DFO Atlantic Fisheries
Research Document 95/3

MPO Pêches de l'Atlantique
Document de recherche 95/3

OCEANOGRAPHIC CONDITIONS AND CLIMATE CHANGE IN THE NEWFOUNDLAND REGION DURING 1994

by

E. Colbourne

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

[1]This series documents the scientific basis for the evaluation of fisheries resources in Atlantic Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the secretariat.

[1]La présente série documente les bases scientifiques des évaluations des ressources halieutiques sur la côte atlantique du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Les Documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au secrétariat.

ABSTRACT

Oceanographic data from the Grand Bank, northeast Newfoundland Shelf, St. Pierre Bank and the southern Labrador shelf during 1994 are compared to historical data from the area. The cold air temperatures experienced in Atlantic Canada during the winter of 1994 had moderated to near normal conditions by the spring of 1994 and to above normal values by the summer. As a result the anomalously cold water temperatures experienced in recent years along the east coast of Newfoundland had moderated in the upper water column (0-30 m depth) and by July surface layer temperatures were up to 2.0 °C above normal at Station 27. Temperatures remained below normal however in deeper water (100-176 m) until the fall, when they returned to near normal values. The Bonavista cold-intermediate-layer (CIL) was slightly above normal in area (7 %) but much less than the past four years (up to 68 % in 1991). Comparisons of historical temperature data from NAFO Subdivisions 3Pn and 3Ps to data collected during April of 1994 indicates that the anomalous cold period that began in the mid 1980s has moderated somewhat but is continuing into 1994 near the bottom over St. Pierre Bank. In addition, large areas with below normal temperatures exist, particularly on the eastern portions of St. Pierre Bank, Placentia Bay and on the continental slope areas.

RÉSUMÉ

Les données océanographiques recueillies en 1994 sur le Grand Banc, le nord-est de la plate-continentale de Terre-Neuve, le banc de St-Pierre et le sud de la plate-forme continentale du Labrador sont comparées aux données historiques de la région. Les températures froides de l'air dans les régions de l'Atlantique au Canada durant l'hiver de 1994 avaient atteint des valeurs quasi normales au printemps de 1994 et des valeurs au-dessus des normales à l'été. Les températures anormalement froides de l'eau enregistrées au cours des dernières années le long de la côte est de Terre-Neuve se sont réchauffées dans la partie supérieure de la colonne d'eau (0-30 cm de profondeur) et, en juillet, les températures de la couche superficielle avaient augmenté jusqu'à 2,0°C au-dessus des normales à la station 27. Les températures sont demeurées au-dessous des normales dans les couches plus profondes (100-176 m) jusqu'à l'automne pour revenir alors à des valeurs quasi normales. La couche froide intermédiaire dans la baie Bonavista a connu des températures légèrement au-dessus des normales dans la région (7 %) mais beaucoup moins importante qu'au cours des quatre dernières années (jusqu'à 68 % en 1991). La comparaison des données historiques sur la température provenant des sous-divisions 3Pn et 3Ps de l'OPANO aux données recueillies en avril 1994 indique que la période anormalement froide qui a débuté au milieu des années 1980 s'est réchauffée quelque peu mais qu'elle se poursuit en 1994 près du fond au-dessus du banc de St-Pierre. De plus, il existe de vastes zones où la température est au-dessous des normales, en particulier sur les parties orientales du banc de St-Pierre, dans la baie de Plaisance et sur le talus continental.

INTRODUCTION

In the last three decades the oceanographic, meteorological, and ice conditions of the Northwest Atlantic have been dominated by three anomalous periods: early 1970s, mid 1980s and the early 1990s. During these periods stronger than normal northwesterly winds during the winter months were mainly responsible for colder than normal air temperatures over the Northwest Atlantic resulting in increased ice cover and eventually colder and fresher than normal oceanographic conditions over most of the continental shelf in Atlantic Canada (Colbourne et al., 1994a, Drinkwater et al., 1992, Narayanan et al., 1994).

This paper presents an overview of the oceanographic conditions in the Northwest Atlantic during 1994. The information is based mainly on data collected from oceanographic, pelagic and groundfish research surveys during 1994 in NAFO Divisions 2J to 3NO and 3Ps. Data from other sources as well as all available historical data for the area are also included in the analysis. The horizontal, vertical and time series of the temperature and salinity fields are compared to a 1961-1990 average in accordance with the World Meteorological Organization.

DATA SOURCES AND ANALYSIS

Oceanographic data for NAFO Divisions 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) the bulk of these data were collected during the stratified random groundfish surveys using XBTs. Data in Subdivisions 3Pn and 3Ps are from the Canadian assessment surveys conducted in February, March and April mainly since 1973. Measurements of temperature and salinity were made using several models of conductivity-temperature-depth (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 and temperature only on Hamilton Bank, in the Bonavista cod migration corridor and on the Grand Bank (Fig. 1 top panel, strata 206, 346 and 372) and from St. Pierre Bank (Fig. 1 bottom panel, box B). 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 $\cos(\omega t - \phi)$ to the data. Unlike the time series of anomalies from fixed points like Station 27 these anomalies are based on data over larger geographical areas such as St. Pierre Bank and therefore may be subject to larger spatial biasing.

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 were contoured along the standard Bonavista and Seal Island transects as well as across the 3Ps region (Fig. 1) by taking all observations within ± 20 minutes of latitude of the standard lines. The observations were then assumed to lie on a line joining the endpoints of the standard transect. The data were then 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 1 week on either side of the time period of the 1994 data collection.

Horizontal surface 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 wide time interval over which the fall survey is conducted plus the fact that this is a 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 water depth.

TEMPORAL ANOMALIES IN TEMPERATURE AND SALINITY

STATION 27

Depth versus time contour maps of temperature and salinity and anomalies based on all XBT and CTD profile data collected at Station 27 during 1994, a total of 65 profiles, are plotted in Figs. 2 and 3. The anomalies were calculated from the mean of all data collected on the station from 1961 to 1990.

The cold isothermal water column during the winter months has temperatures ranging from -1.0 °C to -1.7 °C and remain less than -1.5 °C through to late summer at depths below 85 m. The time series shows upper layer (generally the 0 to 50 m depth range) temperatures decreasing from 0.0 °C in early January to -1.7 °C by early

February, and remained below -1.0 °C until early April, when the surface warming commenced. By the end of April the upper layer temperature had again warmed to above 0.0 °C and to above 14 °C by August at the surface after which the fall cooling commenced.

Temperature anomalies ranged from -0.25 °C to -0.75 °C in January and between -0.25 °C to -0.5 °C in March over most of the water column. By mid April to early May temperatures had warmed to 0.0 °C to 0.5 °C above normal in the depth range of 0 to 85 m and to 2.0 °C above normal by late July in the upper 30 m. From 85 m depth to the bottom temperature anomalies remained up to 0.25 °C to 0.5 °C below normal until mid October after which conditions returned to near normal. Upper layer salinities were near normal with values between 32.0 psu to 32.4 psu during winter and spring and from 32.2 psu to 31.0 psu during summer and early fall, up to 0.8 psu below average. From 50 m to the bottom throughout the time series, salinities were slightly below normal.

The annual time series of monthly temperature and salinity anomalies at Station 27 during 1994 at standard depths again referenced to a 1961 to 1990 average, are shown in Fig. 4. The large positive temperature and negative salinity anomaly in the upper water column during the summer returned to more normal values during the fall. In the depth range of 75 to 175 m there is evidence of summer heat propagating from the surface layers down into deeper water near the bottom with temperature rising to near normal values during late fall.

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. 5). At the surface and at 30 m depth the negative temperature anomalies that began in late 1990 and reached a peak in mid 1991 have moderated to above normal conditions by July of 1994. At the deeper depths of 100 and 175 m strong negative temperature anomalies have persisted since 1983 with a few periods of positive anomalies during the mid to late 1980s. The salinity anomalies shows the large fresher than normal anomaly that began in early 1991 had returned to near normal conditions by early 1993 but returned to slightly fresher conditions by the summer of 1994. 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, 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 station 27 temperature (which is proportional to the total heat content of the water column, ie. $H/\rho C_p$) time series (Fig. 6, upper panel) show 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 somewhat but remains well below the warm 1950s and 1960s. The 0 to 50 m vertically averaged summer salinity (Fig. 6, bottom panel) show 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 have decreased slightly again by the summer of 1994.

DIVISIONS 2J, 3K AND 3L

Figure 1 shows the approximate boundaries of strata 206, 346 and 372 in NAFO Divisions 2J, 3K and 3L (Doubleday, 1981) for which time series of the bottom temperatures were constructed. These strata were selected to show the variations in bottom temperature at different depth ranges on the shelf and banks, from 80 m in 3L to 150 m in 2J and to 330 m in 3KL. Temperature profiles collected in the same stratum on the same day were averaged. The annual cycle was not removed from these time series since it was not statistically significant near the bottom. The time series plots of bottom temperature from 1950 to 1994 for the selected strata are shown in Fig. 7.

The time series in 2J shows a steady increase in the bottom temperature during the 1950s and through most of the 1960s, and a decreasing trend in the early 1970s, early to mid 1980s and since 1988 to the present. Temperature variations ranged from -0.5 °C in the early 1950s, mid 1980s and at present, to highs of 1.0 °C during the 1960s and late 1970s. Bottom temperatures during the fall of 1994 showed a slight increase from the low values experienced from 1991 to 1993.

The time series in Divisions 3KL are bottom temperature of slope water from the deep trough between the Northern Grand Bank and the Funk Island Bank near the shelf edge in about 330 m of water. The temperature in this area remained at about 3.0 °C from 1950 to 1984 when it dropped to approximately 2.5 °C. The spike in 1992 may be the result of aliasing caused by high frequency oscillations in the shelf/slope thermal front which is present near the shelf edge, but more pronounced higher in the water column (Narayanan et al., 1991).

In Division 3L on the plateau of the Grand Bank bottom temperatures remained relatively constant at approximately 0.0 °C from 1950 to the mid 1960s after which there was a weak warming trend. During the early 1970s and mid 1980s bottom temperatures decreased to near -1.0 °C, warmed to above zero values during the latter half of the 1980s and have shown a decreasing trend from 1989 to 1994.

DIVISION 3Ps

The time series of temperature anomalies from region B in Fig. 1 on St. Pierre Bank are shown in Fig. 8 at standard depths of 0, 20, 50 and 75 m. This time series was low pass filtered to suppress the high frequency variations at seasonal scales.

The 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 1994 the sign of the temperature anomalies changed at 20 and 50 m depth but remained negative at the surface and at 75 m depth.

VERTICAL TEMPERATURE, SALINITY AND OXYGEN DISTRIBUTION

2J, 3KL SUMMER

The vertical distribution (depth versus horizontal distance from the shore) of the temperature and salinity fields along the standard Bonavista and Seal Island transects for the summer of 1994 are presented in Fig. 9. The corresponding temperature and salinity anomalies are presented in Fig. 10. These anomalies were calculated from the mean fields for the period July to August of all available data for the transect from 1961 to 1990. No attempts were made to adjust the mean for possible temporal biasing arising from variations in the number of observations within these time intervals.

The summer temperature along the Bonavista transect in the upper 50 m of the water column ranged from 0.0 °C to 5.0 °C near the coast and to 4.0 °C over most of the continental shelf. In deeper water (50 m to the bottom) the temperatures ranged from -1.0 °C to -1.5 °C near the coast, to 0.0 °C to 3.0 °C further offshore near the edge of the continental shelf and beyond. The corresponding temperature anomalies ranged from -0.5 °C near the coast to 0.0 °C to 1.0 °C in the surface layer over the continental shelf and to normal conditions over most of the water column from 50 m to the bottom across the shelf and in deeper water beyond the shelf edge. Temperature anomalies along the Seal Island transect were up to 0.5 °C in the upper layers near the coast and generally from -0.25 °C to -1.0 °C over Hamilton Bank.

Bonavista salinities generally ranged from 31.5 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. The corresponding salinity anomalies show fresher than normal conditions ranging from 0.1 psu to 0.5 psu below average in the upper 20 to 40 m of the water column in the inshore and offshore branches of the Labrador current and from 0.1 psu to 0.2 psu saltier than normal in water depths of 50 m to the bottom over the outer shelf. Salinities in deeper water beyond the shelf edge were about normal. Seal Island salinities were generally 0.1 psu to 0.3 psu fresher than average over most of the shelf.

2J, 3KL AUTUMN

The vertical distribution of the temperature and salinity fields and anomalies along the standard Bonavista and Seal Island transects for the fall of 1994 are presented in Fig. 11 and 12. 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 seasonal warm upper layer has not completely cooled down, so the summer-like structure of the cold intermediate layer (CIL) is still present (Colbourne and Senciall, 1993).

Upper layer temperatures ranged from 7.0 °C near the coast to 2.0 °C offshore, about 0.5 °C warmer than average over the inshore portion of the continental shelf and up to 0.5 °C to 1.0 °C colder than average below 100 m depth (Fig. 12). On the outer shelf and further offshore, beyond the shelf edge, temperatures were about average. Temperature anomalies along the Seal Island transect were very similar. In general, except for the upper layer, temperatures were still below normal over most of the Newfoundland Shelf.

Upper layer salinities off Bonavista ranged from 32.25 psu near the coast to 33.5 psu near the shelf edge. Deep water salinities ranged from 33.5 psu to 34.75 psu near the shelf break. Salinities along the Seal Island transect followed a similar pattern. Salinity anomalies off Bonavista during the fall were generally fresher than normal (0.1-0.4 psu) over the inshore portion of the shelf and saltier than normal (0.1-0.5 psu) over the outer portion of the shelf. Along the Seal Island transect salinities were generally fresher (0.1-0.4 psu) than average.

