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Climatic Variability of Deep Waters off Greenland and in the Labrador Sea

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Abstract

The paper elucidates the distribution of the major water masses and some climatic events in deep water layers of the Labrador Sea area and of the eastern and western slope region. Temperature variance in the bottom water layer of the Labrador Sea (3 500 m depth) amounted to 1K, compared to 0.5K in the deep water layers above the Denmark Strait Overflow (DSOW)-layer. The significant variance of the thermohaline signals pointed to high frequency variability in this layer. Analysis of both time-series revealed a small positive trend which amounted to 0.01 PSU per year (significant), and 0.02 K per year (not significant). Consistency between both, the trend of the temperature/salinity time-series and the vertical coherence profiles at the Cape Desolation Section off West Greenland, and at Section 8A off Labrador, was found. In the water layers dominated by the Irminger Atlantic Water (500–600 m) and by the Labrador Sea Water (1 200–1 500 m), variations of temperature and salinity were significantly coherent (r >0.6, p <0.001). At Fylla Bank, which is located at the shelf slope off Nuuk/West Greenland, consistency between the thermal and haline signal was less expressed than at the previous two sections. A hypothesis is formulated to explain the significant decrease of salinity in the DSOW-layer at the end of the 1950s. It is suggested that this anomaly is part of the Great Salinity Anomaly cycle. Further analysis of this phenomenon points at several low salinity/temperature events throughout the 45 years of observation. Following the above hypothesis of DSOW formation mode and travel time, it would appear that the historic data series point at a regular advection of low salinity/temperature events in the DSOW-layer on a decadal time scale.

Key words: deep waters, climatic variation, Denmark Strait Overflow Water, Great Salinity Anomaly, Greenland, Labrador Sea

Introduction

During the meeting of the NAFO Subcommittee on Environmental Research in June 1992, it was noted that there are oceanographic databases in various institutes of NAFO Contracting Parties, which might not be available to international data centres. It was proposed that analyses of these data should be undertaken to develop climatic time-series, examine consistency of events both vertically and horizontally and explore possible interrelationships with recruitment patterns in fish stocks. A preliminary view of the data suggest the area of interest should comprise the Labrador Sea and its eastern and western slope areas. Based on the Cooperation in Agricultural Research between Russia and Germany, a project accordingly was formulated in June 1994 to evaluate climatological oceanographic data in the ICNAF/NAFO area. It was agreed the data review and analyses should be undertaken in the form of workshops between the two scientific parties.

During workshops held in Hamburg (25–29 September 1995 and 22–26 April 1996), and in Murmansk (19–23 February, 1996), data analysis and interpretation began and first results were presented to the NAFO Scientific Council (Stein and Borovkov, MS 1996; Borovkov and Stein, MS 1996a and b). It is the aim of the present paper to provide a description of the data and methods and to elucidate climatic events in deep water layers and discuss the horizontal coherence of the observed events in the Labrador Sea. The results are presented on the major water masses in the area, the variability of the thermohaline properties in time and depths, and a correlation analysis of the temperature and salinity time-series. Final conclusions and open questions which might initiate future research are given.

Data and Methods

The data used in the context of this paper originate from four sources: 1. Russian observations from the oceanographic standard Section 8A (near the NAFO Standard Section Seal Island, e.g. Stein, MS 1988), 2. German measurements from the Fylla Bank Section Station 4 and the Cape Desolation Section Station 3, both situated at the West Greenland slope region, 3. World Data Centre A (WDC A) Oceanographic Data as provided in the World Ocean Atlas 1994 on CD-ROM, and 4. air temperature data from Nuuk/West Greenland.

A transfer software was prepared to handle the World Data Centre A Oceanographic Data, and a retrieval software, the program ODISys (Oceanographic Data Information System) which is able to handle large amounts of data, gives a graphic overview on the regional and depth distribution, and stores the retrieved data by position, time and parameter for further analysis. For the WMO-square 7505 a retrieval was done for data from the region delimited by: 56°N, 57°N, 50°W, 52°W. Until 1974 the Ocean Weather Ship Bravo was located in this area at 56°30'N, 51°00'W. The data covered an area of about 60x60 nautical miles in the centre of the Labrador Sea, to a water depth greater than 3 500 m. Temperature and salinity data at standard depths (every 500 m between 1 500 m and 3 500 m, inclusive) were extracted by allowing a depth interval of 100 m above and below the standard depth. For example, retrieved data at 3 500 m included all data between 3 400 m and 3 600 m depth. This formed the basis for further discussions and a thorough analysis of temperature and salinity changes. Most of the data originated from the 1960s which resulted from the presence of Ocean Weather Ship Bravo.

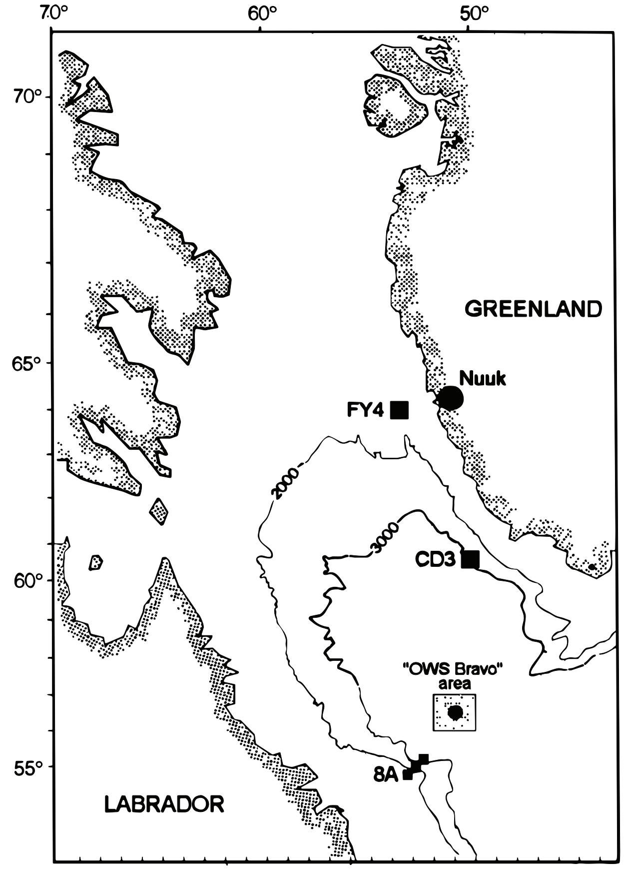


Fig. 1. Location of observation sites at the slope area and in the Labrador Sea (FY4: Fylla Bank Station 4; CD3: Cape Desolation Station 3; 8A: Stations 1, 2, 3 of the Russian Section 8A; Ocean Weather Ship Bravo, "OWS Bravo" area: dot denotes the former position of OWS Bravo, box is delimited by 56°N, 57°N, 50°W, 52°W).

Results

Water Masses

The major water masses present in the area under investigation are: the Irminger Atlantic Water which enters the Labrador Sea off Southwest Greenland and follows the bathymetry, turns west and eventually flows southward along the Labrador slope region (Fig. 1, 2), the Labrador Sea Water (LSW) which is formed by vertical convection in the central Labrador Sea (Lee and Ellett, 1967; Lazier, 1973, 1980, 1988; Wallace and Lazier, 1988), the North Atlantic Deep Water (NADW), and the Northwest Atlantic Bottom Water (NABW).

