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

by

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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 (3,500m depth) amounts 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 points at high frequency variability in this layer. Trend analysis of both time-series reveals a small positive trend which amounts to 0.01 PSU/year (significant), and 0.02 K/year (non-significant). Consistency both between 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 is found. In the water layers dominated by the Irminger Atlantic Water (500-600m) and by the Labrador Sea Water (1,200-1,500m), variations of temperature and salinity are 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 is 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 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.

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

Background

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. 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 was formulated in June 1994 to evaluate climatological oceanographic data in the ICNAF/NAFO area.

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 published (**STEIN and BOROVKOV, 1996; BOROVKOV and STEIN, 1996**). It is the aim of the present paper to elucidate climatic events in deep water layers and discuss the horizontal coherence of the observed events in the Labrador Sea.

After a description of the data and methods, 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 in a discussion section.

Data and Methods

The data used in the context of this paper originate from **four** sources: Russian observations from the oceanographic standard section 8A (near the NAFO Standard Section Seal Island, e.g. **STEIN, 1988**), German measurements from the Fylla Bank Section Station 4 and the Cape Desolation Section Station 3, both situated at the West Greenland slope region, World Data Centre A (WDC A) Oceanographic Data as provided in the World Ocean Atlas 1994 on CD-ROM, and 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 cover an area of about 60x60 nautical miles in the centre of the Labrador Sea with a water depth greater than 3,500m. Temperature and salinity data at standard depths (every 500m between 1,500m and 3,500m inclusive) were extracted by allowing a depth interval of 100m above and below the standard depth. For example, retrieved data at 3,500m include all data between 3,400m and 3,600m depth. This formed the basis for further discussions and a thorough analysis of temperature and salinity changes. Most of the data originate from the 1960s which is due to the presence of Ocean Weather Ship Bravo.

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, turning west and eventually flowing southwards along the Labrador slope region (Fig. 1, 2), the Labrador Sea Water 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, and the Northwest Atlantic Bottom Water.

The Irminger Atlantic Water entering the Labrador Sea off Cape Farewell has core temperatures and salinities above 5°C, 34.96PSU and is located at depths above 500m (**STEIN and WEGNER, 1990**). Centered around 500m depth, the warm component of the Labrador Current leaves the Labrador Sea with temperatures above 3.5°C and salinities above 34.88PSU. Labrador Sea Water (LSW) characteristics range 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 2,000m a pronouced halocline separates the low-salinity Labrador Sea Water from the North Atlantic Deep Water (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 Northwest Atlantic Bottom Water, 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. 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 T,S diagrams reveal the vertical distribution of water masses based on the WDC A-data set. At depths of 1,500m and 2,000m 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 2,500m and 3,000m salinity values range from 34.9PSU to about 34.97PSU. Temperature, however, is significantly different, ranging from 3°C to 3.5°C at 2,500m and 2.5°C to 3°C at 3,000m.

At 3,500m waters are colder and fresher than in the upper layers. Temperatures are 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 seem doubtful (Fig. 3, lower panel), the range of salinity distribution falls 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 reveal little thermal variation (about 0.5K), the "overflow" layer data indicate temperature variance of 1K.

Time-Series of Temperature and Salinity

OWS Bravo

As reported by **BOROVKOV and STEIN (1996)** time-series analysis of WDC A data from 1952 to 1974 reveal a trend of warming at 1,500m depth which abruptly ends around 1972. Salinity at the same depth yields a small increase until 1972 when haline conditions became more diluted. Similar trends are detectable between 500m and 1,500m depths. At 2,000m depth the warming trend is maintained throughout the period of observation (1928 to 1974). There is no abrupt change as given for the 1,500m layer. Salinity reveals periods of lower salinity (around 34.88 PSU), and of more saline conditions from the 1960s onwards (around 34.93PSU).

Variability in the North Atlantic Deep Water layers (2,500m and 3,000m, Figs. 4 and 5) is mainly expressed in the haline signal (upper panel of both figures, line: 5 yr.r.m.). There is 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 levels does not co-vary with the haline signal. At 3,500m depth there is one remarkable event in the salinity time-series at the end of the 1950s which is paralleled by a notable decrease in temperature (Fig. 6). During the end of the 1960s another decrease in both parameters is obvious in the "overflow"-layer, temperatures dropped to the level of the first event (1.6°C), 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 500m and 600m 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 1,200m, 1,500m and 2,000m. Fig. 10 gives the respective time-series for station 3 at 1,200m and the bottom layer. The data reveal a cooling trend between 1970 and 1992 which is clearly expressed at both depths at all stations.

West Greenland Stations

Fylla Bank Station 4 temperature data (Fig. 11) show coherency of thermal events throughout the water column especially for the cold event in the early 1980s. The

general trend of the temperature time-series indicates cooling from the late 1960s onwards (**STEIN, 1996**).
Thermohaline conditions for the depths levels of 1,200m, 1,500m, 2,000m, 2,500m, and 3,000m from the Cape Desolation Section Station 3 are given in Fig. 12. There is a general downward trend incorporated in the temperature and salinity time-series which is analog to the trend seen at section 8A at the western slope of the Labrador Sea. The 3,000m depth layer reveals temperature and salinity characteristics which are representative for the Denmark Strait overflow water.

Correlation Analysis

For the standard depths from 300m to 1,000m, correlations between temperature and salinity were calculated for time-series from the central Labrador Sea area (OWS Bravo). The results indicate high correlation coefficients for the 500m, 600m and the 1,000m standard depth layers (Fig. 13).
Whereas correlations with depth of either temperature or salinity were high at Fylla Bank station 4 between depths of 400m to 800m (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 300m to 0.33 at 800m.
At Cape Desolation Station 3 (Fig. 14, lower panel) correlations between the thermohaline parameters are high in the Irminger Atlantic Water layer (around 500m), at 1,500m depth ($r = 0.65$, p 0.05), and depths 2,500m ($r = 0.97$, p 0.001) and 3,000m ($r = 0.99$, p 0.001). For the latter two depths no correlation profile is given since these standard depths are not available at station 1 of section 8A. There is negative correlation for the 300m level and the 2,000m depth level, and at 1,000m and 1,200m depths correlation is non-significant.
The vertical profiles of correlation coefficients between temperature and salinity at stations 1, 2 and 3 of section 8A (Fig. 14, upper panel) are characterized by a two layer mode: In the upper layer (from 300m to 1,200-1,500m) where Irminger Atlantic Water and Labrador Sea Water are located, the variations in temperature and salinity are consistent. In the deeper layer at depths of 1,500-2,000m the relationship between temperature and salinity dissipates.
Comparison between Cape Desolation Station 3 and section 8A station 1 reveals similar profiles of T,S correlations, with a minimum at 1,000m and 2,000m, and a maximum at the depths of Irminger Atlantic Water and in the Labrador Sea Water layer, i.e. around 500-600m and 1,200-1,500m.
To reveal the influence of any trends, the temperature and salinity time-series for station 1 of section 8A were detrended. From the analysed depths of 300m(0.42), 600m(0.40), 1,000m(0.09) and 1,200m(0.35), only the 600m layer revealed significant correlation using the detrended 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 the Ocean Weather Ship Bravo was located in the centre of this area - show significant differences at deep layers of 2,500m, 3,000m, and 3,500m. Whereas at the first two depth levels rather homogenous thermohaline conditions were encountered, salinity values ranged from 34.9PSU to about 34.97PSU, temperature ranged from 3°C to 3.5°C (2,500m), and 2.5°C to 3°C (3,000m), at 3,500m depth the scatter diagram clearly indicates 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 is documented. Temperature variance in this layer amounts to 1K, compared to 0.5K in the deep water layers above the "overflow"-layer. The significant variance of the thermohaline signals points at high frequency (year-to-year) variability in this layer.
There is 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 (500-600m) and by the Labrador Sea Water (1,200-1,500m), variation of the thermohaline signal is significantly coherent ($r > 0.6$, $p < 0.001$). At Fylla Bank Station 4 which is located at the shelf slope off Nuuk/West Greenland, coherency between the thermal and haline signal is less than at the previous two stations. This 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.

