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Recent Observations on the Deep Waters off West Greenland

by

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Abstract

Based on CTD/Rosette data sampled along NAFO Standard Sections Cape Farewell, Cape Desolation and Frederikshaab, the thermohaline field off the West Greenland continental slope is described. Analysis of temperature reveals warming which is 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 (1100m to 1500m) only the Cape Farewell Section indicated warming which amounts to about 0.1°C/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°C to 4°C and fresher than $34.94*10^{-3}$ (**Wright and Worthington, 1970**), to potential density less than $\sigma_t = 27.8$ (**Lazier, 1973**), and 3.4°C, $34.88*10^{-3}$ (**Talley and McCartney, 1982**). The formation processes on the large, meso- and smaller-scale are analysed by **Clarke and Gascard (1983)**, and **Gascard and Clarke (1983)**. They hypothesized that a 200km 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 to Labrador Sea water to take place. The advection of Labrador Sea water out of the Labrador Sea is described in detail by **Talley and McCartney (1982)**, using a vertical minimum in 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 omponent which arises from the northern branch of the North Atlantic Current (**Clarke, 1984**). At depths between 1500m and 2000m a pronounced halocline separates the low-salinity Labrador Sea Water and the saline, low-oxygen layers of the North Atlantic

Deep Water. The undermost storey of the water column is inhabited by the Northwest Atlantic Bottom Water which derives in large parts its characteristics from the Denmark Strait overflow (**Swift, 1984**). He defines this water mass Θ,S-characteristics near 1°C and salinities near $34.9*10^{-3}$. According to **Mann (1969)** the Denmark Strait overflow water moving well down the east coast of Greenland toward Cape Farewell has changed its Θ,S-characteristics due to mixing with water above it. On the basis of recently collected CTD/Rosette data along the Seal Island-Cape Farewell Section across the Labrador Sea, observations along the Cape Farewell, Cape Desolation and Frederikshaab NAFO Standard Sections, between 1984 and 1988, the thermohaline properties of the West Greenland continental shelf region are described.

Data and Methods

Between November 2, 1984 and November 4, 1984 RV "Walther Herwig" completed NAFO Standard Oceanographic Sections Frederikshaab (stations 95 to 100), Cape Desolation (stations 101 to 105), and between November 6, 1984 and November 8, 1984 Seal Island-Cape Farewell (stations 106 to 123). The location of the 1984 stations is given in Fig. 1a. During 1986, 1987 and 1988 the afore-mentioned sections were completed in part (Fig. 1b). The hydrographic fields were mapped using the KIEL-Multisonde CTD plus Rosette water sampler. Calibration samples were collected at each station, in the central Labrador Sea additionally samples for oxygen determination (Winkler method) were sampled. The CTD was equipped with a bottom sensor. According to this sensor the CTD was lowered down to 5m above the bottom. At this depth the bottom water samples were collected. While heaving, the CTD/Rosette device was stopped in 500dbar intervals for calibration and oxygen probes (Fig. 3). The temperature readings were checked against reversing thermometers, salinity was determined by means of a GUILDLINE laboratory salinometer.
From the Standard Stations isopleth diagrams were constructed to delineate the temporal variability of the slope and deep water masses. Figs. 14 to 17 show temperature/salinity versus time and standard depth for the years 1984, 1986, 1987, 1988.

Results and Discussion

Fig. 1a displays the location of the Standard Oceanographic Sections and the individual CTD/Rosette stations as performed during the 1984 cruise of FRV "Walther Herwig" **(STEIN, 1985)**. The 2000m and 3000m isobaths were taken from General Bathymetric Chart of the Oceans (GEBCO) number 5.04 (1978 edition). The updated positions and depths of the standard stations are published by **STEIN (1988)**.
For a general description of the thermohaline fields on the slope off southwest Greenland, the 1984 data are used since they give the most complete and quasi-synoptic cover of standard stations in this 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 emerges from the thermohaline field (Figs. 2, 3). Being colder than -1.0°C on Hamilton Bank, the polar portion of this