3KL SUMMER OXYGEN DISTRIBUTION

Dissolved oxygen data are now routinely collected along transects of Newfoundland on oceanographic research cruises. 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-9 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 1994 in conjunction with the temperature, salinity and chlorophyll data are shown in Fig. 13. The average oxygen distributions 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. The 1994 survey shows dissolved oxygen saturation levels ranging from 90 % to 100 % from the surface to about 60 m depth and about 85 % to 90 % from 60 m to the bottom. These values are very similar to values measured in 1993 during the same time period and show no evidence of oxygen depletion anywhere in the water column.

3Ps SPRING

A vertical section of the average temperature field for April based on all available historical data from 1961 to 1990 and for April 1994 is shown in Fig. 14. 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 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 1994 temperatures ranged from less than -

0.5 to 0.0 °C in the upper 100 m over Burgeo and Hermitage Channels, up to 2.0 °C below average and from 0.5 °C to 1.0 °C over St. Pierre Bank, up to 1.0 °C below average over the central portion of the bank. Deep water temperatures on the continental slope in 1994 ranged from 0.0 °C to 3.0 °C, up to 2.0 °C to 4.0 °C below the April average.

THE COLD INTERMEDIATE LAYER (CIL)

SUMMER AREA

As shown earlier in Fig. 9 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. During 1994 this cold layer extended offshore to about 240 km, with a maximum thickness of about 200 m corresponding to a cross-sectional area of approximately 28 km^2 compared to the 1961-90 average of 26 km^2. The core of the CIL (temperatures less than -1.5 °C) extends to about 115 km offshore and has a maximum thickness of about 100 m corresponding to a cross-sectional area of approximately 7 km^2 compared to an average of 9 km^2. In July 1993 the CIL of water less than 0.0 °C extended to about 240 km offshore with a maximum thickness of about 250 m, corresponding to a cross-sectional area of 33 km^2 and about 11 km^2 for water less than -1.5 °C. The bottom temperature structure across the shelf was similar in both years.

Figure 15 shows a time series of the CIL cross-sectional area for the Seal Island, Bonavista and Flemish Cap transects. In 1994 the CIL area off Bonavista was about 7 % above normal compared to 28 % in 1993 and up to 68 % in 1991. The CIL area along the Seal Island and Flemish Cap transects remained above normal during the summer of 1994 at about 36 % and 12 % respectively compared to 61 % and 48 % during 1991.

The intensity or minimum core temperatures of the CIL for all three transects from 1948 to 1994 are shown in Fig. 16. The minimum temperatures observed in the core of the CIL off Bonavista were -1.70 °C in 1994 compared to -1.74 °C in 1993, slightly below the average of -1.64 °C. Along the Flemish Cap transect across the central portion of the Grand Bank minimum temperatures have remained below the 1961-90 average since the late 1980s. In general, periods of colder than normal core temperatures are highly correlated with larger than normal CIL areas.

AUTUMN AREA

The 1980 to 1994 time series of CIL area less than 0.0 °C for the Seal Island and Bonavista transects during the fall groundfish survey is shown in Fig. 17. The CIL area along the Bonavista transect shows similar trends as in the summer, however the average area has 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 1994 was about 26 km^2 compared to about 30 km^2 in 1993, 27 km^2 in 1992 and about 22 km^2 in 1991.

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 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. The CIL area during the fall of 1994 was about 14 km^2 compared to 16 km^2 in 1993, 26 km^2 in 1992 and 11 km^2 in 1991.

CIL VOLUME SUMMER AND FALL

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 for 1986, a warm year and for 1994 (Fig. 18). These maps were produced by computing the thickness of the CIL for each temperature profile during the two time periods and gridding them onto a square projection of 0.25° latitude by 0.38° longitude by a finite difference interpolation scheme. The total volume was then calculated by summing the volumes for each grid element of known area.

The 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. The time series of total volume of subzero water over the 2J, 3KL area (Fig. 19) shows maximum values during the cold periods of the mid 1980s and early 1990s. The total volume of subzero water on the shelf increased from approximately 2.7 X 10^4 km^3 during the summer of 1989 to 5.6 X 10^4 km^3 in 1990 a 100 % increase. Since the summer of 1991 the volume of subzero water has been slowly decreasing, however it is still significantly above the values of the early 1980s and from 1986 to 1989. The average volume of sub-zero water on the shelf during the summer is approximately 40,000 km^3 roughly one-third the total volume of water on the shelf. The time series during the fall shows similar trends but the total volume is about one-half the summer values. Due to limited data sets the volume estimates were not calculated prior to 1980.

HORIZONTAL TEMPERATURE FIELD

SURFACE

The average and the 1994 surface (taken as 10 m) temperature field for the summer and fall periods derived from all available data from 1961 to 1990 are shown in Fig. 20. The average upper layer summer temperatures ranged from 5.0 °C to 9.0 °C shoreward of the shelf break in NAFO Divisions 2J3K and from 9.0 °C to 12.0 °C in Division 3L. During 1994 upper layer summer temperatures ranged from approximately 3.0 °C to 9.0 °C in 2J3K, about normal in the south, and up to 1.0 °C below average in the north. In Division 3L the 1994 summer temperatures ranged from 9.0 °C to 14.0 °C, about normal in the north and up to 2.0 °C above average in the south.

During the fall period the upper layer temperatures 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 1994 surface temperatures ranged from 1.0 °C to 1.5 °C in 2J3K and from 2.0 °C to 7 °C in Division 3L, up to 1.0 °C above average in some areas.

BOTTOM

The average (1961-90) and the 1994 summer and fall bottom temperature for the 2J and 3KL area are shown in Fig. 21 (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) in both summer and fall 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 since 1990 has been significantly 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, 1994b). During 1994 the percentage area of water less than -0.5 °C on the continental shelf was still significantly above average.

The 1961-90 average and the 1994 April bottom temperature maps for the 3Ps and 3Pn areas are shown in Fig. 22. 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 temperatures ranged 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 -0.75 °C on the eastern side of St. Pierre Bank to 2.0 °C on the western side. During April 1994 temperatures were up to 1.0 °C above average over Burgeo Bank and Hermitage Channel, near average on the western side of St. Pierre Bank and about 0.5 °C below average on the eastern side

SUMMARY

Time series of temperatures at Station 27 shows below normal values during the winter of 1994 over all depth ranges. By the summer however temperatures had increased to about 2.0 °C above normal in the upper water column and to near normal values in deeper water by the fall. Salinities were near normal in the upper water column during the first half of 1994, slightly below normal in deeper water and significantly below normal during the summer in the upper water column. Time series of temperature anomalies in the 3Ps area show the cold period which started around 1984, continued to the early 1990s with temperatures up to 1.0 °C below average over all depths and up to 2.0 °C below the warmer temperatures of the late 1970s and early 1980s in the surface layers.

The summer area of the CIL across the northeast Newfoundland shelf has returned to near normal at Bonavista but remained above normal on Hamilton Bank and slightly above normal on the Grand Bank. During the fall the CIL increased from 22 km^2 in 1991, 30 km^2 in 1993 and 26 km^2 in 1994 compared to the 1980-1994 average of 24 km^2. In area 2J across Hamilton Bank the fall CIL area had decreased from 27 km^2 in 1992, 16 km^2 in 1993 and to 14 km^2 in 1994. Comparison of data collected along the Bonavista transect during 1994 with all available historical data on the Newfoundland shows near normal values with no evidence of oxygen depletion anywhere over the water column.

Surface temperatures during 1994 ranged from above normal in southern regions of Division 3L to below normal in Division 2J. Large areas of the continental shelf, particularly the Grand Bank, saw a continuation of the below normal bottom temperatures (up to 0.5 °C below average) experienced during 1991-1993.

The below normal air temperatures (Findlay and Deptuch-Stapf, 1991) and above normal ice coverage since the late 1980s have contributed to a lower than normal heat content on the eastern Canadian continental shelf areas. The analysis presented here shows conditions returning to more normal values however widespread negative temperature anomalies still exist over much of the water column particularly in deep water.

ACKNOWLEDGEMENTS

I thank the technical staff of the oceanography section at NAFC for the professional job done in data collection and processing and for the computer software support. I also thank D. Foote for data processing 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. Much of the oceanographic data collection and processing during 1994 was funded by the Northern Cod Science Program (NCSP).

REFERENCES

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.

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

Colbourne, E. and D. R. Senciall. 1993. Temperature, salinity and density along the standard Bonavista transect. Can. Tech. Rep. Hydrogr. Ocean Sci. 150: v+311 p.

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.

Doubleday, W. G., Editor. 1981, Manual on Groundfish Surveys in the Northwest Atlantic, NAFO Sci. Coun, Stu. No. 2, 56p.

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

Drinkwater, K.F., Petrie, B., and Narayanan, S. 1992. Overview of Environmental Conditions in the Northwest Atlantic in 1991. NAFO SCR Doc. 92/73, 36 pp.

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.

Narayanan, S., Carscadden, J., Dempson, B., O'Connell, M., Prinsenberg, S., Reddin, D., and Shackell, N. 1994. Marine Climate off Newfoundland and its Influence on Salmon and Caplin. Can. J. Fish and Aquat. Sci. In press.

Narayanan, S., E. B. Colbourne, and C. Fitzpatrick. 1991. Frontal Oscillations on the NE Newfoundland Shelf. Atmos-Ocean vol 29: NO 3. 547-562.

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.

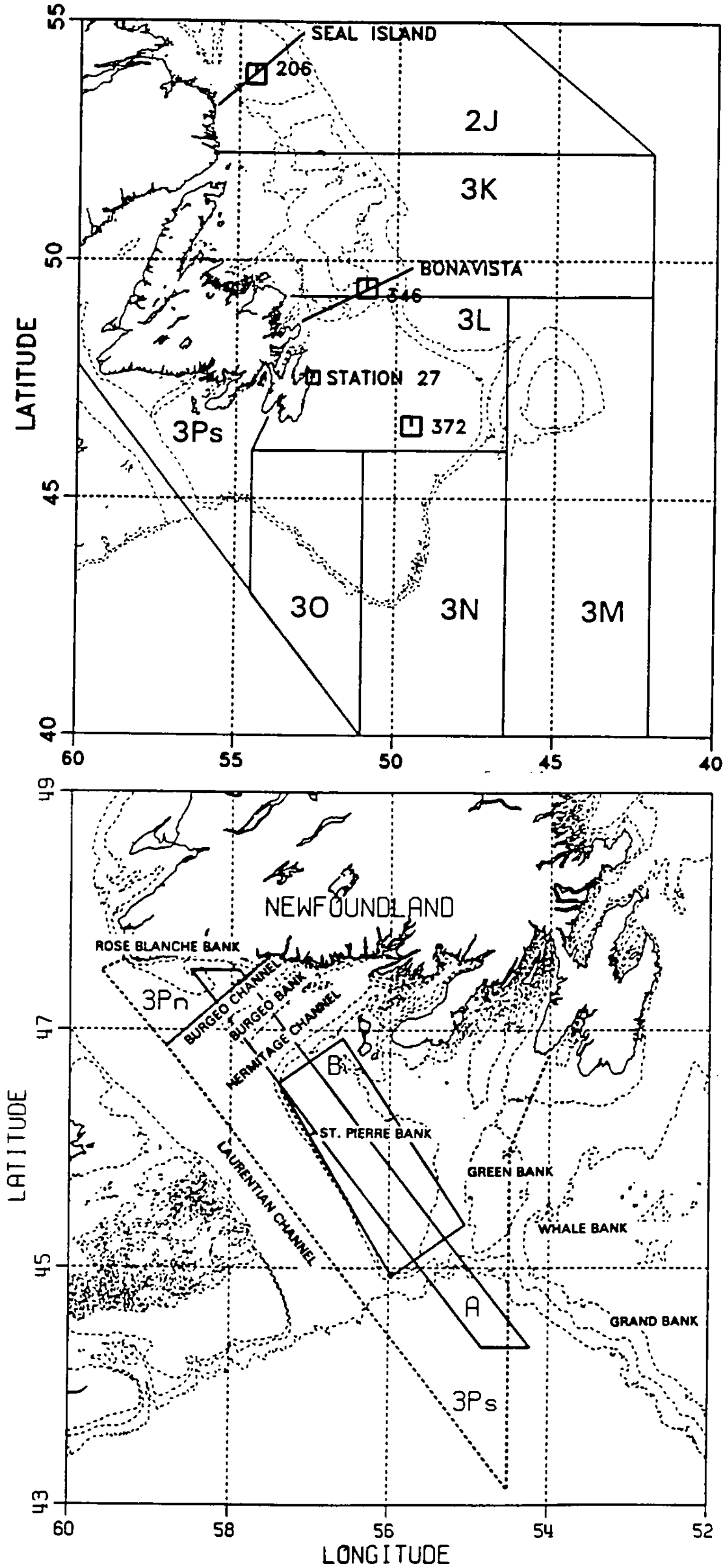

Fig. 1. Location maps showing positions of the Seal Island and Bonavista transects, Station 27 and the approximate positions of strata 206, 346 and 372 (top panel) and Subdivisions 3Pn and 3Ps and the areas A and B from which data were examined (bottom panel).