Detrending of thermohaline time-series reveals that the coherency structure is different for the water masses Irminger Atlantic Water and Labrador Sea Water: in the Irminger Atlantic Water layers coherence is caused by coupled effects of low (long-term) and high frequency variations. In the layers of Labrador Sea Water coherence is 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 for instance, at 0.2 m s^{-1}, covers the about 2,000km from Denmark Strait to the western Labrador Sea in about 100 days. The following hypothesis is 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) indicate the set up of decreasing temperatures during the end of the 1950s. As can be deduced from recent observations off Greenland (**STEIN, 1996**) coldest air temperatures were recorded during the months of January, February and March, mostly accompanied by cold air masses centered at the town of Egedesminde (**BUCH and STEIN, 1989**). This 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 are present in the formation area of the "overflow" water mass. 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 set covered the period from 1962-1986, 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 set 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 (3,500m) in the "OWS Bravo" area was plotted (Fig. 16 gives one value/year if available; means were calculated if more than one observation/year). Although the data are very scanty, there is 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 reveals a small positive trend which amounts to 0.01 PSU/year (significant) and 0.02 K/year (non-significant). The largest deviations from the mean were encountered in the 1950s and during 1960. Correlation of the detrended salinity and temperature time-series yields 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 thermohaline events the air temperature time-series of 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 continous oscillation at decadal time scales with a positive feedback system between ocean and atmosphere: when, for instance, the subtropical ocean gyre is anomalously strong, more warm tropical waters are transported poleward by the western boundary current and its extension, 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 reinforce 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 continous oscillations at about 10 years intervals.
Thus, 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.
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 deep water phenomena in the Labrador Sea region would be incomplete.
Further research could be initiated to answer at least some remaining questions:
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?
Is the historic data base able to show similar events for other sub-polar regions?

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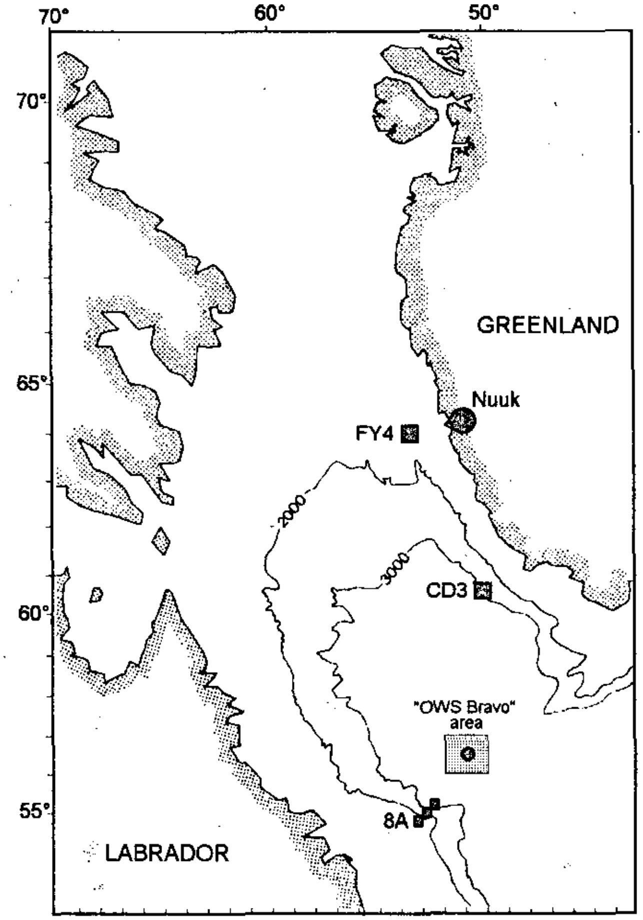


Fig. 1 Location of observation sites at the slope area and in the Labrador Sea (FY4: Fylla Bank Station 4; CD3: Cape Desolation Station 3; 8A: stations 1, 2, 3 of the Russian section 8A; "OWS Bravo" area: dot denotes the former position of OWS Bravo, box is delimited by 56°N, 57°N, 50°W, 52°W)

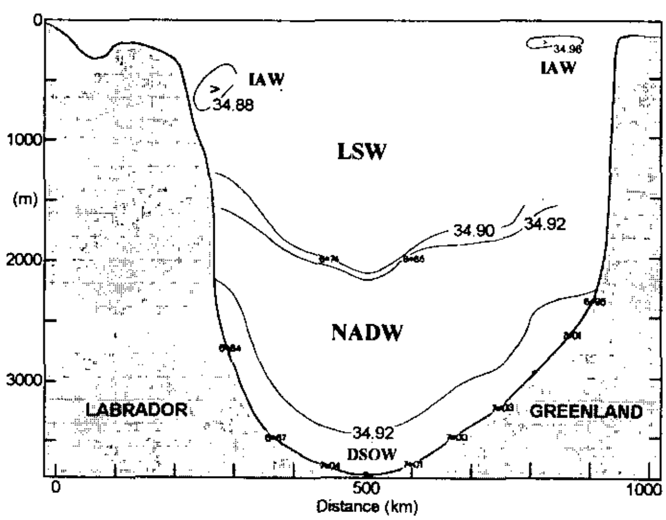


Fig. 2 Vertical distribution of main water masses in the Labrador Sea; core salinities of Irminger Atlantic Water (IAW), halocline between Labrador Sea Water (LSW) and North Atlantic Deep Water (NADW), and upper boundary of Denmark Strait Overflow Water are given acc. to **STEIN and WEGNER (1990)**;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

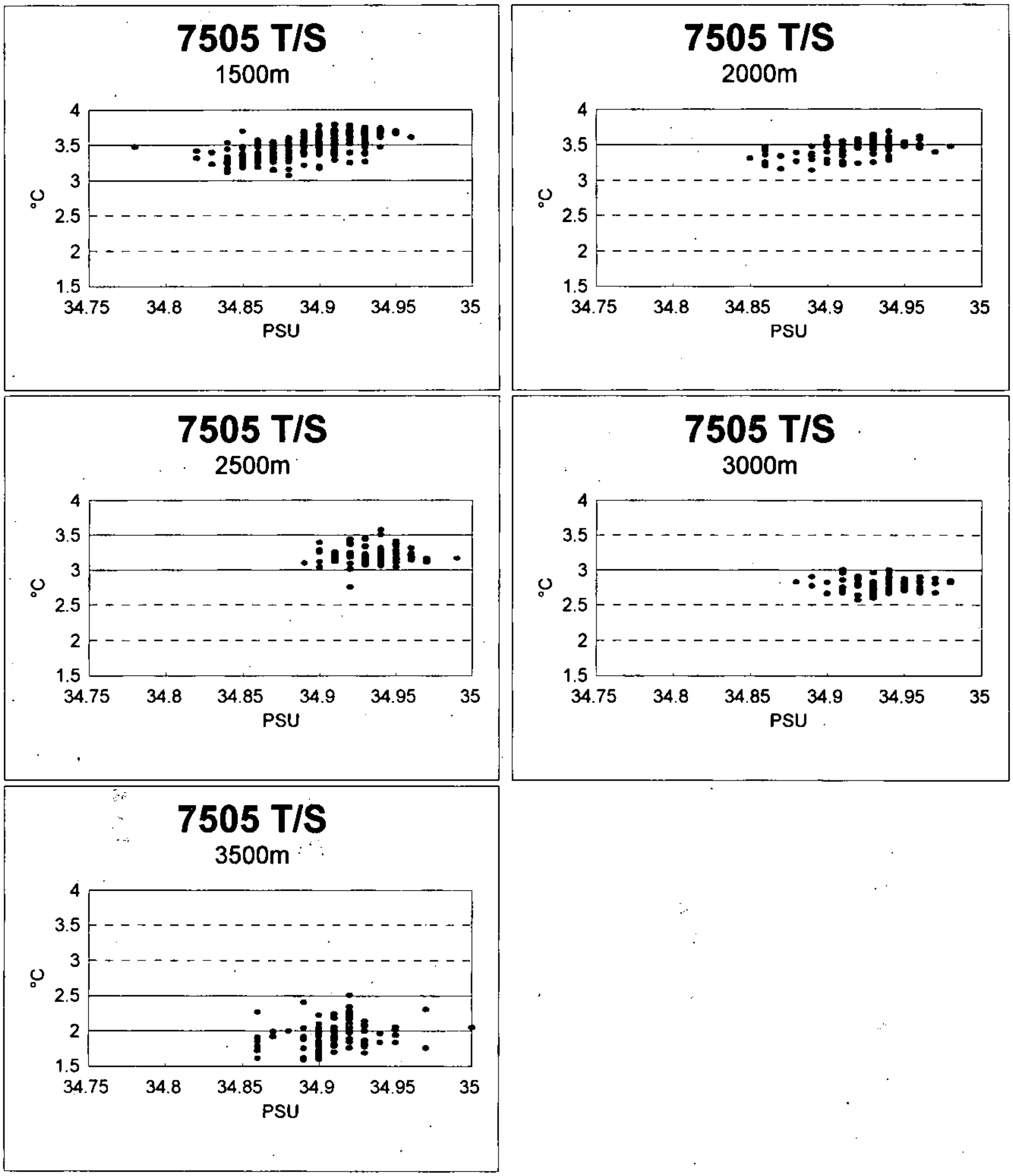


Fig. 3 Temperature/Salinity diagram for depth layers of 1,500m, 2,000m, 2,500m, 3,000m and 3,500m from the area delimited by 56°N, 57°N, 50°W, 52°W