current reflects the 20% of the Labrador Current originating from Baffin Bay as the Baffin Island or Canadian Current **(LAZIER, 1982)**. Centered over the 600-800m isobath on the slope (stations 112, 113) about 80% of the current flow are concentrated **(LAZIER, 1982)**, representing the warm and haline waters arising from the Irminger Current. Off West Greenland the Irminger component of the West Greenland Current is visible by its strongly expressed thermohaline signals (east of station 120). Between these two currents the vast area of the Labrador Sea inhabits about 500km of the section. At depths of 2000m the pronounced halocline separates 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 larger than $34.94*10^{-3}$, oxygen around 6.6ml/l (Fig. 3). The bottom water layer in this area is 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 shows that the O,S-characteristics are less than 2.0°C, $34.92*10^{-3}$ and a considerable amount of water has a salinity less than $34.90*10^{-3}$. The observed salinities of this slope trapped boundary current were found to range from $34.887*10^{-3}$ to $34.894*10^{-3}$. The "new" overflow water entering the Labrador Sea at its eastern slope yields oxygen values up to 7.03ml/l, whereas the "old" overflow water after having done its cyclonic path along the Labrador basin suffers from oxygen consumption and leaves the Labrador Sea with oxygen values as low as 6.84ml/l. This is 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 500dbar, the core of the West Greenland Current is visible (Figs. 2, 3). On its way north the core-salinity decreases by $0.02*10^{-3}$ (Figs. 4a, b). On the shelf the cold, diluted waters of the East Greenland component emerge from Figs. 4 and 5. Both sections indicate the temperature minimum layer at 1500dbar (less than 3.2°C) which is also evident from Fig. 2. These t_{min} layers coincide with the formation layers of LSW. Similar to the Seal Island-Cape Farewell Section, the halocline below 1500dbar indicates the transition zone to the North Atlantic Deep Water which is 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 3000dbar the upper boundary of the Northwest Atlantic Bottom Water is found. Similar to the section across the Labrador Sea (Figs. 2, 3) the O,S-characteristics of this water mass are less than 1.5°C, $34.90*10^{-3}$. 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 $34.893*10^{-3}$ (stations 95 to 98). Off Cape Desolation (Fig. 4b) the corresponding values in the overflow layer were $34.898*10^{-3}$, $34.906*10^{-3}$, and $34.899*10^{-3}$ (stations 105 to 103).

Fig. 1b displays the Standard Stations as performed during the 1986, 1987 and 1988 surveys. The thermohaline conditions on the Cape Farewell, Cape Desolation and Frederikshaab Section during recent observations are shown by means of the 1987 results (Figs. 6 to 11).

Considerably warmer core temperatures and higher core salinities were observed during the 1987 cruise than in 1984, a year which is known to be a rather cold one in West Greenland waters **(STEIN and BUCH, 1985)**. Station 10 (1987) and 123 (1984) which represent Standard Station 4 of the Cape Farewell Section (Figs. 2, 3, and 6) reveal similar thermohaline conditions

in the undermost storey of the water column, whereas the depth range of the LSW indicates warming. At the shelf break the thermohaline front between the cold and the warm component of the West Greenland Current emerges.
Fig. 7 outlines the hydrographic conditions off Cape Desolation as observed on 12 November 1987. A tilted front separates the cold, diluted surface layer from the warm saline core of the Irminger component. It would appear that the slope trapped boundary current of Denmark Strait overflow origin affected nearly 400m of the bottom water if one refers to the lower $34.90*10^{-3}$ isohaline as upper boundary. This is in contrast to the 1984 observations where at Station 4 a layer of about 100m vertical magnitude was found (Fig. 6).
Fig. 8 indicates warming and a slight increase in salinity for the core layer of the Irminger component. As for the hydrographic conditions of the deep LSW layers, there is a slight increase in temperature. The thermohaline conditions in the overflow layer does not show variation relative to the 1984 observations.
Generally one can say that variability, based on the 1984 and 1987 observations, is expressed most in the surface layer (seasonal variability, short-time variability), and in the slope layer, inhabited by the LSW, which might reflect the advected variability (**STEIN, 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 this paper (Figs. 9 to 13). Some numerical values of this evaluation are given in Table 1.

Figs. 9 and 10 indicate a warming trend in the deep layers below the seasonal surface layer of the Cape Farewell Section (station 3, 4). As outlined by the 4.4°C isotherme (Fig. 9) and the 3.4°C isotherme (Fig. 10) the slope of these and adjacent lines reveals increasing heatflow across the Cape Farewell Section into the Labrador Sea. Calculation of thermal coefficients yields **about 0.1°C/year** for these layers. At depths below 1500m there is little variability in the thermohaline fields. From the surface layer (0-200m) of Figs. 9 and 10 it would appear that the cold early eighties (**STEIN and BUCH, 1985**) led to homogenous conditions in the upper water masses. Salinity (Fig. 11) indicates a diluted surface layer for the year 1984. In contrast to the Cape Farewell Section, the Cape Desolation Section reveals a cooling trend for the slope water masses (Fig. 12) above 1500m. Salinity appears to remain unaffected by annual variation. From the Frederikshaab Section (Figs. 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 are homogenous conditions in the slope water region, at station 4 there is 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 - it contained the largest amount of the subsurface warming in Figs. 9 to 14 - has not only had surface contact in its not so far generation area (Irminger Sea), it often reached the surface at or beyond the stations rewied here over the outer slope edge. Therefore it had to be neglected. The core of the deepest water mass, the North Atlantic Deep Water, mostly was not reached by the outer stations.

