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OCEANOGRAPHIC CONDITIONS IN THE NEWFOUNDLAND REGION DURING 1996 WITH COMPARISONS TO THE 1961-1990 AVERAGE

by

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ABSTRACT

Oceanographic observations from St. Pierre Bank, Grand Bank, Flemish Cap, Northeast Newfoundland Shelf and the Labrador Shelf during 1996 are presented and referenced to the long-term (1961-1990) mean. At Station 27 water temperatures were above normal throughout most of the year over the entire water column except during July when surface temperatures were 1.0 °C below normal. Salinities were below normal during most of the year over the entire water column. In the inshore regions temperatures were significantly below normal during early 1990s but had warmed considerably by the summer of 1994 and throughout 1996. The cold-intermediate-layer (CIL) on the Newfoundland Shelf was slightly below normal along the Flemish Cap transect (Grand Bank), below normal along the Bonavista transect and below normal along the Seal Island transect. Minimum CIL core temperatures were normal along the Seal Island transect, slightly above normal along the Bonavista transect and above normal on the Grand Bank. Bottom temperatures on the shelf during the fall period increased significantly over previous years and were up to 0.5 °C above normal. Surface temperatures during the summer were below normal but increased to above normal values over most regions by the fall of 1996. In general, the analysis presented here shows the below normal oceanographic trends in temperature and salinity established in the late 1980s reached a peak in 1991. This cold trend continued into 1993 but started to moderated during 1994 and 1995. During 1996 temperature conditions were above normal over most regions, however, salinity conditions continue slightly below the long-term normal.

RÉSUMÉ

Dans le présent document, on présente les observations océanographiques faites, en 1996, à partir du Banc de Saint-Pierre, du Grand Banc, du Bonnet Flamand, du plateau continental du nord-est de Terre-Neuve et du plateau continental du Labrador et on les compare à la moyenne à long terme (1961-1990). À la station 27, la température de l'eau était supérieure à la normale pendant presque toute l'année, dans toute la colonne d'eau, sauf pendant le mois de juillet où la température superficielle était de 1 °C sous la normale. La salinité était sous la normale pendant presque toute l'année dans toute la colonne d'eau. Dans les régions côtières, la température était significativement inférieure à la normale au début des années 90, mais elle est remontée considérablement au cours de l'été 1994 et en 1996. La couche froide intermédiaire du plateau continental de Terre-Neuve était légèrement inférieure à la normale le long du transect du Bonnet Flamand (Grand Banc), sous la normale le long du transect Bonavista et inférieure à la normale le long du transect de l'île Seal. La température interne minimale de la couche intermédiaire froide était normale le long du transect de l'île Seal, légèrement supérieure à la normale le long du transect Bonavista et au-dessus de la normale sur le Grand Banc. La température de l'eau du fond de la plate-forme pendant l'automne a augmenté significativement ces dernières années pour s'élever jusqu'à 0,5 °C au-dessus de la normale. Les températures superficielles pendant l'été étaient inférieures à la normale, mais, à l'automne 1996, elles avaient atteint des valeurs supérieures à la normale dans presque toutes les régions. En général, l'analyse présentée dans ce document montre que les tendances océanographiques de la température et de la salinité sous la normale, établies à la fin des années 80 ont atteint un pic en 1991. Cette tendance s'est maintenue à la baisse en 1993, mais elle a commencé à montrer une hausse en 1994 et 1995. En 1996, la température était au-dessus de la normale dans presque toute les régions, mais la salinité continue à se maintenir légèrement sous la normale à long terme.

INTRODUCTION

This report presents an overview of oceanographic conditions in the Newfoundland region during 1996, with a comparison to the long-term average conditions based on historical data. The long-term mean was standardized to a base period from 1961-1990 in accordance with the convention of the World Meteorological Organization and recommendation of the NAFO Scientific Council. Most of the long-term averages computed for this report had good temporal coverage over the years 1961-1990 except during the fall period for which most data are from the late 1970s to present. Much of the information presented here is based on oceanographic observations made at Station 27 and along standard cross-shelf transects (Fig. 1a and 1b) during an annual oceanographic survey in July and August since 1946. Data from the inshore regions around Newfoundland including temperature time series from the Long-Term-Temperature-Monitoring-Program (LTTMP), are also used. In addition, all oceanographic observations made during the spring and fall pelagic and groundfish research vessel surveys from the late 1970s to 1996 in NAFO Divisions 2GH, 2J to 3NO and 3Ps are included. Data from all available sources are also used to define the long-term means.

DATA SOURCES AND ANALYSIS

Oceanographic data for NAFO Divisions 2GH,2J3KL, 3NO and 3Ps are available from archives at the Marine Environmental Data Service (MEDS) in Ottawa and the Northwest Atlantic Fisheries Center (NAFC) in St. John's Newfoundland. During the fall period since 1977 (in Division 2J), and since 1981 (in Divisions 2J3KL) to 1989 the bulk of these data were collected during the stratified random groundfish surveys using XBTs. Since 1989 conductivity-temperature-depth (CTD) recorders have replaced XBTs. Data in Subdivisions 3Pn and 3Ps are from the Canadian assessment surveys conducted in February, March and April mainly since 1973, however some historical data dating back to 1950 were available. Measurements of temperature and salinity were made using several models of CTD recorders including Seabird-911s, SBE-25s and SBE-19s. Data from the net-mounted SBE-19 CTDs are not field calibrated, but are checked periodically and are factory calibrated annually. The SBE-25 and 911s are field calibrated on each survey maintaining accuracies of 0.005 °C in temperature and 0.005 psu in salinity.

Time series of temperature and salinity were constructed at standard depths from Station 27, Hamilton Bank, Flemish Cap, St. Pierre Bank and the inshore region around Random Island, Trinity Bay. The 1961-1990 data sets from these areas were sorted by day of the year to determine the annual cycle. Following the general methods of Petrie et al. 1992 and Myers et al. 1990, the seasonal cycle at the selected depths was removed by fitting a least squares regression of the form $\mathbf{cos(\omega t\text{-}\phi)}$ to the data. Unlike the time series of anomalies from fixed points like Station 27 these anomalies are based on data over large geographical areas such as St. Pierre Bank and therefore may exhibit significant spatial variability. Temperature anomalies were constructed for the years 1991 to 1996 from the Long-Term-Temperature-Monitoring thermograph sites by computing monthly means from the continuous time series.

Temperature and salinity measurements made during the deployment of groundfish trawls are used together with other available data to determine the vertical temperature and salinity fields. Vertical cross-sections of the temperature and salinity structure during the fall along the standard Seal Island and Bonavista transect and across the 3Ps region in the spring were formed by averaging all observations within a ± 15 minutes of latitude corridor along the lines shown in Fig. 1a. The observations were then assumed to lie on a line joining the endpoints of the standard transect. The data were quality controlled and interpolated to 5.0 m depths intervals and averaged into 5.0 km bins along the line. During the calculation of anomalies an attempt was made to reduce temporal biasing by extracting historical data within a 1-2 week interval on either side of the time period of the 1996 data collection.

Horizontal surface (10 m) temperature maps are produced from all available data from 1961 to 1990 for a particular time and region of interest. The actual isotherms are derived from unweighted averages of all temperature profiles within a square grid projection of 0.25 degrees of latitude by 0.38 degrees longitude. Some temporal and spatial biasing may be present in the analysis given the large area and wide time interval over which the maps were produced. For example, the annual fall groundfish survey is conducted from mid-October to mid-December a time period when rapid cooling of the upper water column is taking place. Horizontal bottom temperature maps were produced by contouring all bottom of the cast temperature values for the time and region of interest and rejecting values for which the cast depths were not within 5 % of the total water depth.

TEMPORAL ANOMALIES IN TEMPERATURE AND SALINITY

Grand Bank Station 27 (Division 3L)

Depth versus time contour maps of temperature and salinity values and their associated anomalies based on all XBT and CTD profile data collected at Station 27 during 1996 (a total of 59 profiles) are displayed in Figs. 2 and 3. The cold isothermal water column during the winter months has temperatures ranging from 0.0 °C to -1.0 °C and throughout the year near the bottom. The time series shows upper layer (generally the 0 to 50 m depth range) temperatures near constant at about 0.0 °C from January to early April, after which the surface warming commenced. By early May the upper layer temperature had warmed to 2.0 °C and to above 11.0 °C by August at the surface after which the fall cooling commenced.

These temperatures were about 0.5 °C above normal for the winter months over most of the water column. Except for a brief period of negative near surface temperature anomalies centered around July and October, the entire water column was 0.3 to 2.0 °C above normal during the year. Salinities were generally below normal (by about 0.2 psu) throughout the year except during the summer when they were about 0.2 above normal.

The annual time series of monthly temperature and salinity anomalies at Station 27 during 1996 at standard depths again referenced to a 1961 to 1990 average, are shown in Figs. 4 and 5. Temperatures over all depths ranged from near normal to 3.0 °C above normal at 30 m depth in July. The only exceptions were in July when surface temperatures were 1.0 °C below normal and a slight negative temperature anomaly in the upper layer during early autumn. In the depth range of 75 m to the bottom at 176 m temperatures were above normal throughout the year. Salinities were slightly below normal through the year over all depths, except slightly positive near the surface during summer and at 30-50 m in the autumn.

The low passed filtered time series of temperature and salinity anomalies at standard depths show three major cold and fresher than normal periods at near decadal time scales since the early 1970s (Fig. 6). At the surface and at 30 m depth the negative temperature anomalies that began in late 1990 and reached a peak in mid 1991 had moderated to above normal conditions by the summer of 1994 but returned to colder than normal by the summer of 1995 and above normal throughout 1996. At the deeper depths of 100 and 175 m negative temperature anomalies have persisted since 1983 with a few periods of positive anomalies during the mid to late 1980s. During 1994 and 1995 bottom temperatures have been slowly returning to more normal values and by 1996 were above the long-term normal.

Upper layer salinity anomalies show the large fresher than normal anomaly that began in early 1991 had returned to near normal conditions by early 1993 but returned to fresher conditions by the summer of 1995 which continued into 1996. Other periods with colder and fresher than normal salinities particularly in the early 1970s and mid 1980s are associated with colder than normal air temperatures (Findlay and Deptuch-Stapf, 1991), heavy ice conditions and larger than average summer cold-intermediate-layer (CIL) areas on the continental shelf (Drinkwater 1994, Colbourne et al. 1994a).

The vertically averaged annual station 27 temperature (which is proportional to the total heat content of the water column, ie. $H/\rho C_p$) time series (Fig. 7a) shows large amplitude fluctuations, again at near decadal time scales, with cold periods during the early 1970s, mid 1980s and early 1990s. The total heat content of the water column which reached a record low in 1991 has since recovered to values experienced during the warm 1950s and 1960s. The 0 to 50 m vertically averaged summer salinity (Fig. 7a) shows similar behaviour as the heat content time series with large fresher than normal periods corresponding to the colder than normal conditions. The low salinity values of the early 1990s were comparable to values experienced during the 'Great Salinity Anomaly' of the early 1970s (Dickson et al. 1988). During 1993 summer salinities started returning to more normal values but decreased again by the summer of 1995 to near record lows. During 1996 salinities were higher than 1995 but still below the long-term normal. The seasonal cycle of the vertically averaged Station 27 temperature for 1991 and 1996 are compared to a least squares fit to the historical data in Fig. 7b. The anomalous conditions in both the phase and amplitude of the temperature cycle during 1991 are clearly evident in contrast to 1996 when conditions were reversed.

Hamilton Bank (Division 2J)

The time series of temperature and salinity anomalies from 1950 to 1996 on Hamilton Bank are shown in Fig. 8a and 8b at standard depths of 0, 50, 75 and 150 m. Again this time series was smoothed using a five-point running mean to suppress the high frequency variations at seasonal scales so the most recent data will not be included. Observations made during the same day appear as vertical lines and indicates spatial variability in the temperature over the bank at the same depth.

The time series is characterized by large variations with amplitudes ranging from ± 1.0 °C and with periods ranging from 2 to 10 years. The cold periods of the mid 1970s and the mid 1980s and to a lesser extent the early 1990s are present, however, the amplitude of these anomalies vary considerably with depth. Temperature anomalies on Hamilton Bank appear to be moderating, except at the surface where the temperature was below normal during the summer of 1996. The smoothed salinity time series show very similar conditions as elsewhere on the shelf with fresher than normal conditions in the early 1970s, mid 1980s and early 1990s. For the most part these anomalies continued into 1996 with the exception of a positive surface anomaly during the summer of 1996.

Flemish Cap (Division 3M)

The time series of temperature anomalies on the Flemish Cap at various standard depths to at least 100 m (Fig. 9a) are characterized by 3 major cold periods: most of the 1970s, mid 1980s and the late 1980s to early 1990s. The cold period beginning around 1971 continued until 1977 in the upper layers, while temperature anomalies in the 1970s near the bottom at 200 m were insignificant. 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 in the top 100 m of the water column, intense negative temperature anomalies had returned with peak amplitudes reaching near -3.0 °C at

50 m depth. This cold period moderated briefly in 1987 but returned again by 1988. Since 1995 upper layer temperatures have moderated somewhat, however below normal conditions still exist at the surface and below 100 m depth.

The time series of salinity anomalies (Fig. 9b) shows large fresher than normal conditions from 1971 to 1976 and from 1983 to 1986 in the upper 100 m of the water column with peak amplitudes reaching 0.5 psu below normal. Salinities during the early 1990s range from slightly below normal in 1992 (from 20 to 100 m) to slightly above normal in 1995 and 1996. In general, the temperature and salinity anomalies are very similar to those at Station 27 and elsewhere on the continental shelf over similar depth ranges (Colbourne 1993).

St. Pierre Bank (Division 3Ps)

The time series of temperature and salinity anomalies from 1950 to 1996 on St. Pierre Bank are shown in Fig. 10a and 10b at standard depths of 0, 20, 50 and 75 m. Those time series were smoothed to suppress the high frequency variations at seasonal scales, which are also shown as points in this figure. Observations made during the same day appear as vertical lines and indicates spatial variability in the temperature over the bank at the same depth.

The temperature time series is characterized by large variations with amplitudes ranging from ± 1.0 °C and with periods between 5 to 10 years with some higher frequency variations in the upper water column. The cold periods of the mid 1970s and the mid 1980s are coincident with severe meteorological and ice conditions in the Northwest Atlantic and colder and fresher oceanographic anomalies over most of the Canadian continental shelf. During the cold period beginning in 1984 temperatures decreased by up to 2.0 °C in the upper water column and by 1.0 °C in the lower water column and continued below normal until 1990. Since 1991 temperatures have moderated over the top 50 m of the water column but have remained well below average at 75 m depth. During 1992 to 1996 the sign of the temperature anomalies changed at 0 and 20 m depth but remained mostly negative near bottom. During mid 1996 however, conditions appear to moderating. The salinity time series show very limited data, particularly during the 1980s. The available data however show fresher than normal conditions in the early 1970s and early 1990s and near normal salinities during the last 2 years.

Inshore Temperature Time Series

To investigate oceanographic conditions in the inshore regions around Newfoundland a time series of temperature was constructed in the Smith Sound Random Island area (Fig. 1a) for 1995-1996 at 100 m depth and from 1953 to 1996 at 200 m depth. In addition, temperature time series from thermograph monitoring sites in Notre Dame Bay (1981-96), Bonavista Bay (1967-96) and Placentia Bay (1981-96) (Fig. 1b) at 10 m depth were analyzed. As shown in Fig. 11a temperatures around the Smith Sound area during most of 1995 were below the long-term average until late fall when they increased to 2.0 to 3.0 °C above average. During 1996 temperature anomalies ranged from about average to 2.0 °C above average in January and to about 1.5 °C in the fall period. The time series at 200 m depth (Fig. 11b) indicates that warmer (> 0.0 °C) water from the Newfoundland Shelf frequently floods the deep fjords along the coast of Newfoundland, however during the period from early 1991 to late 1995 it was absent.

Monthly mean temperatures were calculated from the thermograph time series and used to generate annual anomalies at 10 m depth for 1991, 1993, 1994 and 1996. These results indicate that temperatures were up to 4.0 to 6.0 °C below average during 1991 and 1993 in the summer months in Notre Dame (Fig. 12a) and Bonavista (Fig. 12b) Bays and up to 2.0 °C below average in Placentia Bay (Fig. 12c). During 1994 temperatures were from 1.0 to 3.0 °C above normal during the summer months and from 1.0 to 3.0 °C above normal throughout most of 1996 at all 3 sites.

TEMPERATURE, SALINITY AND OXYGEN TRANSECTS

Vertical cross-sections of the temperature and salinity fields together with their anomalies along the standard Flemish Cap, Bonavista and Seal Island transects for the summer of 1996 are presented in Figs. 13 to 15. The anomalies were calculated from the mean of all available data for each transect from 1961 to 1990 during the time period of the 1996 survey. No attempts were made to adjust the mean for possible temporal biasing arising from variations in the number of observations within the time interval.

Flemish Cap (Grand Bank 47 °N, Summer)

The summer temperature along the Flemish Cap transect (Fig. 13a) ranges from 9.0 °C near the surface to < 0.0 °C below 75 m across the Grand Bank and < 3.5 °C over the Flemish Cap in the depth range from 80 m to the bottom. These temperatures were more than 2.0 °C below normal in the upper layer over the Grand Bank, about 0.3 to 0.5 °C above normal near bottom over the Grand Bank and about 0.3 to 0.5 °C below normal at depths > 80 m over Flemish Cap. Upper layer salinities (Fig. 13b) were slightly saltier than normal over the Grand Bank and across the Cap to slightly fresher than normal below 50 m depth.

Bonavista (Summer)

Temperatures along the Bonavista transect (Fig. 14a) in the upper 50 m of the water column ranged from 0.0 °C to 8.0 °C near the coast and to 4.0 to 7.0 °C over most of the continental shelf. In deeper water (50 m to the bottom) temperatures ranged from -1.0 °C near the coast and to 0.0 °C to 3.0 °C further offshore near the edge of the continental shelf and beyond. Except for a very thin layer of surface water with below normal temperatures the corresponding temperature anomalies ranged from 0.5 to 2.5 °C above normal over the continental shelf and to 0.0 to 1.5 °C below normal at intermediate depths near the edge of the shelf in the offshore branch of the Labrador Current. Bonavista salinities (Fig. 14b) ranged from 32.0 psu near the surface to 33.5 psu near the bottom over the inshore portion of the transect to 34.75 psu at about 325 m depth near the shelf edge. Again, except for a very thin surface layer the corresponding salinity anomalies show fresher than normal conditions ranging from 0.1 to 0.6 psu below normal over most of the water column with maximum negative anomalies in the offshore branch of the Labrador Current near the shelf edge.

Bonavista Oxygen Distribution (Summer)

Dissolved oxygen data are now routinely collected along transects of Newfoundland on oceanographic research surveys. The measurements are made with a Beckman or YSI type polarographic element dissolved oxygen sensors with factory calibrated end-points at zero and 100 % saturated water oxygen levels. The sensors are interfaced to pumped Seabird-911 or 25 CTD systems. Field calibrations of the oxygen sensors were also carried out by taking water samples with Niskin bottles triggered at standard oceanographic depths during the CTD up cast. The oxygen levels of the samples were determined by semi-automated analytical chemistry using a modified Winkler titration technique where the endpoint is detected photometrically (Jones et al. 1992). The electronic measurements are then corrected from a least-squares linear regression of the titration measurements to the electronic sensor measurements. Oxygen concentrations in ml/l are converted to % saturation by dividing the measured oxygen concentration by the computed solubility of oxygen in sea water at the measured temperature and salinity (Weiss 1970).

The historical oxygen data along the Bonavista transect together with data collected in July 1996 are shown in Fig. 14c. The average dissolved oxygen distribution across the northeast Newfoundland shelf shows saturations ranging form 90 to 100 % in the surface layers to about 80 to 85 % over the shelf in the CIL and about 90 % in deeper water on the continental slope areas. During the summer of 1996 saturation levels ranged from 90 to 100 % from the surface to about 50 m depth over the shelf and to bottom near the shelf edge. Over the inshore portion of the shelf values ranged from 82.5 to 85 % from 100 m to the bottom. These values are very similar to 1994 and 1995 during the same time period and show no evidence of oxygen depletion.

Bonavista (Autumn)

The vertical distribution of temperature and anomalies along the standard Bonavista transect for the fall of 1996 are presented in Fig. 14d. The fall temperature structure across the northeast Newfoundland shelf along the Bonavista transect in the bottom layer is very similar to summer conditions with temperatures ranging from subzero inshore to 3.0 °C near the edge of the continental shelf. The upper layer remains relatively warm and the cold intermediate layer (CIL) is still detectable. In 1996 upper layer temperatures ranged from 4.0 °C near the coast to 3.0 °C offshore, about 0.5 to 1.0 °C warmer than average over the continental shelf and from 0.25 to 1.0 °C warmer than average below 100 m depth.

Seal Island (Summer)

Temperatures along the Seal Island transect (Fig. 15a) ranged from 0.0 to 6.0 °C in the upper 50 m and < 0.0 °C over most of the shelf below 50 m depth and about 3.5 °C beyond the shelf edge. Temperature anomalies along the Seal Island transect ranged from 0.5 to 1.0 °C below normal near the surface to 0.3 to 1.0 °C above normal over the shelf and in the offshore region beyond the shelf edge. Salinities along the Seal Island transect (Fig. 15b) were generally 0.1 to 0.6 psu above normal near the surface, generally below normal over the shelf and normal in deep water at the shelf edge and beyond.

Seal Island (Fall)

Autumn temperatures along the Seal Island transect (Fig. 15c) ranged from 1.0 to 2.0 °C over Hamilton Bank and the inshore regions and about 3.0 to 4.0 °C beyond the shelf edge. Temperature anomalies along the Seal Island transect ranged from 0.25 to 0.5 °C above normal near the surface to 0.5 to 1.5 °C above normal over the shelf and in the offshore region beyond the shelf edge.

Nain Bank (Autumn)

Average early fall temperatures along the Nain Bank transect (Fig. 16) ranges from 1.0 to 2.0 °C in the upper 50 m over the shelf and to 5.0 °C offshore. From 50 m to the bottom over the shelf temperatures range from 0.0 to 1.0 °C and about 3.0 °C beyond the shelf edge. Temperature during 1996 were near to slightly above normal in the surface layers. In the depth range from 50 m to bottom over the bank, the area of 0.0 °C water was somewhat larger than average in 1996.

St. Pierre Bank 3Ps (Spring Temperature)

Vertical cross-sections of the average temperature field for April based on all available historical data from 1961 to 1990 and for April 1996 are shown in Fig. 17. Again no attempts were made to adjust this average for possible temporal or spatial biasing arising from variations in the number of observations within the time interval or within the area. An examination of the data indicates that the observations are well distributed geographically across the complete transect, however, temporally, most of the data have been collected since the early 1970s.

The average April temperature ranges from 1.0 °C to 2.0 °C near the coast and over St. Pierre Bank and beyond the shelf edge in the upper 100 m of the water column. In the deeper water of Burgeo and Hermitage Channels (the deep basins on the left in Fig. 17) and on the continental slope region the temperature ranges from 2.0 °C at approximately 125 m depth to 5.0 °C to 6.0 °C near the bottom. Near the edge of the continental shelf on the Southwestern Grand Bank the temperature field is marked by a strong thermal front separating the warmer slope water from the Labrador Current water over St. Pierre Bank. In this region temperatures increase from 1.0 °C to 2.0 °C at 125 m depth to between 6.0 °C to 7.0 °C at about 175 m depth, a temperature gradient of 1.0 °C per 10 m depth change. In April 1996 temperatures were about 0.75 °C in the upper 100 m over Burgeo and Hermitage Channels, slightly below normal, and from 0.75 °C to 1.5 °C over St. Pierre Bank, again slightly below average over the central portion of the bank but an improvement over 1995 values (Colbourne, 1996). Deep water temperatures on the continental slope in 1996 ranged from 4.0 °C to 7.0 °C, about normal.

Inshore, Southwest Arm and Smith Sound, Trinity Bay (Spring Temperature)

Vertical cross-sections of spring temperatures based on data collected in 1991-1992 by Wroblewski et al. (1993), and by the Department of Fisheries and Oceans in 1995-1996 (Fig. 1a, inset) are shown in Figs. 18. Temperature during 1991 and 1992 in Southwest arm, Trinity Bay (Fig. 18a) ranges from -0.8 °C near the bottom in the depth range of 200-300 m, to -1.5 °C at mid depths and to above 0.0 °C at the surface during the spring of 1992. During 1995 conditions had warmed by about 0.5 °C over most of the water column and during 1996 by about 1.0 °C with above 0.0 °C water below 200 m depth (Fig. 18b). Very similar conditions prevailed in Smith Sound slightly to the north of Southwest Arm again with warm water (0.0 to 0.5 °C) below 200 m depth (Fig. 18c).

THE COLD INTERMEDIATE LAYER (CIL)

Summer Area

As shown earlier, in Fig. 14, the vertical temperature structure on the Newfoundland continental shelf is dominated by a cold layer of water, commonly referred to as the CIL (Petrie et al. 1988), trapped between the seasonally heated upper layer and warmer slope water near the bottom. For example, along the Bonavista transect during 1996 this cold layer extended offshore to about 250 km, with a maximum thickness of about 200 m corresponding to a cross-sectional area of about 24.1 km^2, compared to the 1961-90 average of 26.8 km^2.

Figure 19a shows a time series of the CIL cross-sectional area for the Seal Island, Bonavista and Flemish Cap transects, the positions of which are shown in Fig 1a. In 1996 the CIL area off

Bonavista was about 10 % below normal compared to 30 % below normal in 1995, 7 % above normal in 1994, 28 % in 1993 and up to 68 % in 1991. The CIL area along the Seal Island transect was also below normal by about 12 % in 1996 compared to 32 % during 1995. During 1994 the CIL along the Seal Island transect was 36 % above normal and up to 61 % above normal in 1991. Along the Flemish Cap transect the CIL was slightly below normal during the summer of 1996 (24 km^2 versus an average of 25 km^2) the first time since 1981. In 1995 it was about 18 % above normal (29.8 km^2) compared to 12 % in 1994 and to 48 % during 1991. In general, the total cross-sectional area of sub-zero °C water, except for the Flemish Cap transect, is continuing a below normal trend established in 1995.

The intensity or minimum core temperatures of the CIL for all three transects from 1948 to 1996 are shown in Fig. 19b. The minimum temperature observed in the core of the CIL along the Seal Island transect during the summer of 1996 was about -1.57 °C, which was about normal. Core temperatures along the Bonavista transect were -1.55 °C compared to a normal of -1.63 °C and for the first time in about 10 years above normal along the Flemish Cap transect at about -1.32 °C compared to the normal of -1.52 °C.