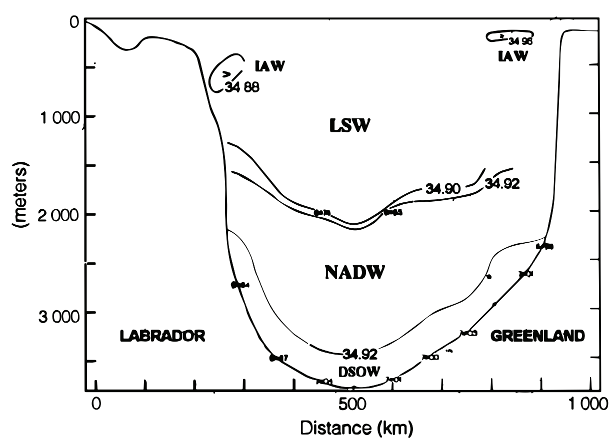


Fig. 2. Vertical distribution of main water masses in the Labrador Sea; core salinities of Irminger Atlantic Water (IAW), halocline between Labrador Sea Water (LSW) and North Atlantic Deep Water (NADW), and upper boundary of Denmark Strait Overflow Water are given according to Stein and Wegner (1990); some oxygen data are inserted from Stein and Wegner (1990).

The Irminger Atlantic Water entering the Labrador Sea off Cape Farewell has core temperatures and salinities above 5°C, 34.96PSU respectively, and is located at depths above 500 m (Stein and Wegner, 1990). Centered around 500 m depth, the warm component of the Labrador Current leaves the Labrador Sea with temperatures above 3.5°C and salinities above 34.88PSU. The LSW characteristics range in temperatures from 3° to 4°C and salinity less than 34.94PSU (Wright and Worthington, 1970), to 3.4°C and 34.88PSU (Talley and McCartney, 1982). At depths of 2 000 m a pronounced halocline separates the low-salinity LSW from the NADW. The latter water mass is characterized by salinities above 34.94PSU and oxygen contents of about 6.6ml/l (Stein and Wegner, 1990). The bottom water in the area, the NABW, is derived in large part from the Denmark Strait overflow (DSOW) (Swift, 1984). Temperature and salinity characteristics are less than 2°C and less than 34.92PSU, respectively. As exemplified recently by Stein and Wegner (1990), the "new" overflow water entering the Labrador Sea at its eastern slope yields oxygen values up to 7.03 ml/l, whereas the "old" overflow water after completing its cyclonic path along the Labrador basin leaves the Labrador Sea with oxygen values as low as 6.84 ml/l.

The temperature/salinity diagrams reveal the vertical distribution of water masses based on the WDC A-data set. At depths of 1 500 m and 2 000 m the LSW clearly emerges if one takes the characteristics as given by Wright and Worthington (1970) for the water mass range, or the definition given by Talley and McCartney (1982) for the fixed point (Fig. 2, 3).

At depths of 2 500 m and 3 000 m salinity values ranged from 34.9PSU to about 34.97PSU. Temperature, however, was significantly different, ranging from 3° to 3.5°C at 2 500 m and 2.5° to 3°C at 3 000 m. At 3 500 m, the waters were colder and fresher than in the upper layers. Temperatures were well below 2.5°C and mostly below 2°C, consistent with overflow water. Except for the three high values between 34.95 and 35PSU which seemed doubtful (Fig. 3, lower panel), the range of salinity distribution fell within literature definitions of the DSOW (Swift, 1984; Stein and Wegner, 1990). The lower end of the salinity range might represent near-bottom values as given in these references.

Whereas the upper layers revealed little thermal variation (about 0.5K), the "overflow" layer data indicated temperature variance of 1K.

Time-Series of Temperature and Salinity

Ocean Weather Ship Bravo. As reported by Borovkov and Stein (1996), the time-series analysis of WDC A data from 1952 to 1974 revealed a trend of warming at a depth of 1 500 m, which abruptly ended around 1972. Salinity at the same depth yielded a small increase until 1972, and then haline conditions became more diluted. Similar trends were detectable between 500 m and 1 500 m depths. At 2 000 m depth the warming trend was maintained throughout the period of observation (1928 to 1974). There was no abrupt change as observed for the 1 500 m layer. Salinity revealed periods of lower salinity (around 34.88 PSU), and of more saline conditions from the 1960s onwards (around 34.93PSU).

Variability in the NADW layers (2 500 m and 3 000 m) was mainly expressed in the haline signal as depicted by the 5-year running mean lines in Fig. 4 and 5. There was a marked increase in salinity after the end of the 1950s, and the higher salinities were maintained until the end of the time-series. The thermal signal at both 2 500 m and 3 000 m layers (Fig. 4 and 5) did not co-vary with the haline signal. At 3 500 m depth there was one remarkable event in the salinity time-series at the end of the 1950s which was paralleled by a notable decrease in temperature (Fig. 6). During the late-1960s another decrease in both parameters was obvious in the "overflow" layer, when temperatures dropped to the level of the first event (1.6°C) and salinity decreased by about 0.02PSU.

Section 8A. Variation in temperature and salinity of the Irminger Atlantic Water layer off Labrador at Station 1 of Section 8A based upon the Russian data are given in Fig. 7 for the 500 m and 600 m depths. Between 1962 and 1972, a period of warm, saline conditions (temperatures around 4°C, salinities above 34.9PSU) was observed. This was followed by a period of cold, diluted conditions between 1974 and 1992 (temperatures around 3.4°C, salinities below 34.88PSU). During cold events, temperatures dropped below 3.4°C and salinities below 34.82PSU. Anomalous high salinities (above 34.9PSU) were recorded in 1982 and 1983. Figures 8 and 9 display the time-series of temperature and salinity at Stations 1, 2 of Section 8A for the depths 1 200 m, 1 500 m and 2 000 m. Figure 10 gives the respective time-series for Station 3 at 1 200 m and the bottom layer. The data revealed a cooling trend between 1970 and 1992 which was clearly expressed at both depths at all stations.

West Greenland Stations. The Fylla Bank Station 4 temperature data (Fig. 11) showed coherence of thermal events throughout the water column especially for the cold event in the early-1980s. The general trend of the temperature time-series indicated cooling from the late-1960s onwards (Stein, MS 1996a and b).