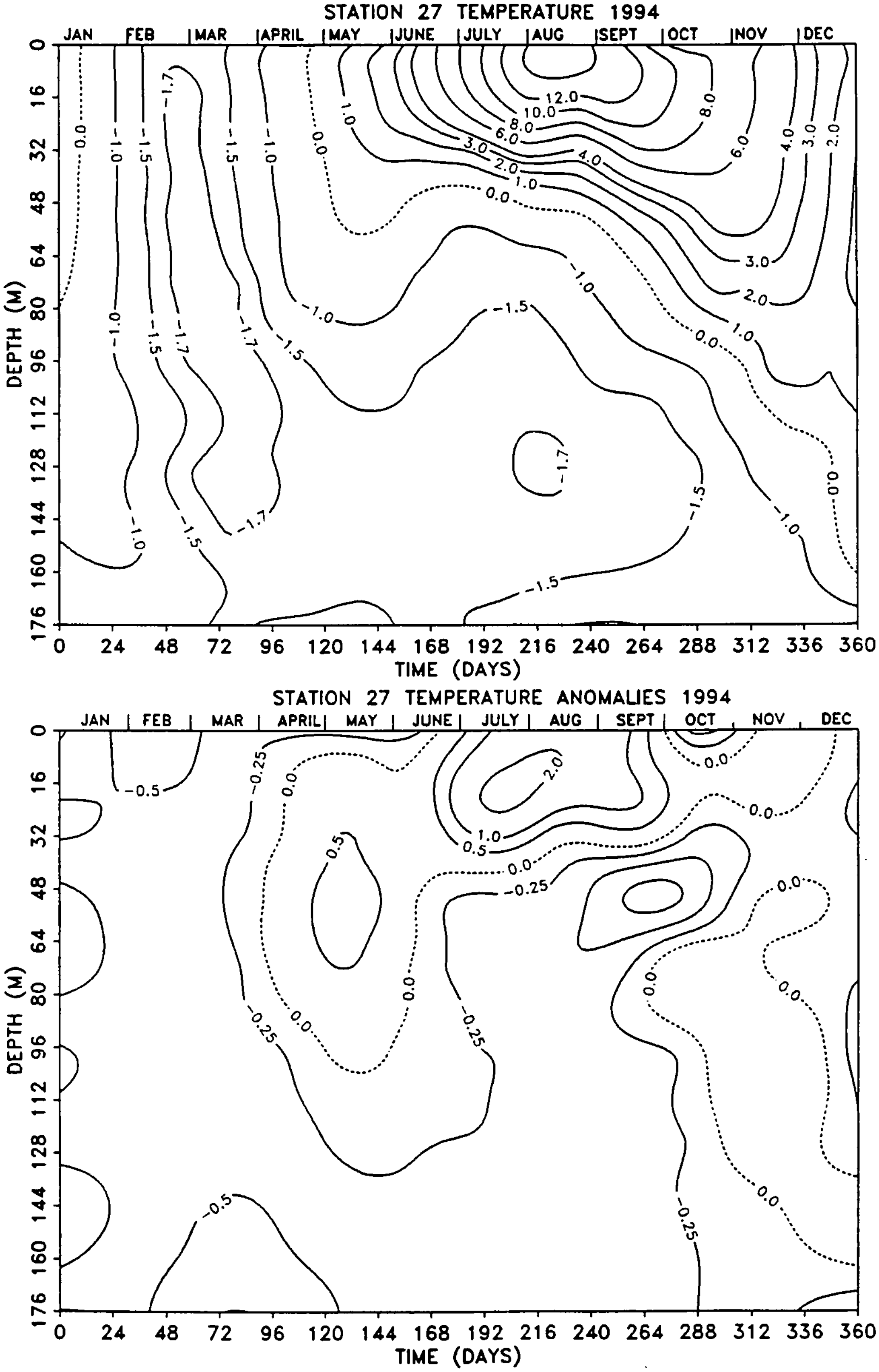

Fig. 2. Depth versus time contour plots of temperatures and anomalies at Station 27 for 1994.

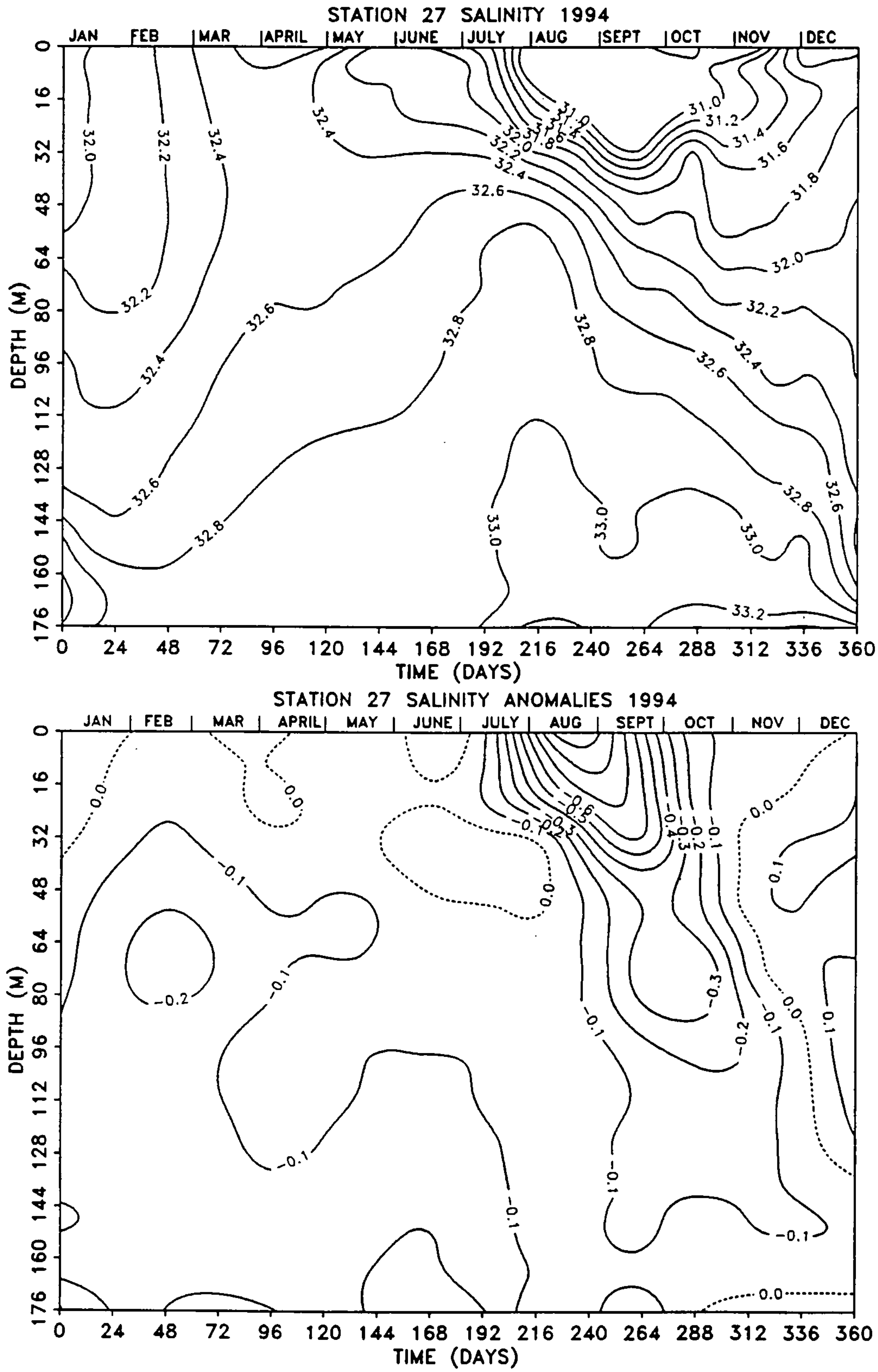

Fig. 3. Depth versus time contour plots of salinity and anomalies at Station 27 for 1994.

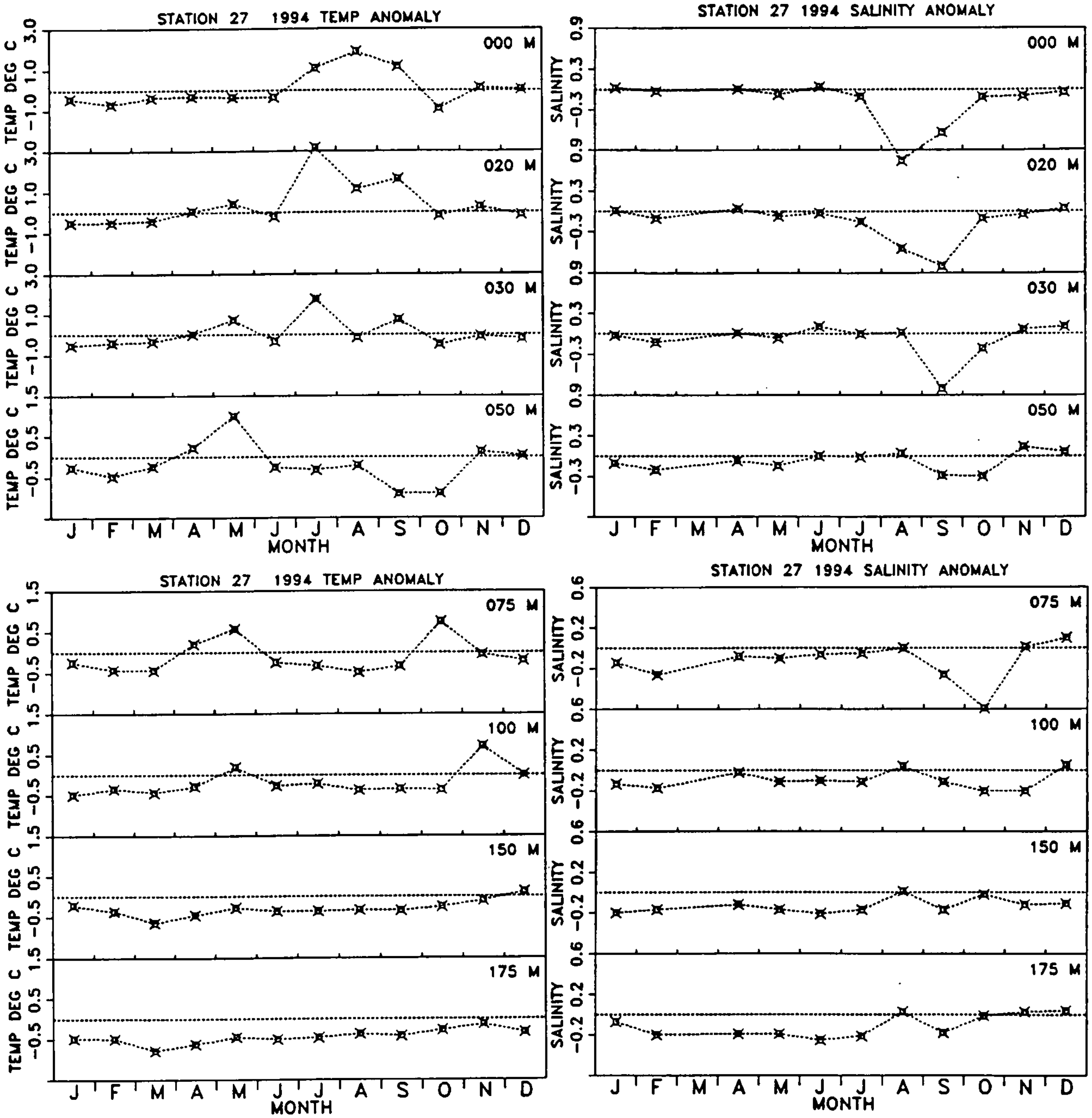

Fig. 4. Time series of monthly temperature and salinity anomalies at Station 27 at standard depths during 1994.

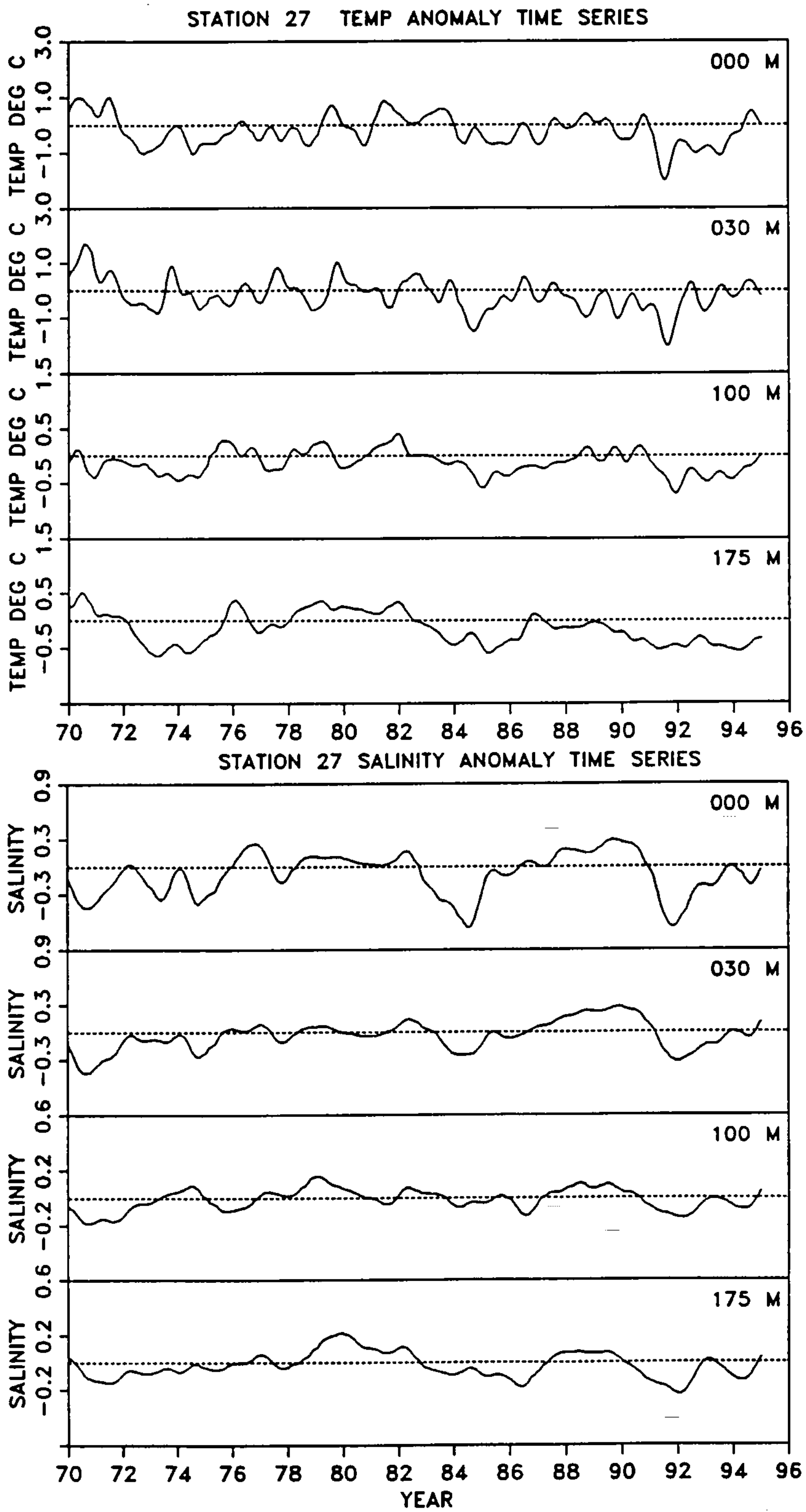

Fig. 5. Low passed filtered time series of temperature and salinity anomalies at Station 27 at standard depths from 1970 to 1994.

