NAFO Sci. Coun. Studies, 14: 29–37

# Recent Thermohaline Observations on the Deep Waters off West Greenland

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## Abstract

Based on conductivity, temperature, depth recorder with rosette mounted reversing bottle (CTD/Rosette) data sampled along NAFO Standard Cape Farewell, Cape Desolation and Frederikshaab, the thermohaline field off the West Greenland continental slope is described. Analysis of temperature revealed warming which was not consistent throughout the area investigated. The warming of the near-surface layers lasted from 1984 to 1988 along all Sections, whereas for the deep layers (1,100 to 1,500 m) only the Cape Farewell Section indicated warming which amounted to about 0.1° C per year.

## Introduction

Labrador Sea Water (LSW) obtains its characteristics by convective formation in the central Labrador Sea (Lee and Ellett, 1967; Lazier, 1973; Talley and McCartney, 1982; Clarke and Gascard, 1983; Gascard and Clarke, 1983). Low salinity and high oxygen content are typical of this water mass which is found at mid-depth north of 40° N in the North Atlantic Ocean. The definitions of LSW range from 3° to 4° C and salinity less than $34.94 * 10^{-3}$ (Wright and Worthington, 1970), to 3.4° C, $34.88 \pm 10^{-3}$ (Talley and McCartney, 1982) with potential density less than $\sigma_t = 27.8$ (Lazier, 1973). The formation processes on the large, meso- and small-scale have been analyzed by Clarke and Gascard (1983), and Gascard and Clarke (1983). They hypothesized that a 200 km scale cyclonic gyre forms in winter in the western Labrador Sea and that this gyre retains the developing deep mixed layers in this area long enough for the transformation of it into LSW to take place. The advection of LSW out of the Labrador Sea is described in detail by Talley and McCartney (1982), using a vertical minimum to potential vorticity as the primary tracer for this water mass. The flow of water masses off West Greenland reflects the existence of two current components forming the near surface current regime of the West Greenland Current. This is the East Greenland component which derives its thermohaline properties in the Arctic Ocean and off East Greenland, and the Irminger component which arises from the northern branch of the North Atlantic Current (Clarke, 1984). At depths between 1,500 and 2,000 m a pronounced halocline separates the low-salinity LSW and the saline, low-oxygen layers of the North Atlantic Deep Water. The lowermost layer of the water column is occupied by the Northwest Atlantic Bottom Water which derives, in large parts, its characteristics from the Denmark Strait overflow (Swift, 1984). Swift defined, $\theta$, S-characteristics of this water mass to be near 1° C and $34.9 * 10^{-3}$. According to Mann (1969) the Denmark Strait overflow water moving well down the east coast of Greenland toward Cape Farewell changed its $\theta$,S-characteristics due to mixing with water above it.

In this study recent observations on the deep waters of West Greenland are presented. On the basis of conductivity, temperature, depth recorder with rosette mounted reversing bottle (CTD/Rosette) data collected between 1984 and 1988 along the Seal Island-Cape Farewell Section across the Labrador Sea, observations along the Cape Farewell, Cape Desolation and Frederikshaab NAFO Standard Sections, the thermohaline properties of the West Greenland continental shelf region are described.

## Data and Methods

Between 2 and 4 November 1984 RV *Walther Herwig* completed NAFO Standard Oceanographic Sections Frederikshaab (stations 95 to 100), Cape Desolation (stations 101 to 105), and between 6 and 8 November 1984 Seal Island–Cape Farewell (stations 106 to 123). The locations of the 1984 stations are given in Fig. 1A. During 1986, 1987 and 1988 these sections were completed only in part (Fig. 1B). The hydrographic fields were mapped using a *KIEL-Multisonde* CTD plus Rosette water sampler.

Calibration samples were collected at each station, while in the central Labrador Sea additional samples for oxygen determination (Winkler method) were collected. The CTD was equipped with a bottom sensor and according to this sensor the CTD was lowered down to 5 m above the bottom. At that depth the bottom water samples were collected. While retrieving, the CTD/Rosette device was stopped in 500 dbar intervals for calibration and oxygen probes. The temperature