Autumn Area

The 1982 to 1996 time series of CIL area less than 0.0 °C for the Seal Island and Bonavista transects during the fall groundfish surveys are shown in Fig. 20. The CIL area along the Bonavista transect (bottom panel) shows similar trends as in the summer, however the average area in this time period have decreased from 33 km^2 during the summer to 24 km^2 in the fall as a result of summer heating and vertical mixing over the water column. The CIL area during the fall of 1996 along the Bonavista transect was about 10 km^2 compared to about 7 km^2 in 1995, 26 km^2 in 1994, 30 km^2 in 1993, 27 km^2 in 1992 and about 22 km^2 in 1991. No fall data were available along this transect during 1982.

The Seal Island CIL area is more variable and smaller in average magnitude than the more southerly Bonavista transect, with some years when 0.0 °C water was completely eroded by summer heating and fall convection. The average CIL area during the fall along this transect was about 13 km^2 with a standard deviation of about 11 km^2. There were no CIL waters during the fall of 1996 compared to about 14 km^2 in 1994, 16 km^2 in 1993, 26 km^2 in 1992 and 11 km^2 in 1991. Data for the fall of 1995 were not available.

CIL Volume (Summer and Autumn)

The total volume of water on the Newfoundland and southern Labrador shelves shoreward of the 1000 m isobath and within NAFO divisions 2J3KL is approximately 2.0×10^{14} m^3. The calculation of the volume of sub-zero water overlying the continental shelf is described by Colbourne and Mertz (1995). The spatial variation in the amount of subzero water on the shelf in different years is determined by contouring the thickness of the layer of water less than 0.0 °C on the Northeast Newfoundland Shelf in NAFO Divisions 2J and 3KL during the summer and fall periods. The isolines of CIL thickness show large variations from summer to fall of the same year and from cold years to warmer years (Colbourne, 1995). The average thickness of the CIL is maximum (> 150 m) along the east coast of Newfoundland within 100 km of the shore and decreases to 0.0 m near the edge of the shelf, on the southern Grand Bank and on Hamilton Bank during warm years in the fall. During the summer and fall of 1996 the thickness of the CIL was below average from the Grand Bank to Hamilton Bank (Fig. 21).

The time series of total volume of subzero water over the 2J, 3KL area (Fig. 22) shows maximum values during the cold periods of the mid 1980s and early 1990s. The total volume of subzero °C water on the shelf increased from approximately 3.3 X 10^4 km^3 during the summer of 1989 to 5.6 X 10^4 km^3 in 1990 a 70 % increase. Since 1991 the volume of subzero °C water on the Newfoundland Shelf during summer and fall has been slowly decreasing, and by 1995 it had decreased to values of the early 1980s and from 1986 to 1989. The 1996 volume increased slightly in summer but is still below average. The average volume of subzero °C water on the shelf during the summer is approximately 4.0 x 10^{13} ± 0.9 m^3 (40,000 km^3) roughly one-quarter of the total volume of water on the shelf. The time series during the fall shows similar trends but the total volume is reduced to 2.4 x 10^{13} ± 0.8 m^3 about one-half the summer values. Due to limited data sets the volume estimates were not calculated prior to 1980. The time series of the volume of subzero °C water over the 2J3KL area and the average CIL cross sectional areas along widely spaced transects (Seal Island, Bonavista and Flemish Cap) exhibits some differences but are highly correlated with correlation coefficients of 0.85 and 0.76 for the summer and fall periods respectively (Colbourne and Mertz 1995) (Fig. 23).

HORIZONTAL TEMPERATURE FIELD

2GH Bottom Temperature

Figure 24 shows horizontal maps of bottom temperature from all available data in the time period from September 15 to October 15, for the 1961-90 average and for 1996. The normal bottom temperature for this time period ranges from less than 0.0 °C near the coast to 0.5 to 1.0 over Saglek Bank and from 0.5 to 2.0 °C over Nain Bank. Along the edge of the Labrador Shelf the temperature ranges from 2.0 to 3.0 °C. During the fall of 1996 temperatures ranged from 0.0 to 0.5 °C over Saglek Bank, about 0.5 °C below normal and from 0.5 to 2.0 °C over Nain Bank again somewhat below normal.

2J3KL Surface and Bottom

Figure 25 shows horizontal maps of the average and the fall 1996 near surface (10 m) temperature field in the 2J3KL region from all available fall data from 1961-90 and for 1996. During the fall period the average near surface temperature have cooled down to between 1.0 °C to 1.5 °C in Division 2J3K and from 1.5 °C to 6.0 °C in Division 3L. During the fall of 1996 surface temperatures ranged from 1.5 °C to 3.0 °C in 2J3K and from 3.0 °C to 8 °C in Division 3L, up to 1.0 °C above average in the north and more than 2.0 °C above average in the south.

The average (1961-90) and the 1996 fall bottom temperature for the 2J3KL area are shown in Fig. 26 (isotherms are -1, -0.5, 0, 1, 2, and 3 °C, bathymetry lines are 300 and 1000 m). The average bottom temperature over most of the northeast Newfoundland shelf (2J3K) ranges from less than 0.0 °C inshore, to 3.0 °C offshore at the shelf break. The average temperature over most of the Grand Bank varies from -0.5 °C to 0.0 °C and to 3.0 °C at the shelf break. In general, bottom isotherms follow the bathymetry exhibiting east-west gradients over most of the northeast shelf. The percentage area of water less than -0.5 °C over the Grand Bank and northeast shelf from 1990 to 1994 was much larger than the 1961-1990 average. In 1992 and 1993 the bottom temperature anomalies ranged from -0.25 °C to -0.75 °C over the northeast shelf and from -0.25 °C to -1.0 °C over the Grand Bank (Colbourne 1994). During the fall of 1996 bottom temperatures warmed over most areas on the Newfoundland Shelf with anomalies up to 0.5 °C above normal in many places. During 1996 the percentage area of water less than -0.5 °C on the Grand Bank was below average with a complete absence of sub-zero °C water on the Northeast Newfoundland Shelf from the Northern Grand Bank to Nain Bank. Similar conditions existed during the fall of 1995.

3PS Bottom (Spring)

The 1961-90 average and the 1996 April bottom temperature maps for the 3Ps and 3Pn areas are shown in Fig. 27. In general, the bottom isotherms follow the bathymetry around the Laurentian Channel and the Southwestern Grand Bank increasing from 2.0 °C at 200 m depth to 5.0 °C in the deeper water. The average April bottom temperature ranges from 5.0 °C in the Laurentian, Burgeo and Hermitage Channels to about 3.0 °C to 4.0 °C on Rose Blanche Bank and on Burgeo Bank and from 0.0 °C on the eastern side of St. Pierre Bank to 2.0 to 3.0 °C on the western side. During April 1996 temperatures were about average over Burgeo Bank and Hermitage Channel and along the western side of St. Pierre Bank. On St. Pierre Bank temperatures ranged from 0.0 to 2.0 °C still somewhat below average but they represent an increase over 1995 values, particularly on the eastern side of the bank where temperatures in 1995 were sub-zero °C. In general, it appears that the moderating conditions on the Newfoundland Shelf during the last couple of years have started to influence condition in the 3Ps region.

SUMMARY

Time series of temperatures at Station 27 shows above normal values during most of 1996 over all depth ranges. The only exceptions were in July when surface temperatures were 1.0 °C below normal and a slight negative temperature anomaly in the upper layer during early autumn. Salinities were slightly below normal over all depths during most of the year.

Temperature anomalies on St. Pierre Bank show the cold period which started around 1984, continued to the spring of 1995 but showed some evidence of moderation during the spring of 1996. Bottom temperatures on Hamilton Bank and the Grand Bank during the fall period of 1996 increased significantly over previous years and were up to 0.5 °C above normal. Time series of temperature and salinity anomalies around the Flemish Cap area show conditions similar to the adjacent continental shelf areas over the same depth ranges. The latest cold period which started around 1988 with temperature anomalies up to 2.0 °C below normal throughout the upper 100 m of the water column in 1993 show some moderation in the intermediate depths but remained below normal at the surface and near bottom up to the summer of 1996. The salinity time series show near normal conditions during the late 1980s and early 1990s compared to the mid 1980s when salinities were up to 0.6 psu below normal in the upper 100 m of the water column. In the inshore regions temperatures were significantly below normal during early 1990s but had warmed considerably by the summer of 1994 and throughout 1996.

The summer 1996 area of the CIL was normal on the Grand Bank, 10 % below normal off Bonavista and 12 % below normal on Hamilton Bank. During the fall, the Bonavista CIL decreased from 26 km^2 in 1994 to 10 km^2 in 1996 compared to the 1980-1994 average of 24 km^2. Along the Seal Island transect the fall CIL was completely eroded, the first time since 1988. Since 1991 the total volume of subzero °C water on the Newfoundland Shelf during summer and fall has been slowly decreasing, and by 1996 it has decreased to values of the early 1980s and from 1986 to 1989. The Newfoundland Shelf dissolved oxygen levels were near to slightly above average during the summer of 1996.

Surface temperatures during the fall of 1996 were above normal over most regions. During the fall of 1996 large areas of the continental shelf, particularly the Grand Bank, saw a significant increase in bottom temperatures (up to 0.5 °C above average) compared to the low values experienced during 1991-1994.

In general the analysis presented here shows the below normal oceanographic trends in

temperature and salinity established in the late 1980s reached a peak in 1991. This cold trend continued into 1993 but started to moderate during 1994 and 1995. During 1996 temperature conditions were above normal over most regions, however, salinity conditions continue slightly below the long-term normal.

ACKNOWLEDGEMENTS

I thank C. Fitzpatrick, D. Senciall, P. Stead and J. Walpert of the oceanography section at NAFC for the professional job in data collection and processing. I also thank the many scientists at the NAFC for collecting and providing much of the data contained in this analysis and to the Marine Environmental Data Service in Ottawa for providing most of the historical data. I would also like to thank the captain and crew of the CSS Parizeau.

REFERENCES

Colbourne, E. 1993. Oceanographic Conditions on the Flemish Cap during the Summer of 1993, with Comparisons to the Long-Term Average. NAFO SCR Doc. 93/107, Ser. No. N2300. 16p.

Colbourne, E. 1994. Environmental conditions during the fall of 1993 in NAFO Divisions 2J3KL. NAFO SCR Doc. 94/28, Ser. No. N2394. 26p.

Colbourne, E. 1995. Oceanographic conditions and Climate Change in the Newfoundland Region During 1994. DFO AFRD. 95/3.

Colbourne, E., 1996. Oceanographic Conditions in NAFO Subdivisions 3Pn and 3Ps During 1995 and 1996 with Comparisons to the Long-Term (1961-1990) Average. DFO Atlantic Fisheries Research Document 96/94.

Colbourne, E. and G. Mertz. 1995. Spatial and Temporal Variability in the CIL on the Newfoundland Shelves. NAFO SCR Doc. 95/33, Ser. No. N2542. 14p.

Colbourne, E. B., S. Narayanan, and S. Prinsenberg. 1994a. Climatic Change and Environmental Conditions in the Northwest Atlantic during the period 1970-1993. ICES mar. Sci. Symp., 198:311-322.

Dickson, R.R., Meincke, J., Malmberg, S. A., and Lee, A. J. 1988. The "Great Salinity Anomaly" in the northern North Atlantic 1968-82. Progr. Oceanogr. 20:103-151.

Drinkwater, K. F. 1994. Overview of Environmental Conditions in the Northwest Atlantic in 1993. NAFO SCR Doc. 94/20, Ser. No. N2385. 61p.

Findlay, B.F., and Deptuch-Stapf, A. 1991. Colder than normal temperatures over northeastern Canada during the 1980s. Climate Perspectives, April Monthly Review, 13:9-12.

Jones, E. P., F. Zemlyak, and P. Stewart. 1992. Operating Manual for the Bedford Institute of Oceanography Automated Dissolved Oxygen Titration System. Can. Tech. Rep. of Hydrography and Ocean Sci. 138: iv+51 p.

Myers, R. A., S. A. Akenhead, and K. Drinkwater. 1990. The Influence of Hudson Bay Runoff and Ice-Melt on the Salinity of the Inner Newfoundland Shelf. Atmos.- Ocean 28, No 2: pp. 120-157.

Petrie, B., S. Akenhead, J. Lazier and J. Loder. 1988. The Cold Intermediate Layer on the Labrador and Northeast Newfoundland Shelves, 1978-1986. NAFO Sci. Coun. Stu. 12: 57-69.

Petrie, B., Loder, J., Lazier, J., and Akenhead, S. 1992. Temperature and salinity variability on the eastern Newfoundland shelf: the residual field. Atmosphere-Ocean 30:120-157.

Weiss, R. F. 1970. The solubility of nitrogen, oxygen and argon in water and seawater. Deep-sea Res. 17: 721-735.

Wroblewski, J. S., A. Collier and W. Bailey. 1993. Ocean Temperatures in the Random Island Region, 1991 - 1992. Data Report No. 1. Chair in Fisheries Oceanography, Memorial University of Newfoundland, Canada.

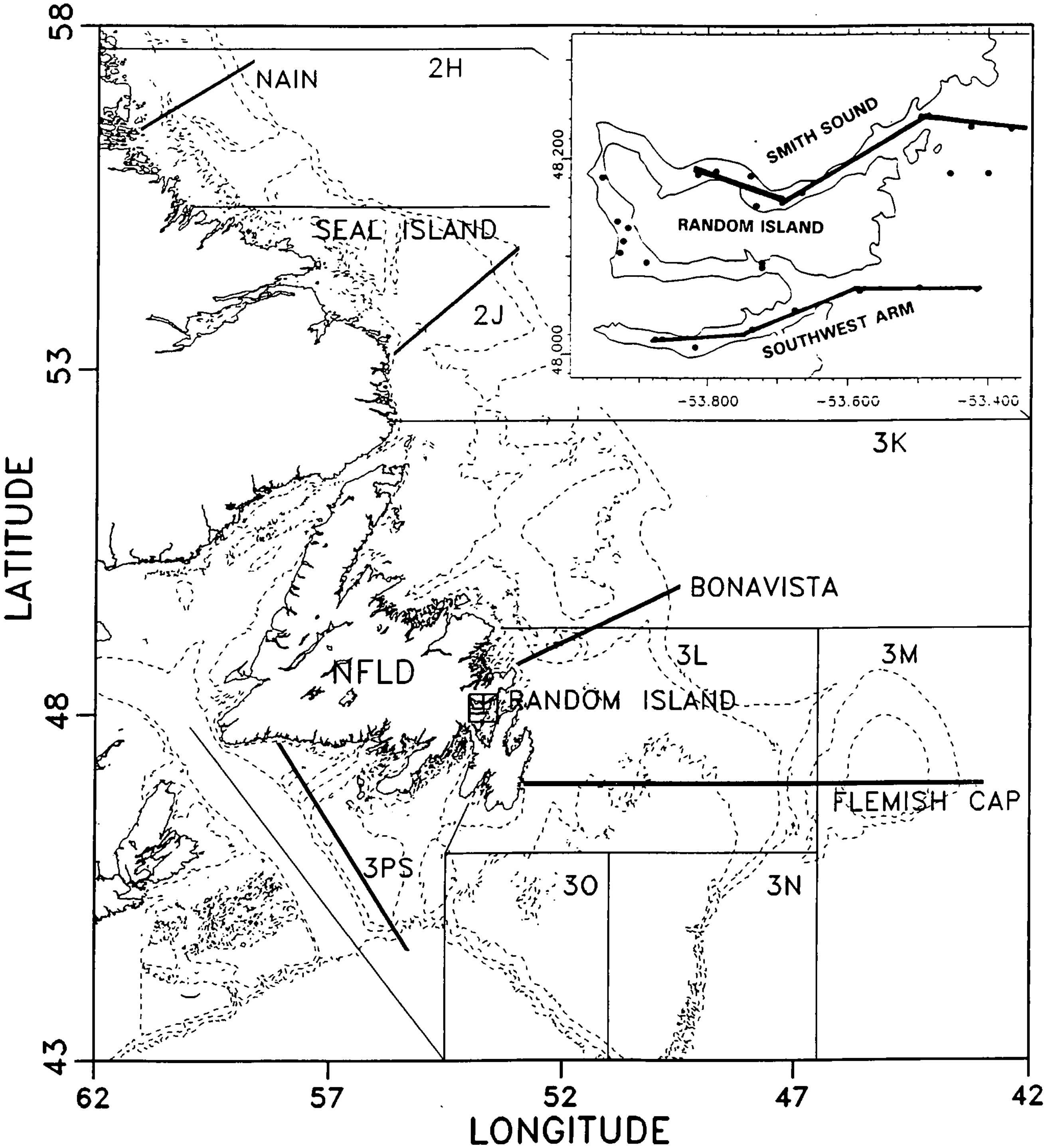


Fig. 1a. Location map showing the position of the Nain Bank, Seal Island, Bonavista, Flemish Cap (47 °N) and the 3Ps transects. The Random Island transects along Smith Sound and Southwest Arm are shown in the inset.

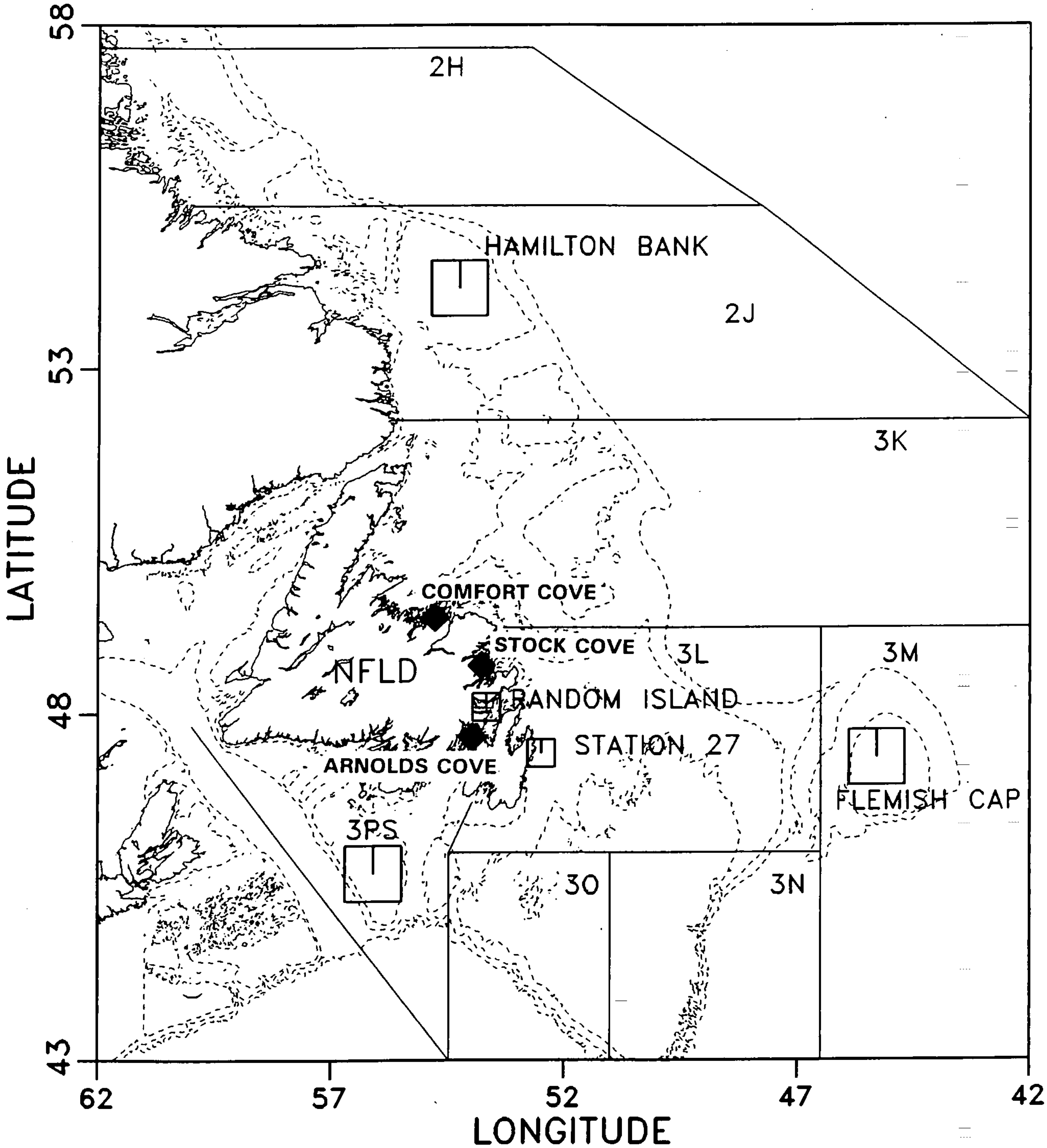


Fig. 1b. Location maps showing the approximate positions of areas where temperature and salinity time series were constructed (squares), including Station 27. The triangles are Long-Term-Temperature-Monitoring (LTTM) sites.

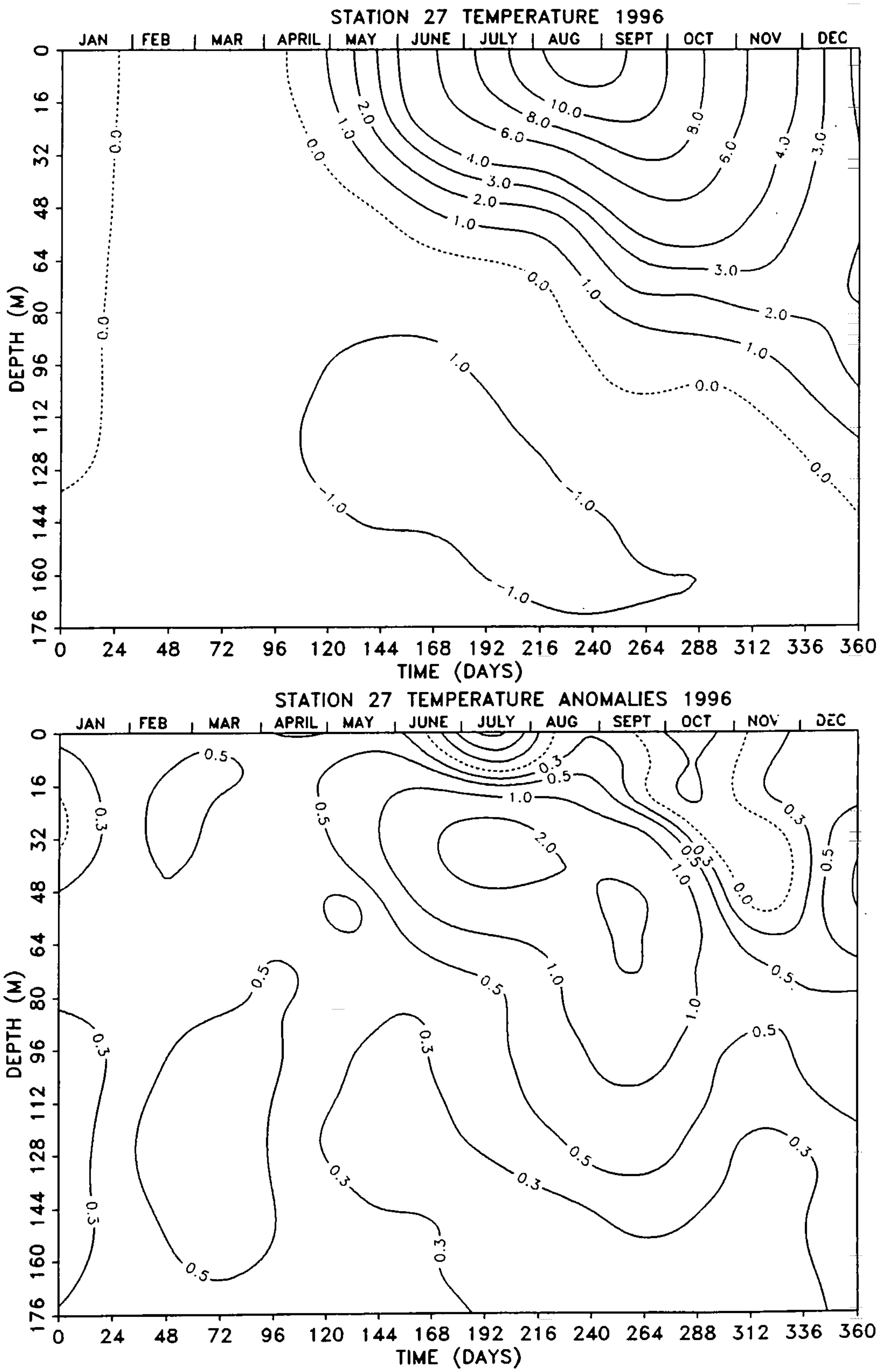


Fig. 2. Depth versus time contour plots of temperatures and anomalies at Station 27 for 1996.