Thermohaline conditions for the depth levels of 1 200 m, 1 500 m, 2 000 m, 2 500 m and 3 000 m from the Cape Desolation Section Station 3 are given in Fig. 12. There was a general downward

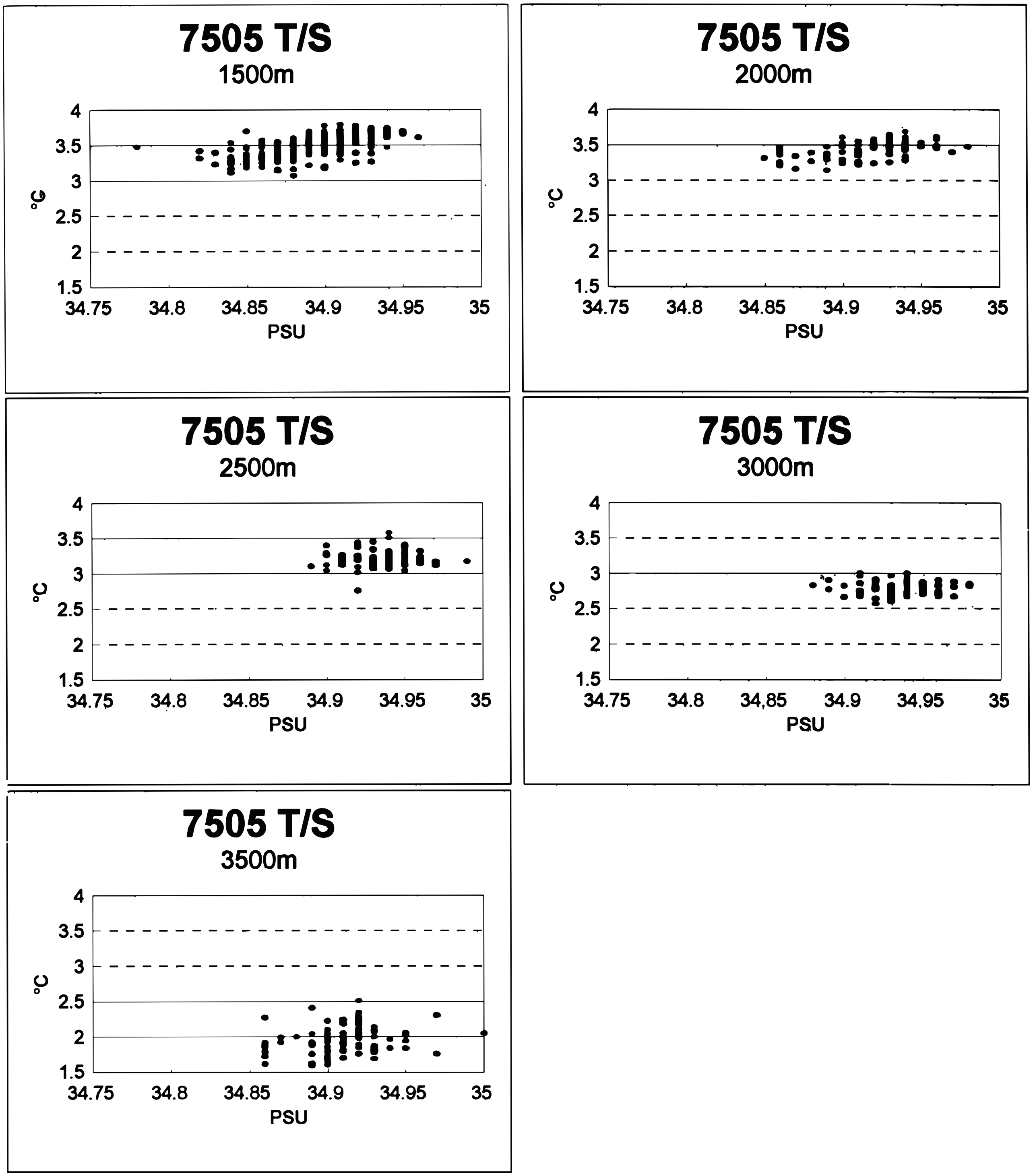


Fig. 3. Temperature/Salinity diagram for depth layers of 1 500 m, 2 000 m, 2 500 m, 3 000 m and 3 500 m from the area delimited by 56°N, 57°N, 50°W, 52°W.

trend incorporated in the temperature and salinity time-series which was analogous to the trend seen at Section 8A at the western slope of the Labrador Sea. The 3 000 m depth layer revealed temperature and salinity characteristics which were representative for the Denmark Strait overflow water.

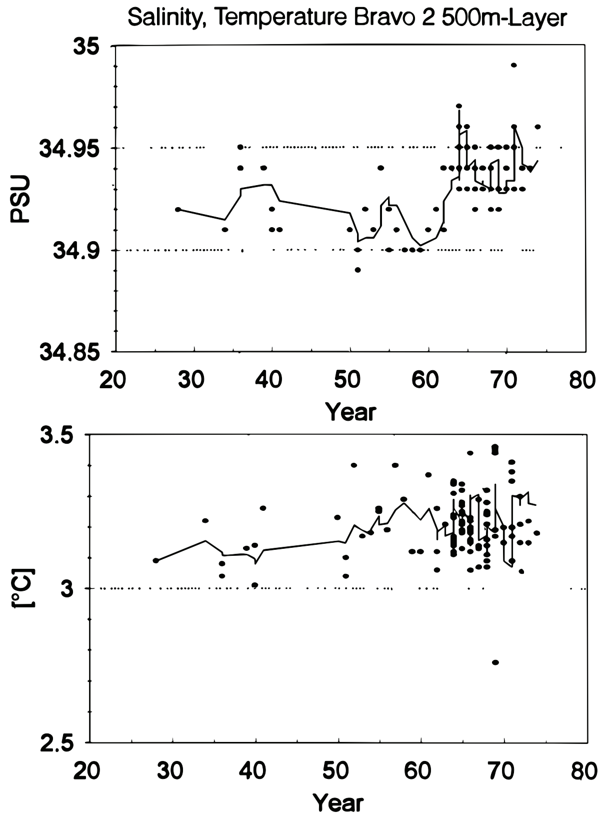


Fig. 4. Salinity and temperature time-series 2 500 m depth for the area delimited by 56°N, 57°N, 50°W, 52°W.

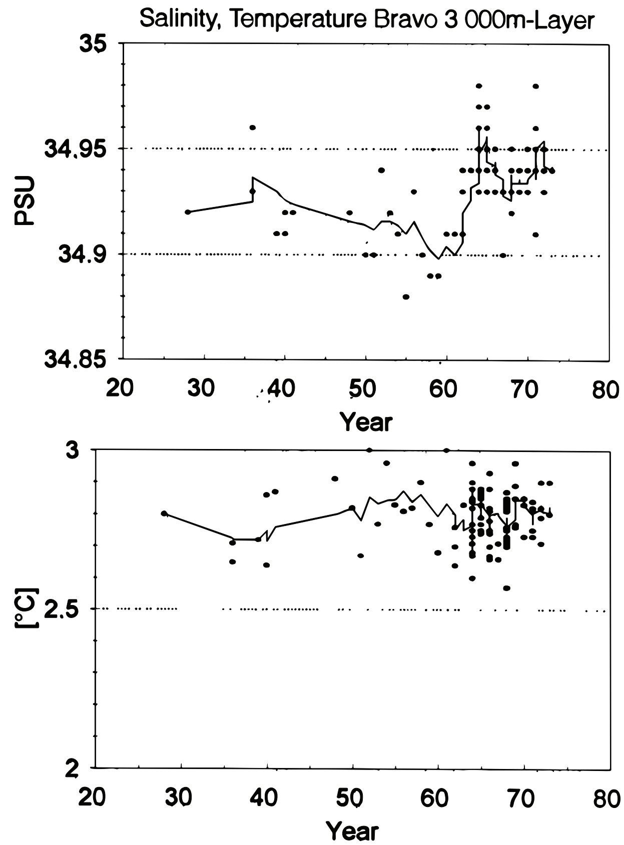


Fig. 5. Salinity and temperature time-series 3 000 m depth for the area delimited by 56°N, 57°N, 50°W, 52°W.

