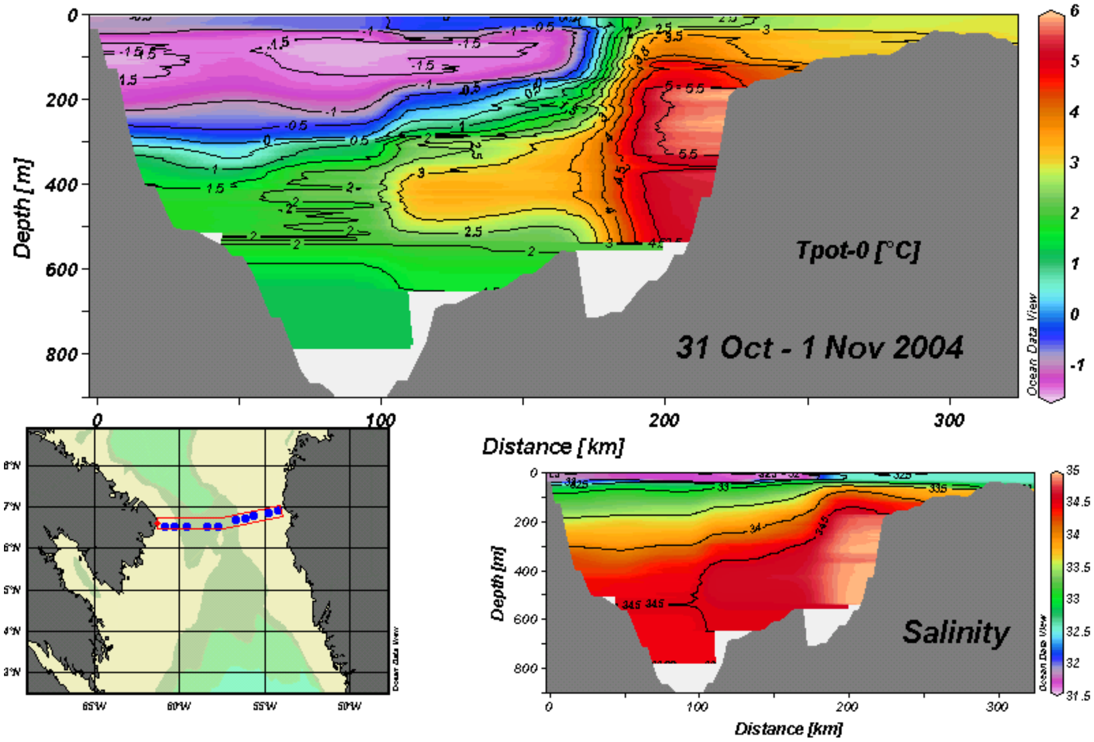

Fig. 7. Vertical distribution of temperature and salinity along the Holsteinsborg-Baffin Island section; data: 31 October-1 November 2004

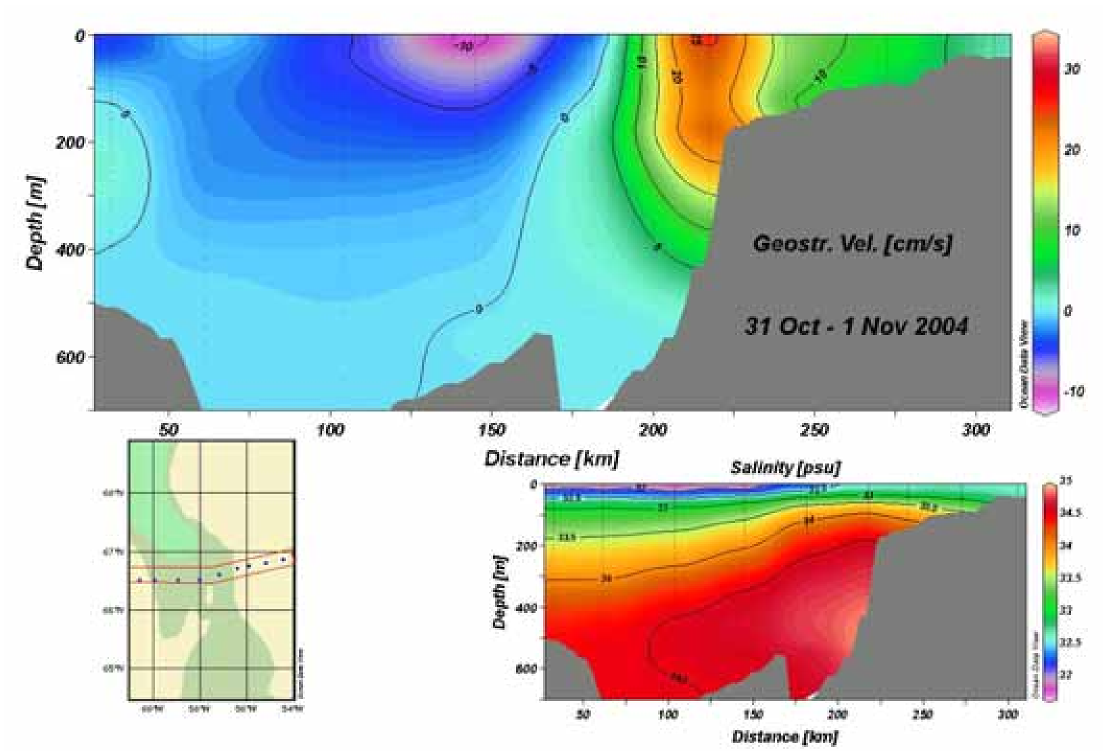

Fig. 8. Vertical distribution of geostrophic currents along the Holsteinsborg-Baffin Island section; data: 31 October-1 November 2004.