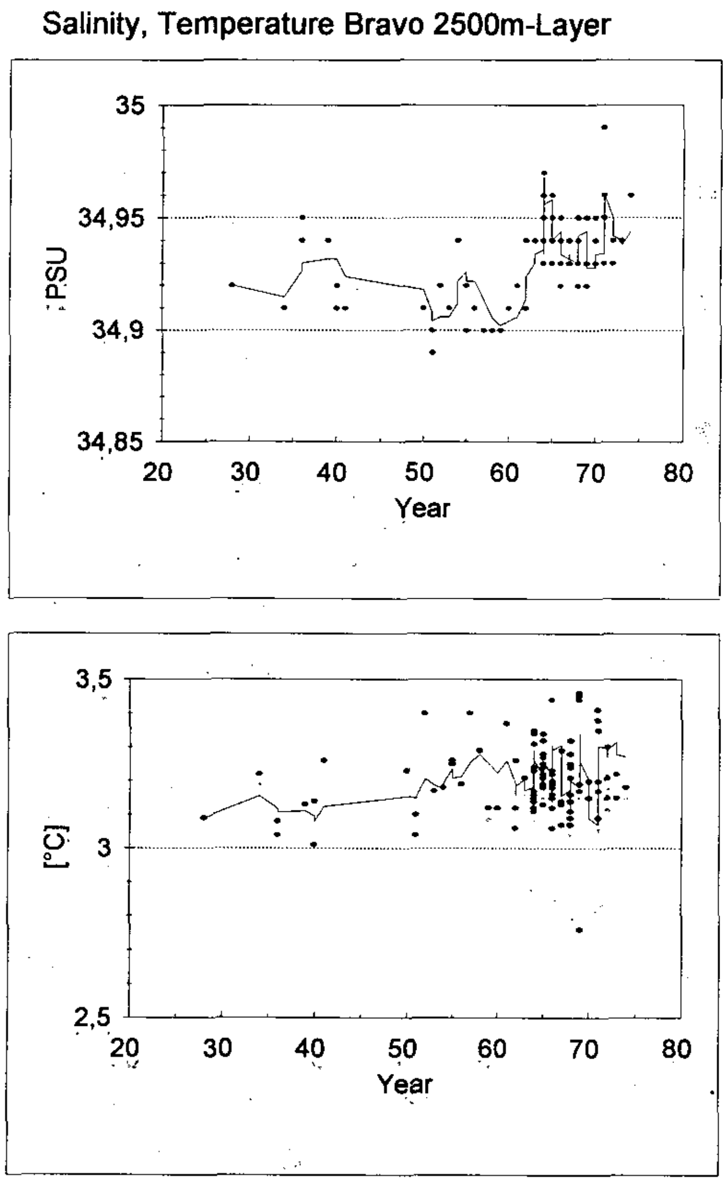


Fig. 4 Salinity and temperature time-series 2,500m depth for the area delimited by 56°N, 57°N, 50°W, 52°W

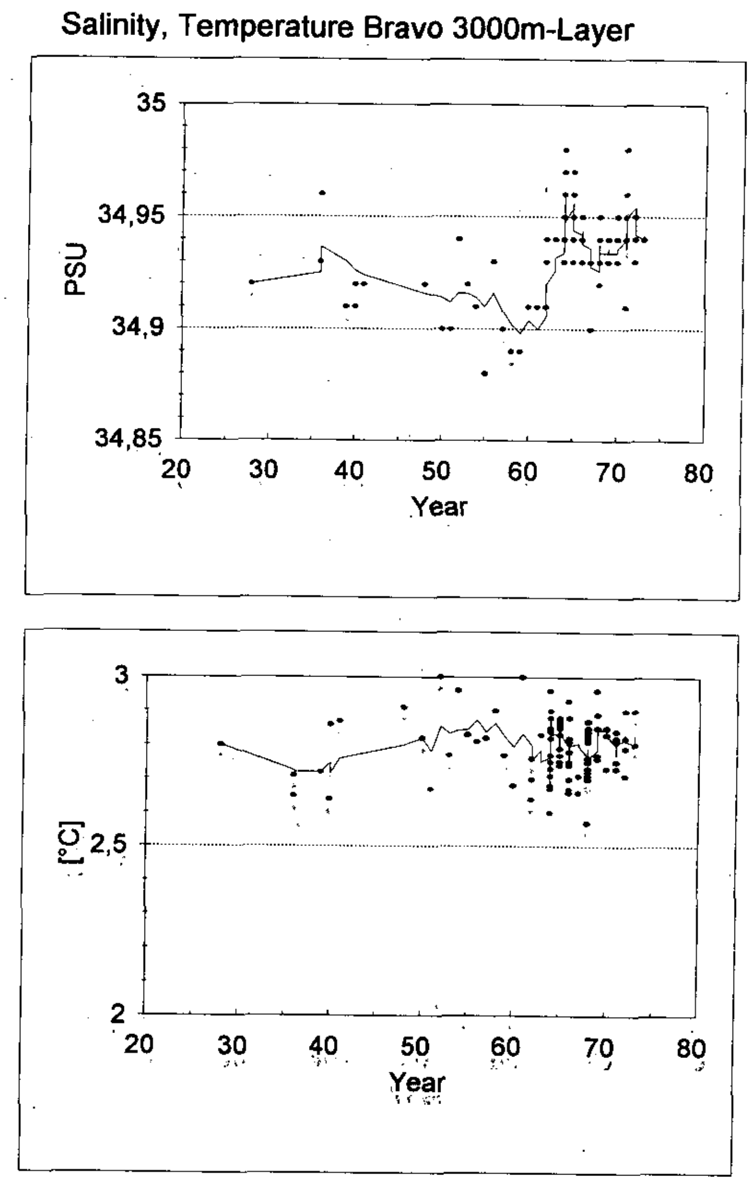


Fig. 5 Salinity and temperature time-series 3,000m depth for the area delimited by 56°N, 57°N, 50°W, 52°W

