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Oceanographic conditions in NAFO Divisions 2J 3KLMNO during 1999 with comparisons to the long-term (1961-1990) average

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ABSTRACT

Oceanographic observations from Hamilton Bank on the Southern Labrador Shelf to the Southern Grand Bank on the Newfoundland Shelf during 1999 are presented referenced to their long-term (1961-1990) means. Temperatures at Station 27 ranged from 0.25^o to 1^{o}C above normal during the winter months over most of the water column. The spring warming of the water column in the inshore Newfoundland Region began about 2 weeks earlier than normal and maximum summer surface temperatures reached a near record high of 15^{o}C. As a result temperatures were over 2^{o}C above normal at the surface during June and July. Bottom temperatures throughout the year ranged from 0.25^o to 0.5 ^{o}C above normal. Salinities at Station 27 were above normal during the winter months and below normal during the rest of the year. During the summer and fall of 1999 the cross-sectional area of sub-zero ^{o}C (CIL) water off Bonavista, Hamilton Bank and on the Grand Bank decreased over 1998 values continuing the below normal trend established in 1995. Bottom temperatures on the Northern Grand Bank during the spring of 1999 were up to 1°C above average and over the central and Southern Grand Bank they were up to 1-3^{o}C above the long-term average. During the fall bottom temperatures from Hamilton Bank to the southern Grand Bank were significantly above normal. The area of sub-zero ^{o}C water covering the bottom on all major banks in the Newfoundland Region during the fall, and on the Grand Banks during spring, had decreased to near 0%. In general, during 1999 ocean temperatures were above normal over most areas continuing the trend established in 1996. The main exception during 1999 was the colder-than-normal temperature anomaly associated with the Labrador Current which was evident in the standard transect data off eastern Newfoundland during the summer months and at Station 27 by early fall.

RÉSUMÉ

Des observations océanographiques réalisées en 1999 du banc Hamilton, au sud du plateau continental du Labrador, au sud du Grand Banc, sur le plateau de Terre-Neuve, sont présentées dans l’optique des moyennes à long terme (1961-1990). À la station 27, les températures ont varié de 0,25º à 1ºC au-dessus de la normale pendant l’hiver dans la plus grande partie de la colonne d’eau. Le réchauffement de printemps de l’eau de la partie côtière de la région de Terre-Neuve a débuté 2 semaines environ avant la date normale et la température de surface maximale d’été a atteint la valeur presque record de 15ºC. Les températures de surface ont donc été de plus de 2ºC supérieures aux normales de juin et juillet. Les températures au fond ont été supérieures aux normales de 0,25º à 0,5 ºC tout au long de l’année. Les salinités, à la station 27, ont été supérieures à la normale pendant l’hiver et inférieures à la normale le reste de l’année. Pendant l’été et l’automne de 1999, la superficie transversale de la couche d’eau de moins de zéro ºC (CFI) au large de Bonavista, sur le banc Hamilton et sur le Grand Banc, a diminué par rapport à 1998, ce qui a maintenu la tendance à des valeurs inférieures à la normale apparue en 1995. Les températures au fond, dans la partie nord du Grand Banc au printemps de 1999, ont été de jusqu’à 1°C supérieures à la moyenne et supérieures de 1 à 3ºC à la moyenne à long terme dans le centre et le sud du Grand Banc. À l’automne, les températures au fond, du banc Hamilton au sud du Grand Banc, étaient

significativement supérieures aux normales. La zone de température inférieure à zéro ºC, couvrant le fond de la plupart des bancs importants de la région de Terre-Neuve à l'automne et le Grand Banc au printemps, a diminué à près de 0%. De façon générale en 1999, les températures de l'océan ont été supérieures aux normales dans la plupart des zones et s'inscrivaient dans la tendance apparue en 1996. La seule exception notée en 1999 a trait à une anomalie de température inférieure à la normale associée au courant du Labrador qui apparaissait clairement au sein des données de transect standard à l'est de Terre-Neuve, pendant l'été, et à la station 27, au début de l'automne.

INTRODUCTION

This report presents an overview of oceanographic conditions in the Newfoundland region during 1999, with a comparison to long-term average conditions based on historical data. Where possible the long-term averages were standardised to a base period from 1961-1990 in accordance with the convention of the World Meteorological Organization and recommendation of the North Atlantic Fisheries Organization's (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. The information presented here is based on oceanographic observations made at Station 27 throughout the year and standard cross-shelf transect (Fig. 1) data obtained during an annual oceanographic survey in July and August. Temperature data from three Long-Term-Temperature-Monitoring-Program (LTTMP) sites in the inshore regions of Newfoundland are also used. In addition, oceanographic observations made during the spring and fall pelagic and ground fish research vessel surveys from the late 1970s to 1999 in NAFO Divisions 2J to 3KLMNO are included. Data from all available sources are used to help define the long-term means and conditions during 1999.

DATA SOURCES AND ANALYSIS

Oceanographic data are available from archives at the Marine Environmental Data Service (MEDS) in Ottawa and maintained in databases at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia and at the Northwest Atlantic Fisheries Center (NAFC) in St. John's Newfoundland. Since 1977 (in Division 2J), and from 1981 (in Divisions 3KL) to 1989 the bulk of the fall data were collected during random stratified groundfish surveys. From 1971 to 1988 temperature data on these surveys were collected using bottles at standard depths and/or MBT/XBTs, which were deployed usually at the end of each fishing set. Since 1989 net-mounted conductivity-temperature-depth (Seabird model SBE-19 CTD systems) recorders have replaced XBTs. This system records temperature and salinity data during trawl deployment and recovery and for the duration of the tow. Data from the net-mounted SBE-19 CTDs are not field calibrated, but are checked periodically and factory calibrated annually, maintaining an accuracy of 0.005^{o}C in temperature and 0.005 in salinity. The XBT measurements are accurate to within 0.1^{o}C.

Time series of temperature and salinity anomalies were constructed at standard depths from Hamilton Bank, Station 27 and the Flemish Cap. The 1961-1990 dataset 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 depth was determined by fitting a least squares regression of the form $\mathbf{cos(\omega t\text{-}\phi)}$ to the data. Where ω is the annual frequency, $\mathbf{t}$ is the time in days and ϕ is the phase. The fitted values were the mean, the annual frequency ω and two of its harmonics. The seasonal cycle was then removed to determine anomalies. These anomalies (except Station 27) are based on data collected over relatively large geographical areas and therefore may exhibit variability due to spatial differences in the monthly estimates. Temperature anomalies were also constructed for the inshore region of Notre Dame Bay, Bonavista Bay and Placentia Bay from the Long-Term-Temperature-Monitoring thermograph sites by computing monthly means from the continuous hourly time series.

Bottom temperature grids for the Newfoundland Shelf were produced from all available data from 1961 to 1990 and for the spring and fall of 1999. All bottom-of-the-cast temperature values for each time period (except those for which the cast depths were not within 10% of the total water depth) were interpolated onto a regular grid and contoured using a geostatistical (2-diminsional Kriging) procedure. Bottom temperature anomalies were computed by taking the difference between the 1999 and the average grids. Some temporal and spatial biasing may be present in the analysis given the large area and wide time interval over which the surveys were conducted. For example, the annual fall ground fish survey normally starts early to mid-October and finishes around mid-December, a time period when rapid cooling of the water column is taking place.

Near-bottom temperature data from the ground fish assessment surveys were used to compute a time series of the area covered by water in selected temperature ranges. The mean near-bottom temperature for each grid element was calculated as described above and its area integrated to produce a yearly estimate of the percentage of the total area within each temperature range. This areal index is expressed as a percentage of the total surveyed area. The mean near-bottom temperature time series was also constructed for each region. The selected temperature ranges were $\leq 0^{o}$C, 0-1^{o}C and $\geq 1^{o}$C. Potential sources of error in this analysis include temporal biasing, arising from the wide time interval during which a typical survey is conducted. This source of error is probably small, however, given the low magnitude of the annual cycle over most of the near-bottom depths encountered. An additional source of error that can potentially affect the results, particularly along the shelf edge, occurs when the spatial scales of temperature variations are shorter than the grid size. This effect however will probably be small, particularly over the Banks where the landscape is relatively flat.

TEMPERATURE AND SALINITY TRENDS

Station 27 (Division 3L)

A total of 45 temperature and salinity profiles were collected in the Avalon Channel at Station 27 off Cape Spear (Fig. 1) during 1999. The data from this time series are presented in several ways to highlight seasonal and interannual variations over the entire water column. The annual surface temperature and salinity cycles together with the 1961-1990 normal curves are shown in Fig. 2. Surface salinity values were below normal during the spring and summer months, with the salinity minimum arriving earlier than normal and the low salinities lasting longer. Surface temperatures were above normal from early spring until September with the annual warming beginning in early May, about 2 weeks earlier than normal. Maximum summer surface temperatures reached a near record high of 15^{o}C.

Depth versus time contour maps of temperature and salinity values and their associated anomalies for 1999 are displayed in Figs. 3 and 4. The cold near isothermal water column during the winter months has temperatures ranging from 0^{o}C to –1^{o}C. These temperatures persisted throughout the year, in the bottom layers. The surface layer temperatures were near constant at about 0^{o}C from January to early April, after which the surface warming commenced. By late April upper layer temperatures had warmed to 2^{o}C and to near 15^{o}C by August at the surface, after which the fall cooling commenced. These temperatures ranged from 0.25^{o} to 1^{o}C above normal for the winter months over most of the water column and over 2^{o}C above normal at the surface during June and July. By late summer a negative temperature anomaly developed over the upper 100-m of the water column with anomalies exceeding 0.5°C below normal. These cold anomalies may have been caused by the advection of cold water from the Labrador Coast that was observed during the summer. Bottom temperatures throughout the year ranged from 0.25^{o} to 0.5^{o}C above normal. Surface salinities reached a maximum of >32.2 by late February and decreased to a minimum of <30.5 by late August. These values ranged from about normal during the winter months to 0.2-0.5 below normal during the summer months. In the depth range from 50 to 100-m, salinities generally ranged from 32.4 to 32.7 and near bottom they varied throughout the year between 33 and 33.5. Except for the positive anomaly during the winter months salinities were generally below normal during most of 1999.

The interannual time series of temperature and salinity anomalies at standard depths show three major colder and fresher-than-normal periods at near decadal time scales since the early 1970s (Figs. 5 and 6). At the surface, the negative temperature anomalies that began in late 1990, reaching a peak in mid-1991, had moderated to above normal conditions by the summer of 1994 and have continued above normal up to 1999. At 100-m depth, temperatures have oscillated above and below normal. Near bottom at 175-m, temperatures were generally below normal from 1983 to 1994, the longest continuous period on record. During 1994 and 1995 bottom temperatures begin to warm and by 1996 were above the long-term average. Bottom temperatures during both 1998 and 1999 remained above the long-term average. Upper layer salinity anomalies show the large fresher-than-normal anomaly that began in early 1991 had moderated to near normal conditions by early 1993 but returned to fresher conditions by the summer of 1995 and continued into 1996. Salinities approached near normal values during 1997 and 1998 but decreased to mostly below normal values during 1999. Other time periods with colder temperatures and fresher-than-normal salinities, particularly in the early 1970s and mid-1980s, are associated with strong positive NAO index anomalies, colder-than-normal winter air temperatures, heavy ice conditions and larger than average summer cold-intermediate-layer (CIL) areas on the continental shelf (Drinkwater 1994, Colbourne et al. 1994, Drinkwater et al. 1996).

The vertically averaged (0-176 m) annual temperature anomaly (which is proportional to the water column heat content anomaly) time series (Fig. 7) shows large amplitude fluctuations at near decadal time scales, with cold periods during the early 1970s, mid-1980s and early 1990s. During the time period from 1950 to the late 1960s the heat content of the water column was generally above the long-term mean. It reached a record low during 1991, a near record high during 1996, near normal in 1997 and 1998 and above normal during 1999. The 0-50 m vertically-averaged summer (July-September) salinity anomalies (Fig. 7) show similar behaviour as the heat content time series with fresher-than-normal periods corresponding to the colder-than-normal conditions. The magnitude of negative salinity anomaly on the inner Newfoundland Shelf during the early 1990s is comparable to that experienced there 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, these increased to near normal values in 1997 and 1998 but fell again to below normal values in 1999.

Hamilton Bank (Division 2J)

Time series of temperature and salinity anomalies from 1950 to 1999 on Hamilton Bank are shown in Fig. 8a and 8b at standard depths of 0, 50, 75 and 150 m. The monthly average values show high frequency variations, which may indicate spatial variability over the bank at the same depth level. It should also be noted that the monthly averages consist of a variable number of observations. A low frequency trend was calculated by smoothing the time series using a five-point running mean. This suppresses the high frequency variations at seasonal scales and gives a general indication of long-term trends.

The time series is characterised by large variations with amplitudes ranging from ±1^{o}C and with periods ranging from 2 to 10 years. The cold periods of the early 1970s, the mid-1980s and the early 1990s are apparent, however, the amplitude of the anomalies vary considerably with depth. The long-term trend indicates that temperatures on Hamilton Bank have moderated, particularly in the deeper layers, being above normal since the mid-1980s, similar to conditions further south at Station 27. During 1999 the monthly average temperatures were above normal over most of the water column. 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. The below average trend established in the early 1990s continued into 1996, however, measurements made during 1997 to 1999 indicate a trend of increasing salinity except at the surface.

Flemish Cap (Division 3M)

Similar to the Newfoundland Shelf, the monthly temperature anomalies on the Flemish Cap (Fig. 9a) are characterised 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 below 100-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, negative temperature anomalies had returned. This cold period moderated briefly in 1987 but returned again by 1988 and continued into the early 1990s. From 1995 to 1998 temperatures moderated and were above normal during 1999.

The time series of salinity anomalies (Fig. 9b) show 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 0.6 below normal. The trend in salinity values during the early 1990s ranged from slightly above normal at the surface to slightly below normal at deeper depths. In general, temperature and salinity anomalies on the Flemish Cap are very similar to those at Station 27 and elsewhere on the continental shelf over similar depth ranges (Colbourne 1998).

Coastal Near-Surface Temperatures

Hourly temperature measurements at 10-m depth were made at inshore monitoring sites at Comfort Cove in Notre Dame Bay since 1981, Stock Cove in Bonavista Bay since 1967 and at Arnold's Cove in Placentia Bay since 1981 as part of the LTTMP (Fig. 1). The complete time series were used to calculate monthly means from which temperature anomaly time series were constructed (Fig. 10). Temperatures at Arnold's Cove were above normal during the first 8 months of 1998, below normal during the rest of the year but warmed to above normal values during 1999, reaching near 4^{o}C above normal during the summer months. During the latter half of 1998 temperatures at Comfort Cove fluctuated above and below normal but increased to above normal values from May to October of 1999, reaching over 4^{o}C above normal during July. At Stock Cove temperatures were above normal for most of 1998, except during the fall months and above normal from January to July of 1999. The negative anomaly during August at Stock Cove was due to the upwelling of colder sub-surface water caused by an extended period of strong offshore wind forcing. These events are frequently observed near shore along the East Coast of Newfoundland during the summer months.

STANDARD TRANSECTS

In 1976 the International Commission for the Northwest Atlantic Fisheries (ICNAF) adopted a suite of standard oceanographic stations along transects in the Northwest Atlantic Ocean from Cape Cod (USA) to Egedesminde (West Greenland) (Anon. 1978). Four of these transects are occupied annually during mid-summer on an annual oceanographic survey conducted by DFO's Newfoundland Region, they are: (1) the Seal Island transect on the Southern Labrador Coast and Hamilton Bank; (2) the White Bay transect which crosses the relatively deeper portions of the Northeast Newfoundland Shelf; (3) the Bonavista transect off the East Coast of Newfoundland; and (4) the Flemish Cap transect which crosses the Grand Bank at 47°N and continues eastward across the Flemish Cap. In this section the results from the Seal Island, Bonavista and the Flemish Cap transects for the summer of 1999 are presented.

Temperature and Salinity

Seal Island

Temperatures along the Seal Island transect (Fig. 11a) ranged from 0^{o}C at 30-m depth to between 5^{o}C to 6^{o}C at the surface. Temperatures below 50-m were generally sub-zero ^{o}C over most of the shelf except near bottom where they range from 1-3^{o}C. Near the shelf break temperatures increase up to 4^{o}C. Temperature anomalies in the surface layer along the Seal Island transect ranged from 0.25^{o} to 1.0^{o}C below normal near-shore and at the shelf break to 1^{o}C above normal in the offshore region beyond the shelf edge. Below 50-60 m and near bottom, temperatures ranged from 0.25-1.5^{o}C above normal. Surface salinities along the Seal Island transect (Fig. 11b) ranged from 31.5 near-shore to greater than 33.25 offshore. Below the surface layer salinities ranged from 32-34.5 near bottom over the shelf. Except for a weak sub-surface negative anomaly near the shelf edge, salinities were above normal along the entire transect during July by up to 0.4.

Bonavista

Temperatures along the Bonavista transect (Fig. 12a) in the upper 20-m of the water column ranged from 10^{o}C-12^{o}C in the inshore regions but decreased to 8^{o}C along the offshore portion of the transect. These values were up to 2^{o}C above normal near the coast and up to 1^{o}C below normal at about 100 km from Cape Bonavista and offshore to the edge of the shelf. Most of the intermediate depth temperatures were slightly below normal while deep-water (200-300 m) temperatures were up to 1.5^{o}C above normal. Bonavista transect salinities (Fig. 12b) ranged from 31.25 near the surface in the inshore region to 34.25 in the offshore region. Bottom salinities ranged from 32.5 over the inshore portion of the transect, to 34.75 at about 325-m depth near the shelf edge. Salinities were fresher than normal (up to 0.6) in the upper 200-m over the inshore half of the transect and saltier-than-normal (by up to 0.5) in the offshore half of the transect. The fresher-than-normal salinities inshore were also observed at Station 27. Bottom salinities across the shelf in water deeper than 200-m were near to slightly above normal.

Flemish Cap

Summer temperatures along the Flemish Cap transect (Fig. 13a) ranged from about 12^{o}C near the surface to sub-zero ^{o}C below 50-m in the Avalon Channel and at the edge of the Grand Bank in the core of the Labrador Current. Over the Flemish Cap temperatures were greater than 12^{o}C at the surface and about 4-5^{o}C at 80-m depth to the bottom. The values were about 2^{o}C above normal in the upper layer near the coast, below normal at mid-shelf and above normal in the offshore areas. Bottom temperatures over most of the Grand Bank were near 0.5^{o}C above normal. Over the Flemish Pass and Cap temperatures ranged from 0.5-1.5^{o}C above normal, except east of the Cap, where temperatures were up to 1^{o}C below normal. Salinities along the transect (Fig. 13b) were slightly fresher than normal in the Avalon Channel, at the edge of the Grand Bank and to the east of the Flemish Cap. These are regions where the Labrador Current flows southward indicating fresh-than-normal water being advected from the north.

CIL Time Series

As shown above in the cross shelf transect plots the vertical temperature structure on the Newfoundland Continental Shelf during the summer is dominated by a layer of cold sub-zero ^{o}C water trapped between the seasonally heated upper layer and warmer slope water near the bottom. This water mass is commonly referred to as the cold intermediate layer or CIL (Petrie et al. 1988). The cold, relatively fresh, shelf water is separated from the warmer saltier water of the continental slope by a strong temperature and salinity front near the edge of the continental shelf. Figure 14a shows a time series of the CIL cross-sectional area of sub-zero ^{o}C water for the Seal Island, Bonavista and Flemish Cap transects.

Along the Bonavista transect during the summer of 1999 the CIL extended offshore to about 190 km, with a maximum thickness of about 175 m corresponding to a cross-sectional area of about 20.2 km^2 (Fig. 12a), compared to the 1961-90 average of 26.8 km^2. This value is about 25% below normal compared to 5% below normal in 1998 and 28% below normal in 1997. From 1990 to 1994 the CIL area was above normal reaching a peak of more than 60% in 1991. The CIL area along the Seal Island transect was also below normal by about 49% during 1999, compared to 15% in 1998 and 38% during 1997. 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 about 14% below normal in 1999 compared to about normal in 1998 and up to 20% above normal in 1997. During 1995 it was about 18% above normal compared to 12% in 1994 and to 48% during 1991. In general, the total cross-sectional area of sub-zero ^{o}C water on the Newfoundland Shelf in 1999 is continuing the below normal trend established in 1995 (Fig. 14a).

Minimum temperatures measured in the core of the CIL for all three transects during the summer from 1950 to 1999 are shown in Fig. 14b. The minimum temperature observed along the Seal Island transect during 1999 was -1.33^{o}C compared to a normal of -1.57°C. Core temperatures along the Bonavista transect were slightly above normal at -1.58^{o}C and along the Flemish transect they were -1.45^{o}C compared to a normal of -1.52°C. These values represent an increase over 1997 and 1998 values at all three sites.

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 2×10^5 km^3. The calculation of the volume of sub-zero ^{o}C water overlying the continental shelf has been described by Colbourne and Mertz (1995). The amount of sub-zero ^{o}C water is principally determined by the thickness of the layer of water less than 0^{o}C on the shelf. The isolines of CIL thickness show large variations from summer to fall of the same year and from cold years to warm 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 zero 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 sub-zero ^{o}C water over the 2J 3KL area shows maximum values during the cold periods of the mid-1980s and early 1990s (Fig. 15). The total volume of sub-zero ^{o}C water on the shelf increased from approximately $3.3 \text{ X } 10^4$ 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 sub-zero ^oC water on the Newfoundland Shelf has been slowly decreasing, and by 1995 it had decreased to values of the early and mid-to-late 1980s. The 1999 volumes decreased slightly relative to 1998 values in both summer and fall. During the last 5 years the volume of CIL water has been below average. The 1980 to 1998 average volume of sub-zero ^oC water on the shelf during the summer is 4.0 ± 0.9 x 10^4 km^3, roughly 20% 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 ± 0.8 x 10^{14}, km^3 about 60% of the summer value. Due to data limitations, the volume estimates were not calculated prior to 1980. Time series of the volume of sub-zero ^oC 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).

Geostrophic Circulation and Transport

The historical (1950-1999) summer (July-August) temperature and salinity data along the Seal Island, Bonavista and Flemish Cap transects were used to compute geostrophic currents relative to 300 m from the horizontal gradient of the steric height using the geostrophic balance relationship according to Gill (1982). The density profiles were first extrapolated to the surface and interpolated to 5-m depth intervals. In addition, all historical data that were not part of the synoptic observations made along the transect were excluded from the analysis.