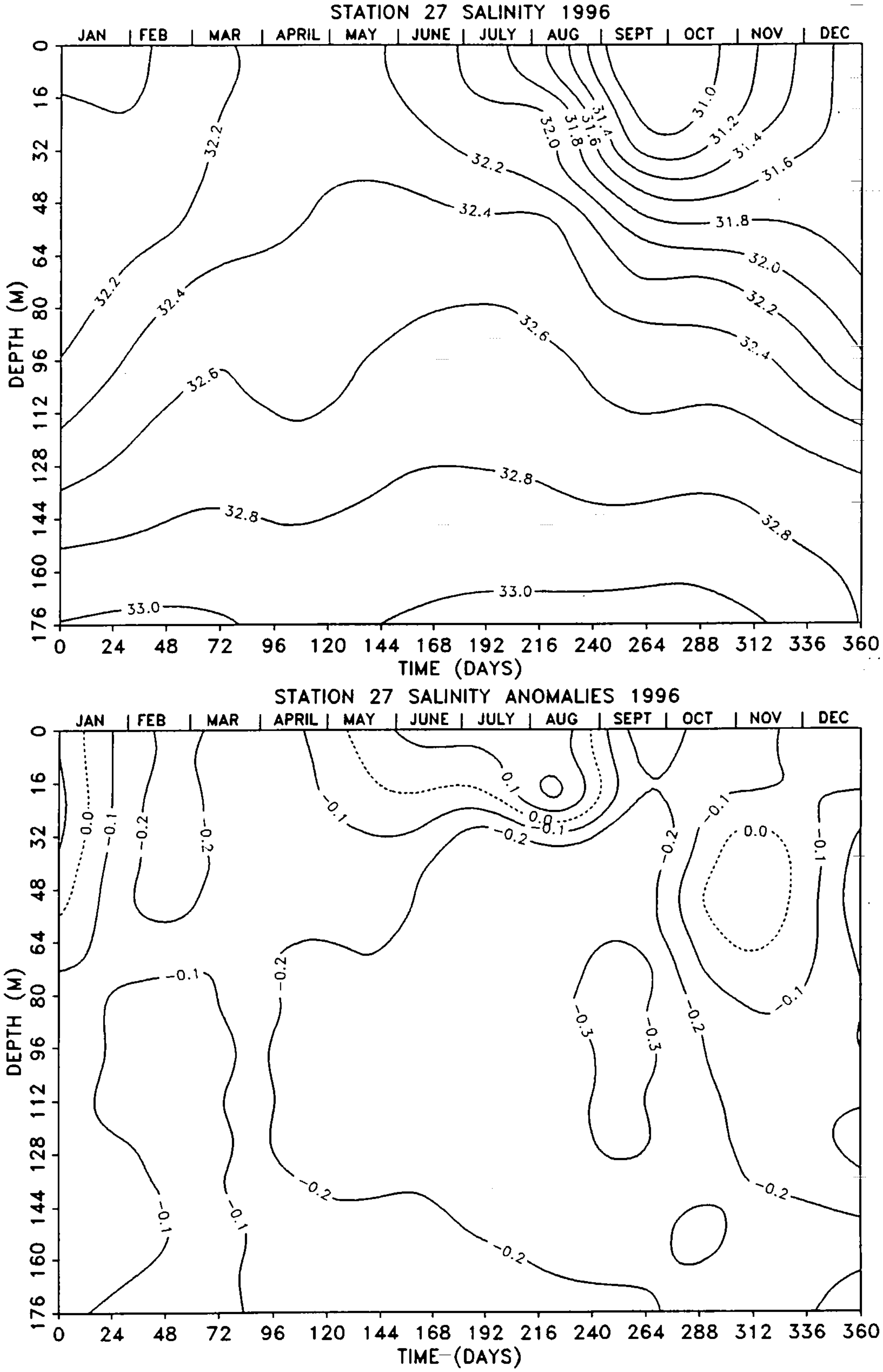


Fig. 3. Depth versus time contour plots of salinity and anomalies at Station 27 for 1996

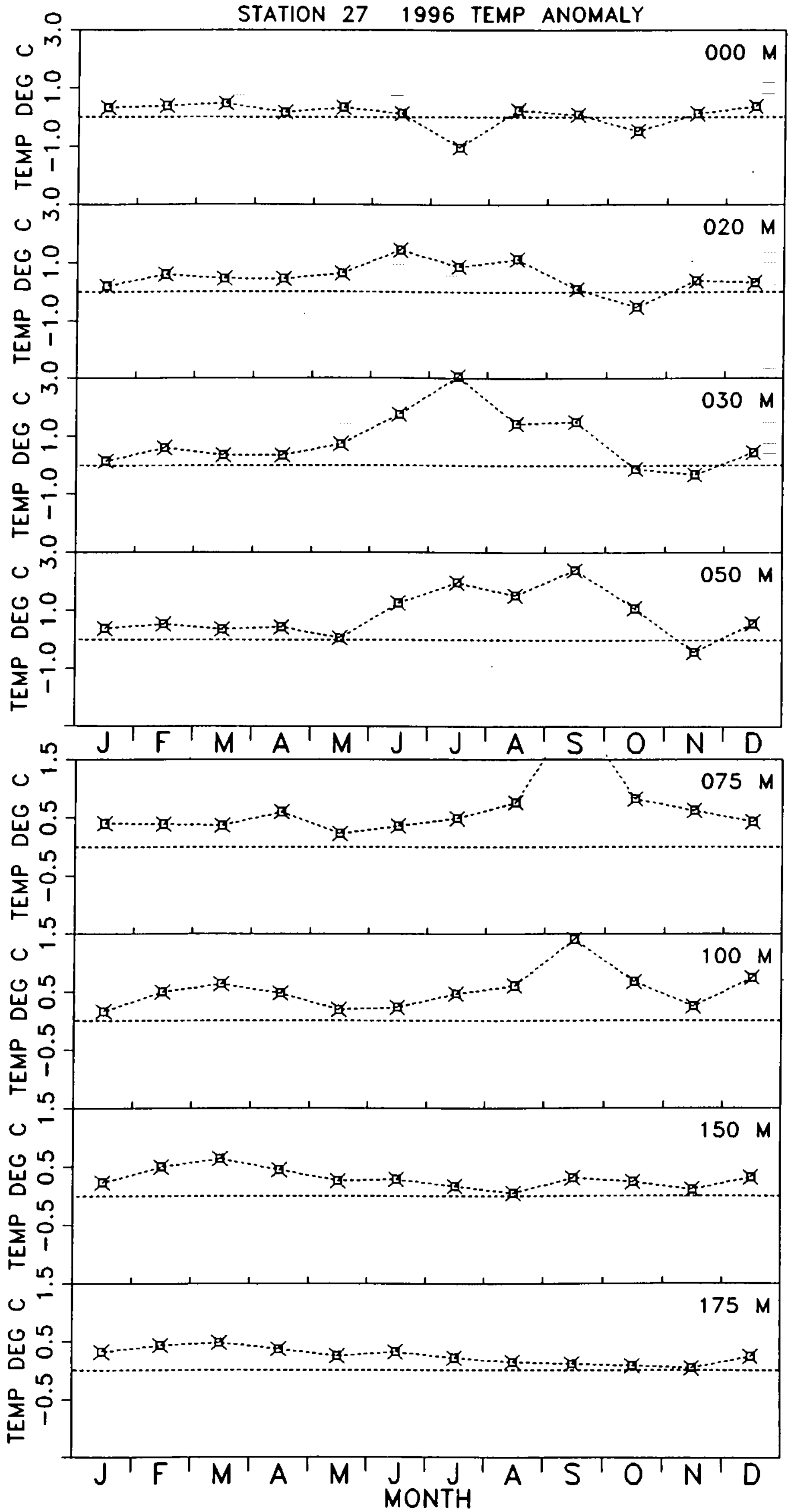


Fig. 4. Time series of monthly temperature anomalies at Station 27 at standard depths during 1996.

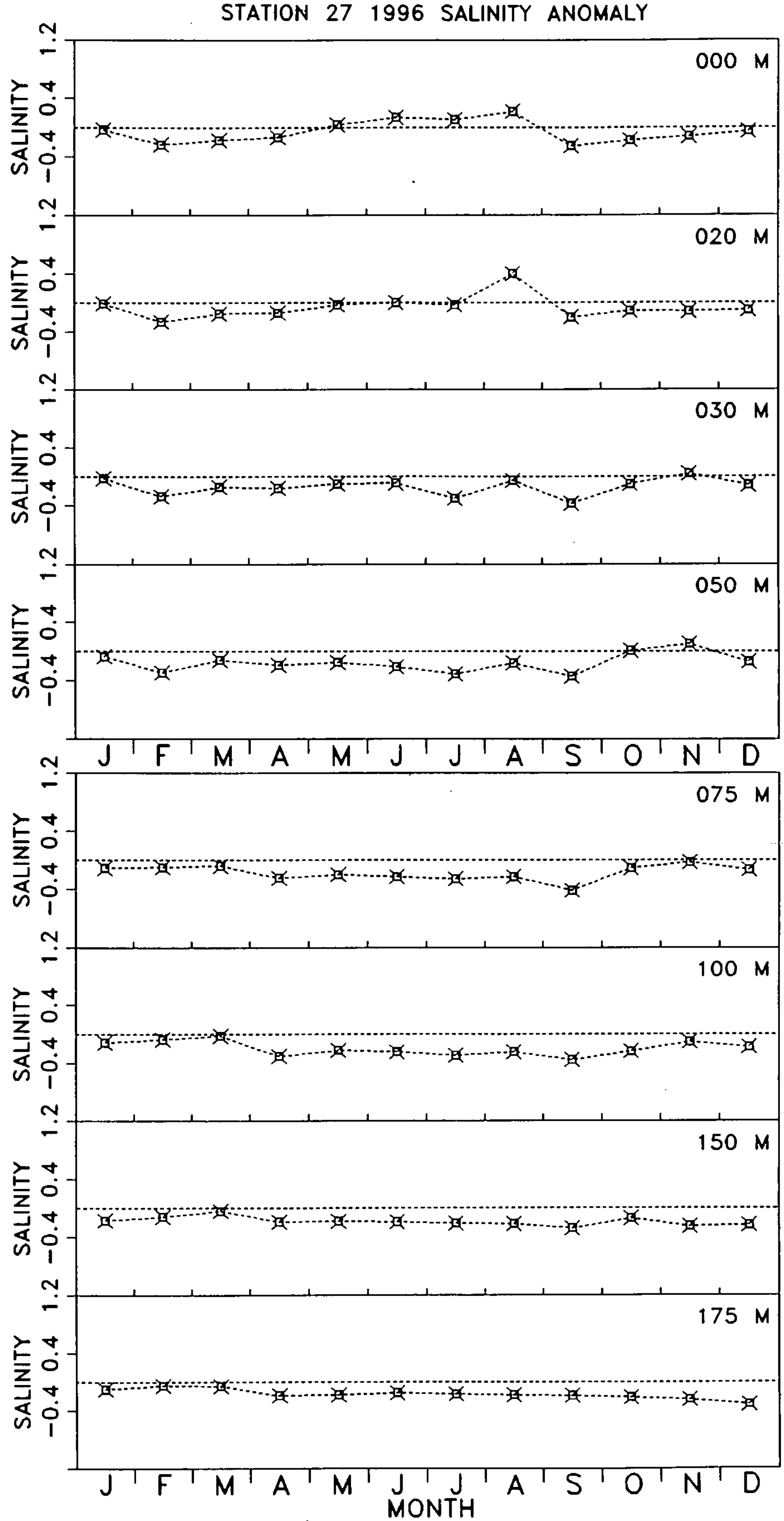


Fig. 5. Time series of monthly salinity anomalies at Station 27 at standard depths during 1996.

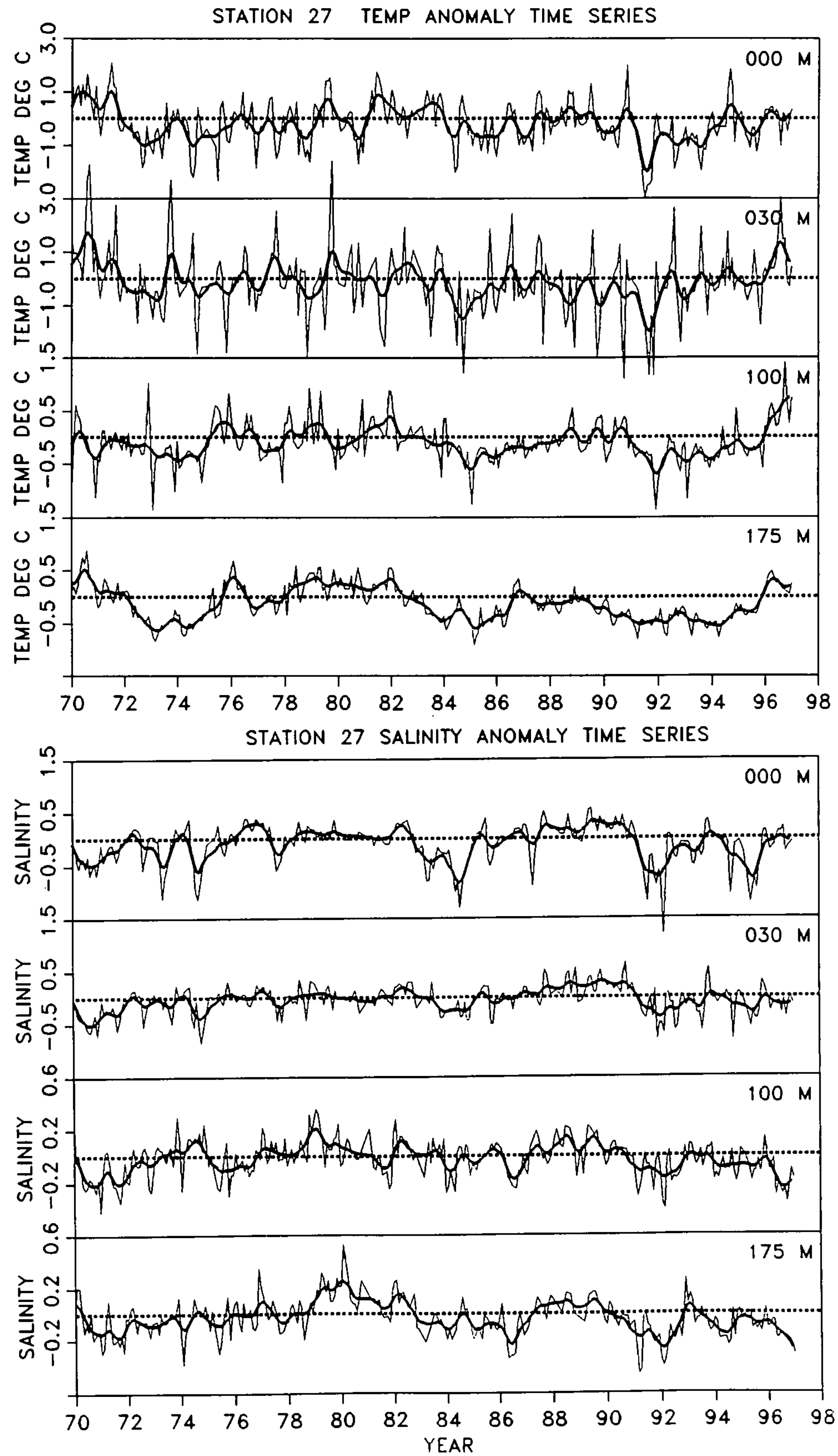


Fig. 6. Time series of monthly temperature and salinity anomalies at Station 27 at standard depths from 1970 to 1996. The heavy lines are the low-passed filtered time series.

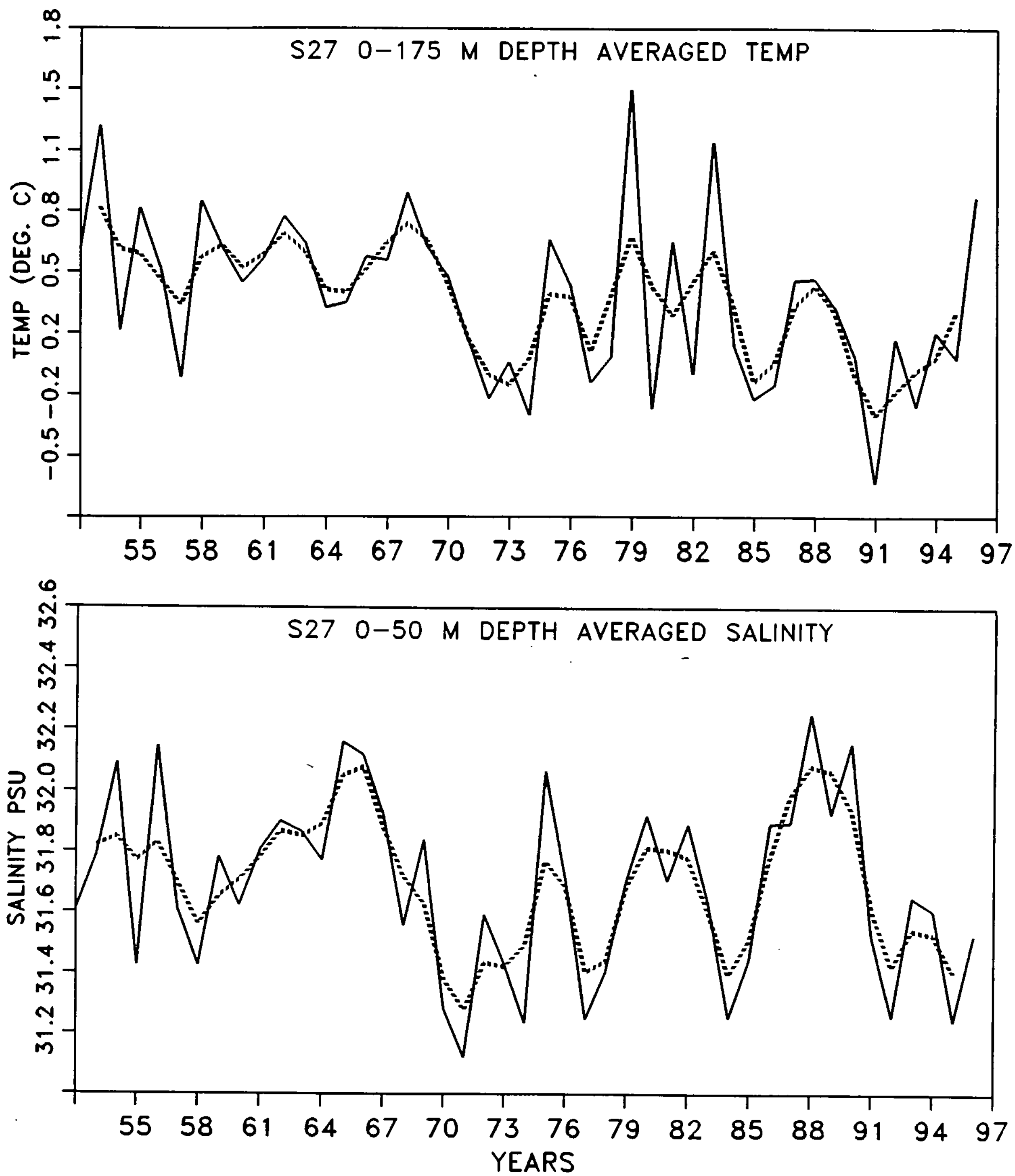


Fig. 7a. Time series of the vertically averaged (0-176 m) Station 27 temperature and the vertically averaged (0-50 m) summer (July-Sept.) Station 27 salinity. The dashed lines are the three year running means.

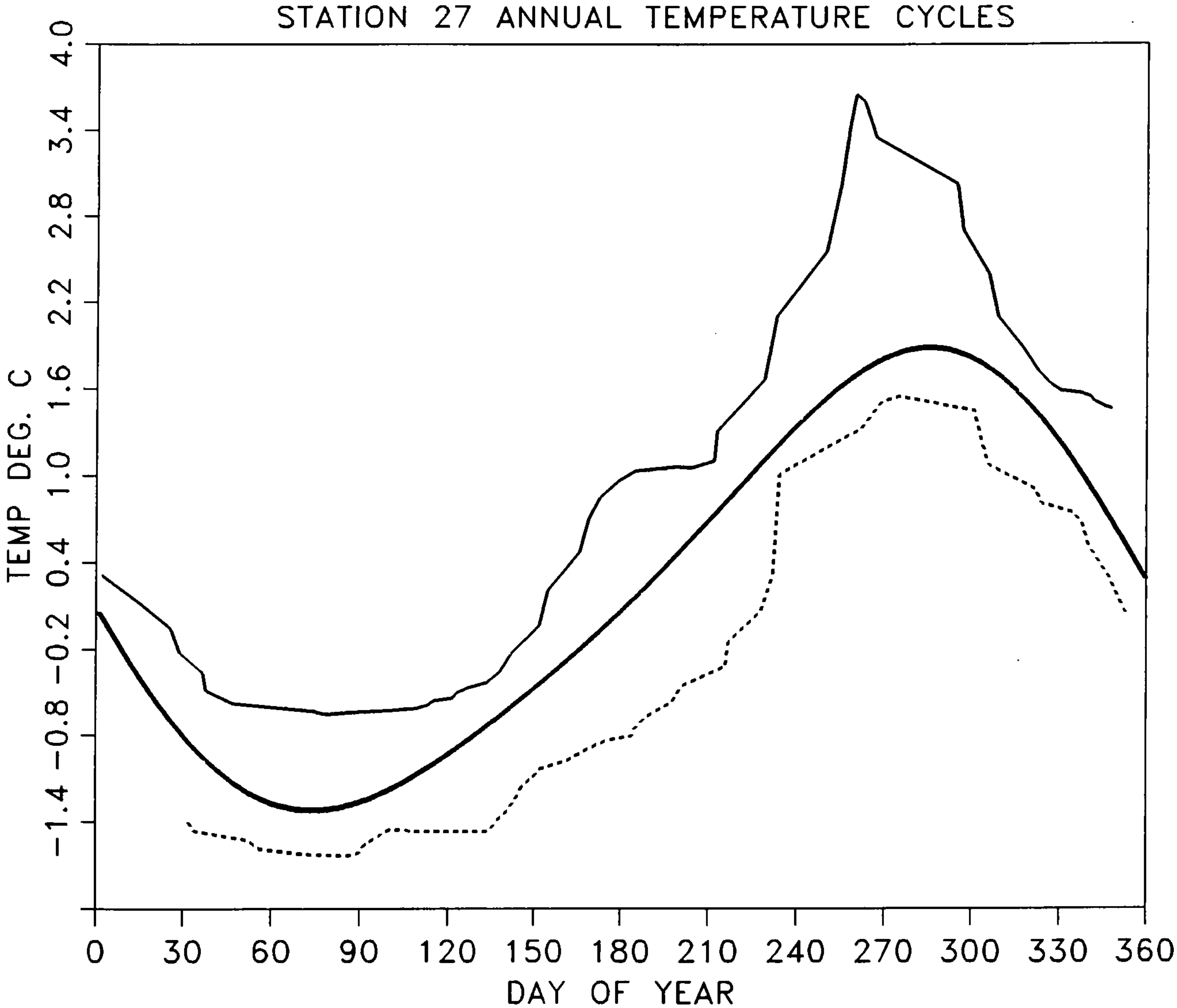


Fig. 7b. The vertically averaged (0-176 m) Station 27 seasonal temperature cycle. The heavy solid line represents the 1961-1990 average, the dashed and solid lines are the 1991 and 1996 cycles respectively.

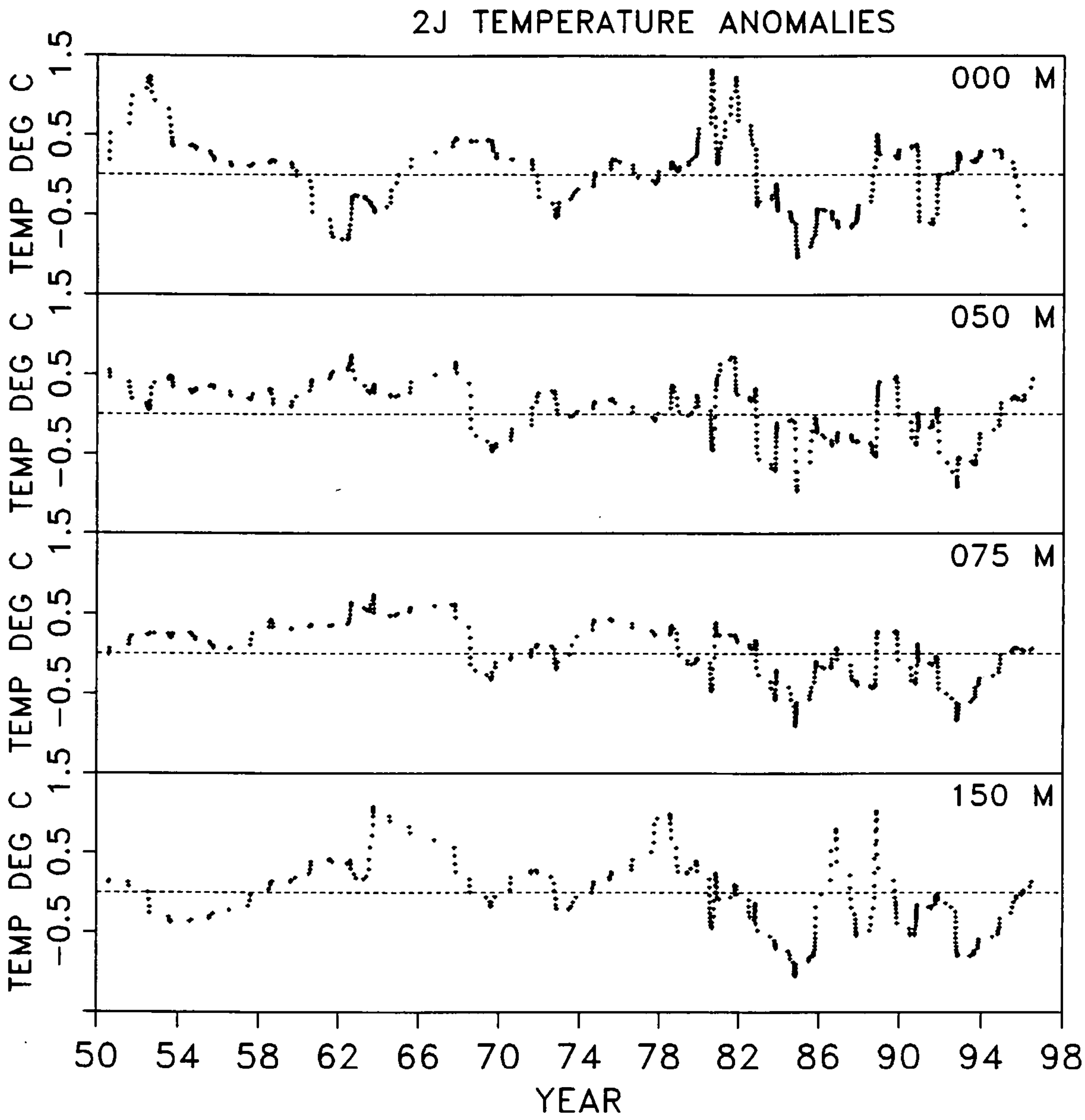


Fig. 8a. Smoothed time series of temperatures anomalies on Hamilton Bank (Fig. 1b) in Division 2J at depths of 0, 50, 75 and 150 m.