Correlation Analysis

For the standard depths from 300 m to 1 000 m, correlations between temperature and salinity were calculated for time-series from the central Labrador Sea area observed from the Ocean Weather Ship Bravo. The results indicated high correlation coefficients for the 500 m, 600 m and 1 000 m standard depth layers (Fig. 13).

Whereas correlations with depth of either temperature or salinity were high at Fylla Bank Station 4 between depths of 400 m to 800 m (i.e. for temperature between 0.66 and 0.84 and for salinity between 0.60 and 0.82), the correlations between temperature and salinity were rather low, dropping from 0.5 at 300 m to 0.33 at 800 m.

At Cape Desolation Station 3 (Fig. 14) correlations between the thermohaline parameters were high in the Irminger Atlantic Water layer (around 500 m), at 1 500 m depth (r = 0.65, p 0.05), and depths 2 500 m (r = 0.97, p 0.001) and 3 000 m (r = 0.99, p 0.001). For the latter two depths no correlation profile is given since these standard depths were not available at Station 1 of Section 8A. There was a negative correlation for the 300 m level and the 2 000 m depth level, and at 1 000 m and 1 200 m depths the correlation was not significant.

The vertical profiles of correlation coefficients between temperature and salinity at Stations 1, 2 and 3 of Section 8A (Fig. 14) were characterized by a two layer mode: in the upper layer (from 300 m to 1 200–1 500 m) where Irminger Atlantic Water and Labrador Sea Water were located, the variations in temperature and salinity were consistent. In the deeper layer at depths of 1 500–2 000 m, the relationship between temperature and salinity dissipated.

Comparison between Cape Desolation Station 3 and Section 8A Station 1 revealed similar profiles of temperature and salinity correlations, with a minimum at 1 000 m and 2 000 m, and a maximum at the depths of Irminger Atlantic Water and in the Labrador Sea Water layer, i.e. around 500–600 m and 1 200–1 500 m.

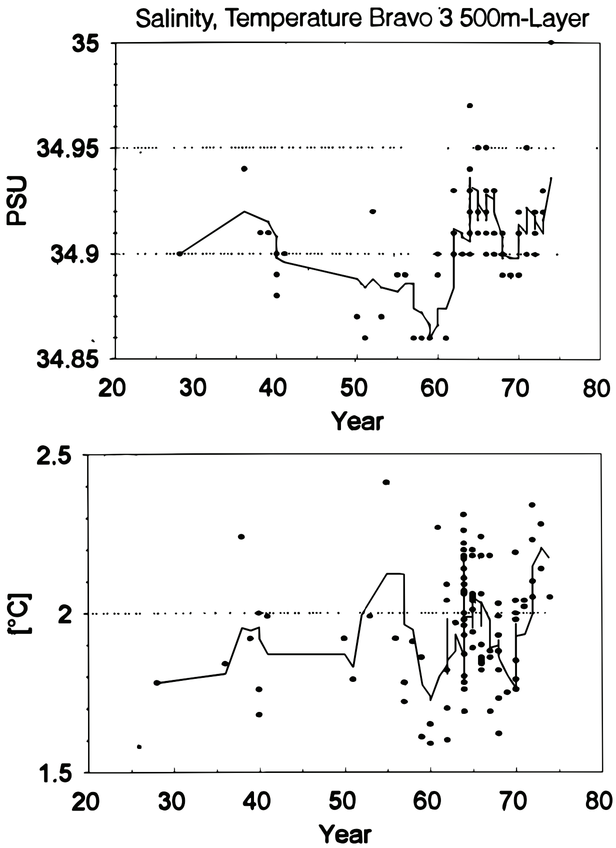


Fig. 6. Salinity and temperature time-series 3 500 m depth for the area delimited by 56°N, 57°N, 50°W, 52°W.

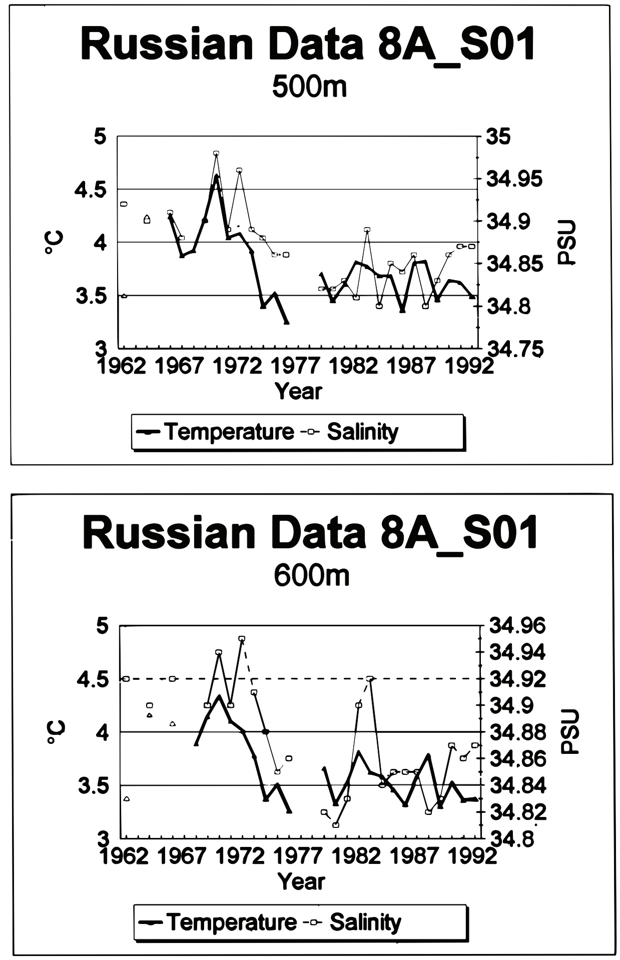


Fig. 7. Salinity and temperature time-series at 500 m and 600 m depth at Station 1 of Section 8A.

In order to observe the influence of any trends, the temperature and salinity time-series for Station 1 of Section 8A were de-trended. From the analyzed depths of 300 m (0.42), 600 m (0.40), 1 000 m (0.09) and 1 200 m (0.35), only the 600 m layer revealed significant correlation using the de-trended time-series (correlation coefficients are given in brackets).

Discussion

Water mass characteristics in the area bounded by 56°N, 57°N, 50°W, 52°W, from 1964 until 1974 when the Ocean Weather Ship Bravo was located in the centre of this area, showed significant differences at deep layers of 2 500 m, 3 000 m and 3 500 m. Whereas at the 2 500 m and 3 000 m depth levels rather homogenous thermohaline conditions were encountered, salinity values ranged from 34.9PSU to about 34.97PSU and the temperatures ranged from 3°C to 3.5°C at 2 500 m, and 2.5°C to 3°C at 3 000 m, while at 3 500 m depth the scatter diagram clearly indicated colder and fresher conditions than at the upper layers. With temperatures ranging well below 2.5°C and mostly below 2°C, at this depth level the Denmark Strait Overflow Water mass was documented. Temperature variance in this layer amounted to 1K, compared to 0.5K in the deep water layers above the "overflow" layer. The significant variance of the thermohaline signals pointed to a high frequency (year-to-year) variability in this layer.