Thus only the eastern part of the LSW remained. As far as the core was reached in the different sections, the minimum temperatures and salinities as well as the relating depth of the different years are given in Table 1. In addition the table contains the temperature and salinity differences relative to the 1984 data.

The table shows that the depth range of the core of the eastern LSW was relatively constant (1100m to 1510m) 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 (Figs. 2 to 8) - and a deepening to the north are indicated in general.

In the core temperatures of the Cape Farewell Section, a general warming of about 0.1°C during the period 1984 to 1988 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 the different meteorological influences (e.g. air pressure, wind) during the period 1984 to 1988.

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

Acknowledgements

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Table 1 Temperatures and salinities in the core of the eastern Labrador Sea Water 1984 to 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

	Year	Depth [m]	Temp. [°C]	Sal. S*10^-3	Delta t_{84} [°K]	Delta s_{84} S*10^-3
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

	Year	Depth [m]	Temp. [°C]	Sal. S*10^-3	Delta t_{84} [°K]	Delta s_{84} S*10^-3
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
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

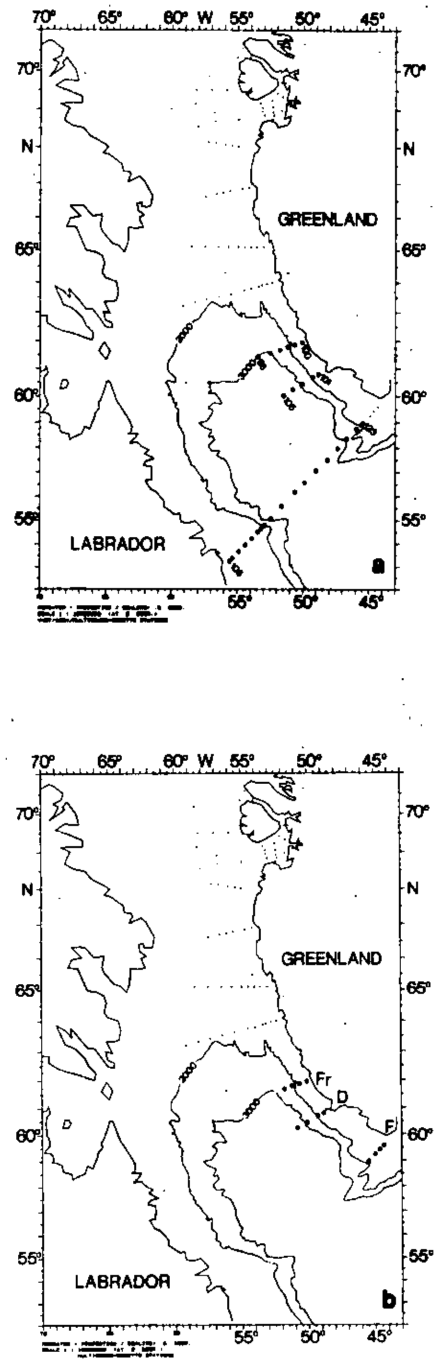

Fig 1 Location of Standard Oceanographic Sections and Stations (a) Stations occupied between November 2, 1984 and November 4, 1984 by FRV "Walther Herwig", (b) Stations occupied during the 1986, 1987 and 1988 cruises of FRV "Walther Herwig" (F: Cape Farewell; D: Cape Desolation; Fr: Frederikshaab).

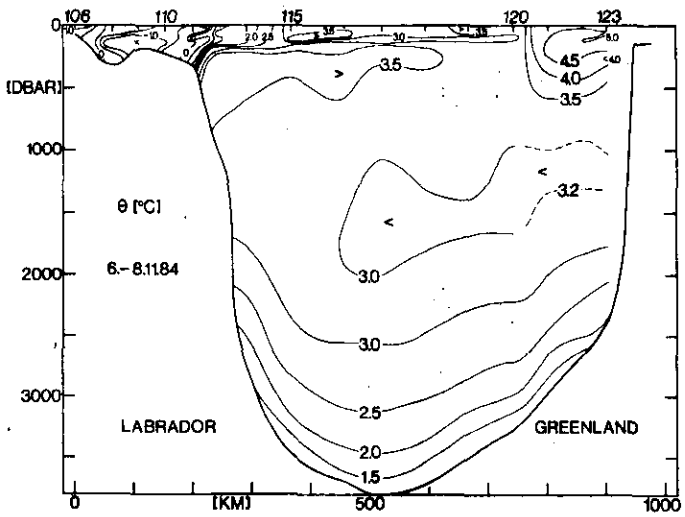

Fig. 2 Potential Temperature along the Seal Island-Cape Farewell Section, November 6, 1984 to November 8, 1984.