The geostrophic speed of the southward flowing Labrador Current along the Seal Island transect for 1998 and 1999 shows distinct inshore and offshore branches (Fig. 16). The inshore branch is located within about 125 km from the shore and the offshore branch, which is about 100 km wide, is centered at about 220 km offshore over the 500-m isobath. In the offshore branch, current speeds range from 0.05 m/s at 175-m depth to greater than 0.2 m/s in the upper water column. In the inshore branch, current speeds are generally less than 0.01 m/s. Currents over mid-shelf on Hamilton Bank appear to reverse direction flowing north with speeds generally less that 0.08 m/s.

Geostrophic currents along the Bonavista transect for 1998 reveal distinct offshore and inshore branches of the Labrador Current, however for 1999 the baroclinic current appears broad with no well defined inshore and offshore components (Fig. 17). Current speeds in the upper 200-m of the water column generally ranged from 0.05-0.15 m/s. During 1998 the offshore feature was about 125 km wide with speeds ranging from 0.05 m/s at 200-m depth to greater than 0.20 m/s in the upper 50-m of the water column. The inshore branch during 1998 was within 100 km of the shore with speeds also reaching near 0.20 m/s.

Geostrophic currents perpendicular to the Flemish Cap transect for 1998 and 1999 show the well-known features of the circulation. The strong baroclinic component of the offshore branch of the Labrador Current near the edge of the Grand Bank, the general anticyclonic circulation around the Cap and the northward flowing water of the North Atlantic Current east of the Cap are evident (Fig 18). The inshore branch of the Labrador Current is weak and restricted to the Avalon Channel region within 50 km of the coast. Typical geostrophic speeds range from 0.05-0.10 m/s in the gyre over the Cap and near 0.20 m/s to the east of the Cap in the North Atlantic Current and greater than 0.20 m/s in the surface layer near the offshore edge of the Grand Bank. During 1999 the offshore branch of the Labrador Current was narrow and (less than 100 km) with higher current speeds than in 1998.

The volume transport for all transects was calculated by integrating the speed both vertically through the water column and horizontally in the offshore direction across the shelf. A common reference level of 135-m was chosen for these calculations partly to compare with previous work, but also because this was the deepest level common to all three transects that did not intersect the bottom, thus eliminating potential problems associated with a bottom reference level. Also, the main interest was to examine variations in volume transport during recent ocean climate changes on the continental shelf. These climate changes resulted in variations in upper layer shelf stratification due mainly to salinity changes resulting from increased ice formation and melt which may influence the strength of the geostrophic component of the Labrador Current.

The time series of volume transport of the offshore branch of the Labrador Current for the three transects show large interannual variations with an average transport of between 0.4-0.5 Sv (1 Sv = 10^6 m^3/s) to the south relative to 135 m (Fig. 19). In general, the time series indicates higher than average transport during the late 1950s and into the 1960s, lower than average values during the cold period of the early 1970s and to a less extent during the cold period of the mid-1980s. During the late 1980s the transport increased to above average values, which for the most part continued into the mid-to-late 1990s.

These results show some similarity with those obtained by Myers et al. (1989) during the same time period (1950-1986). That is, they show a significant, albeit weak, negative correlation between the upper layer geostrophic transport along the Seal Island and Flemish Cap transects and the NAO index indicating reduced transport during cold periods. Also the results support the suggestion by Petrie and Drinkwater (1993) that increased transport of Labrador Current Water around the southeast Grand Bank during warm periods (mid 1960s) on the Northeast Newfoundland Shelf resulted in colder conditions on the Scotian Shelf. In addition, the increased transport of Labrador Current Water on the Newfoundland Shelf may have contributed to the cold conditions observed on the Scotian Shelf during the late 1990s (Drinkwater et al. 1999).

BOTTOM TEMPERATURE ANALYSIS

Canada has been conducting stratified random groundfish trawl surveys in NAFO Sub-areas 2 and 3 since 1971. Each NAFO Division has been stratified based on the depth contours of available standard navigation charts. Areas within each division with a selected depth range were divided into strata and the number of fishing stations in an individual stratum are based on an area weighted proportional allocation (Doubleday 1981). Temperature profiles of the water column are available for each fishing set in each stratum. Surveys have been conducted for the following NAFO Divisions, time periods and depth ranges: 3P in winter and/or spring from 1972 to 1999, in water depths down to 366 m until 1979 and to 548 m since then; 3L in spring from

1971-1999, except 1983 and 1984; 3NO in spring from 1971-1999, except 1983 in 3N and 1972, 1974 and 1983 in 3O, in water depths down to 366 m in most years and more recently to 548 m; 2J fall from 1977-1999; 3K in fall from 1978-1999; 3L in fall from 1981-1999; 3NO in fall from 1990-1999.

In this section the 1999 near-bottom temperature fields and their anomalies for NAFO Divisions 2J and 3KLNO on the Newfoundland Shelf are presented for spring and fall. Interannual variations are then examined by computing the areal extent of the bottom covered with water in various temperature ranges. The purpose of this analysis is to provide some indication of potential changes in temperature dependent habitat of various fish species.

3LNO spring

The 1999 spring bottom temperatures and their anomalies for the Divisions 3LNO are shown in Fig. 20. In the northern areas spring bottom temperatures ranged from sub-zero ^{o}C in the inshore regions of the Avalon Channel to over 3^{o}C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1^{o}C to above 3.5^{o}C on the Southeast Shoal and above 3^{o}C along the edge of the Grand Bank. During the spring of 1999 sub-zero ^{o}C water was restricted to a small area in the Avalon Channel and above normal conditions persisted over all of the Northern Grand Bank with temperatures up to 1^{o}C above average. Over the central and southern Grand Bank bottom temperatures ranged from 1-3^{o}C above the long-term average.

Shown in Fig. 21 are time series of the areal extent of the bottom covered by water with temperatures $\leq$0^{o}C, between 0^{o}-1^{o}C and $\geq$1^{o}C during spring and for the Grand Bank region in fishing strata with water depths within 100-m and for all strata. From 1975 to 1983 most of the bottom area was covered by water above 0^{o}C with only approximately 20% covered by sub-zero ^{o}C water. Since 1984 there was a large increase in the area of sub-zero ^{o}C water with percentages averaging about 50% but reaching a maximum of more than 70% during 1991. Since 1994 there has been a general decrease in the percentage area of the bottom covered by sub-zero ^{o}C water and a corresponding increase in the area covered by water $\geq$1^{o}C. The area covered by water in the 0^{o}-1^{o}C temperature range varied from a high of near 40% in 1978, less than 20% in 1983, 1984 and 1993 to near 25% in 1998 (Fig. 21b). During the spring of 1998 and 1999 water with temperatures above 1^{o}C covered 50-60% of the bottom area on the Grand Bank, compared to about 10% in 1990. The 1998 and 1999 values represents the largest area of relatively warm water on the Grand Bank since 1983. During 1999 the area of sub-zero ^{o}C water on the Grand Bank decreased to near 0%.

The time series of average bottom temperature for the 3LNO region (Fig. 22) shows a downward trend that started in 1984 superimposed on large interannual variations of about 1^{o}C amplitude. This trend continued until the early 1990s. The highest temperature in the 24-year record occurred in 1983 when the average temperature was 3.2^{o}C and the lowest temperature of

-0.3^{o}C occurred in 1991. Recently, temperatures have increased over the lows of the early 1990s with the average bottom temperature during the spring of 1999 reaching 2^{o}C, overall, and to 1.8^{o}C in strata with water depths less than 100-m.

2J fall

Bottom temperatures during the fall of 1999 (Fig. 23) in Division 2J ranged from less than 1^{o}C inshore, to above 3.5^{o}C offshore at the shelf break. Bottom temperatures over Hamilton Bank ranged from less than 1.5^{o}C on the inshore portion of the bank, to almost 3^{o}C on the southern portion. Bottom temperature anomalies were up to 1.5^{o}C above normal on Hamilton Bank and generally above normal over most of the 2J area.

Shown in Fig. 24 are time series of the areal extent of the bottom covered by water with temperatures ≤0^{o}C, 0^o-1^{o}C, and ≥1^{o}C for NAFO Division 2J during the fall period, for strata less than 200-m and for all strata in the division. The percent area of the bottom covered by sub-zero ^{o}C water in this region is very low during the fall with significant amounts appearing only during the cold periods of the early to mid-1980s and early 1990s, when it ranged between 20% to 40% (Fig. 24b). On Hamilton Bank and in the near shore region in strata with depths less than 200-m however, the percent area of sub-zero ^{o}C water reached a maximum of 80% in 1984 and over 90% in 1993. The area covered by water in the 0^o-1^{o}C temperature range varied from a low of about 0% in 1977 to near 40% in 1984, but in water depths ≤200-m these percentages were much higher, reaching near 75% in 1989. In the temperature range ≥1^{o}C for strata less than 200-m depth the bottom area ranged from 100% in 1977 to near 0% during cold periods. Since 1995 the area of the bottom covered with water ≥1^{o}C increased considerably, while the area of sub-zero ^{o}C water decreased to near 0%. In general, the trends are more extreme in water depths ≤200-m. The bottom temperatures in Division 2J during the fall average about 2^{o}C, overall, and less than 1^{o}C on the banks (depths ≤200-m) with sub-zero ^{o}C values during the cold periods of the early to mid-1980s and early 1990s. Since 1996 the average bottom temperature increased to above normal values from the record low in 1993 (Fig. 25).

3K Fall

The fall 1999-bottom temperatures and their anomalies for NAFO Division 3K are shown in Fig 26. Most of this area has water depths greater than 200-m, as a result relatively warm slope water with temperatures between 2^o-3^{o}C floods through the deep troughs between the Northern Grand Bank and Southern Funk Island Bank and between Northern Funk Island Bank and Southern Belle Isle Bank. Bottom temperatures on these banks during the fall of 1999 were generally around 3^{o}C, which were up to 1^{o}C above the long-term average. Near the edge of the continental shelf in water depths below 500-m temperatures are generally around 3.5^{o}C.

Shown in Fig. 27 are time series of the areal extent of the bottom covered by water with temperatures ≤0^{o}C, between 0^o-1^{o}C, and ≥1^{o}C for NAFO Division 3K for all strata and for strata with water depth ≤300 m. These include most of the inner Northeast Newfoundland Shelf, Funk

Island Bank and Southern Belle Isle Bank. The percent area of the bottom covered by sub-zero ^{o}C water in this region is generally less than 30%, again with significant greater amounts appearing only during the cold periods of the early to mid-1980s and the early 1990s. In water depths ≤300-m the percent area is higher but generally less than 50% (Fig 27b). Since 1995, the area covered by sub-zero ^{o}C water has been insignificant. The area covered by water in the 0^{o}-1^{o}C temperature range has remained relatively constant, generally less than 25% with no significant trends. In the temperature range ≥1^{o}C, the bottom area covered ranged from about 55% in 1982 to near 90% in 1986 and around 80% since 1995. Again in water depths ≤300-m the cold periods of the early 1980s and 1990s are evident with percentages less than 40% during these time periods. Since 1995 however this area has increased to near 75% and has remained relatively high at about 65% up to 1998 and to over 80% in 1999. The time series of the average bottom temperature in Division 3K during the fall ranged from 1^{o}C in 1982 to 2.3^{o}C in 1986 with an overall average of about 2^{o}C. In water depths ≤300-m temperatures were near 0^{o}C during the cold periods of the mid-1980s and early 1990s, but since 1995 they have increased to above average values (Fig. 28).

3LNO fall

The fall 1999 bottom temperature and temperature anomaly maps for NAFO Divisions 3LNO are shown in Fig. 29. Fall temperatures generally range from sub-zero ^{o}C on the Northern Grand Bank and in the Avalon Channel to 3^{o}C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1^{o}C to above 6^{o}C on the Southeast Shoal and to above 3^{o}C along the edge of the Grand Bank. During the fall of 1999 temperatures over all the surveyed area were above normal, reaching up to 3^{o}-4^{o}C above normal on the shallow Southeast Grand Bank.

Shown in Fig 30 are time series of the areal extent of bottom covered with water ≤0^{o}C, between 0-1^{o}C, and ≥1^{o}C for NAFO Divisions 3LNO during the fall period. In general, the percentage area of the bottom covered by sub-zero ^{o}C water decreased significantly during 1995 to roughly one-half the values during the first half of the 1990s. The area covered by water in the 0^{o}-1^{o}C temperature range on the Grand Bank varied from a low of 12% to near 40% with no significant trend evident. A corresponding increase in the areal extent of water ≥1^{o}C occurred during 1995. From 1995 to 1998 this remained relatively constant at about 50% but increased to over 80% during 1999. Again the trends were more pronounced on the Grand Bank in water depths ≤100-m.

The average bottom temperature for all strata in Divisions 3LNO during the fall decreased from approximately 1.5^{o}C during 1990 to 1^{o}C during 1993, then increased to approximately 1.8^{o}C during 1995 and remained relatively constant up to 1998 and then increased to over 2.5^{o}C during 1999 the highest on record (Fig. 31). On the Grand Bank in water depths generally less than 100-m the average temperature decreased from 1.2^{o}C in 1990 to 0.3^{o}C in 1994, then increased to about 1.5^{o}C in 1995 and remained relatively constant through to 1998 but increased to near 2.8^{o}C during the fall of 1999 also establishing a record.

SUMMARY

Temperatures at Station 27 ranged from 0.25° to 1 °C above normal during the winter months over most of the water column. The spring warming of the water column in the inshore Newfoundland Region began about 2 weeks earlier than normal and maximum summer surface temperatures reached a near record high of 15°C. As a result temperatures were over 2°C above normal at the surface during June and July. By early fall, however, a negative temperature anomaly developed over the upper water 100-m of the water column with anomalies reaching 0.5°C below normal. Bottom temperatures throughout the year ranged from 0.25° to 0.5°C above normal. Salinities at Station 27 were about normal during the winter months but decreased to below normal values during the spring reaching 0.5°C below normal by July. In general, salinities were fresher-than-normal during most of 1999.

During the summer of 1999 the CIL cross-sectional area off Bonavista and Hamilton Bank and on the Grand Bank decreased over 1998 values continuing the below normal trend established in 1995. The total volume of sub-zero °C water on the Newfoundland Shelf during both summer and fall of 1999 also continued their below normal trends established in 1995. Minimum CIL core temperatures were above normal along the three transects.

Bottom temperatures on the Northern Grand Bank during the spring of 1999 were up to 1°C above the long-term average with a very small area of sub-zero °C values restricted to the deeper portions of the Avalon Channel. Over the central and Southern Grand Bank bottom temperatures ranged from 1-3°C above the long-term average. During the fall, bottom temperatures from Hamilton Bank to the Southern Grand Bank were significantly above normal. The extent of bottom water with temperatures above 1°C during the spring was about 50% of the total area of the banks during 1998 the first significant amount since 1984 and this increased to near 70% in 1999. During the spring and fall of 1999, the area of sub-zero °C water covering the bottom on all major banks in the Newfoundland Region had decreased to near 0%.

In general, 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, summer salinity values continue to be slightly below the long-term normal. During 1997 to 1999 ocean temperatures continued above normal over most areas. The main exception during 1999 was the colder-than-normal temperature anomaly primarily associated with the inshore portion of the Labrador Current which was evident in the standard transect data during the summer months and at Station 27 by early fall.

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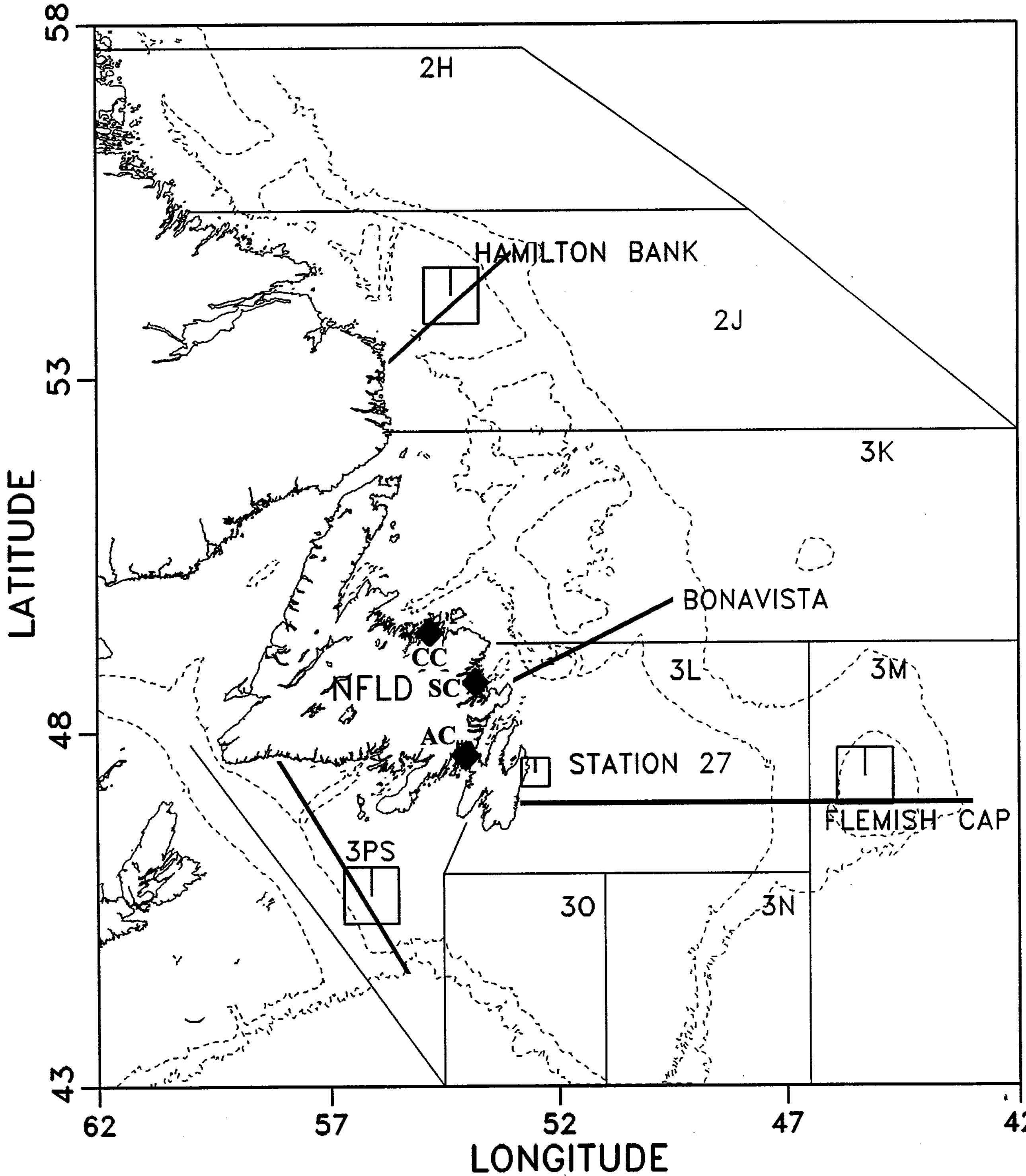


Fig. 1. Location map showing the position of the Seal Island, Bonavista and Flemish Cap (47 °N) transects. The locations of the Long-Term-Temperature-Monitoring (LTTM) sites Arnold's Cove (AC), Stock Cove (SC), Comfort Cove (CC) and Station 27 are also shown. Bathymetry contours are 300 and 1000 m.

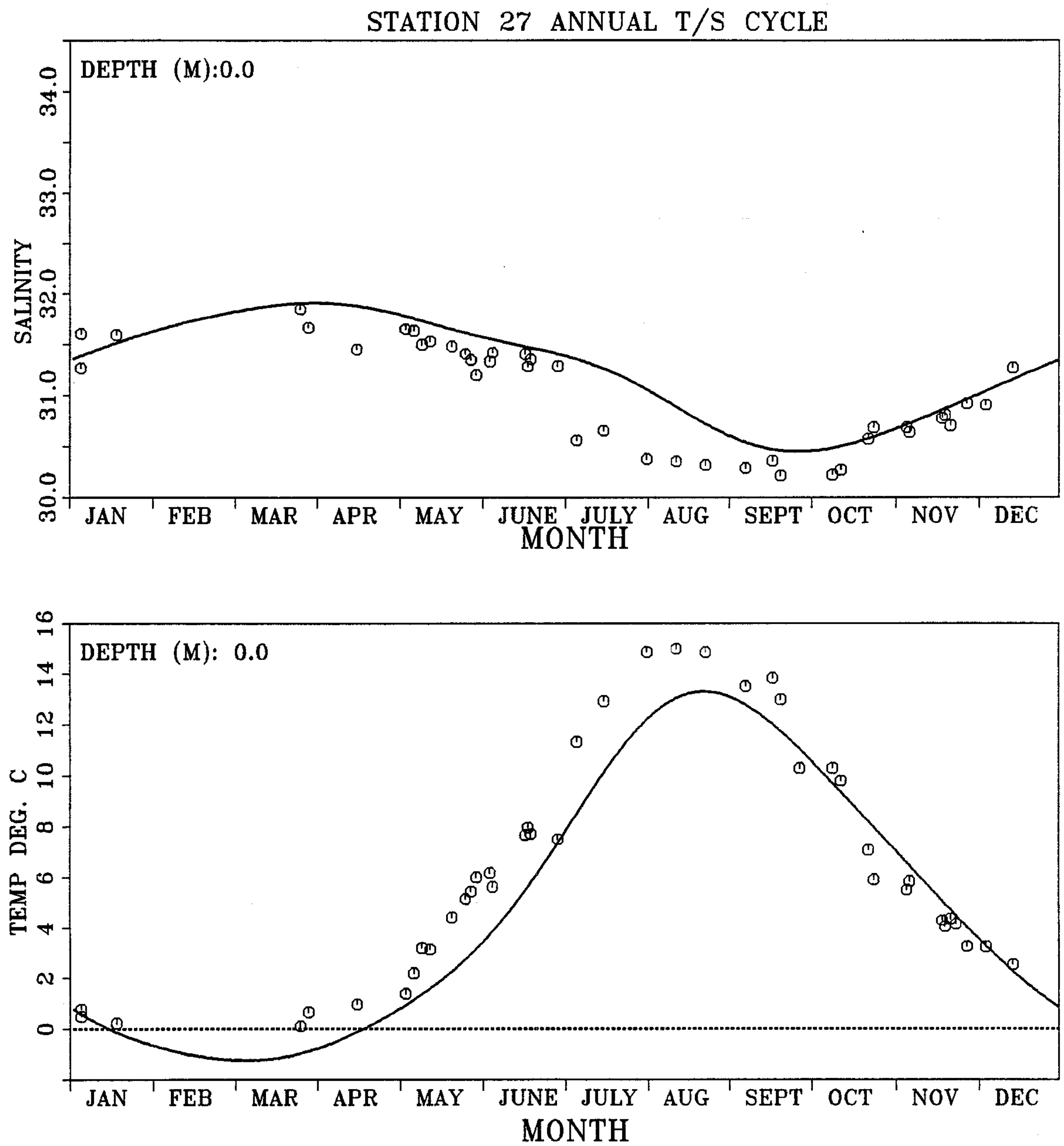


Fig. 2. The 1999 surface temperature and salinity annual cycles at Station 27. The 1961-1990 normals are shown as the solid lines.

