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Oceanographic Variability on the Flemish Cap

by

E. B. Colbourne and K. D. Foote

Science Branch, Department of Fisheries and Oceans
P. O. Box 5667, St. John's, Newfoundland, Canada A1C 5X1

ABSTRACT

Oceanographic observations on the Flemish Cap from the early 1990s to 1997 are compared to the long-term mean and to conditions during the past several decades. The mean temperature and salinity fields and their annual cycles were first established and used to calculate anomaly time series. The interannual time series shows a relatively warm time period from the 1950s through the 1960s but three colder and fresher than normal periods since the early 1970s. During early 1993 temperature anomalies reached a maximum of more than 2.0 °C below normal in the upper water column and about 0.5 °C below normal near bottom over the Cap. In general, it was found that the water property anomaly patterns on the Flemish Cap are highly correlated to those observed in the inshore branch of the Labrador Current at Station 27 and in other areas of the Newfoundland Continental Shelf. Studies have shown that these conditions are linked to the large-scale atmospheric winter circulation, sea ice conditions, local atmospheric forcing and advection. An examination of local air-sea heat flux indicates that advection of Labrador Current water into the region may be the principle cause of oceanic variability over the Flemish Cap. Finally, an examination of recent summer acoustic Doppler current measurements and geostrophic current calculations indicate the predominance of an anticyclonic gyre circulation around the Cap, however, the results exhibit a high degree of interannual variability.

Introduction

This paper describes oceanographic conditions on the Flemish Cap in NAFO Division 3M during the past several decades with particular emphasis on the period from the early 1990s to 1997. Several research studies and annual oceanographic reviews have shown that since the early 1970s the oceanographic, meteorological, and sea ice conditions in the Northwest Atlantic have been dominated by three anomalous periods: early 1970s, mid 1980s and the early 1990s (Colbourne et al. 1994, Drinkwater 1996, Drinkwater et al. 1997). The results of these studies show a strong correlation between the winter atmospheric circulation in the North Atlantic and ocean conditions. It was found that winters with high North Atlantic Oscillation (NAO) index corresponded to increased winter northwesterly winds over eastern Canada. These winds brought colder than normal air temperatures to Atlantic Canada resulting in increased ice cover and colder and fresher than normal oceanographic conditions to the continental shelves of Atlantic Canada.

Much of what is known about the oceanography on the Flemish Cap was learned during the international research effort conducted from the mid-1970s to early 1980s under the auspices of the International Commission for the Northwest Atlantic Fisheries (ICNAF). This work was aimed at understanding the physical and biological processes controlling fish production on the Cap. Numerous studies of the thermohaline properties and water mass circulation on Flemish Cap were completed during this research project. Stein (1996) presented an overview of many of these research activities, emphasizing the physical oceanographic aspects. A comprehensive bibliography is presented in this overview. Keeley (1981) published an analysis of historical monthly mean temperature and salinity data along the standard Flemish Cap Section that included observations from 1910 to 1980. Also, Drinkwater and Trites (1986) published spatially averaged temperature and salinity from all available bottle data from 1910 to 1982 over the Flemish Cap area. More recent reviews of oceanographic conditions in the region compared 1993 and 1995-1997 observations with the long-term mean (Colbourne 1993; 1995; 1996; 1997, Parsons et al. 1998). These reviews were based mainly on data collected on the Cap during an annual oceanography summer survey and a limited amount of data collected on fish assessment surveys. Additionally, Cervifio and Prego (1996) presented hydrographic conditions on the Flemish Cap in July of 1996 from a fisheries research survey conducted by the European Union.

The purpose of this paper is to consolidate recent oceanographic observations on the Flemish Cap and compare oceanographic conditions during the early 1990s to the long-term mean and to conditions during the past several decades. Of particular interest is the extent to which trends in the Flemish Cap water properties compared with those on the Newfoundland Shelf during the cold period of the early 1990s.

The Study Area

The Flemish Cap is a relatively deep bank located east of the Grand Banks of Newfoundland centered at about 47° N, 45° W (Fig. 1) in NAFO Division 3M. Minimum water depths are about 150 m. The diameter of the bank at the 500-m isobath is about 200 km, a total area of approximately 3.0 X 10^4 km^2. To the west, the Flemish Pass with water depths of about 1100 m separates the Cap from Grand Bank of Newfoundland. At the 2000-m isobath the Flemish Cap appears as an eastward extension of the Newfoundland Continental Shelf Slope.

The water mass on the Flemish Cap is comprised mainly of two sources, North Atlantic Current water from the south and Labrador Current water from the north. The general circulation in the vicinity of the Flemish Cap is shown in Figure 1b. These waters are subjected to large annual and interannual variations due to storm forced mixing, variations in atmosphere-ocean heat flux and through advection into the area. The seasonally modified water mass has higher temperatures than that over the adjacent Grand Bank over most of the water column. For example, near bottom at 150-m depth, temperatures over the Grand Bank are generally near 0.0 °C, compared to about 3.0 °C to 4.0 °C over the Flemish Cap (Colbourne and Senciall 1996). Surface temperatures on the Cap range from a minimum of 3.0 °C during winter to above 13.0 °C during summer compared to sub-zero values on the Newfoundland Shelf. As a result the region is relatively free of pack ice with ice encroaching only briefly during February and March of severe ice years.

Temperature and Salinity Variability

Mean Annual Conditions

The annual depth versus time mean (1961-90) temperature and salinity over central Flemish Cap centered on the 47 °N line is shown in Figure 2. The water column is nearly isothermal at about 4.0 °C from late January until April in the upper layer and remains at about 4.0 °C throughout the year at depths below approximately 75 m. Seasonal warming of the upper layer commences by early-May and progresses at a rate of about 0.1 °C per day until late-August or early-September when it reaches a maximum of between 12.0 °C and 13.0 °C. The seasonally warmed upper layer reaches a maximum depth of about 80 to 90 m by late-November by which time the surface layer is cooling. In January, salinity ranges from about 33.75 practical salinity units (PSU) in the upper water column to about 34.5 PSU near the bottom (Fig. 2). Conditions tend to be uniform throughout the year with depth except in the upper-layer, which experience a gradual freshening, reaching a minimum of 33.25 PSU by late summer. At depths greater than 80 m, salinities remain at about 34.0 to 34.5 PSU over the entire year.

The seasonally averaged vertical distribution of temperature and salinity over the Flemish Cap along the standard 47° N transect are shown in Fig. 3. The average winter temperature over the Cap is about 4.0 °C over most depths with the colder Labrador Current water present on the Flemish Pass side of the Cap where temperatures decrease to 1.0 °C. East of the Cap temperatures increase to between 4.0 °C to 5.0 °C. Average winter salinity range from 33.75-34.0 PSU in the upper layer increasing to 34.5-34.75 PSU near bottom over the Cap. During spring temperatures begin to warm to above 5.0 °C near the surface and continue around 4.0 °C below the surface layer, again with colder temperatures adjacent to the Labrador Current in the Flemish Pass area. Spring salinities are very similar to winter values ranging from 33.75 at the surface to 34.75 PSU below 200-m depth. The average summer temperature (Fig. 3c) shows the seasonally heated upper layer with temperatures ranging from 5.0 °C at 50 m depth to greater than 10.0 °C at the surface and about 4.0 °C below 50 m depth. In the Flemish Pass area, again the cold Labrador Current is evident with temperatures decreasing to 1.0 °C to 2.0 °C. The corresponding summer average salinities show the freshening of the upper layer with salinities decreasing to between 33.0 to 33.5 PSU. In water depths greater than 250 m salinities are generally constant around 34.75 PSU. With the exception of the near surface layer, which has cooled significantly, similar temperature and salinity conditions prevail during fall (Fig. 3d).

The seasonal averaged surface temperature ranges from 3.0 °C to 4.0 °C during winter to 3.0 °C to 6.0 °C during spring, from 10.0 °C to 12.0 °C during summer and from 7.5 °C to 9.0 °C in the fall (Fig. 4a). To the west and northwest the cold offshore branch of the Labrador Current is present and to the southeast the warm waters of the North Atlantic Current is visible, with temperatures reaching more than 15.0 °C. Near bottom over the Cap temperatures ranged from 3.5 °C to 4.0 °C throughout most of the year (Fig. 4b).

Recent Anomalies

Presented in Fig. 5 are vertical distributions of temperature and salinity anomalies during July of 1993, 1995, 1996, and 1997 along the 47° N transect across the Flemish Cap. The normal was defined as the 30 year period from 1961-1990 in accordance with the convention of the World Meteorological Organization and recommendations of the NAFO Scientific Council. The anomalies were calculated, by subtracting the gridded averaged July data from the summer transect data for each year. No adjustment for temporal biasing arising from variations in the number of observations throughout the month was made. During 1995 the observations across the Cap were made on July 18. An examination of the historical data distribution for July shows that about 40 % of the data were collected before July 20 with a median date of July 25. An examination of the annual temperature cycle over the Flemish Cap shows that the temperature normally changes by approximately 0.5 °C in the time interval from July 18 to 25 in the near surface layers (0 to 20 m) and about 0.1 °C at 50 m depth. This indicates that in near surface areas, where the annual cycle is the strongest, the temperature anomalies may be biased low, assuming normal atmospheric heat flux into the ocean.

The vertical temperature anomaly distribution in early July of 1993 shows values ranging from 1.5 °C to 2.5 °C below normal in the surface layers (Fig. 5a). In water depths greater than 50 m to the bottom, anomalies ranged from 0.5 °C to 1.5 °C below normal along the Flemish Pass, located near the offshore edge of the Labrador Current. On the offshore portion of the bank in deeper waters, temperatures ranged from about 0.0 °C to 1.5 °C below normal. The corresponding salinities in July 1993 ranged from about 0.1 to 0.3 PSU fresher than normal in the upper 100 m of the water.

During 1995, in the 0 to 50 m depth range, temperature anomalies ranged from -1.5 °C in the Flemish Pass to -0.5 °C over the Cap and to normal values over the offshore portion of the continental slope (Fig. 5b,). In the depth range of 100 m to the bottom over the Cap temperatures were 0.5 °C to 1.0 °C below normal and about 0.3 °C below normal below 300-m depth. For comparison, during 1993 temperature anomalies in the upper layer were up to 2.5 °C below normal and about 1.0 °C to 1.5 °C below normal in the depth range of 100 m to the bottom over the Cap. In deeper water (below 250 m) anomalies were generally around 0.5 °C below normal in the Flemish Pass. Salinities in 1995 were higher than normal by 0.2 to 0.4 PSU in the depth range of 0 to 50 m and about normal over the rest of the water column (Fig. 5b). In contrast, 1993 salinities in the upper layer over the Cap were slightly fresher than normal by 0.2 to 0.3 PSU (Fig 5a.) and near normal below 150-m depth.

During 1997, upper layer (0-50 m) temperature anomalies (Fig. 5d) ranged from 0. °C to 1.5 °C above normal on the Flemish Pass side of the Cap, around 0.0 °C to 1.0 °C above normal over the Cap and from 1.0 °C to 2.0 °C above normal on the eastern side of the Cap. East of the Cap on the continental slope temperatures were 1.0 °C to 1.5 °C below normal. These values were considerably warmer than the 1996 values (Fig. 5c). Below the surface layer temperature anomalies ranged from 0.0 °C to 0.5 °C below normal, similar to 1996 values in some areas, however the bottom temperatures on the Cap from 150 to 300 m depths were near normal. The positive surface anomalies during 1997 over the Cap are in contrast to the generally negative anomalies experienced over most of the Grand Bank during the same time period and the negative anomalies experienced over the Cap in July of 1993, 1995 and 1996.

The corresponding salinities anomalies in both 1996 and 1997 were similar, with a saltier than normal (by 0.2 to 0.6 PSU) surface layer (0 to 50 m thick) across the Cap (Figs. 5c and 5d). In the depth range of 50 m to the bottom over the Cap anomalies were slightly positive in 1997 and slightly negative in 1996. In the deeper water of the Flemish Pass and on the continental slope to the east of the Cap, values were near normal. In contrast, 1993 salinities in the upper layer over the Cap were slightly fresher than normal by 0.2 to 0.3 PSU (Colbourne 1993).

The vertical distributions of chlorophyll and dissolved oxygen saturation for July of 1997 along the standard NAFO transect across the Flemish Cap are shown in Fig. 5e. The chlorophyll concentrations show relatively high values over the Flemish Cap compared to over the adjacent Grand Bank during 1997, 1996 and 1995 (Colbourne 1996). The higher values were confined to a surface layer from 0 to 50-m depth (Fig. 5e, top panel). The higher chlorophyll values over the Flemish Cap during mid summer appear to be a common occurrence and may indicate a delayed or extended offshore plankton bloom relative to the Newfoundland Shelf areas.

Dissolved oxygen levels during 1997 were about 7.0 ml/l in the upper 100-m of the water column over the Flemish Pass area and from 7.0 to 6.5 in water depths from 100 m to the bottom over the bank. These correspond to oxygen saturation levels (Fig. 5e, bottom panel) ranging from 97.5 to 110 % from the surface to about 50 m depth and from 90 to 97 % in the depth range of 50 m to the bottom. The super-saturated values in the top 50-m of the water column correspond to the high chlorophyll concentrations encountered over the Flemish Cap. These saturation levels are similar to that observed during 1993, 1995 and 1996 and indicate a well-oxygenated water column.

Spring and summer temperatures for the time period 1990-1996 indicate anomalies in the range of 1.0 °C to 2.0 °C below normal at the surface, over some areas and about 0.5 °C below normal near bottom (Fig. 6). The Temperature-Salinity diagram shown in Fig. 7 clearly shows the influence of cross-shelf exchange between the Grand Bank and Flemish Cap region during early 1990s.

Annual Temperature and Salinity Cycles

To examine the spatial variability in the temperature and salinity fields of the Flemish Cap Region the historical data set was grouped into 3 areas (Fig. 1a) labelled FP, for Flemish Pass, FC, for Flemish Cap and NA, for North Atlantic. These areas were selected based on the local bathymetry, available data and on local oceanographic influences. The data for each area for all years were sorted by day of the year to determine the annual cycle. Data points considered as outliers were rejected. Following the methods of Akenhead (1987), Petrie et al. (1991) and Colbourne at al. (1994), the seasonal cycles in the temperature and salinity fields at selected water depths were determined by fitting a least-squares regression to the data. The fit was made to the mean and the sum of 3 sine and cosine pairs, representing the annual cycle and 2 harmonics. Temperature and salinity values for all years plotted by day at depths of 0, 50 and 200 m for the region over the Flemish Cap (FC) show the temporal distribution of the data throughout the year as well as the scatter from the mean (Figs. 8 and 10). These plots indicate sufficient data to adequately fit the seasonal cycles for both temperature and salinity. The largest annual cycle in the water temperature occurs in the upper layers where the strongest coupling to the annual solar flux exists. The amplitude and phase of the annual component of the surface temperature cycle over the Cap is 4.5 °C compared to 6.9 °C at Station 27 (Fig 1a), while the phase at both locations is about 243 days. On the Cap the seasonal temperature cycle ranges from a minimum of 3.0 °C in February to 13.0 °C in August with a mean of 7.4 °C. The amplitude of the seasonal temperature cycle decreases with depth and is not significant below 100 m depth. Both the amplitude and phase of the seasonal temperature cycle is near uniform in the upper 20-30 m of the water column. The amplitude decreases from 13.0 °C in the surface layer to about 4.0 °C below 75-m depth while the phase increases rapidly below the mixed layer (Fig. 9).

The amplitude and phase of the annual component of the surface salinity cycle is about 0.45 PSU and 88 days respectively, compared to 0.66 PSU (89 days) at Station 27 (Petrie et al. 1991 and Colbourne and Fitzpatrick 1994). The seasonal salinity cycle ranges from a maximum of 34.0 PSU in March to about 33.2 PSU in September with a mean of 33.5 PSU. The seasonal surface salinity cycle shows a weak maximum during the winter months with a minimum occurring in late summer to early fall. Below 50-m depth the cycle is not significant (Fig. 10). In general, Petrie et al. (1991) showed that while the temperature phase is nearly uniform across the shelf, the salinity phase shows significant latitudinal and cross-shelf variability due to spatial variations in ice formation and melts. During ice production near surface salinities increase because of salt rejection producing an annual salinity cycle maximum during winter. Similarly, low salinities occur in areas where large volumes of ice melts during the spring and summer months. Our results indicate that even though the salinity phase is similar to Station 27, the Flemish Cap is somewhat isolated from the freshening effects of continental shelf ice melt and hence displays a smaller salinity range compared with the adjacent Grand Banks.

Interannual Trends

Temperature and salinity anomalies at standard depths over the period 1950-1997 were constructed by subtracting the least squares fit to the seasonal cycle from each observation. Observations made within the same month were averaged. To highlight the long-term trends the monthly anomalies were low pass filtered by applying a simple running mean to the time series. Time series of temperature and salinity anomalies for the areas defined above are referenced to the 1961-1990 standard base period. Unlike the time series at fixed points (e.g. Station 27) these time series are based on a smaller data set distributed over a wider geographical area, hence some of the scatter in the monthly values may be due to spatial and temporal biasing in the data.

The time series of temperature anomalies at depths of 0, 20, 50, 75, 100, 200, 500 and 1000 m in the Flemish Pass (FP) region are shown in Figure 11. The general trends are characterized by large amplitude fluctuations ranging from about ± 2.0 °C at time scales ranging from one year to near decadal. Superimposed on the trend are large amplitude monthly variations due in part, to high frequency changes in the water properties, but also as a result of spatial variation at constant depth within the selected area and as discussed above, variations in the number of observations within a month. The amplitude of the temperature anomalies tends to decrease with increasing water depth. Below 200-m depth the anomalies are insignificant and the number of observations limited.

The Flemish Pass time series are characterized by 3 major cold periods: most of the 1970s, the mid-1980s and the late-1980s to early-1990s. Prior to the early 1970s the anomalies for the most part were near normal to above normal. The cold period, beginning around 1971, continued until 1977. Temperature anomalies reached values of near 2.0 °C below normal over the upper water column in 1974. From 1978 to 1984, the temperature anomalies showed a high degree of variability in the upper water column with a tendency towards positive anomalies. By 1985, intense negative temperature anomalies had returned with peak amplitudes reaching between 2.0 °C to 3.0 °C below normal in the top 50 m of the water column. This cold period moderated briefly in 1987 and 1988 but fell below normal again by 1989 and continued to drop until they reached a minimum of 2.0 °C below normal by the summer of 1993. This most recent cold period continued until 1996 when temperatures warmed to normal values, which continued into 1997.

The time series of salinity anomalies in the Flemish Pass region show large fresher-than-normal conditions from 1971 to 1975, corresponding to the "Great Salinity Anomaly" (Dickson et al. 1988). From 1983 to 1986 in the upper 100-m of the water column salinities were again below normal with peak amplitudes reaching 0.6 PSU. Salinities during the early 1990s were slightly below normal increasing to above normal conditions in 1997. Similar to the temperature anomalies, the salinity anomaly amplitudes were maximum in the upper mixed layers where the effects of ice melt and run-off are the largest and similar to the temperature anomalies the salinity anomalies were insignificant at depths greater than 200 m (Figs. 11c and 11d).

The time series of temperature and salinity anomalies in area FC on the Flemish Cap (Fig. 12) and in area NA to the east of the Cap (Fig. 13) show very similar trends as in area FP. The three colder and fresher than normal periods at near decadal time scales since the 1970s and the relatively warm 1950s and 1960 are all evident. A notable trend is the apparent decrease in the amplitude of both the temperature and salinity anomalies with increasing distance from the Newfoundland Continental Shelf, indicating perhaps, the significance of shelf ice conditions and coastal runoff on the local water property anomalies. Also, both the temperature and salinity anomaly amplitudes are maximum closer to the surface in all areas where the influence of variations in the atmosphere-ocean heat flux and continental shelf ice conditions are the largest. It should also be noted that the salinity anomaly during the early 1990s on the Flemish Cap was much weaker than that of the mid-1980s and early 1970s and also much weaker than that of the early 1990s on the Newfoundland Shelf (Fig. 14b and 14d).

In general, the water property anomaly patterns presented for the Flemish Cap region are highly correlated to that observed in the inshore branch of the Labrador Current at Station 27 ($r=0.72$ at $p < 0.05$, Fig. 14). Indeed, similar conditions existed over most of the Newfoundland Continental Shelf during the same time period, from NAFO Divisions 3LNO in the south to 2J in the north (Colbourne et al. 1994). Several studies have shown that these conditions are linked to the large-scale atmospheric winter circulation, sea ice conditions, local atmospheric forcing and advection from upstream (Colbourne et al. 1994, Drinkwater 1996, Drinkwater et al. 1997). Umoh et al. (1995) indicated that the annual temperature variation on the Newfoundland Shelf could largely, but not completely, explained by variations in the local air-sea heat flux. They also recognized the possible importance of advection from upstream sources. As shown in Fig. 14 and 15 the NAO index anomalies are highly correlated with variations in temperature and salinity both at Station 27 and on the Flemish Cap indicating similar forcing agents. However, the correlation with the local air-sea heat flux over the Cap is not significant, indicating the possible dominance of advection of Labrador Current water into the region as the principle cause of ocean variability on the Flemish Cap.

Circulation on Flemish Cap

General

Two major current systems dominate the circulation and influence the water mass properties around the Flemish Cap. The offshore branch of the Labrador Current bifurcates at the north eastern corner of the Grand Bank and flows to the south through the Flemish Pass and to the east and south-east around the northern and eastern slopes of the Cap transporting cold, relatively low salinity water into the region. To the southeast the North Atlantic Current transports warmer, high salinity water to the Northeast along the Southeast slope of Grand Bank and the Flemish Cap (Fig. 1b). The circulation over the center of the Cap is dominated by an anticyclonic gyre (Kudlo et al. 1984, Ross 1981) (Figs. 16 and 17). These types of flows are frequently formed when an incident current in a stratified fluid interacts with an isolated topographical feature through a redistribution of vorticity (Herbert and Bryan 1976). The thermohaline properties of the water mass over the central Cap within this gyre consists mostly of seasonally modified Labrador Current water, while the properties along the periphery of the bank especially along the south and eastern portions are derived from a mixture of Labrador Current and North Atlantic water.

The stability of the gyre circulation pattern on the Cap is strongly influenced by atmospheric forcing at weather band frequencies (about 2-10 days). Kudlo et al. (1984) have shown that the flow over the Cap consist of several types of circulation patterns ranging from pronounced gyre circulation to cross bank meandering type flows (Fig. 16). From an initial qualitative analysis of atmospheric data it was found that the frequency of the meandering type flows coincided with the passage of storm systems and were more frequent during the winter months, when the mean wind speed was the largest. During summer when storm activity was reduced, the anticyclonic circulation predominated. Anderson (1992) estimated an index of relative gyre strength from the same data set, based on the difference in the dynamic height of the water over the Cap to that southeast of the Cap (Fig. 18). His analysis showed large variations, but the general seasonal cycle was evident, with increased gyre strength in the summer and fall months.

The time scale for a complete circulation of a parcel of water around the Cap, referred to as the re-circulation times, were found to be not generally equivalent to residence times of the water mass over the Cap. The available data suggest that residence times can be significantly less than re-circulation times. For example, Loder et al. (1988) used drifter tracks calculated mean re-circulation times of 67-78 days along the 400 m isobath with residence times of about 32 days. This indicates that variability in the meandering cross-bank flow may be the most significant circulation feature from a biological perspective. As postulated by Kudlo and Borovkov (1977) and by Kudlo and Boytsov (1979), the stability of the circulation patterns around the Flemish Cap may influence the retention of ichthyoplankton on the bank. This is probably a factor in determining the year-class strength of various species such as cod, redfish and shrimp. Their hypothesis however has not been tested (Lilly 1987). In fact, Anderson (1992) did not find a significant correlation between the annual variations in redfish abundance and water mass circulation for the years 1979-81.