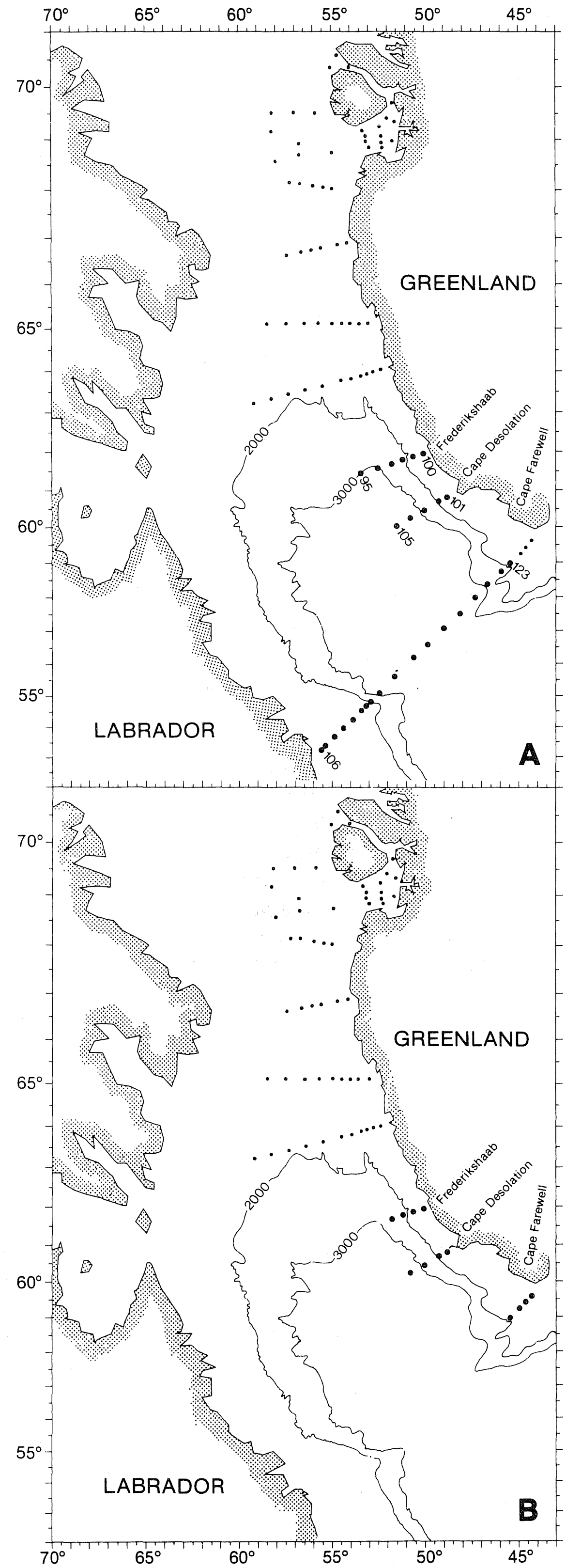


Fig. 1. Location of Standard Oceanographic Sections and stations occupied during cruises of RV *Walther Herwig* from (**A**) 2-8 November 1984, and (**B**) 1986-88.

readings were checked against reversing thermometers, salinity was determined by means of a *GUILDLINE* laboratory salinometer.

## Results and Discussion

### Standard oceanographic sections

The Standard Oceanographic Section locations (Fig. 1A) and the individual CTD/Rosette stations as performed during the 1984 cruise of RV *Walther Herwig* have been described by Stein (MS 1985). The 2,000 and 3,000 m isobaths were taken from the 1978 edition General Bathymetric Chart of the Oceans (GEBCO) number 5.04. The updated positions and depths of the standard stations are published elsewhere (Stein, MS 1988). For a general description of the thermohaline fields on the slope off Southwest Greenland, the 1984 data were used since they gave the most complete and quasisynoptic coverage of the standard stations in the area performed during this decade.

On the western side of the section, between stations 106 and 111, the cold and fresh component of the Labrador Current emerged from the thermohaline field (Fig. 2, 3). Being colder than -1.0° C on Hamilton Bank, the polar portion of this current reflects the report that 20% of the Labrador Current originating from Baffin Bay is from the Baffin Island or Canadian Current (Lazier, 1982). Centered over the 600-800 m isobath on the slope (stations 112, 113), about 80% of the current flow is concentrated (Lazier, 1982). This represents the warm and haline waters arising from the Irminger Current. Off West Greenland, the Irminger component of the West Greenland Current was visible by its strongly expressed thermohaline signals (east of station 120). Between these two currents the vast area of the Labrador Sea occupied about 500 km of the section. At depths of 2,000 m the pronounced halocline separated the low-salinity LSW with salinities slightly less than $34.84*10^{-3}$, and the saline oxygen layers of the North Atlantic Deep Water with salinities greater than $34.94*10^{-3}$ and oxygen content around 6.6 ml/l (Fig. 3). The bottom water layer in this area was very uniform. As mentioned above, Swift (1984) explains the Northwest Atlantic Bottom Water being derived in large part from the Denmark Strait overflow. Examination of the temperature and salinity sections showed that the $\theta$, S-characteristics were less than 2.0° C and $34.92*10^{-3}$ and a considerable amount of water had a salinity less than $34.90*10^{-3}$. The observed salinities of this slope trapped boundary current ranged from $34.887*10^{-3}$ to $34.894*10^{-3}$. The "new" overflow water entering the Labrador Sea at its eastern slope yielded oxygen values up to 7.03 ml/l, whereas the "old" overflow water after completing its cyclonic path along the Labrador basin suffered from oxygen depletion to leave the Labrador Sea with oxygen values as low as 6.84 ml/l. This is