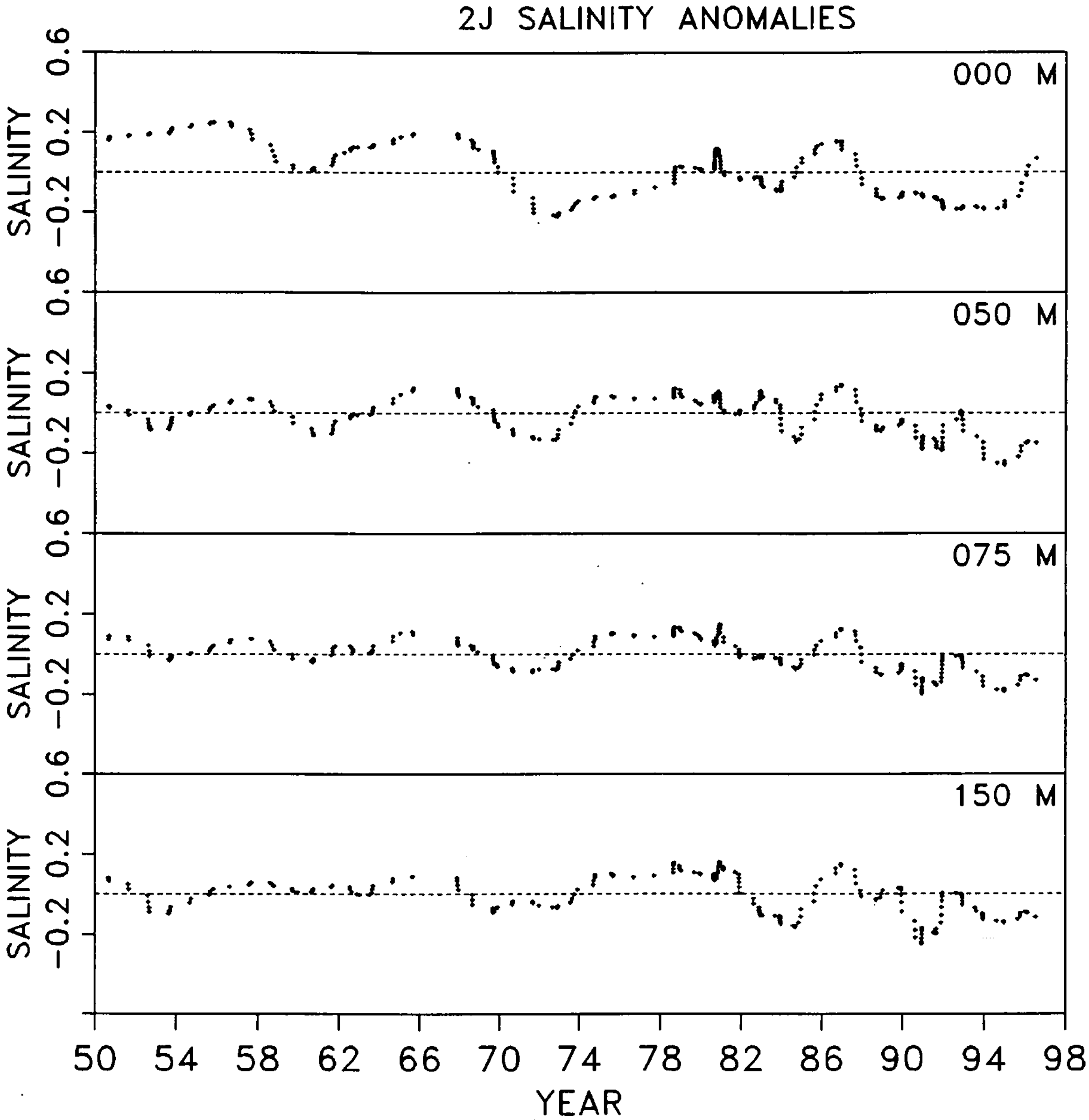


Fig. 8b. Smoothed time series of salinity anomalies on Hamilton Bank (Fig. 1b) in Division 2J at depths of 0, 50, 75 and 150 m.

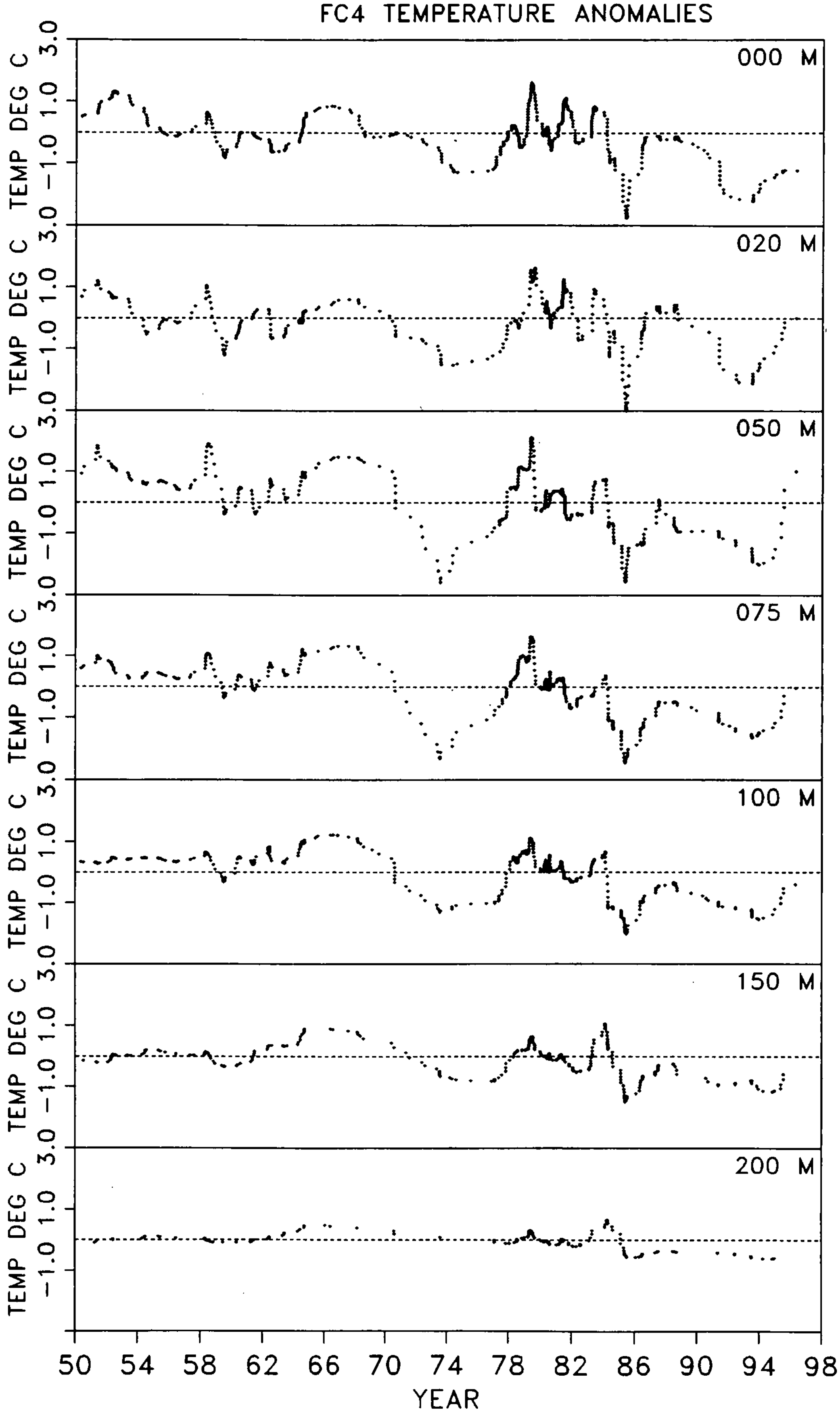


Fig. 9a. Smoothed time series of temperature anomalies at standard depths to 200 m on the Flemish Cap.

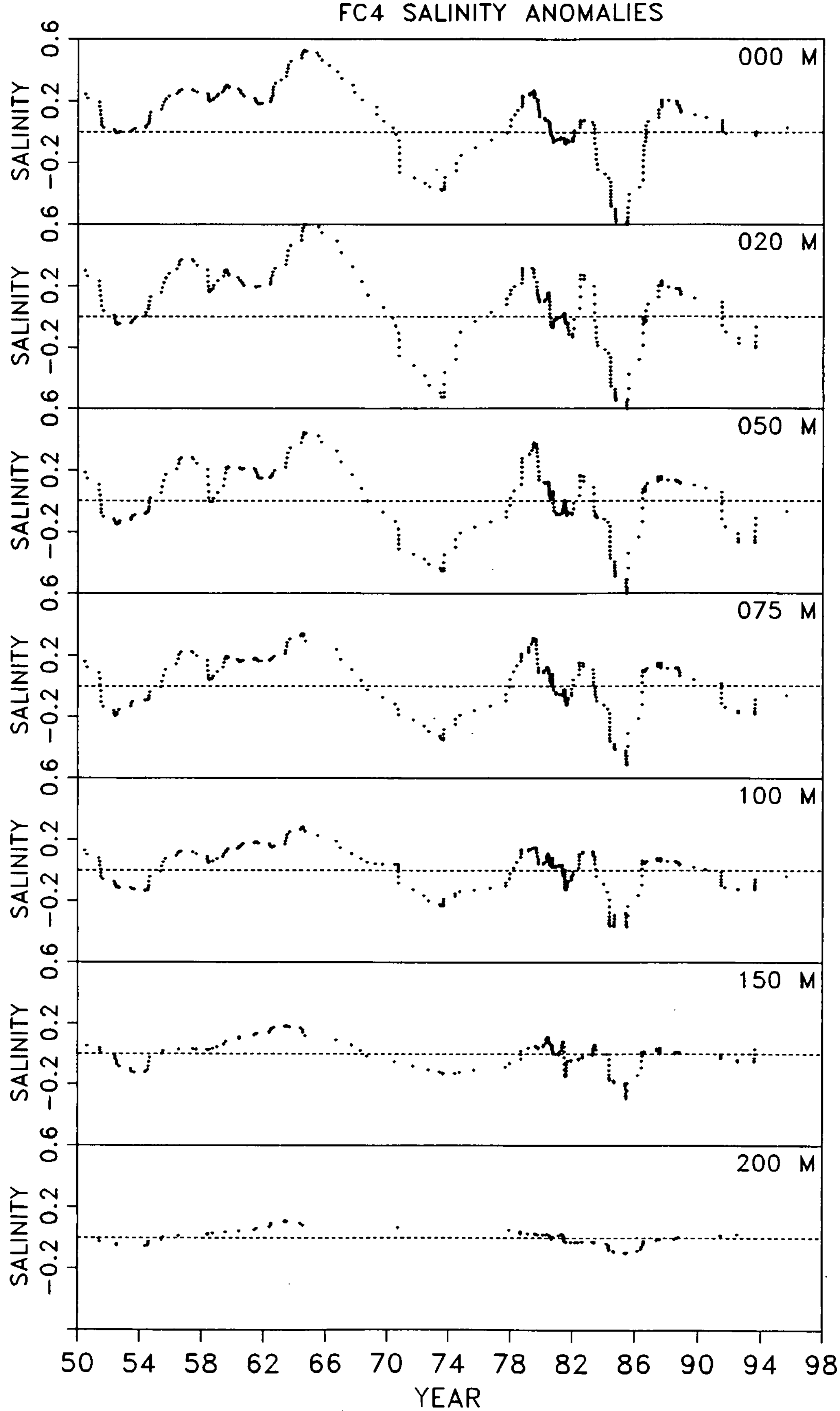


Fig. 9b. Smoothed time series of salinity anomalies at standard depths to 200 m on the Flemish Cap.

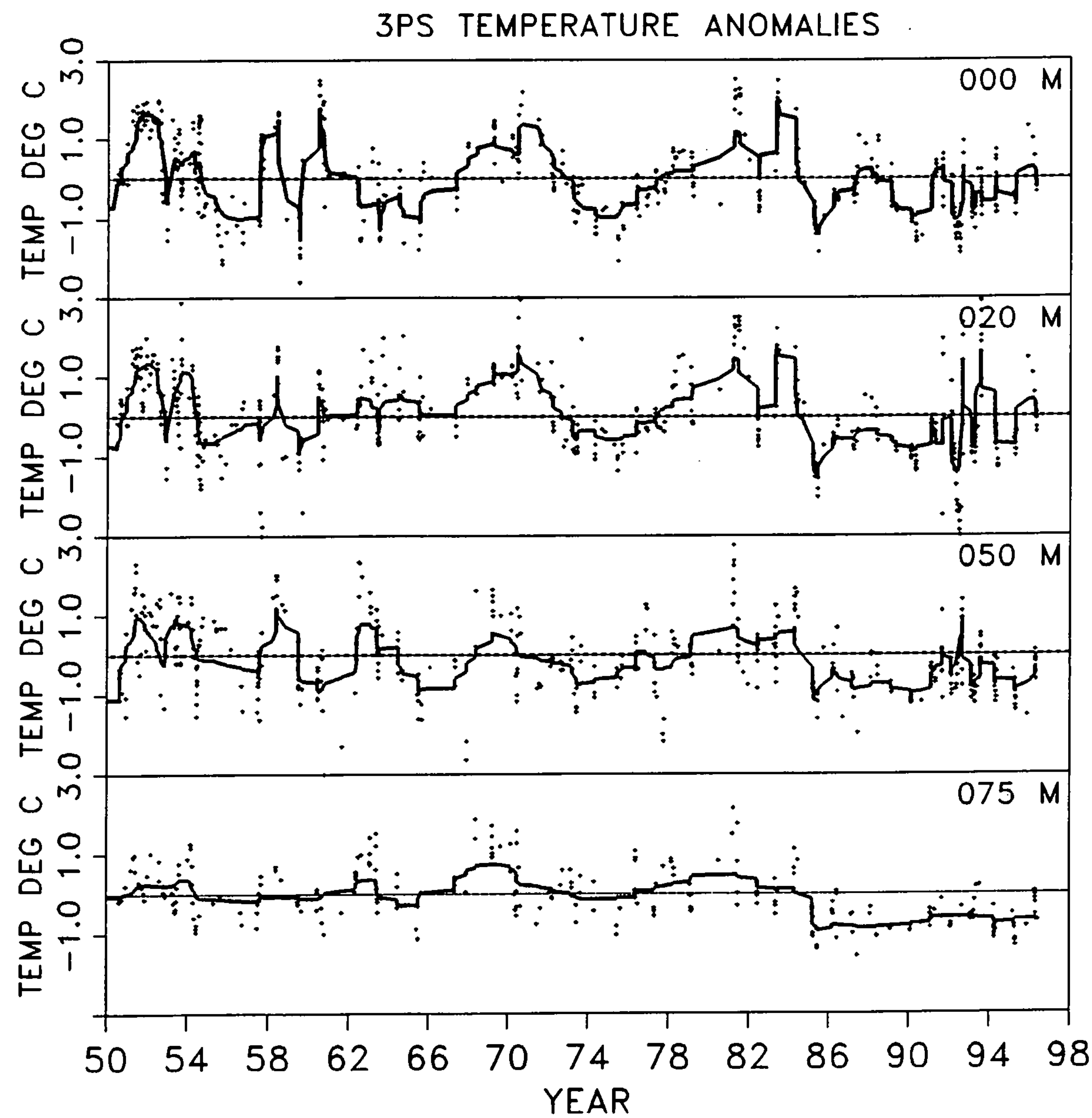


Fig. 10a. Time series of temperature anomalies at standard depths of 0, 20, 50 and 75 m on St. Pierre Bank (Fig. 1b) in Subdivision 3Ps. The solid line represents the smoothed temperature anomalies.

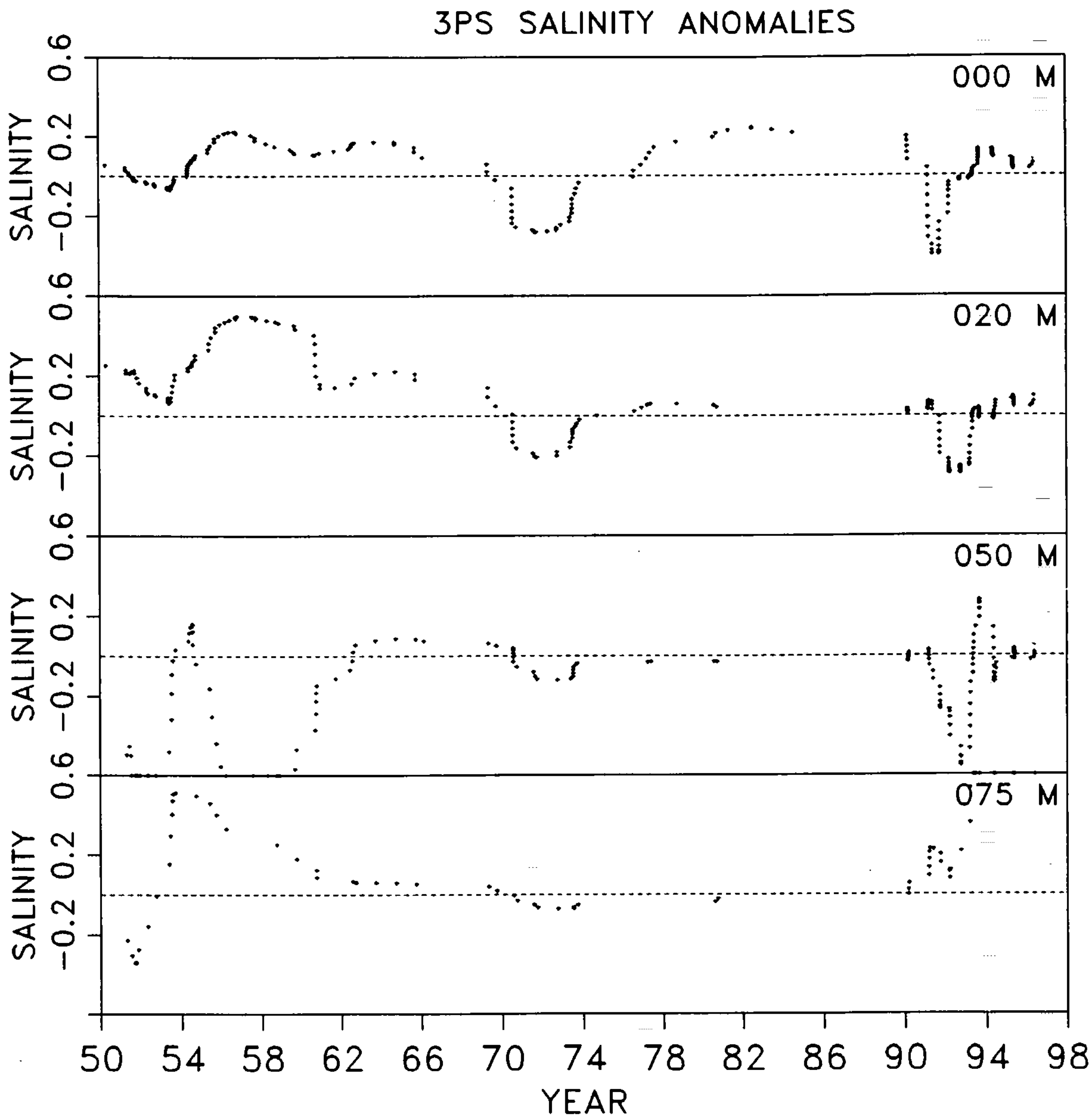


Fig. 10b. Smoothed time series of salinity anomalies at standard depths of 0, 20, 50 and 75 m on St. Pierre Bank (Fig. 1b) in Subdivision 3Ps.

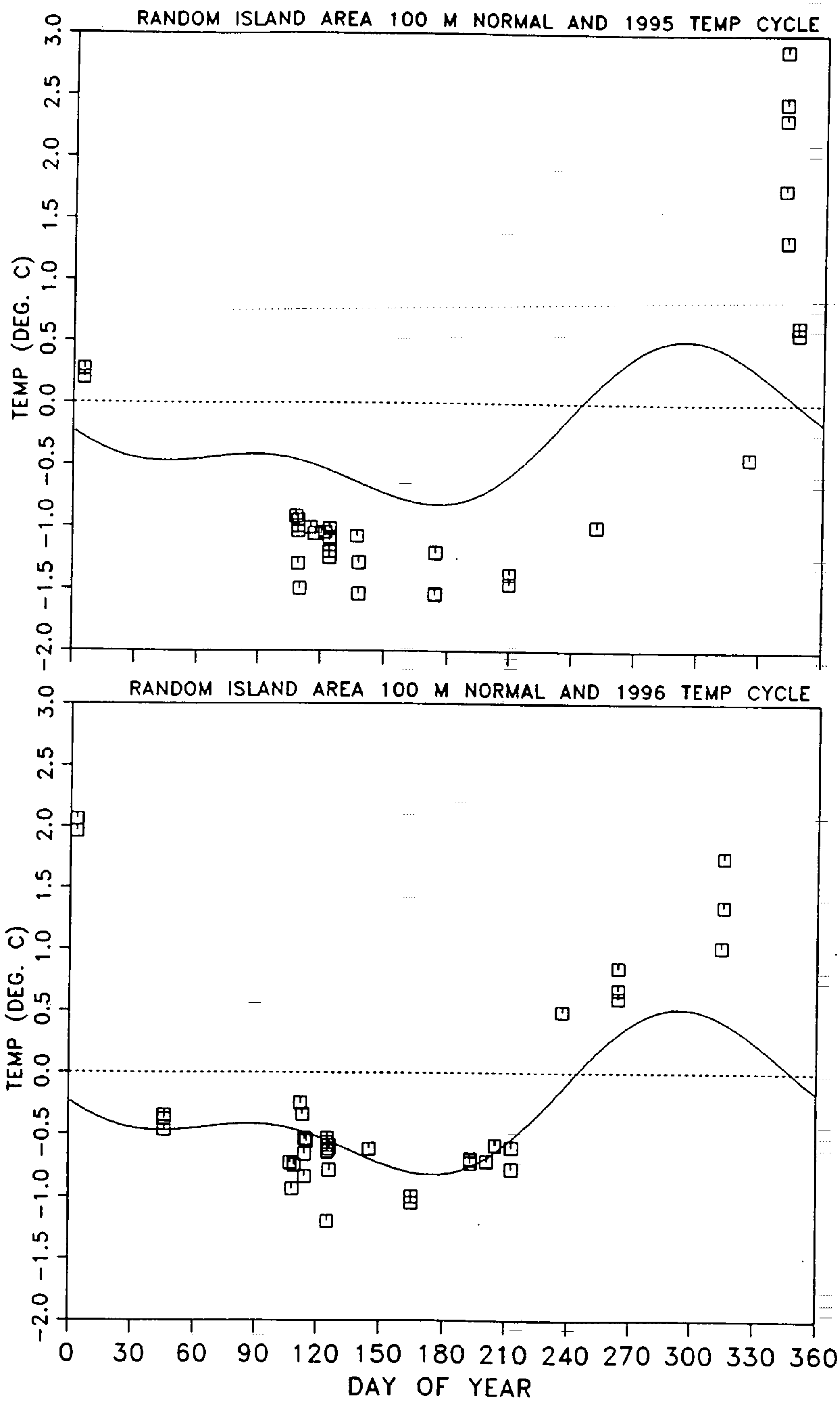


Fig. 11a. Annual temperature anomalies for 1995 and 1996 at 100 m depth for the Random Island area (Fig. 1b). The solid curve represents a least squares fit to the 1961-1990 historical 100 m temperature data.

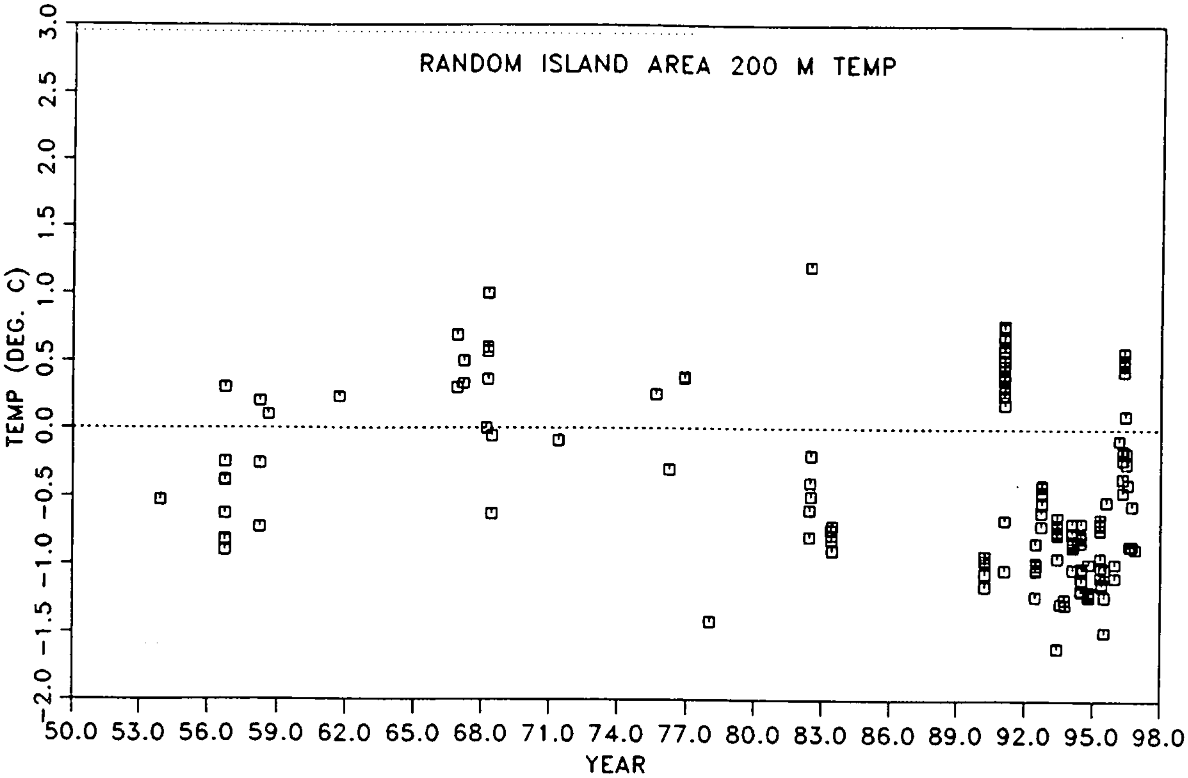


Fig. 11b. Time series of temperatures at 200 m depth for the Random Island area (Fig. 1).