Recent Acoustic Doppler Current Measurements

From 1993 to 1997 (except 1994) mid-summer currents on the Flemish Cap were measured with hull-mounted 150 kHz, RDI acoustic Doppler current profilers (ADCP) at a spatial resolution of 4.0 m vertically by approximately 1.5 km horizontally. An example of these results is shown in Fig. 19.. The measurements were restricted to water depths less than 500 where bottom referencing was possible. The useful range of the 150 kHz ADCP for current measurements in this area is about 10 to 300-m depth. More information on ADCP data collection and subsequent analysis is presented by Colbourne et al. 1993 and 1997.

The survey in July 1993, showed a detailed view of the currents along the 47° N line across the center of the Cap (Colbourne, 1993). In the Flemish Pass, the offshore edge of the Labrador Current, up to 200 m deep, flowed at about 15 cm/s in a general southerly along-shelf direction (Fig. 20a). Over the Flemish Cap itself, the circulation was predominately anticyclonic with northward currents of 5-15 cm/s over the western portion of the bank and southward currents of 5-15 cm/s over the eastern portion. These data suggest re-circulation times of roughly 10 weeks along the 500-m isobath (assuming gyre width of approximately 200 km) at an average current speed of about 10 cm/s. Further up on the bank, within the 200-m isobath, re-circulation times were in the order of 50 days at 10 cm/s.

The circulation around the Cap was predominately anticyclonic in all surveys since 1993 with typical re-circulation times ranging from 50 to 70 days. Figure 20b shows a vertical cross-section of the north-south currents over the Flemish Cap during July of 1996 and 1997 along 47° N latitude. The 1997 measurements show a northward component ranging from 2.5 to 10 cm/s over the shoreward portion of the Cap in the Flemish Pass area and over the Cap in water depths below 50-m depth. In the surface layer and east of the Cap currents were generally southward with speeds ranging from 2.5 to 10 cm/s. The 1997 measurements indicate a much weaker circulation than that observed in 1996 when currents were in excess of 25 cm/s.

Geostrophic Calculations

The anticyclonic rotation of the water mass around the Flemish Cap was described by Kudlo and Burmakin (1972), Kudlo and Borovkov (1975) and Kudlo et al. (1984) using geostrophic currents calculated from density measurements. The geostrophic currents perpendicular to the 47° N line, estimated from the density data collected during 1993 and from 1995 to 1997 are shown in Fig. 21. Also included is an earlier example from 1968. These calculations which are referenced to 300 meters, or to the bottom, in water depths less than 300 m, show the well-known features of the circulation, particularly the 1968 example. The strong baroclinic component of the offshore branch of the Labrador Current westward of the Cap, the general anticyclonic circulation around the Cap and the northward flowing water of the North Atlantic Current east of the Cap are all evident. The results however differ significantly from the direct current measurements made with the ADCPs, thus indicating the potential importance of wind driven and tidal currents on the Flemish Cap. Finally, both the directly measured currents and the geostrophic estimates show considerable variability between different years, for example, the 1997 geostrophic currents indicate a much weaker anticyclonic gyre than the 1996 data.

To determine the magnitude of interannual variations in the strength of the anticyclonic circulation around the Cap we calculated the geostrophic circulation across the Cap along the 47° N line from 1950 to 1997. The analysis was restricted to data from the near synoptic mid-summer transects across the Cap, carried out by Canadian annual oceanographic surveys. The total northward transport on the western side of the Cap and the southward transport on the eastern side were computed in 150 km sections, both east and west of the center of the Cap. The results show a high degree of variability but indicate a consistent transport to the south on the offshore portion of the Cap. The transport on the western side for the most part is to the north; consistent with anticyclonic rotation, however, variations are significant and in some cases a reverse flow is present (Fig. 22). This would seem to indicate that variations in the Gulf Stream and the North Atlantic Current, particularly since the early 1980s, might have played a role in the stability of the gyre. It should be noted however, that these results are from a mid-summer synoptic survey of conditions on the

Cap and the available data preclude a definite examination of long-term trends in the stability of the gyre on an annual basis. In the absence of more seasonal data, a more extensive examination of the geostrophic wind speed over the Cap similar to the analysis of Kudlo et al. (1984) may provide a better indication of trends in the stability of the circulation. No doubt, variations in the Labrador Current, the Gulf Stream and the Northwest Atlantic Current also play important roles in the circulation and the stability of the circulation around the Flemish Cap.

Summary

Using the historical oceanographic data, conditions on the Flemish Cap from 1993 to 1997 were compared to the long-term mean and to conditions during the past several decades. The amplitude and phase of the annual component of the surface temperature cycle over the Cap is 4.5 °C compared to 6.9 °C at Station 27, while the phase at both Station 27 and on the Cap is about 243 days. The seasonal temperature cycle ranges from a minimum of 3.0 °C in February to 13.0 °C in August with a mean of 7.4 °C. Similarly the amplitude and phase of the annual component of the surface salinity cycle is about 0.4 PSU and 90 days, again the amplitude is less than at Station 27. The seasonal surface salinity amplitude ranges from a maximum of 34.0 PSU in March to about 33.2 PSU in September with a mean of 33.5 PSU.

The interannual time series shows a relatively warm time period from the 1950s through the 1960s and three colder and fresher than normal periods since the early 1970s. During early 1993 temperature anomalies reached a maximum of more than 2.0 °C below normal in the upper water column and about 0.5 °C below normal near bottom over the Cap. Temperature anomalies were more significant in the top 100 m of the water column and tended to be higher in western areas of the Cap, closer to the Newfoundland Shelf. In general, it was found that the water property anomaly patterns on the Flemish Cap are highly correlated to those observed in the inshore branch of the Labrador Current at Station 27 and in other areas of the Newfoundland Continental Shelf. Studies have shown that these conditions are linked to the large-scale atmospheric winter circulation, sea ice conditions, local atmospheric forcing and advection. An examination of the local air-sea heat flux over the Flemish Cap indicates that advection of Labrador Current water into the region may be the principle cause of oceanic variability in the region.

Finally, an examination of recent summer acoustic Doppler current measurements and geostrophic current calculations indicate the predominance of anticyclonic circulation around the Cap, with re-circulation times between 50-70 days, consistent with the results of earlier studies. However, the results, which were based on a single summer survey, exhibit a high degree of interannual variability.

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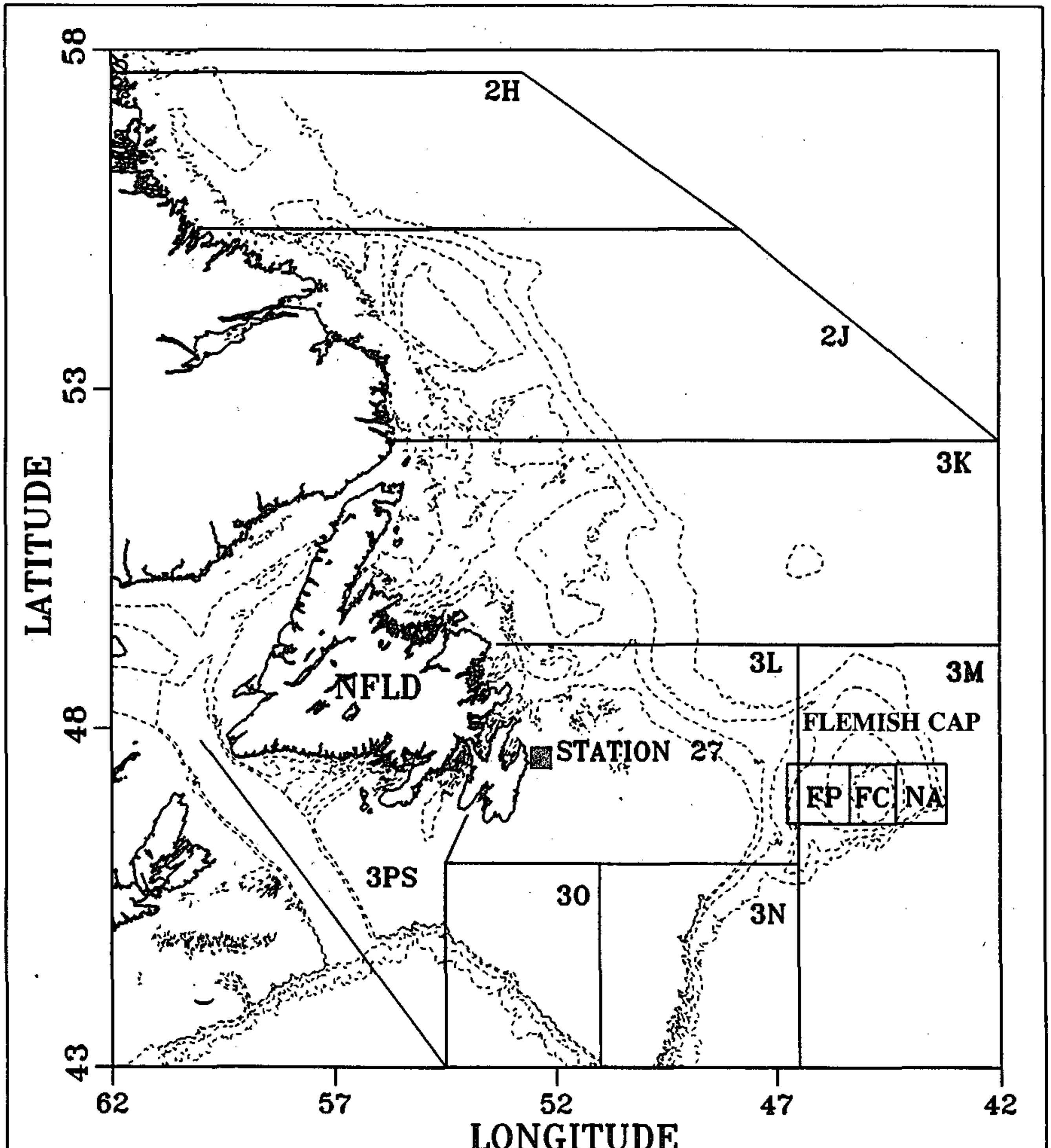


Fig. 1a. Regional location map, showing the general location of the Flemish Cap area. The boxes FP, FC and NA correspond to areas where temperature and salinity time series were constructed. Bathymetry lines are 300, 1000 and 2000 m. The position of Station 27 is also shown.

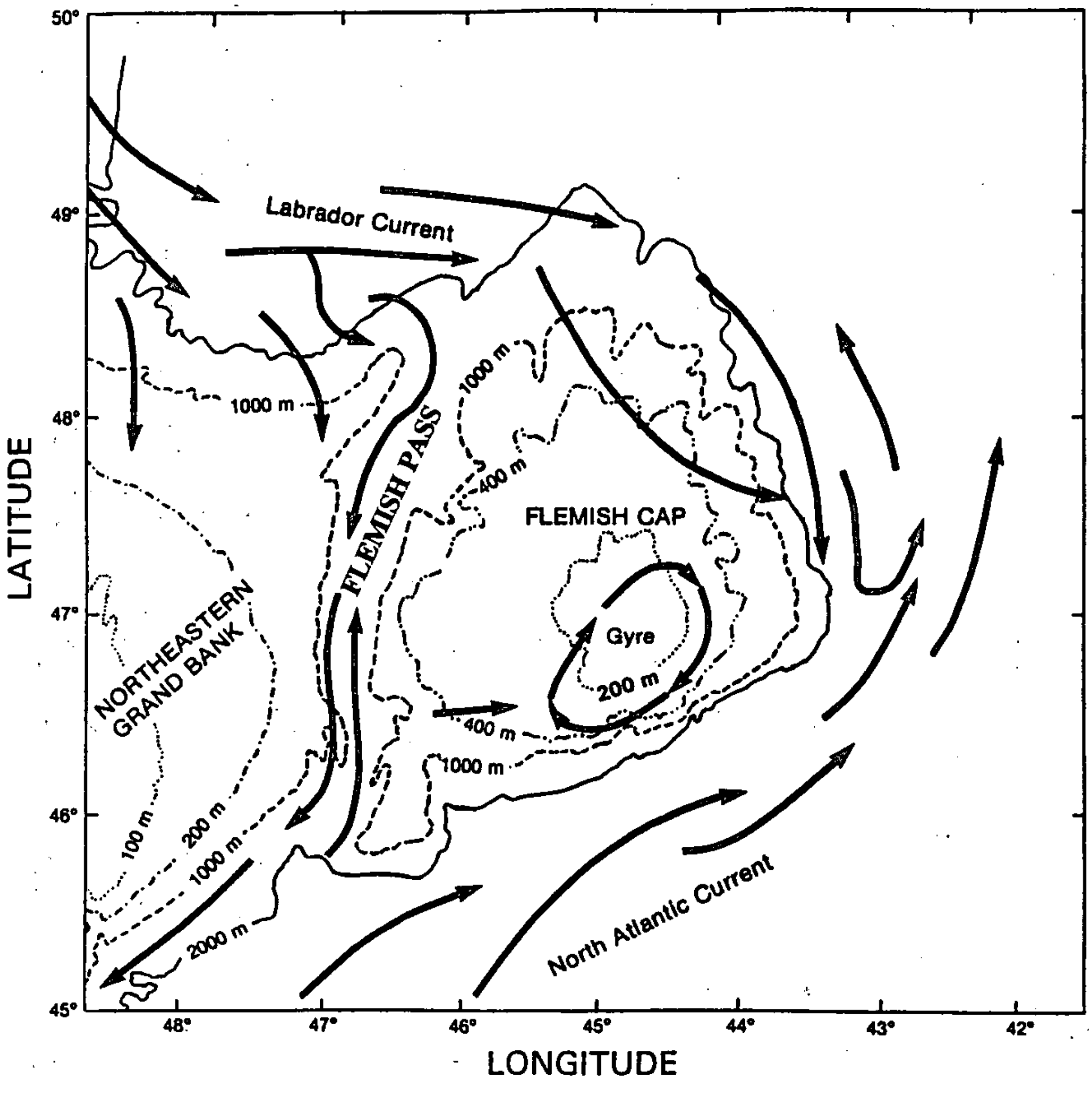


Fig. 1b. A schematic indicating the major circulation features around the Flemish Cap (Adapted from Anderson, 1984).

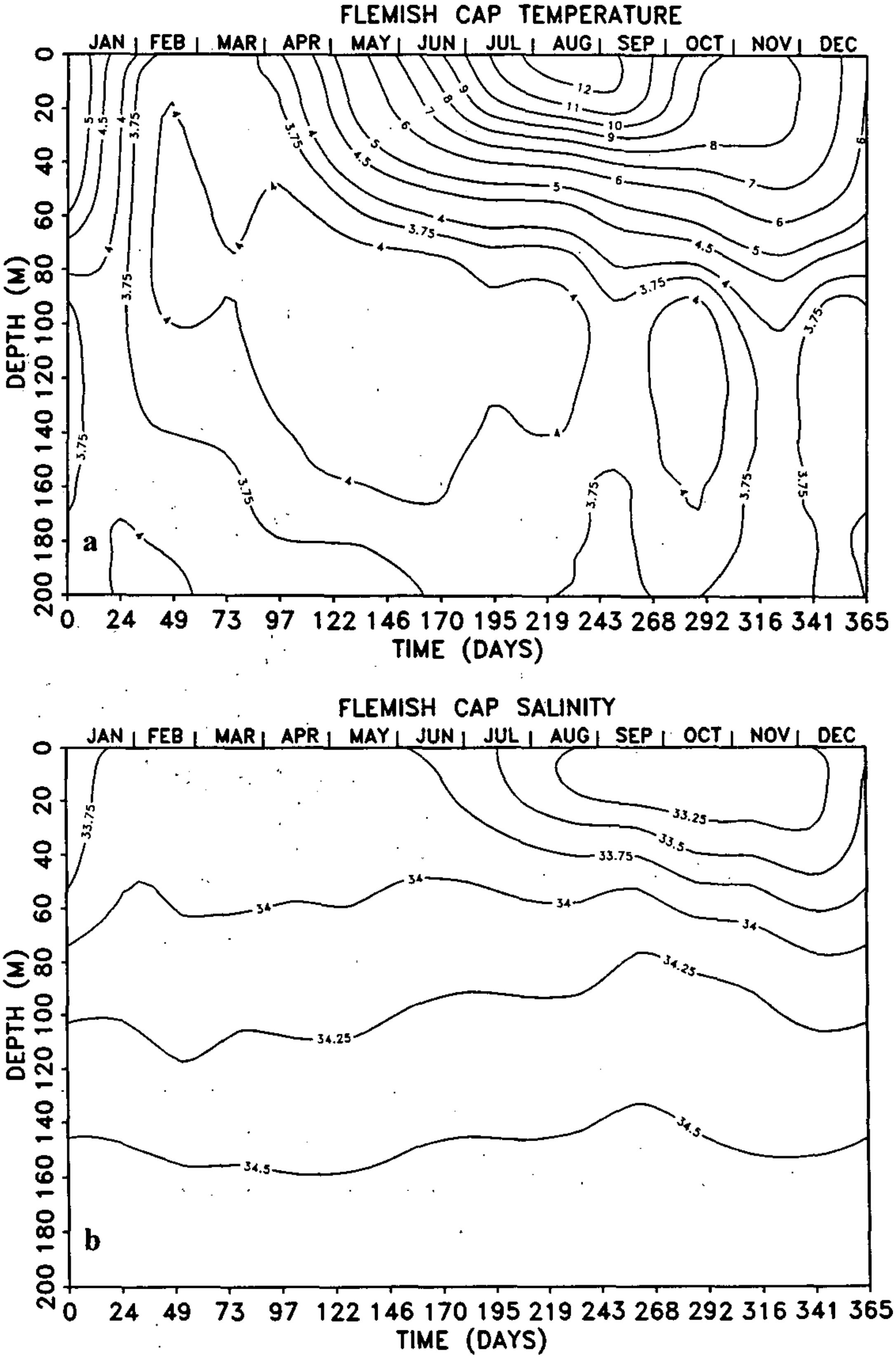


Fig. 2. The monthly mean (a) temperature and (b) salinity over the central Flemish Cap along 47° N based on all available historical data from 1961 to 1990.

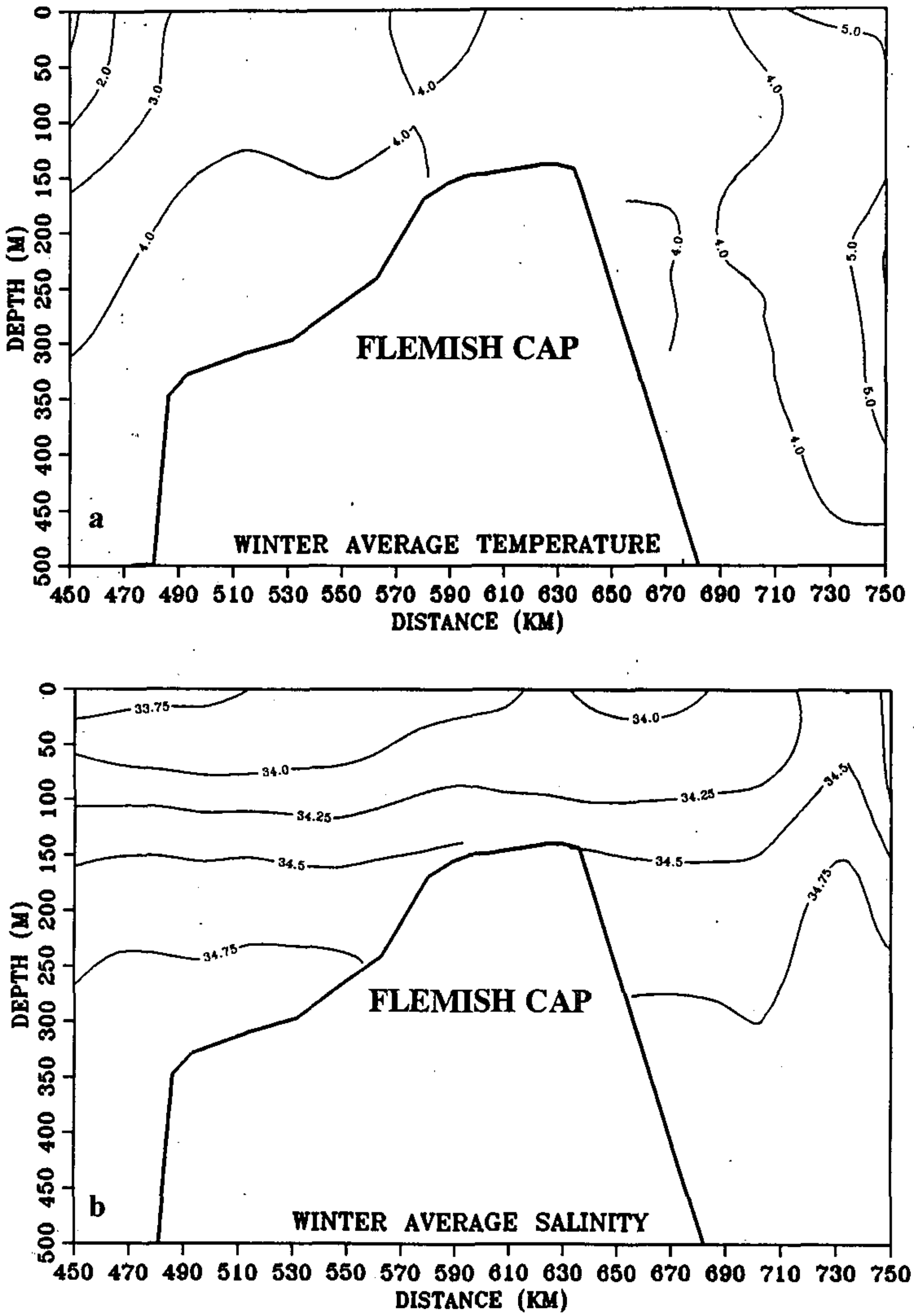


Fig. 3a. Vertical distribution of the winter mean (a) temperature and (b) salinity over the Flemish Cap along 47° N based on all available historical data from 1961-1990.

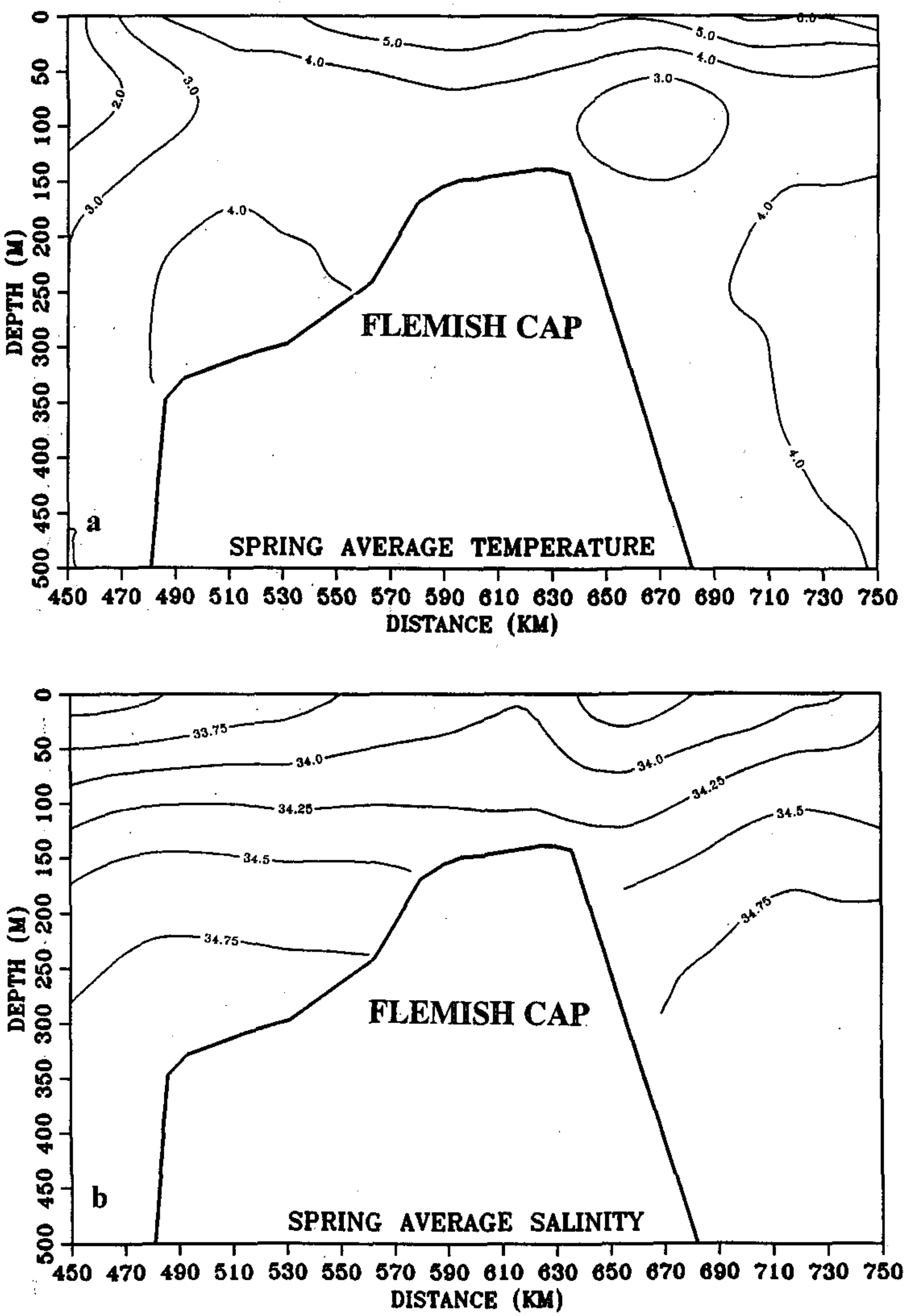


Fig. 3b. Vertical distribution of the spring mean (a) temperature and (b) salinity over the Flemish Cap along 47° N based on all available historical data from 1961-1990.