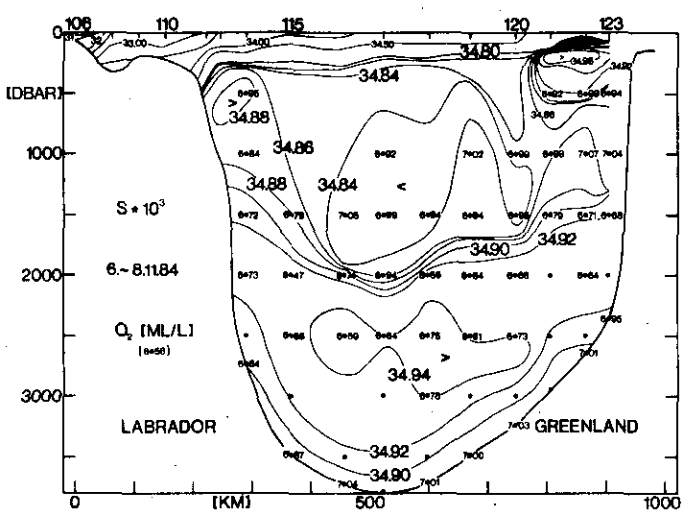

Fig. 3 Salinity and Oxygen along the Seal Island-Cape Farewell Section, November 6, 1984 to November 8, 1984 (dots indicate depths of calibration samples).

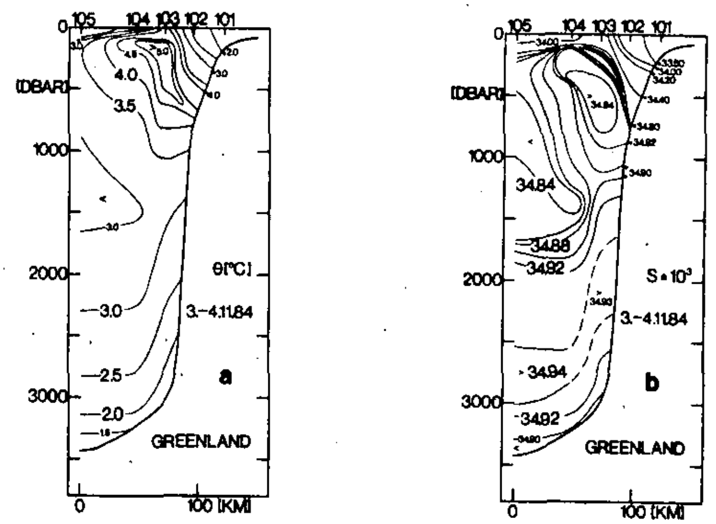

Fig. 4 (a): Potential Temperature, (b): Salinity along the Cape Desolation Section, November 3, 1984 to November 4, 1984.

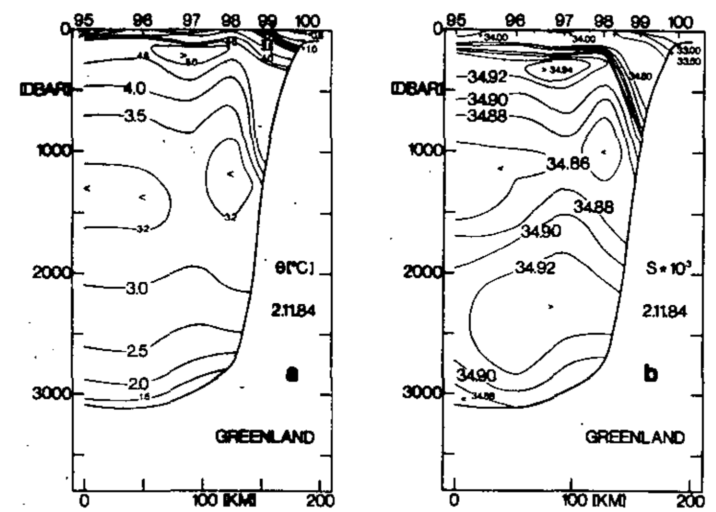

Fig. 5 (a): Potential Temperature, (b): Salinity along the Frederikshaab Section, November 2, 1984 .