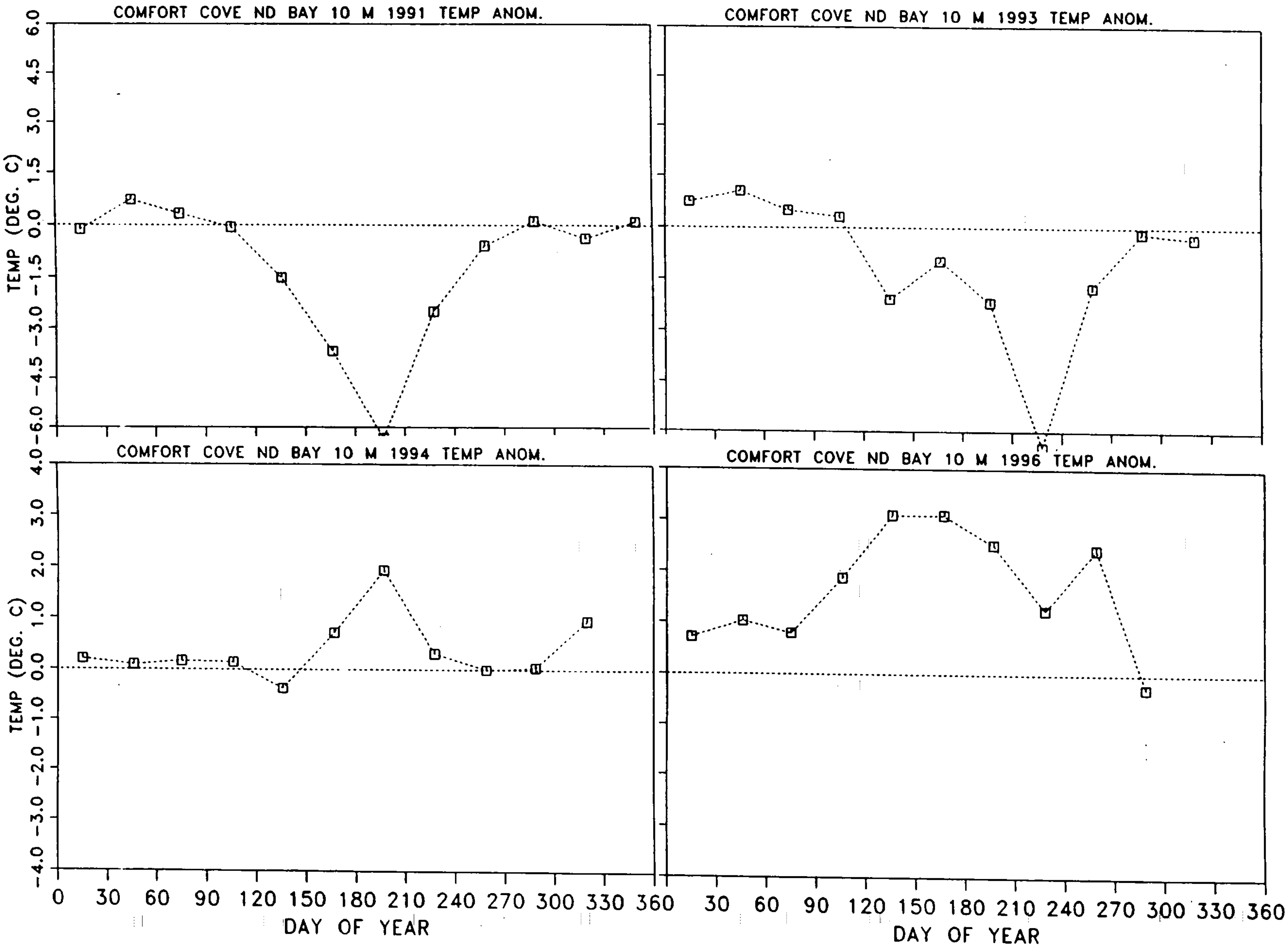


Fig. 12a. Annual temperature anomalies for 1991, 1993, 1994 and 1996 at 10 m depth for Comfort Cove, Notre Dame Bay (Fig. 1b).

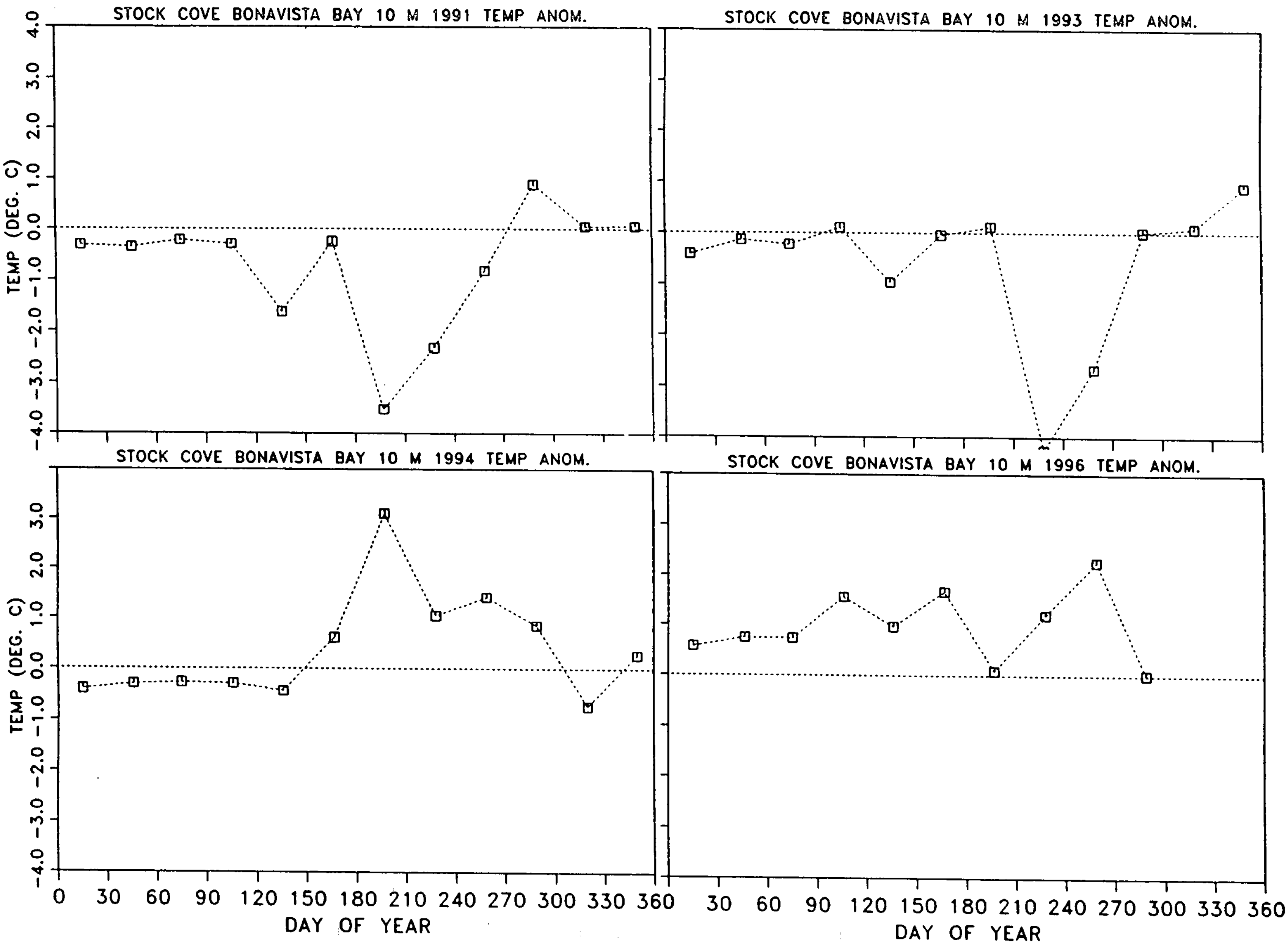


Fig. 12b. Annual temperature anomalies for 1991, 1993, 1994 and 1996 at 10 m depth for Stock Cove, Bonavista Bay (Fig. 1b).

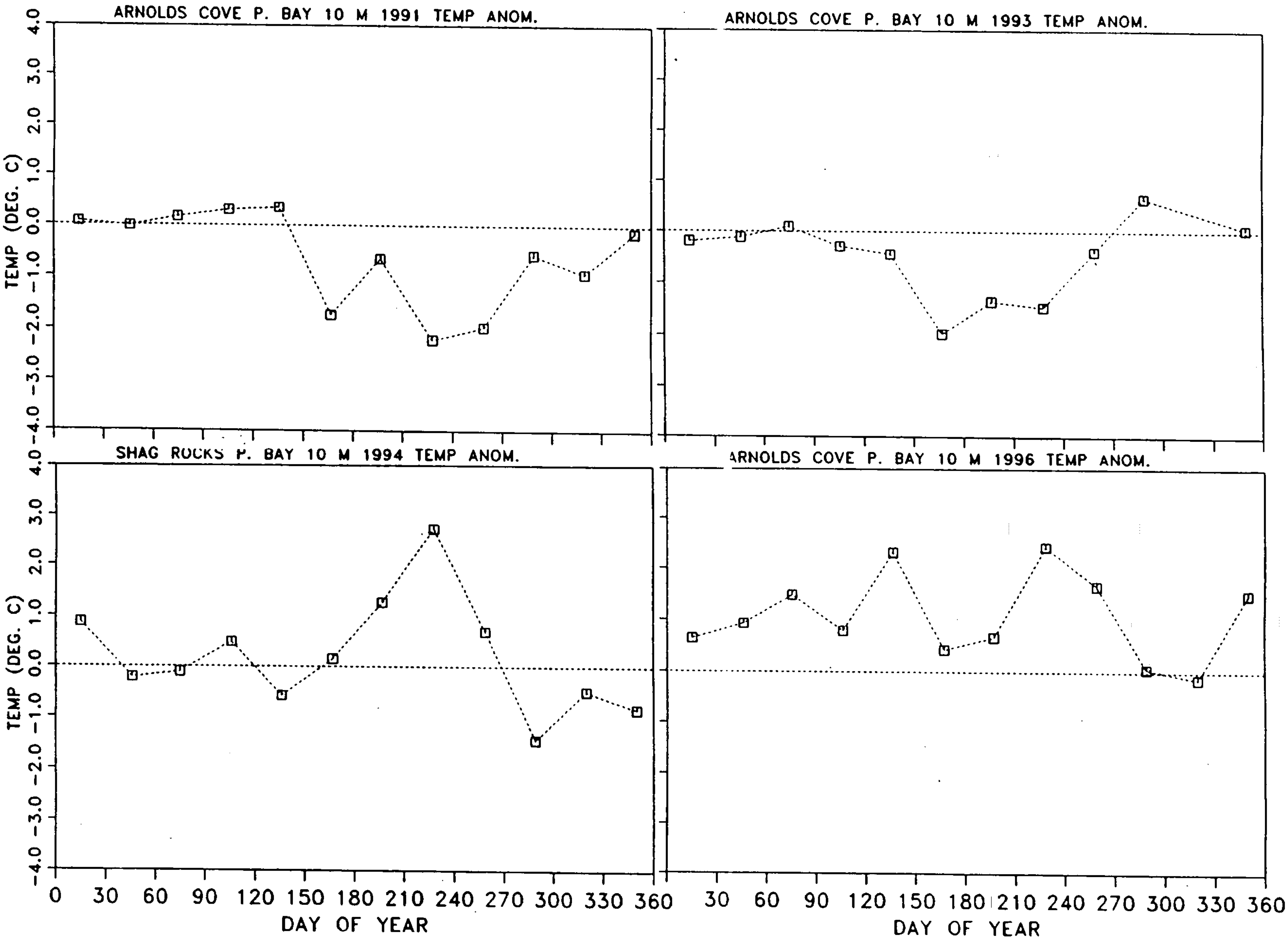
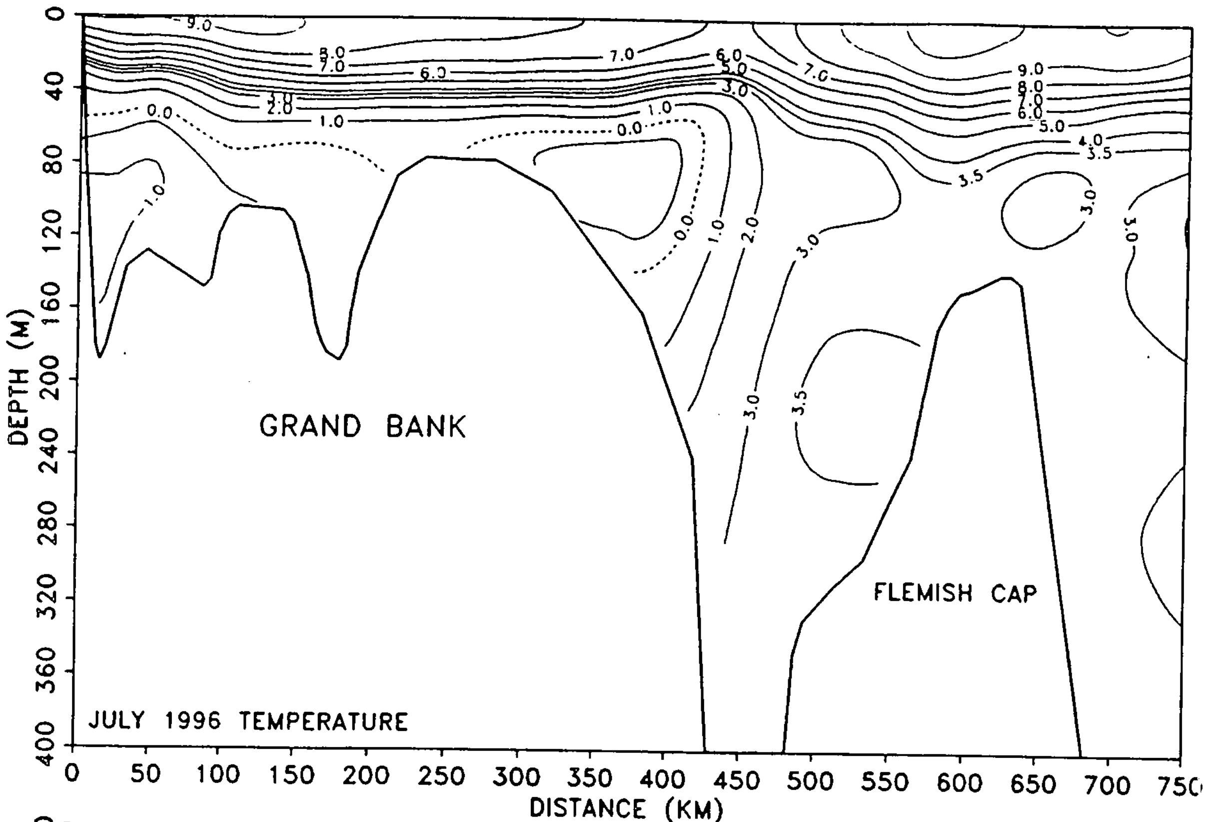


Fig. 12c. Annual temperature anomalies for 1991, 1993, 1994 and 1996 at 10 m depth for Arnolds Cove, Placentia Bay (Fig. 1b).



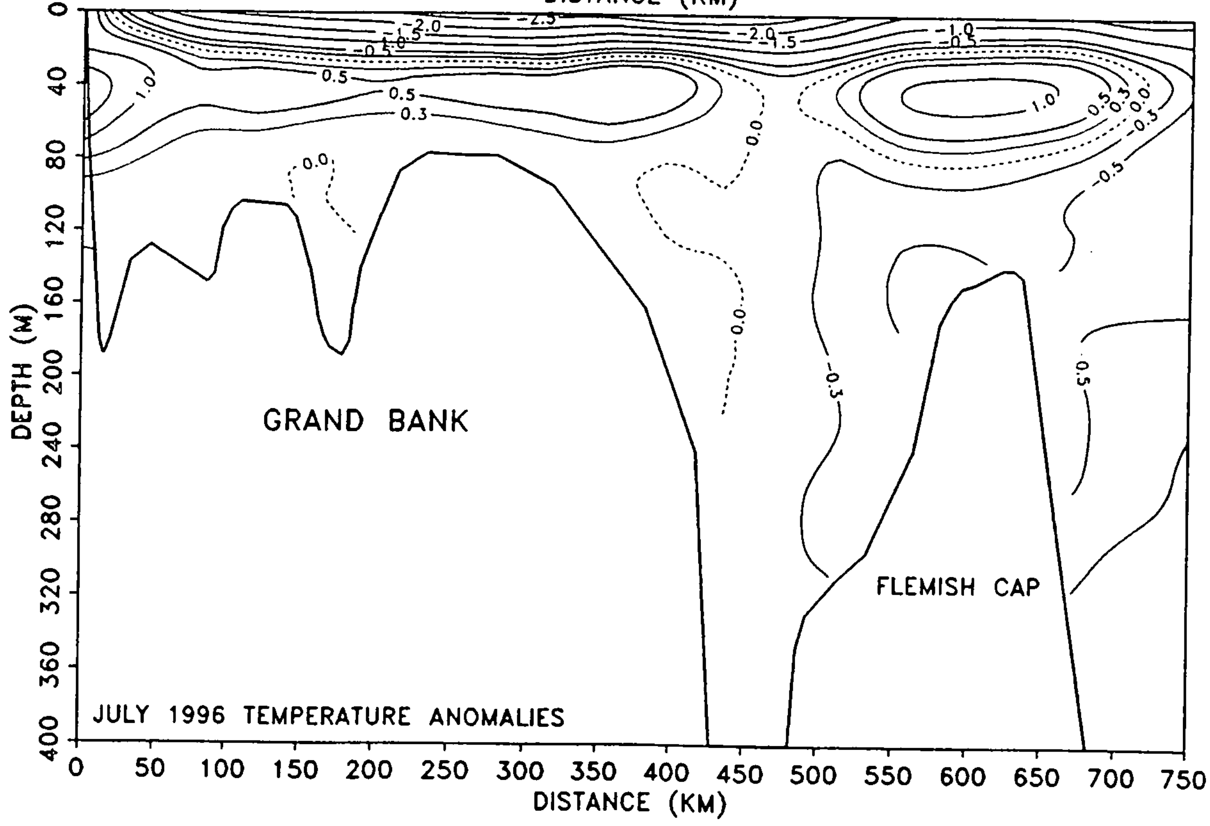


Fig. 13a. The vertical distribution of temperature and temperature anomalies along the standard Flemish Cap transect for the summer (July) of 1996.

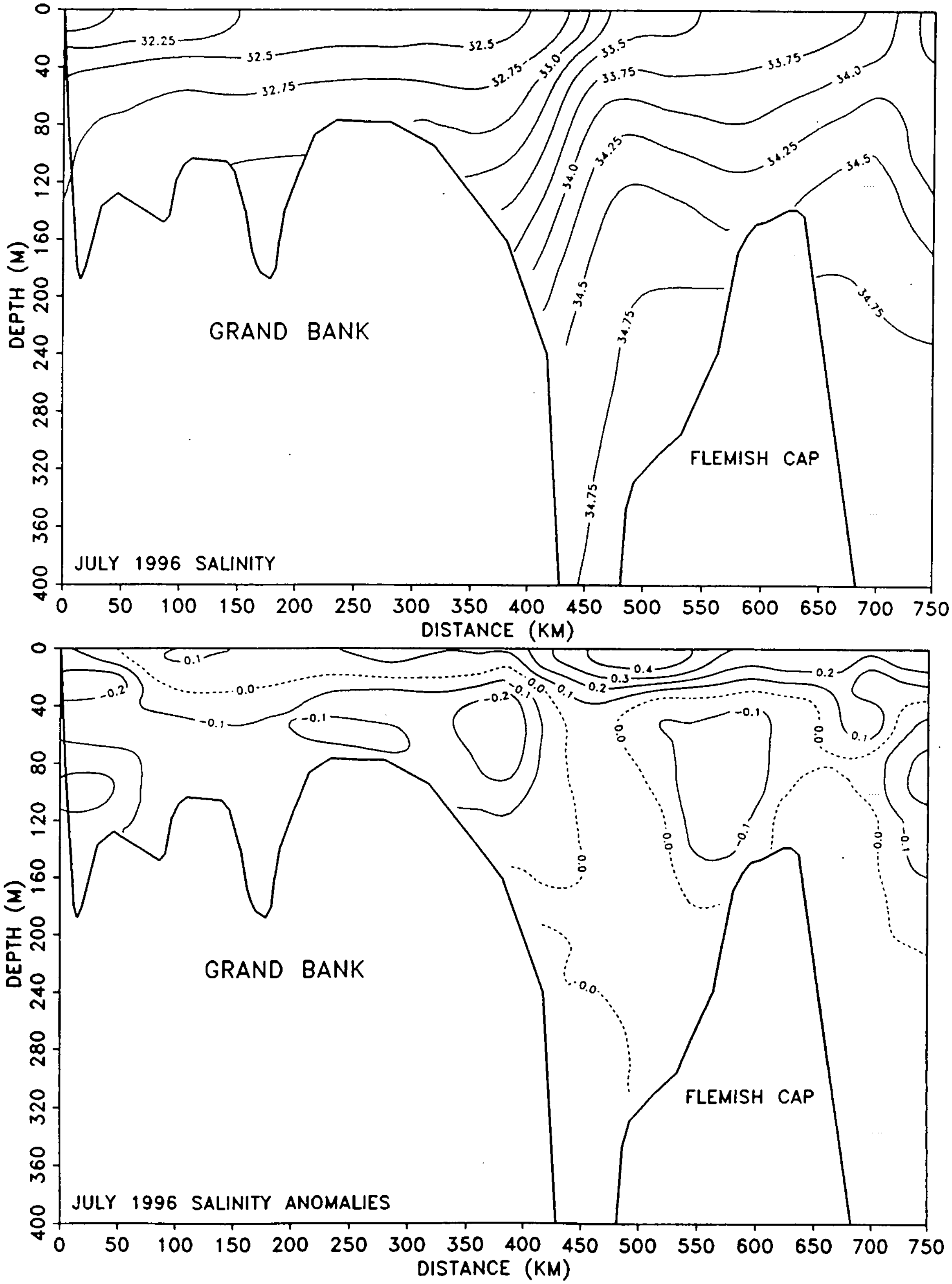


Fig. 13b. The vertical distribution of salinity and salinity anomalies along the standard Flemish Cap transect for the summer (July) of 1996.

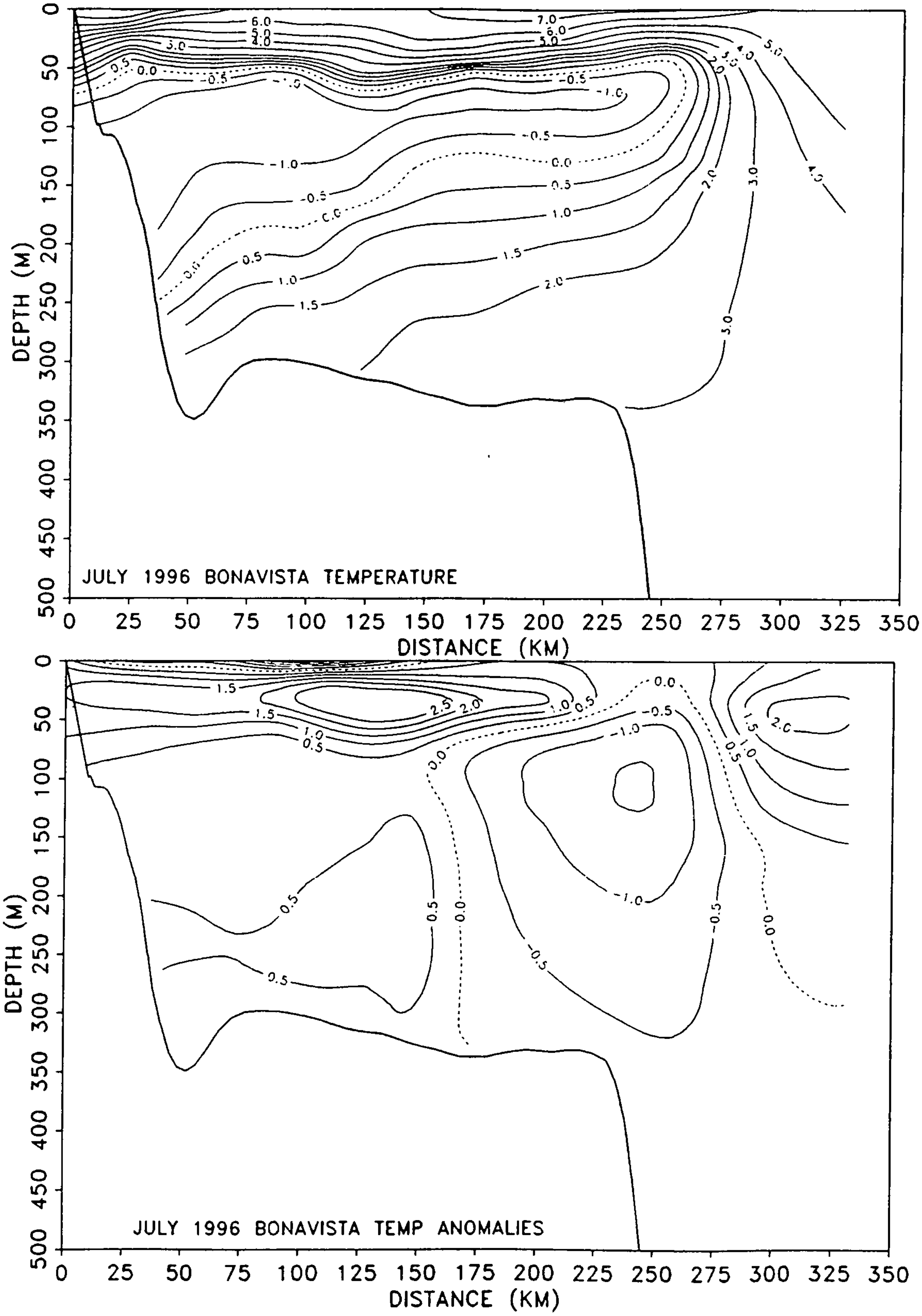


Fig. 14a. The vertical distribution of temperature and temperature anomalies along the standard Bonavista transect for the summer (July) of 1996.