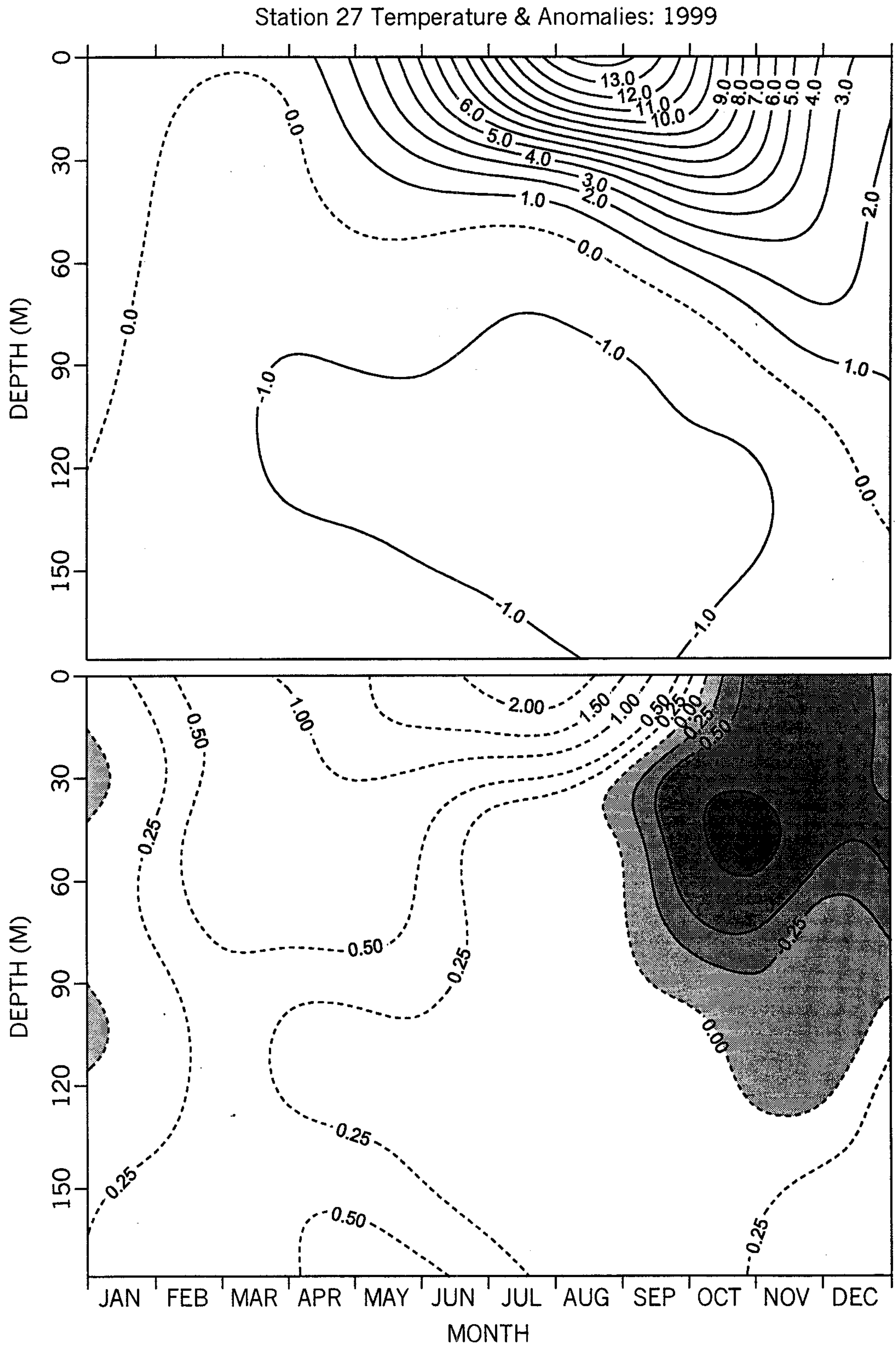


Fig. 3. Monthly temperatures (top panel) and anomalies (bottom panel) in °C at Station 27 as a function of depth for 1999.

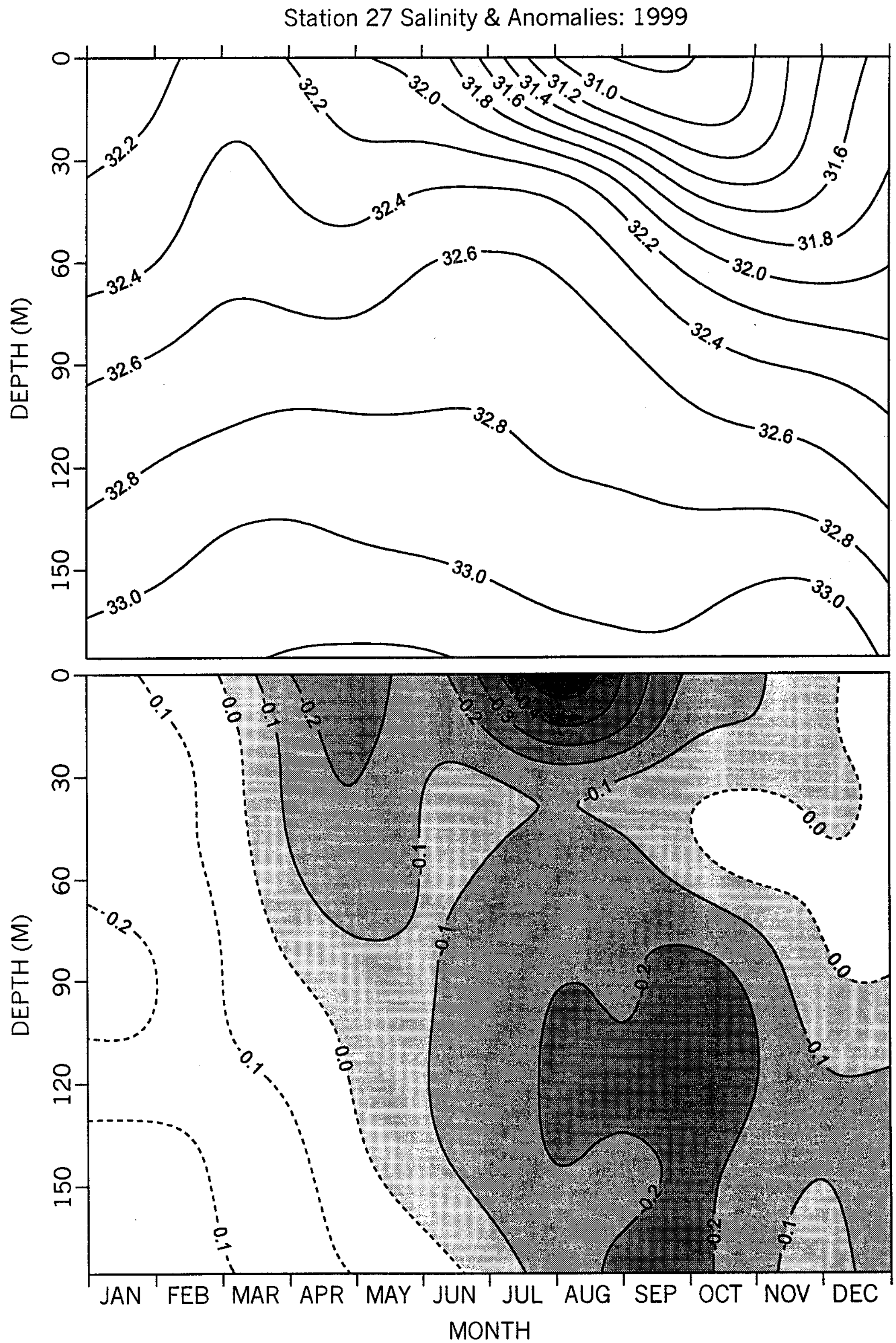


Fig. 4. Monthly salinity (top panel) and anomalies (bottom panel) at Station 27 as a function of depth for 1999.

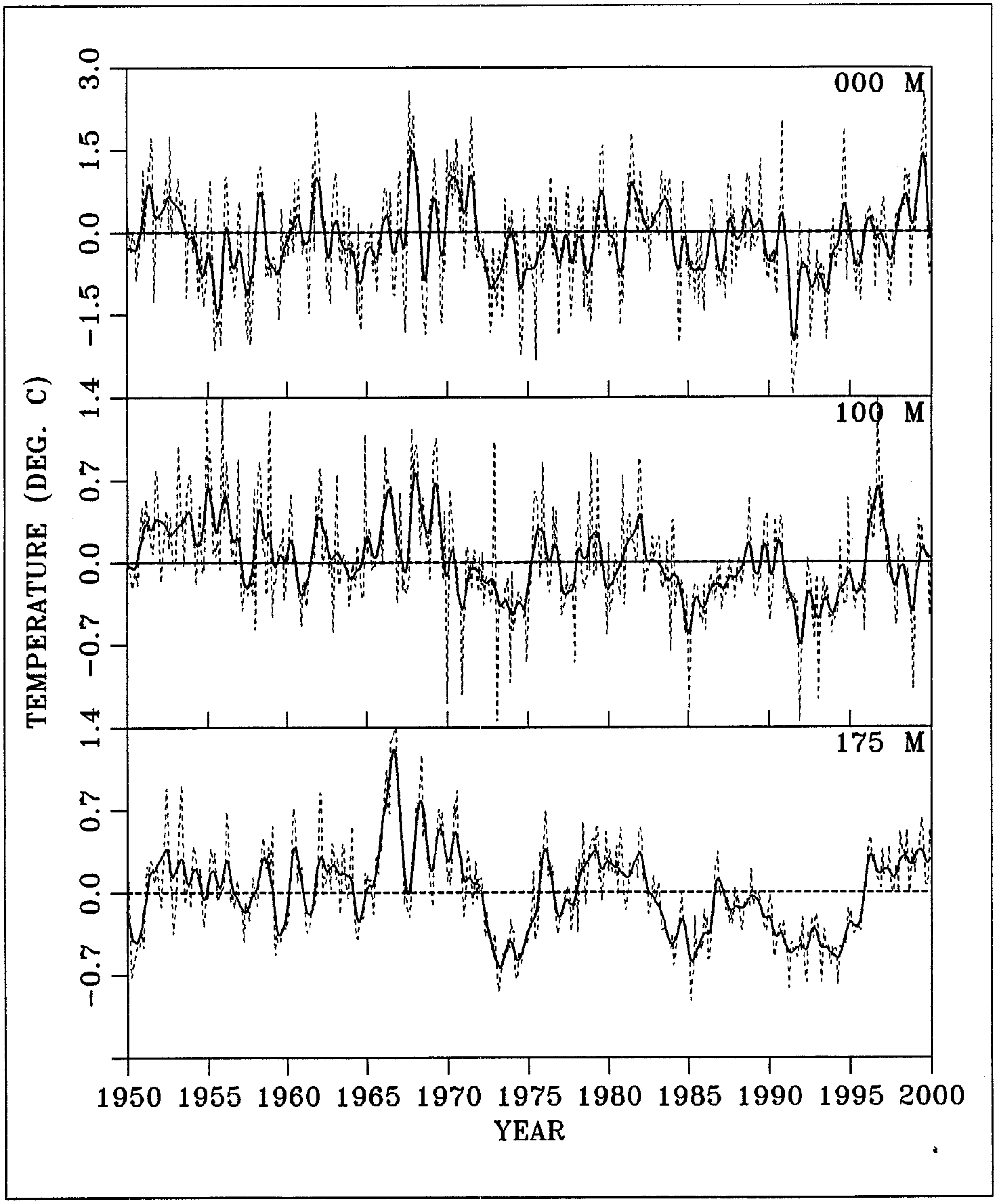


Fig. 5. Time series of monthly temperature anomalies at Station 27 at standard depths from 1950 to 1999. The heavy lines represent the low-passed filtered values.

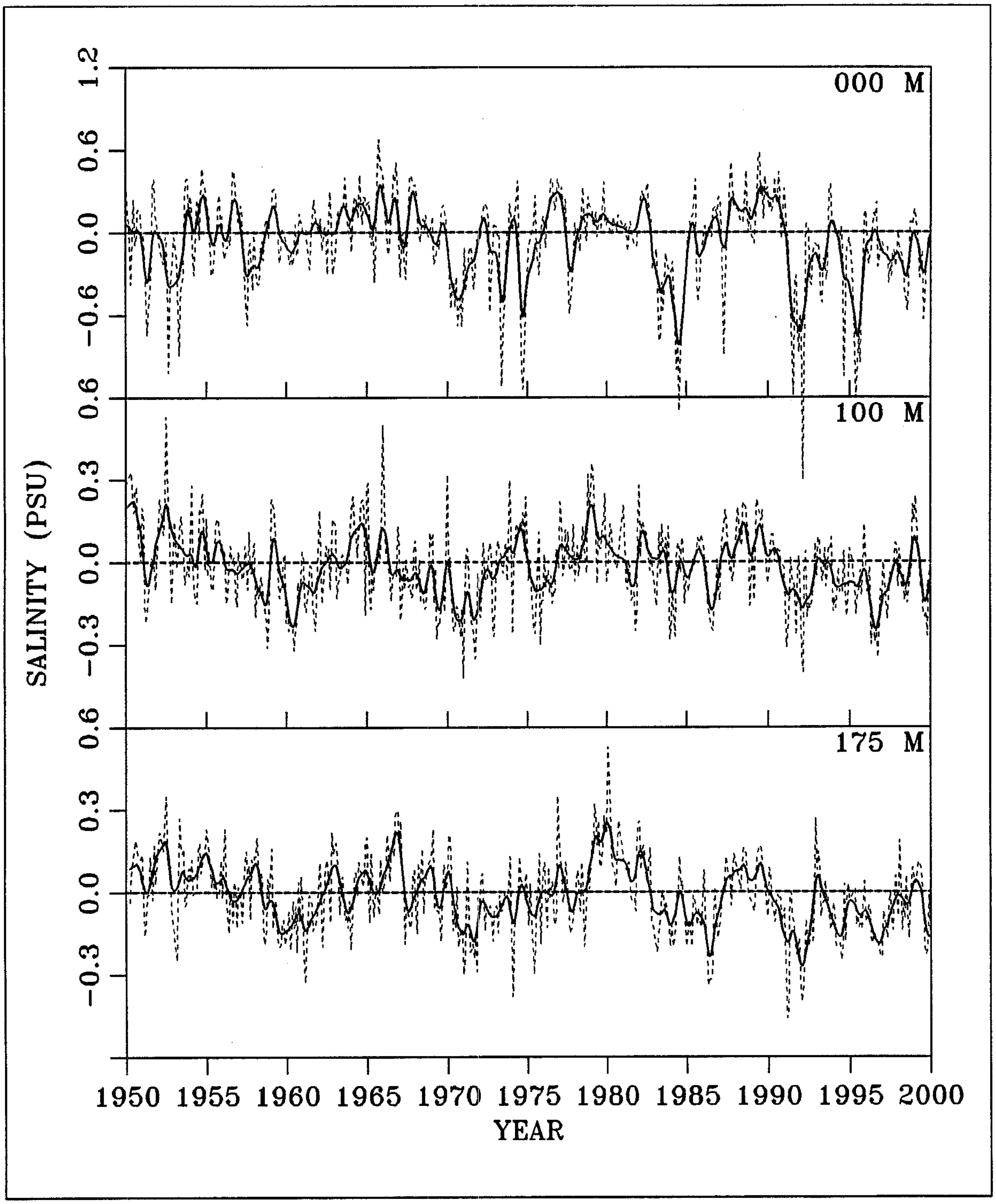


Fig. 6. Time series of monthly salinity anomalies at Station 27 at standard depths from 1950 to 1999. The heavy lines represent the low-passed filtered values.

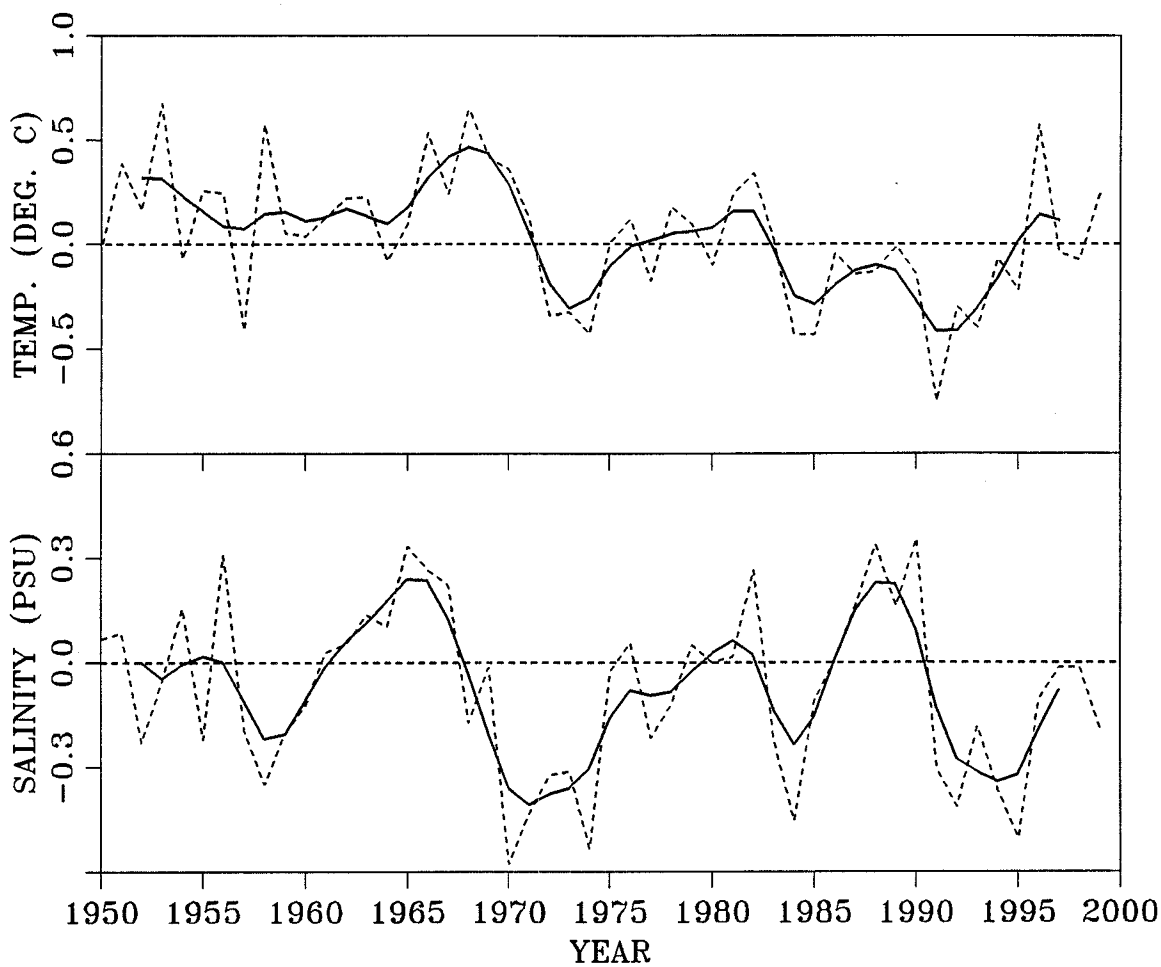


Fig. 7. Time series of the annual vertically averaged (0-176 m) Station 27 temperature anomalies and the vertically averaged (0-50 m) summer (July-Sept.) Station 27 salinity anomalies. The heavy lines are the three-year running means.