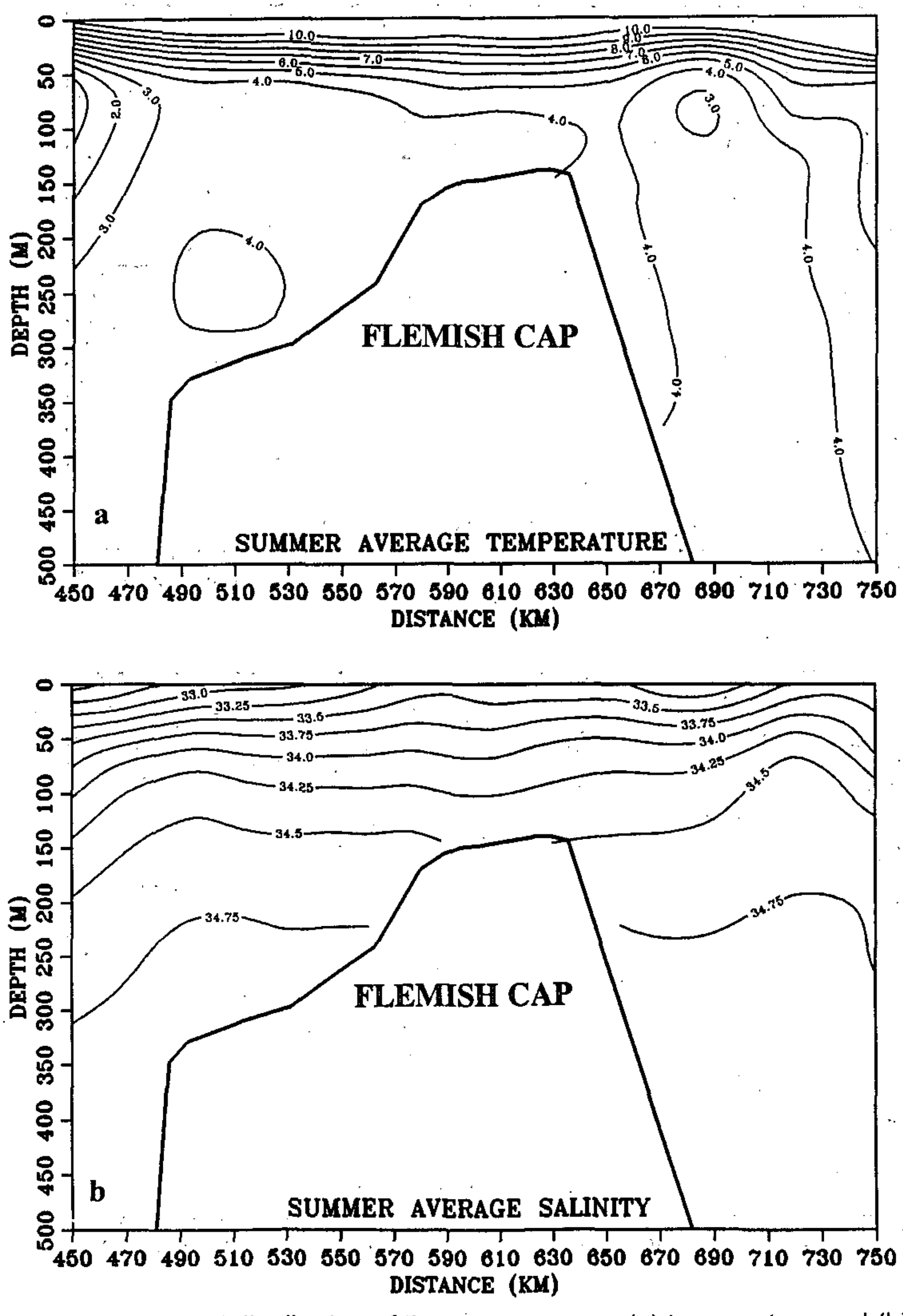


Fig. 3c. Vertical distribution of the summer mean (a) temperature and (b) salinity over the Flemish Cap along 47° N based on all available historical data from 1961-1990.

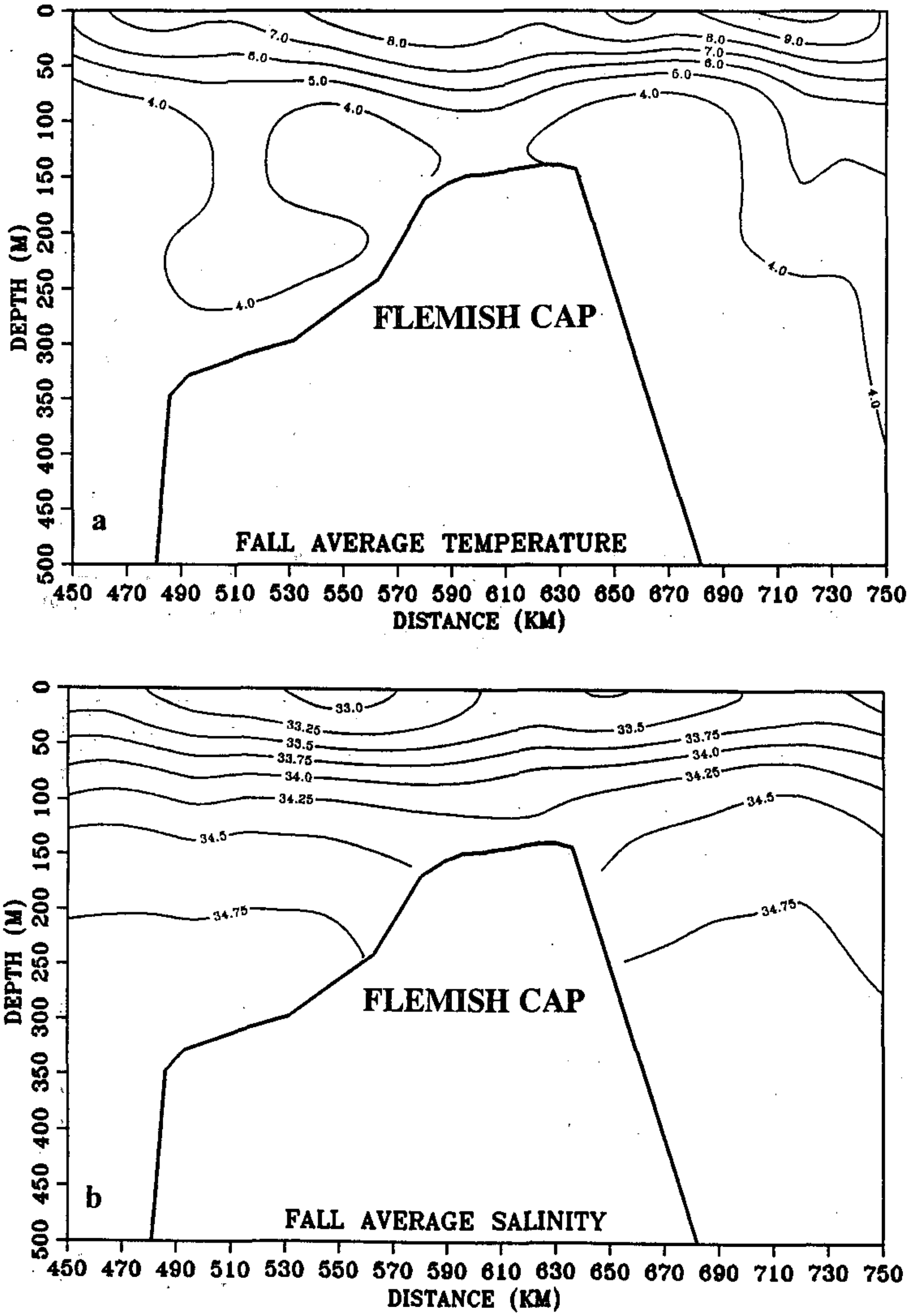


Fig. 3d. Vertical distribution of the autumn mean (a) temperature and (b) salinity over the Flemish Cap along 47° N based on all available historical data from 1961-1990.

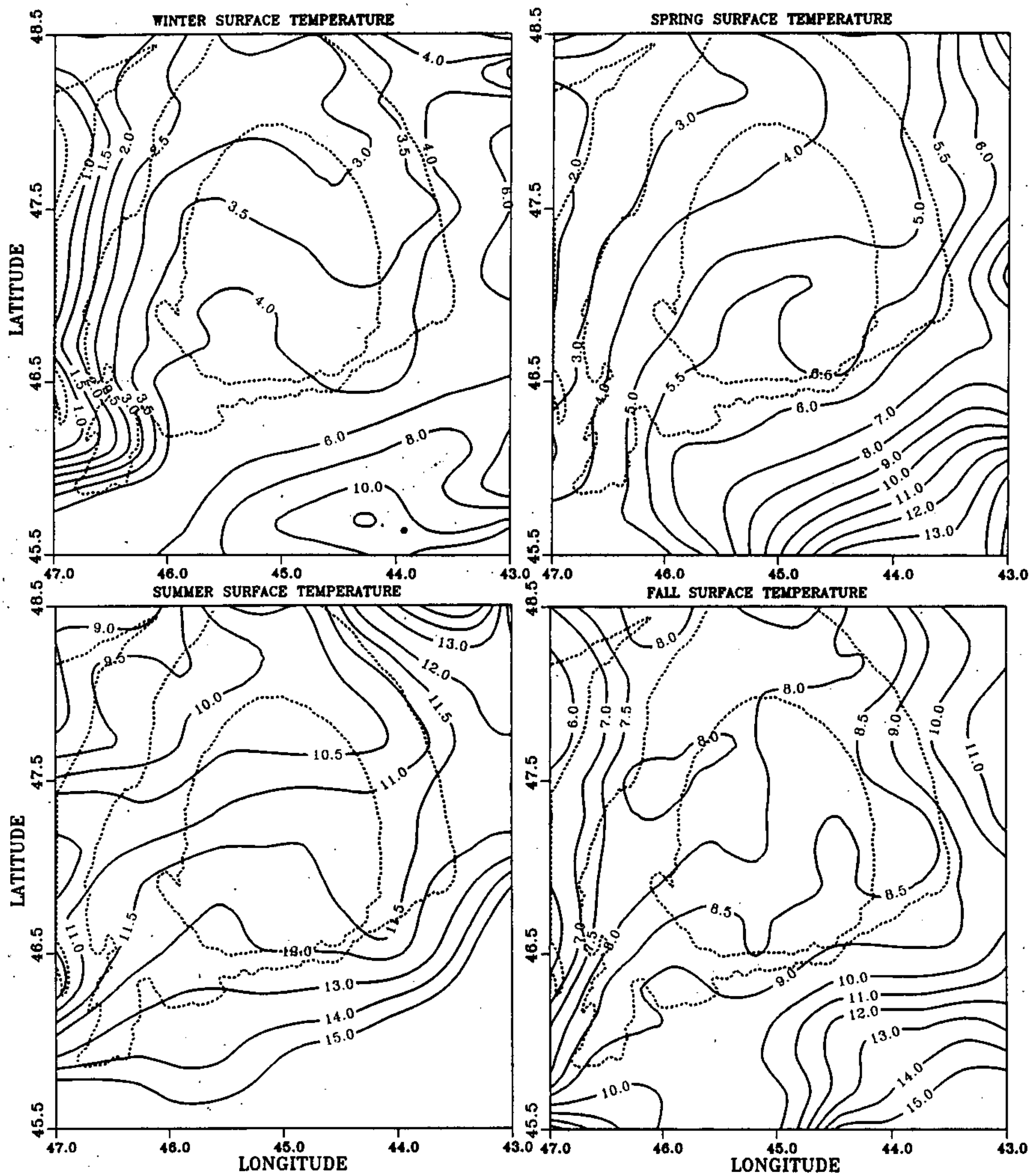


Fig. 4a. Seasonal surface temperature maps of the Flemish Cap region based on all available historical data from 1961-1990.

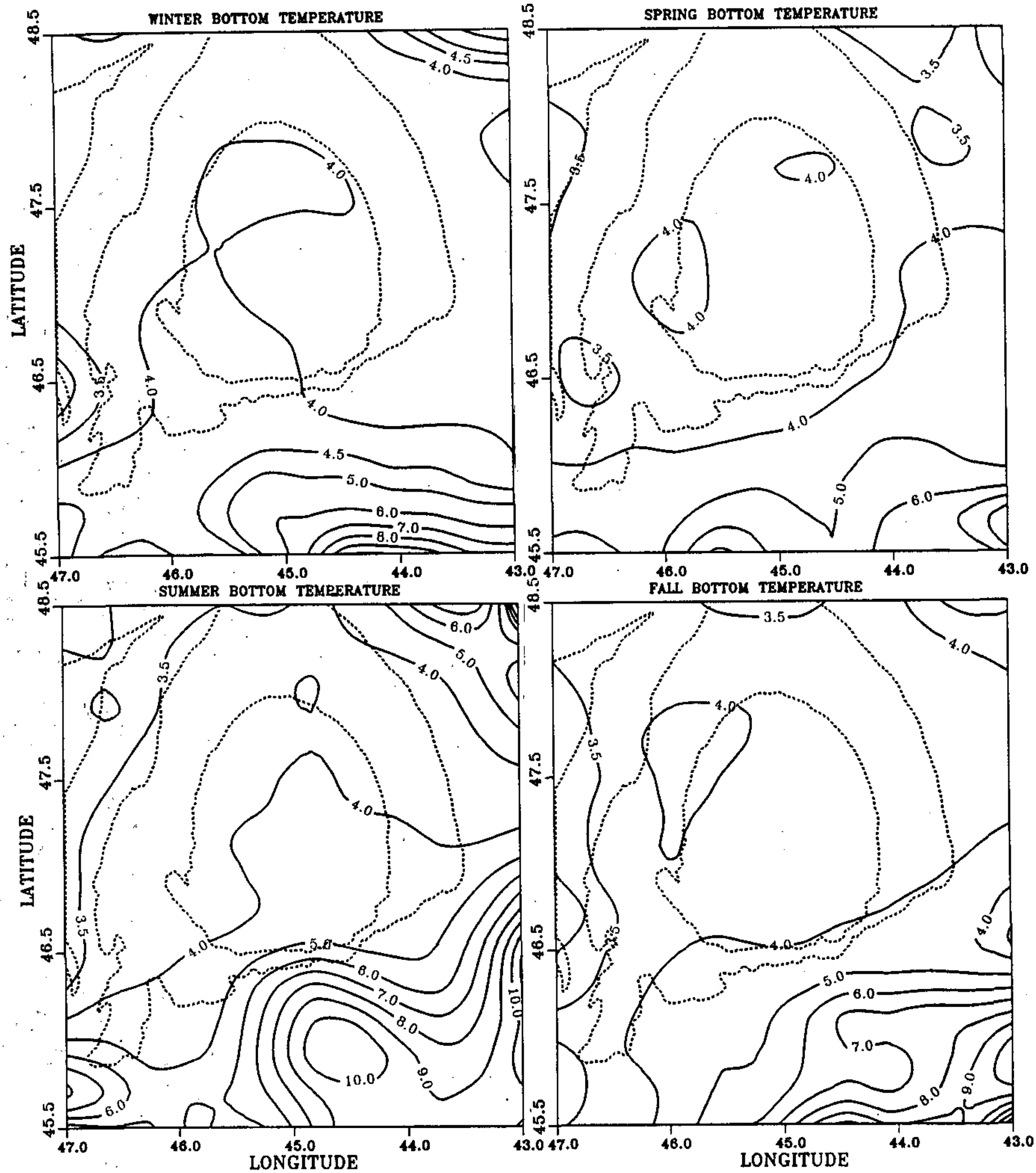
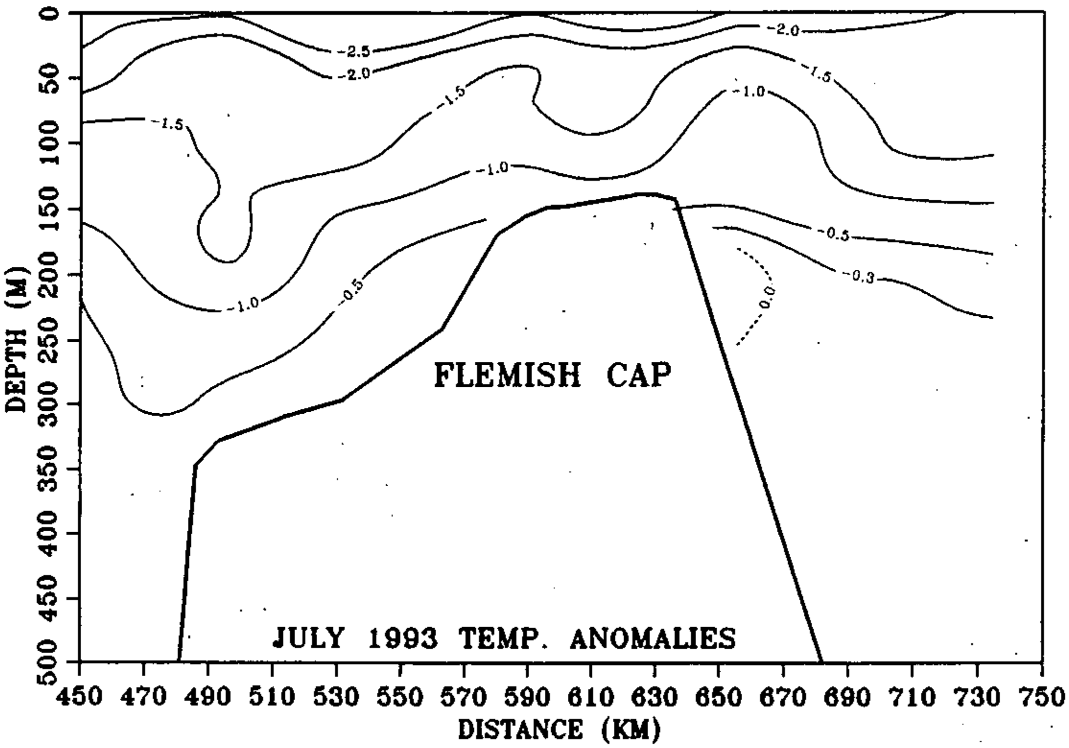


Fig. 4b. Seasonal bottom temperature maps of the Flemish Cap region based on all available historical data from 1961-1990.



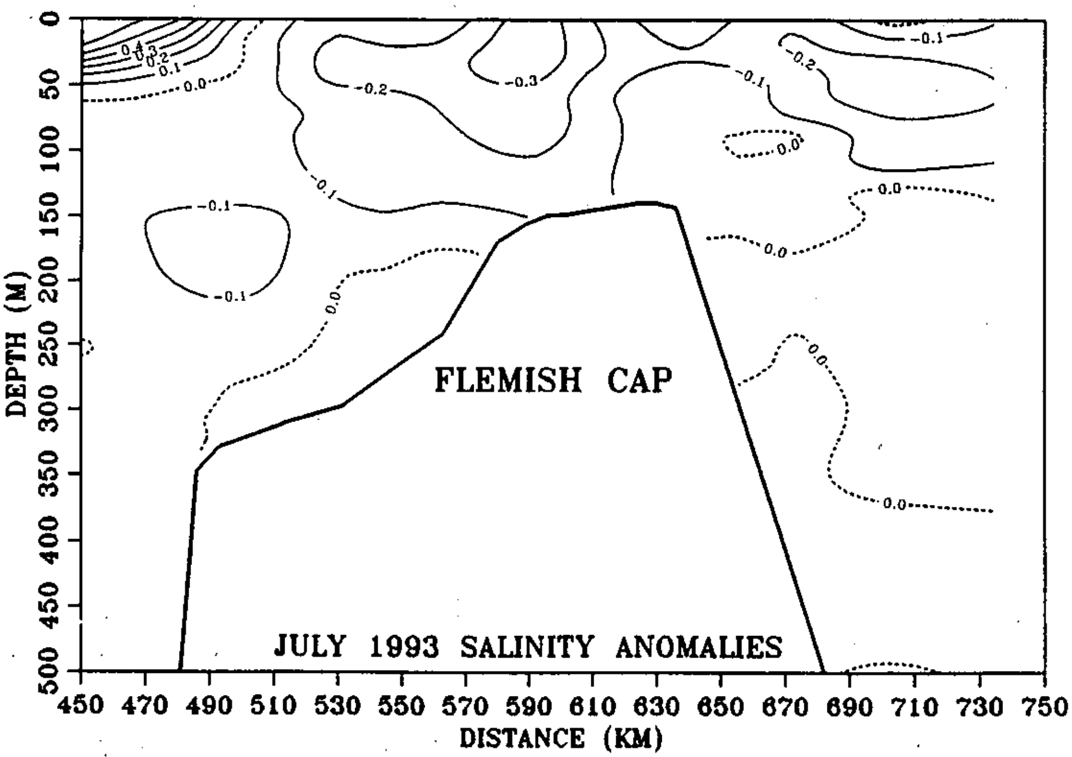
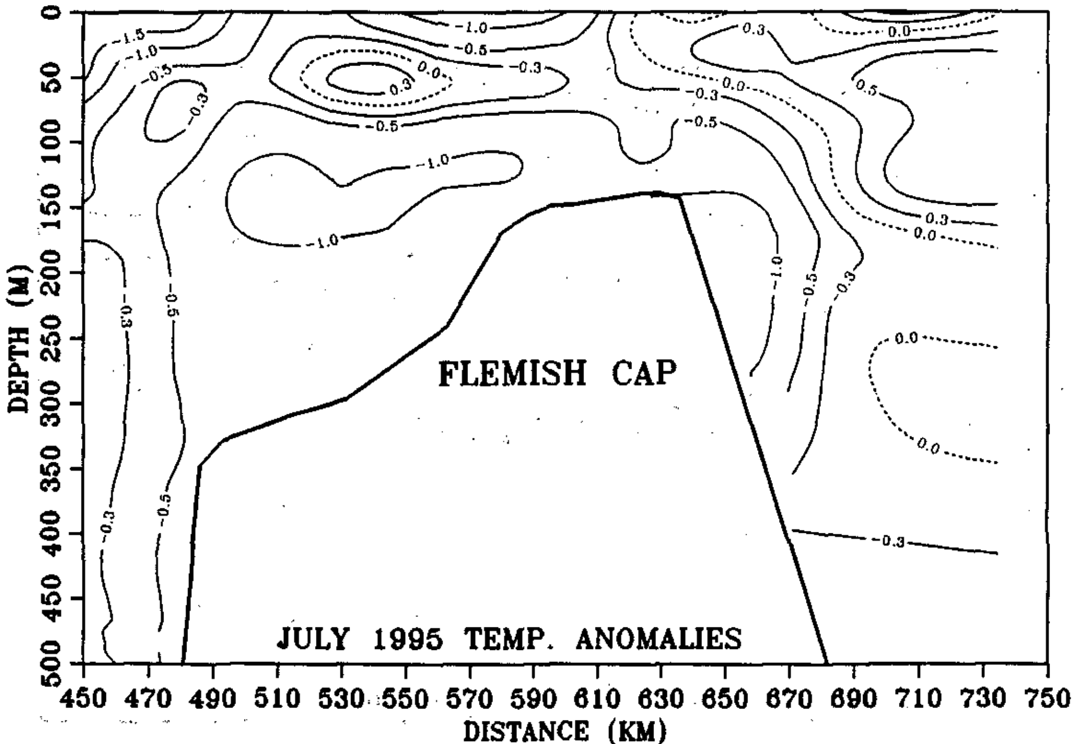


Fig. 5a. The vertical distribution of temperature and salinity anomalies over the Flemish Cap (along 47° N) for July of 1993.