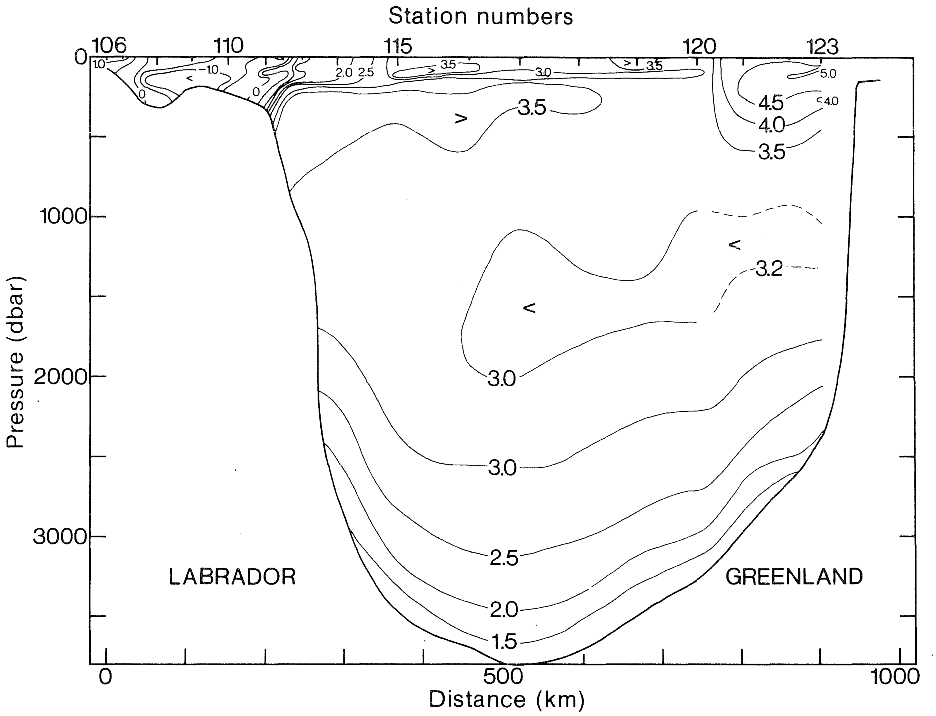


Fig. 2. Potential temperature along the Seal Island-Cape Farewell Section, 6-8 November 1984.

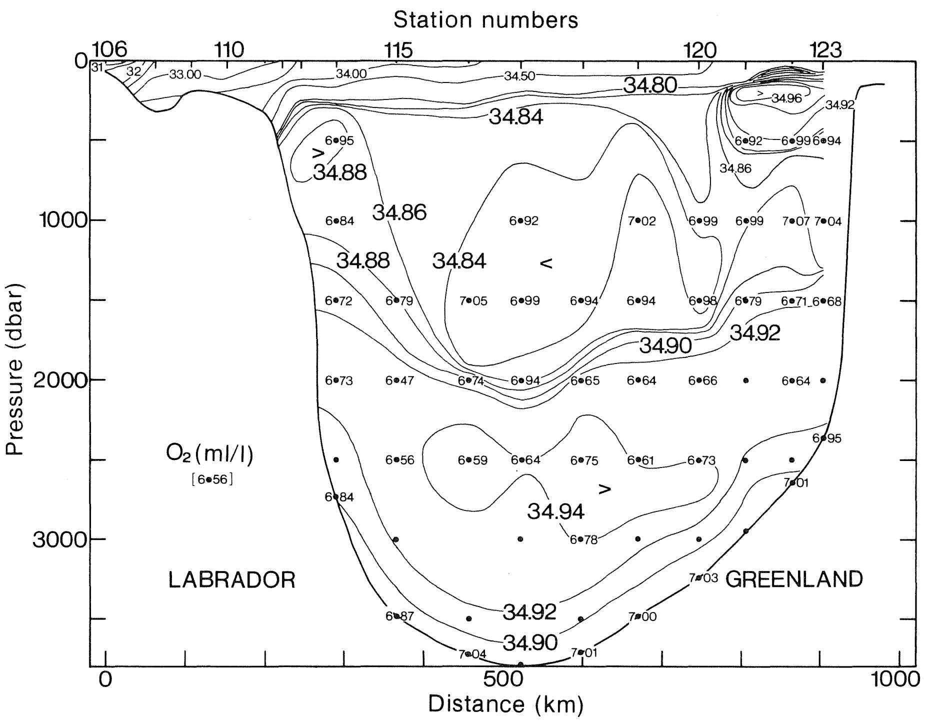


Fig. 3. Salinity and oxygen along the Sea Island-Cape Farewell Section, 6-8 November 1984 (dots indicate depths of calibration samples).

consistent with the oxygen values given by Swift (1984) for the deep layers of the Labrador Sea.

On the Greenland side of the Cape Farewell Section, east of station 120 at about 500 dbar, the core of the West Greenland Current was visible (Fig. 2, 3). On its way north the salinity in the core decreased by $0.02*10^{-3}$ (Fig. 4A, B) and on the shelf, the cold diluted waters of the East Greenland component emerged (Fig. 4 and 5). Both sections indicated the temperature min-

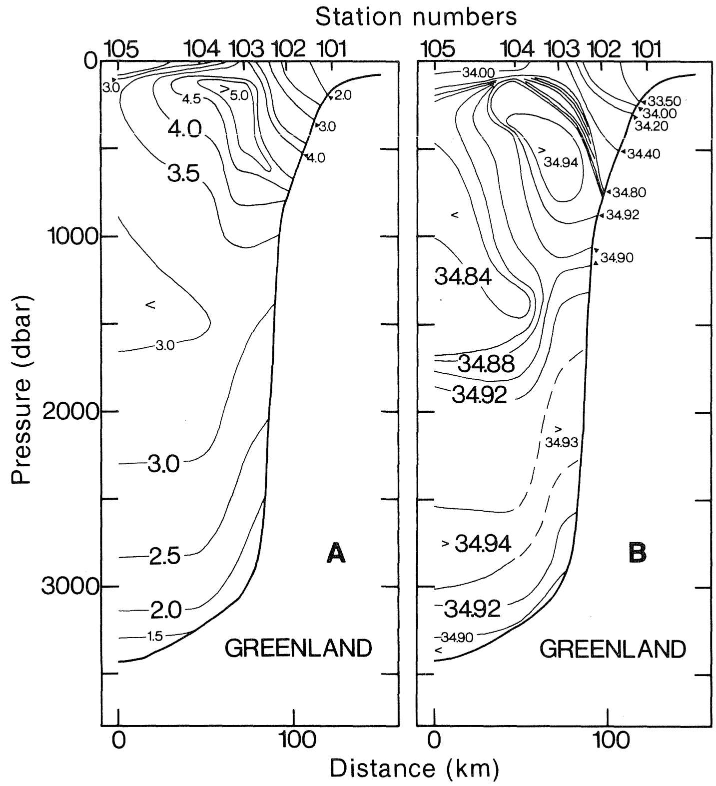


Fig. 4. (**A**) potential temperature and (**B**) salinity along the Cape Desolation Section, 3-4 November 1984.