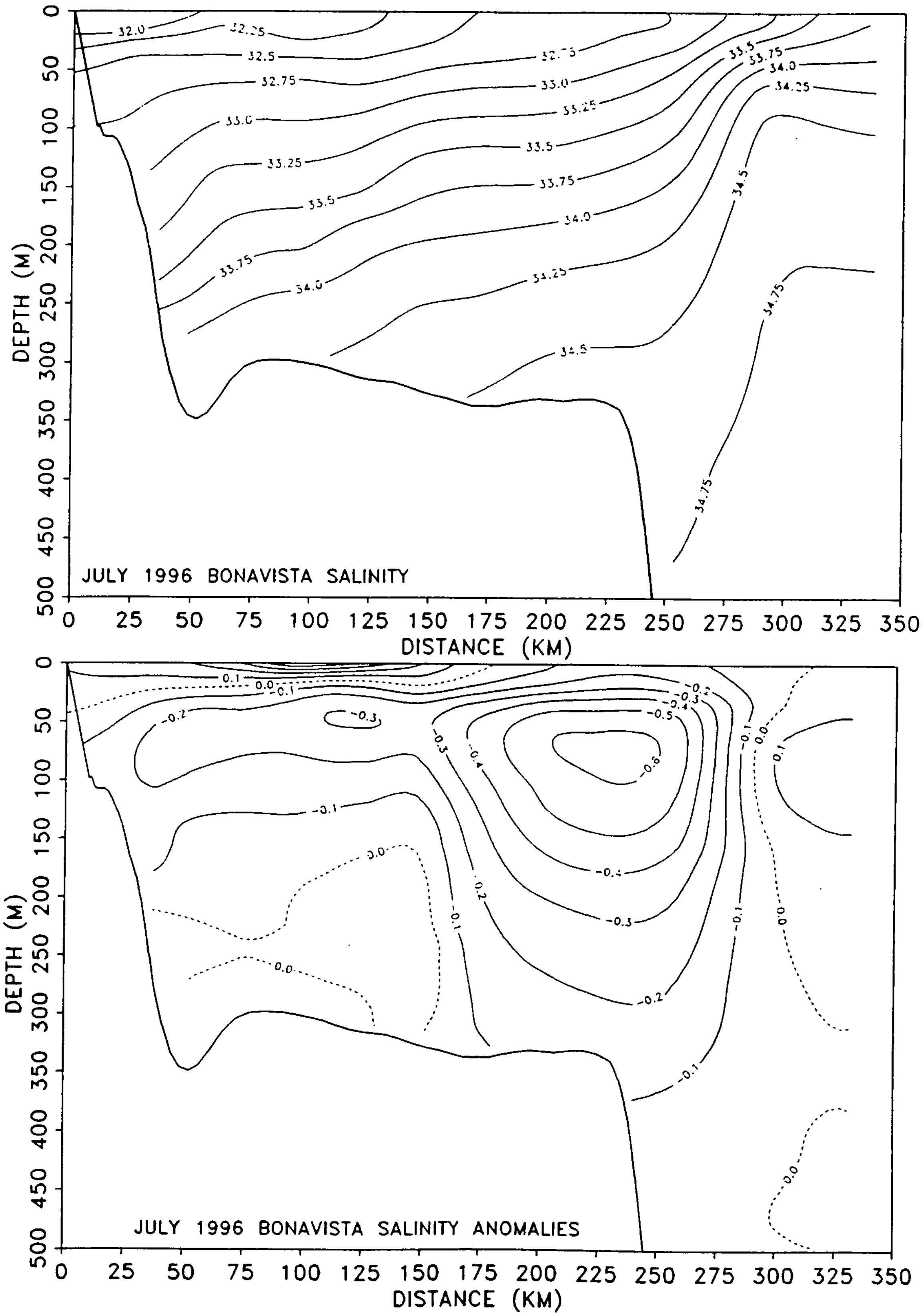


Fig. 14b. The vertical distribution of salinity and salinity anomalies along the standard Bonavista transect for the summer (July) of 1996.

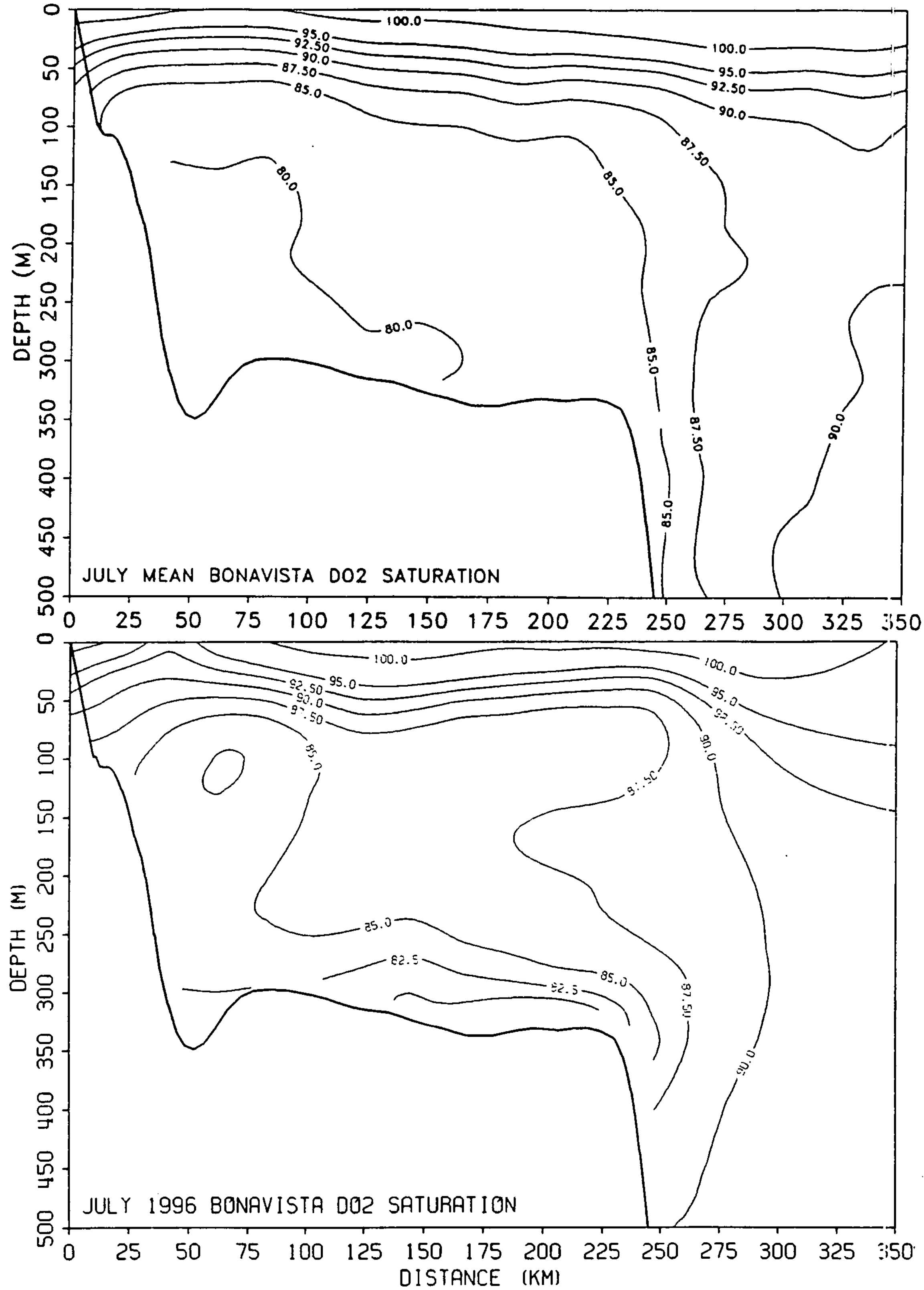


Fig. 14c. The vertical distribution of dissolved oxygen saturation along the standard Bonavista transect for the average of historical data (top panel) and for July, 1996 (bottom panel).

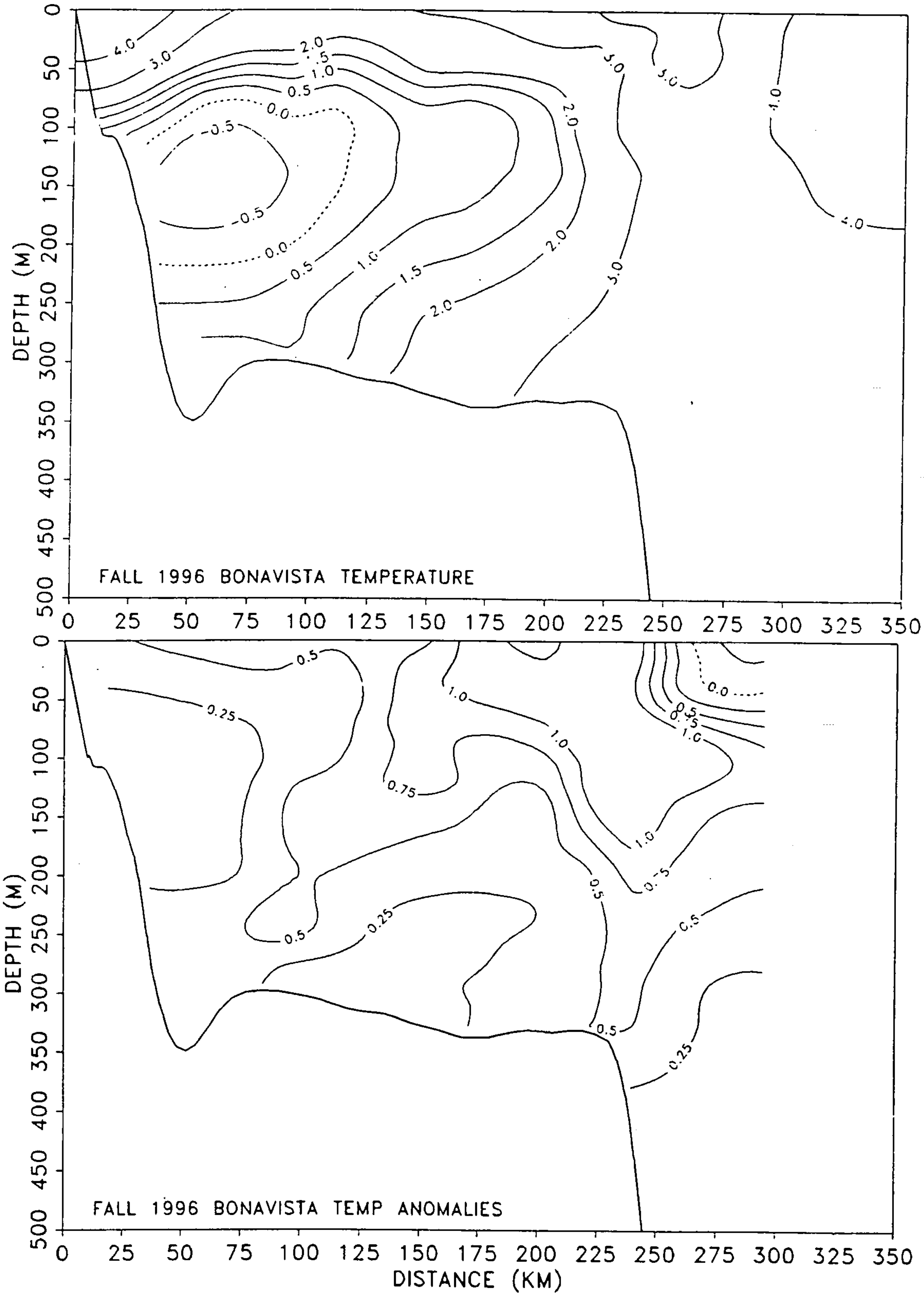


Fig. 14d. The vertical distribution of temperature and temperature anomalies along the standard Bonavista transect for the fall of 1996.

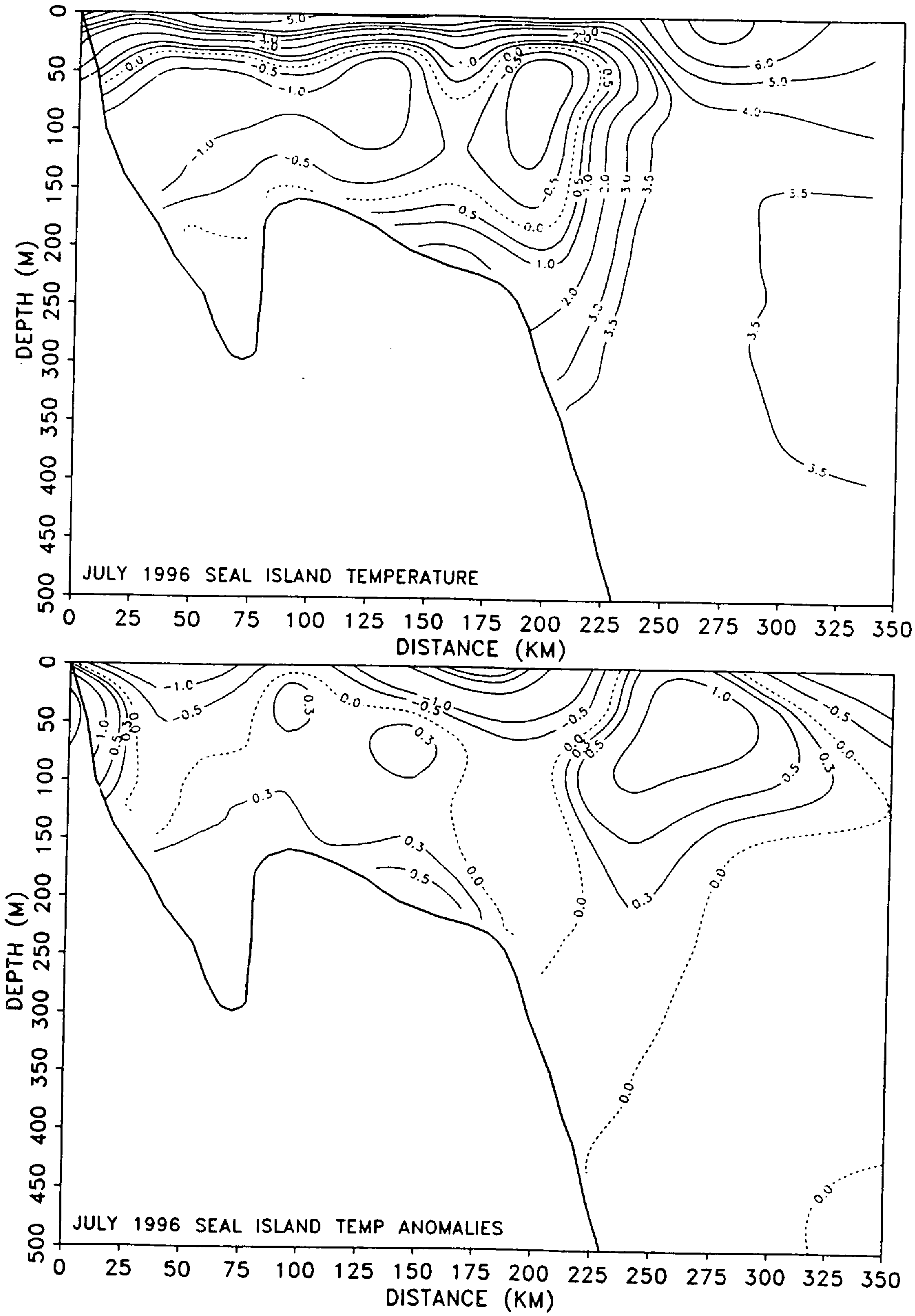


Fig. 15a. The vertical distribution of temperature and temperature anomalies along the standard Seal Island transect for the summer (July) of 1996.

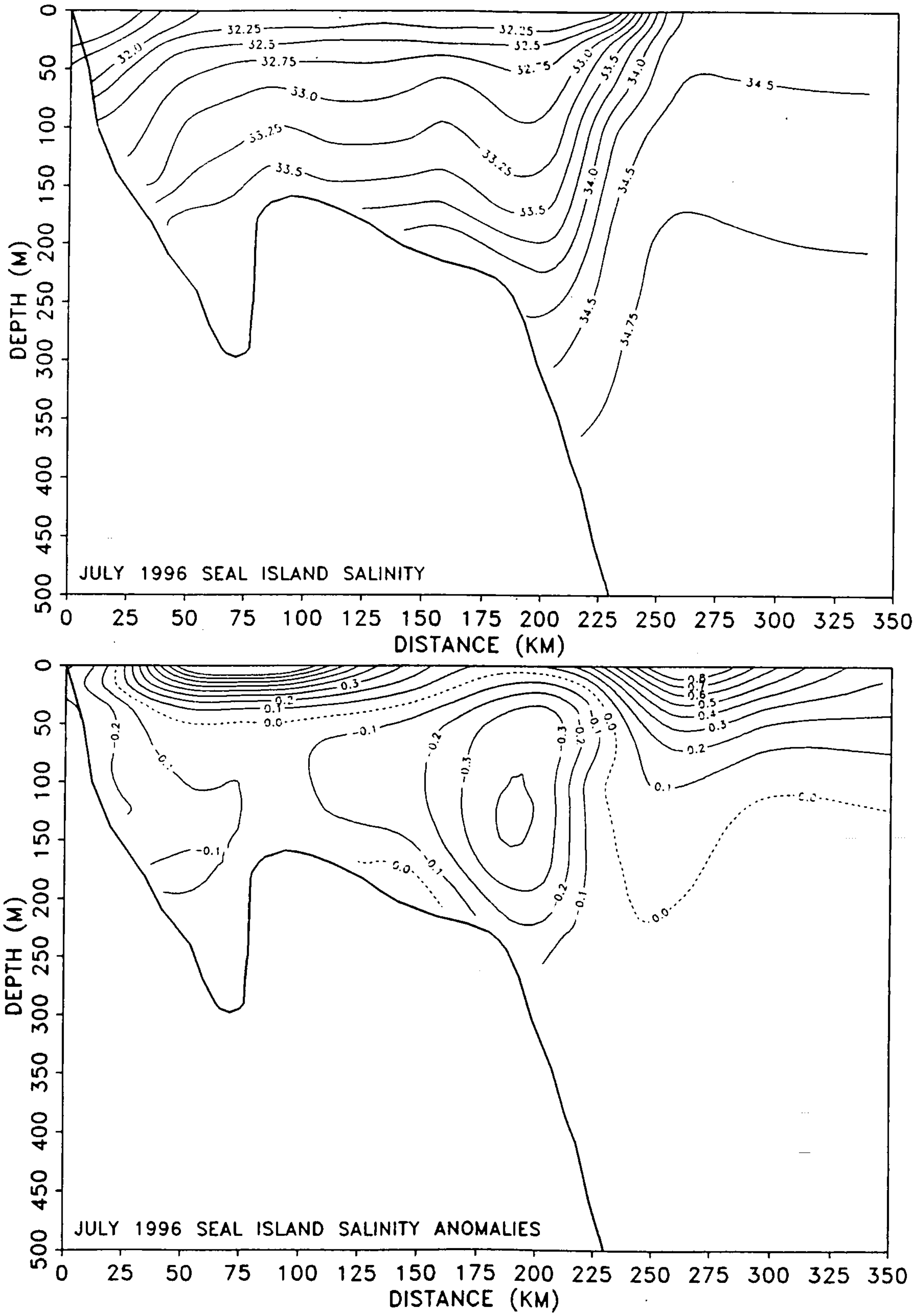


Fig. 15b. The vertical distribution of salinity and salinity anomalies along the standard Seal Island transect for the summer (July) of 1996.

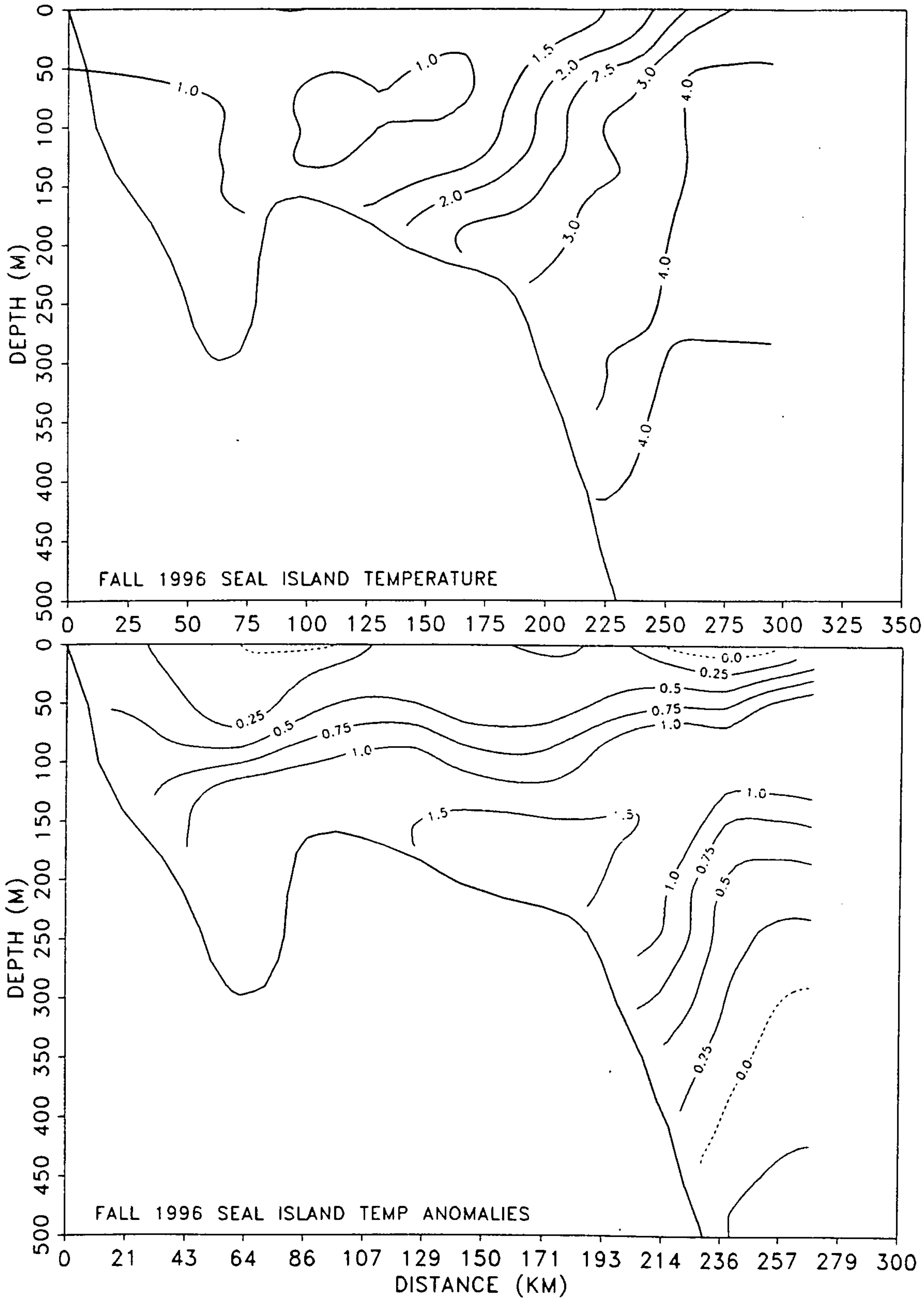


Fig. 15c. The vertical distribution of temperature and temperature anomalies along the standard Seal Island transect for the fall of 1996.

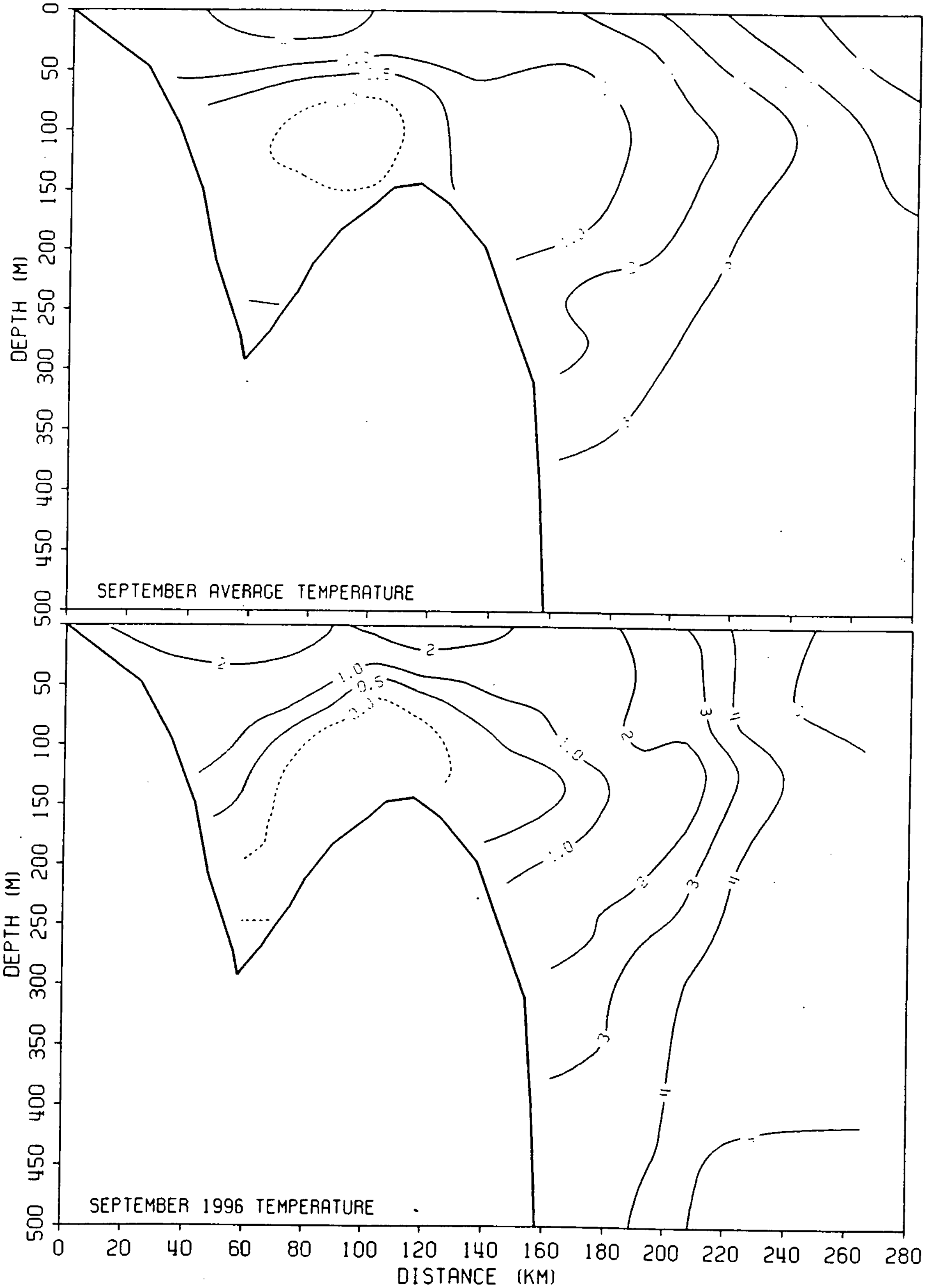


Fig. 16. The vertical distribution of the fall average and the fall 1996 temperature along the standard Nain Bank transect.