There was similarity both between the trend of the temperature/salinity time-series, and the vertical coherence profiles at Station 3 of the Cape Desolation Section off West Greenland and at Station 1 of Section 8A off Labrador. In the water layers dominated by the Irminger Atlantic Water (500–600 m) and by the LSW (1 200–1 500 m), variation of the thermohaline signal was significantly coherent ($r > 0.6$, $p < 0.001$). At Fylla Bank Station 4 which is located at the shelf slope off Nuuk/West Greenland, coherence between the thermal and haline signal was less than at Stations 2 and 3. This

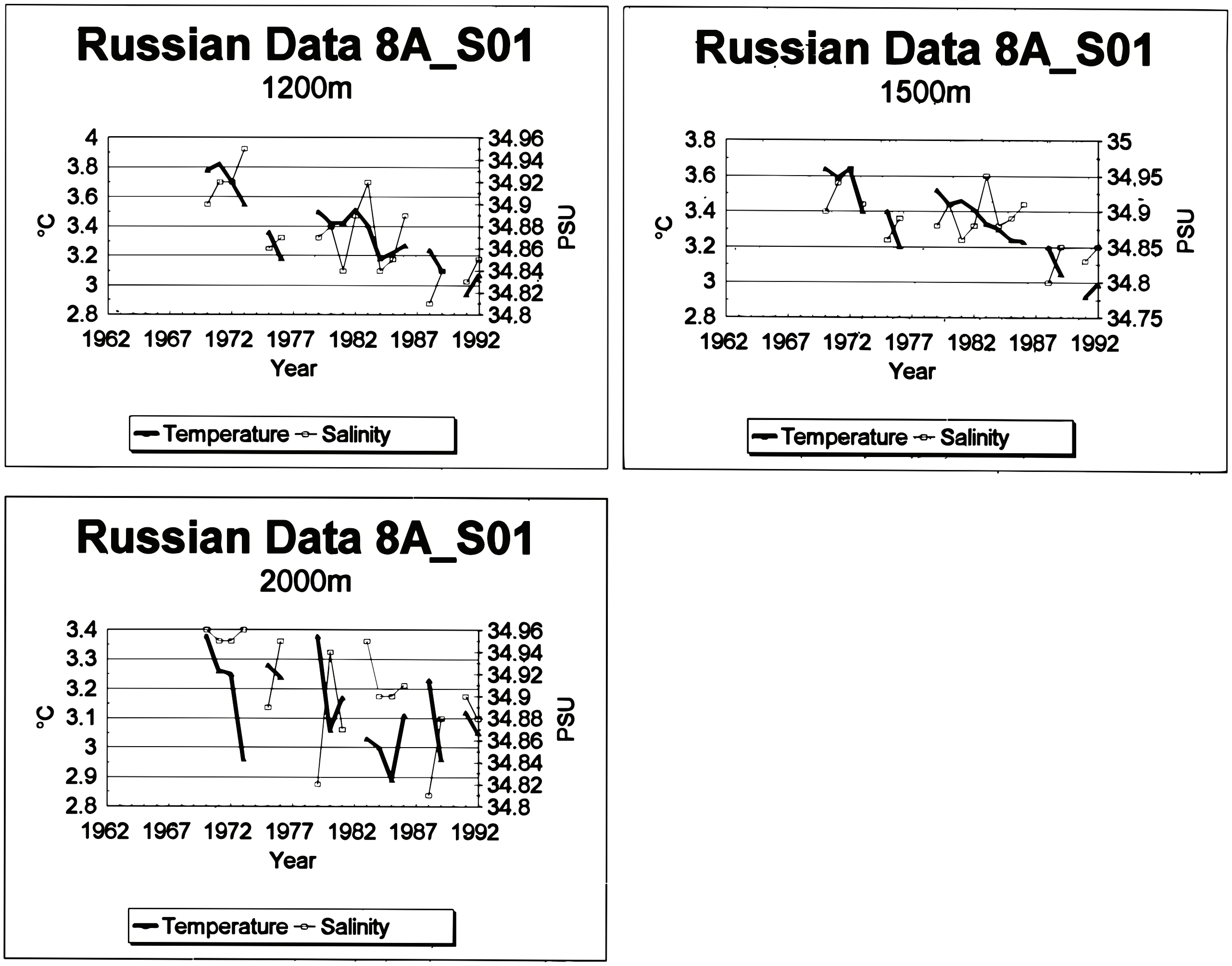
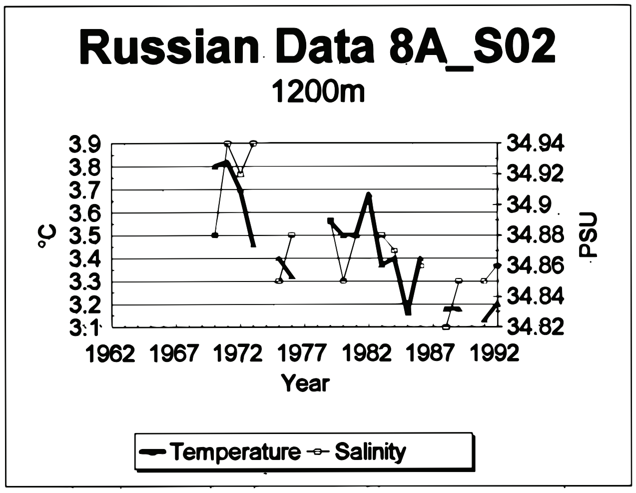


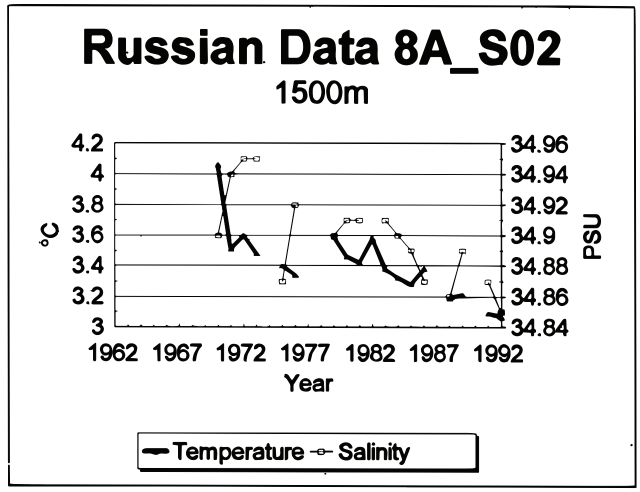
Fig. 8. Salinity and temperature time-series at 1 200 m, 1 500 m and 2 000 m depth at Station 1 of Section 8A.

condition might reflect interactions between shelf water masses which are influenced by the cold and diluted current component of the West Greenland current system, and the slope water masses which are under the influence of the Irminger Atlantic Water.

De-trending of thermohaline time-series revealed that the coherency structure was different for the water masses of Irminger Atlantic Water and Labrador Sea Water. In the Irminger Atlantic Water layers, the coherence was caused by coupled effects of low (long-term) and high frequency variations. In the layers of Labrador Sea Water coherence was caused only by low frequency variation.