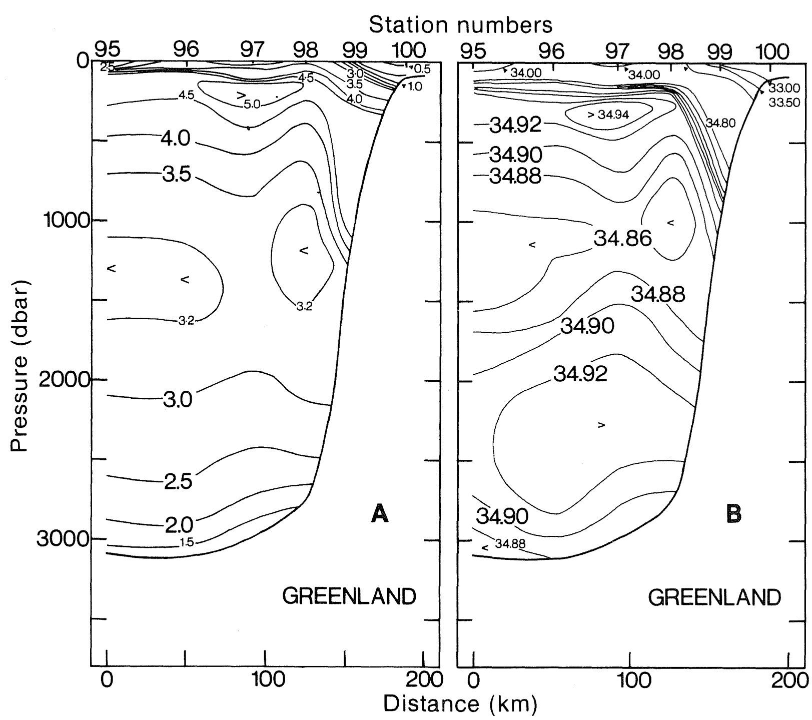


Fig. 5. (**A**) potential temperature, and (**B**) salinity along the Frederikshaab Section, 2 November 1984.

imum layer at 1,500 dbar (less than 3.2° C) which was also evident from Fig. 2. These minimum temperature layers coincide with the formation layers of LSW. Similar to the Sea Island–Cape Farewell Section, the halocline below 1,500 dbar indicated the transition zone to the North Atlantic Deep Water which was less saline off Frederikshaab (stations 95 to 100) than off Cape Desolation and off Cape Farewell (>34.92*10$^{-3}$ instead of >34.94*10$^{-3}$). At about 3,000 dbar the upper boundary of the Northwest Atlantic Bottom Water was found. Similar to the section across the Labrador Sea (Fig. 2, 3), the $\theta$, S-characteristics of this water mass were less than 1.5° C and 34.90*10$^{-3}$. Off Frederikshaab (Fig. 5B) the salinity of the near-bottom layer amounted to 34.863*10$^{-3}$, 34.883*10$^{-3}$, 34.887*10$^{-3}$, and 34.893*10$^{-3}$ at stations 95 to 98 respectively. Off Cape Desolation (Fig. 4B) the corresponding values in the overflow layer were 34.898*10$^{-3}$, 34.906*10$^{-3}$, and 34.899*10$^{-3}$ at stations 105 to 103 respectively.

The standard stations as performed during the 1986, 1987 and 1988 surveys are shown in Fig. 1B. The thermohaline conditions on the Cape Farewell, Cape Desolation and Frederikshaab Section during recent observations are shown by means of the 1987 results (Fig. 6 to 11).

Considerably warmer core temperatures and higher core salinities were observed during the 1987 cruise than in 1984, a year which was known to be rather cold in West Greenland waters (Stein and Buch, 1985). Station 10 (1987) and 123 (1984) which represent Standard Station 4 of the Cape Farewell Section (Fig. 2, 3 and 6) revealed similar thermohaline conditions in the lowermost layer of the water column, whereas the depth range of the LSW indicated warming. At the shelf break the thermohaline front between the cold and the warm component of the West Greenland Current emerged.

The hydrographic conditions off Cape Desolation as observed on 12 November 1987 are outlined in Fig. 7. A tilted front separated the cold diluted surface layer from the warm saline core of the Irminger component. If the lower 34.90*10$^{-3}$ isohaline is referred to as upper boundary, it would appear that the slope trapped boundary current of Denmark Strait overflow origin affected nearly 400 m of the bottom water. This is in contrast to the 1984 observations where at Station 4 a layer of about 100 m in vertical magnitude was found (Fig. 6).

Figure 8 indicated warming and a slight increase in salinity for the core layer of the Irminger component.