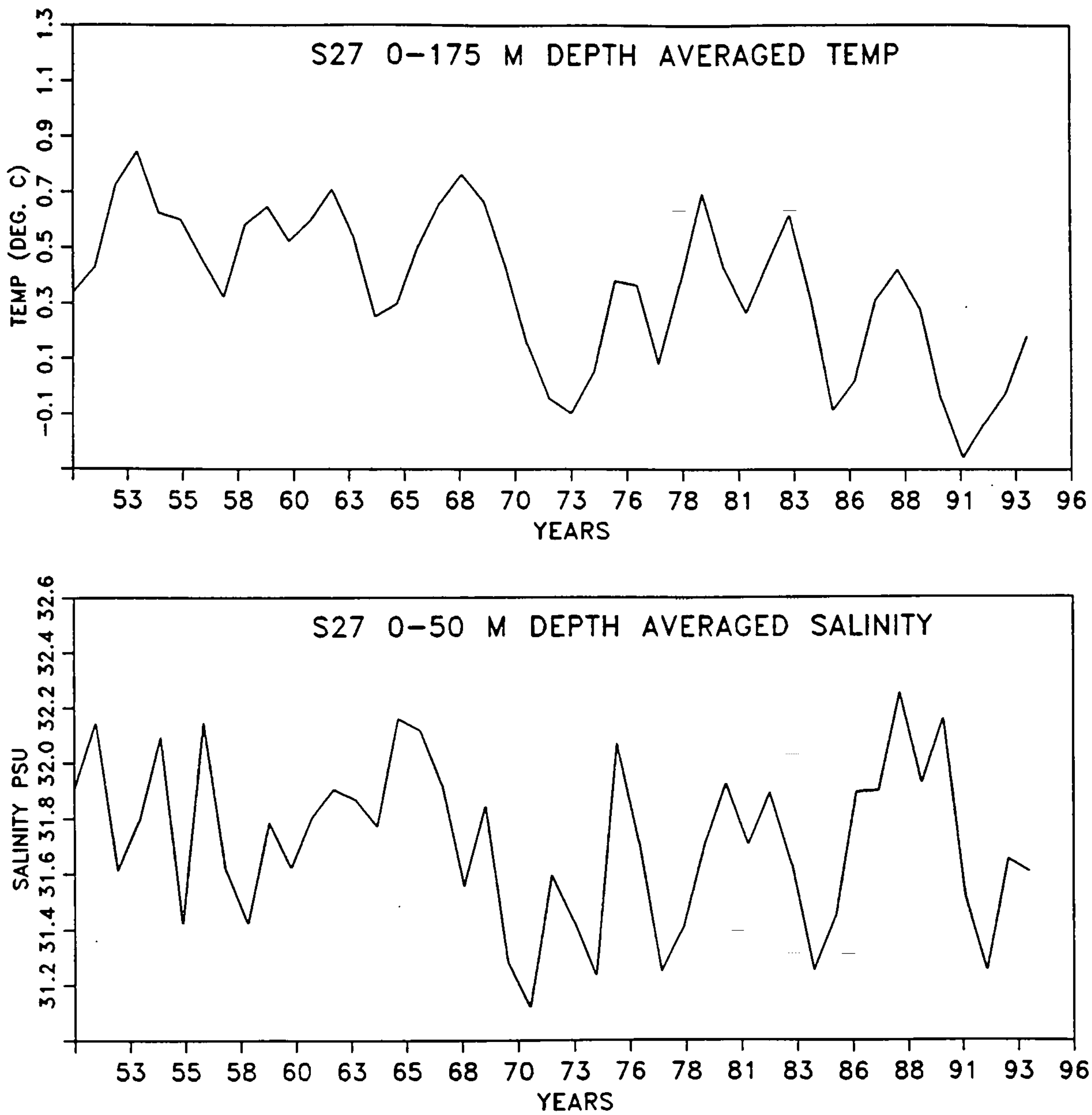

Fig. 6. Time series of the vertically averaged (0-176 m) Station 27 temperature and the vertically averaged (0-50 m) summer (July -Sept.) Station 27 salinity.

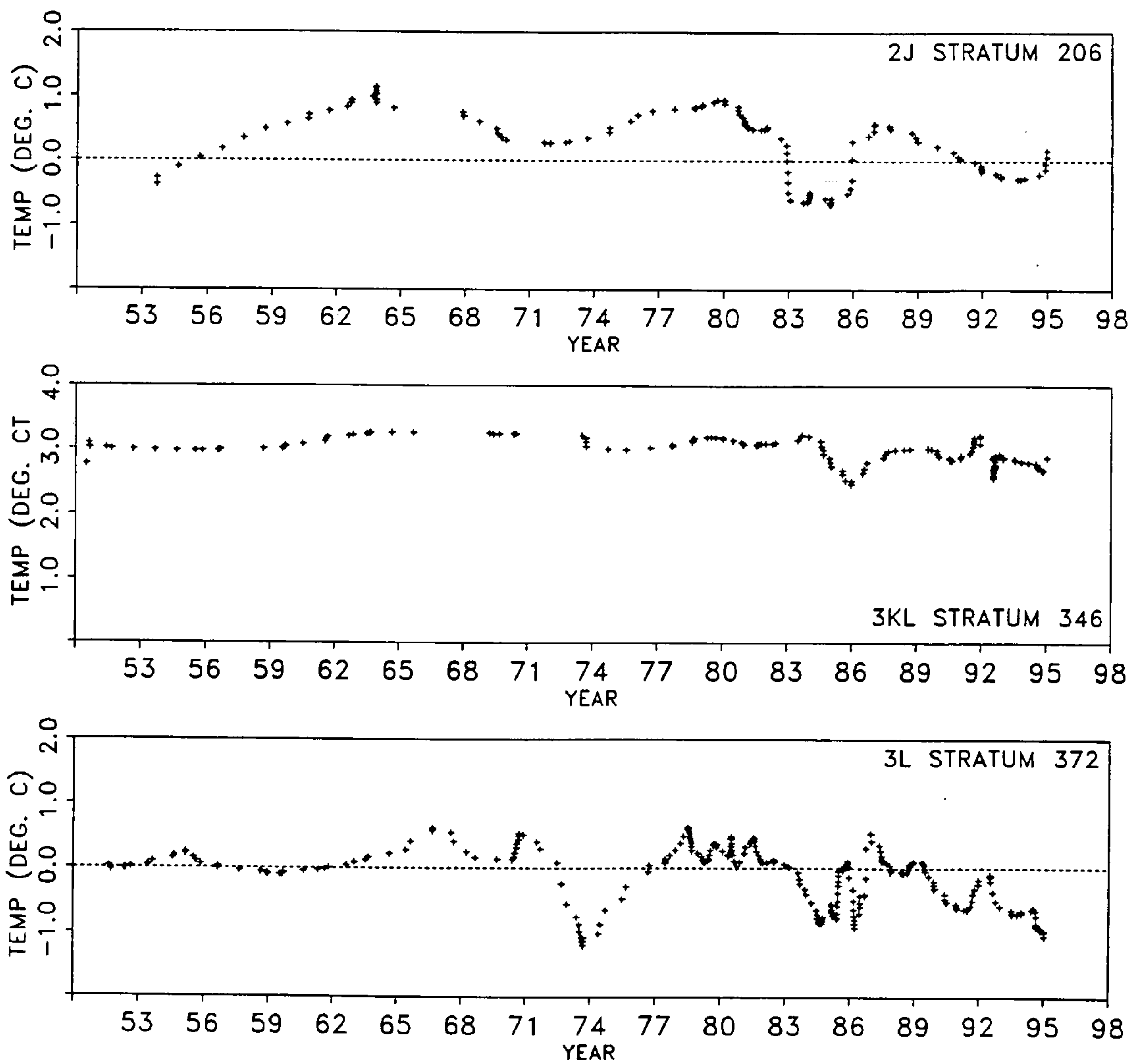

Fig. 7. Time series of bottom temperatures for strata 206 in NAFO Division 2J, 346 in Division 3KL and 372 in Division 3L, the locations of which are shown in Fig. 1.

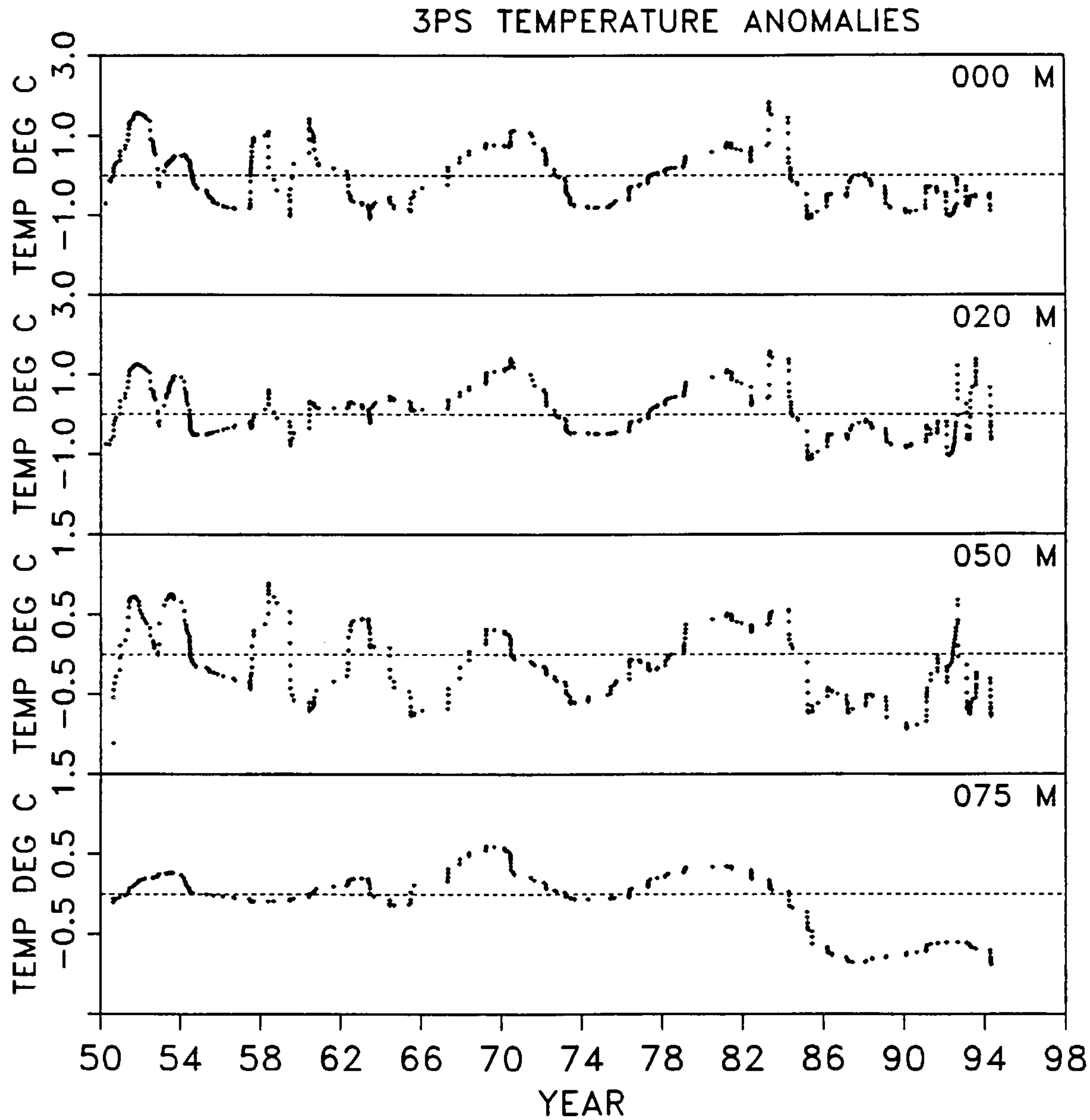

Fig. 8. Time series of temperature anomalies at standard depths of 0, 20, 50 and 75 m for box B in Subdivision 3Ps shown in Fig. 1.