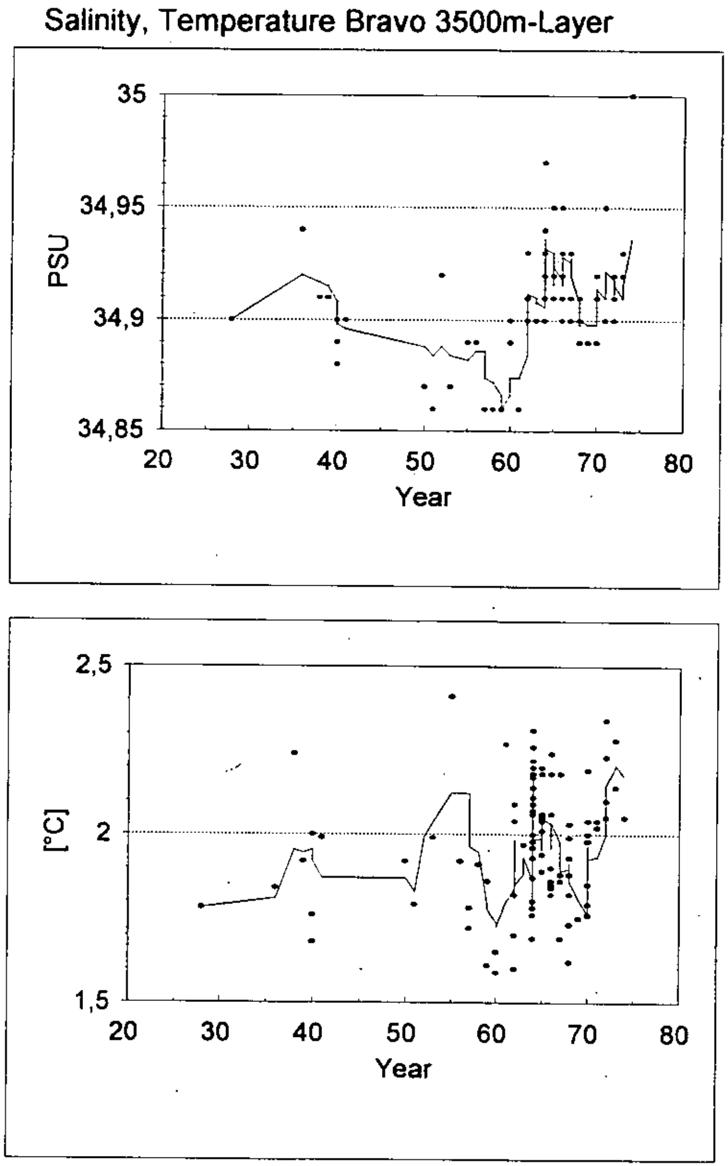


Fig. 6 Salinity and temperature time-series 3,500m depth for the area delimited by 56°N, 57°N, 50°W, 52°W

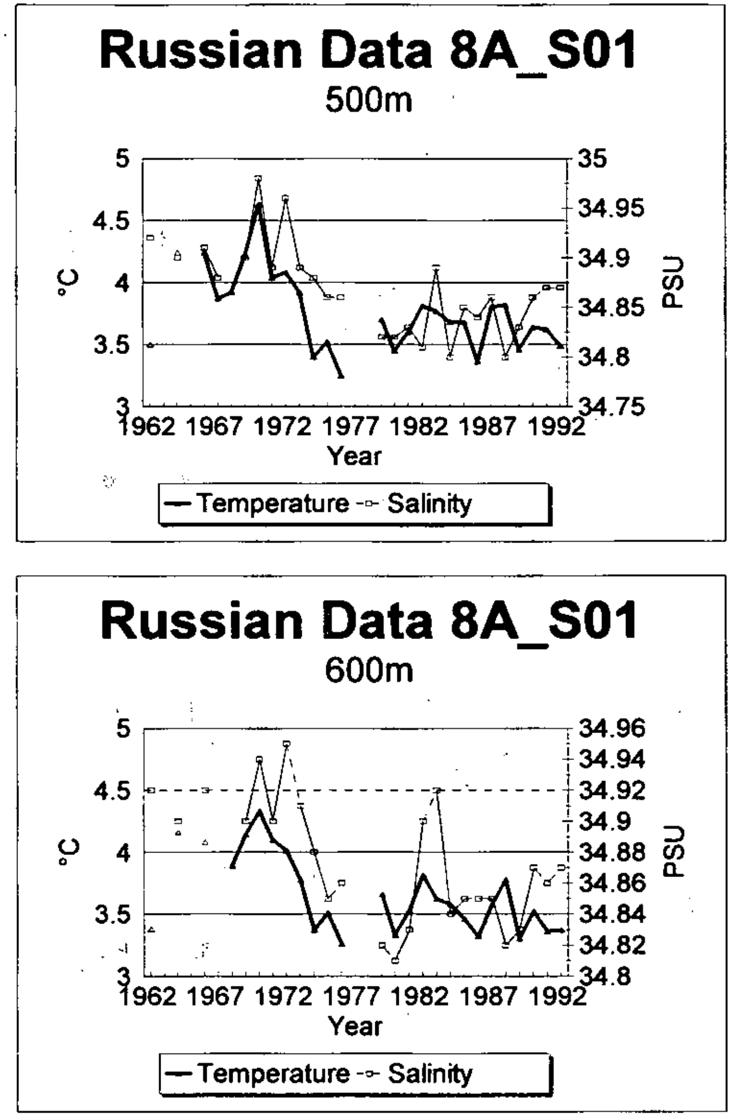
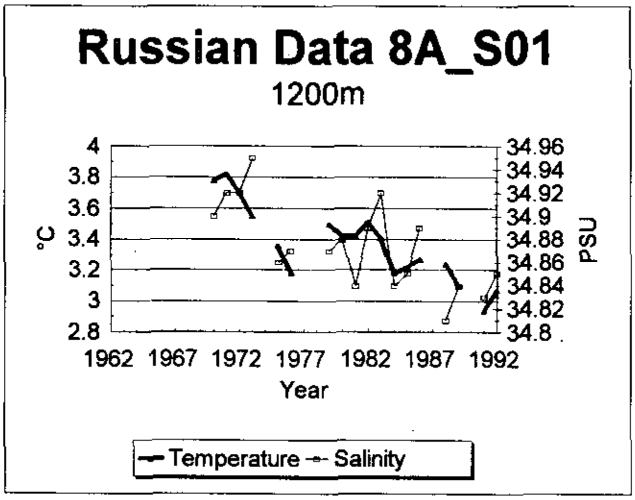
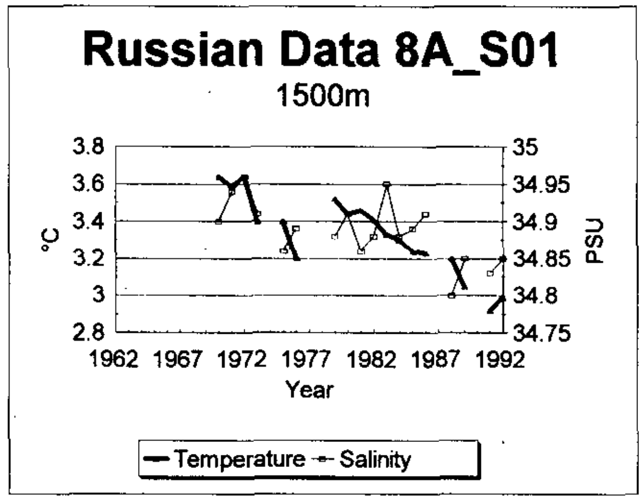


Fig. 7 Salinity and temperature time-series at 500m and 600m depth at station 1 of section 8A





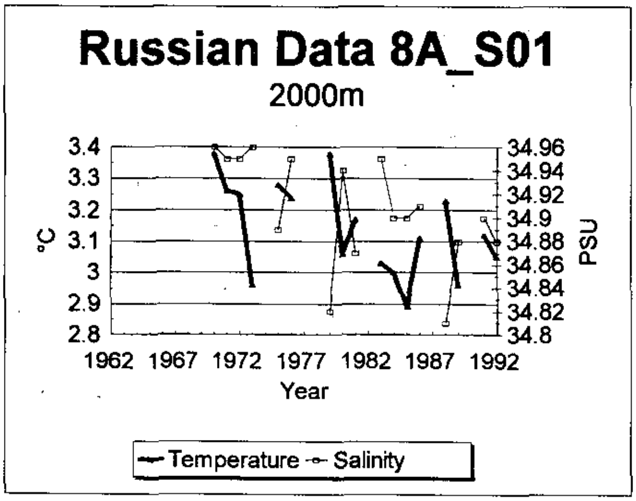


Fig. 8 Salinity and temperature time-series at 1,200m, 1,500m and 2,000m depth at station 1 of section 8A