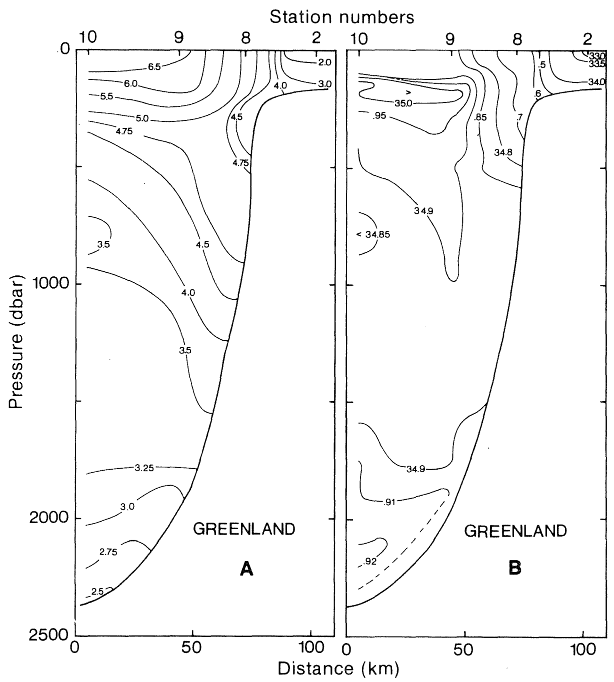


Fig. 6. (**A**) potential temperature, and (**B**) salinity along the Cape Farewell Section, 12-13 October 1987.

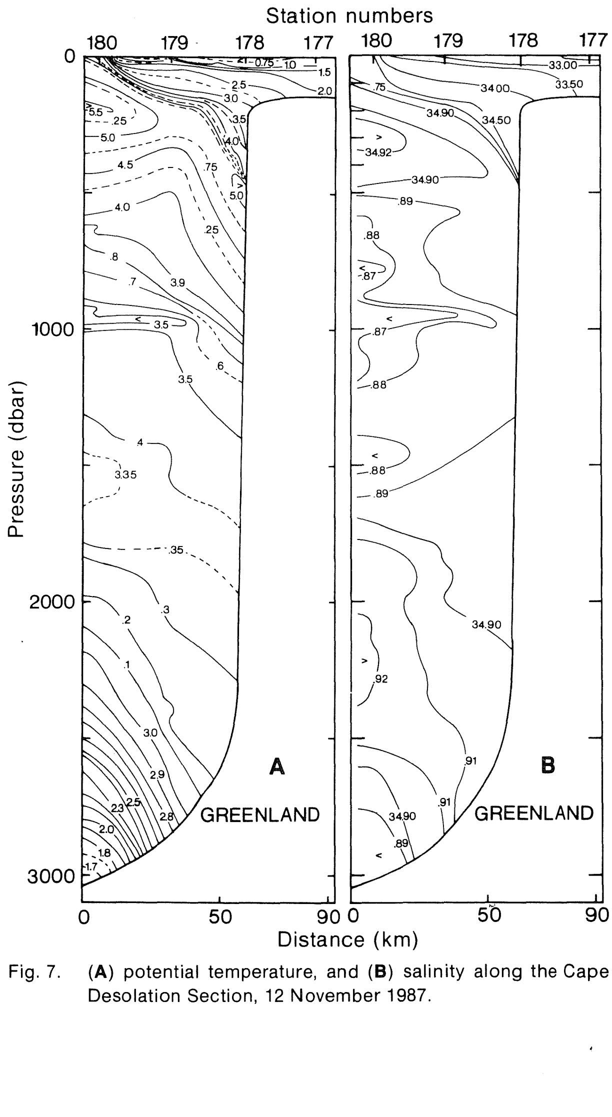


Fig. 7. (**A**) potential temperature, and (**B**) salinity along the Cape Desolation Section, 12 November 1987.

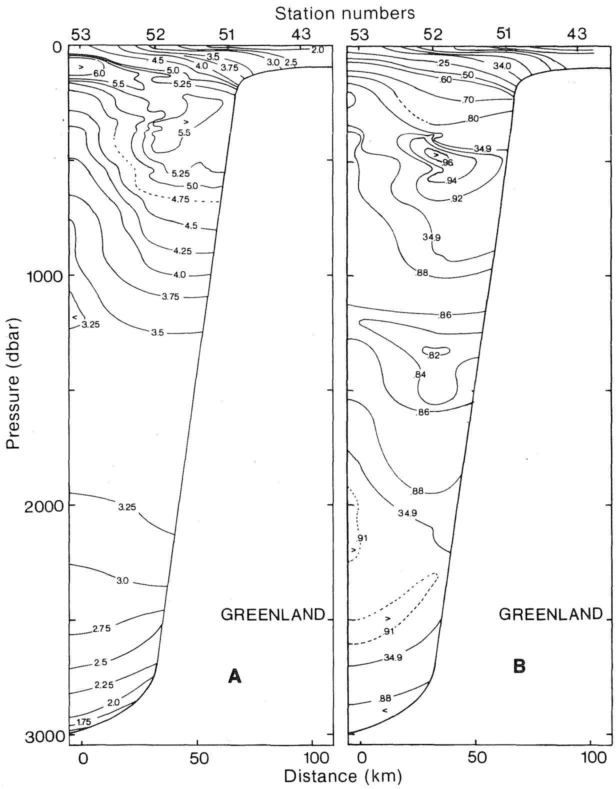


Fig. 8. (**A**) potential temperature, and (**B**) salinity along the Frederikshaab Section, 18–19 October 1987.

Similarly the hydrographic conditions of the deep LSW layers show there was a slight increase in temperature. The thermohaline conditions in the overflow layer did not show variation relative to the 1984 observations. In general, based on the 1984 and 1987 observations, the variability was expressed mostly in the surface layer (seasonal variability, short-time variability) and in the slope layer occupied by the LSW. The feature may in fact be reflected in the advected variability (Stein, MS 1989).