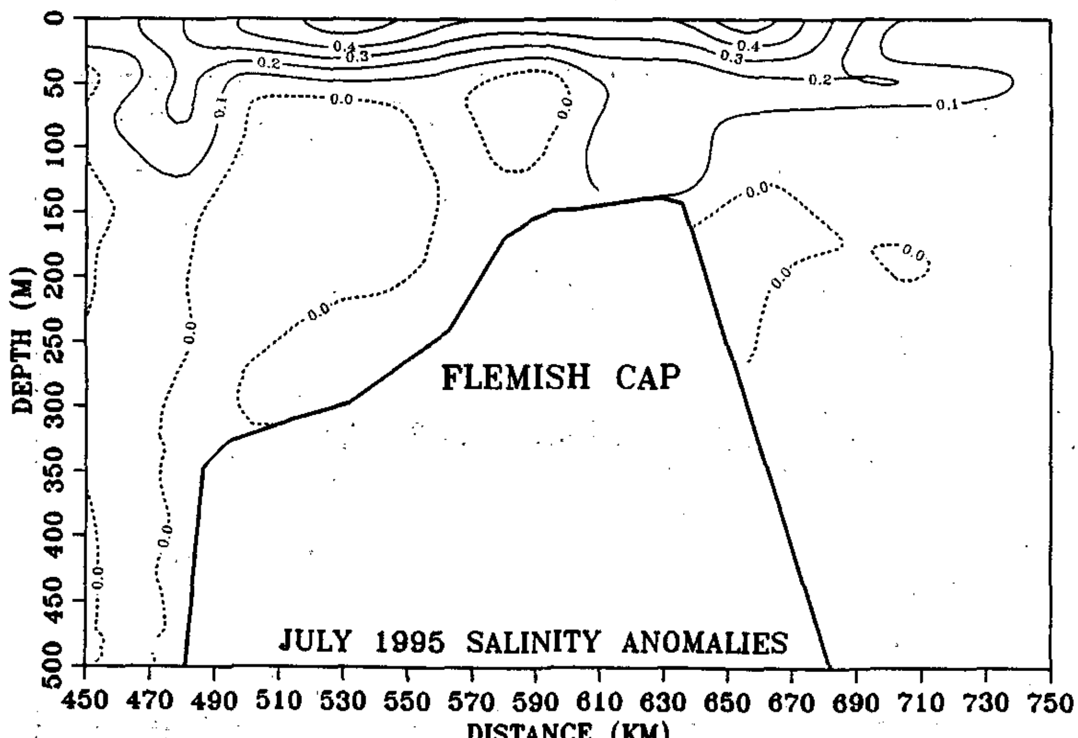


Fig. 5b. The vertical distribution of temperature and salinity anomalies over the Flemish Cap (along 47° N) for July of 1995.

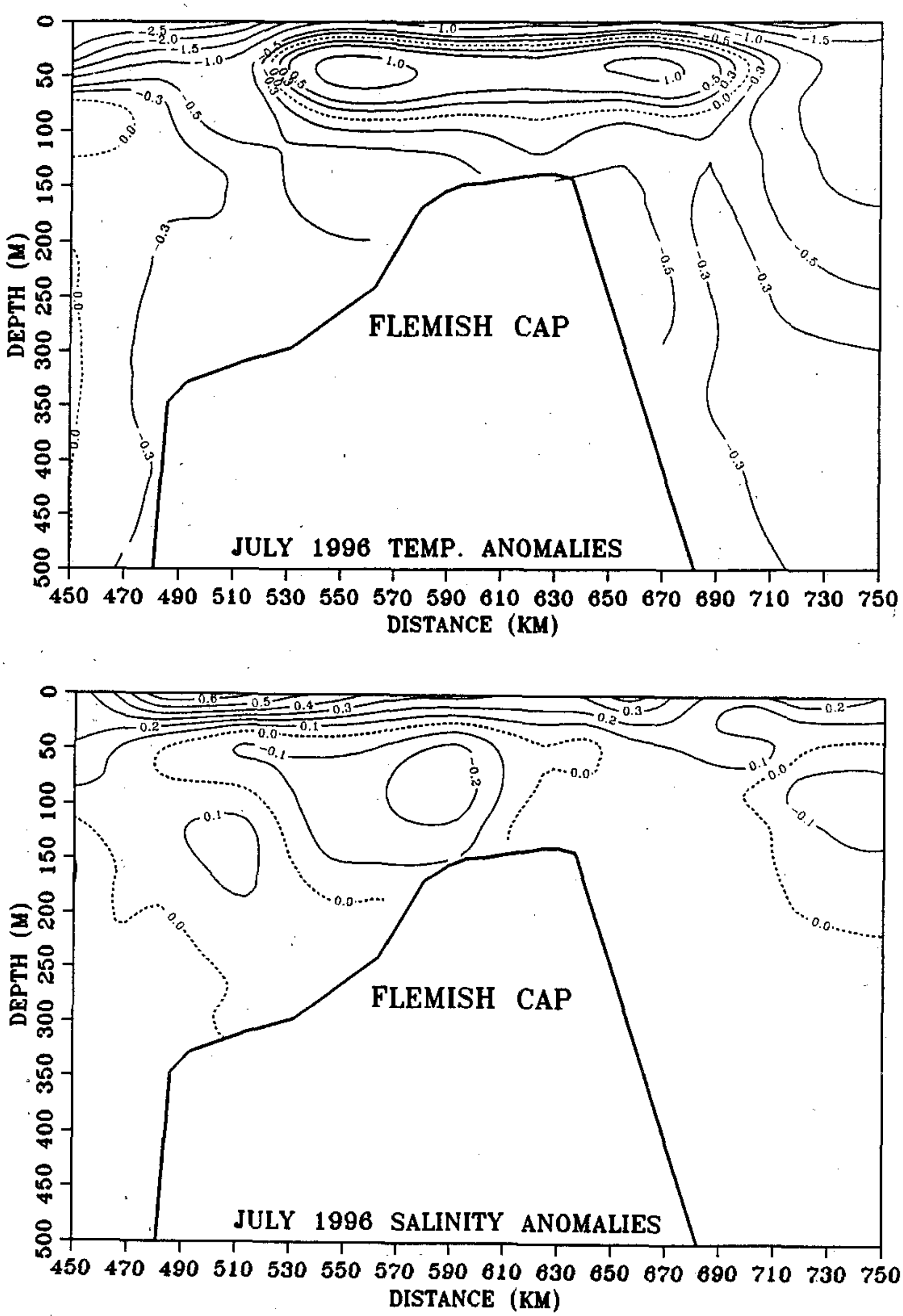


Fig. 5c. The vertical distribution of temperature and salinity anomalies over the Flemish Cap along 47° N) for July of 1996.

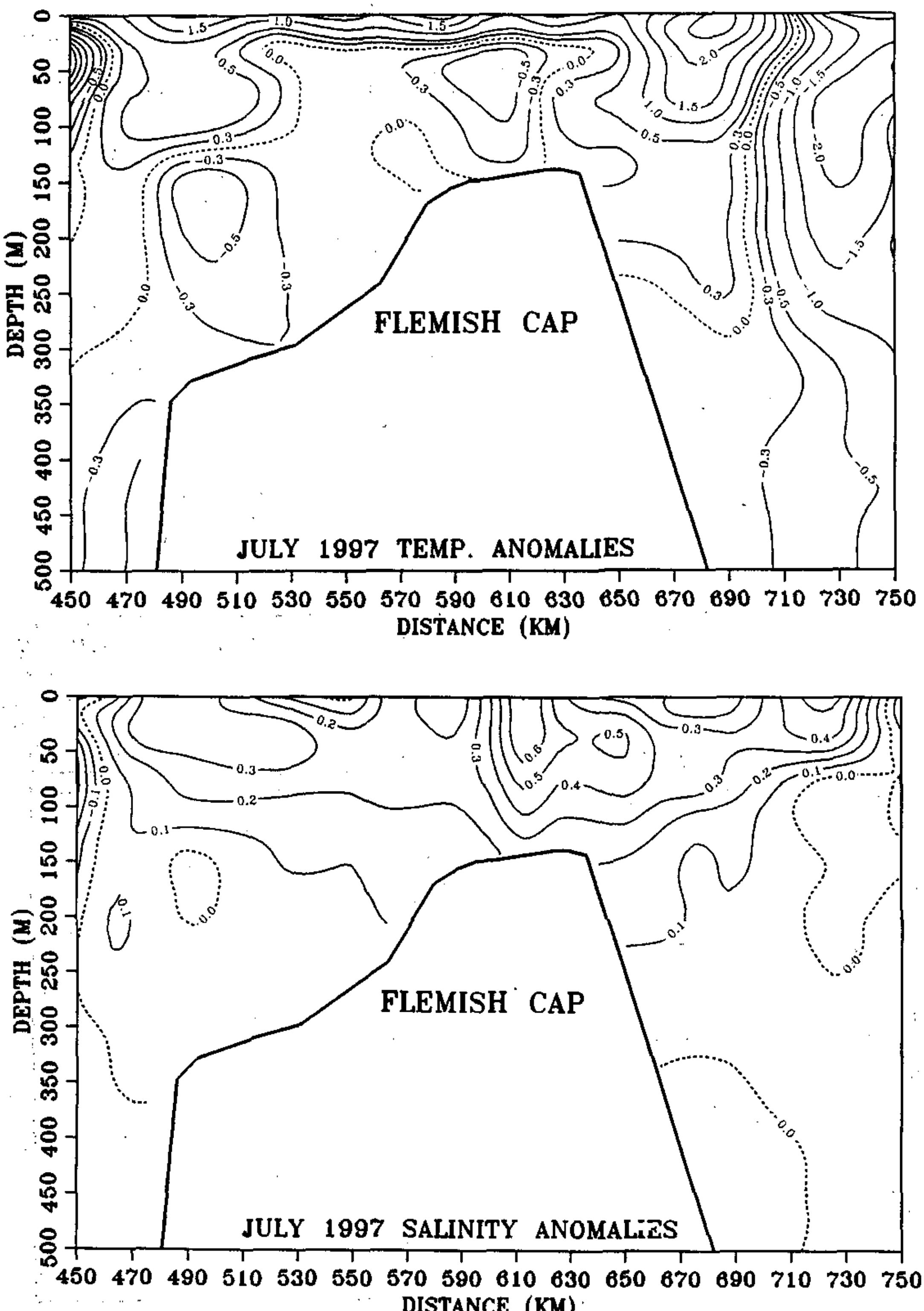


Fig. 5d. The vertical distribution of temperature and salinity anomalies over the Flemish Cap (along 47° N) for July of 1997.

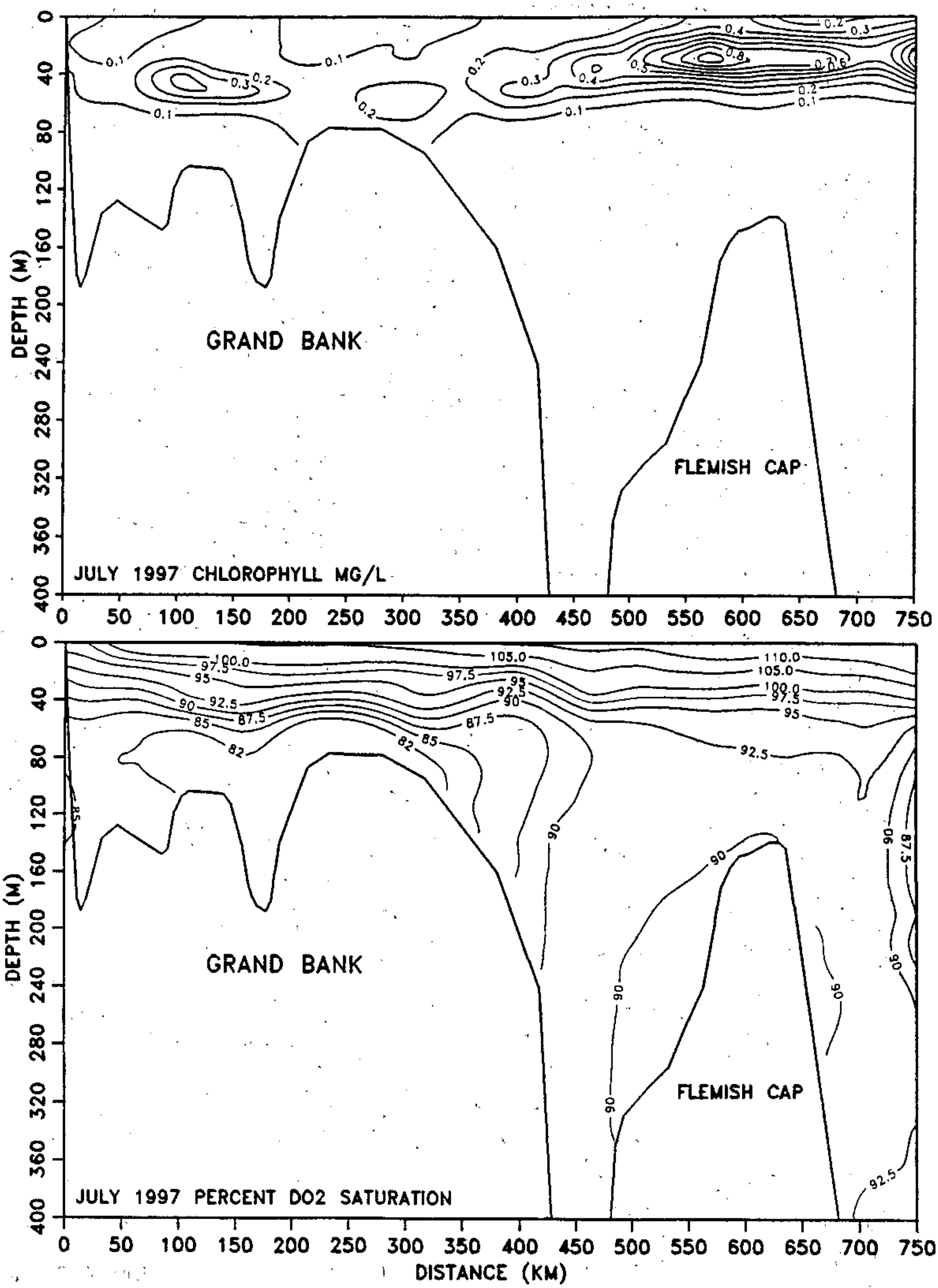


Fig. 5e. The vertical distribution of chlorophyll concentrations and dissolved oxygen along the 47° N transect for July of 1997.

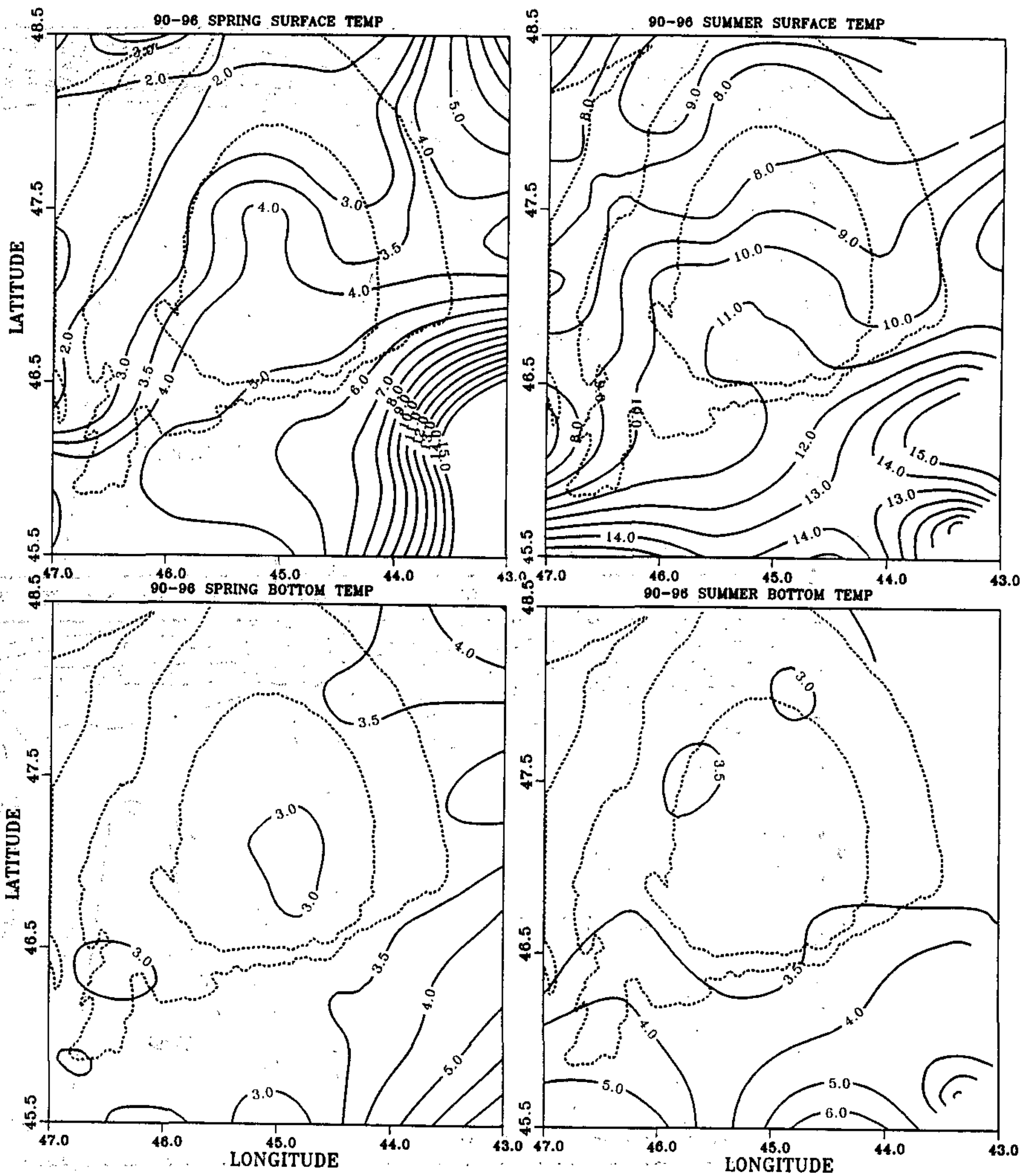


Fig. 6. The spring and summer surface and bottom temperature maps of the Flemish Cap region based on all available data collected between 1990 -1996.

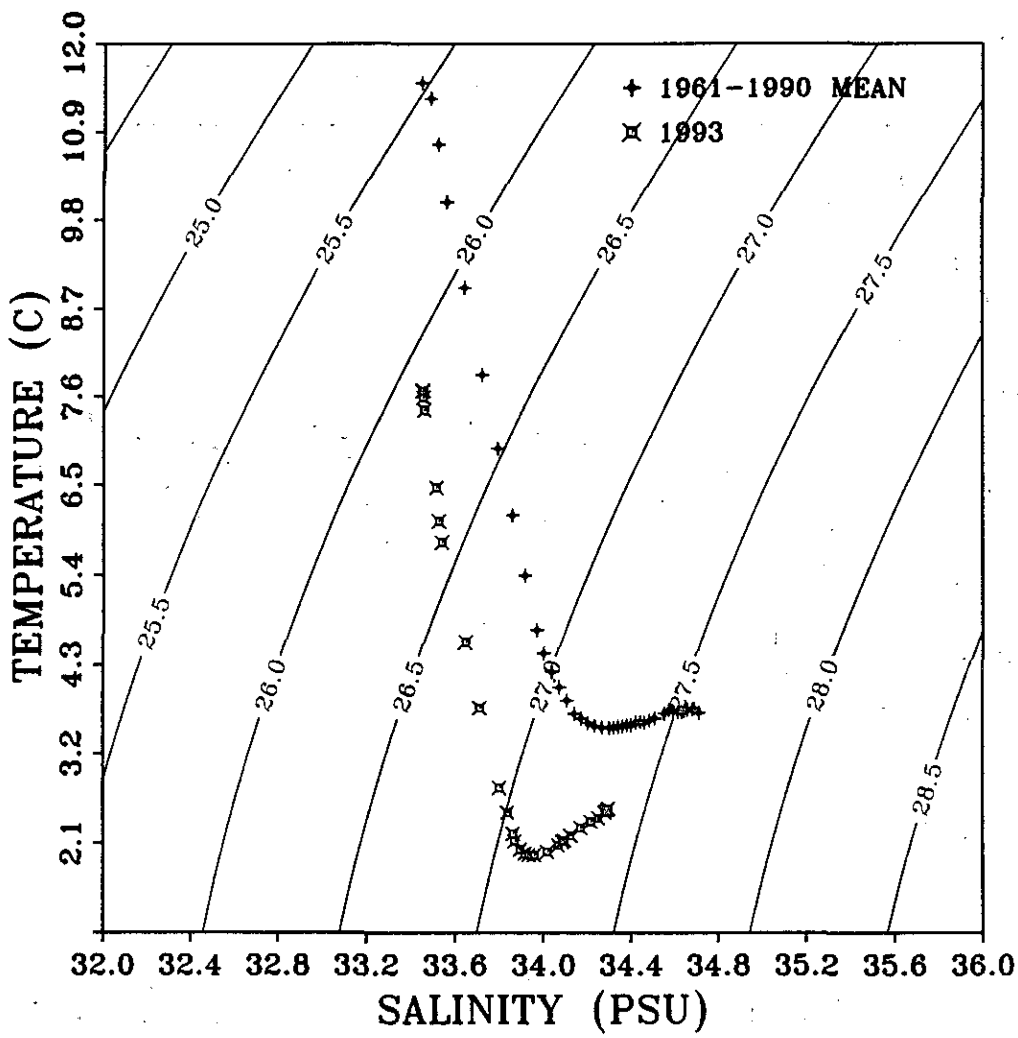


Fig. 7. Temperature-salinity diagram for the Flemish Cap based on the 1961-90 mean and for July of 1993.