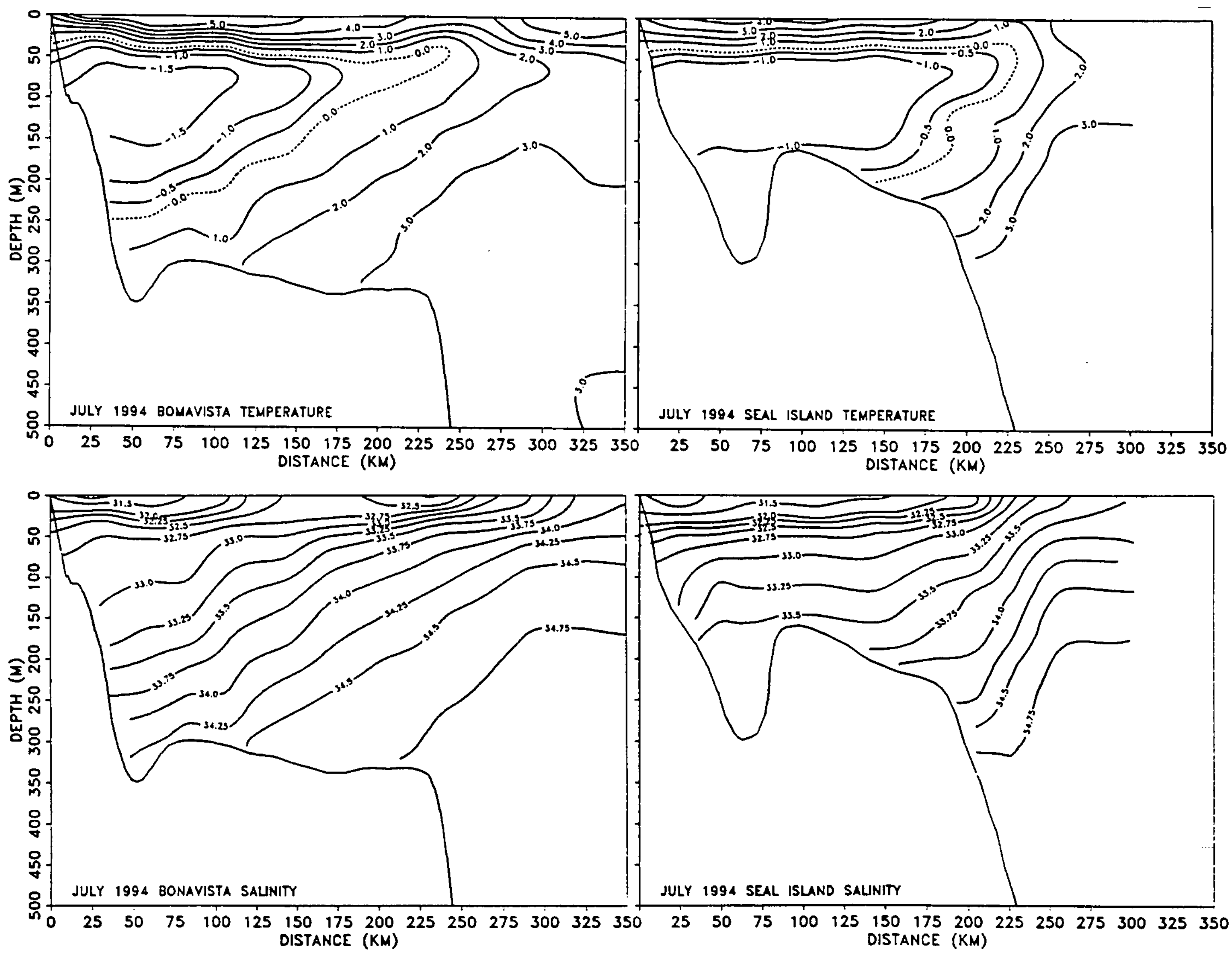

Fig. 9. The vertical distribution of temperature and salinity along the standard Bonavista and Seal Island transects for the summer (July) of 1994.

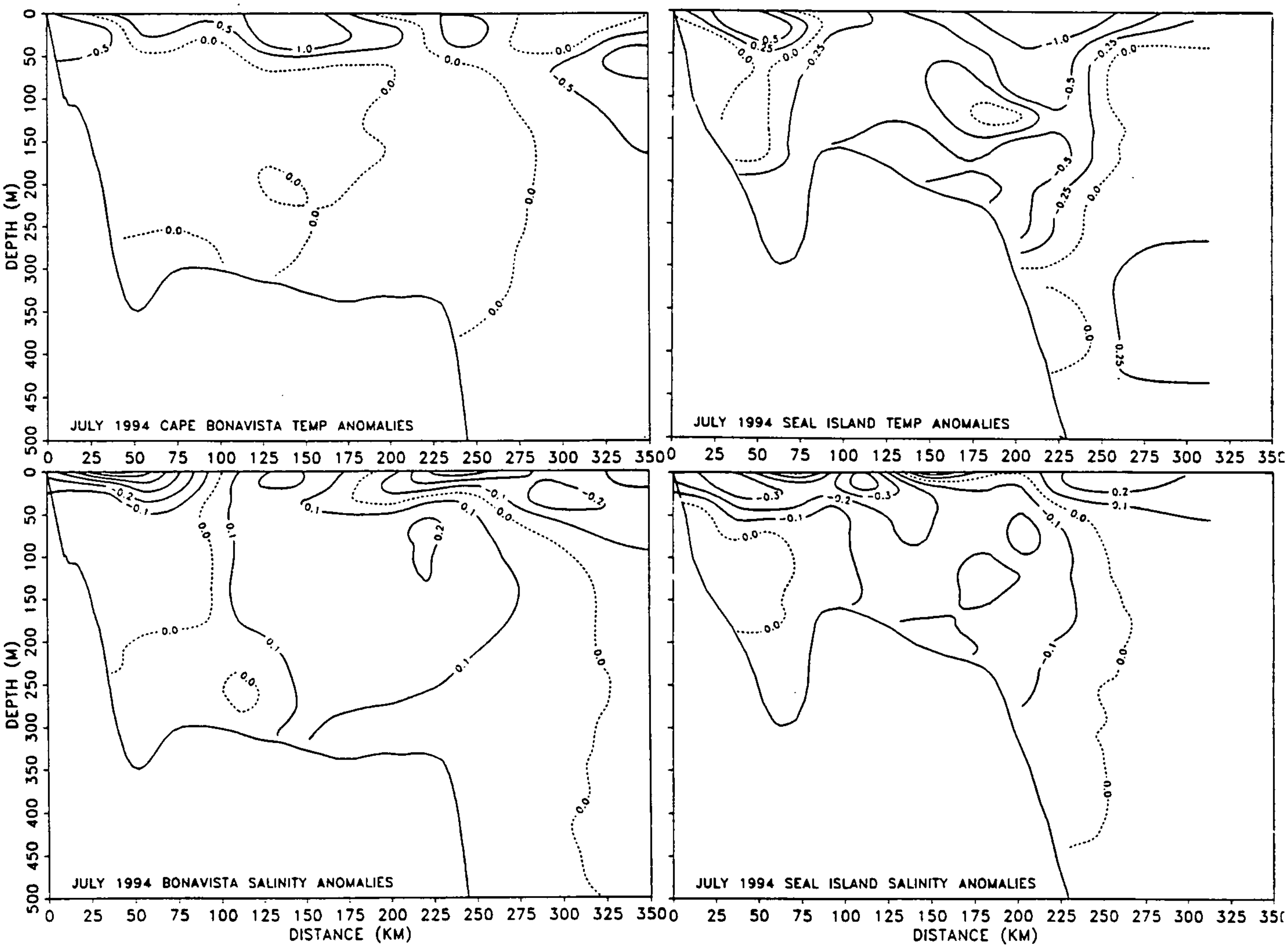

Fig. 10. The vertical distribution of temperature and salinity anomalies along the standard Bonavista and Seal Island transects for the summer (July) of 1994.

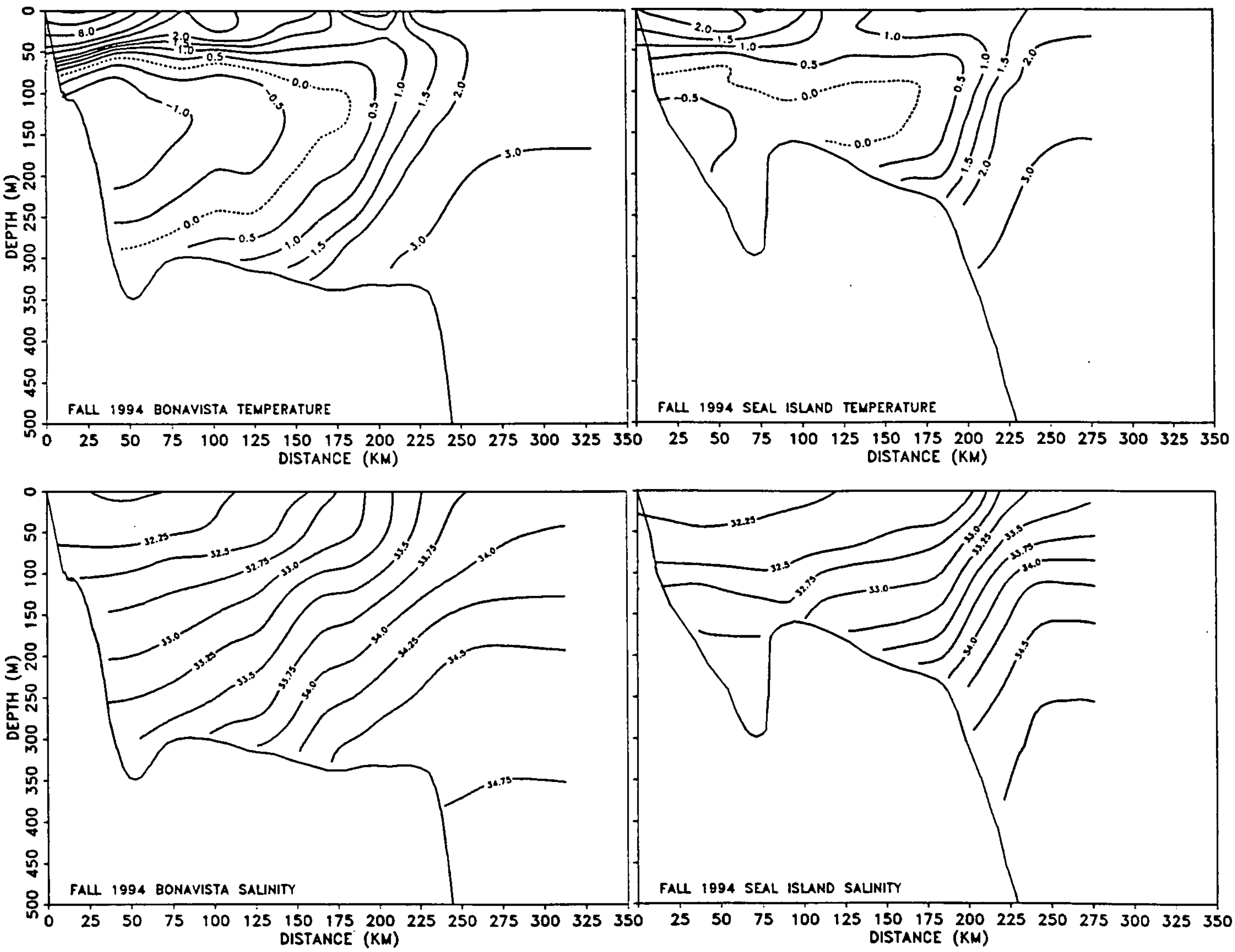

Fig. 11. The vertical distribution of temperature and salinity along the standard Bonavista and Seal Island transects for the fall (Nov. -Dec.) of 1994.