**Temporal variability of slope water masses**

To evaluate the variability in the composition of the slope water masses in more detail, the Standard Station data profiles of temperature and salinity were reduced to standard depths and plotted against depth and time. Some examples of this analysis are displayed in Fig. 9 to 13 and some numerical values of this evaluation are given in Table 1.

A warming trend in the deep layers below the seasonal surface layer of the Cape Farewell Section (stations 3, 4) was indicated in Fig. 9 and 10. As outlined by the 4.4° C isotherm (Fig. 9) and the 3.4° C isotherm (Fig. 10) the slopes of these and adjacent lines revealed increasing heatflow across the Cape Farewell Section into the Labrador Sea. Calculation of thermal coefficients yielded about 0.1° C per year for these layers. At depths below 1,500 m there was little variability in the

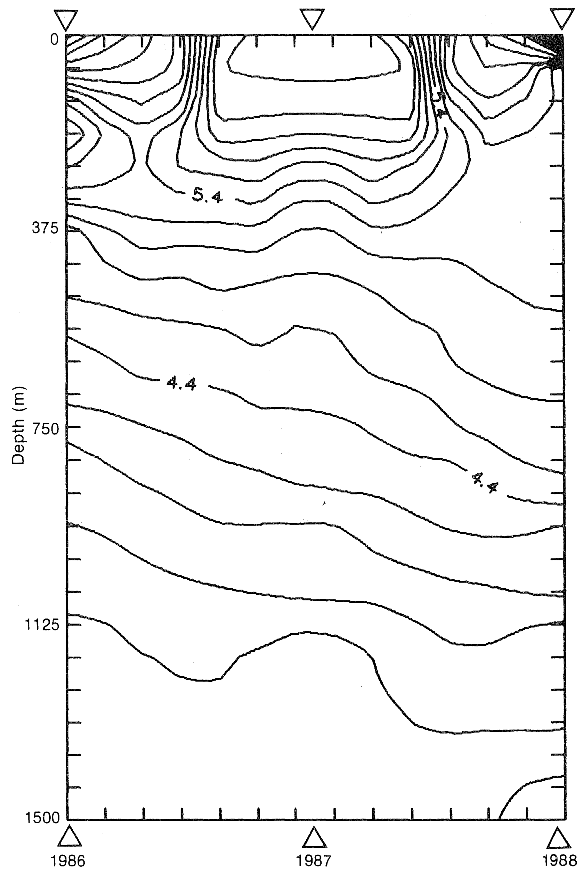


Fig. 9. Isopleths of temperature at station 3 of the Cape Farewell Section during the period 1986–88.

TABLE 1. Temperatures and salinities in the core of the eastern Labrador Sea Water during 1984, 1986, 1987 and 1988.

| Year | Depth (m) | Temp. (°C) | Sal. S*10$^{-3}$ | Delta $t_{84}$ (°K) | Delta $S_{84}$ S*10$^{-3}$ |
|---|---|---|---|---|---|
| | | **Cape Farewell — Station 4** | | | |
| 1984 | 1270 | 3.00 | 34.84 | | |
| 1986 | 1100 | 3.25 | 34.86 | +0.25 | +0.02 |
| 1987 | 1290 | 3.33 | 34.87 | +0.33 | +0.03 |
| 1988 | 1320 | 3.38 | 34.88 | +0.38 | +0.04 |
| | | **Cape Desolation — Station 3** | | | |
| 1984 | 1170 | 3.37 | 34.90 | | |
| 1986 | 1420 | 3.28 | 34.87 | -0.09 | -0.03 |
| 1987 | 1130 | 3.41 | 34.87 | +0.04 | -0.03 |
| 1988 | 1263 | 3.25 | 34.87 | -0.12 | -0.03 |
| | | **Frederikshaab — Station 3** | | | |
| 1984 | 1500 | 3.09 | 34.87 | | |
| 1986 | 1490 | 3.44 | 34.87 | +0.35 | 0.00 |
| 1987 | 1510 | 3.28 | 34.83 | +0.19 | -0.04 |
| 1988 | 1450 | 3.34 | 34.87 | +0.25 | 0.00 |
| | | **Frederikshaab — Station 4** | | | |
| 1984 | 1350 | 3.25 | 34.88 | | |
| 1986 | 1250 | 3.52 | 34.86 | +0.27 | -0.02 |
| 1987 | 1180 | 3.23 | 34.84 | -0.02 | -0.04 |
| 1988 | 1240 | 3.32 | 34.87 | +0.07 | -0.01 |