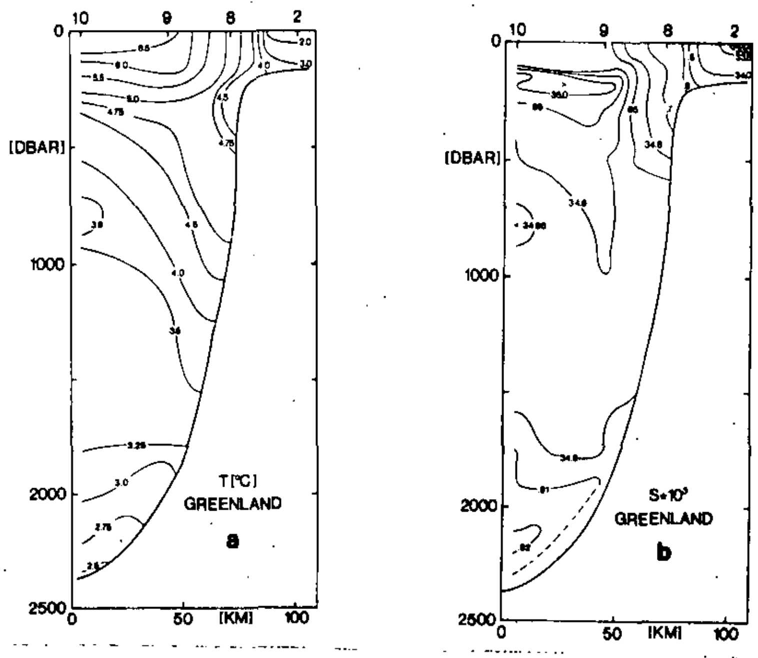

Fig. 6 (a): Potential Temperature, (b): Salinity along the Cape Farewell Section, October 12, 1987 to October 13, 1987.

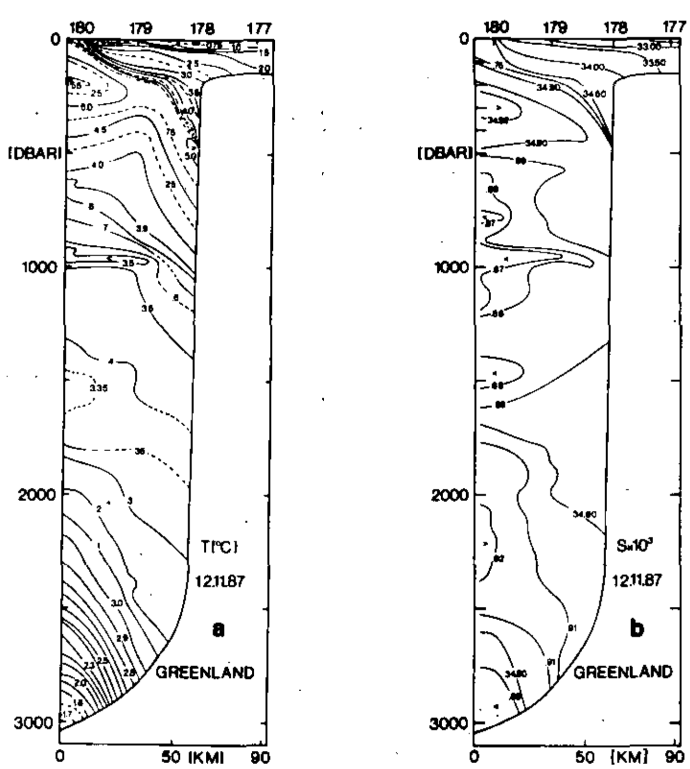

Fig. 7 (a): Potential Temperature, (b): Salinity along the Cape Desolation Section, November 12, 1987.

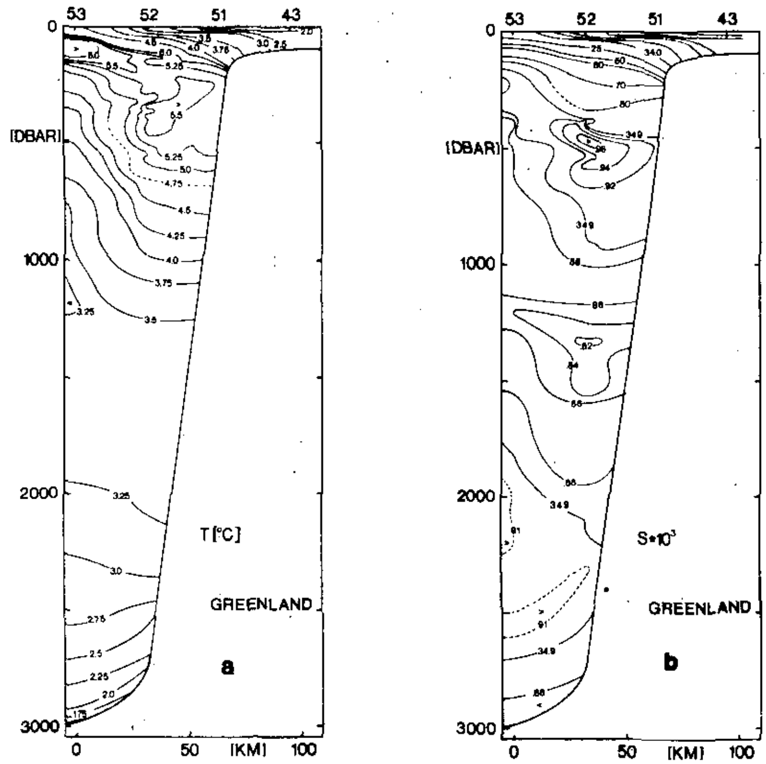

Fig. 8 (a): Potential Temperature, (b): Salinity along the Frederikshaab Section, October 18, 1987 to October 19, 1987.