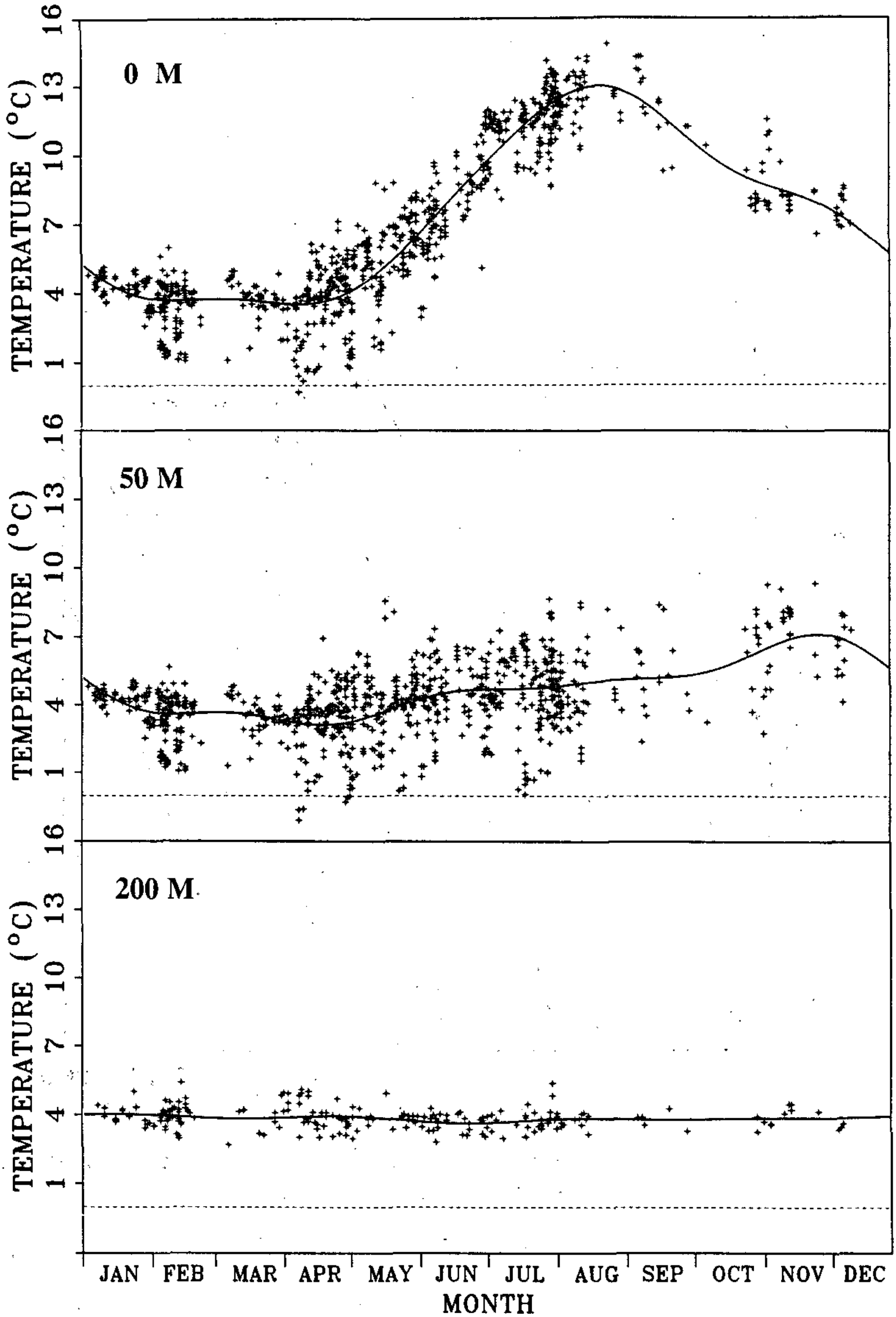
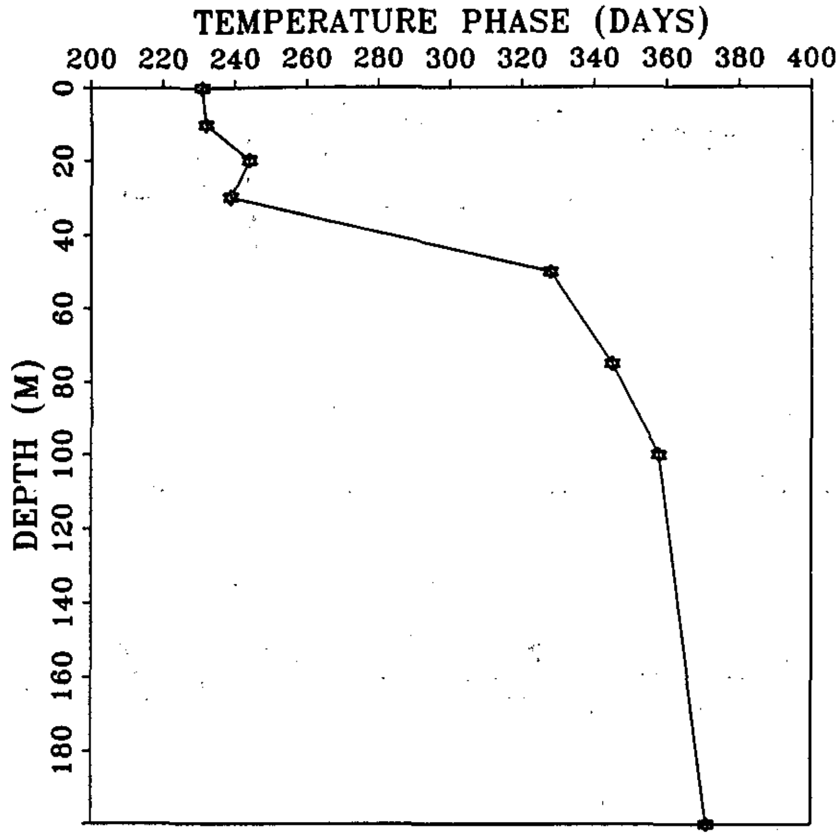


Fig. 8. The Flemish Cap (area FC, Fig. 1a) seasonal temperature cycle at depths of 0, 50 and 200 m.



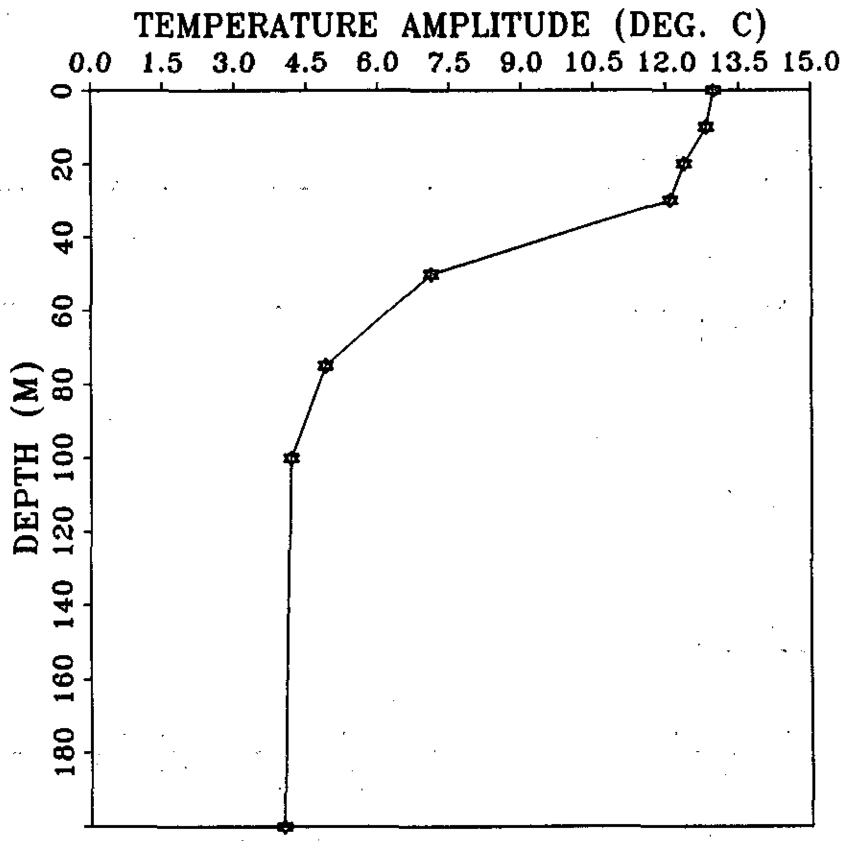


Fig. 9. The phase and amplitude of the seasonal temperature cycle for area FC of Fig. 1a on the Flemish Cap.

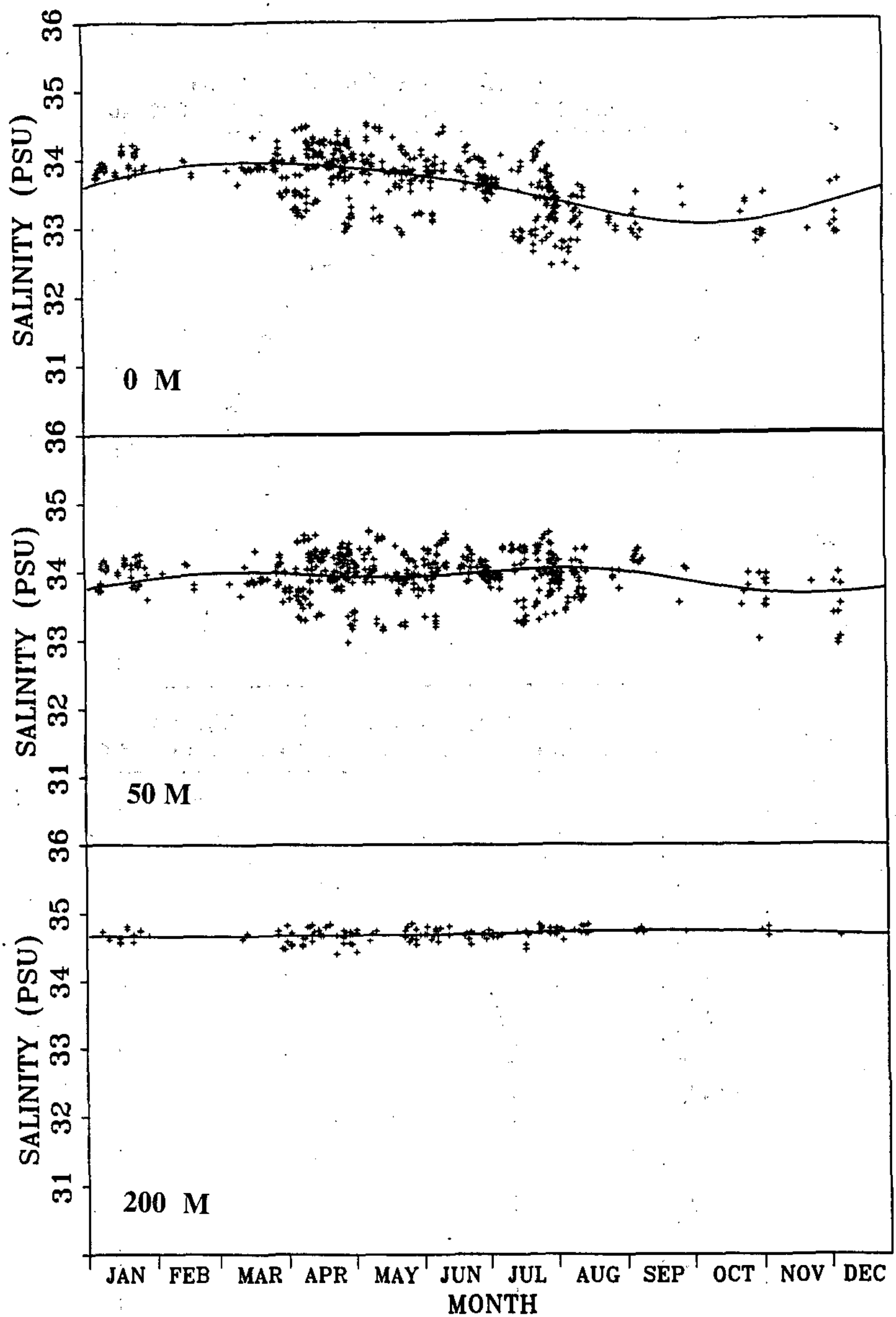


Fig. 10. The Flemish Cap (area FC, Fig. 1a) seasonal salinity cycle at depths of 0, 50 and 200 m.

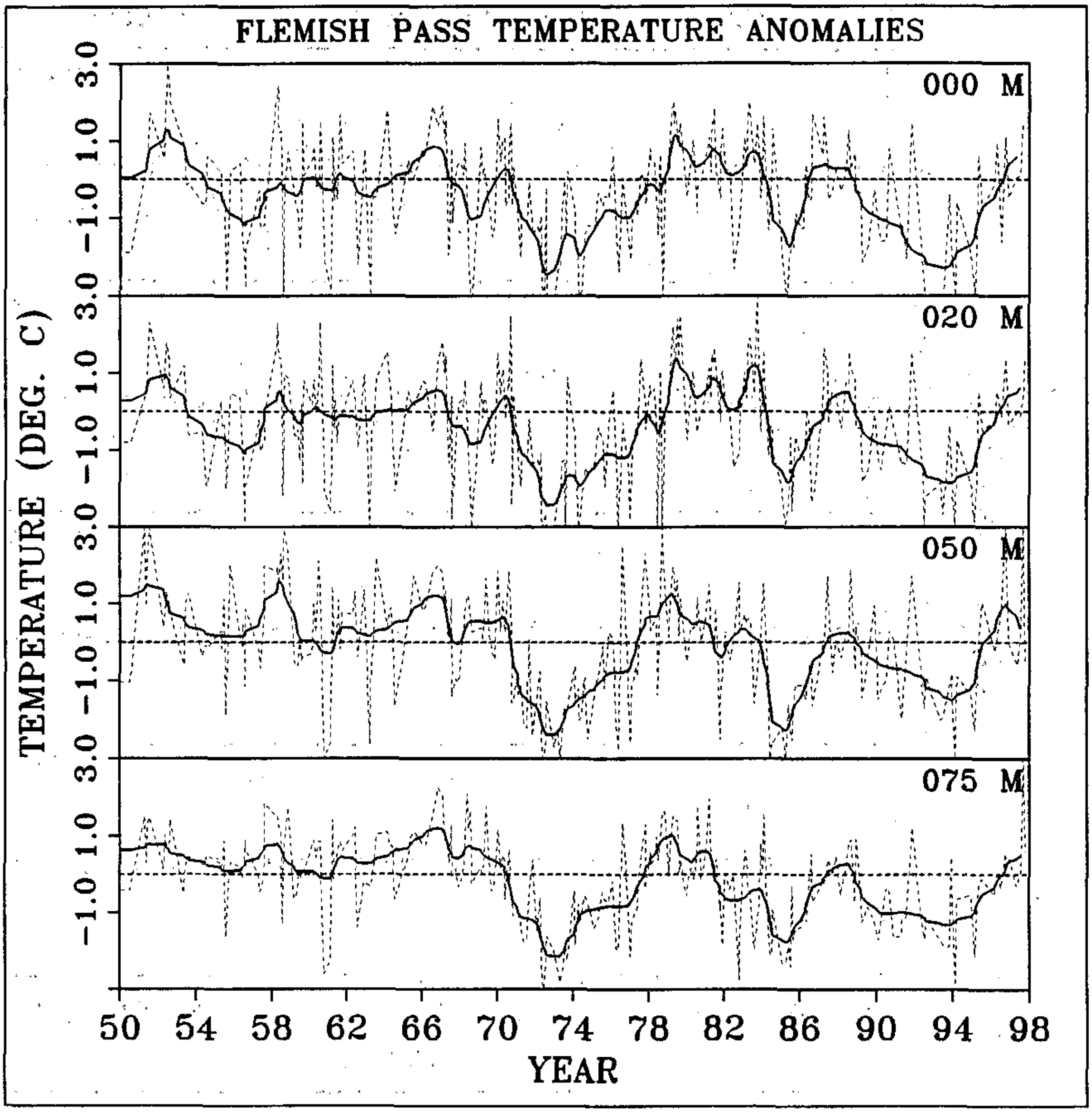


Fig. 11a. Time series of temperature anomalies in the Flemish Pass (area FP, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

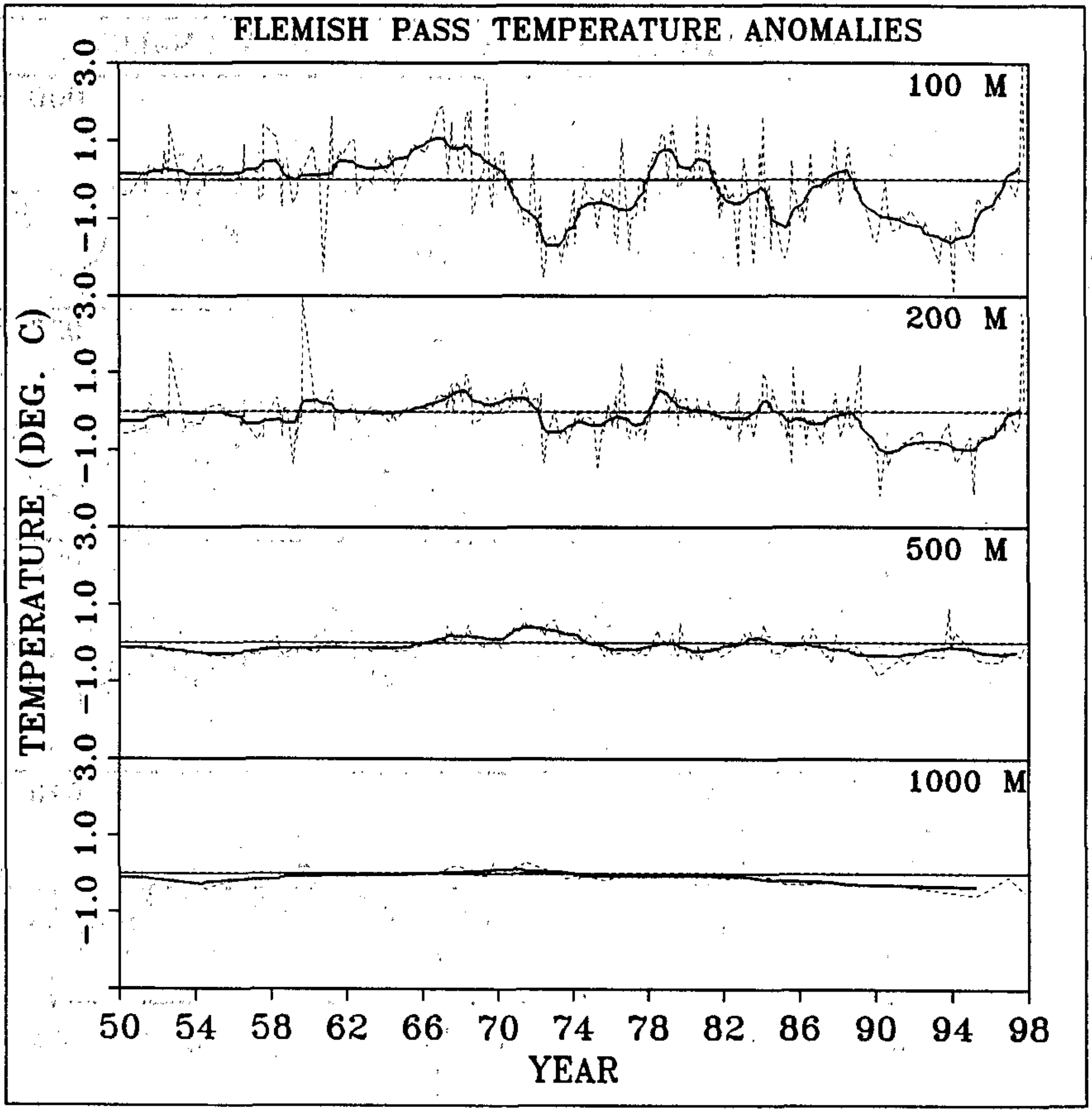


Fig. 11b. Time series of temperature anomalies in the Flemish Pass (area FP, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

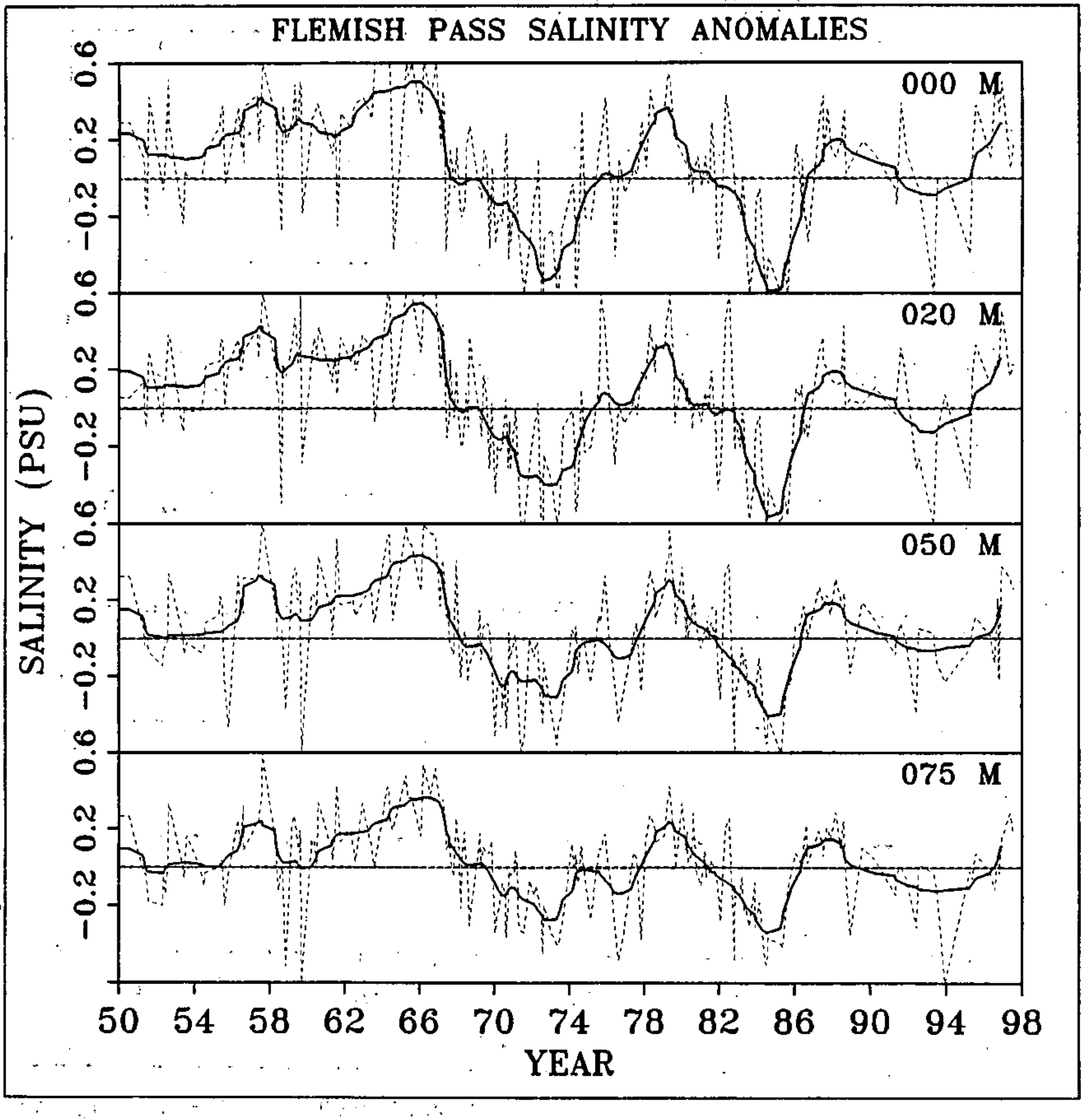


Fig. 11c. Time series of salinity anomalies in the Flemish Pass (area FP, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