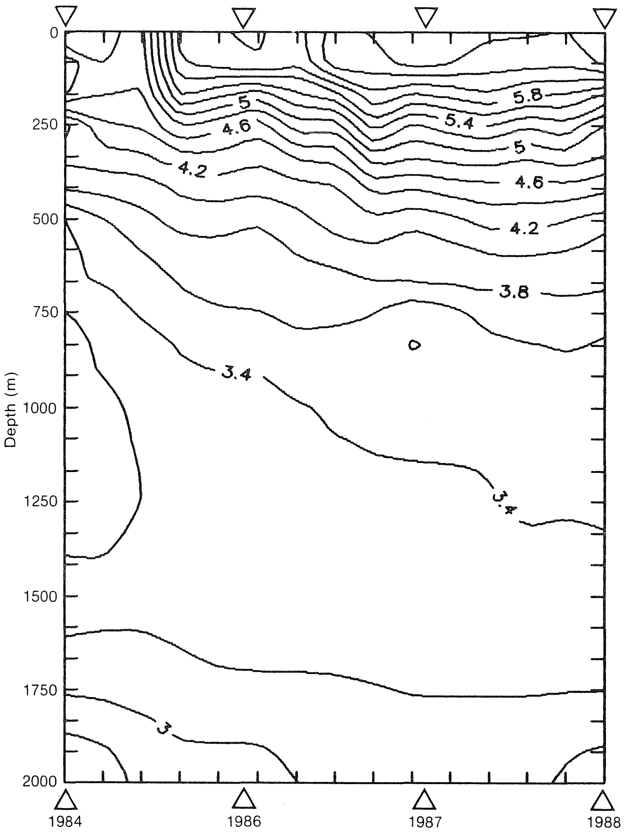


Fig. 10. Isopleths of temperature at station 4 of the Cape Farewell Section during 1984, 1986, 1987 and 1988.

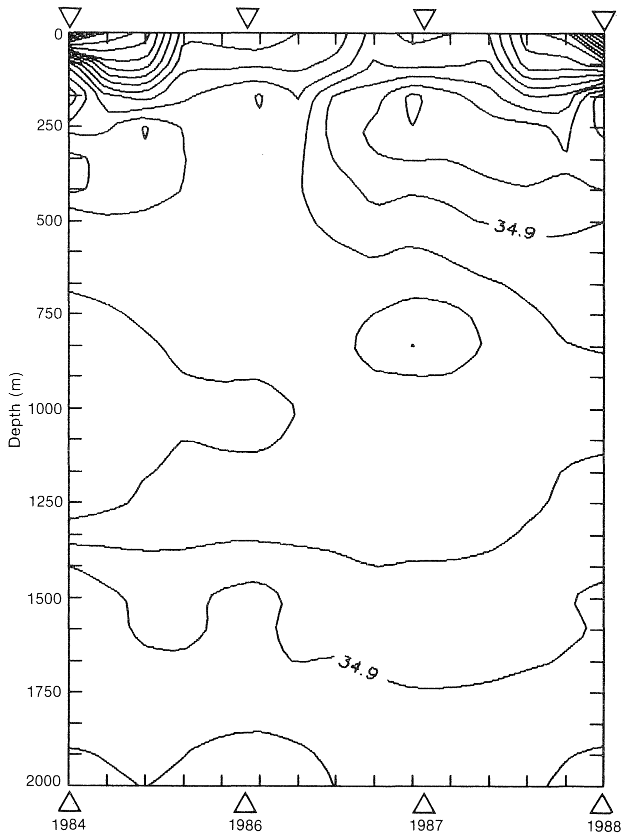


Fig. 11. Isopleths of salinity at station 4 of the Cape Farewell Section during 1984, 1986, 1987 and 1988.

thermohaline fields. From the surface layer (0–200 m) of Fig. 9 and 10 it would appear that the cold early-1980s (Stein and Buch, 1985) led to homogenous conditions in the upper water masses. Salinity (Fig. 11) indicated a diluted surface layer for the year 1984. In contrast to the Cape Farewell Section, the Cape Desolation Section revealed a cooling trend for the slope water masses (Fig. 12) above 1,500 m. Salinity appeared to remain unaffected by annual variation.

From the Standard Stations, isopleth diagrams were constructed to delineate the temporal variability of the slope and deep water masses. Figure 14 shows temperature/salinity *versus* time and standard depth for the years 1984, 1986, 1987 and 1988.

From Frederikshaab Section (Fig. 13, 14) the thermal fields at stations 3 and 4 indicate warming between 1984 and 1986, whereas from 1986 onwards there are alternating thermal trends. At station 3 (Fig. 13) there were homogenous conditions in the slope water region, at station 4 there was a decrease of heat content from 1986 to 1987 and a fairly homogenous situation between 1987 and 1988 (Fig. 14).

To get an impression of the temporal temperature and salinity changes of the water masses out of the direct meteorological influence, the core values of the subsurface layers of the different years were taken into account. The Irminger component which contained the largest amount of the subsurface warming (Fig. 9 to 14) has not only had surface contact with its not-so-far generation area (Irminger Sea), it also often reached the surface at or beyond the stations reviewed here over the outer slope edge. Therefore, this component has to be neglected. Similarly, the core of the deepest water mass, the North Atlantic Deep Water, was not often reached by the outer stations.

Thus, only the eastern part of the LSW remained within the area considered. The extent to which the core was reached in the different sections are given in Table 1, with the minimum temperatures and salinities as well as the related depth of the core in the different years. In addition, the table contains the temperature and salinity differences relative to the 1984 data. The tabulation shows that the depth range of the core of the eastern LSW was relatively constant (1,100 m to 1,510 m) from year to year. Even from section to section the depth variation did not increase, although a deepening towards the coast according to the slope of all isolines (Fig. 2 to 8) and a deepening to the north, were indicated in general.