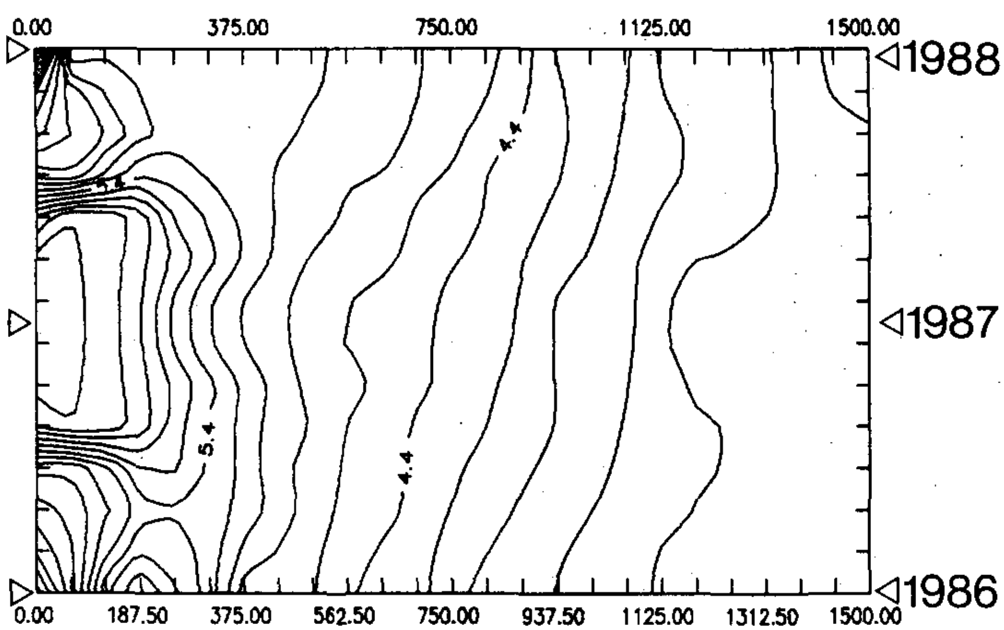

Fig. 9 Isopleths of Temperature Cape Farewell Section Standard Station 3, 1986, 1987, 1988.

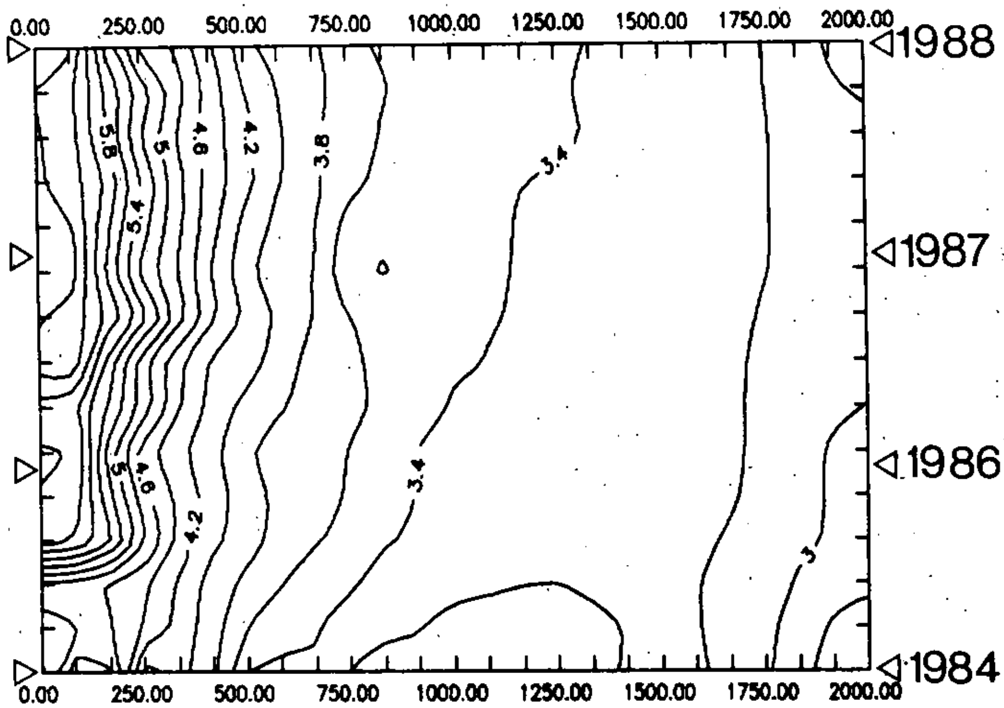

Fig. 10 Isopleths of Temperature Cape Farewell Section Standard Station 4, 1984, 1986, 1987, 1988.