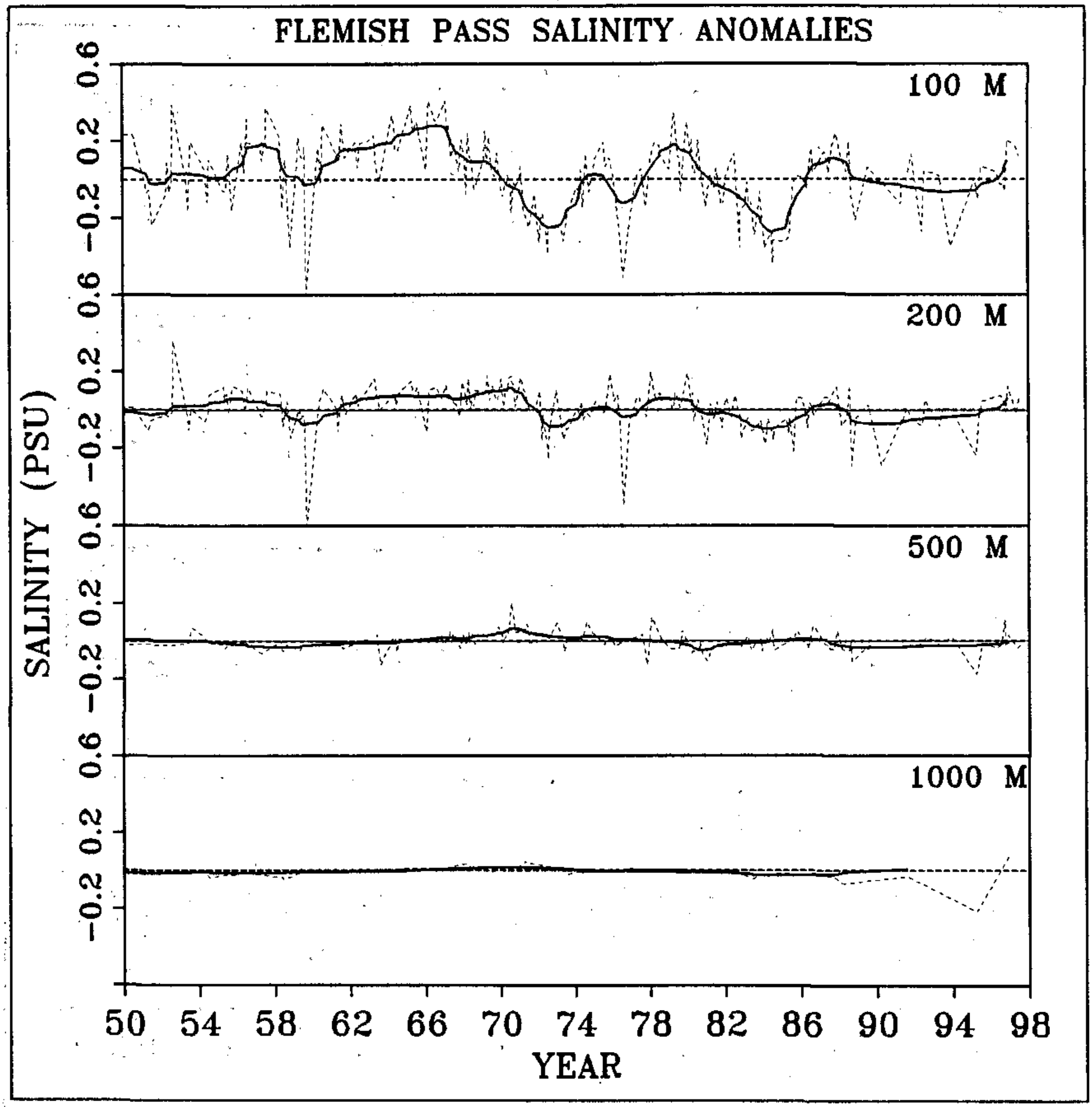


Fig. 11d. Time series of salinity anomalies in the Flemish Pass (area FP, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

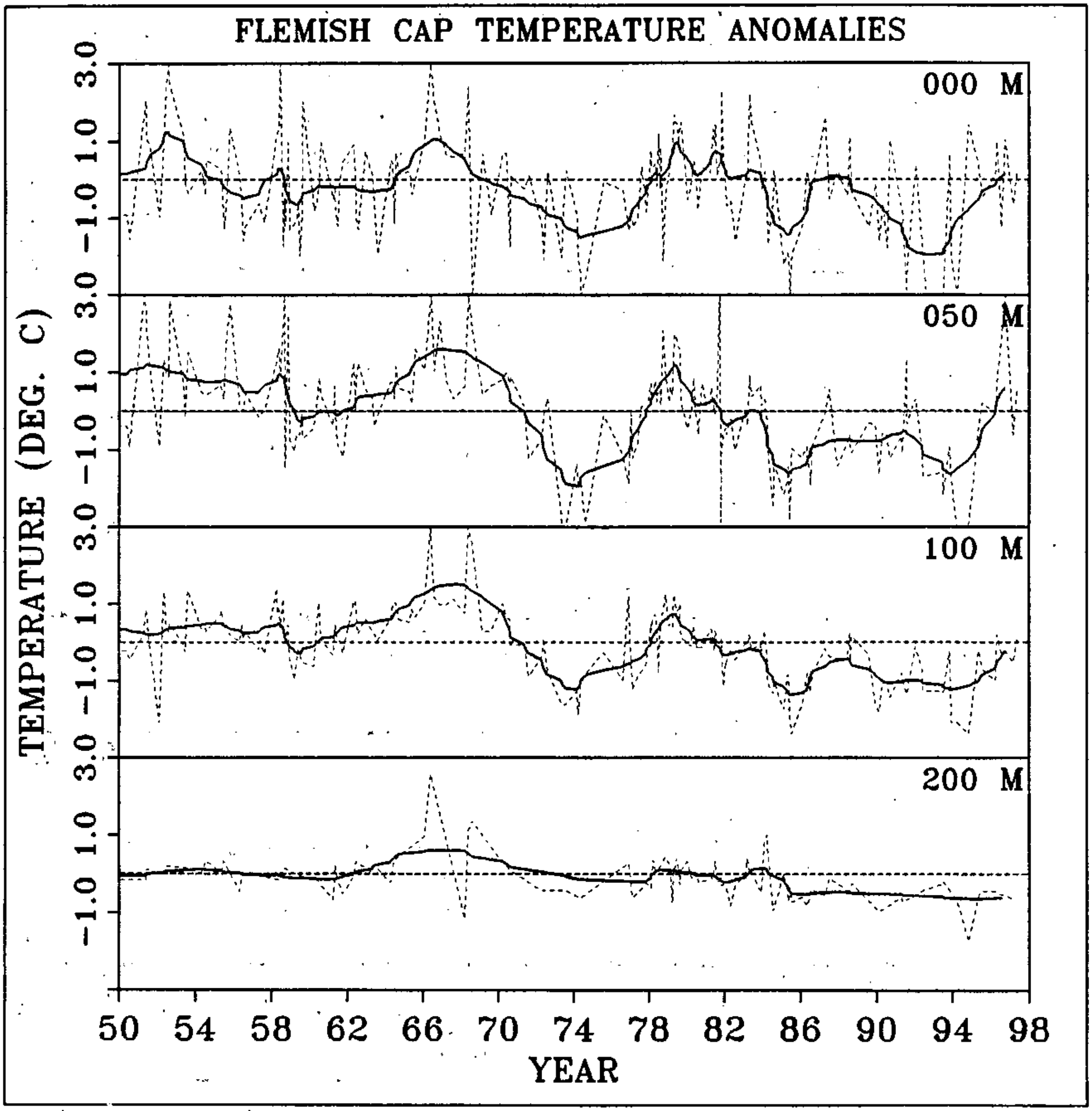


Fig. 12a. Time series of temperature anomalies on the Flemish Cap (area FC, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

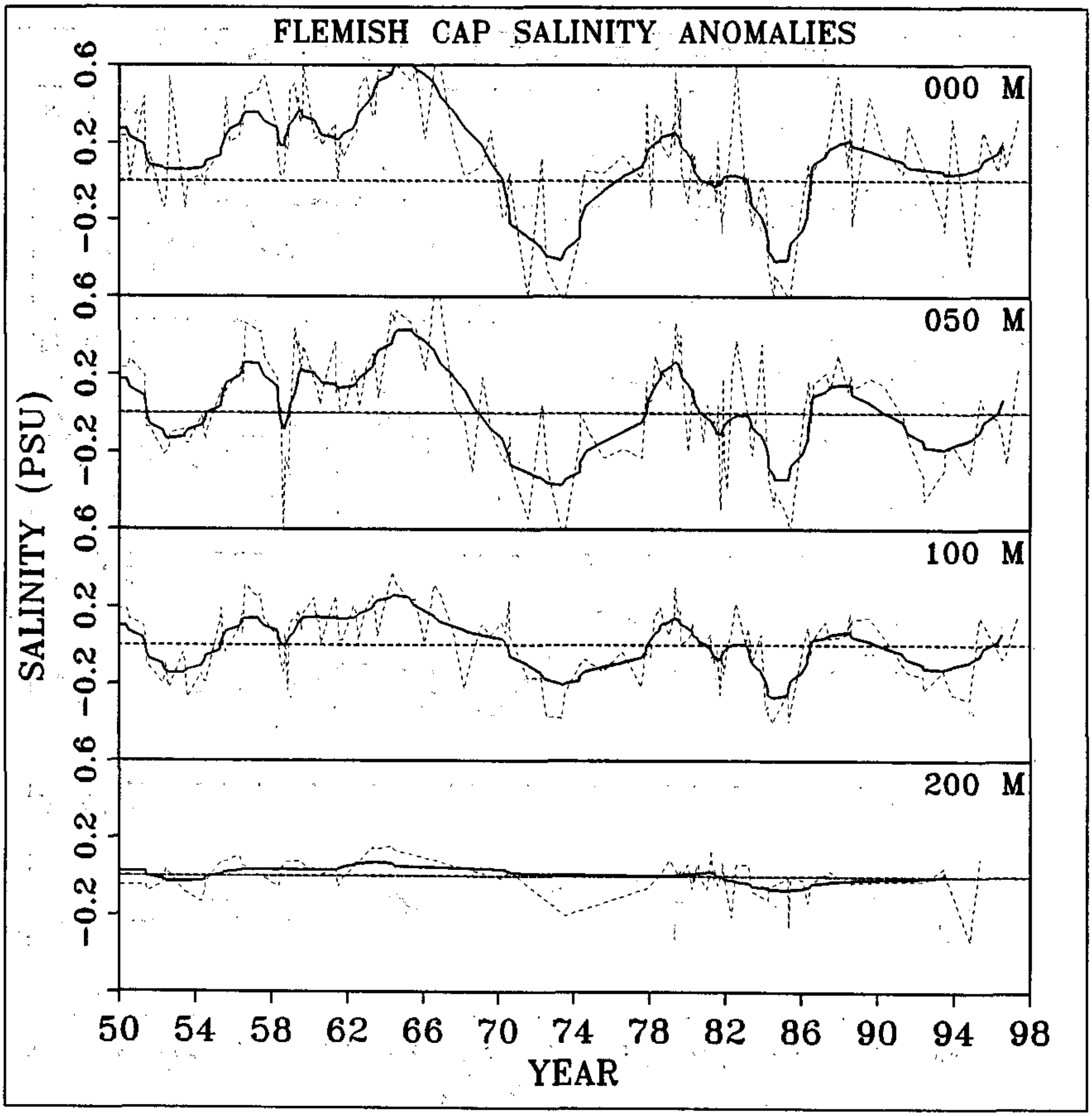


Fig. 12b. Time series of salinity anomalies on the Flemish Cap (area FC, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

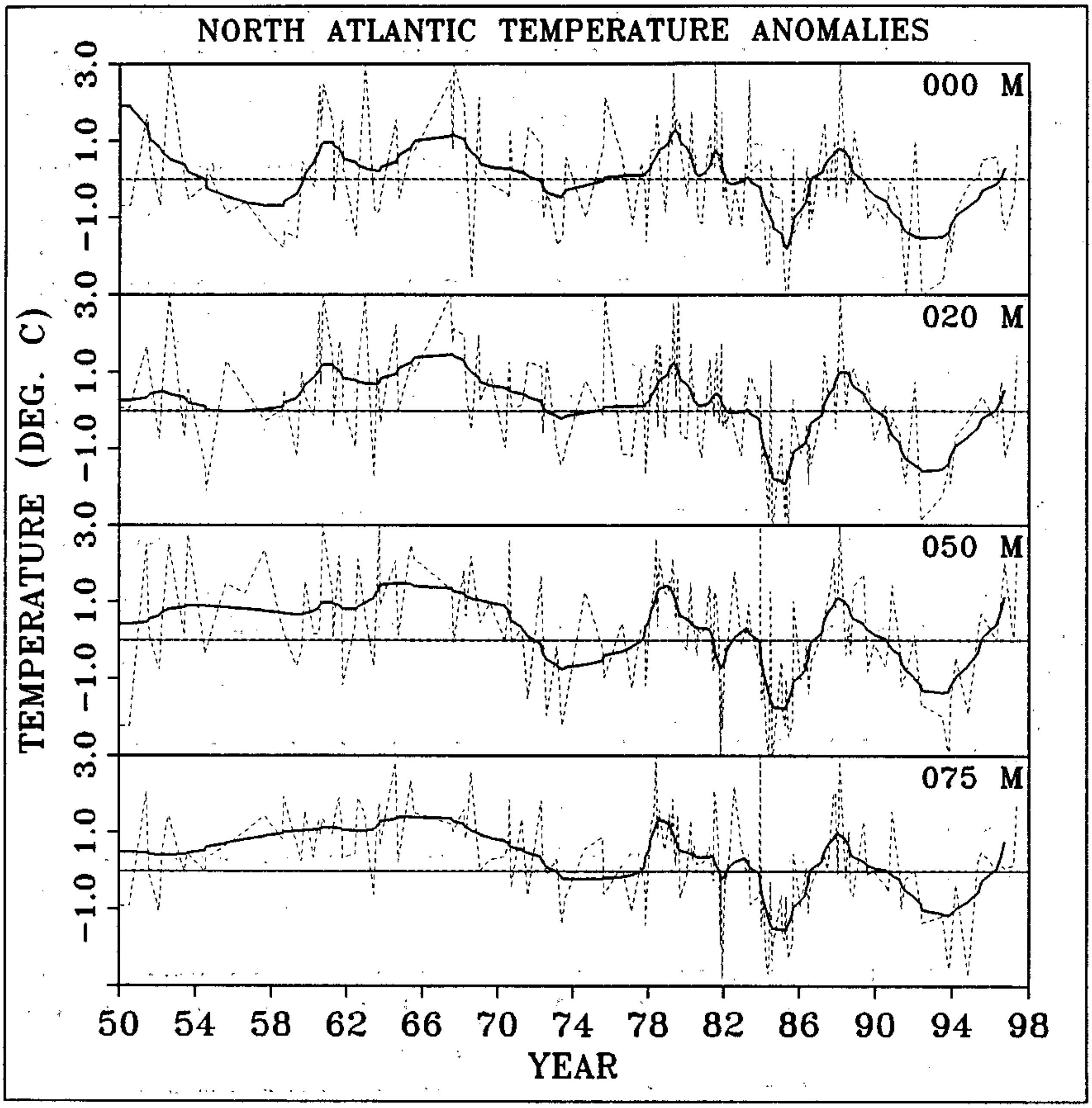


Fig. 13a. Time series of temperature anomalies east of the Flemish Cap (area NA, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

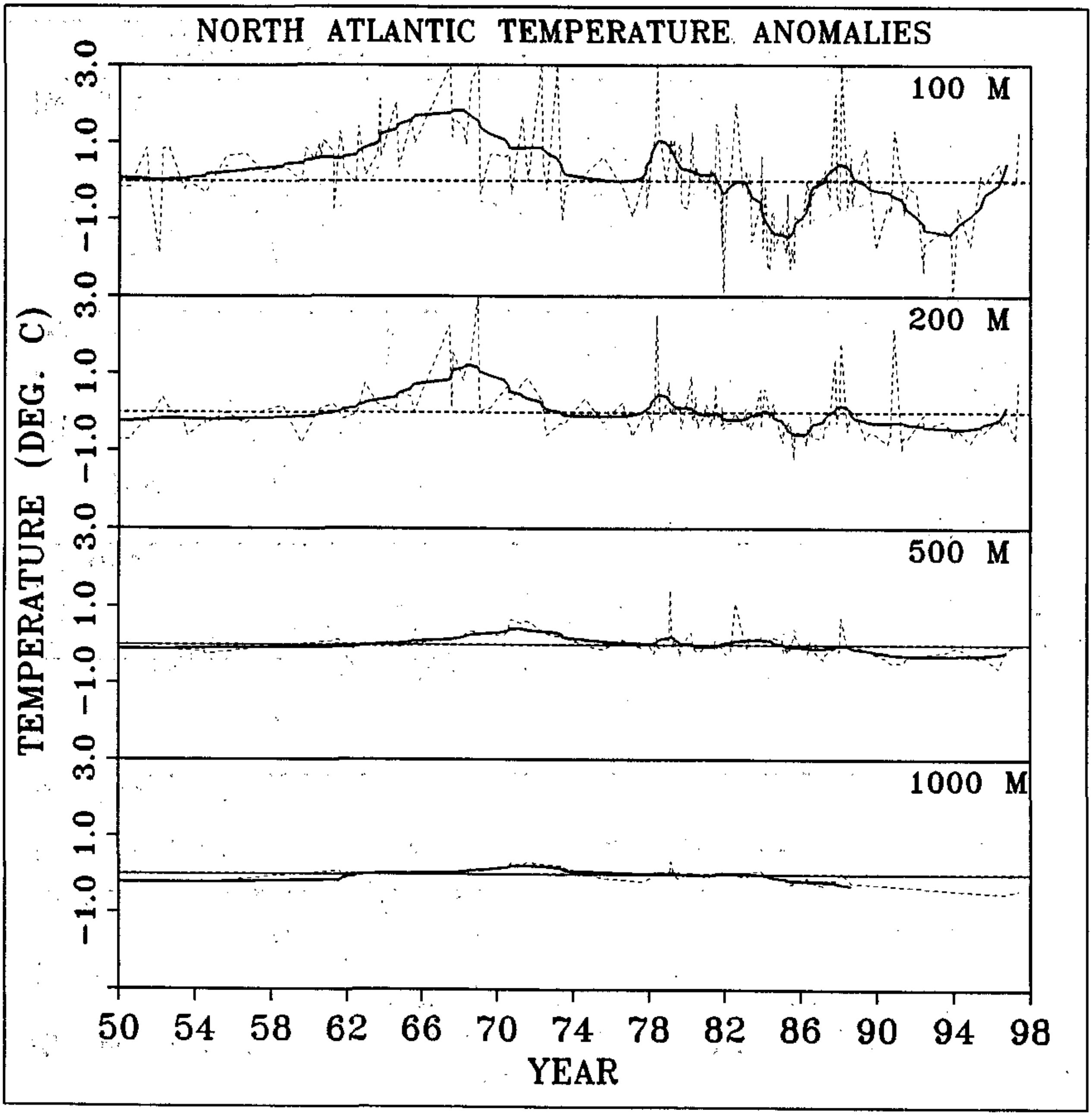


Fig. 13b. Time series of temperature anomalies east of the Flemish Cap (area NA, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

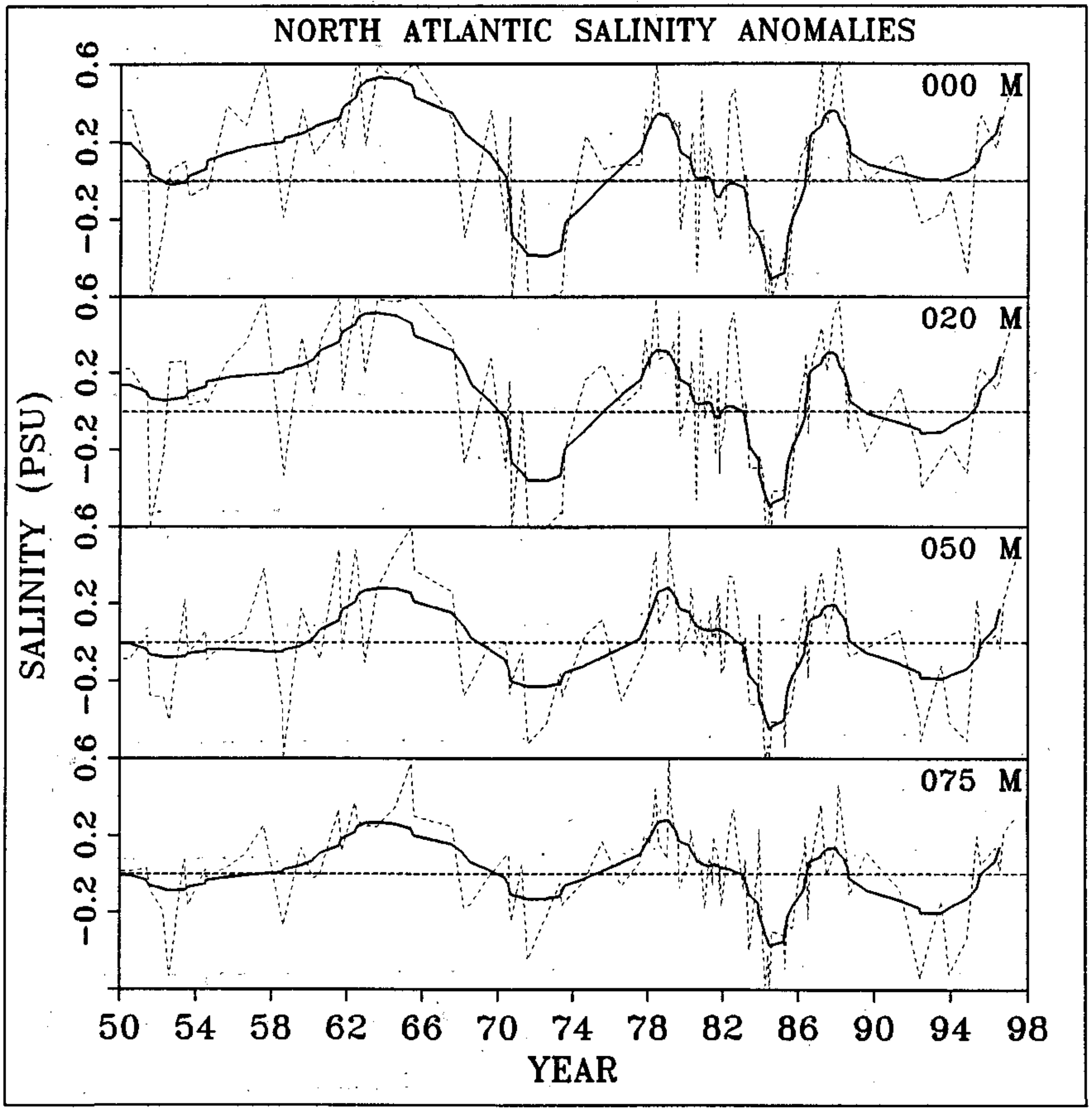


Fig. 13c. Time series of salinity anomalies east of the Flemish Cap (area NA, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

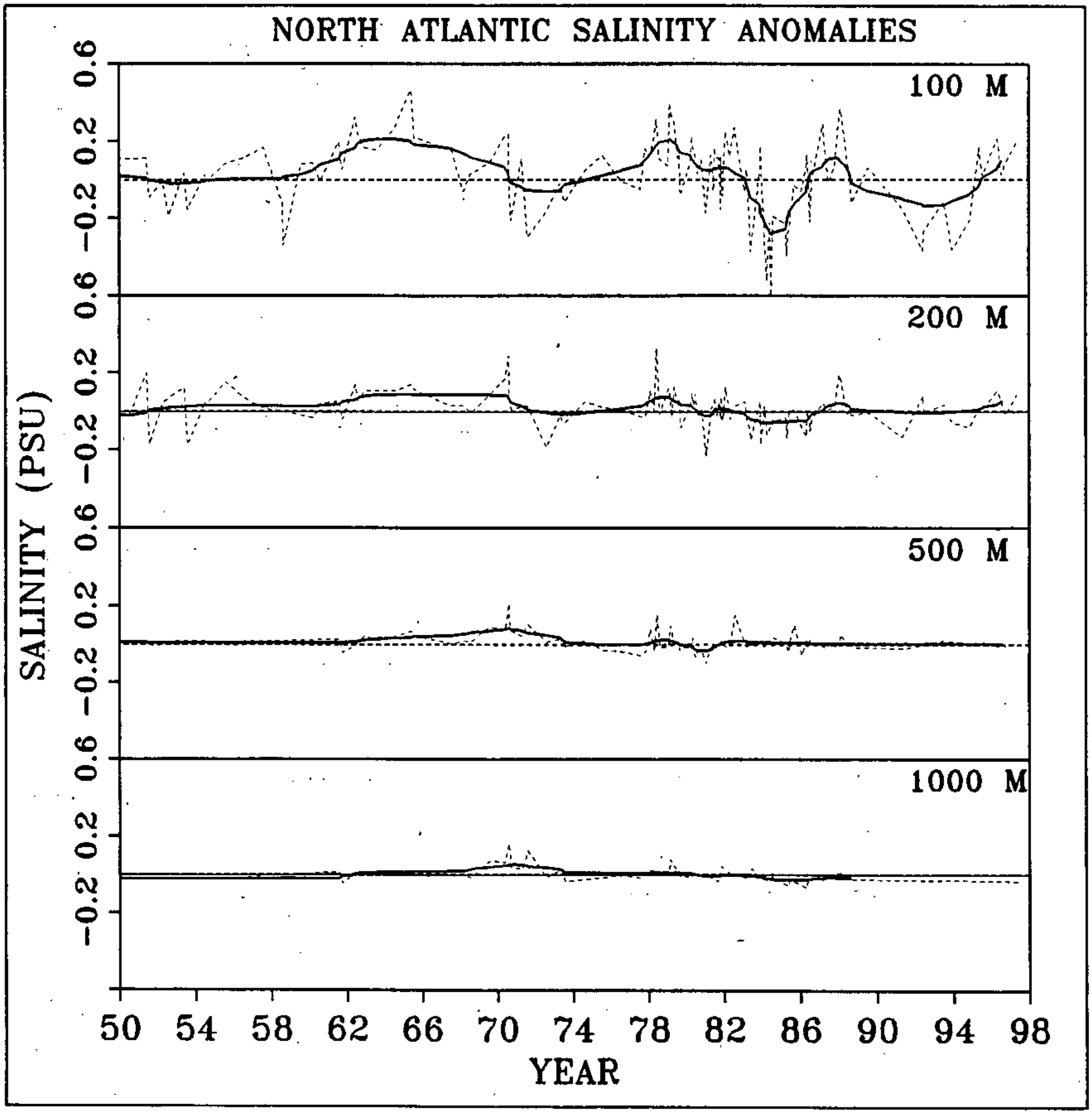


Fig. 13d. Time series of salinity anomalies east of the Flemish Cap (area NA, Fig. 1a) at standard depths. The dashed lines are the monthly values and the heavy line represents the long-term trend.