The anomalous haline event in the "overflow" layer (Fig. 6) suggests a further search for possible interrelation mechanisms. As denoted by Lazier (1988), the boundary currents that supply the bottom water of the Labrador Sea are more concentrated and faster than the diffuse eddy dominated transports of the open ocean. The boundary current at 0.2 m per second for instance covers the about 2 000 km from Denmark Strait to the western Labrador Sea in about 100 days. The following hypothesis is therefore offered to explain the decrease of salinity at the end of the 1950s: during the time of formation of the "overflow" water mass, north of the Denmark Strait, anomalous cold and diluted conditions must have been present in the source region. Winter air temperature records from Greenland (Fig. 15) indicated the set up of decreasing temperatures during the late-1950s. As can be deduced from recent observations off Greenland (Stein, MS 1996a and b) coldest air temperatures were recorded during the months of January, February and March, mostly accompanied by cold air masses centered at the town of





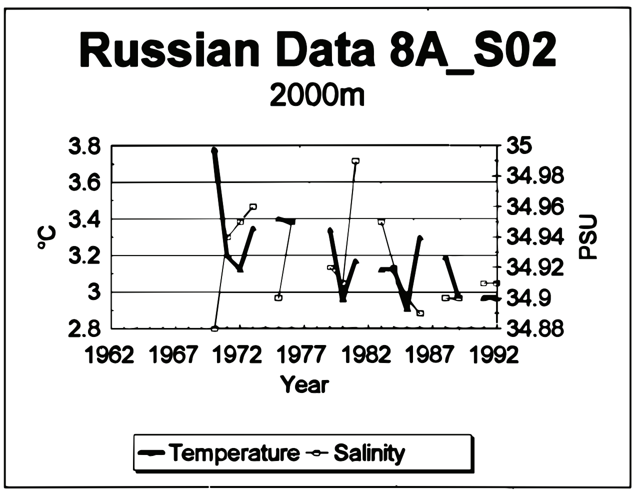


Fig. 9. Salinity and temperature time-series at 1 200 m, 1 500 m and 2 000 m depth at Station 2 of Section 8A.

Egedesminde (Buch and Stein, 1989). This in turn led to anomalous sea ice formation off East and West Greenland during the first quarter of the year. With the progress of the seasons, cold and diluted surface waters became present in the formation area of the "overflow" water mass. Thus, with a travel time of about 100 days, the surface signal could have reached the site of observation in the central Labrador Sea during the months of August, 1959 and July, 1960. The record low values were 1.61°C/ 34.86PSU (1959) and 1.59°C/ 34.89PSU (1960). Lazier (1988) concludes that the Overflow Water is the source of the fluctuations in the deep layers of the Labrador Sea, and that temperature decreases may be caused by the large low salinity anomaly or Great Salinity Anomaly (GSA) as reported by Dickson *et al.*, (1988). Lazier's (1988) data covered the period from 1962–86, and for that time-interval he found two events which match the 1968 and 1981 GSA events north of the Denmark Strait.

The present data suggests a further large anomaly in the decade of the 1950s. To elucidate this phenomenon in further detail, especially with regard to decadal climate variability in the North Atlantic (Latif *et al.*, 1996), the historic temperature/ salinity time-series from the DSOW-layer (3 500 m) in the Ocean Weather Ship Bravo area was plotted (Fig. 16 gives one value per year if available; means were calculated for more than one observation per year). Although the data were very scanty with one observation in 1928, one in 1936 and a major gap in the 1940s, the composite of the available temperature and salinity data suggests several low salinity/temperature events throughout the 45 years of observation when salinities were at 34.86PSU and temperatures dropped to 1.8°C or less. Trend analysis of both time-series revealed small positive trends which amounted to 0.01 PSU per year (significant) in salinity and 0.02 K per year (not significant) in temperature. The largest deviations

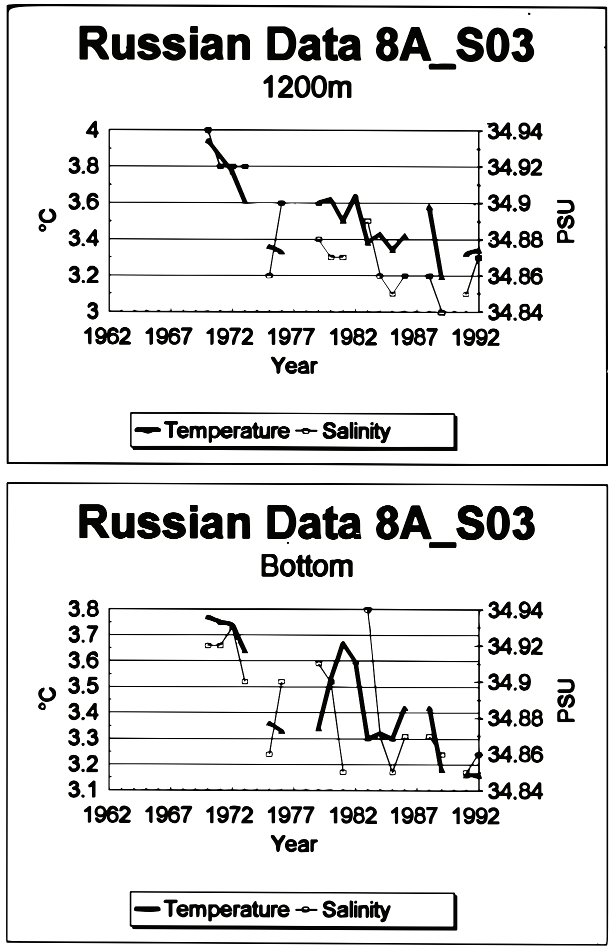


Fig. 10. Salinity and temperature time-series at 1 200 m depth and in the bottom water layer at Station 3 of Section 8A.

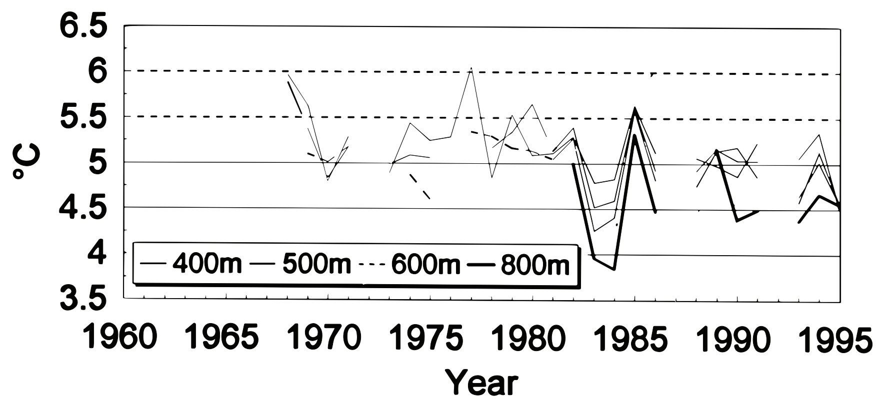


Fig. 11. Temperature time-series at Fylla Bank Station 4 for standard depths 400 m, 500 m, 600 m, and 800 m.