In the core temperatures of the Cape Farewell Section, a general warming of about 0.1° C during the

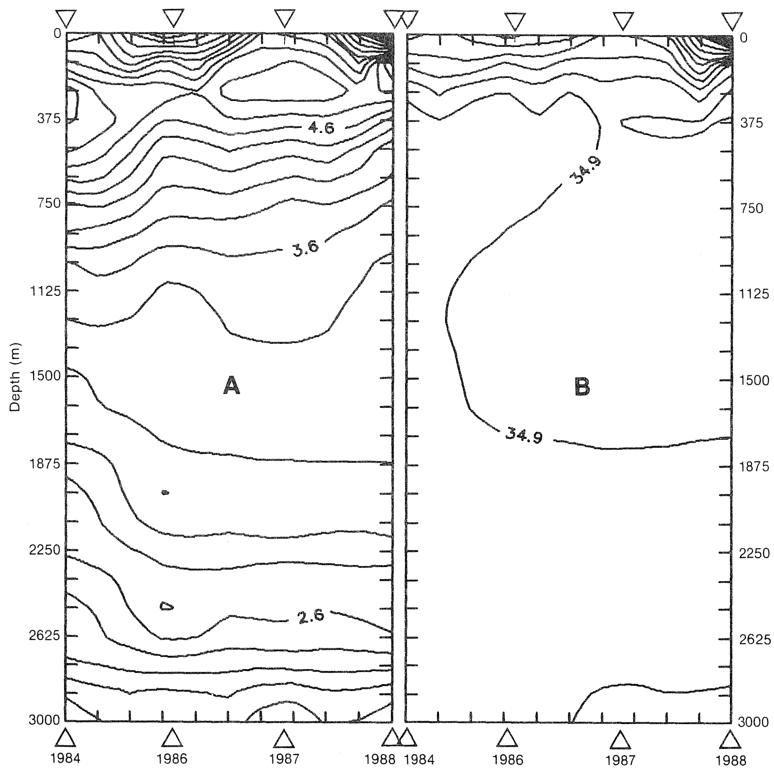


Fig. 12. Isopleths of (**A**) temperature, and (**B**) salinity at station 3 of the Cape Desolation Section during 1984, 1986, 1987 and 1988.

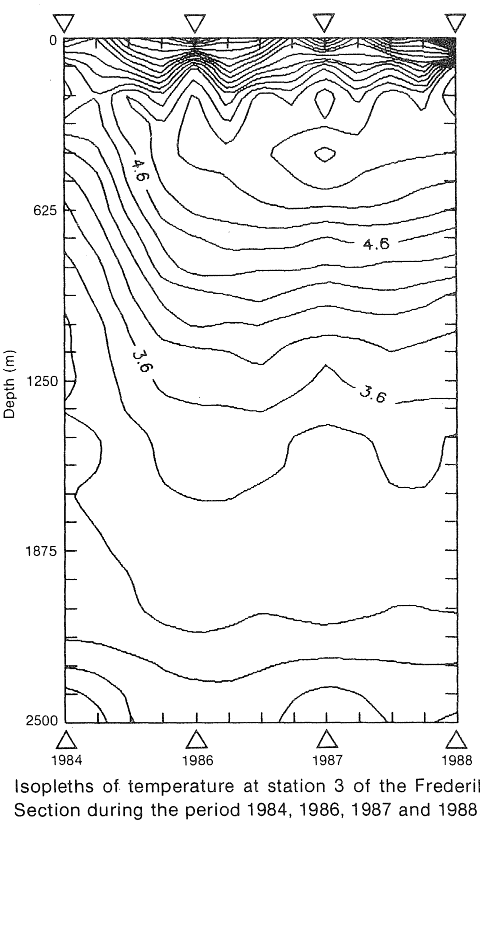


Fig. 13. Isopleths of temperature at station 3 of the Frederikshaab Section during the period 1984, 1986, 1987 and 1988.

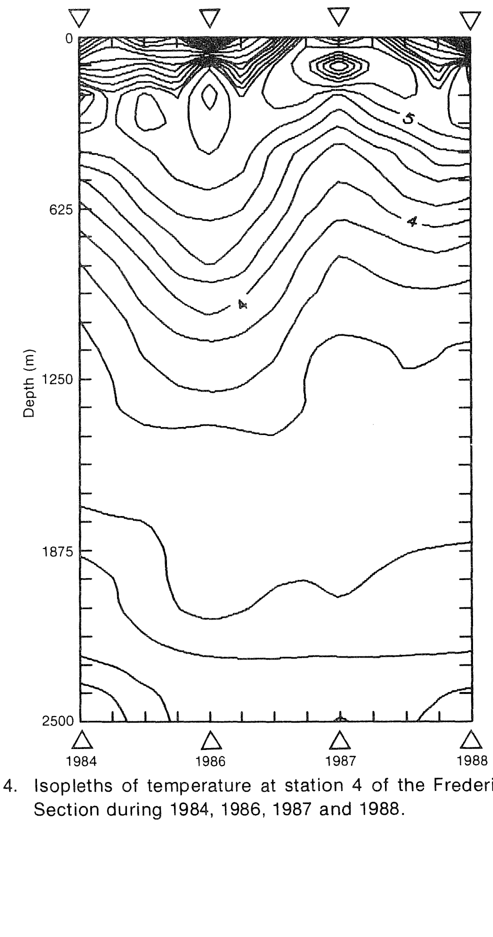


Fig. 14. Isopleths of temperature at station 4 of the Frederikshaab Section during 1984, 1986, 1987 and 1988.

period 1984–88 occurred. However, this tendency was not found in the sections further north, although a contrary development could not be found in these sections. It would appear that, the positive as well as the negative differences, compared to an optional standard 1984 were due to the topographically induced meandering of the current along the slope and different meteorological influences (e.g. air pressure, wind) during the period 1984–88.

To confirm the apparent warming in the Cape Farewell Section and as an effect of a general temperature increase in the area investigated and in the order of the magnitude of the global heating given by Strong (1989), a much more complete data set in time and space would be required.

## Acknowledgements

The authors express their thanks to H. Cenek and B. Schillat for the compilation of the data files and figures.

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