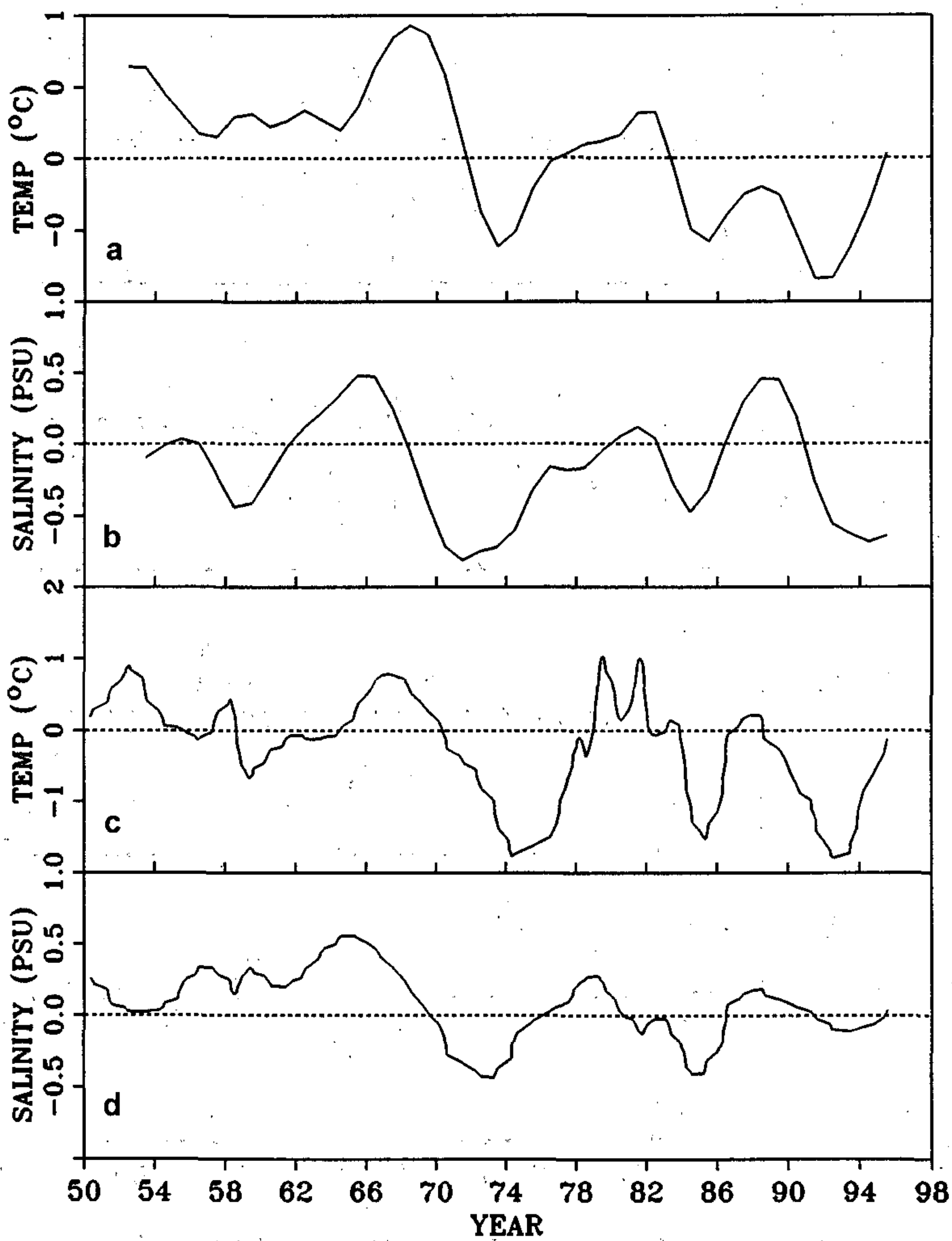


Fig. 14. Low-passed filtered time series of Station 27 vertically averaged (a) temperature and (b) salinity and the Flemish Cap upper layer (c) temperature and (d) salinity anomalies.

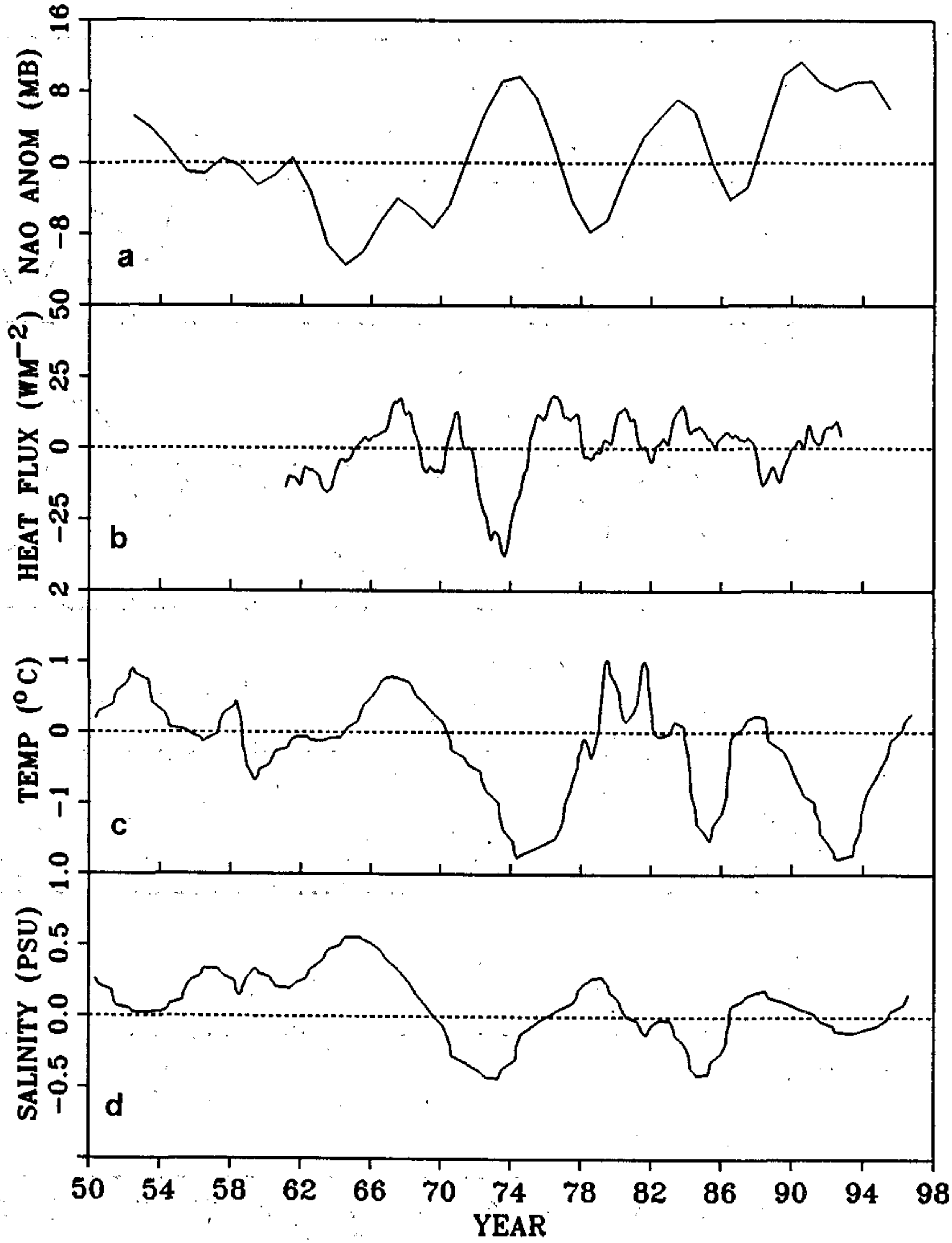


Fig. 15. Low-passed filtered time series of (a) the North Atlantic Oscillation Index (NAO) anomalies, (b) the Flemish Cap monthly air-sea heat flux anomalies and (c) the Flemish Cap upper layer temperature and salinity anomalies.

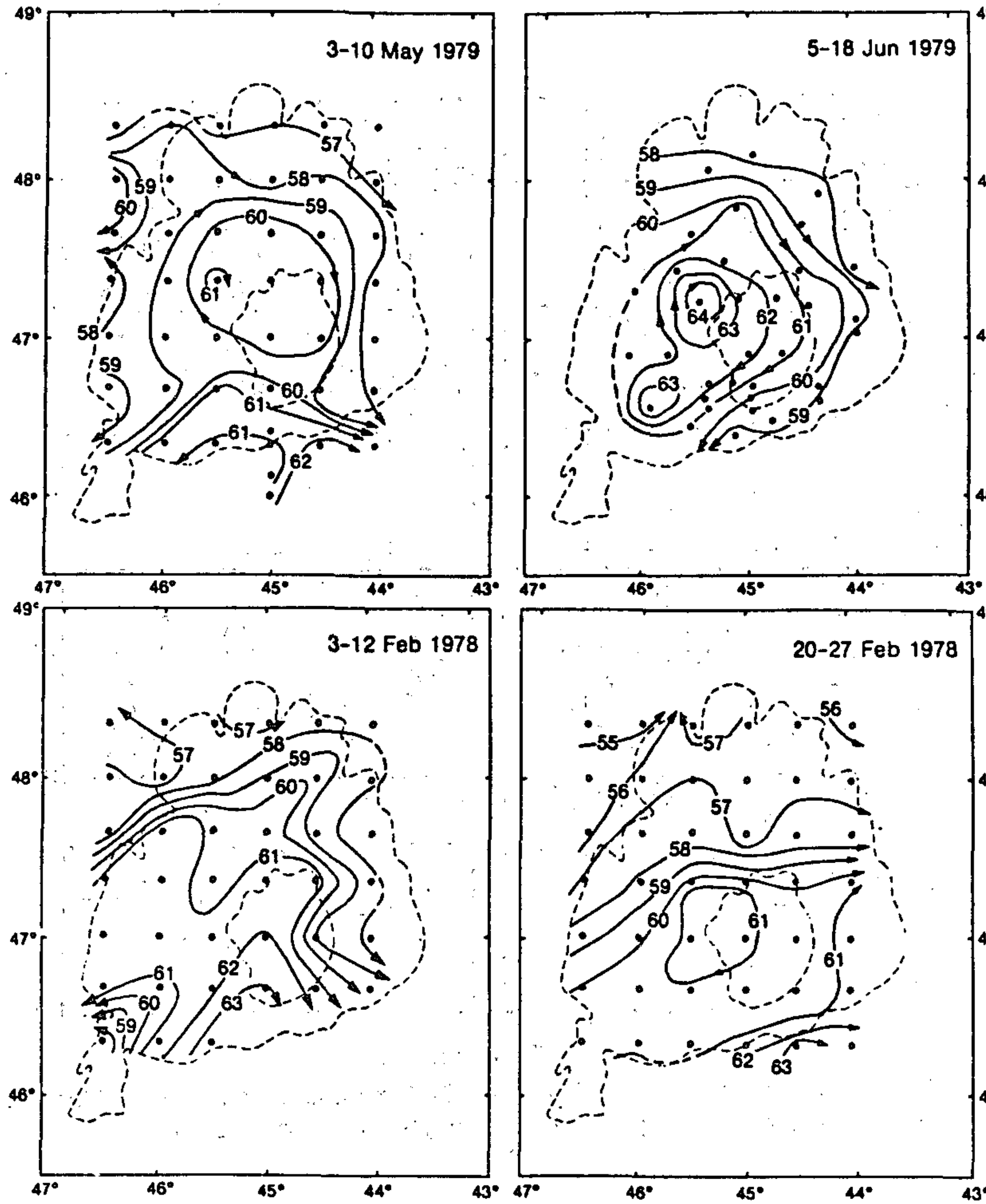


Fig. 16. Geostrophic circulation over the Flemish Cap for the winter of 1978 and spring of 1979 (adapted from Kudlo et al. 1984).

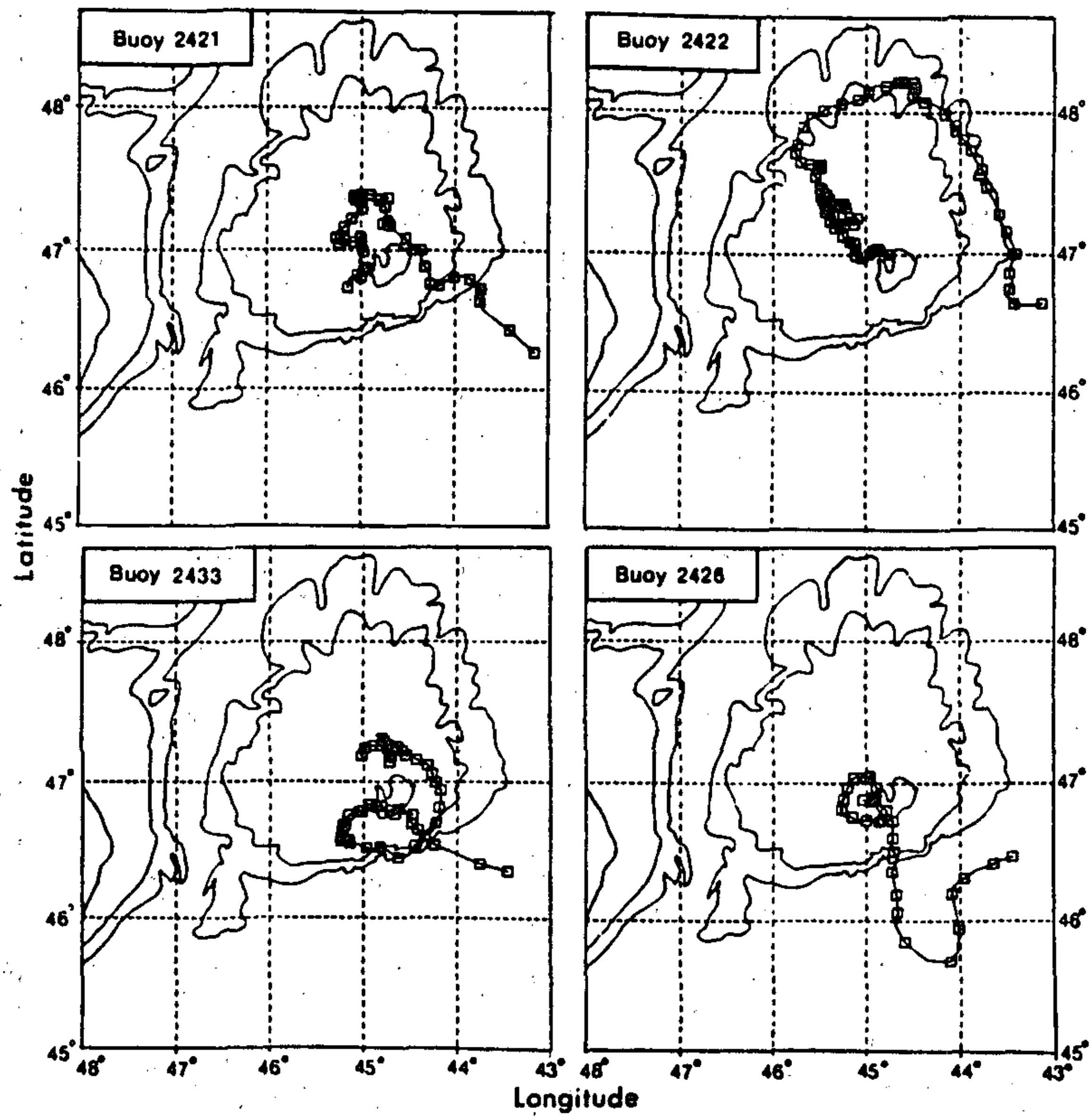


Fig. 17. Drift tracks of buoys drogued at 2-10 m depth on the Flemish Cap during winter and spring of 1979-80 (adapted from Ross 1981).

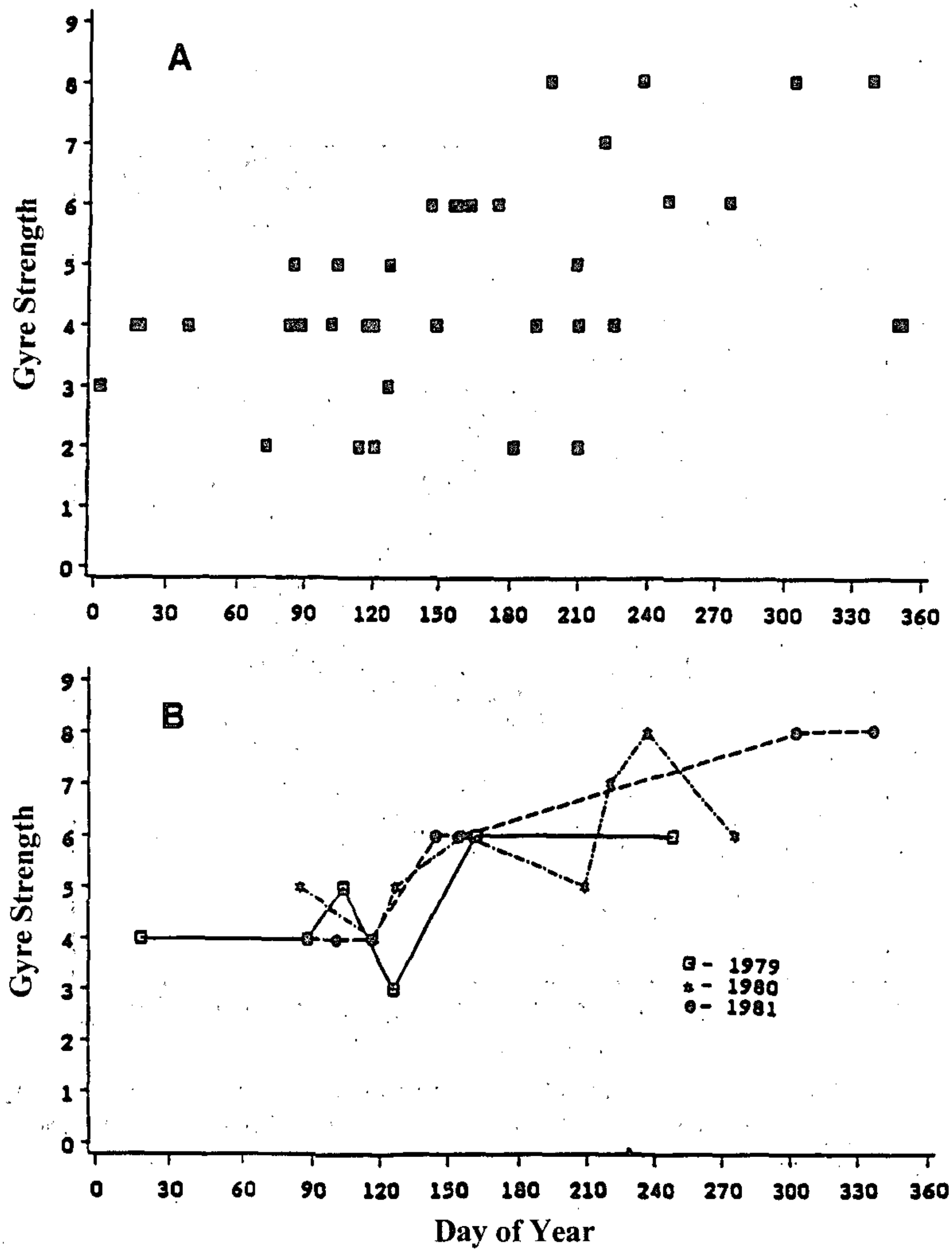


Fig. 18. Relative gyre strength over the Flemish Cap based on the geostrophic circulation charts produced by the U.S.S.R. studies and published by Kudlo et al. 1984 (adapted from Anderson 1992). Panel (*a*) shows the entire data set and panel (*b*) shows variations among specific years.

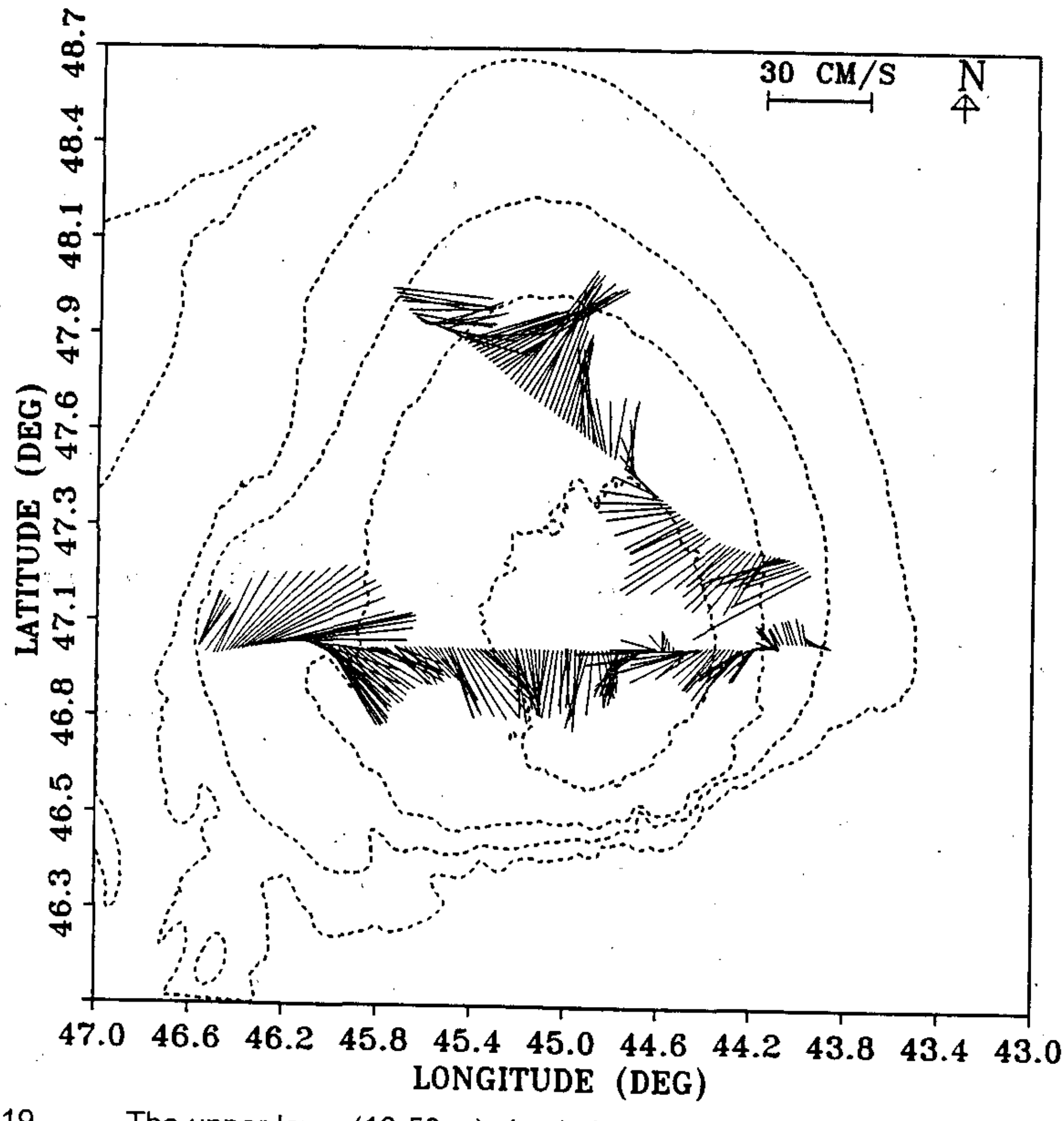


Fig. 19. The upper layer (10-50 m) circulation around the Flemish Cap during July of 1996 measured with a ship mounted acoustic Doppler current profiler (ADCP).