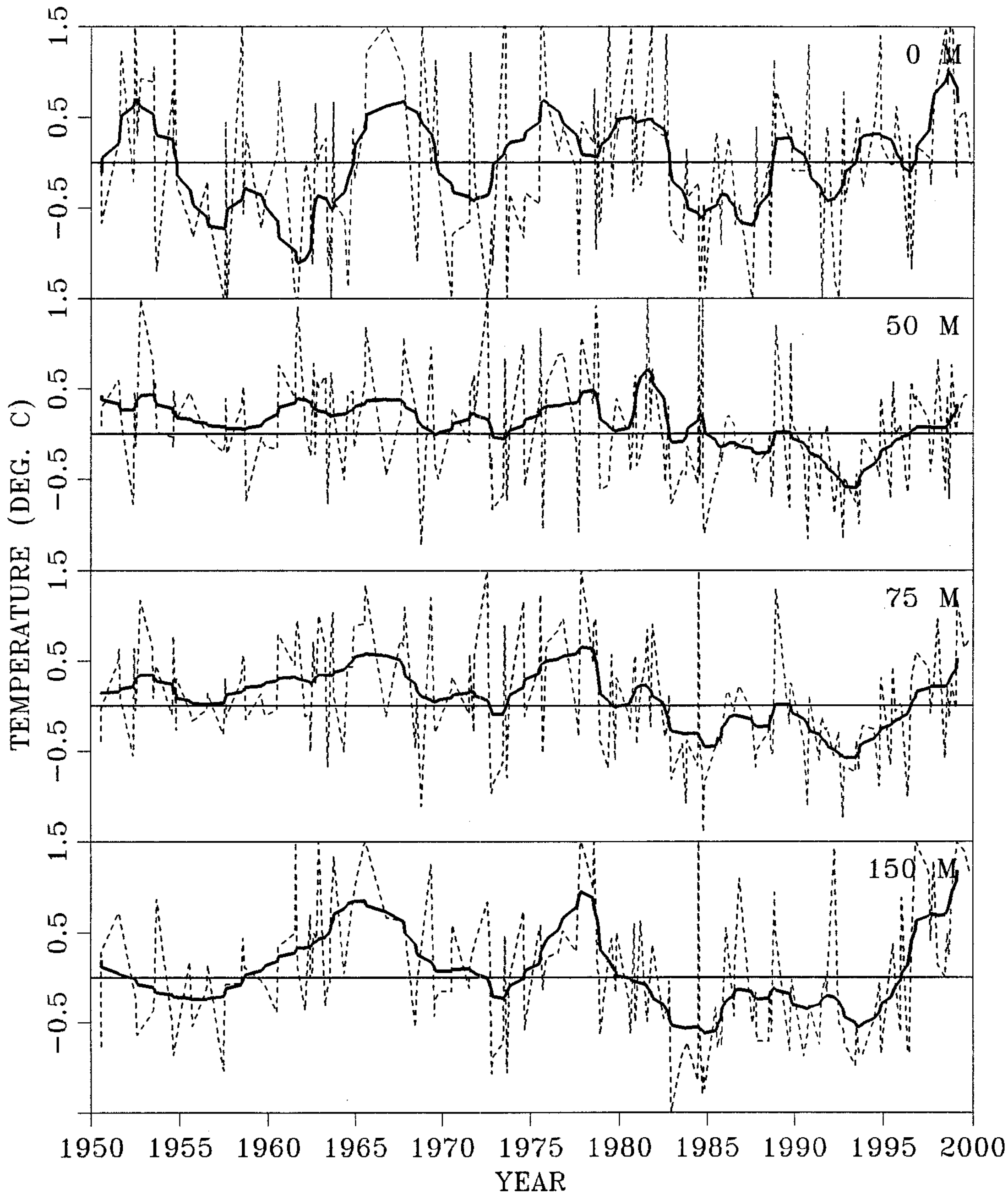


Fig. 8a. Time series of monthly temperature anomalies at standard depths of 0, 50, 75 and 150 m on Hamilton Bank in NAFO Division 2J. The solid line represents the smoothed temperature anomalies.

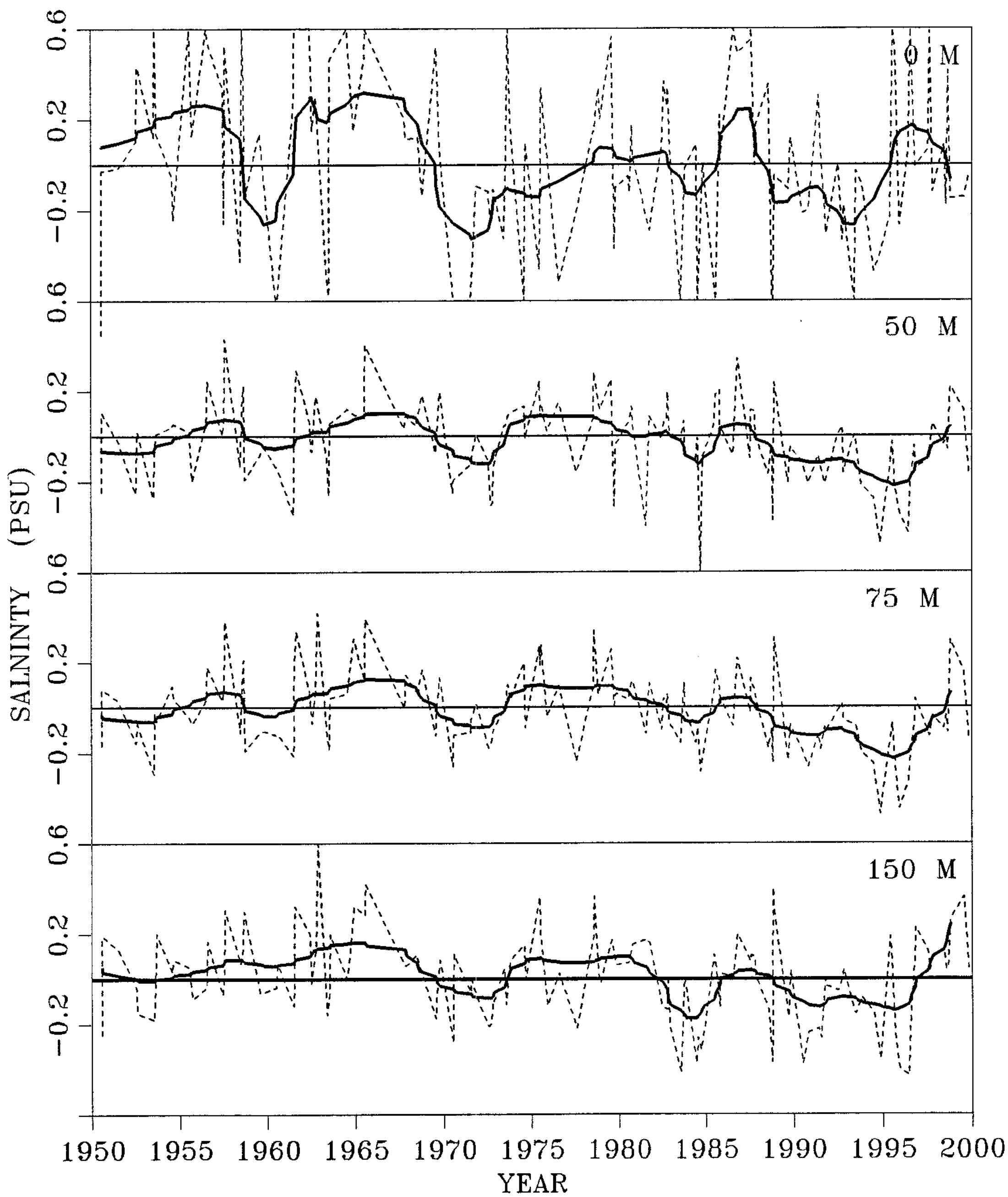


Fig. 8b. Time series of monthly salinity anomalies at standard depths of 0, 50, 75 and 150 m on Hamilton Bank in NAFO Division 2J. The solid line represents the smoothed salinity anomalies.

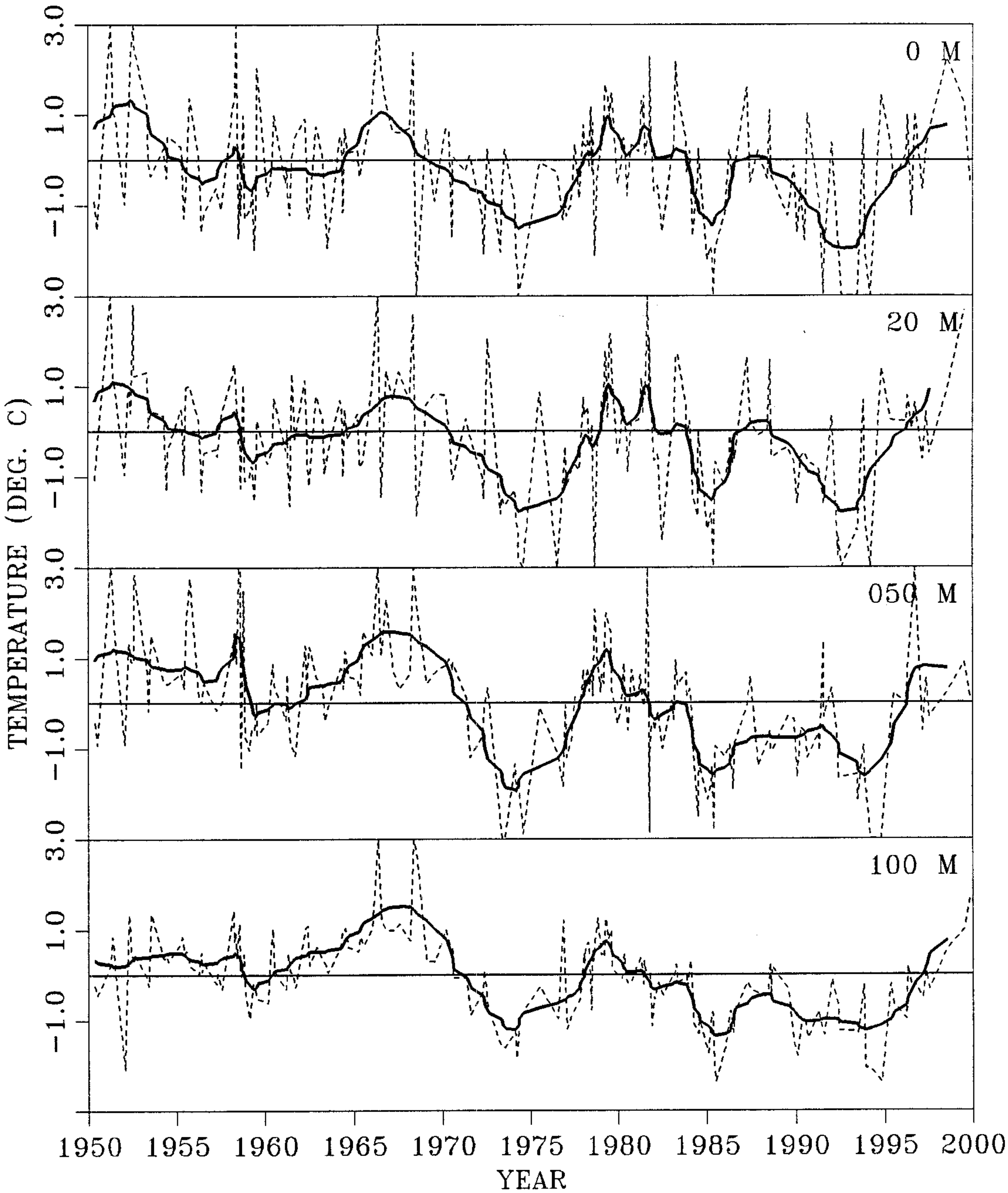


Fig. 9a. Time series of monthly temperature anomalies at standard depths of 0, 20, 50 and 100 m on the Flemish Cap in NAFO Division 3M. The solid line represents the smoothed temperature anomalies.

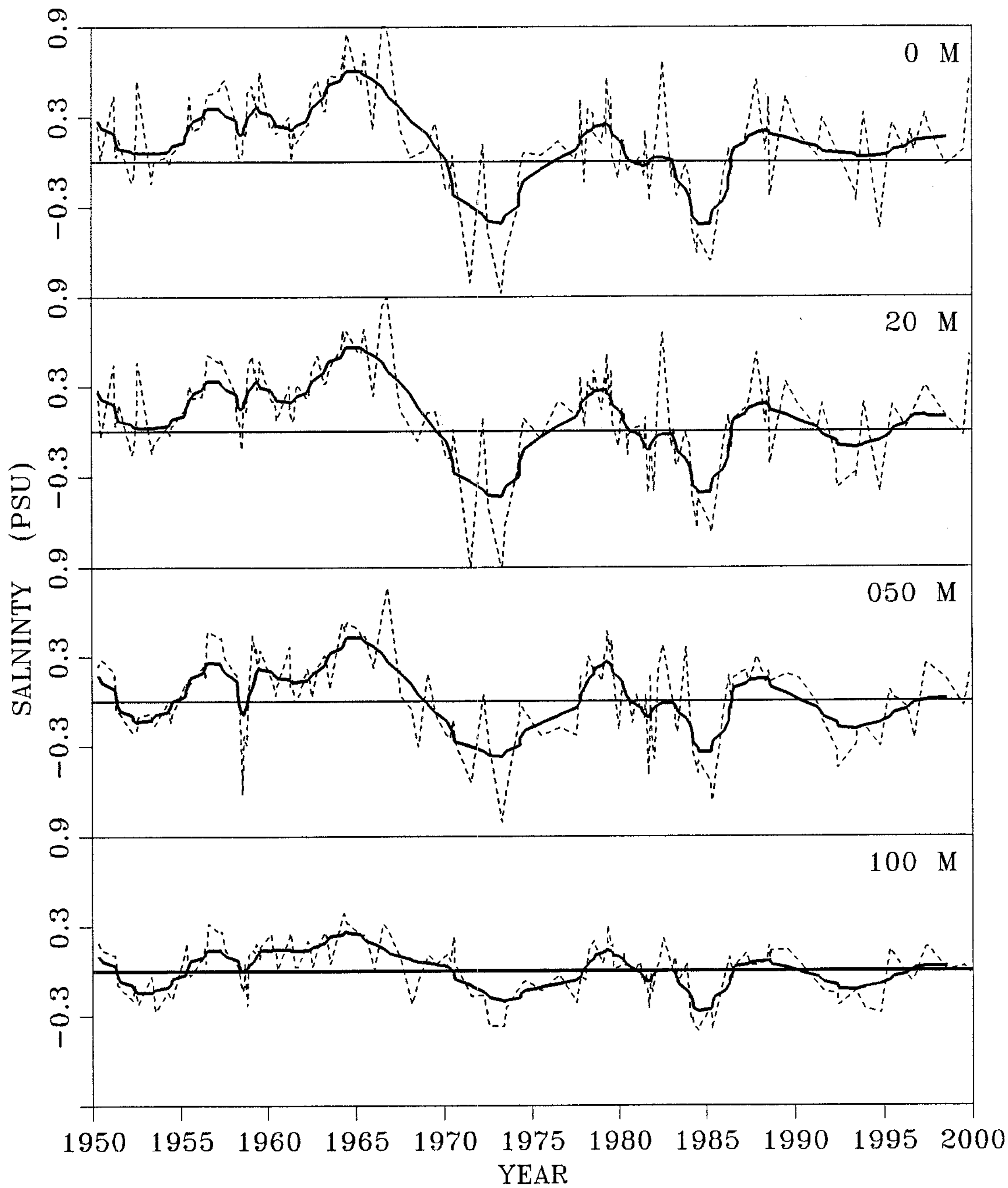


Fig. 9b. Time series of monthly salinity anomalies at standard depths of 0, 20, 50 and 100 m on the Flemish Cap in NAFO Division 3M. The solid line represents the smoothed salinity anomalies.

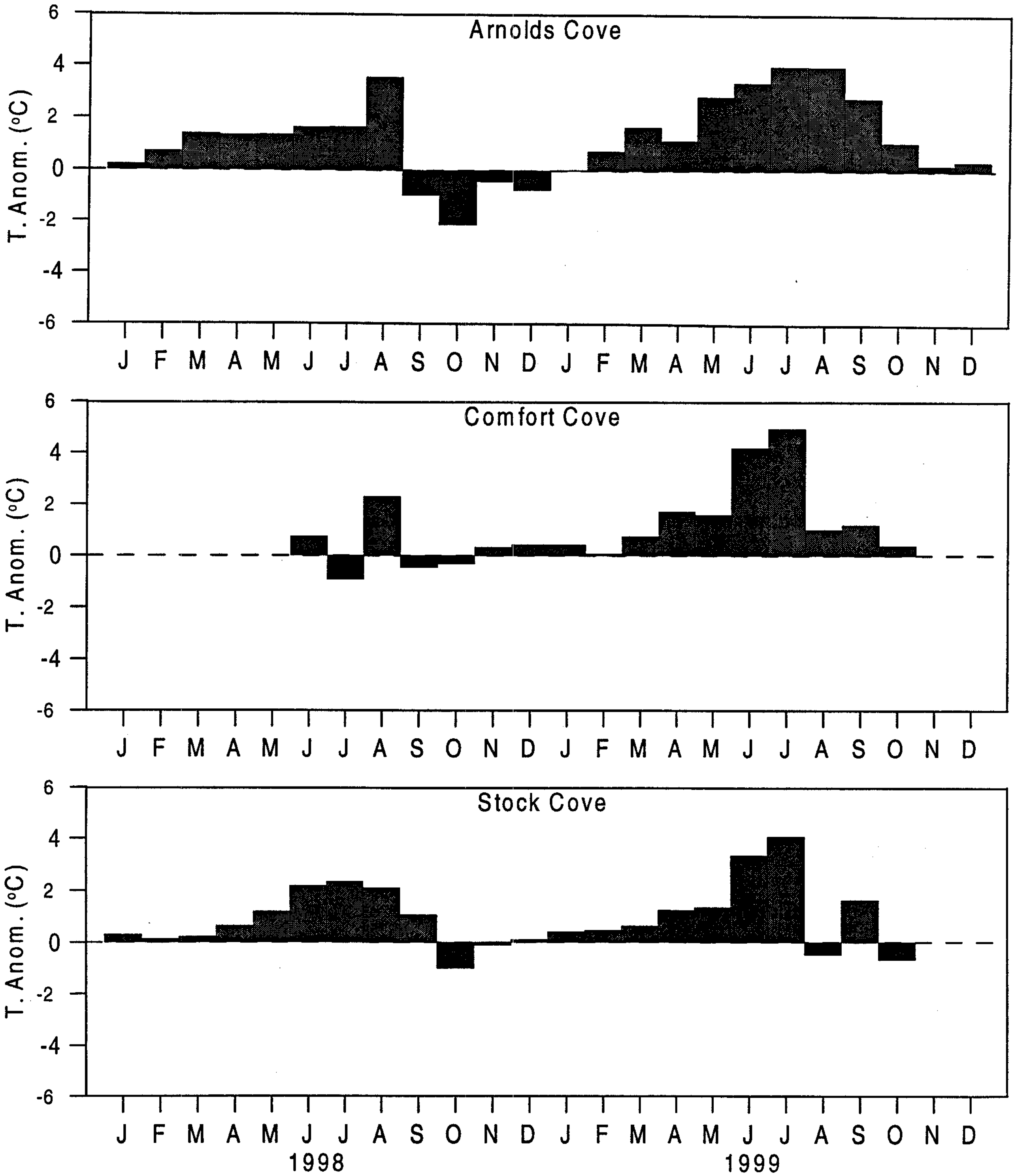


Fig. 10. Monthly temperature anomalies at 10 m depth for Comfort Cove, Notre Dame Bay, Stock Cove, Bonavista Bay, Station 27 and for Arnold's Cove, Placentia Bay (Fig. 1) during 1999.

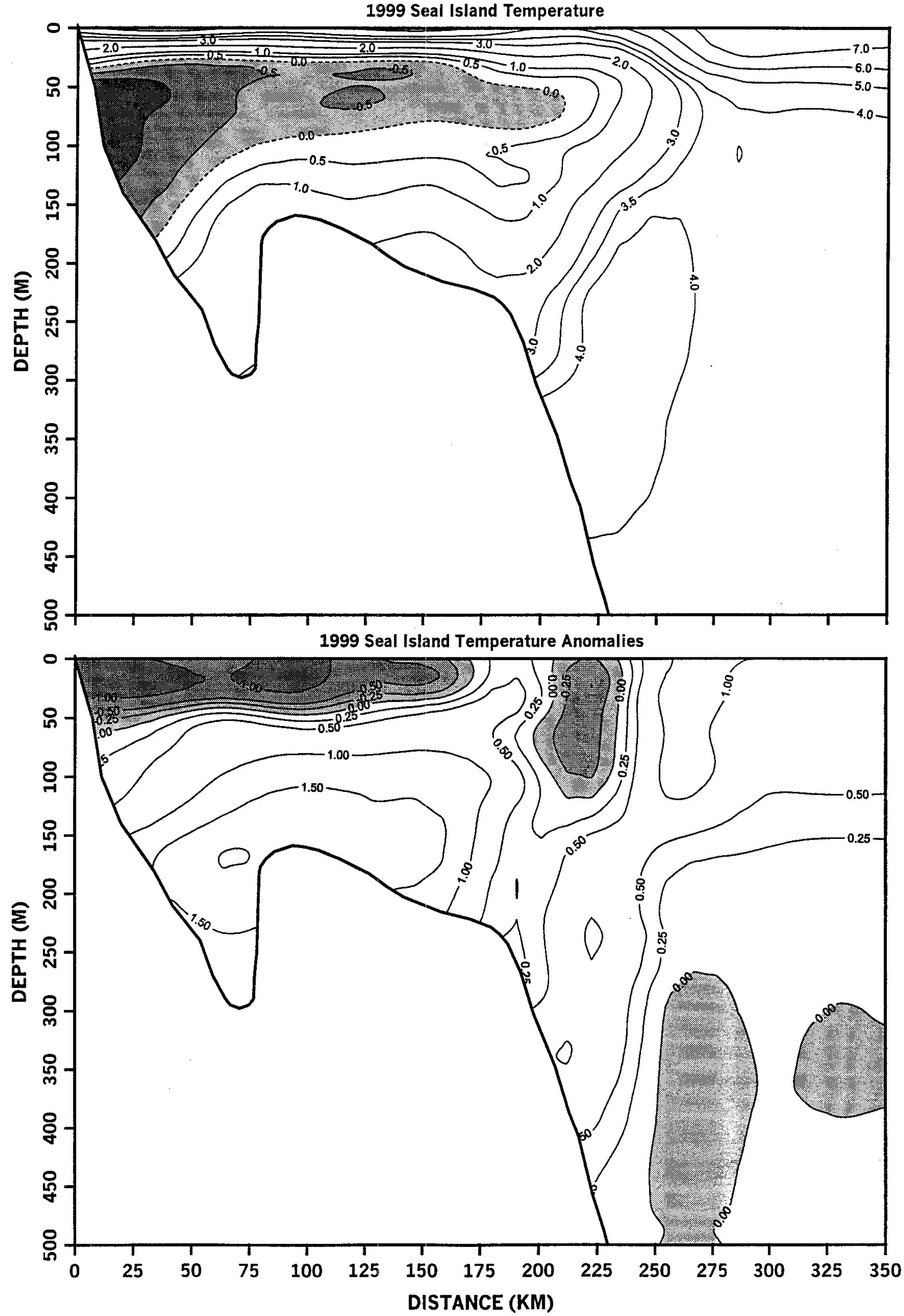


Fig. 11a. A vertical cross-section of temperature and temperature anomalies in °C along the standard Seal Island transect for the summer of 1999. Negative values are shaded.