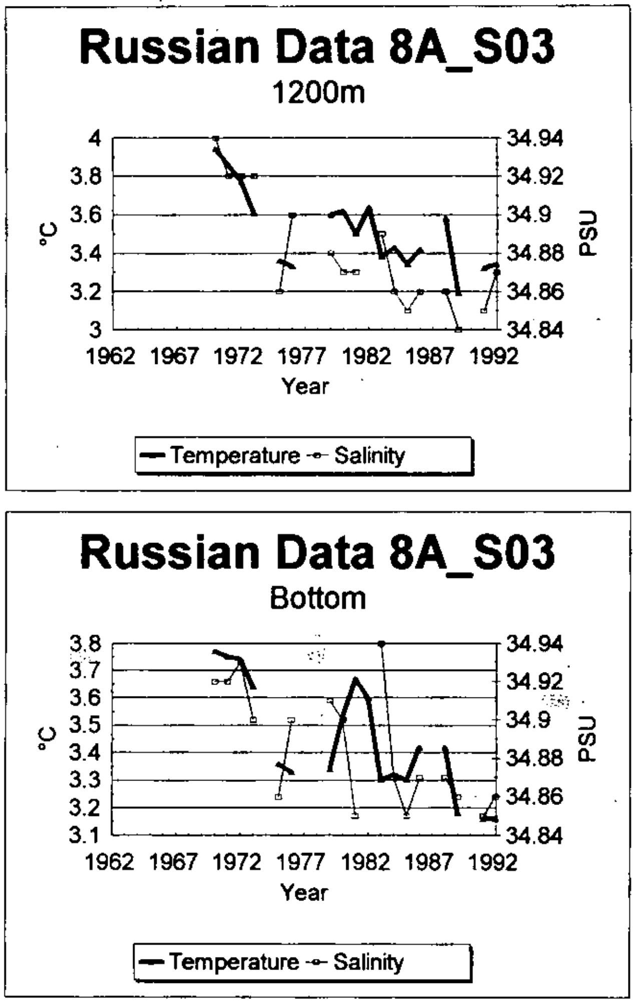


Fig. 10 Salinity and temperature time-series at 1,200m depth and in the bottom water layer at station 3 of section 8A

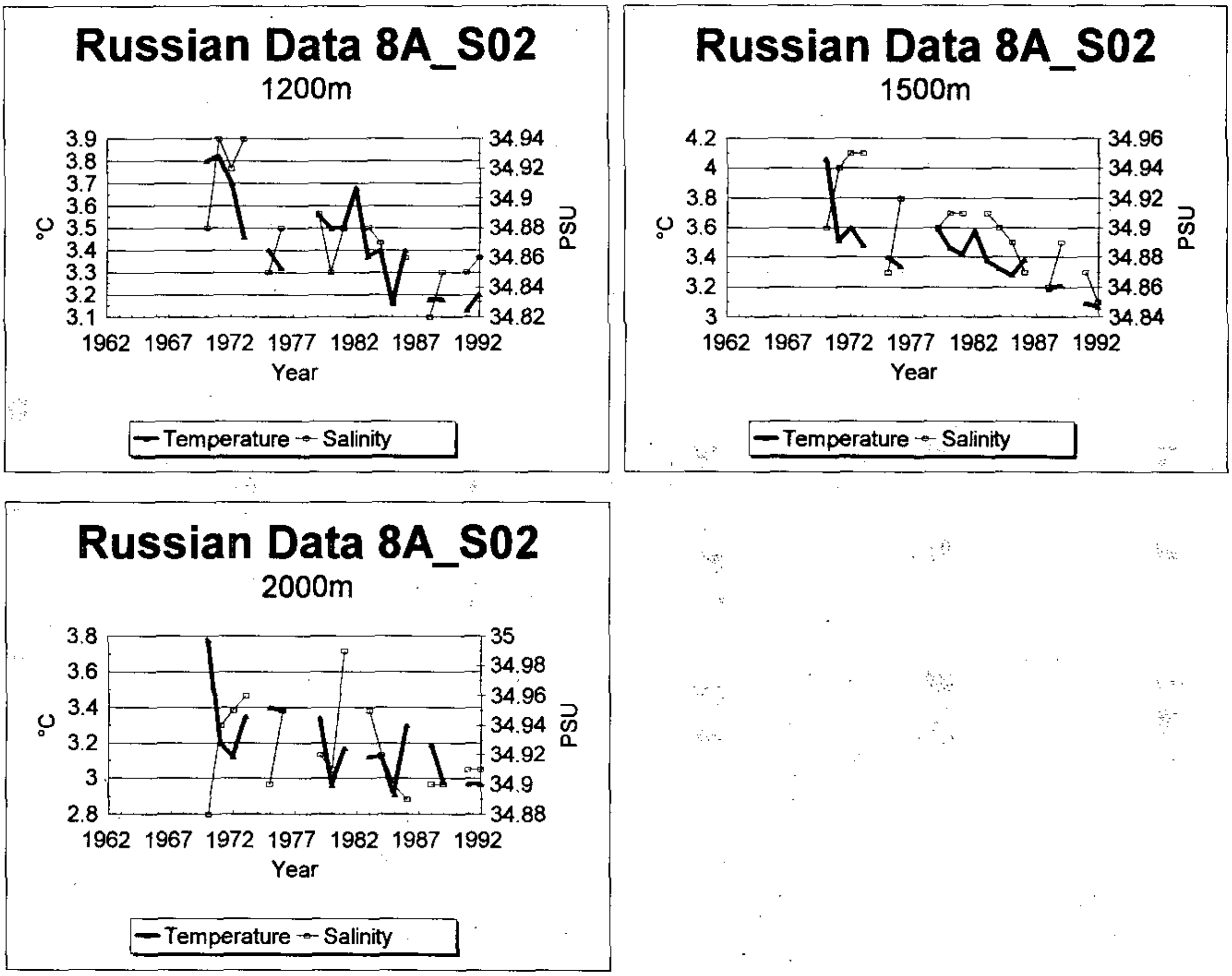


Fig. 9 Salinity and temperature time-series at 1,200m, 1,500m and 2,000m depth at station 2 of section 8A

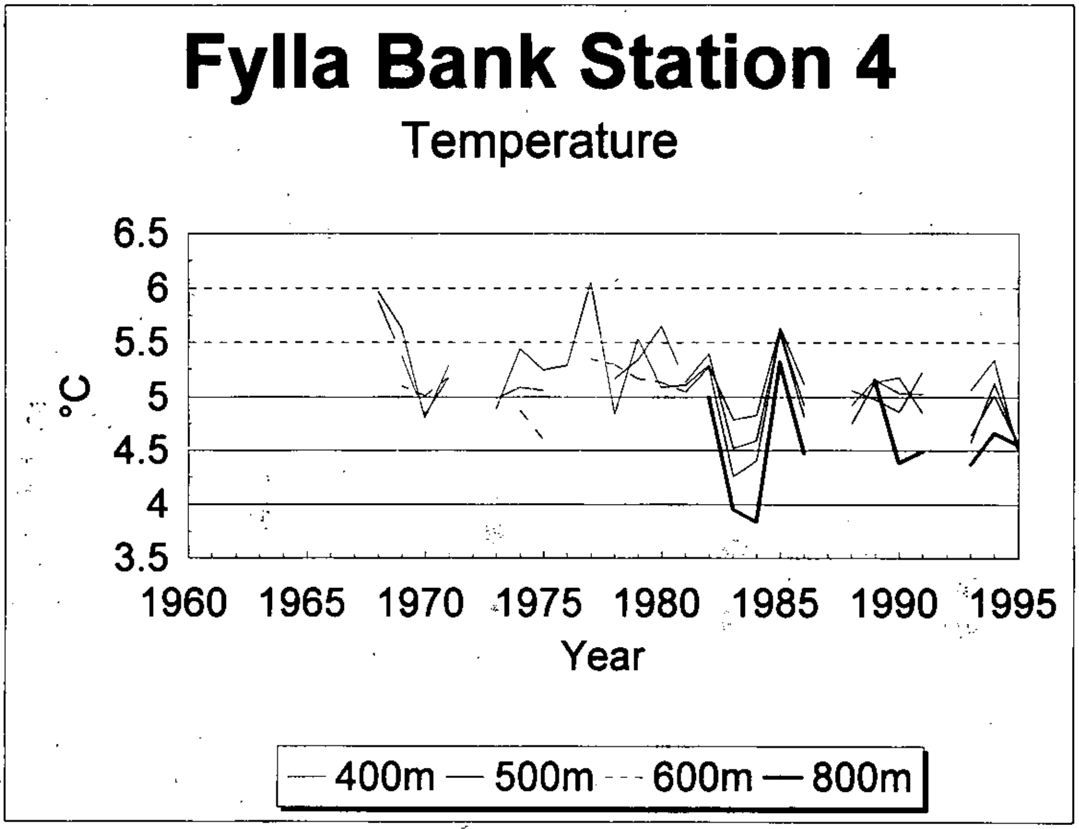


Fig. 11 Temperature time-series at Fylla Bank Station 4 for standard depths 400m, 500m, 600m, and 800m