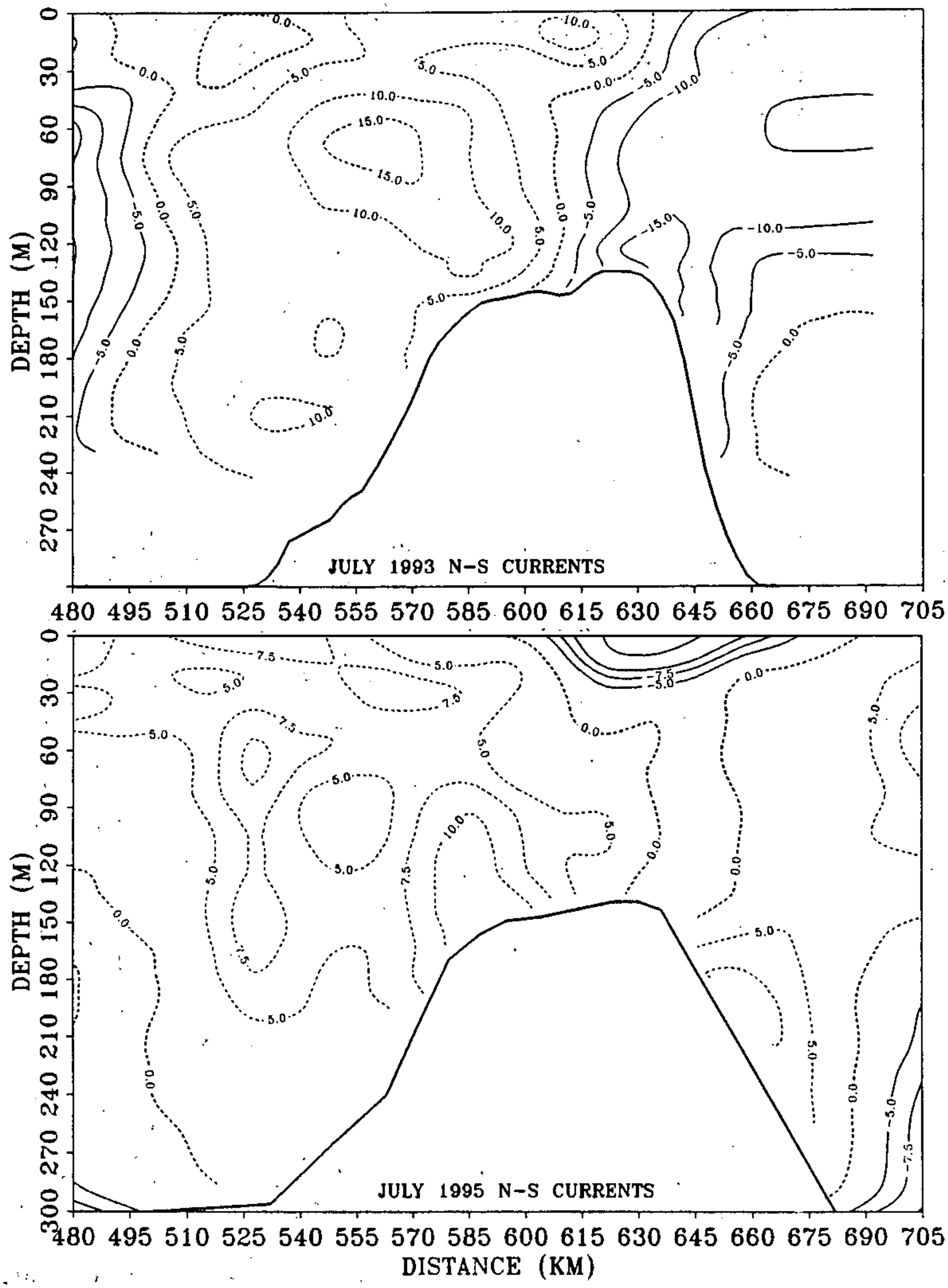


Fig. 20a. A vertical cross-section of the north-south current field (cm/s) over the Flemish Cap along 47° N during July 1993 and 1995 measured with a ship mounted ADCP. Negative currents are southward, positive currents northward.

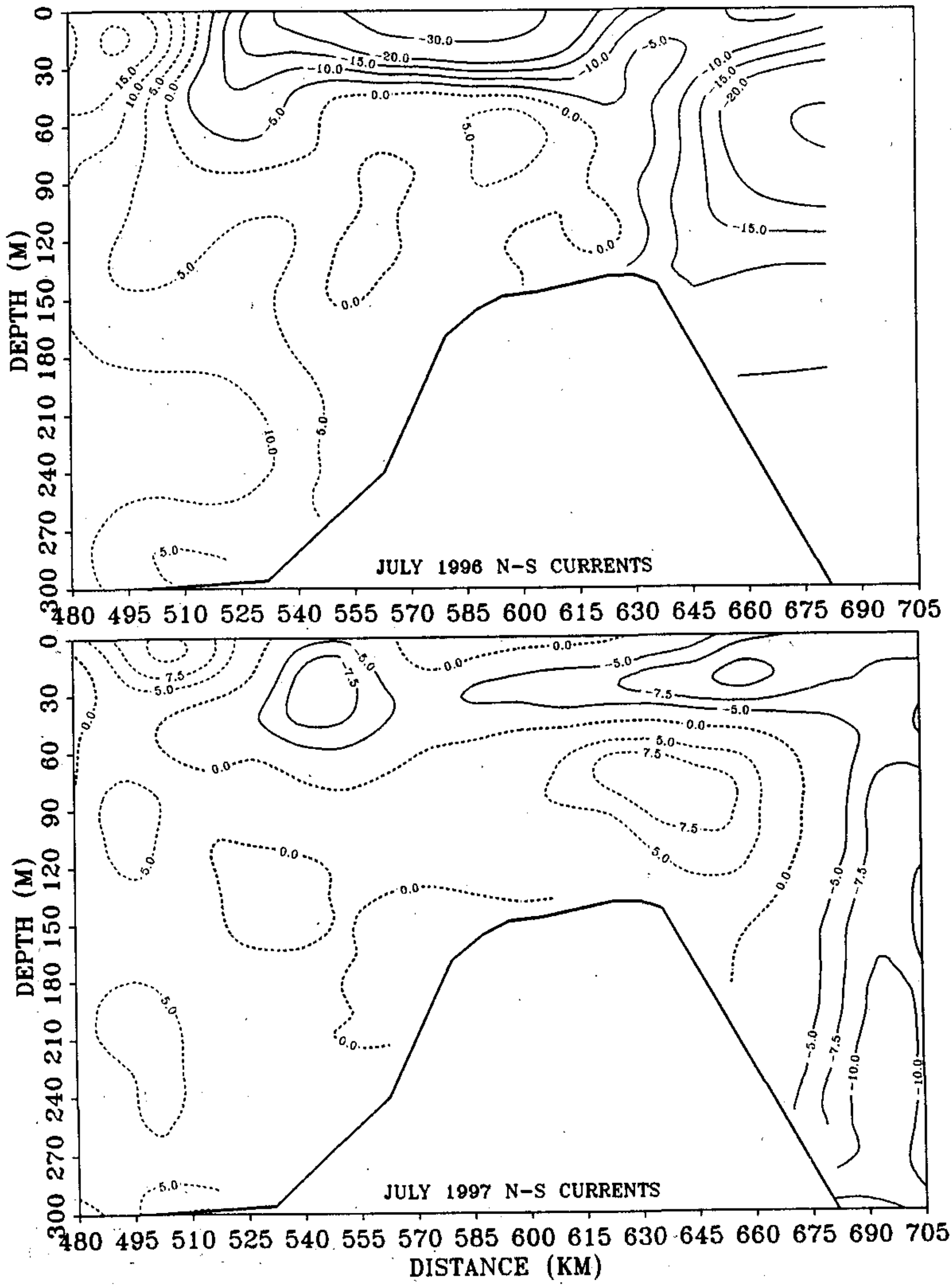


Fig. 20b. A vertical cross-section of the north-south current field (cm/s) over the Flemish Cap along 47° N during July 1996 and 1997 measured with a ship mounted ADCP. Negative currents are southward, positive currents northward.

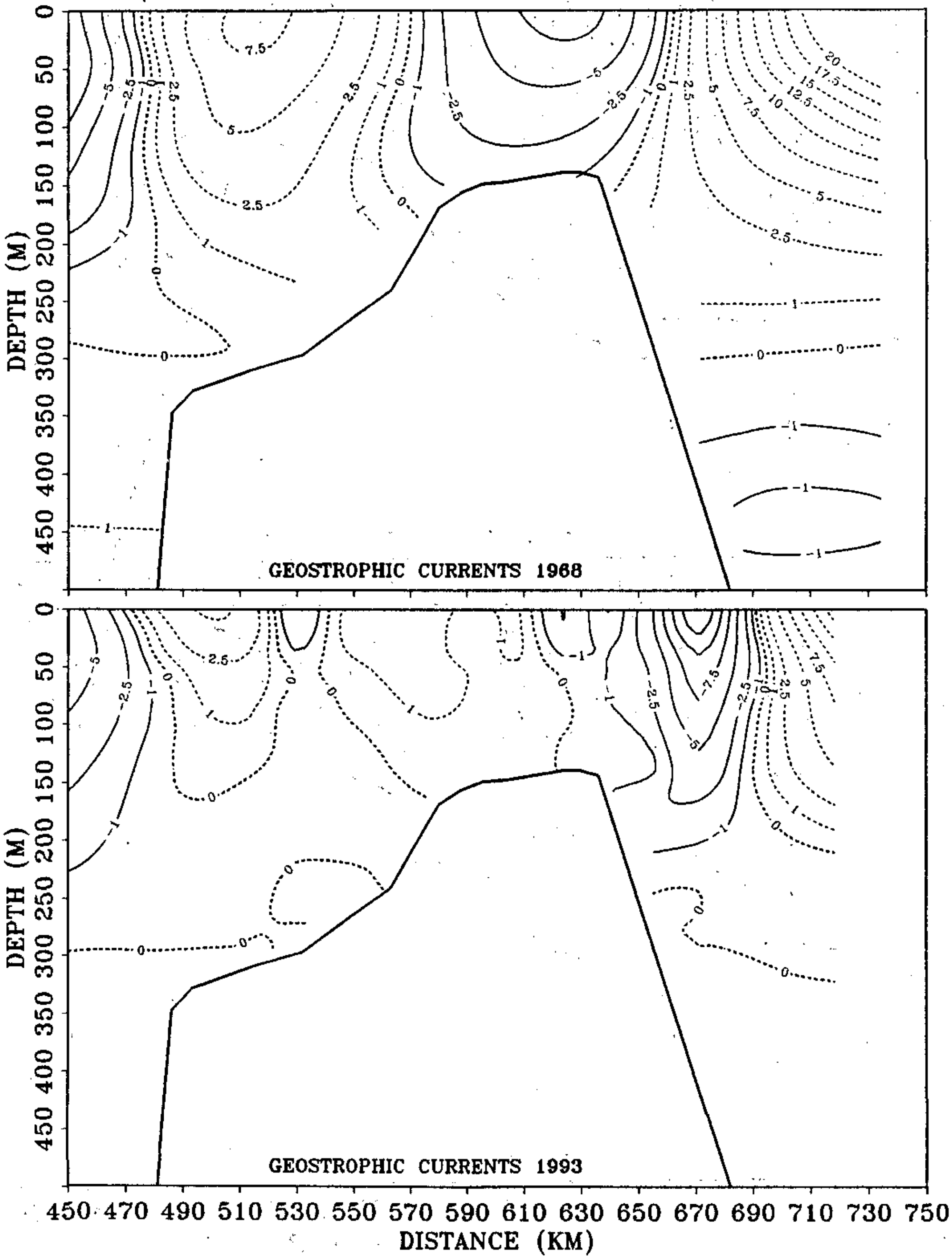


Fig. 21a. The vertical distribution of the N-S geostrophic current field over the Flemish Cap during July of 1968 and 1993. Negative currents (solid line) are southward.

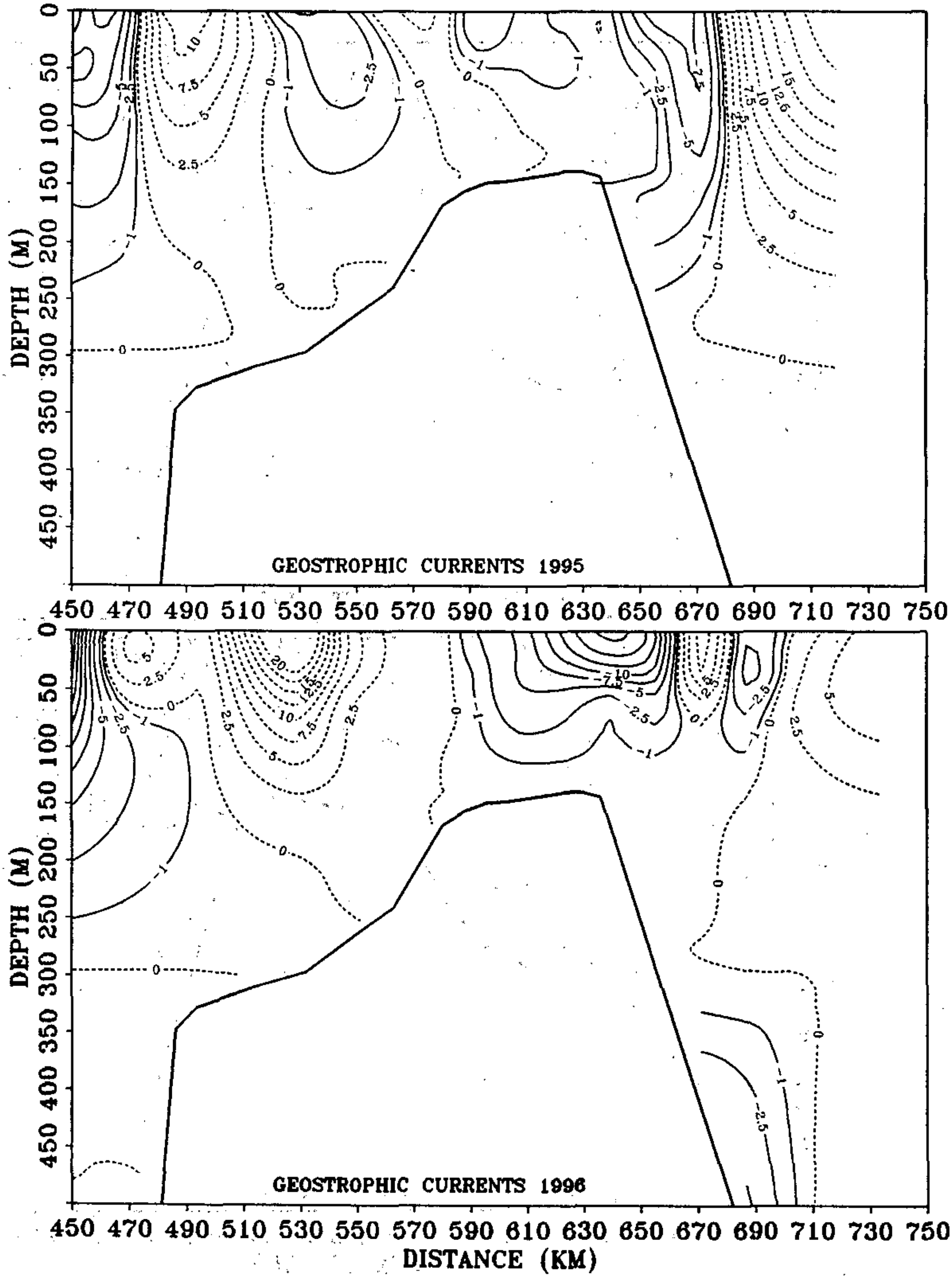


Fig. 21b. The vertical distribution of the N-S geostrophic current field over the Flemish Cap during July of 1995 and 1996. Negative currents (solid line) are southward.

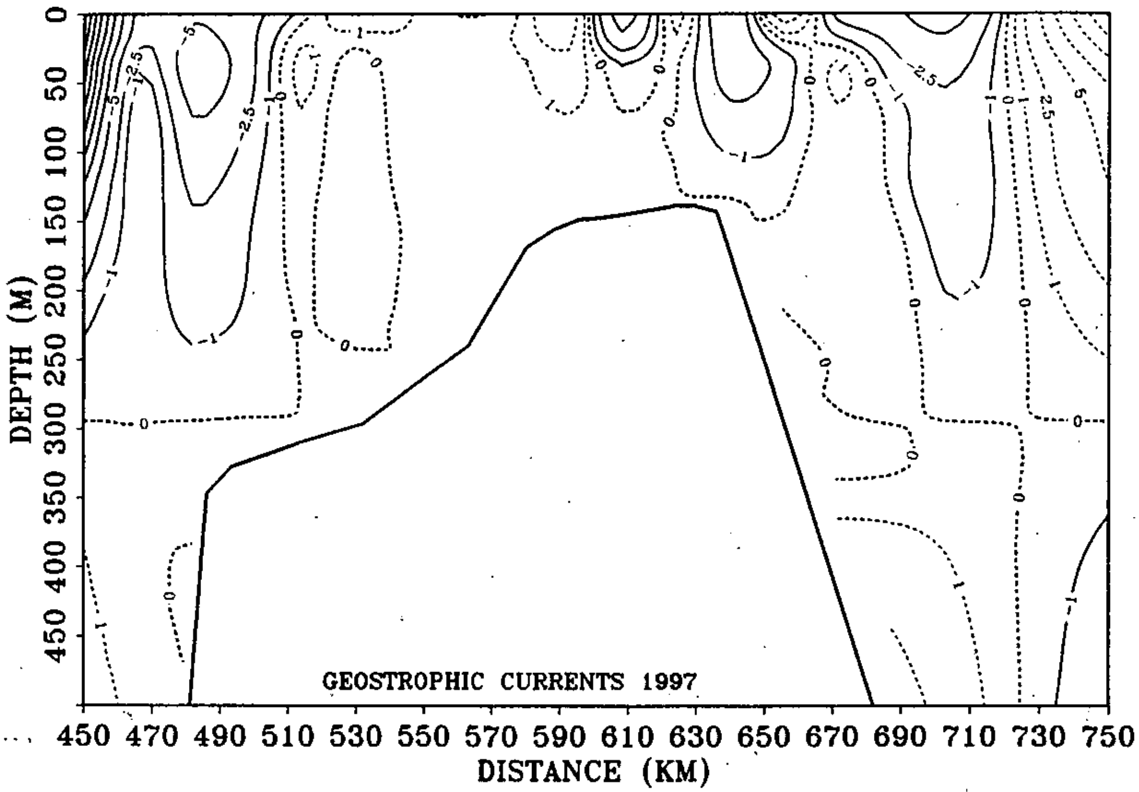


Fig. 21c. The vertical distribution of the N-S geostrophic current field over the Flemish Cap during July of 1997. Negative currents (solid line) are southward.

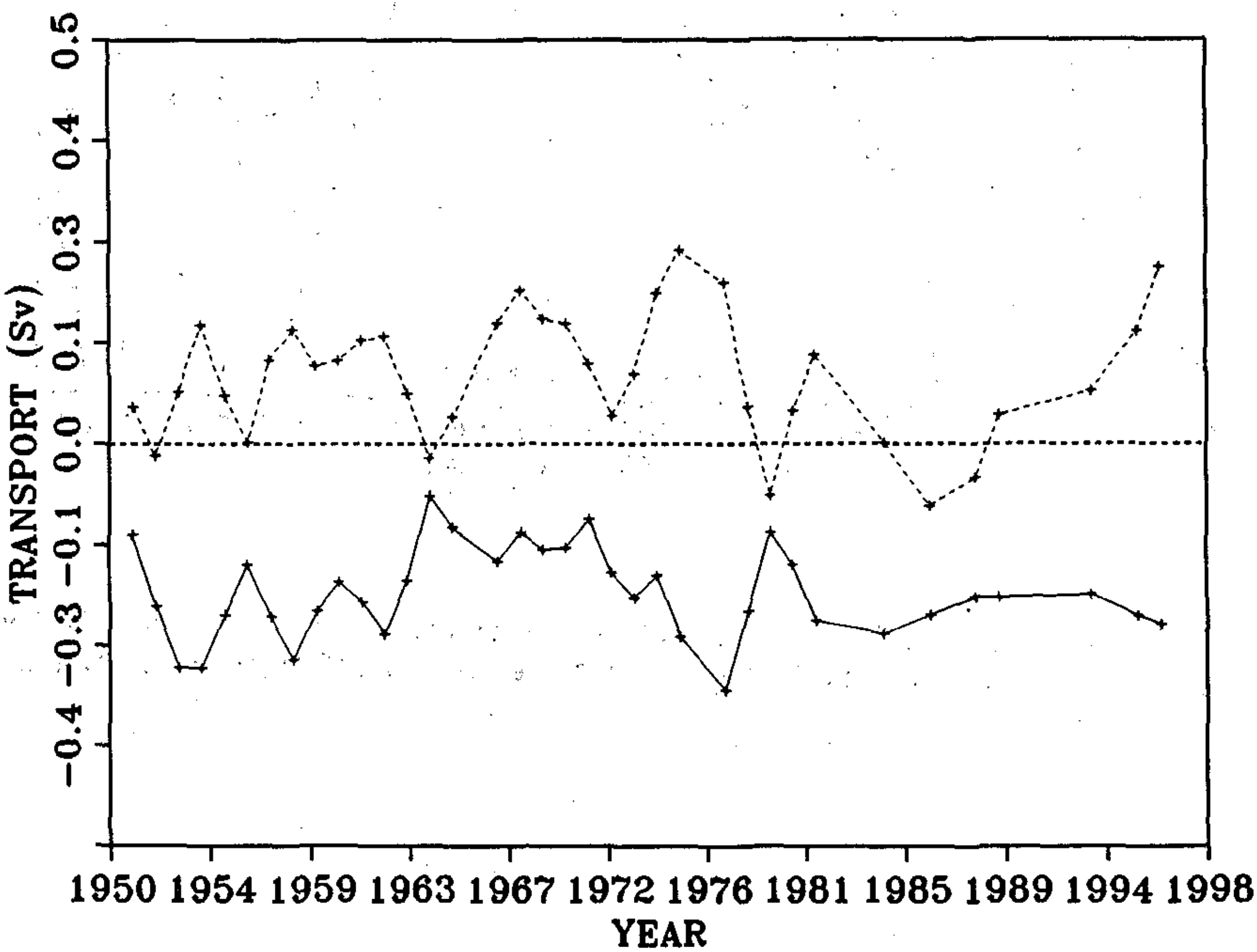


Fig. 22. Time series of gyre strength calculated from the summer geostrophic transport through the 47° N transect across the Flemish Cap. The dashed line is the northward transport on the western side of the Cap and the solid line is the southward transport on the eastern portion of the Cap. The data were 3-point smoothed to highlight the interannual trends.