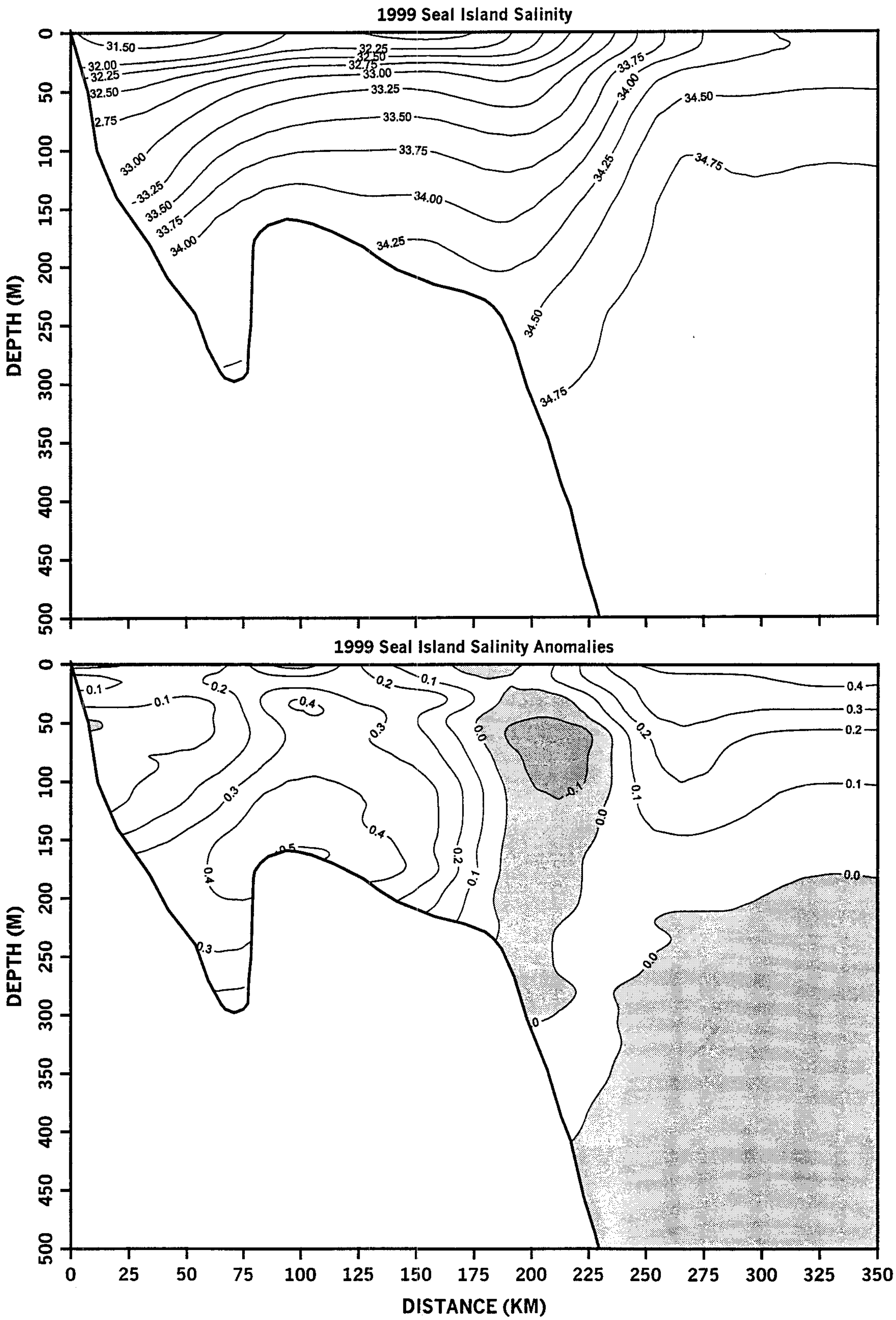


Fig. 11b. A vertical cross-section of salinity and salinity anomalies along the standard Seal Island transect for the summer of 1999. Negative values are shaded.

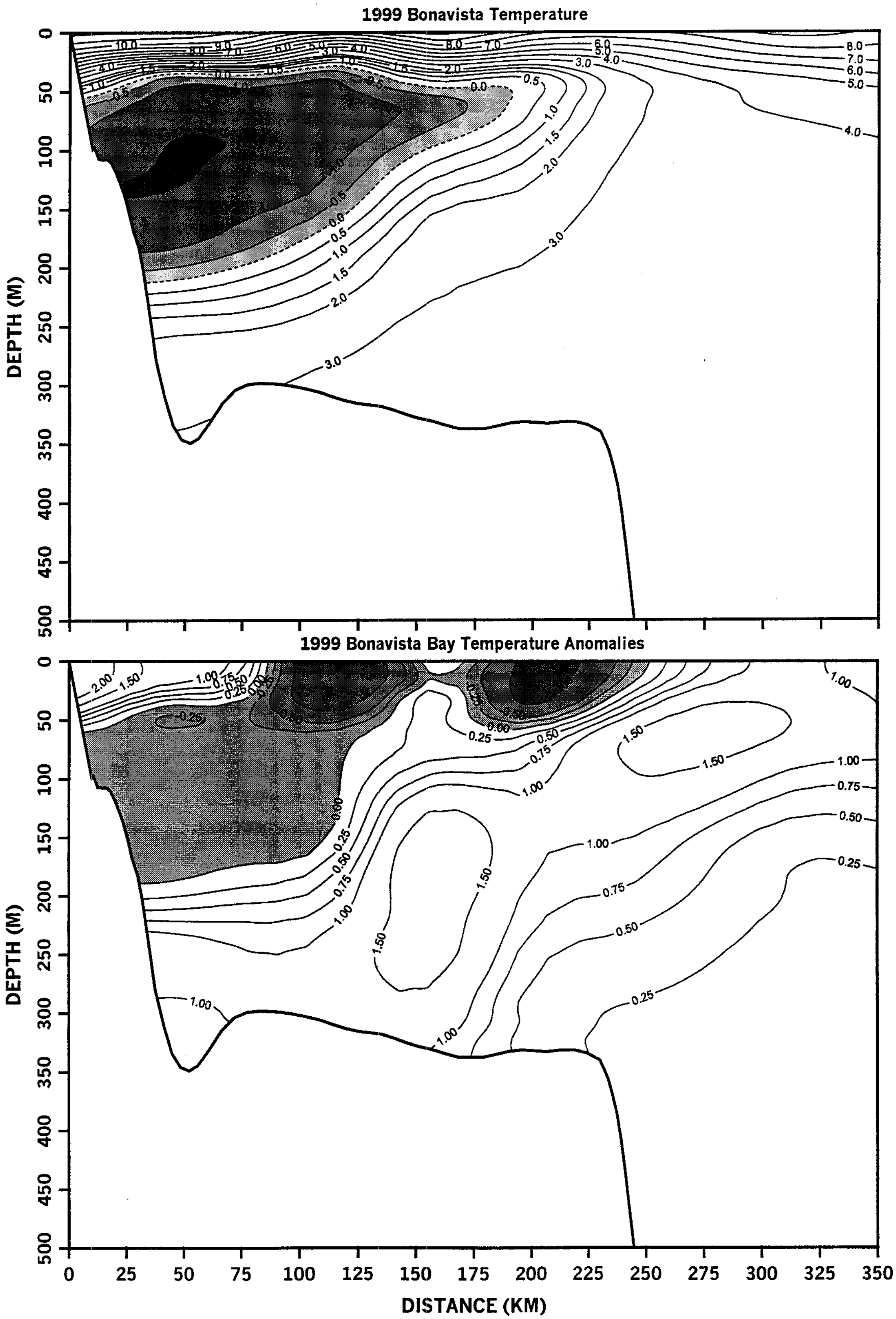


Fig. 12a. A vertical cross-section of temperature and temperature anomalies in °C along the standard Bonavista transect for the summer of 1999. Negative values are shaded.

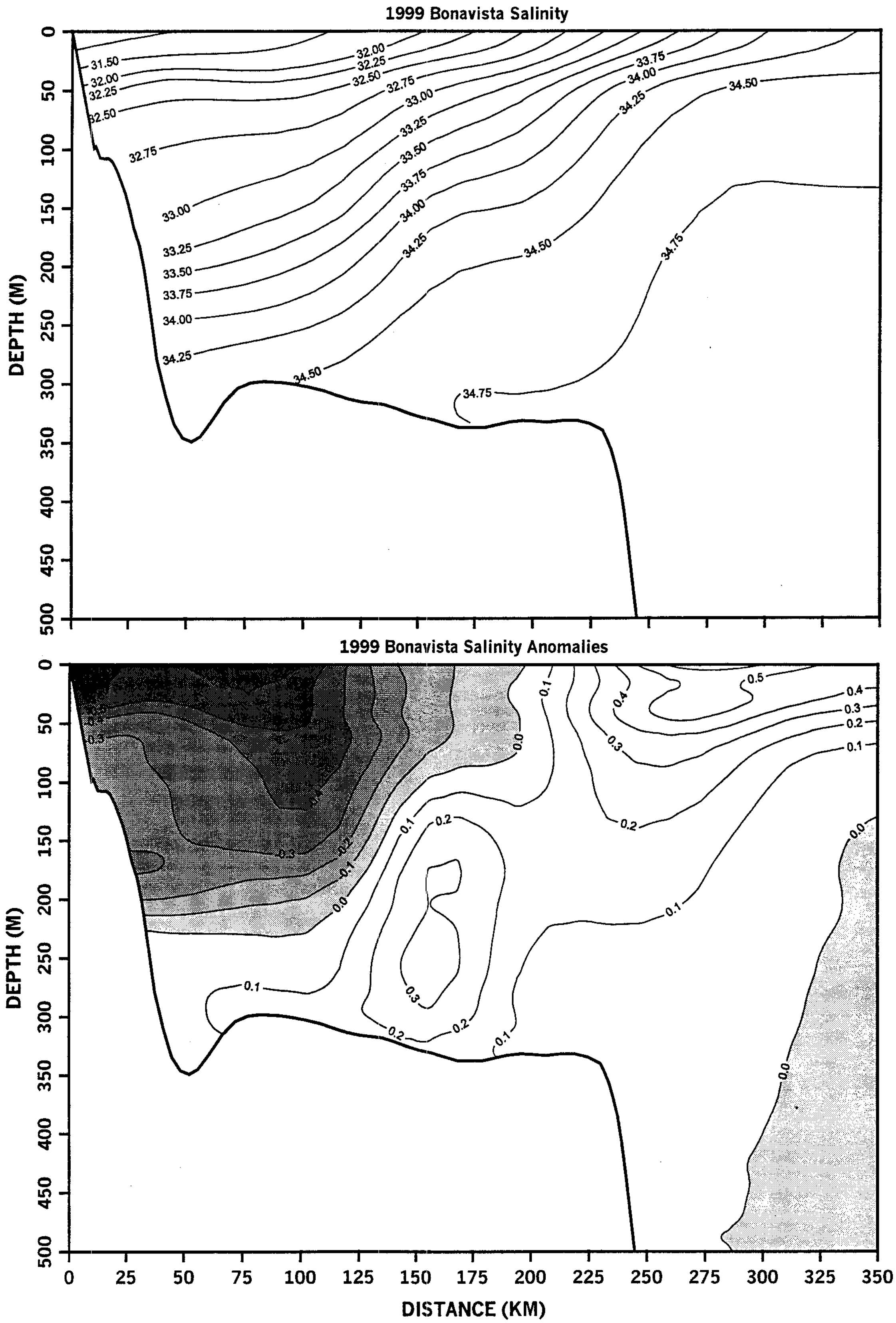


Fig. 12b. A vertical cross-section of salinity and salinity anomalies along the standard Bonavista transect for the summer of 1999. Negative values are shaded.

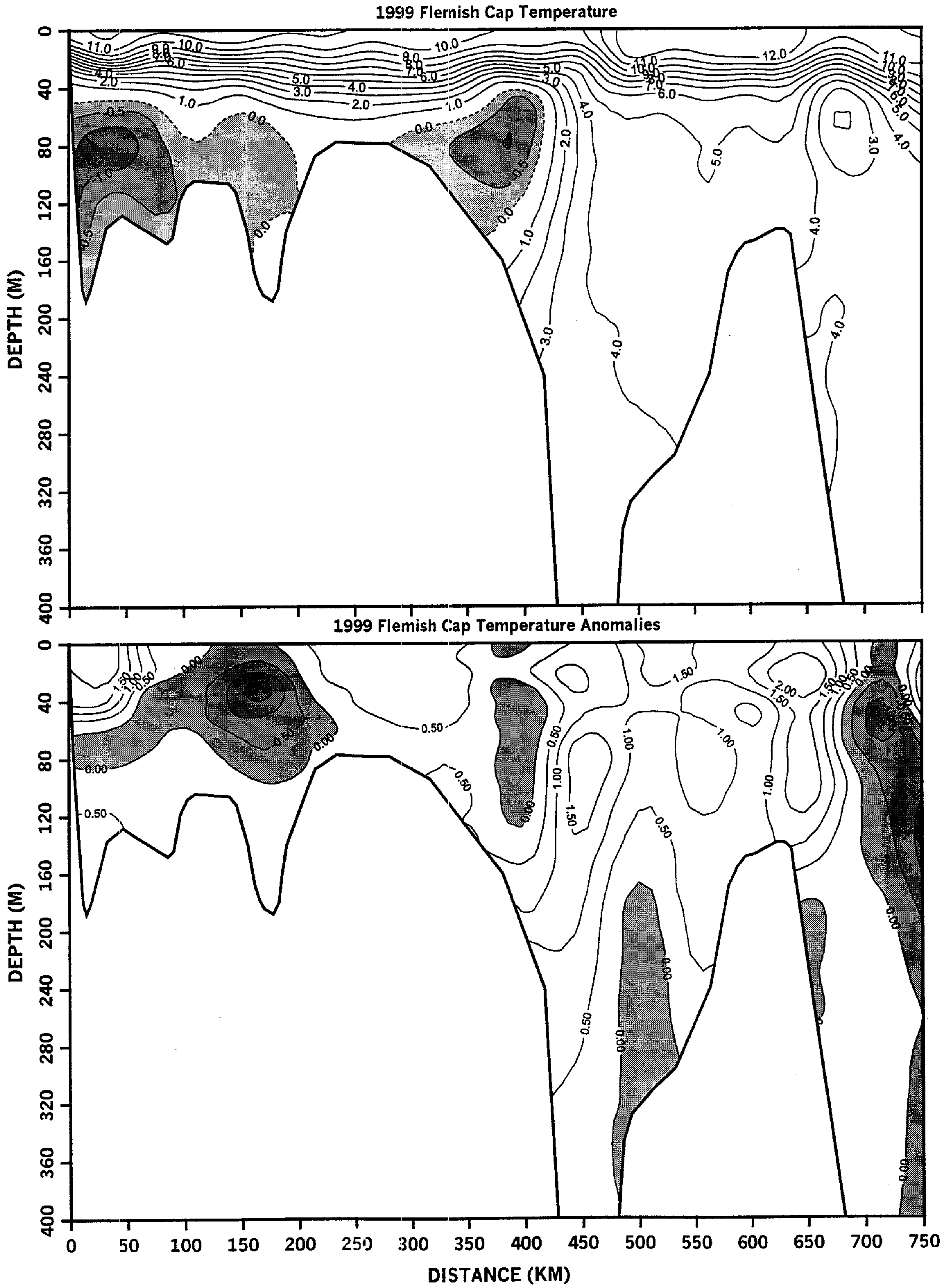


Fig. 13a. A vertical cross-section of temperature and temperature anomalies in °C along the standard Flemish Cap transect for the summer of 1999. Negative values are shaded.

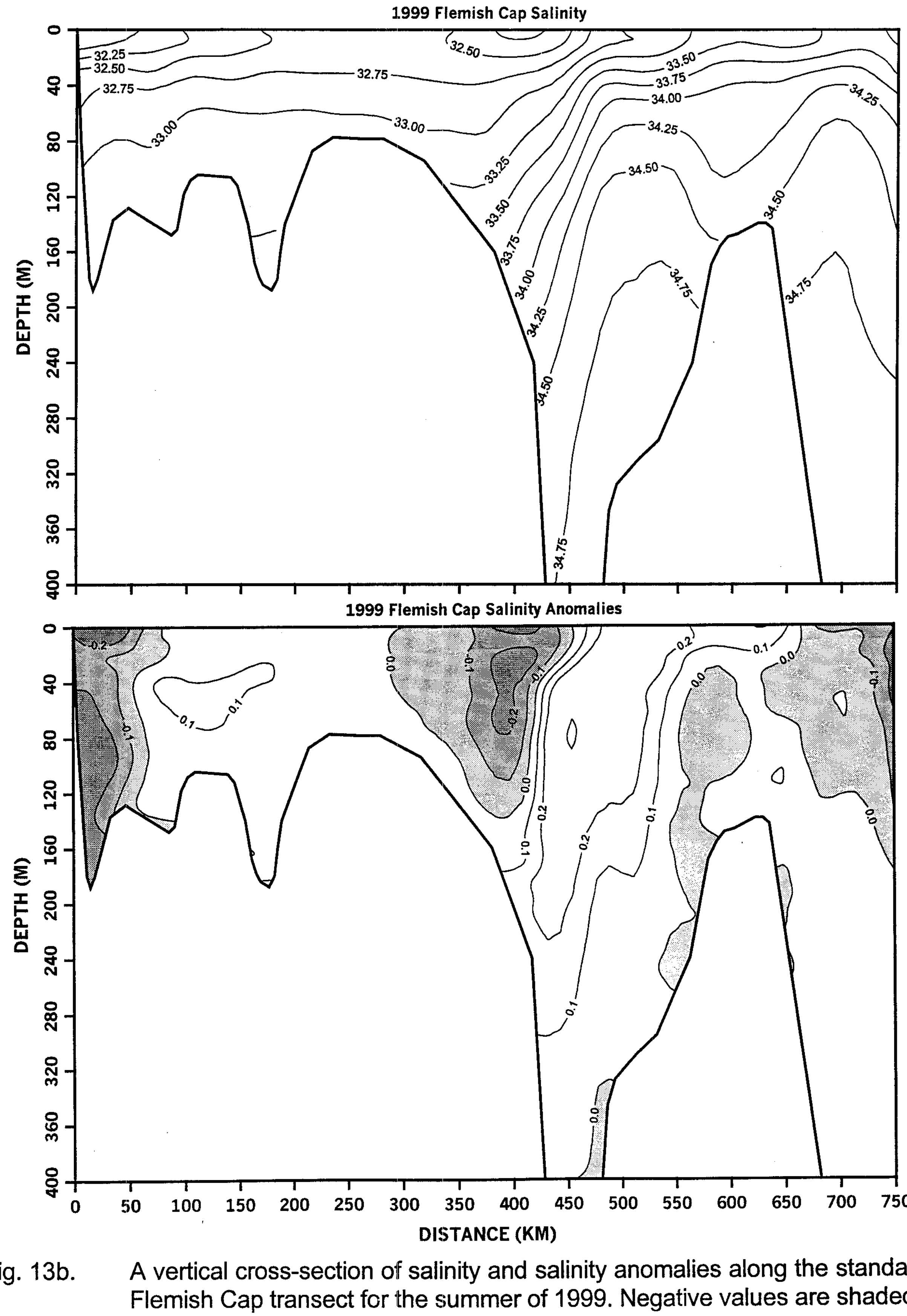


Fig. 13b. A vertical cross-section of salinity and salinity anomalies along the standard Flemish Cap transect for the summer of 1999. Negative values are shaded.

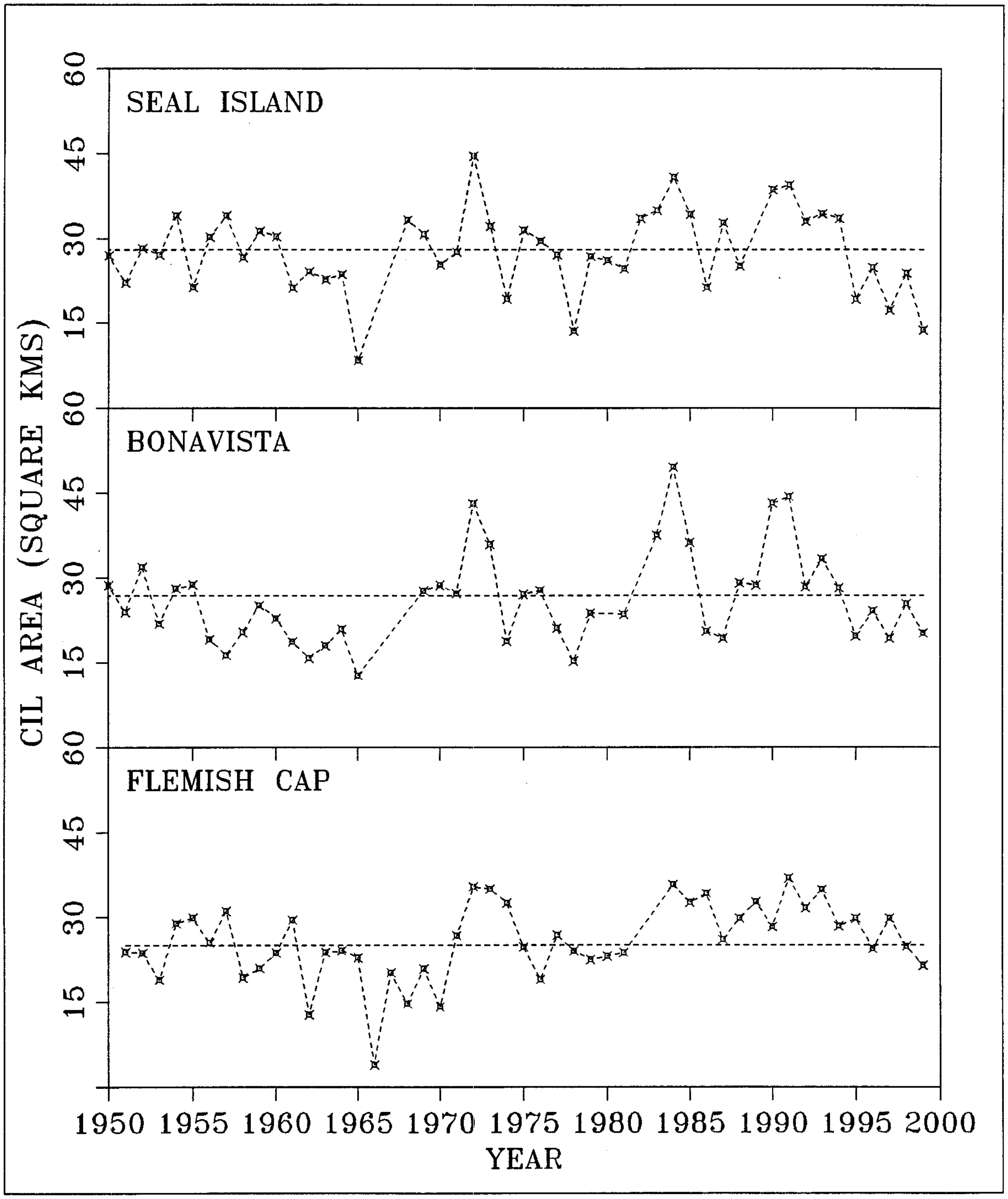


Fig. 14a. Time series of CIL cross-sectional area along the Seal Island, Bonavista and Flemish Cap transects. The horizontal dashed lines represent the 1961-90 average.