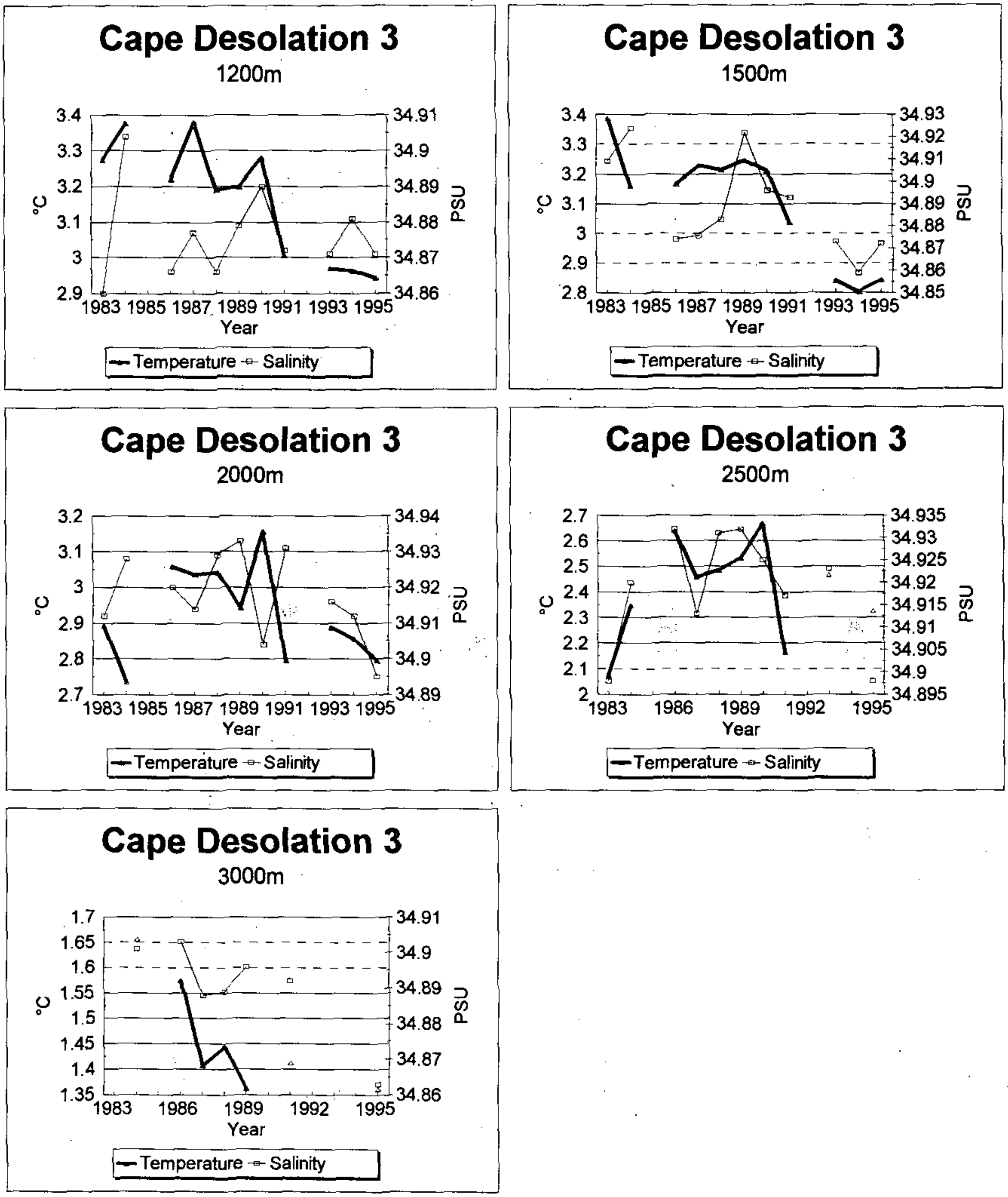


Fig. 12 Salinity and temperature time-series at 1,200m, 1,500m, 2,000m, 2,500m, and 3,000m depth at Station 3 of Cape Desolation Section

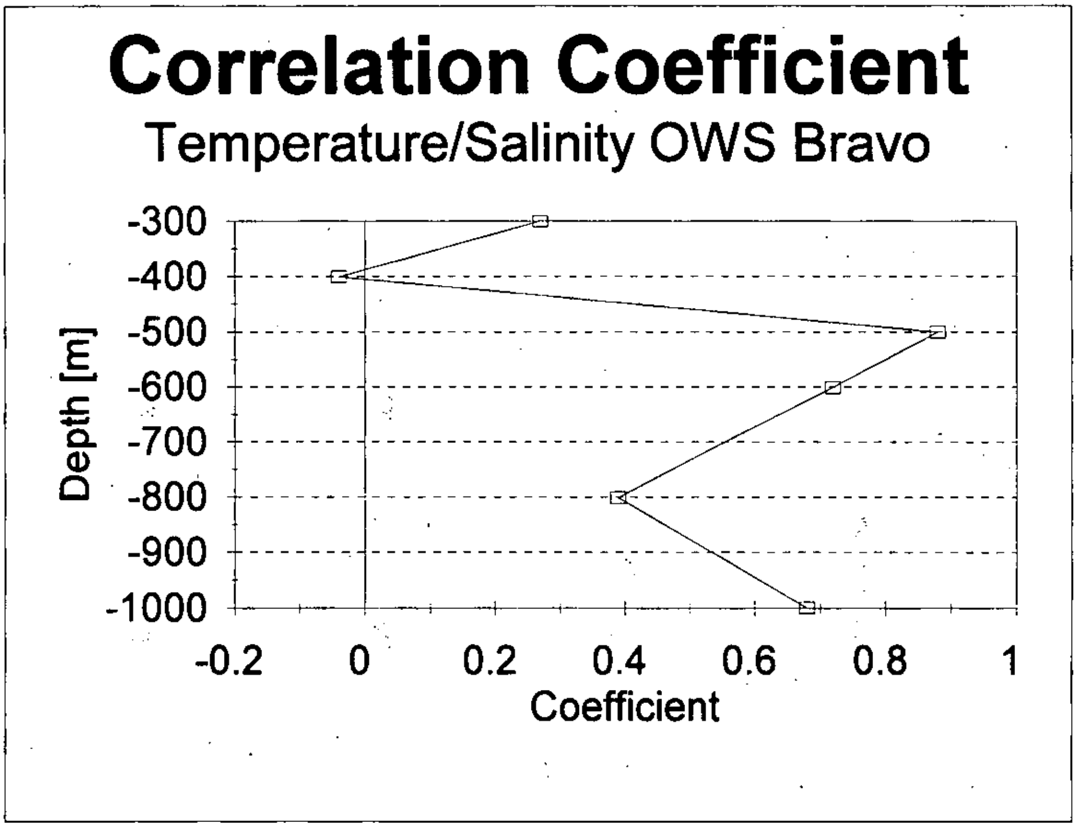
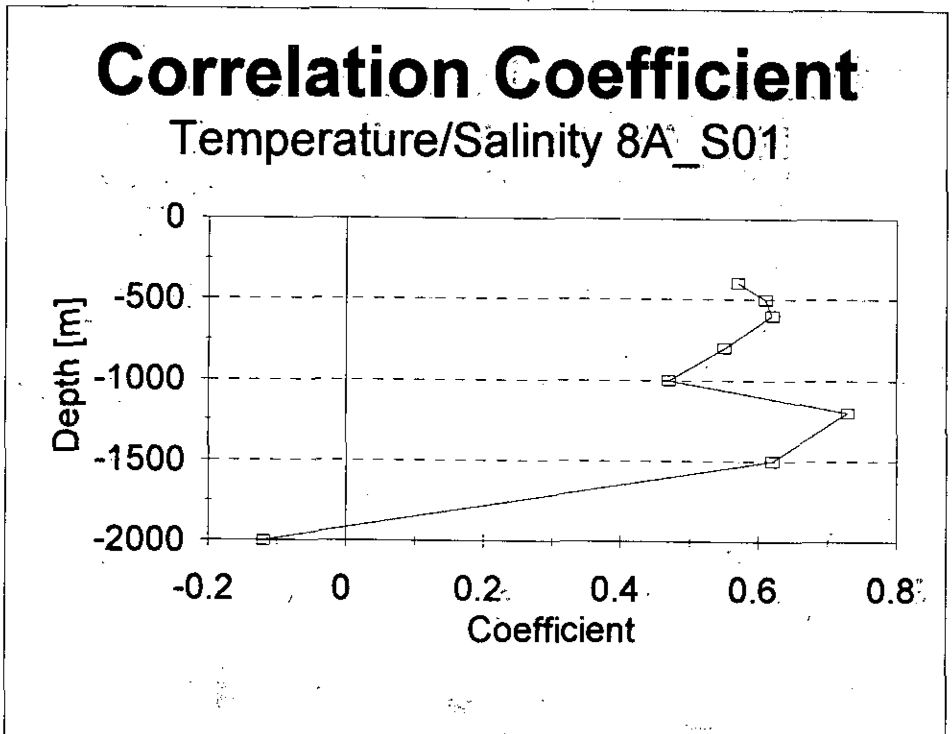