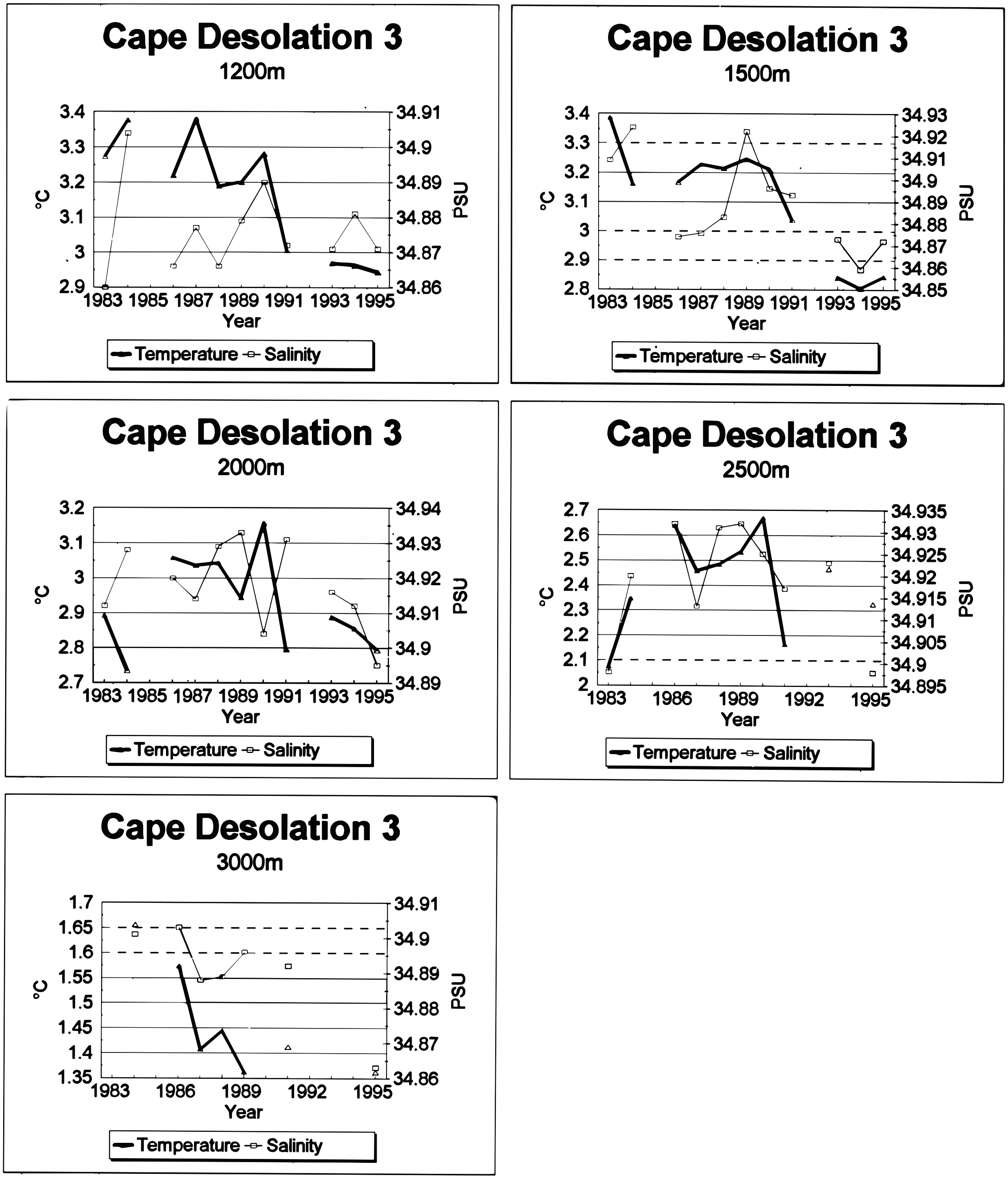


Fig. 12. Salinity and temperature time-series at 1 200 m, 1 500 m, 2 000 m, 2 500 m, and 3 000 m depth at Station 3 of Cape Desolation Section.

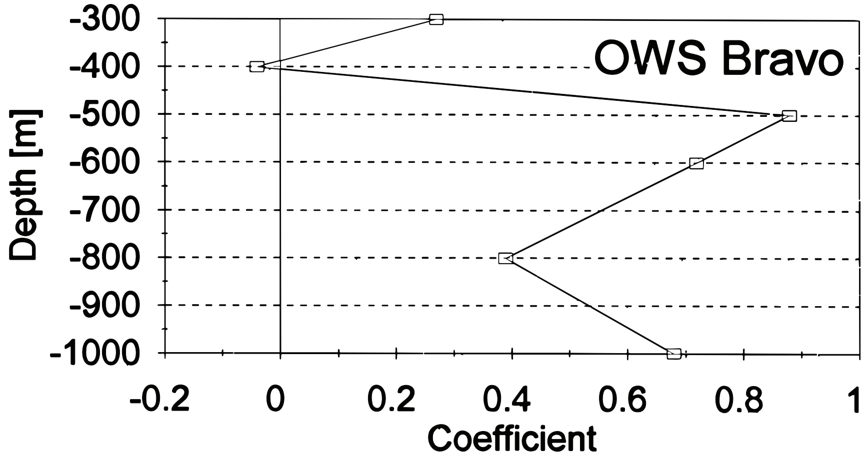


Fig. 13. Vertical profile of correlation coefficients between temperature and salinity for the area delimited by 56°N, 57°N, 50°W, 52°W.

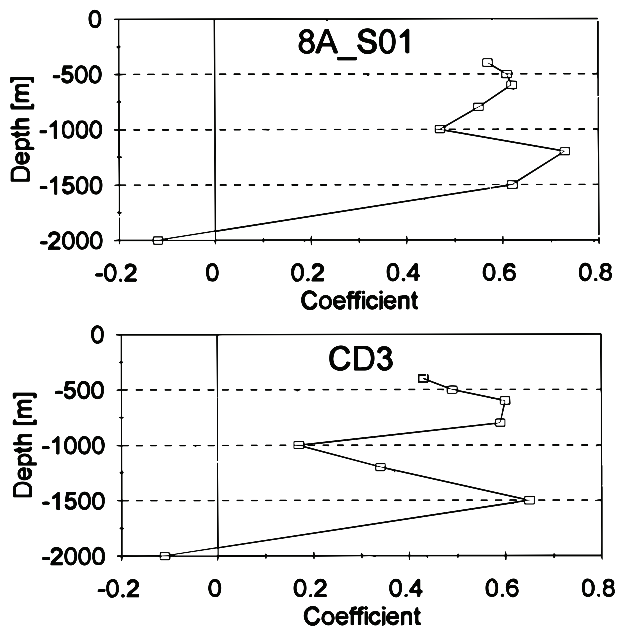


Fig. 14. Vertical profiles of correlation coefficients between temperature and salinity for Station 1 of Section 8A and Station 3 of Cape Desolation Section.

from the mean were encountered in the 1950s and during 1960. Correlation of the de-trended salinity and temperature time-series yielded non-significant results ($r = 0.25$; $p > 0.09$). Low salinity events were observed in the following years (month of observation in brackets): 1928 (6), 1940 (6), 1951 (7), 1957 (7), 1958 (7), 1959 (8), 1960 (7), 1962 (7), 1969 (11).