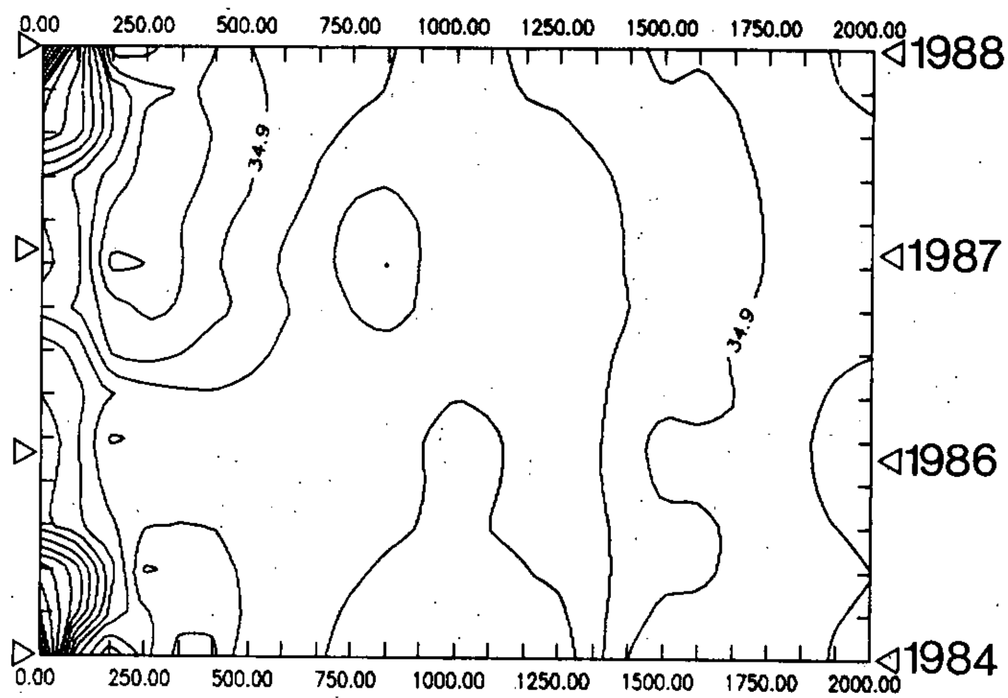

Fig. 11 Isopleths of Salinity Cape Farewell Section Standard Station 4, 1984, 1986, 1987, 1988.

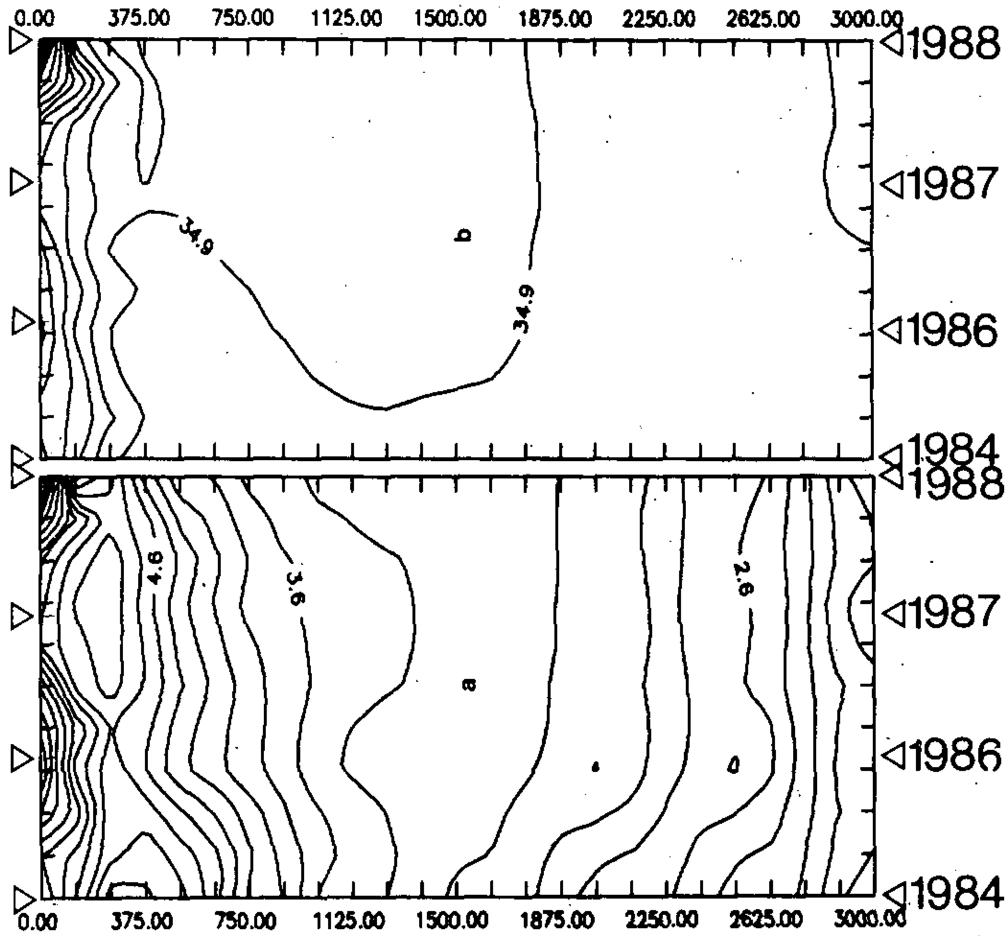

Fig. 12 Isopleths of Temperature (a), and Salinity (b) Cape Desolation Section Standard Station 3, 1984, 1986, 1987, 1988.