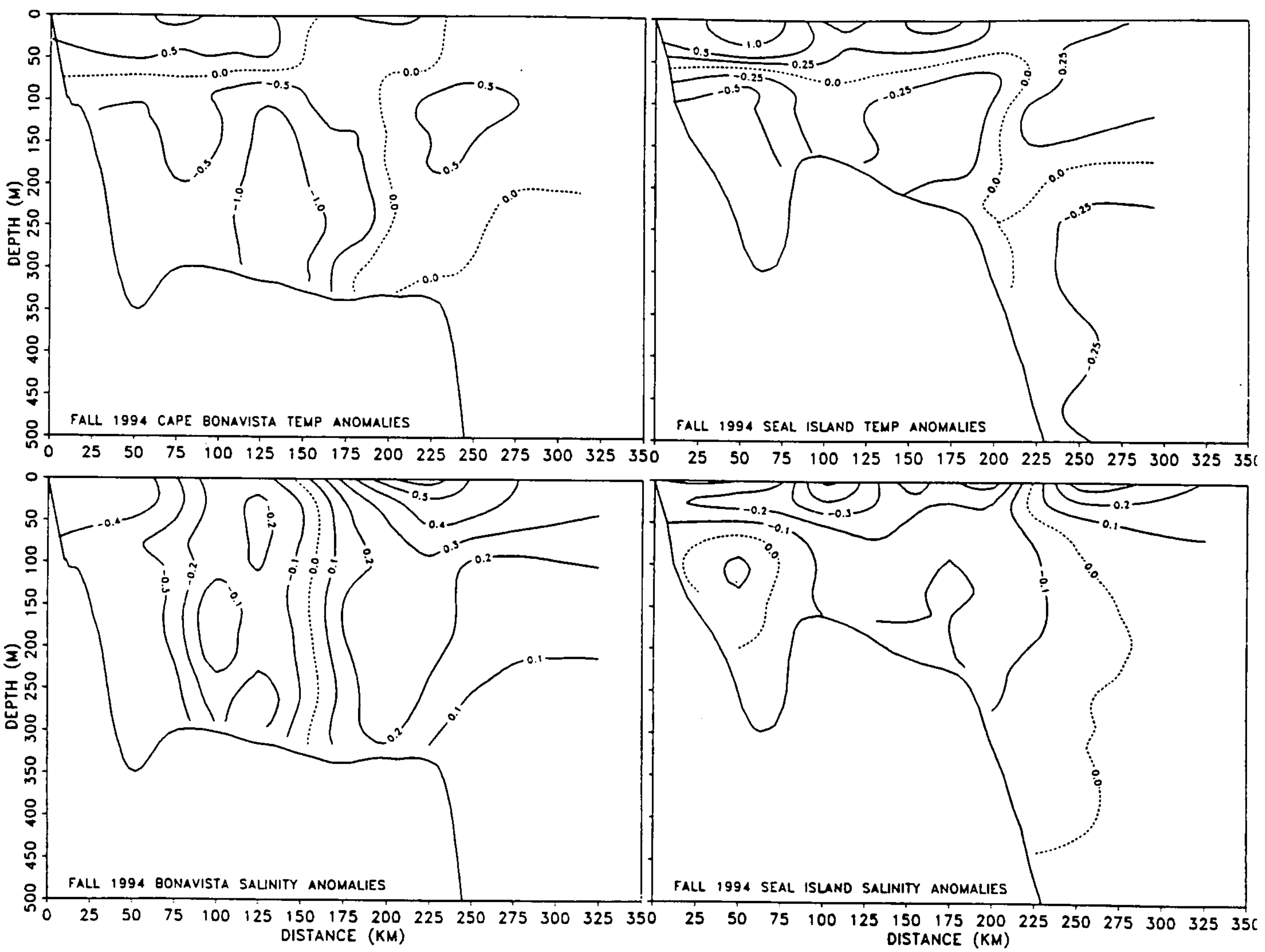

Fig. 12. The vertical distribution of temperature and salinity anomalies along the standard Bonavista and Seal Island transects for the fall (Nov.-Dec.) of 1994.

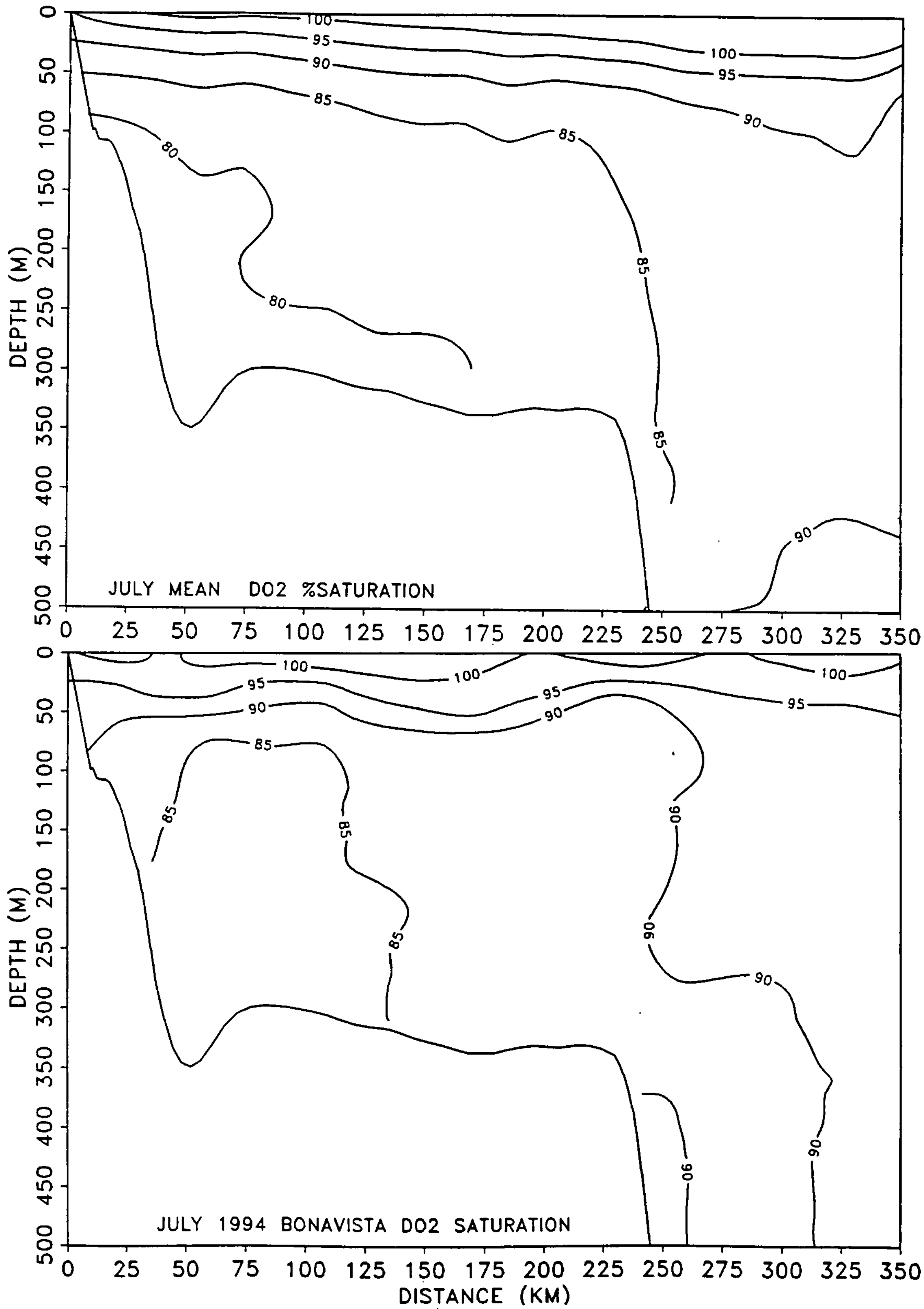

Fig. 13. The vertical distribution of dissolved oxygen saturation along the standard Bonavista transect for the average of historical data (top panel) and for July, 1994 (bottom panel).

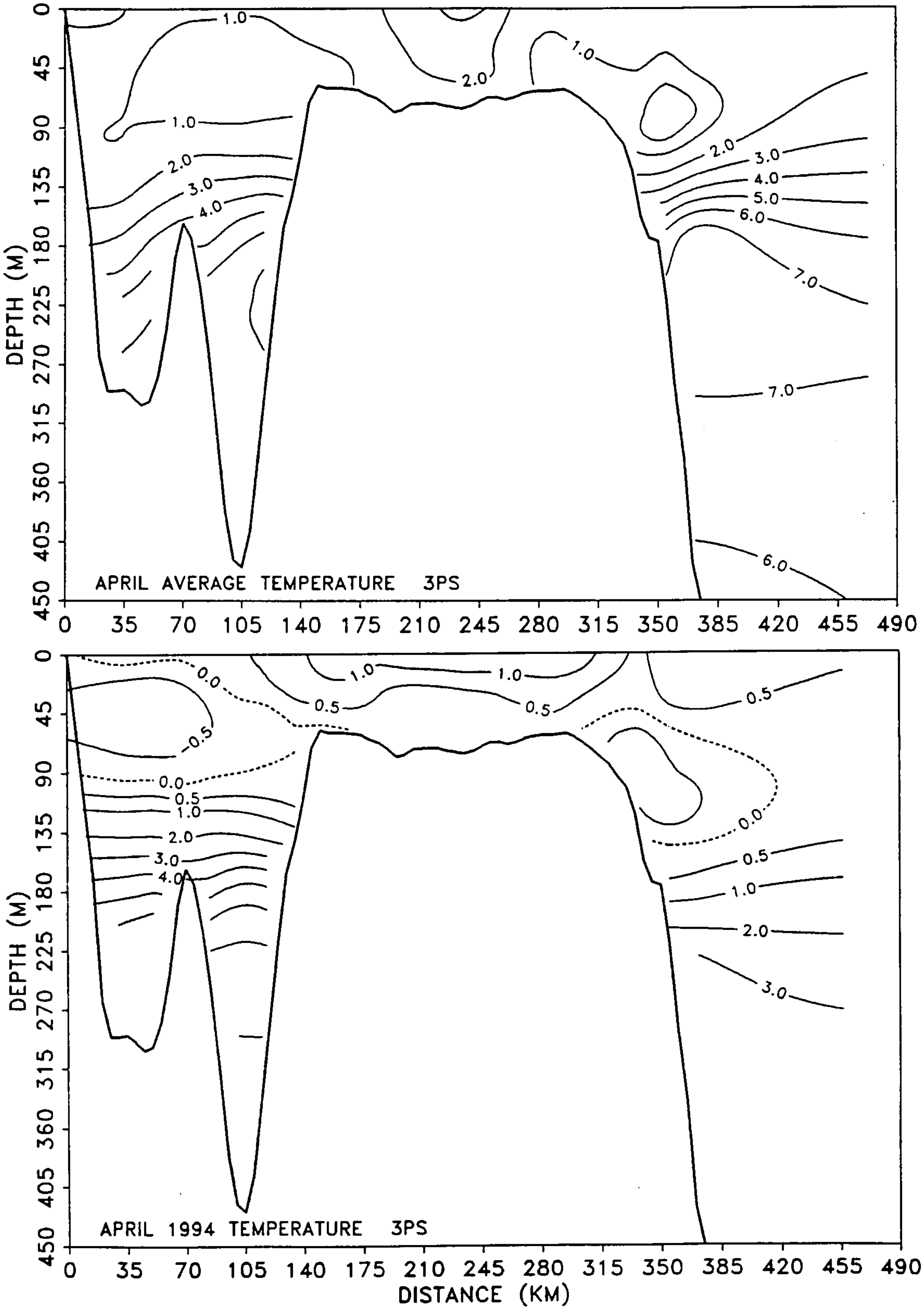

Fig. 14. The average and the 1994 April temperature along the transect shown in Fig. 1 for NAFO Subdivisions 3Pn and 3Ps.

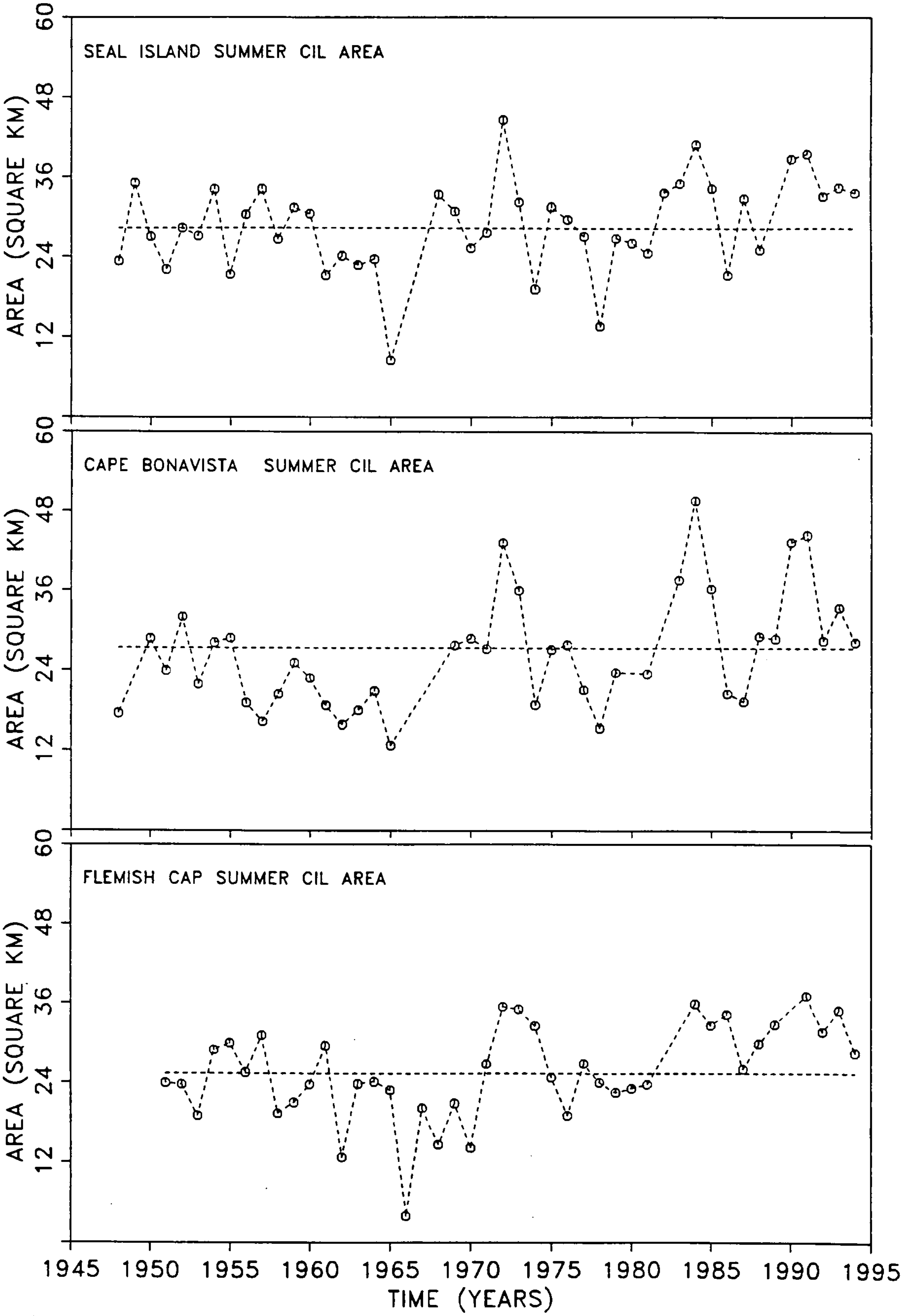

Fig. 15. Time series of CIL area along the Seal Island, Bonavista and Flemish Cap transects. The dashed line represents the 1961-90 average.