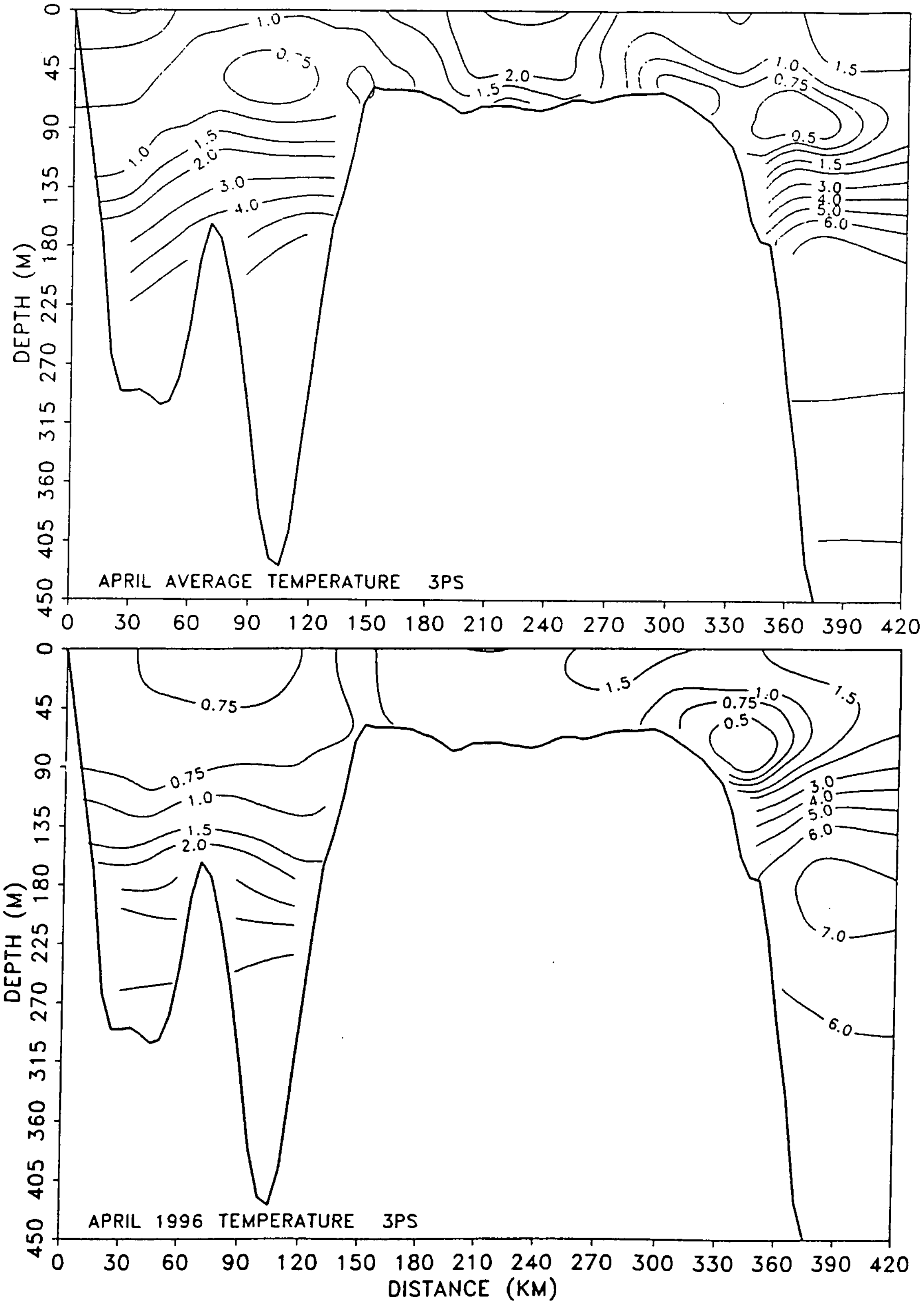


Fig. 17. The average and the 1996 April temperature along the transect shown in Fig. 1 for NAFO Subdivisions 3Pn and 3Ps.

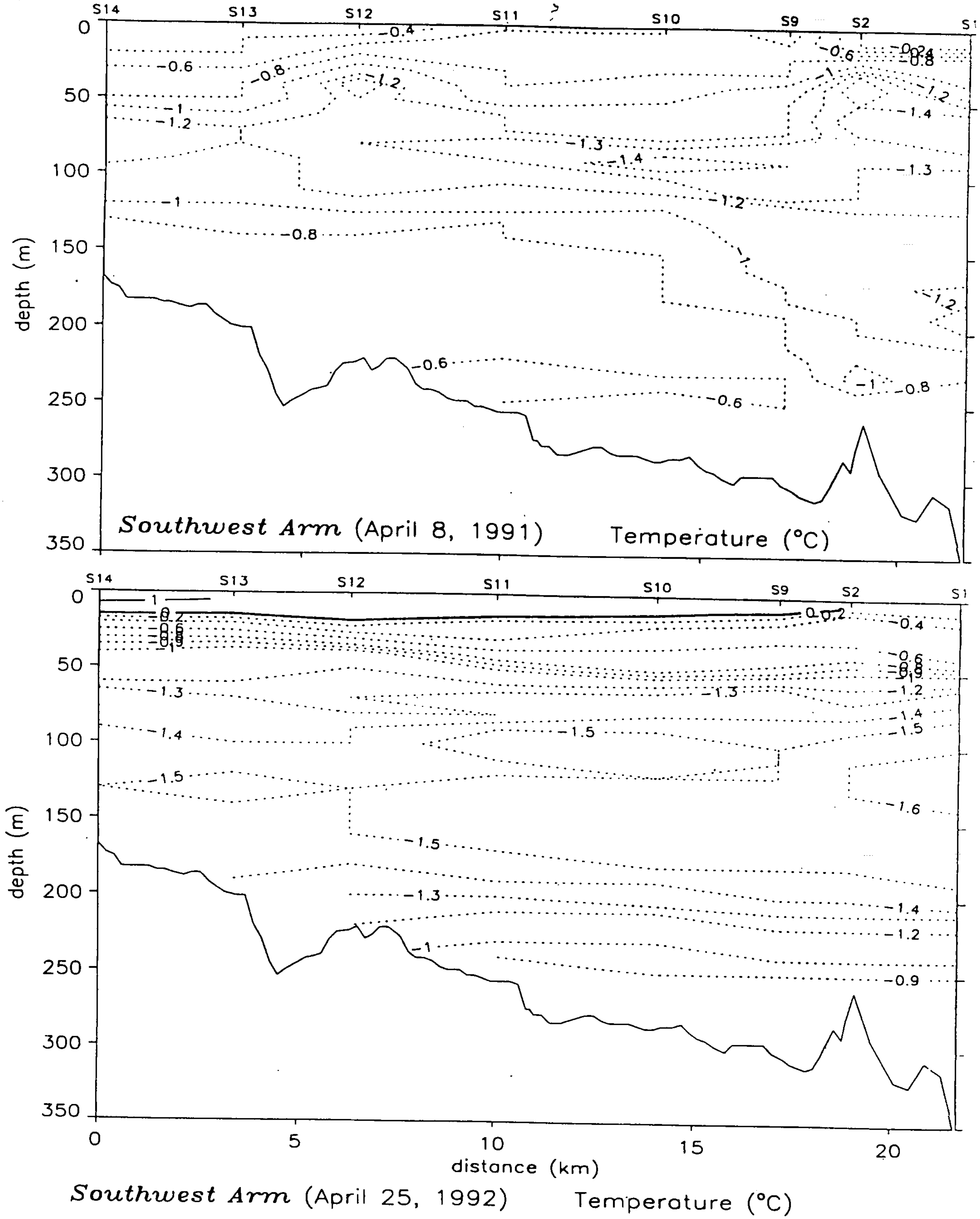


Fig. 18a. The vertical distribution of temperature along Southwest Arm, Trinity Bay for April of 1991 and 1992 (from Wroblewski et al. 1993).

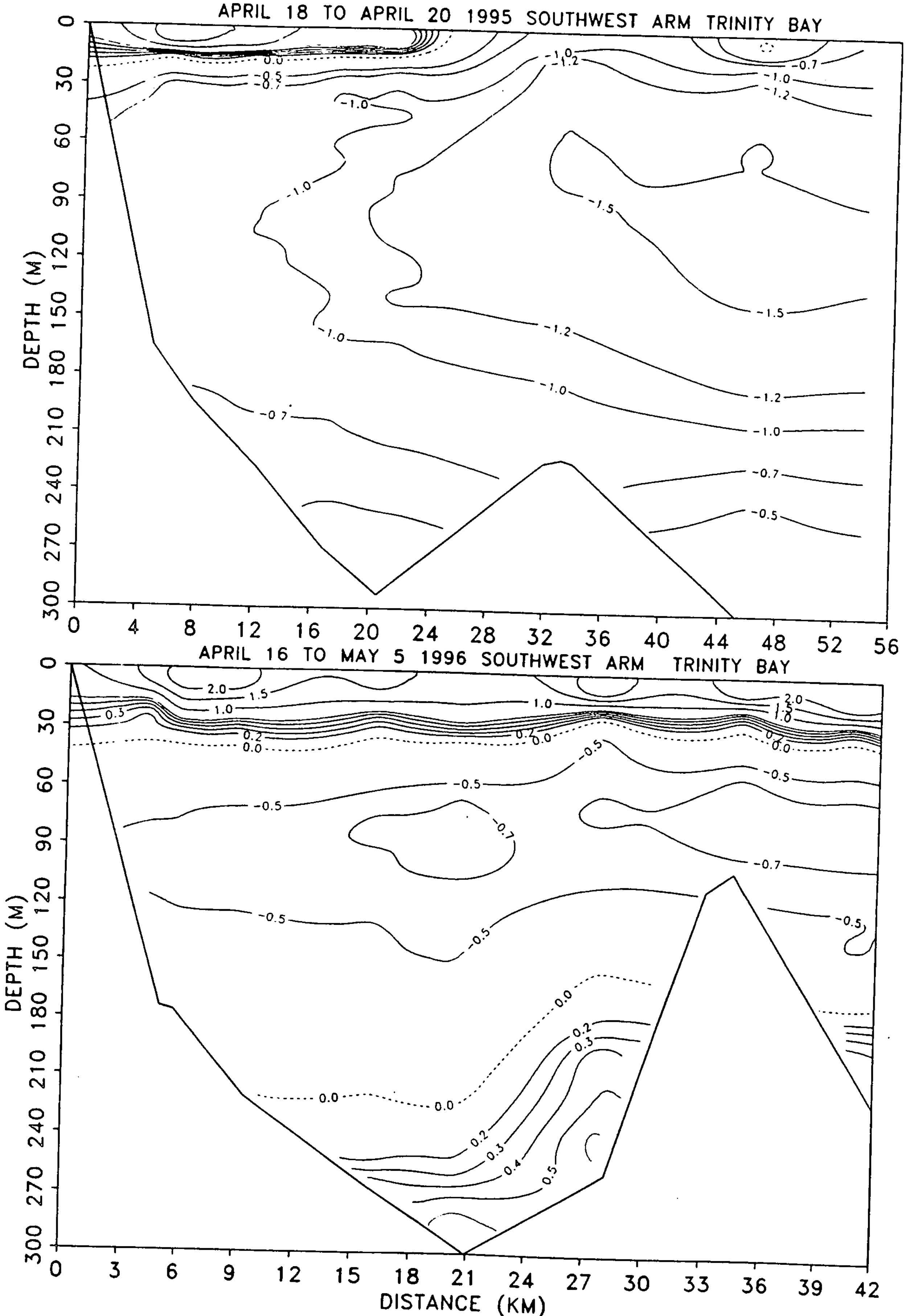


Fig. 18b. The vertical distribution of temperature along Southwest Arm, Trinity Bay for April 1995 and 1996.

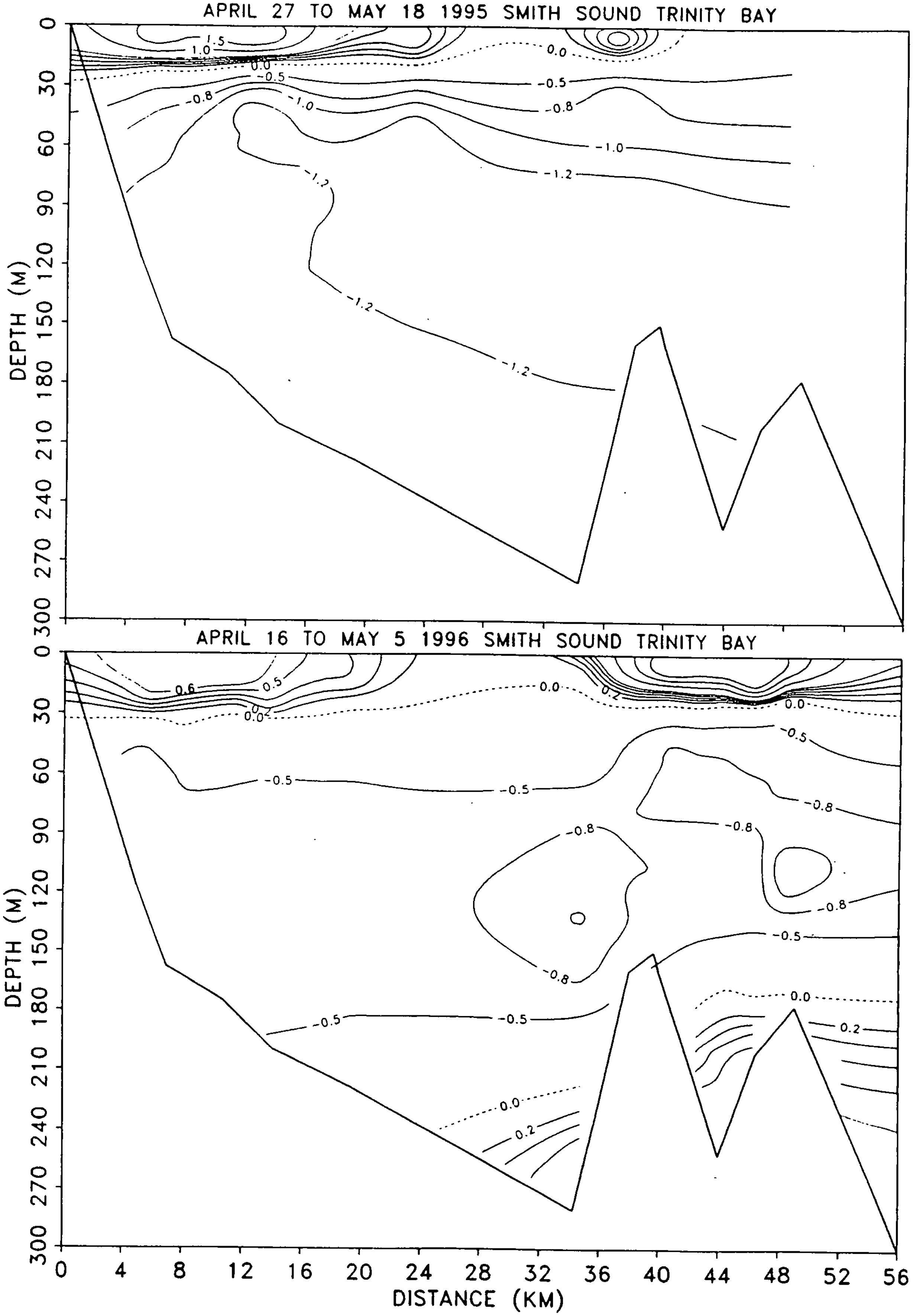


Fig. 18c. The vertical distribution of temperature along Smith Sound, Trinity Bay for Spring (April-May) 1995 and 1996.

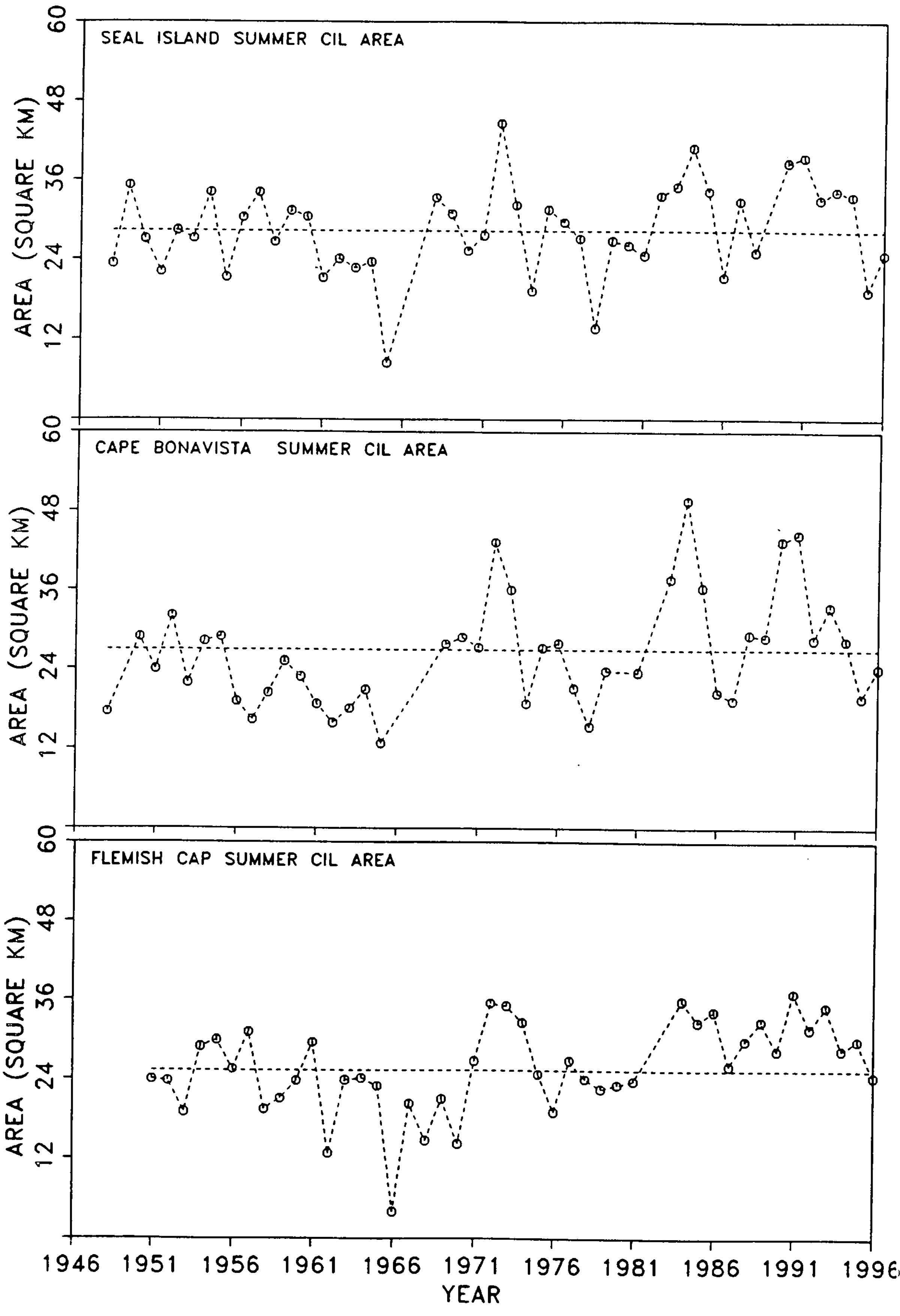


Fig. 19a. Time series of CIL area along the Seal Island, Bonavista and Flemish Cap transects. The dashed line represents the 1961-90 average.

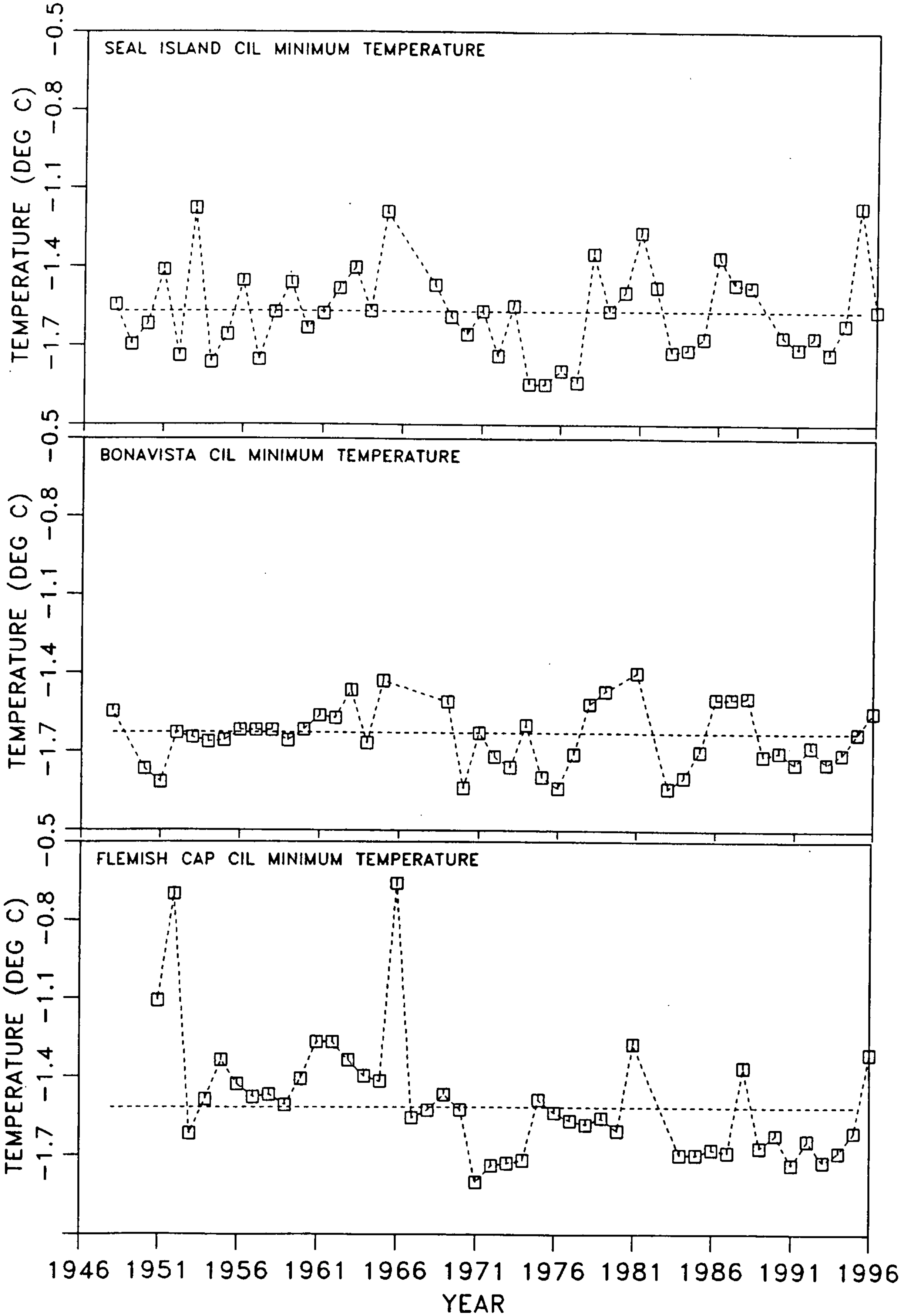


Fig. 19b. Time series of CIL minimum temperature along the Seal Island, Bonavista and Flemish Cap transects. The dashed line represents the average.

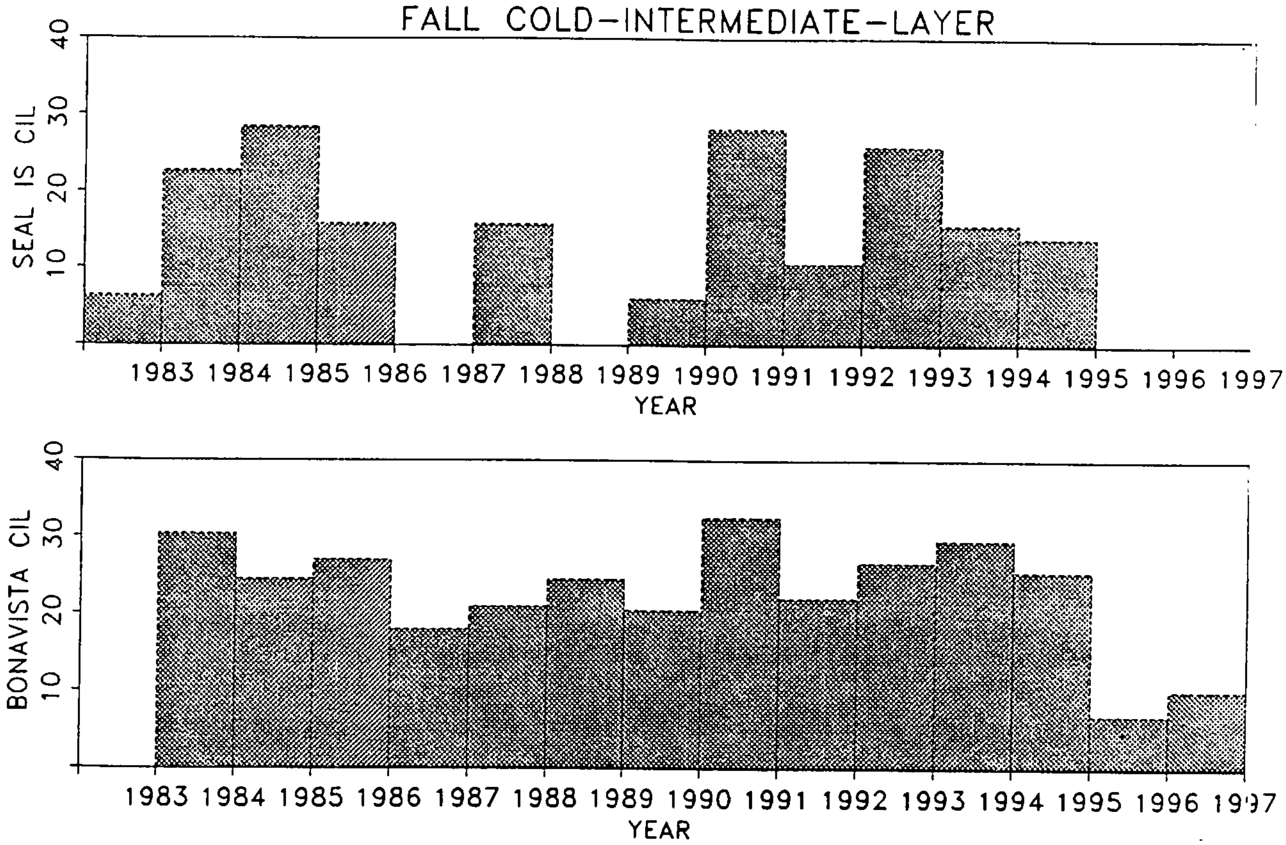


Fig. 20. Time series of CIL cross sectional area less than 0.0 °C during the fall for the Seal Island (top panel) and for the Bonavista transects (bottom panel).