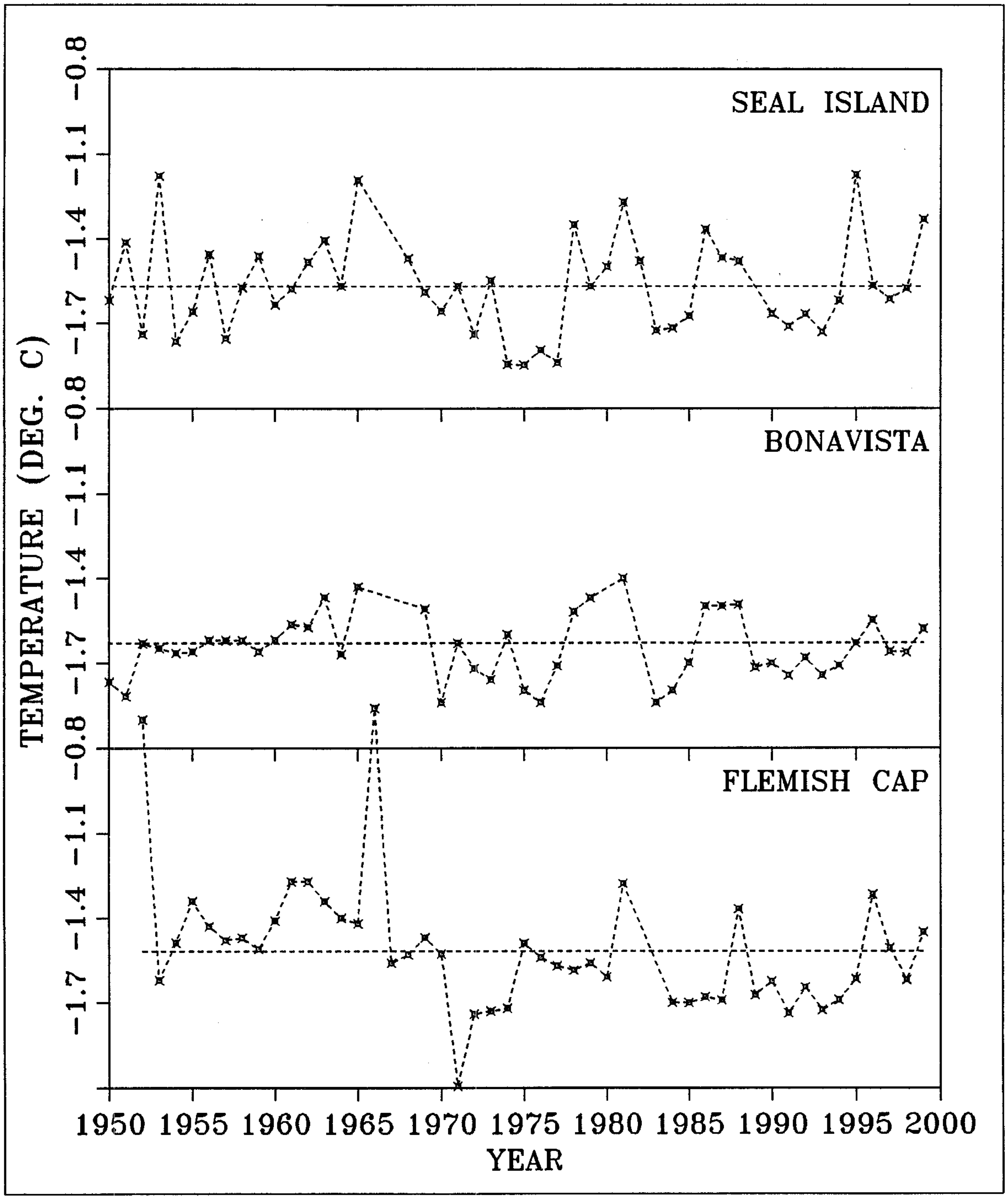


Fig. 14b. Time series of CIL minimum temperature along the Seal Island, Bonavista and Flemish Cap transects. The horizontal dashed lines represent the 1961-90 average.

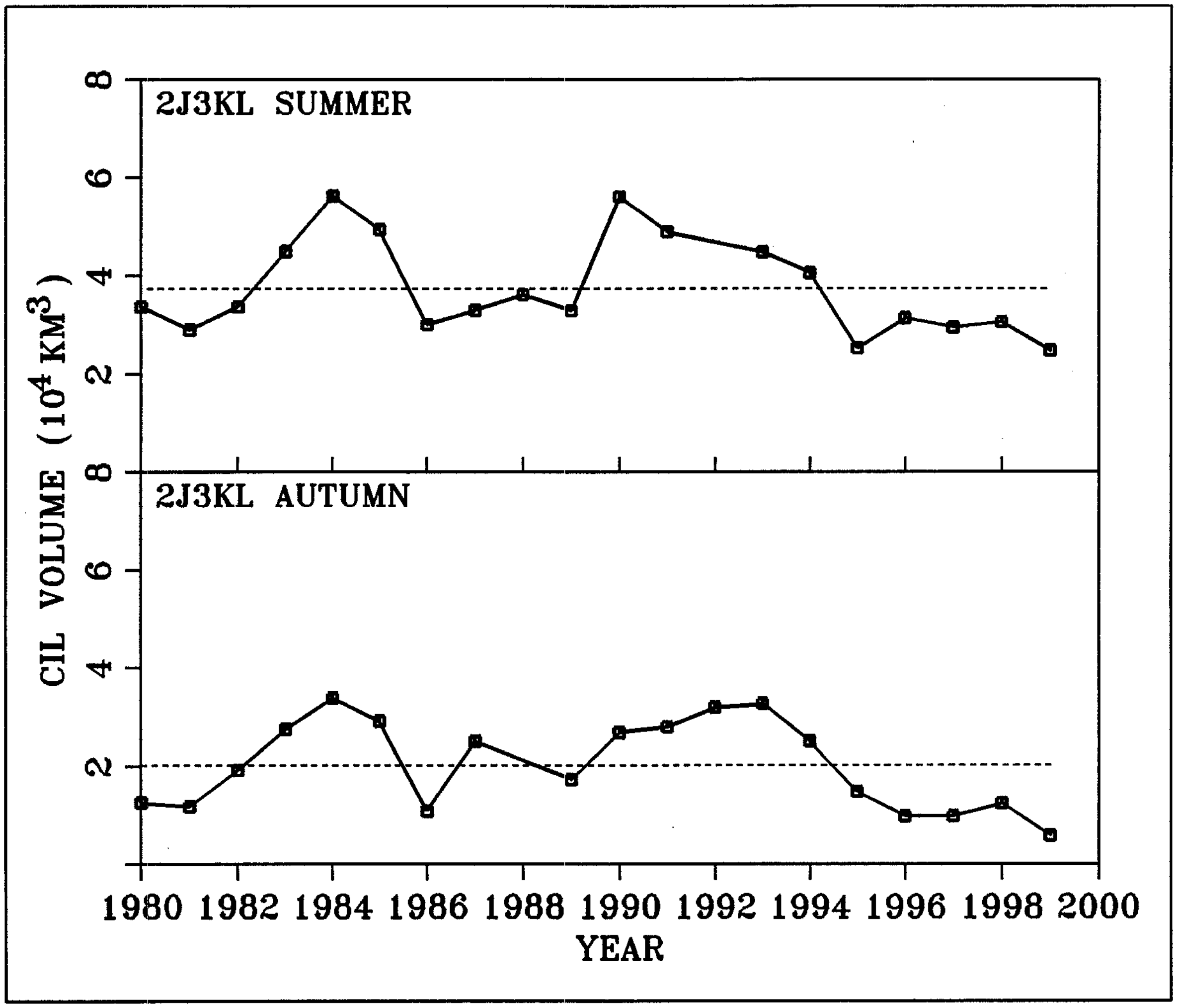


Fig. 15. Time series of summer and fall CIL volumes (km^3) over the 2J to 3KL areas from 1980 to 1999. The horizontal dashed line is the 1980-1998 average.

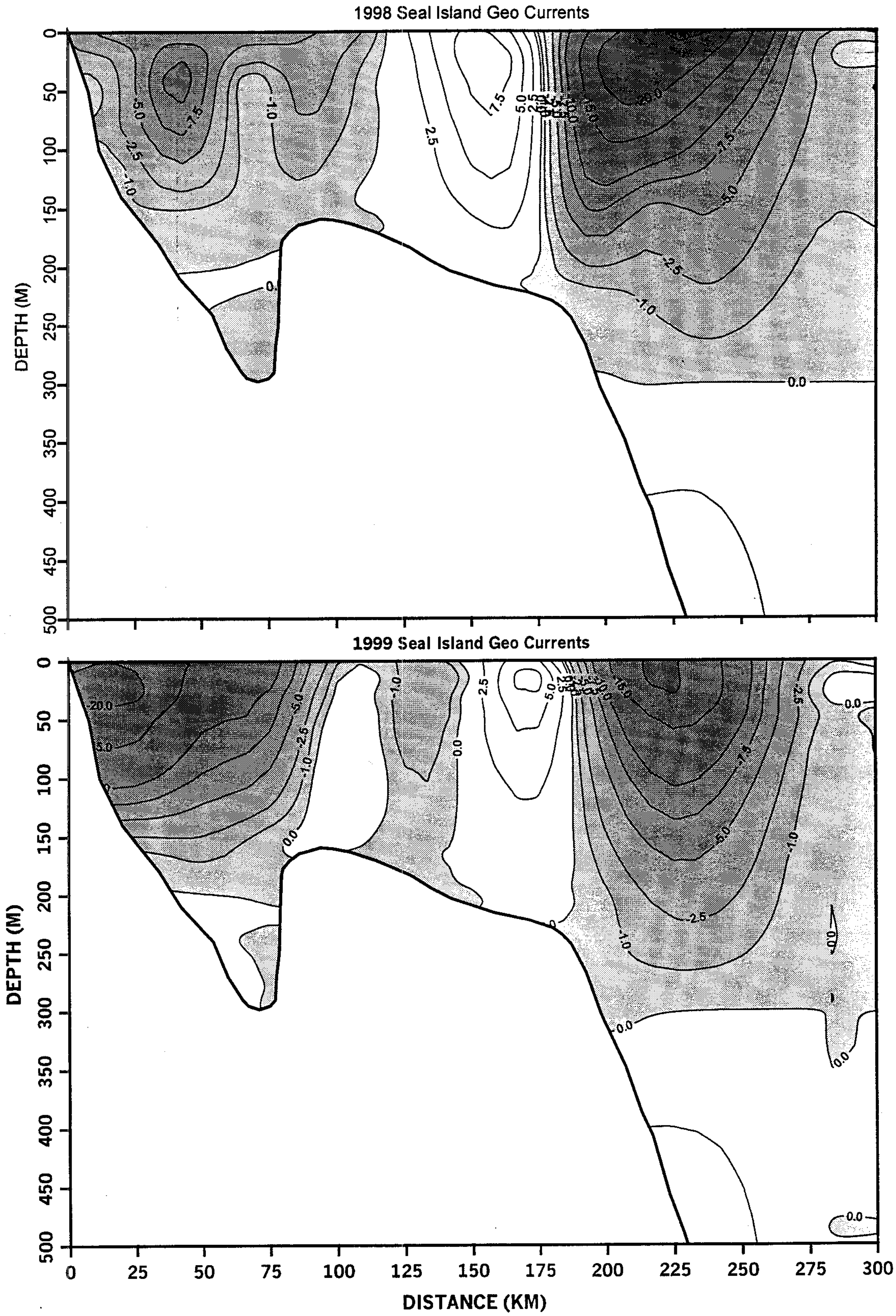


Fig. 16. A vertical cross-section of geostrophic currents (cm/s) along the standard Seal Island transect for the summer of 1998 and 1999. Negative southward values are shaded.

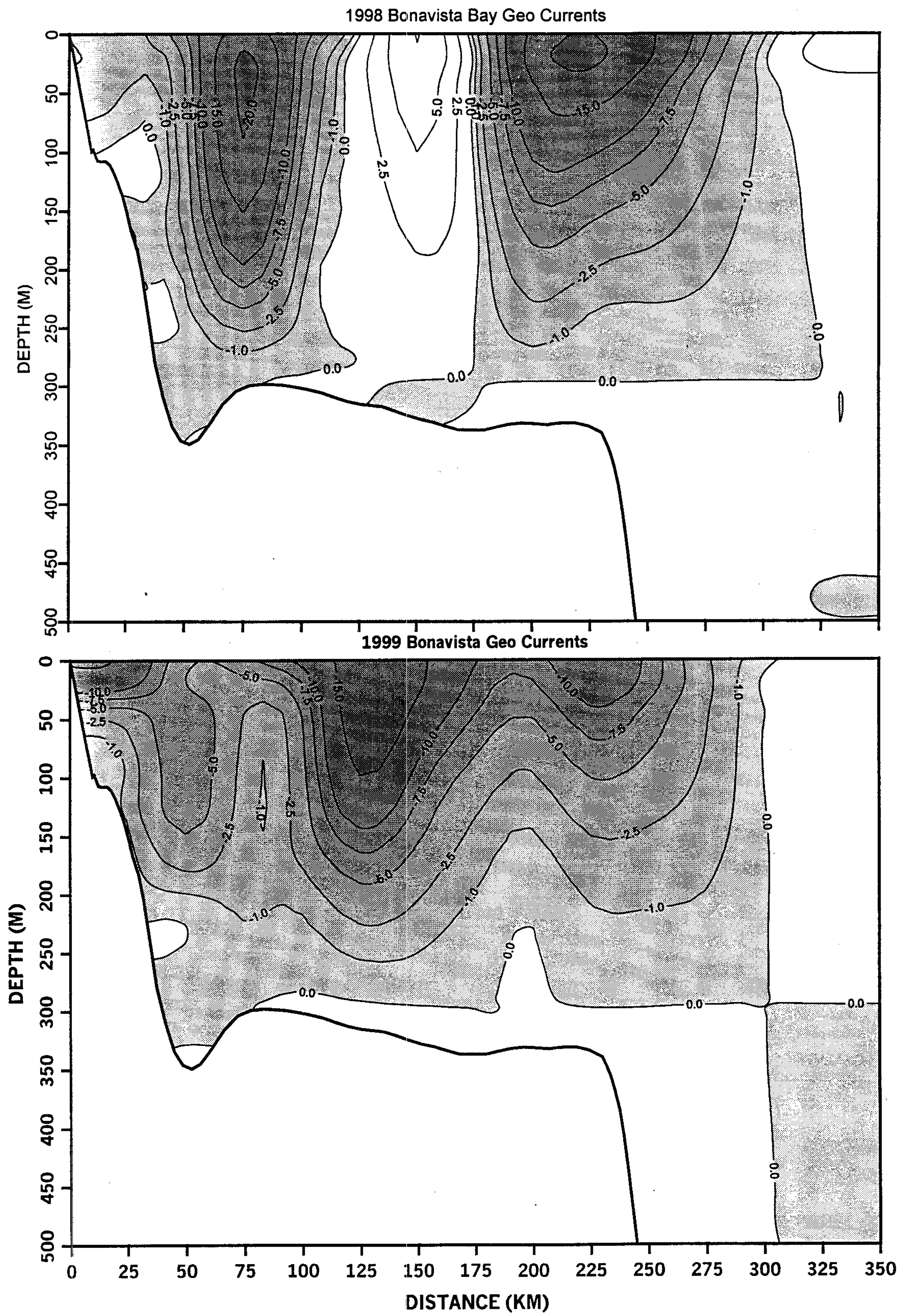


Fig. 17. A vertical cross-section of geostrophic currents (cm/s) along the standard Bonavista transect for the summer of 1998 and 1999. Negative southward values are shaded.

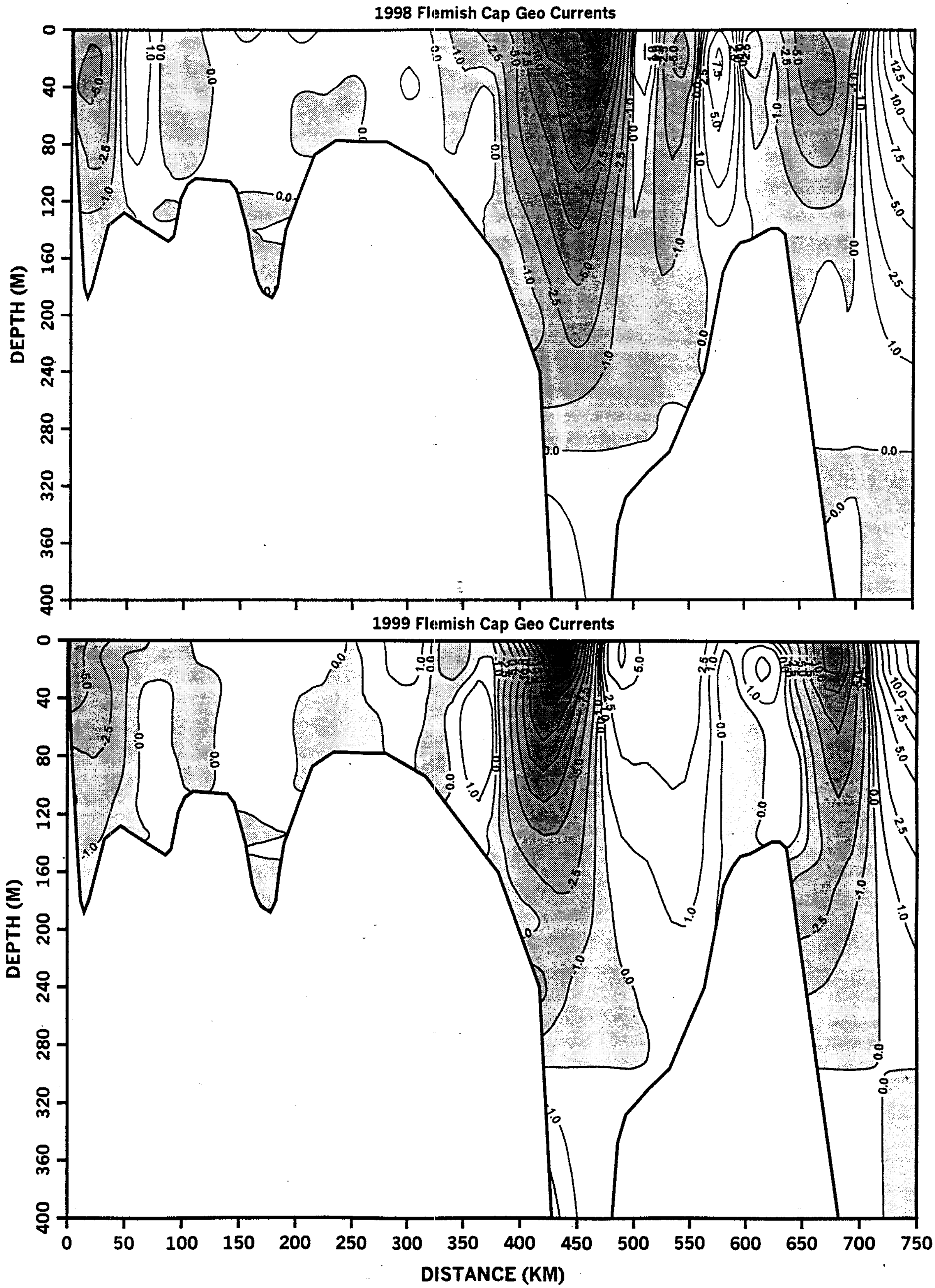


Fig. 18. A vertical cross-section of geostrophic currents (cm/s) along the standard Flemish Cap transect for the summer of 1998 and 1999. Negative southward values are shaded.