Fig. 13 Vertical profile of correlation coefficients between temperature and salinity for the area delimited by 56°N, 57°N, 50°W, 52°W .



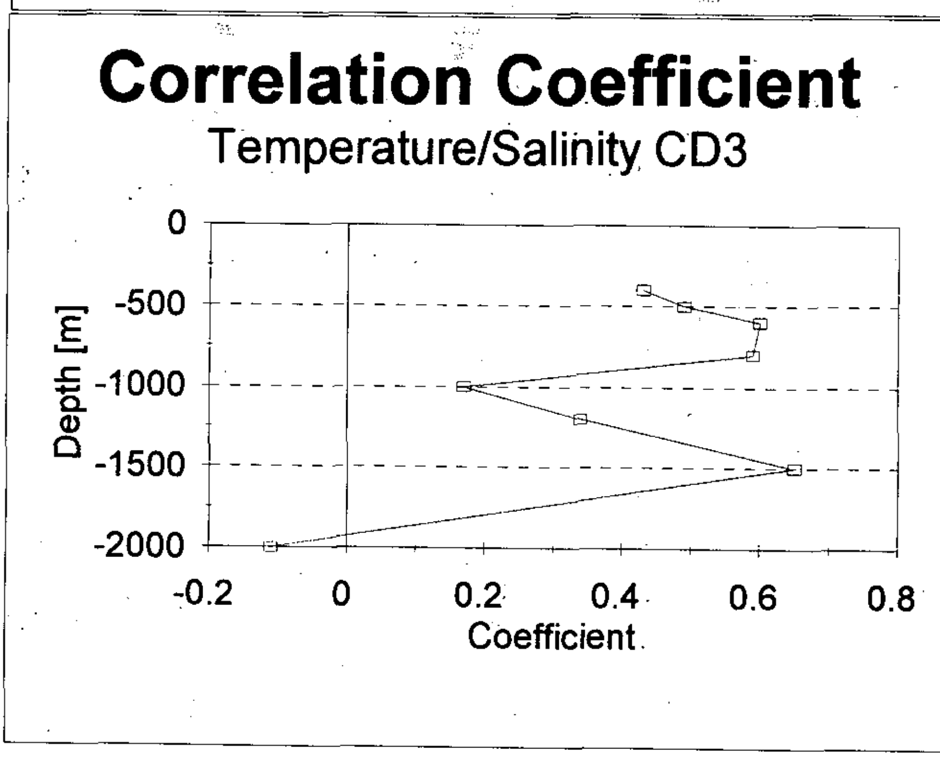


Fig. 14 Vertical profiles of correlation coefficients between temperature and salinity for station 1 of section 8A and Station 3 of Cape Desolation Section

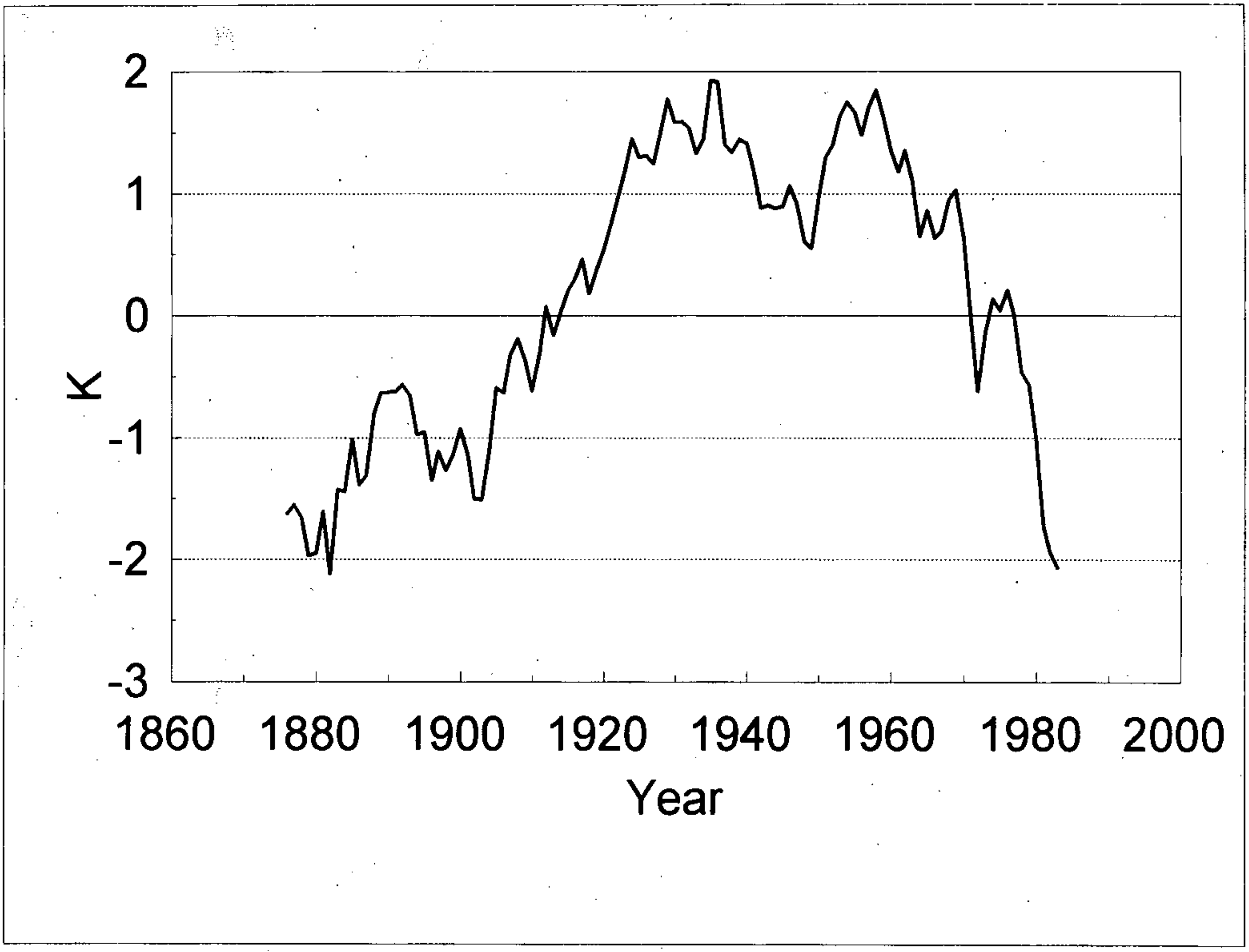
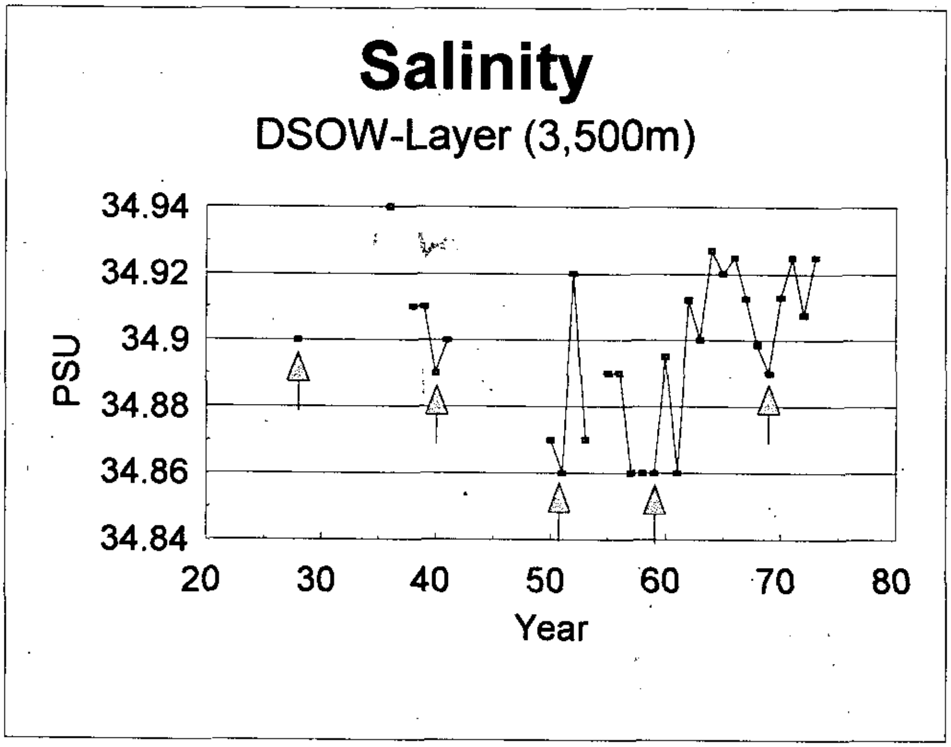