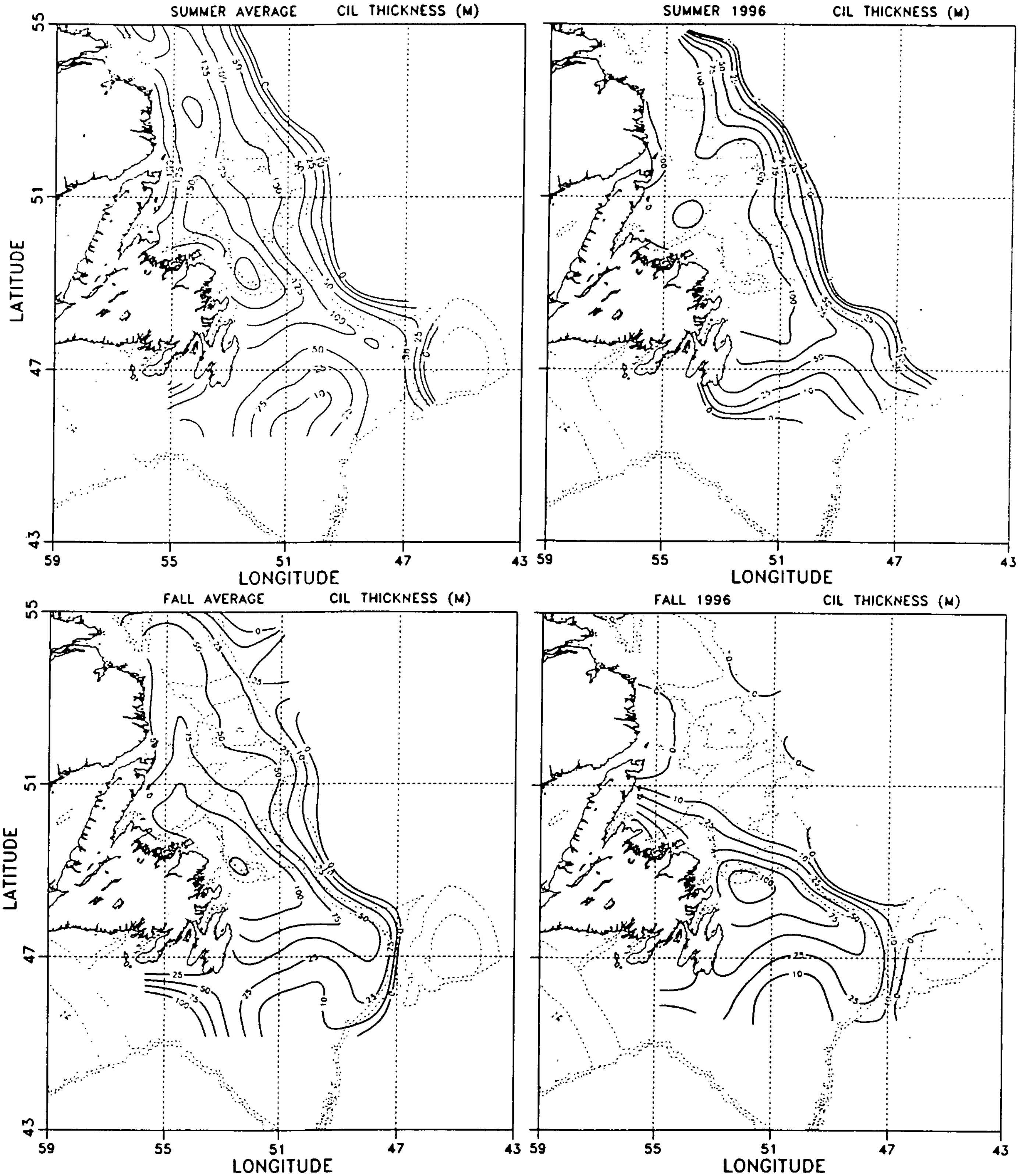


Fig. 21. Horizontal maps of the average summer and fall CIL thickness (m) over the 2J to 3KL areas and for the summer and fall of 1996.

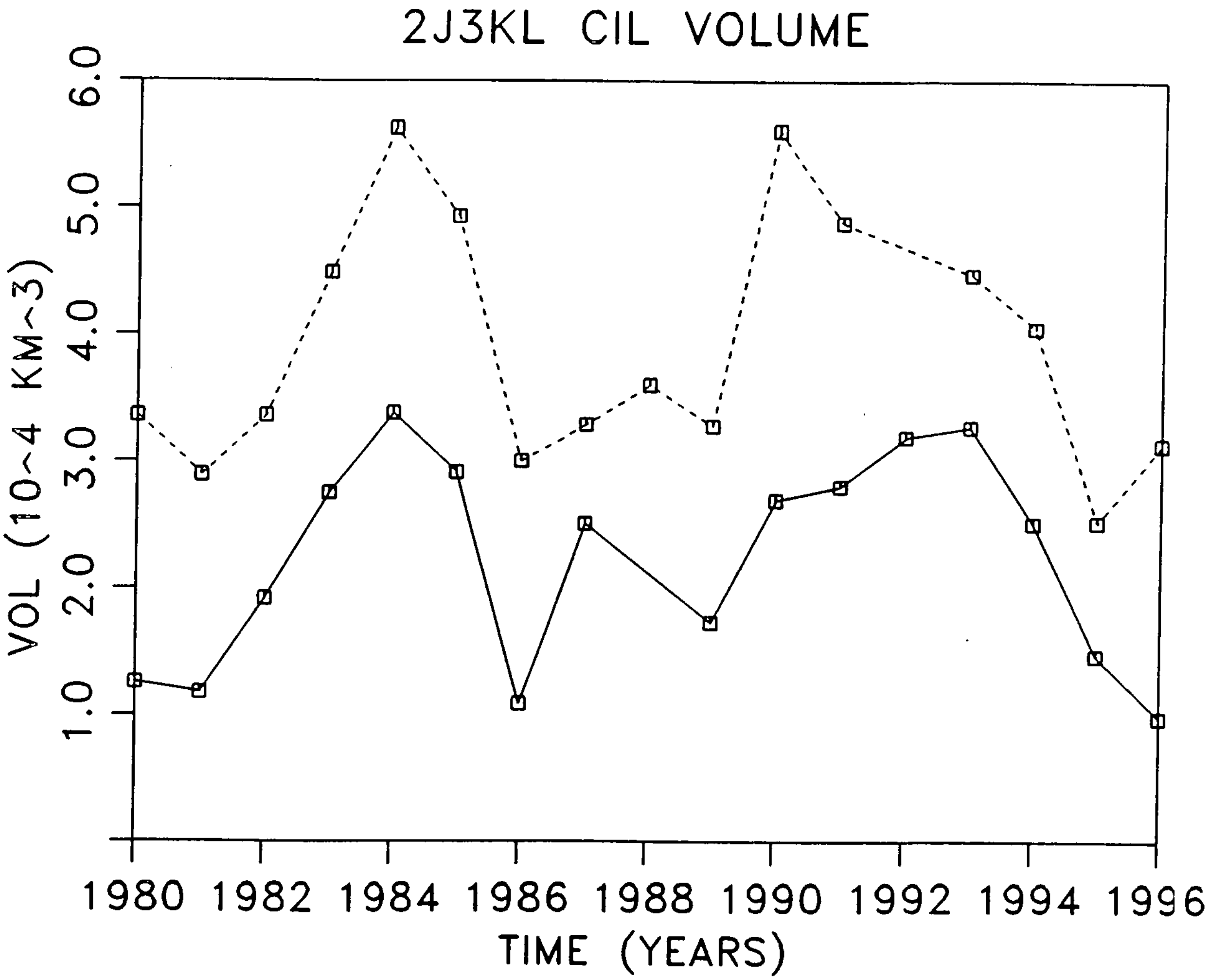


Fig. 22. Time series of summer (dashed line) and fall (solid line) CIL volumes (km^3) over the 2J to 3KL areas from 1980 to 1996.

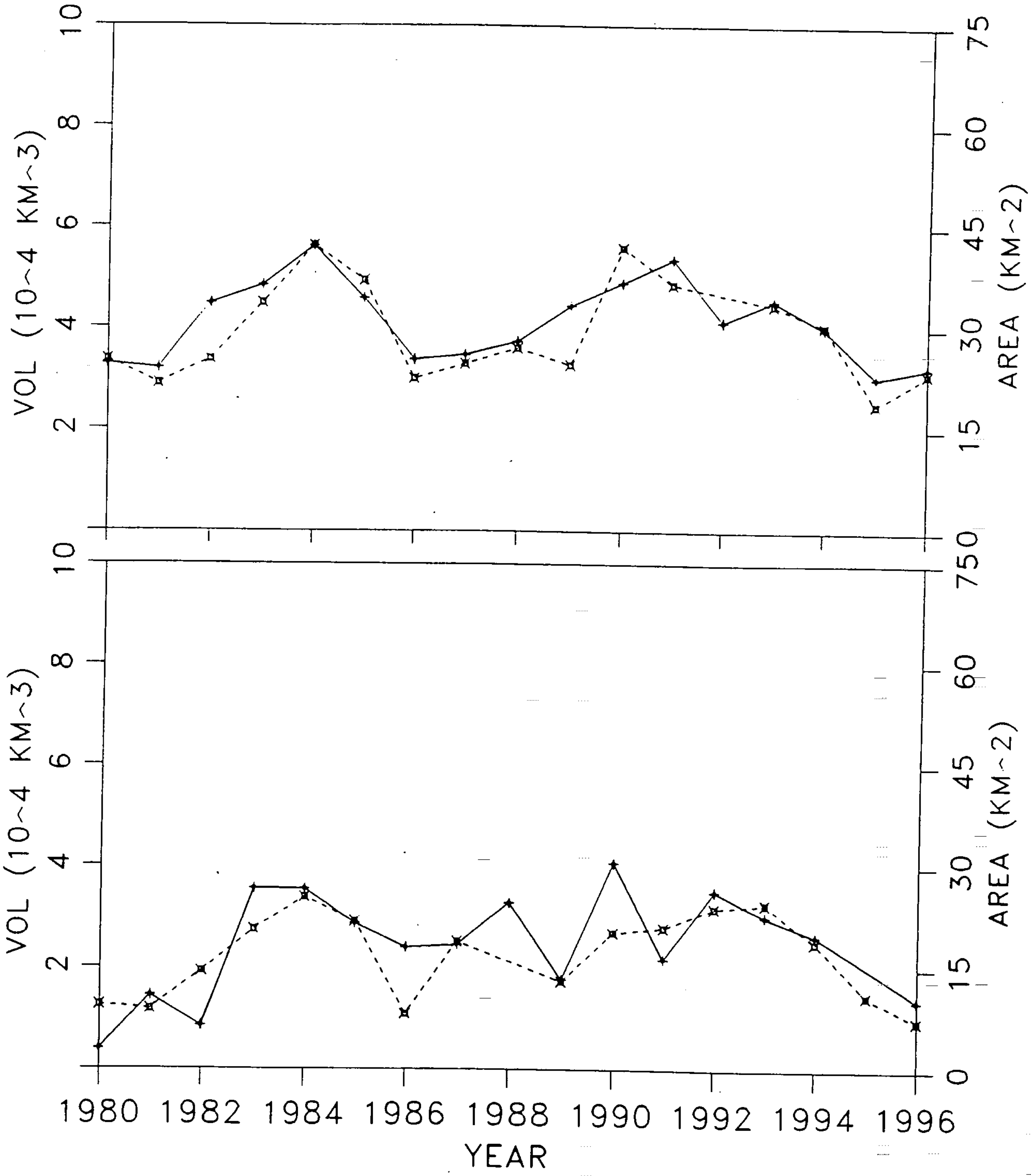


Fig. 23. Time series of summer (top panel) and fall (bottom panel) CIL volumes in NAFO Divisions 2J and 3KL (dashed lines) and the average area of the Seal Island, Bonavista and Flemish Cap transects (solid lines) from 1980 to 1996.

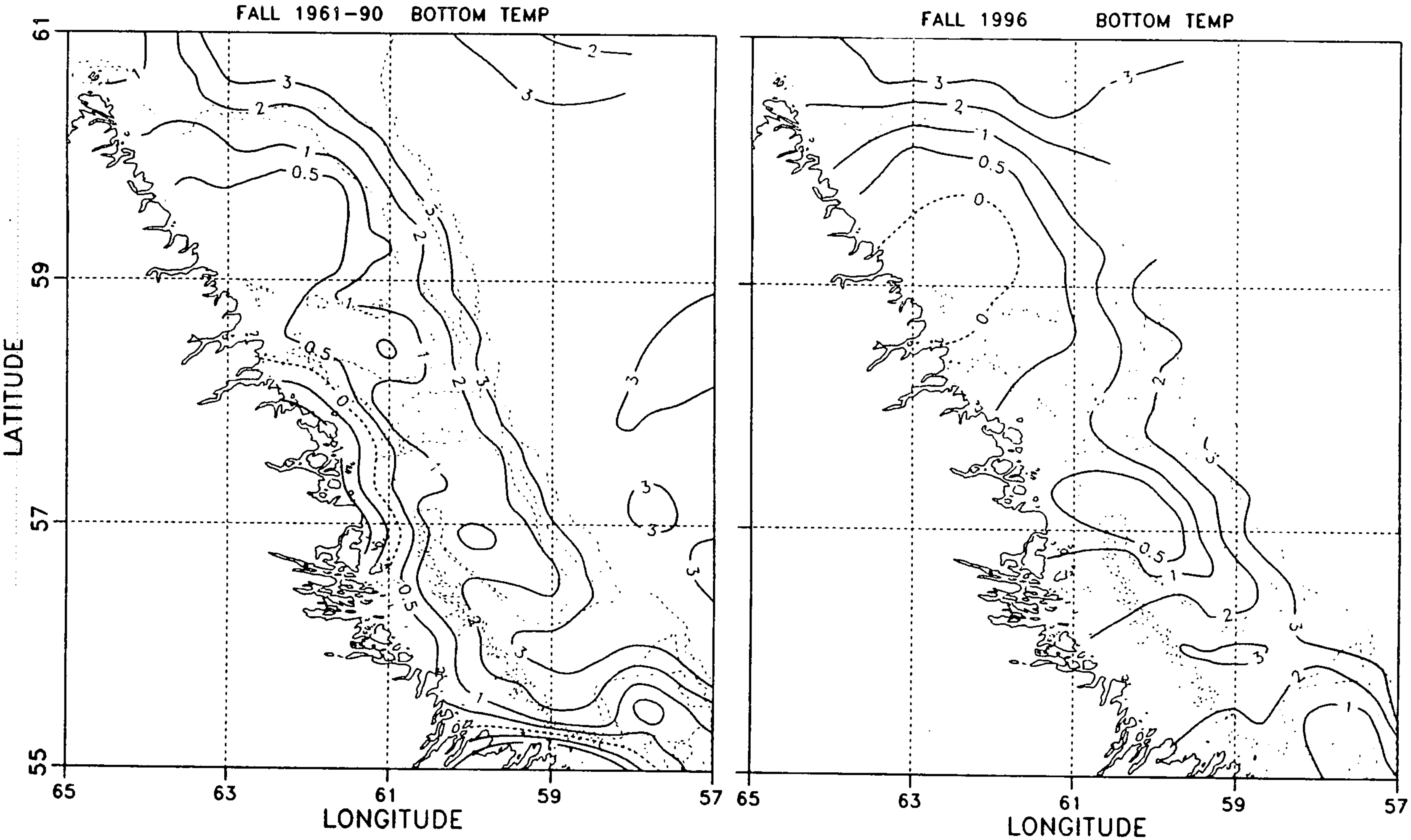


Fig. 24. Horizontal bottom temperature maps for the fall average (1961-1990) and for the fall of 1996 for the Labrador Shelf (2GH) region.

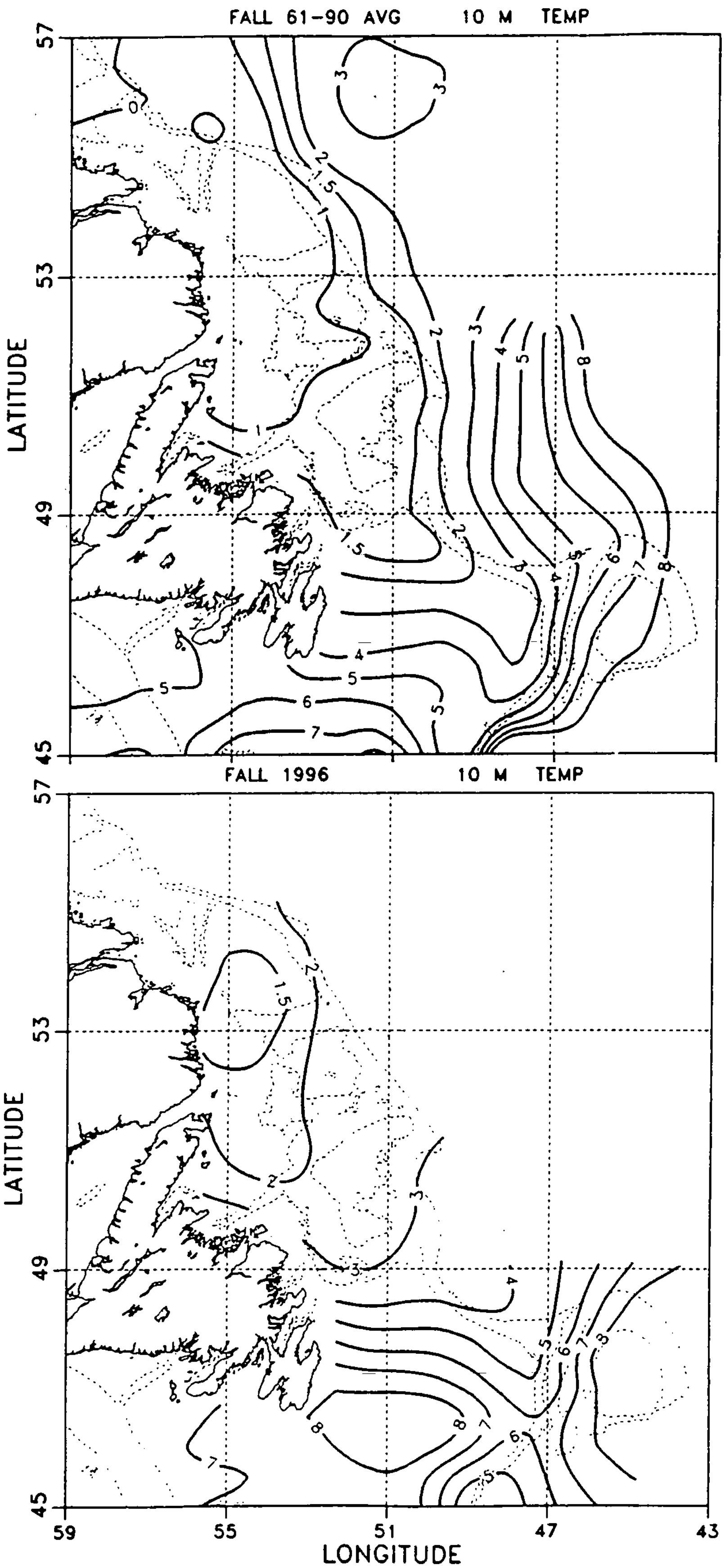


Fig. 25. Horizontal surface (10 m) temperature maps for the fall average (1961-1990) and for the fall of 1996 for the Newfoundland Shelf region.

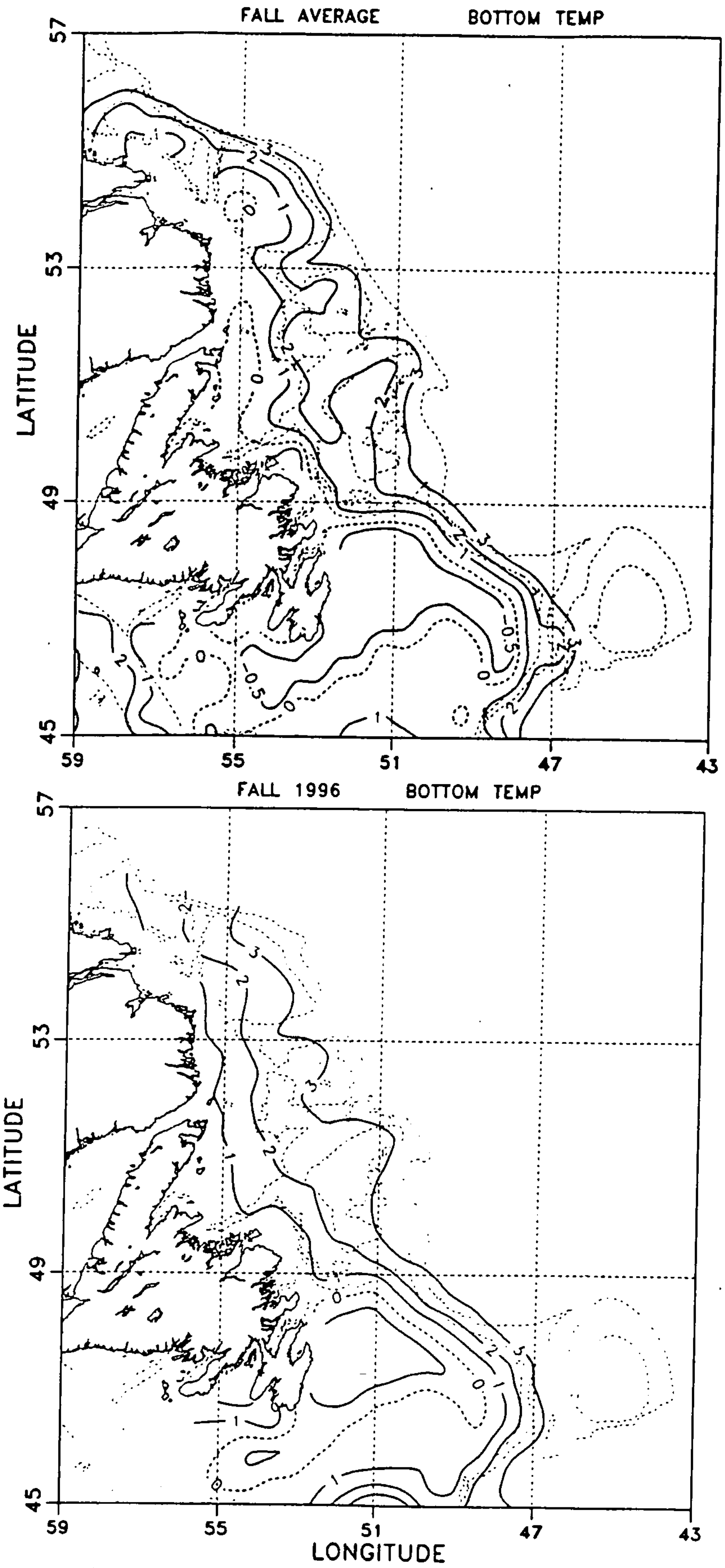


Fig. 26. Horizontal bottom temperature maps for the fall average (1961-1990) and for the fall of 1996 for the Newfoundland Shelf region.

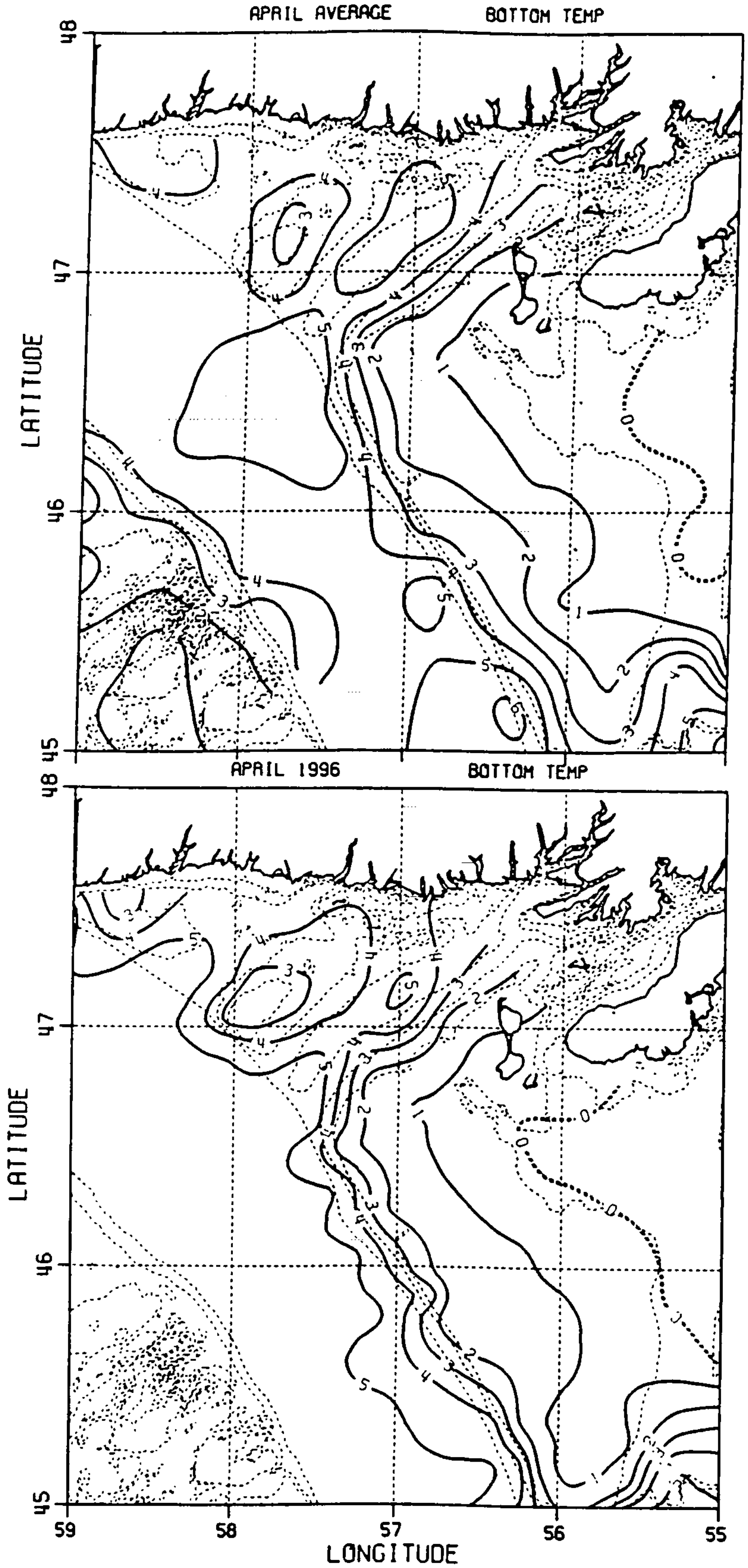


Fig. 27. Horizontal bottom temperature maps for the April average and April of 1996 in NAFO Subdivisions 3Pn and 3Ps.