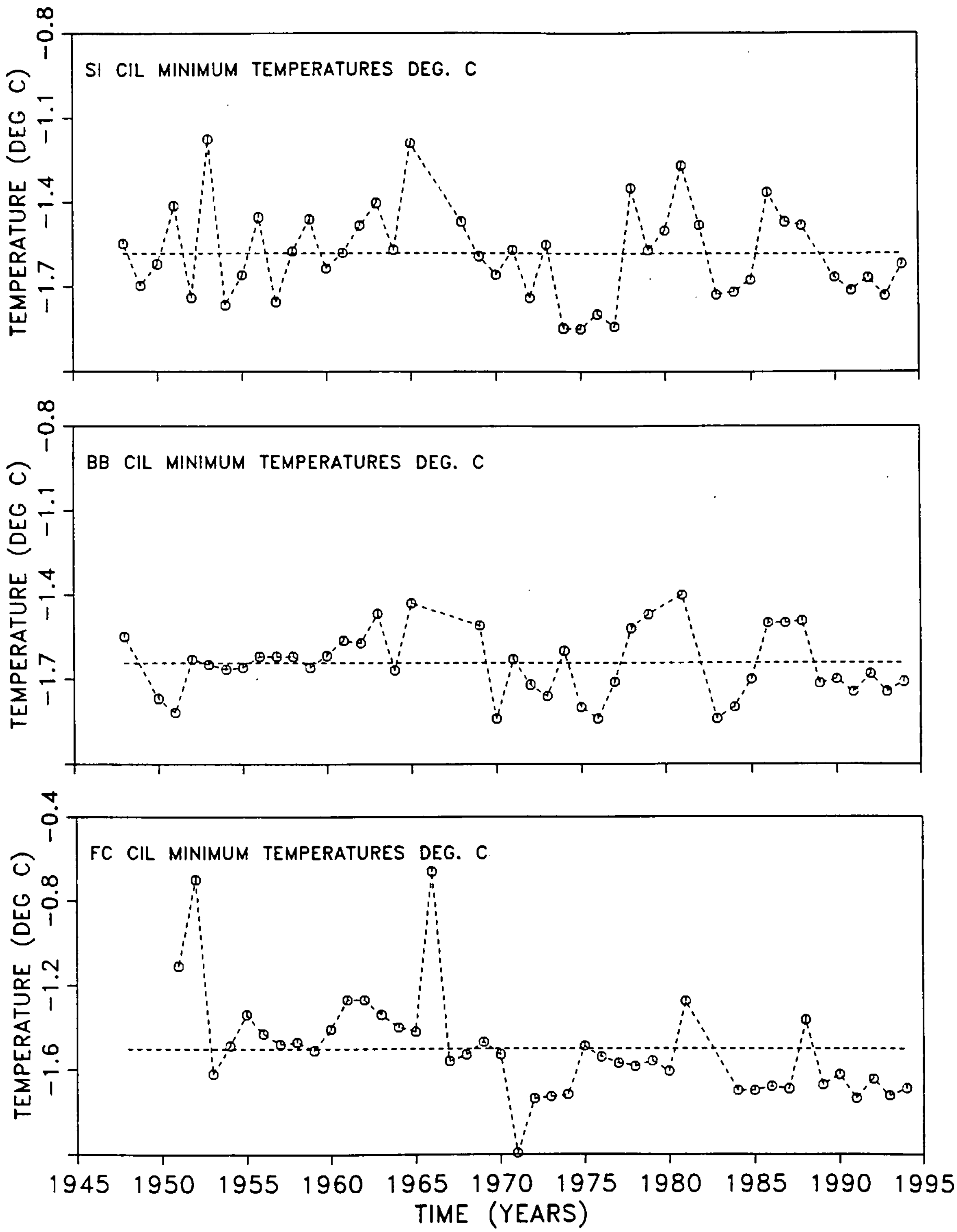

Fig. 16. Time series of CIL minimum temperature along the Seal Island, Bonavista and Flemish Cap transects. The dashed line represents the average.

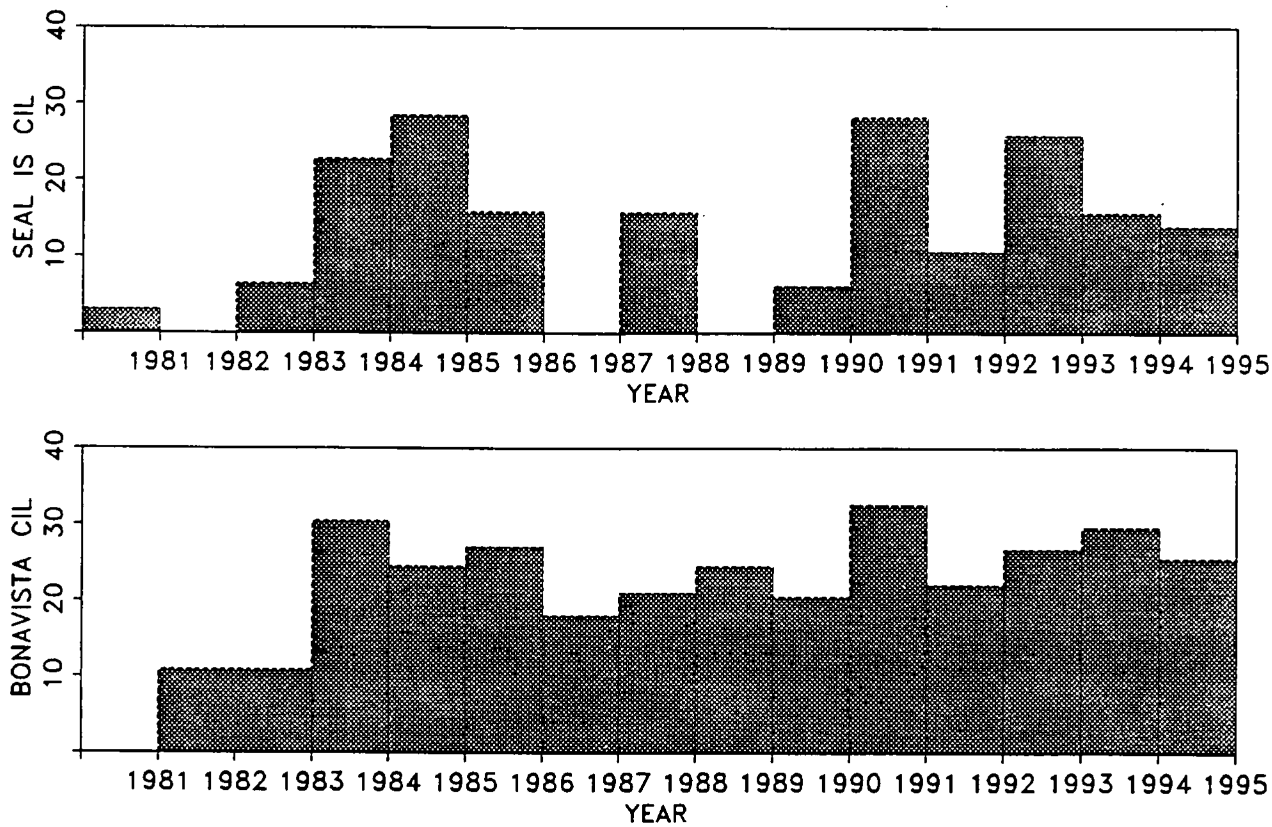

Fig. 17. Time series of CIL cross sectional area less than 0.0 °C during the fall for the Seal Island (top panel) and for the Bonavista transects (bottom panel).

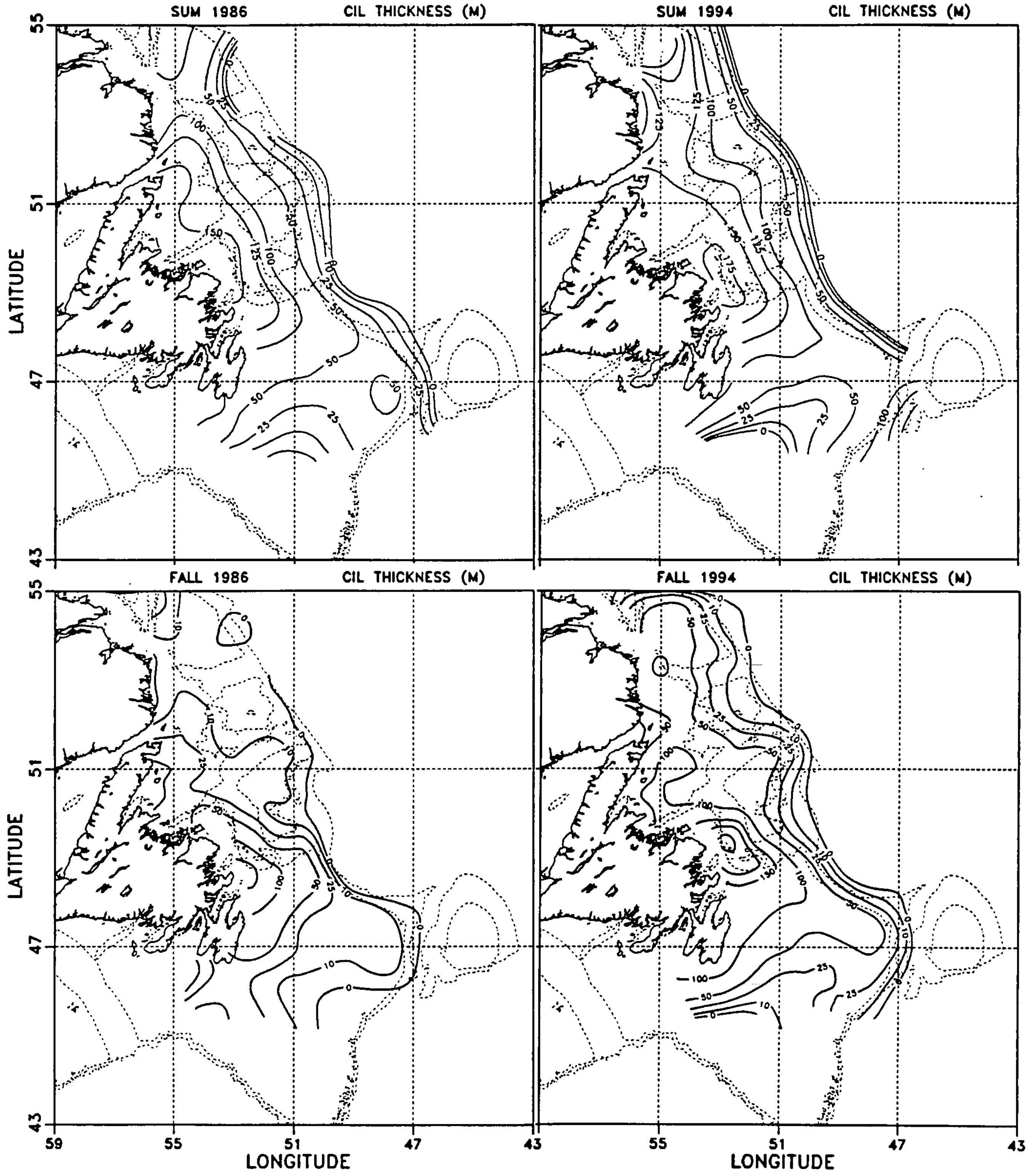

Fig. 18. Horizontal maps of the summer and fall CIL thickness (m) over the 2J to 3KL areas for 1986 and for 1994.