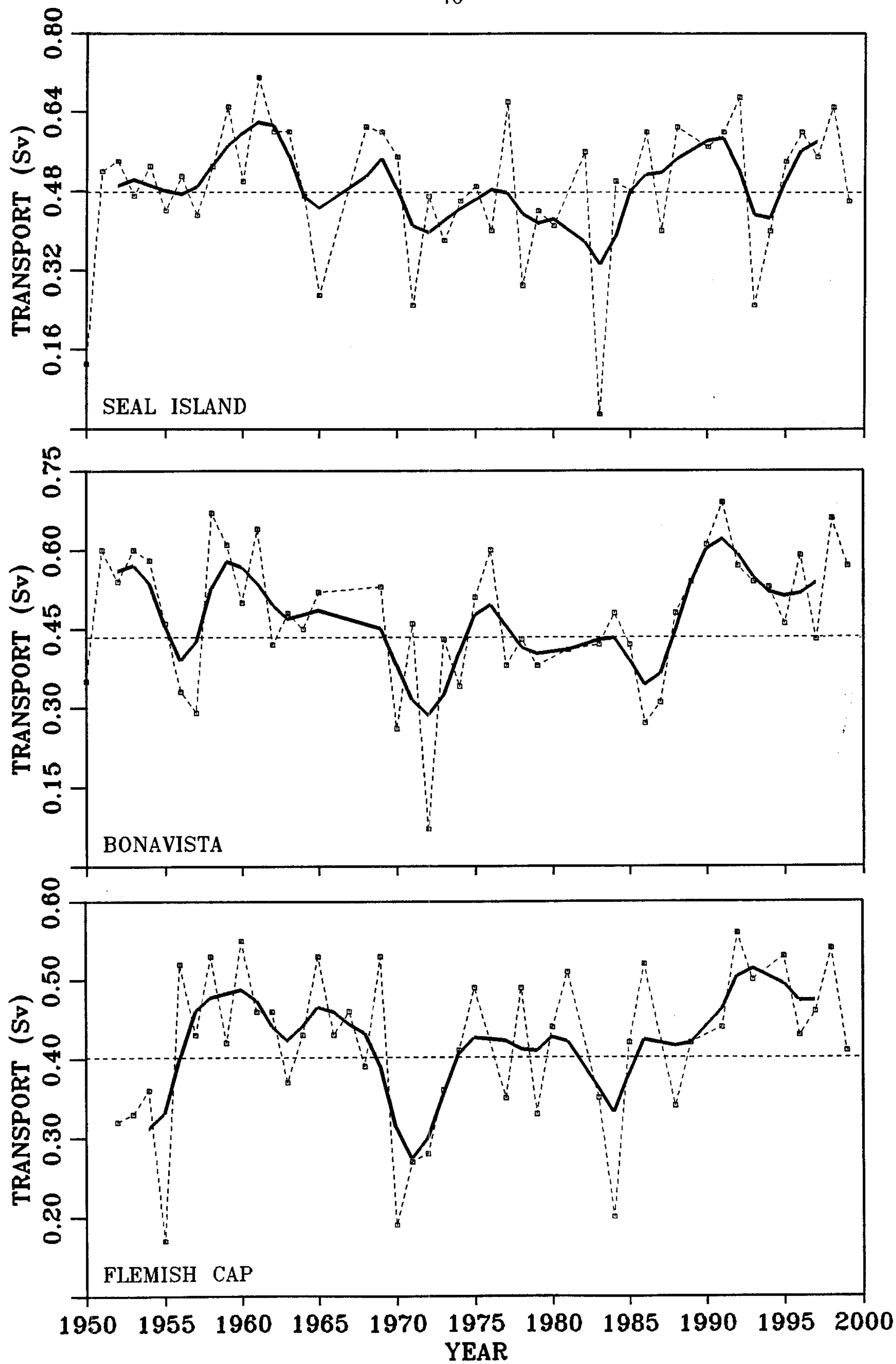


Fig. 19. Time series of geostrophic transport (10^6 m^3/s) relative to 130-m depth of the offshore branch of the Labrador Current through the Seal Island, Bonavista and Flemish Cap transects. The horizontal dashed lines represent the 1961-90 average.

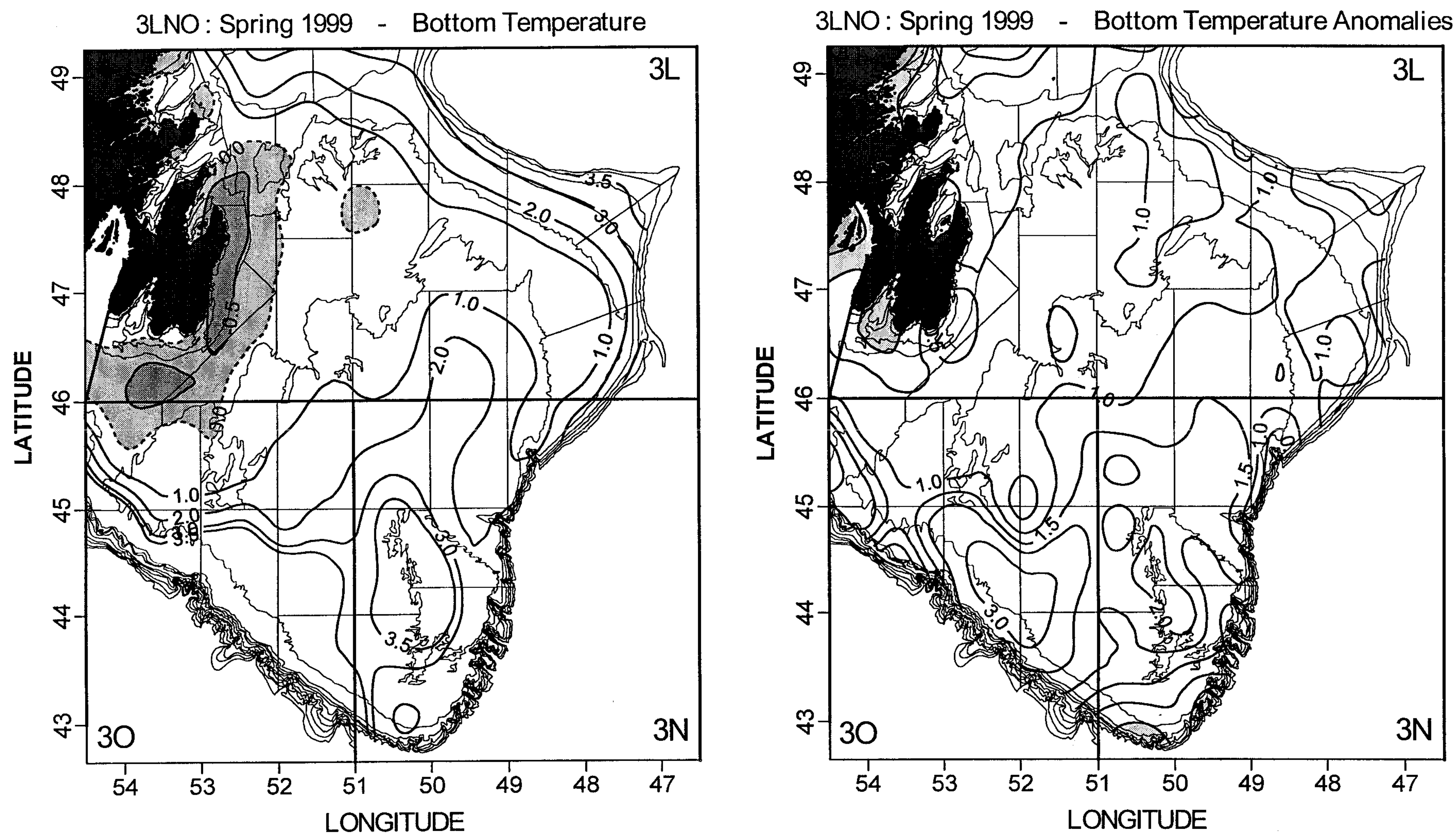


Fig. 20. Horizontal bottom temperature and anomaly contours (in °C) for the spring of 1999 from the ground fish 3LNO survey of the Grand Bank region.

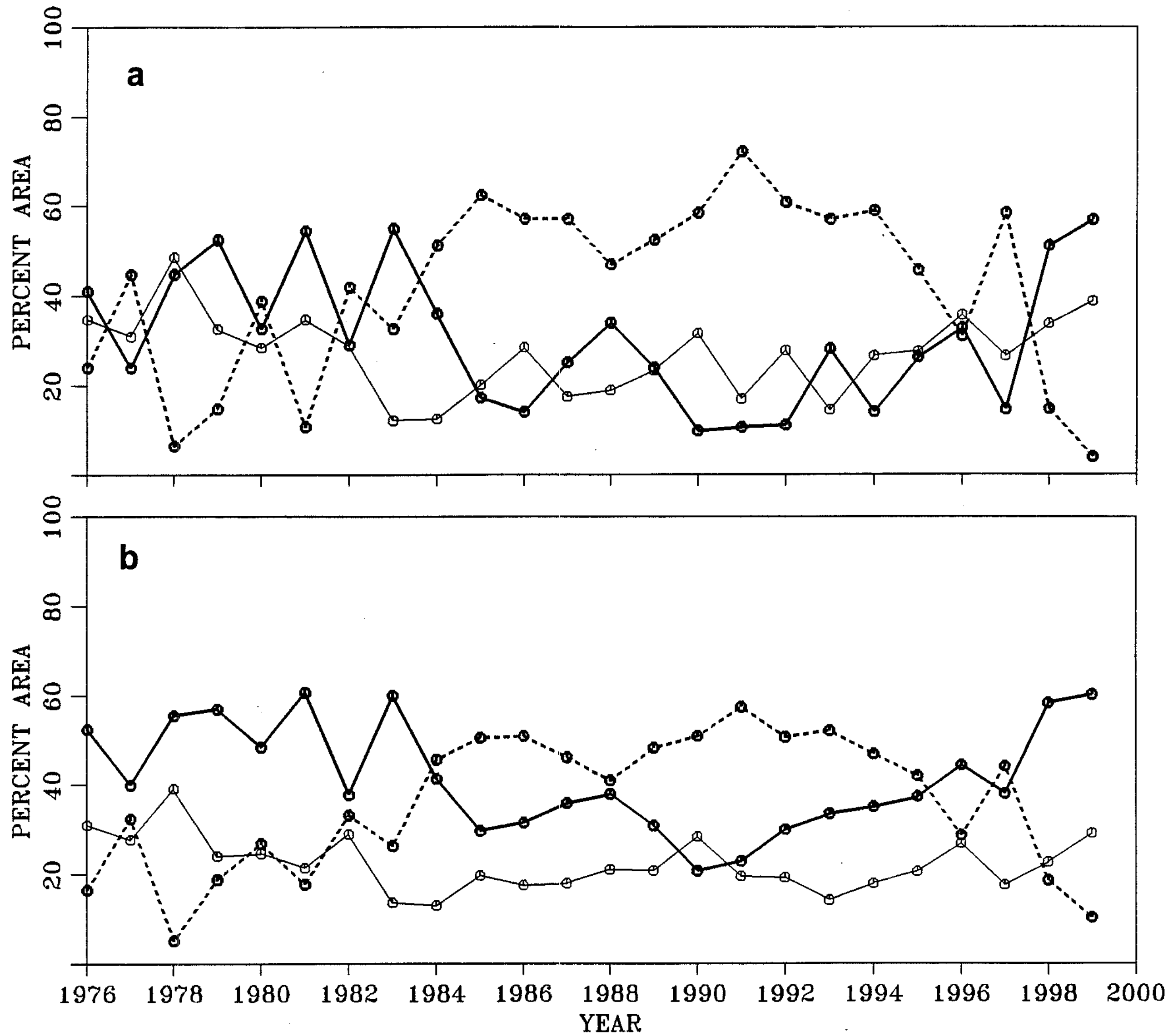


Fig. 21. Time series of the percentage area of Divisions 3LNO covered by water with bottom temperatures ≤ 0°C (dashed line), 0-1°C (light solid line) and ≥1°C (heavy solid line) during spring for (a) strata ≤ 100-m and (b) for all strata.

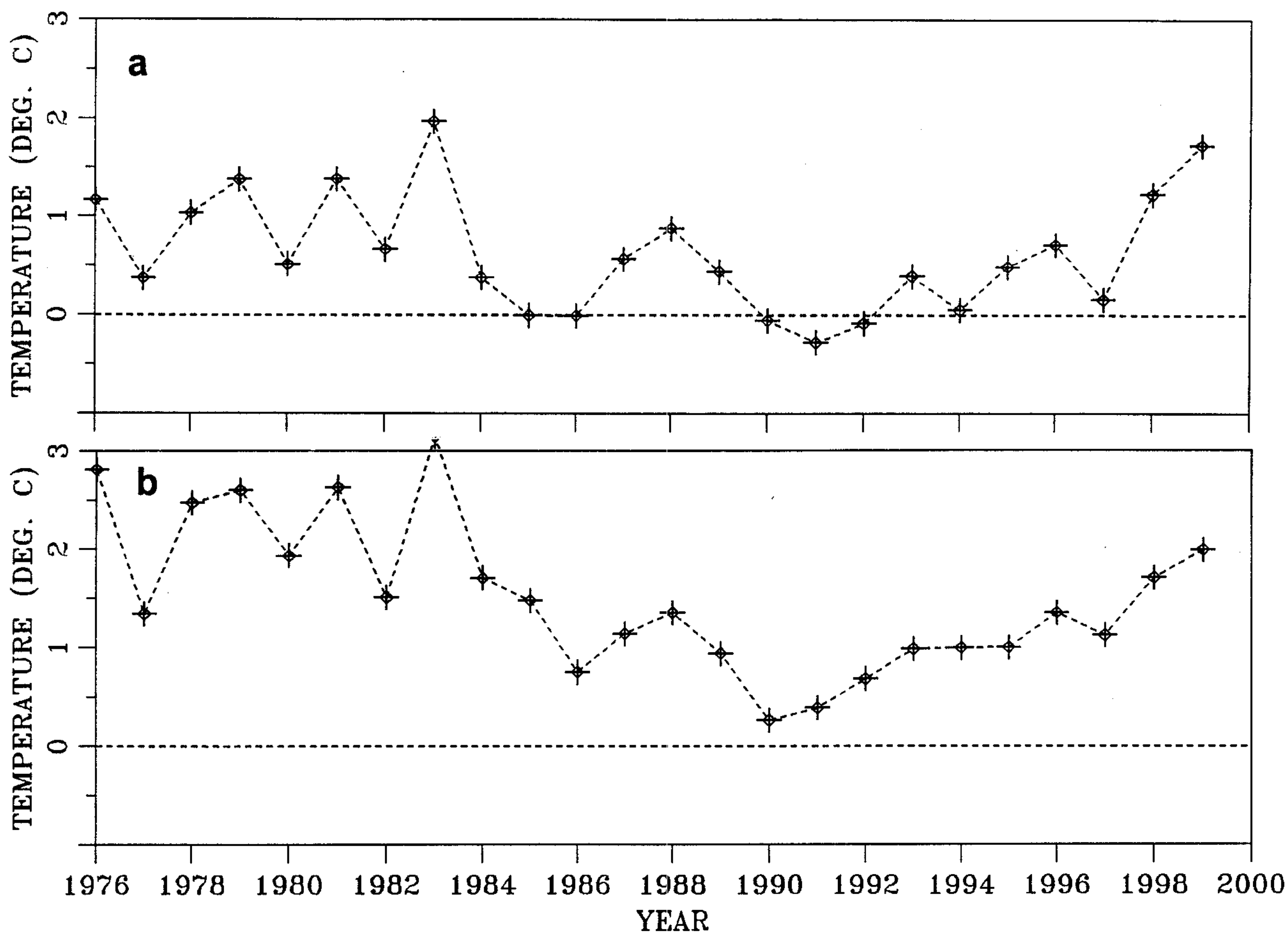


Fig. 22. Time series of mean bottom temperature (in °C) for Divisions 3LNO during spring for (a) strata ≤ 100-m and (b) for all strata.

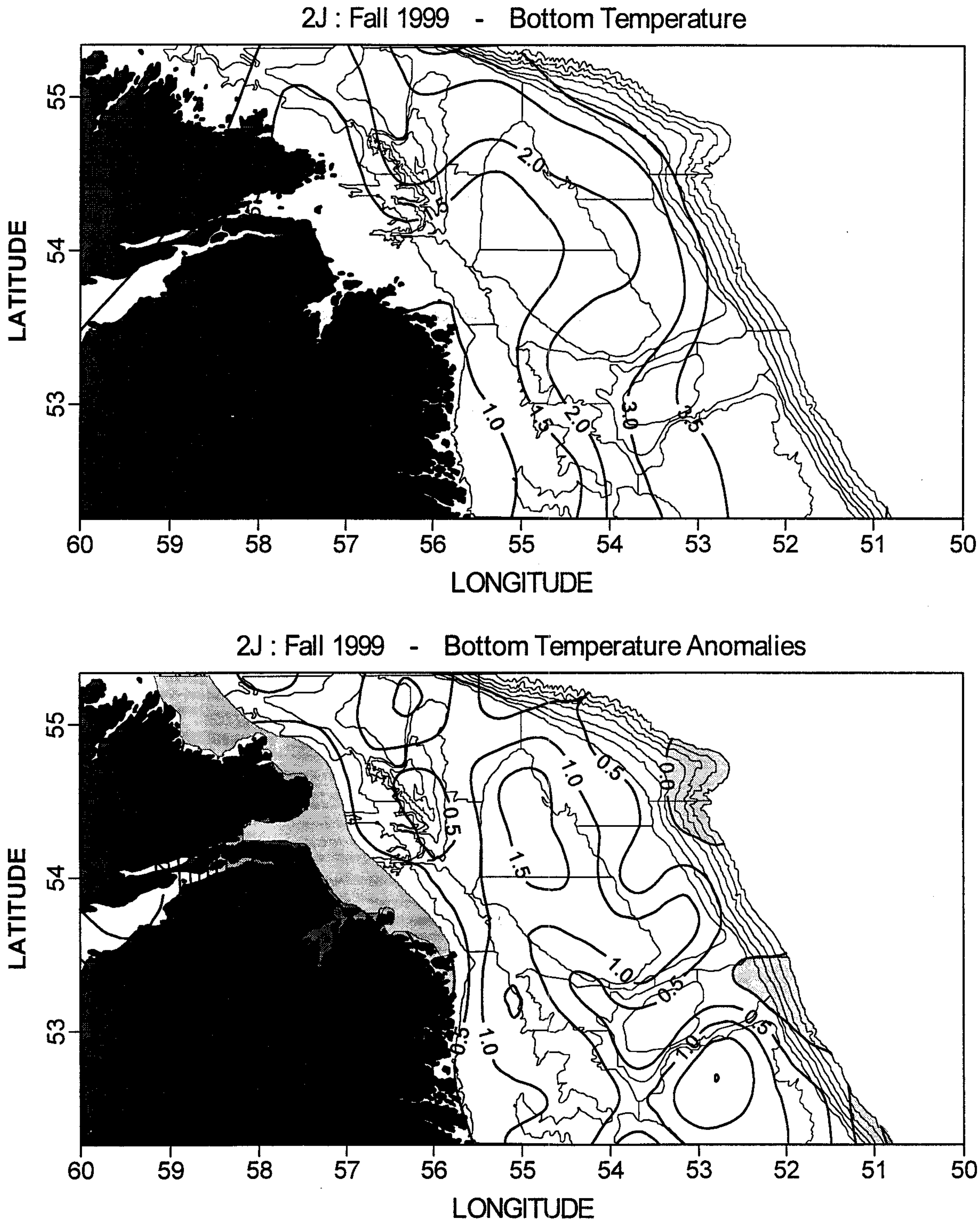


Fig. 23. Horizontal bottom temperature and anomaly contours (in °C) for the fall of 1999 from the ground fish Division 2J survey.

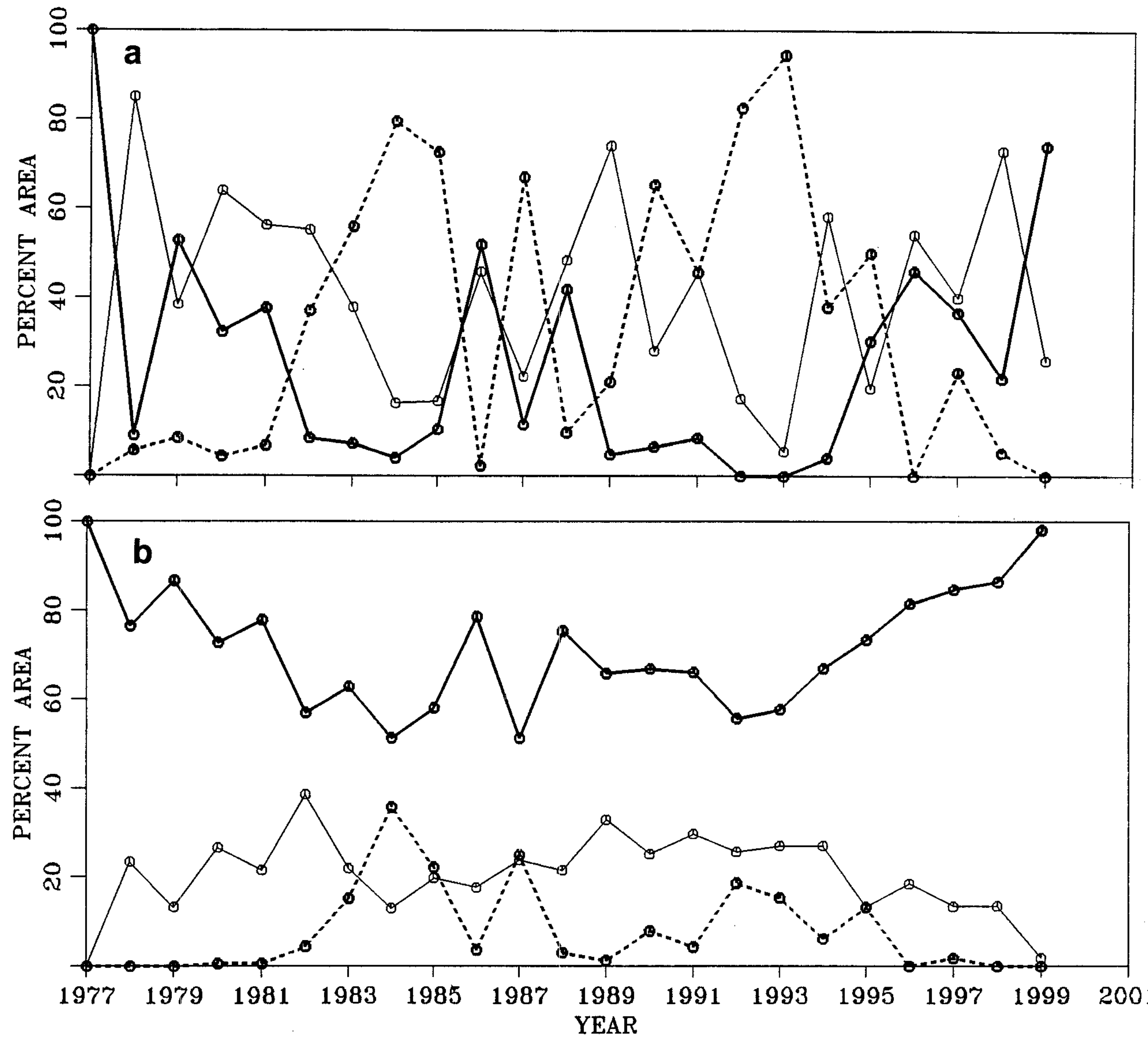


Fig. 24. Time series of the percentage area of Division 2J covered by water with bottom temperatures ≤ 0°C (dashed line), 0-1°C (light solid line) and ≥1°C (heavy solid line) during fall for (a) strata ≤ 200-m and (b) for all strata.