Following the above given hypothesis of DSOW formation mode and travel time, it would appear that the historic data series point at a regular advection of low salinity/temperature events in the DSOW-layer on a decadal time scale. For the years of these thermohaline events, the air temperature time-series at Nuuk (Fig. 17) indicates thermal events or strong gradients (marked by arrows). Whether these atmospheric events are the precondition for DSOW formation or not remains speculative.

Latif *et al.* (1996) explain continuous oscillation at decadal time scales with a positive feedback

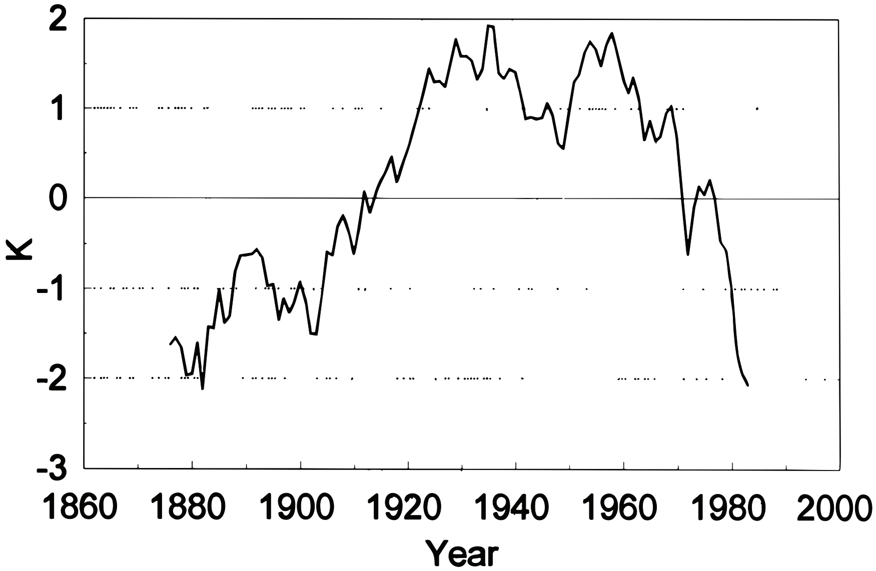


Fig. 15. Air temperature time-series at Nuuk (winter season, JFM mean anomaly, 13 year running mean 1883–1995 (rel. 1876–1995)).

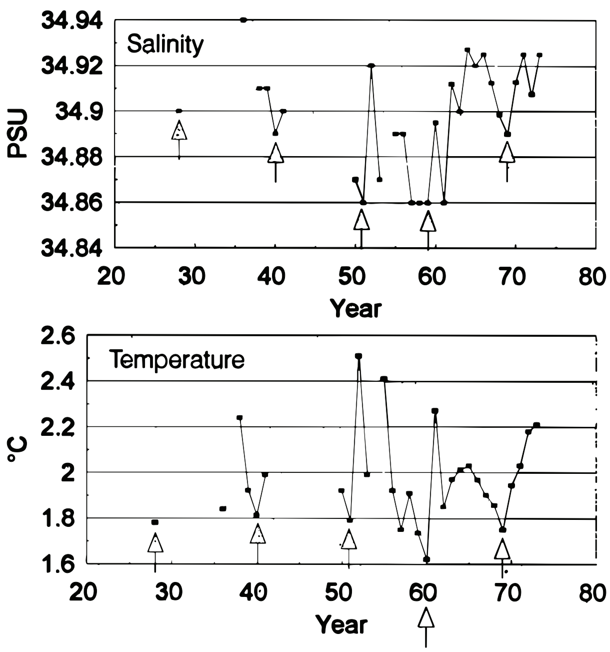


Fig. 16. Salinity and temperature time-series of DSOW-layer (3 500 m); arrows indicate low temperature/salinity events.

system between ocean and atmosphere. For instance, when the subtropical ocean gyre is anomalously strong, more warm tropical waters are transported toward the pole by the western boundary current and its extensions, leading to a positive SST anomaly in mid-latitudes. The atmospheric response to this SST anomaly involves a weakened storm track and the associated changes at the air-sea interface, and reinforces the initial SST anomaly. The atmospheric response, however, consists also of a wind stress curl anomaly which spins down the subtropical ocean gyre, thereby reducing the poleward heat transport and the initial SST anomaly. The ocean adjusts with some time lag to the change in the wind stress curl, and it is this transient ocean response that allows such continuous oscillations at about 10 years intervals. Thus, the SST anomalies as formed during the "event" years off East Greenland could be formed in part by reduced poleward heat transport and regional cooling/dilution.

In conclusion it is important to recognize that the historic Oceanographic Data set as provided in the World Ocean Atlas 1994 on CD-ROM provides an excellent data base for backward facing investigations. Without this data base, analysis of the deep water phenomena in the Labrador Sea region would be incomplete.

Further research could be initiated to answer at least some questions that arise:

- Are the thermohaline events as revealed for the period of 45 years prior to 1973, part of a periodic mechanism which has been recently called the Great Salinity Anomaly (Dickson *et al.*, 1988)?
- Do these events belong to those processes in the ocean which are on decadal scales?

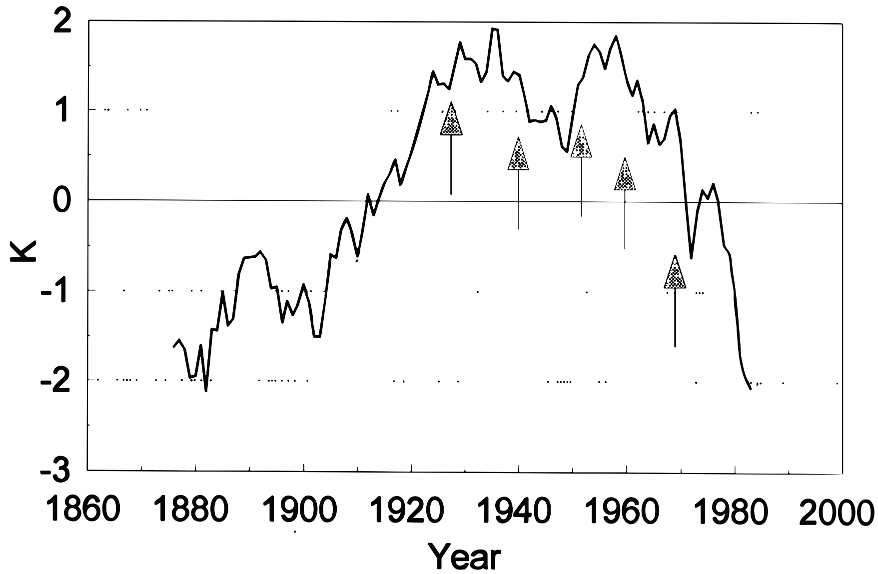


Fig. 17. Air temperature time-series at Nuuk (winter season, JFM mean anomaly); arrows indicate times when low temperature/salinity events were encountered in the DSOW-layer (c.f. Fig. 16).

- Is the historic data base able to show similar events for other sub-polar regions?

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