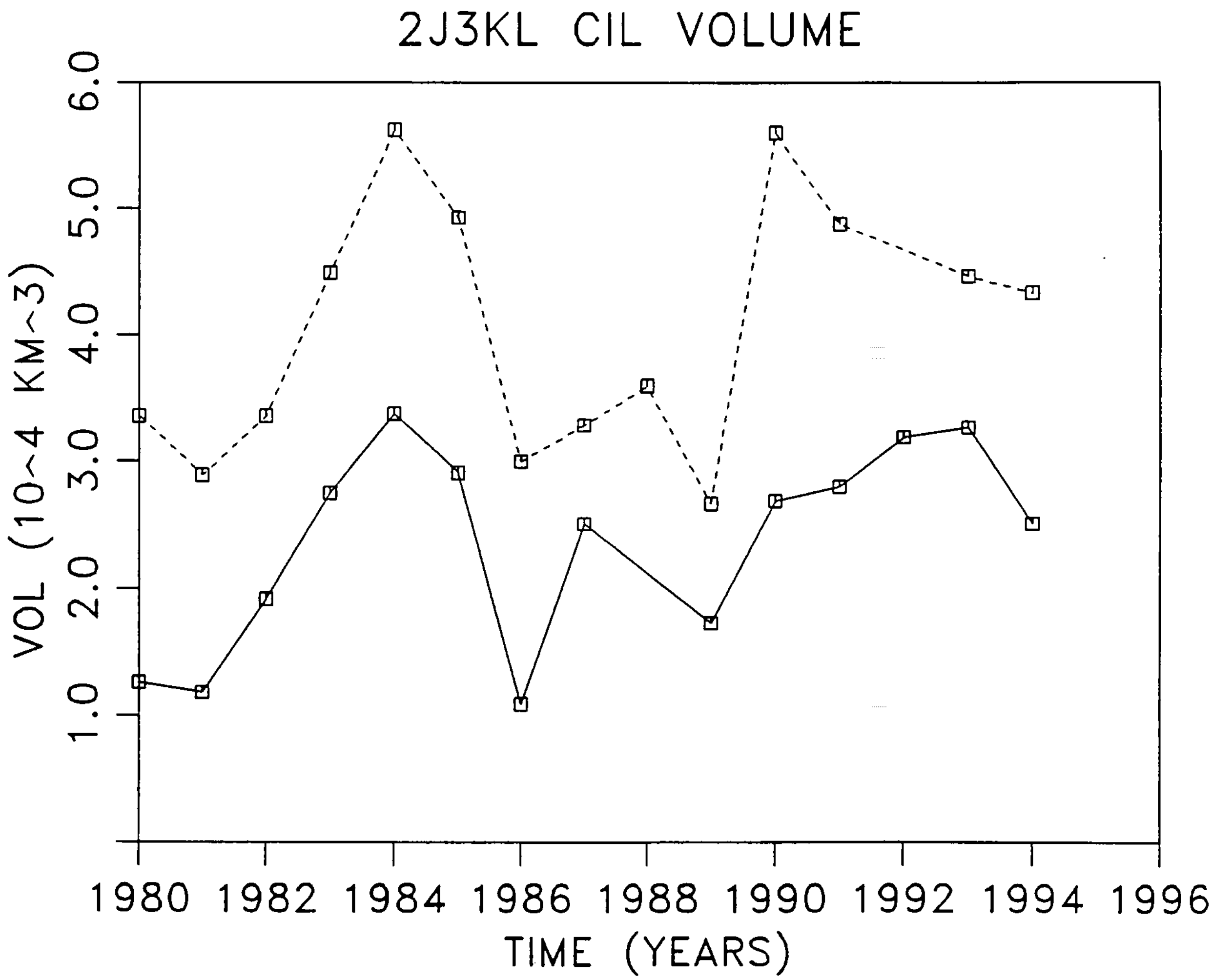

Fig. 19. Time series of summer (dashed line) and fall (solid line) CIL volumes (km^3) over the 2J to 3KL areas from 1980 to 1994.

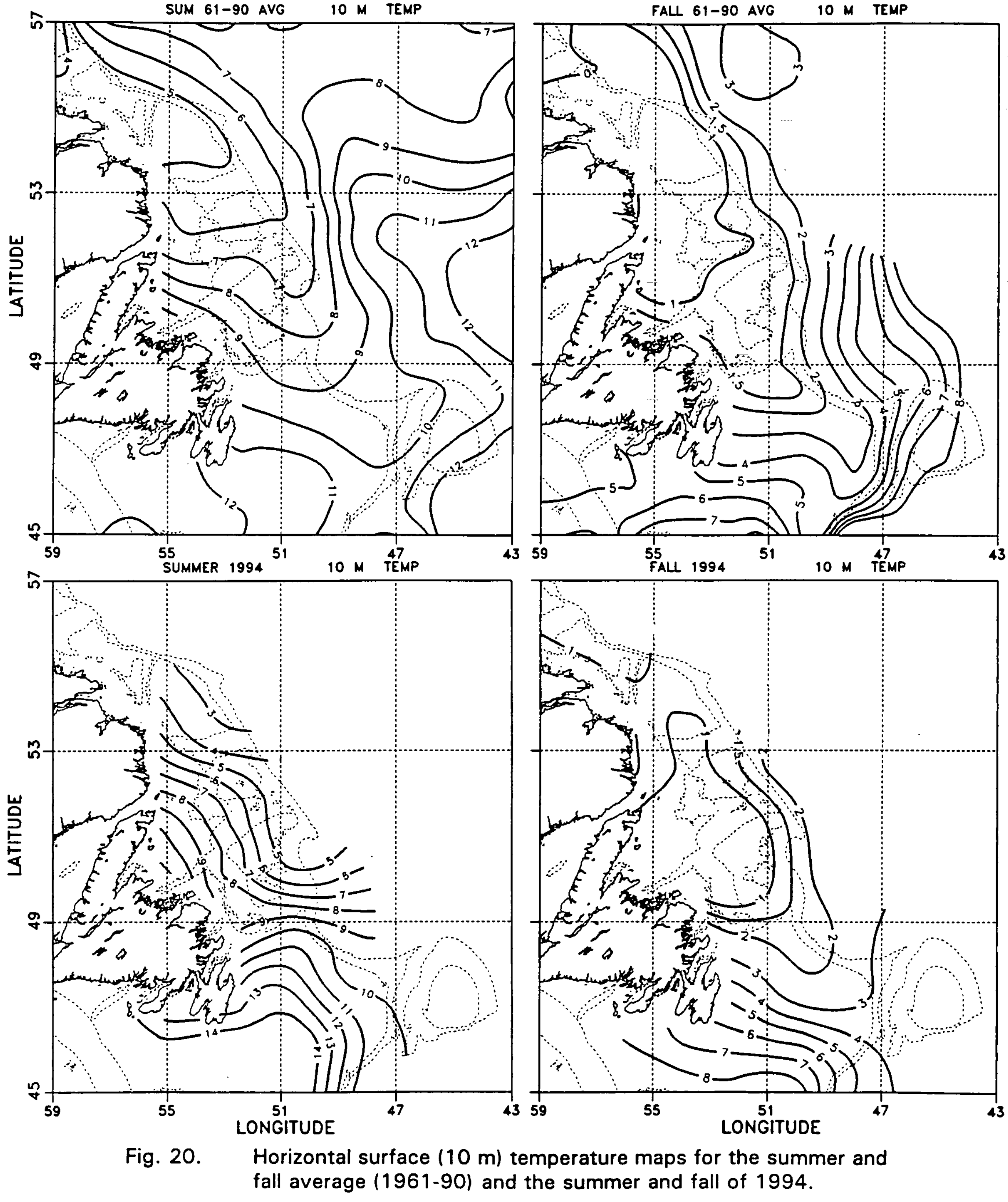

Fig. 20. Horizontal surface (10 m) temperature maps for the summer and fall average (1961-90) and the summer and fall of 1994.

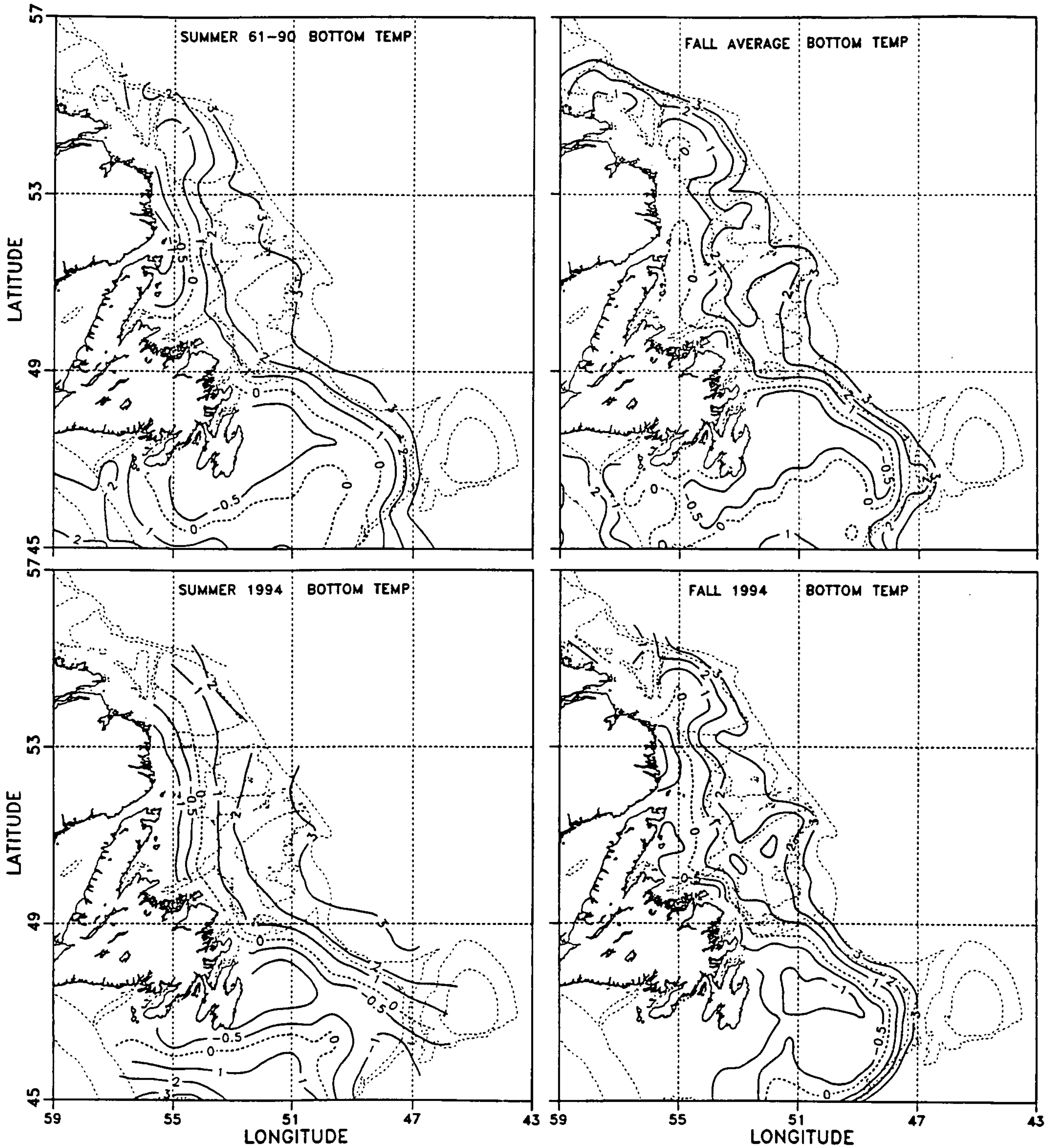

Fig. 21. Horizontal bottom temperature maps for the summer and fall average (1961-90) and the summer and fall of 1994.

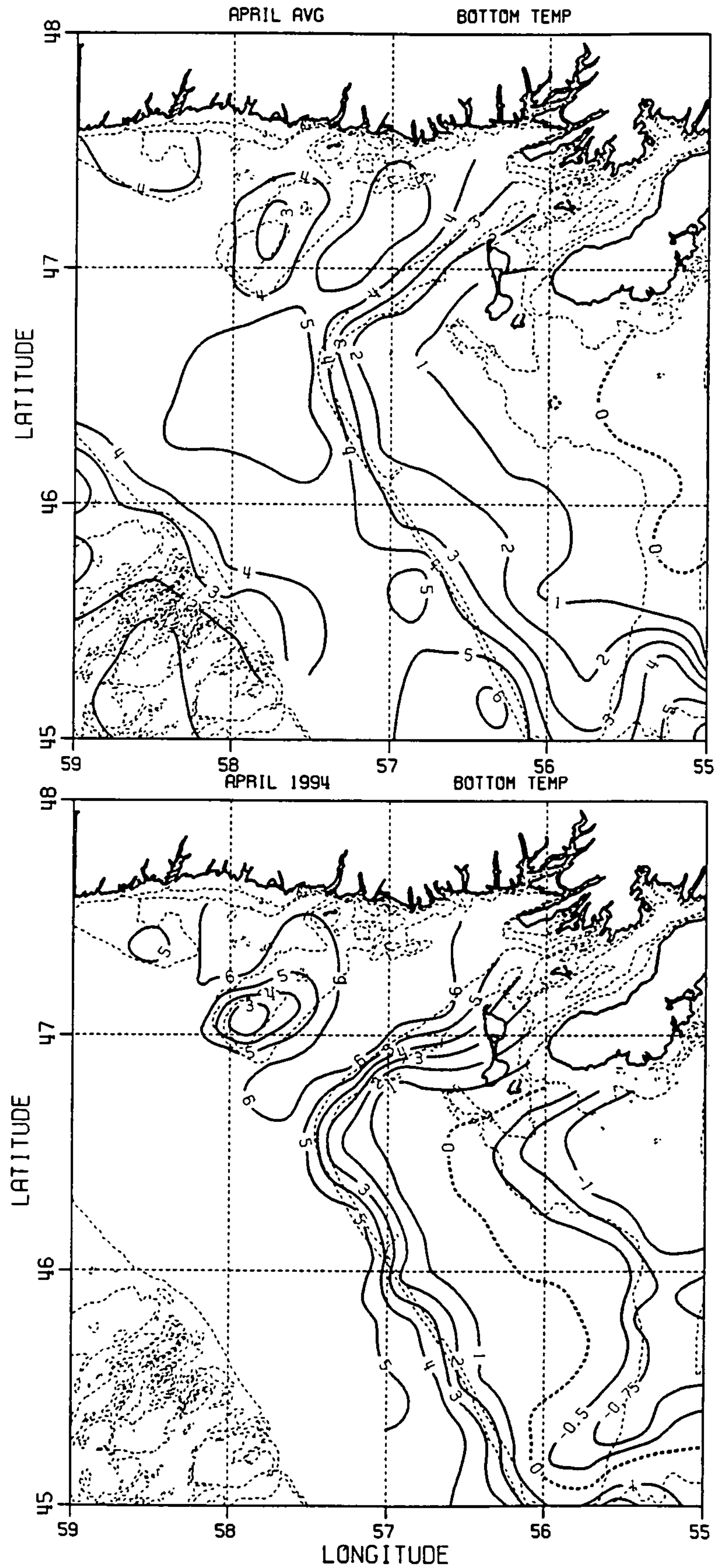

Fig. 22. Horizontal bottom temperature maps for the April average and April of 1994 in NAFO Subdivisions 3Pn and 3Ps.