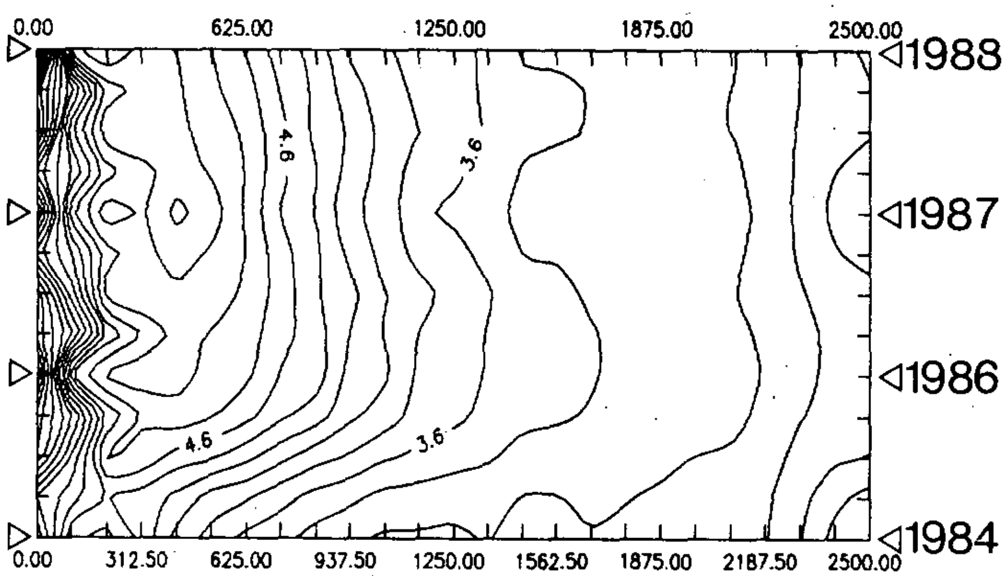

Fig. 13 Isopleths of Temperature Frederikshaab Section Standard Station 3, 1984, 1986, 1987, 1988.

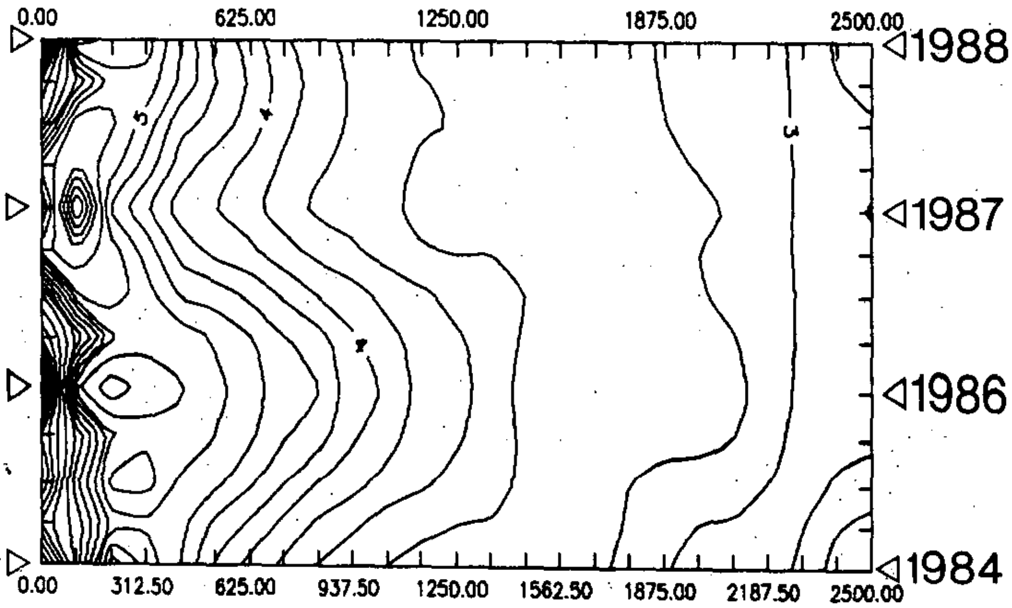

Fig. 14 Isopleths of Temperature Frederikshaab Section Standard Station 4, 1984, 1986, 1987, 1988.