Fig. 15 Air temperature time-series at Nuuk (winter season, JFM mean anomaly, 13 yr.r.m. 1883-1995 (rel. 1876-1995))



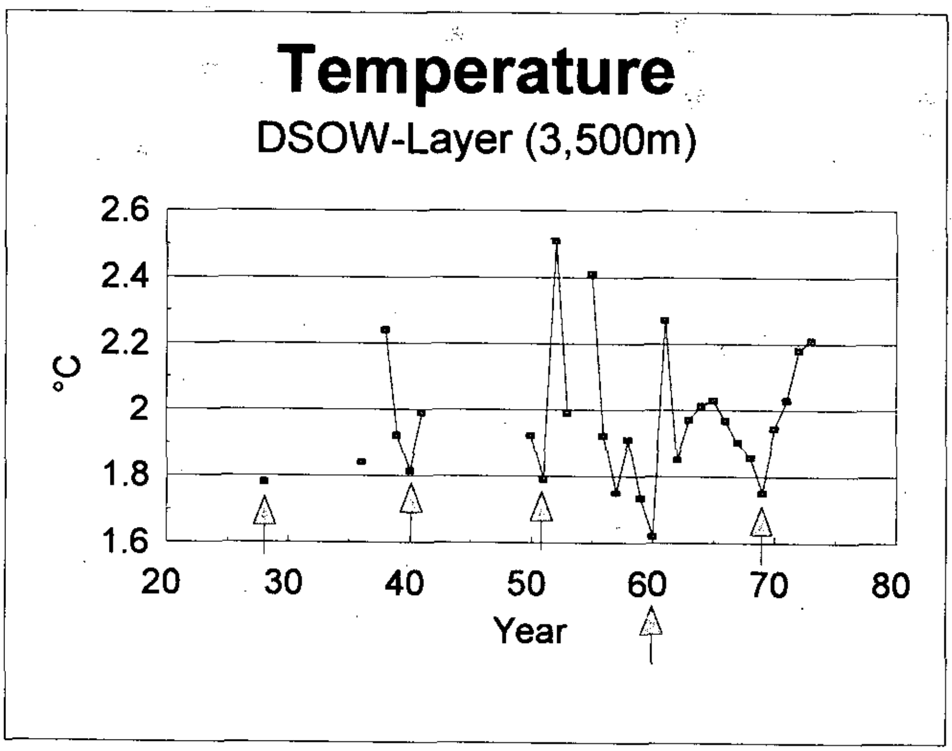


Fig. 16 Salinity and temperature time-series of DSOW-layer (3,500m); continous time axis; arrows indicate low temperature/salinity events

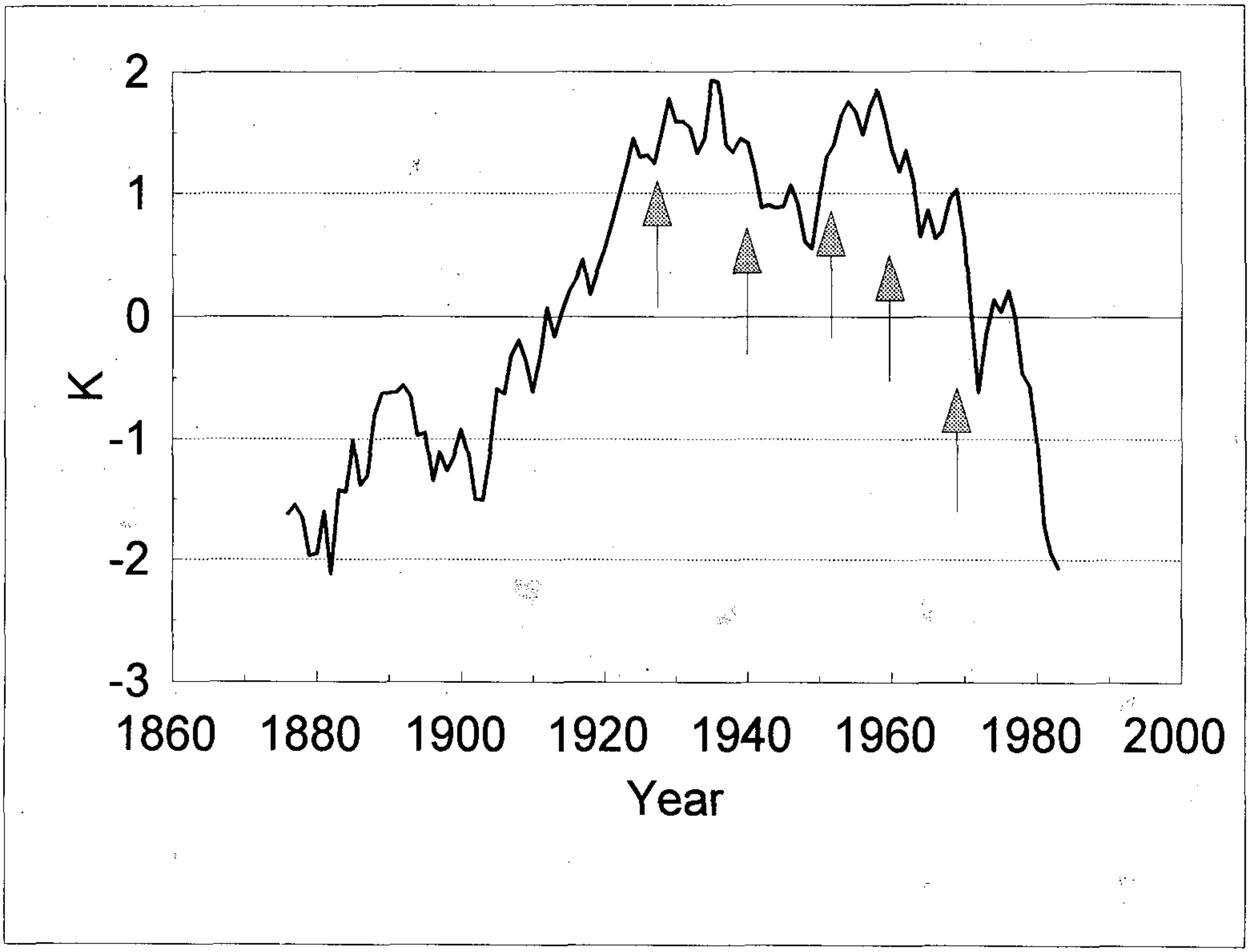


Fig. 17 Air temperature time-series at Nuuk (winter season, JFM mean anomaly); arrows indicate times when low temperature/salinity events were encountered in the DSOW-layer (c.f. Fig. 16)