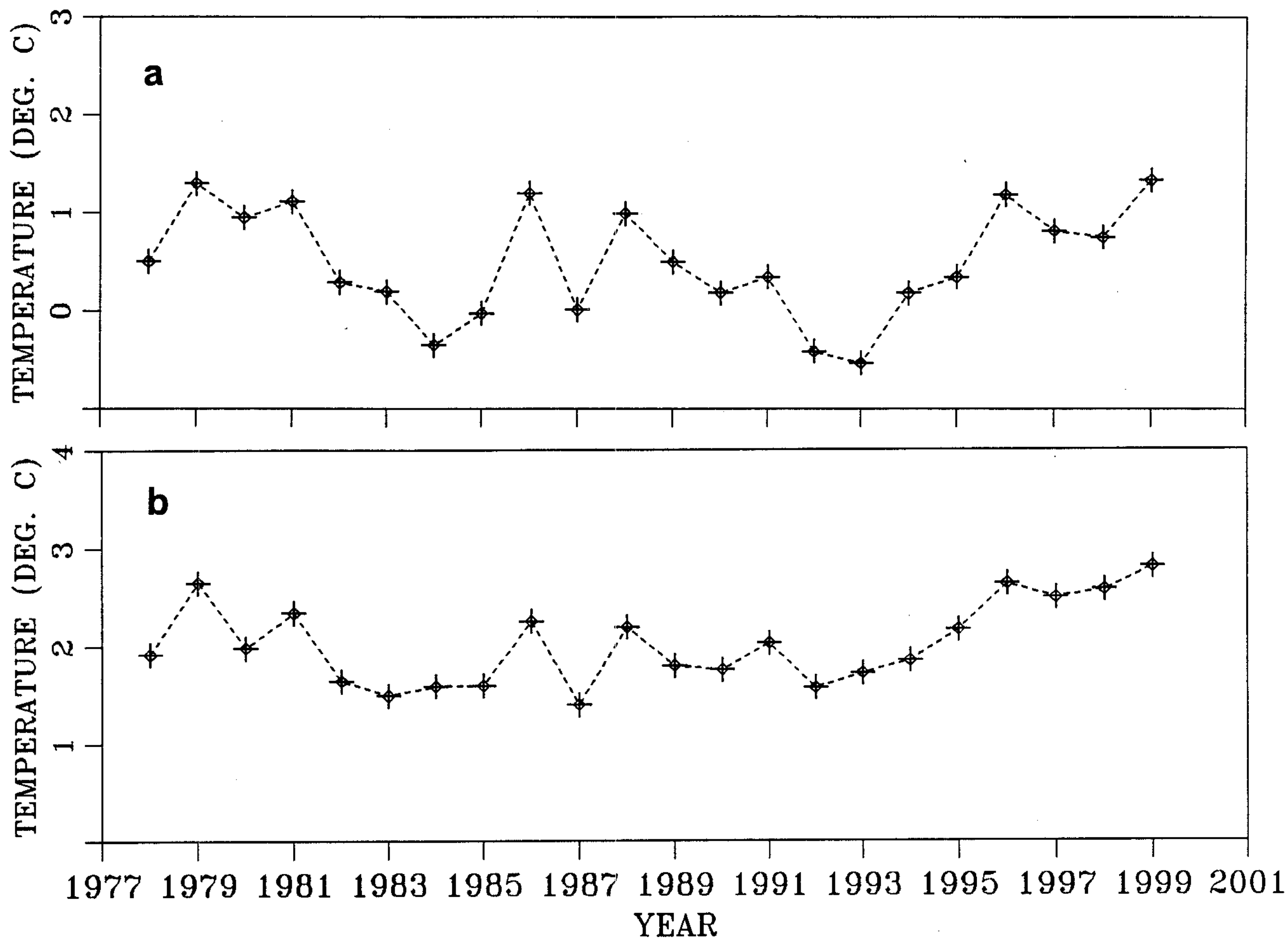
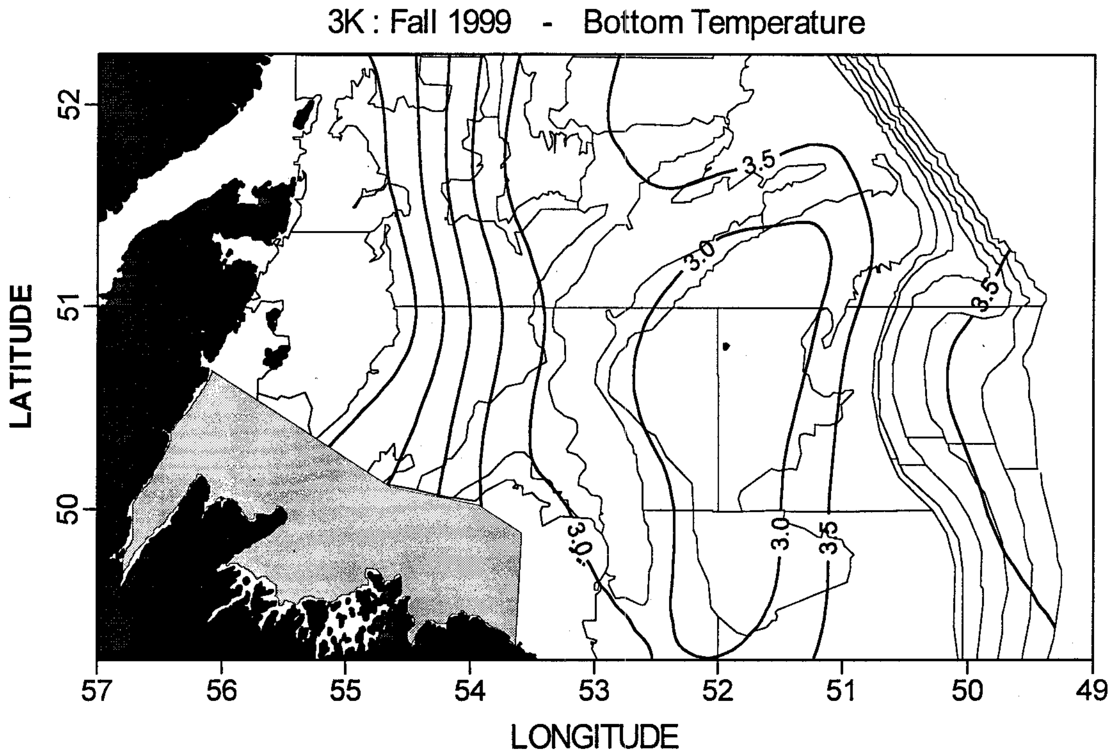


Fig. 25 Time series of mean bottom temperature (in °C) for Division 2J during fall for (a) strata ≤ 200-m and (b) for all strata.



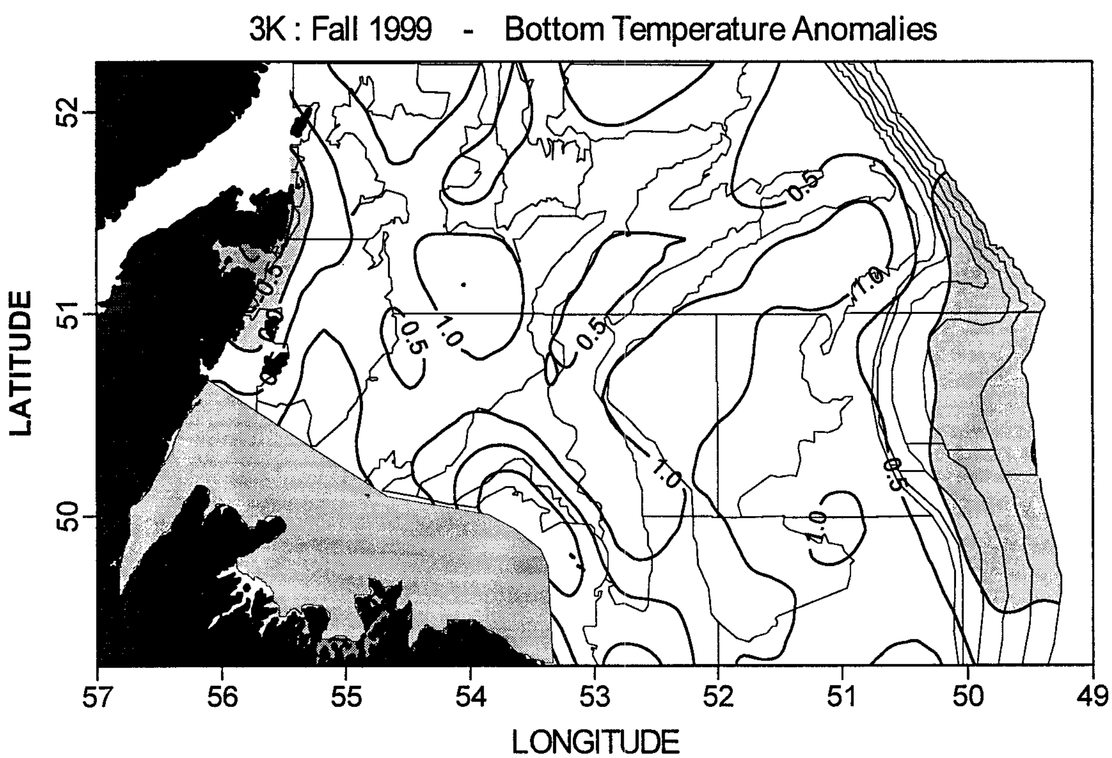


Fig. 26. Horizontal bottom temperature and anomaly contours (in °C) for the fall of 1999 from the ground fish Division 3K survey.

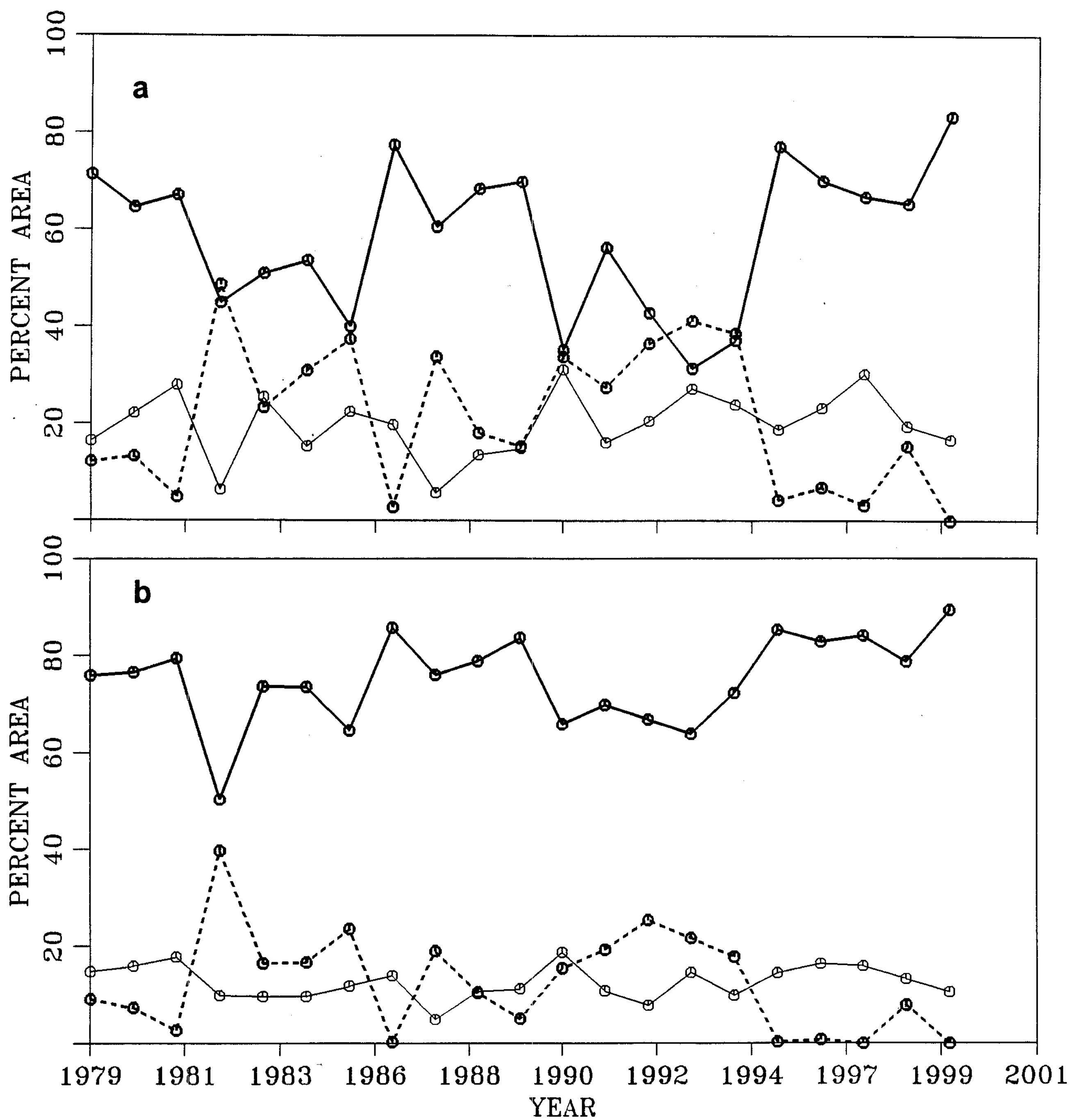


Fig. 27. Time series of the percentage area of Division 3K covered by water with bottom temperatures ≤ 0°C (dashed line), 0-1°C (light solid line) and ≥1°C (heavy solid line) during fall for (a) strata ≤ 300-m and (b) for all strata.

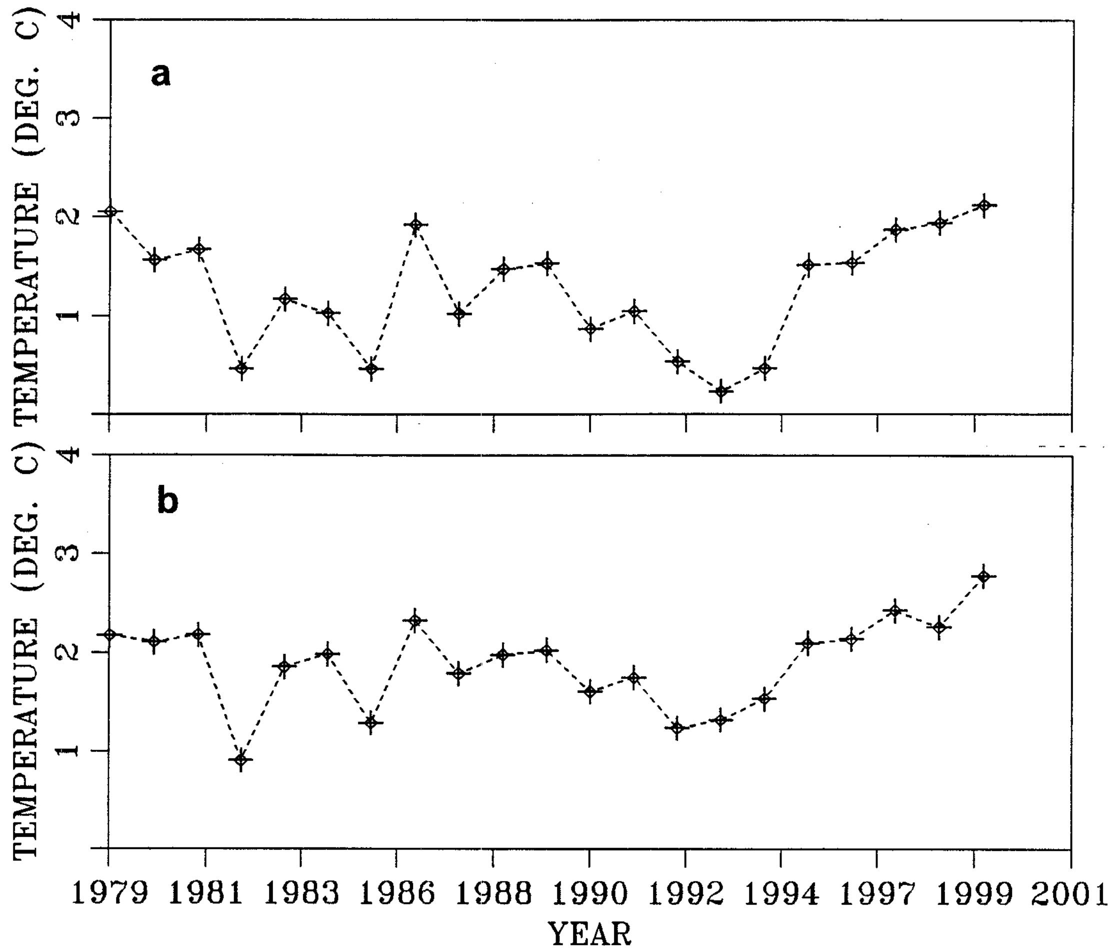
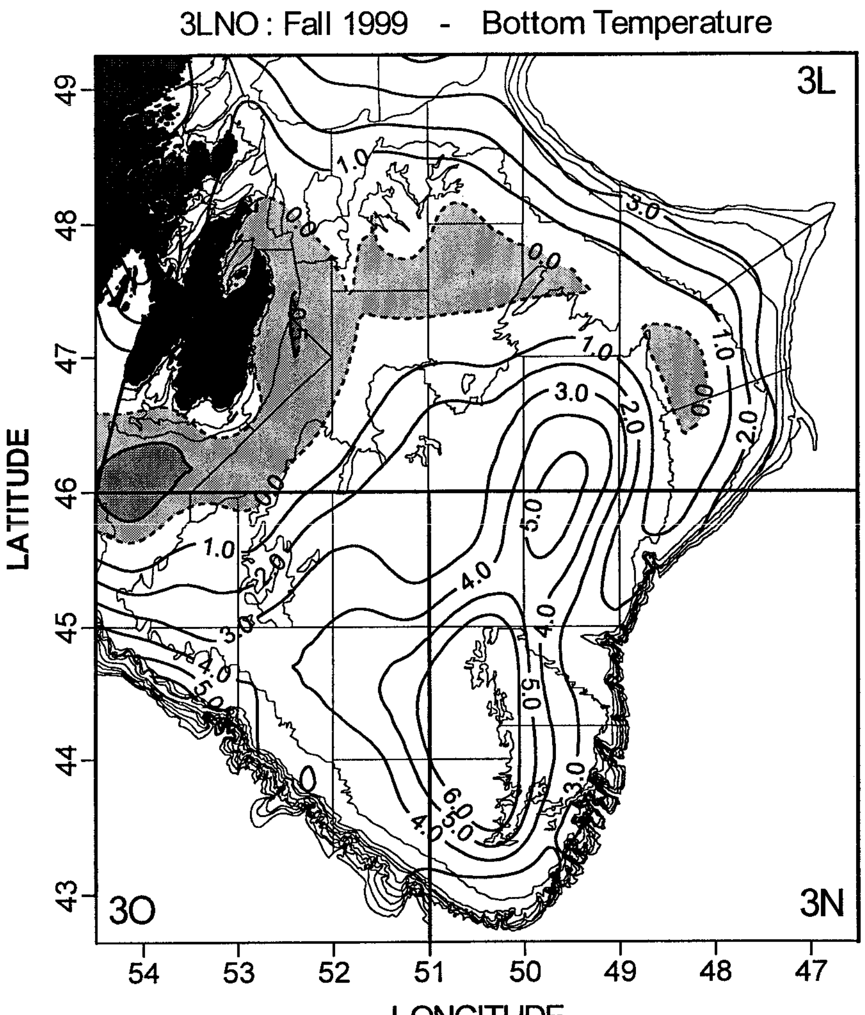


Fig. 28 Time series of mean bottom temperature (in °C) for Division 3K during fall for (a) strata ≤ 300-m and (b) for all strata.



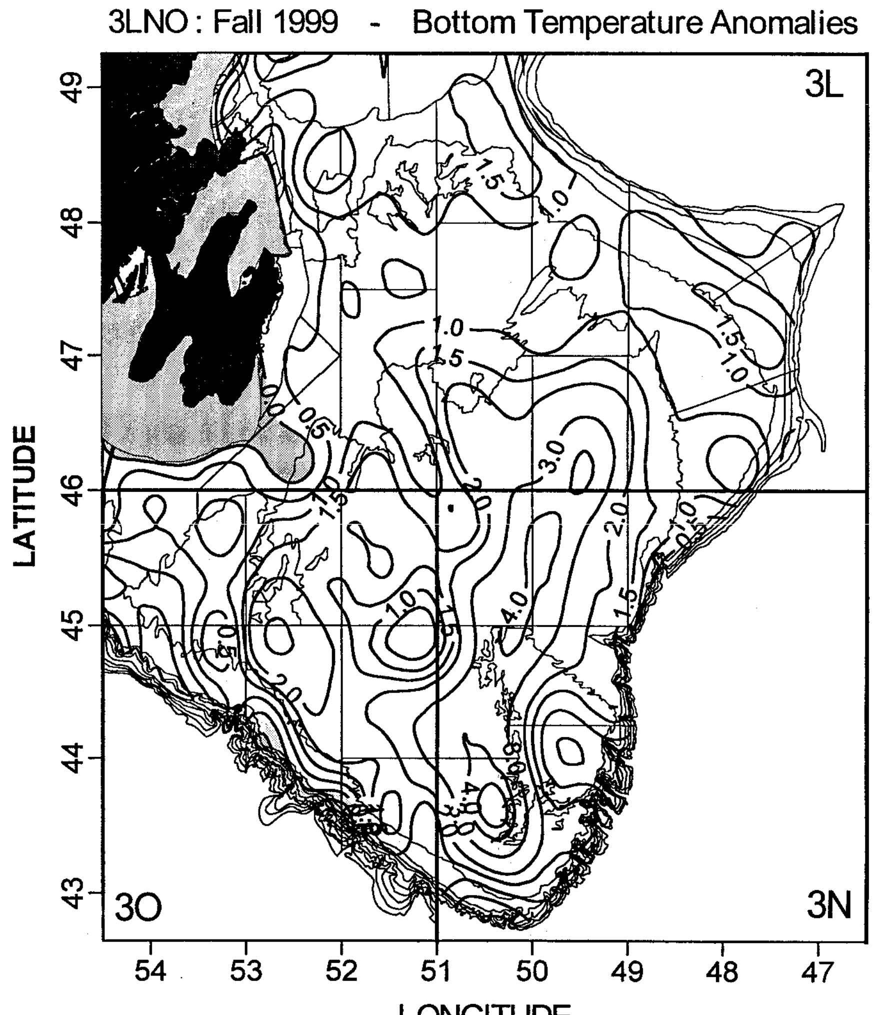


Fig. 29. Horizontal bottom temperature and anomaly contours (in °C) for the fall of 1999 from the ground fish survey in Divisions 3LNO.

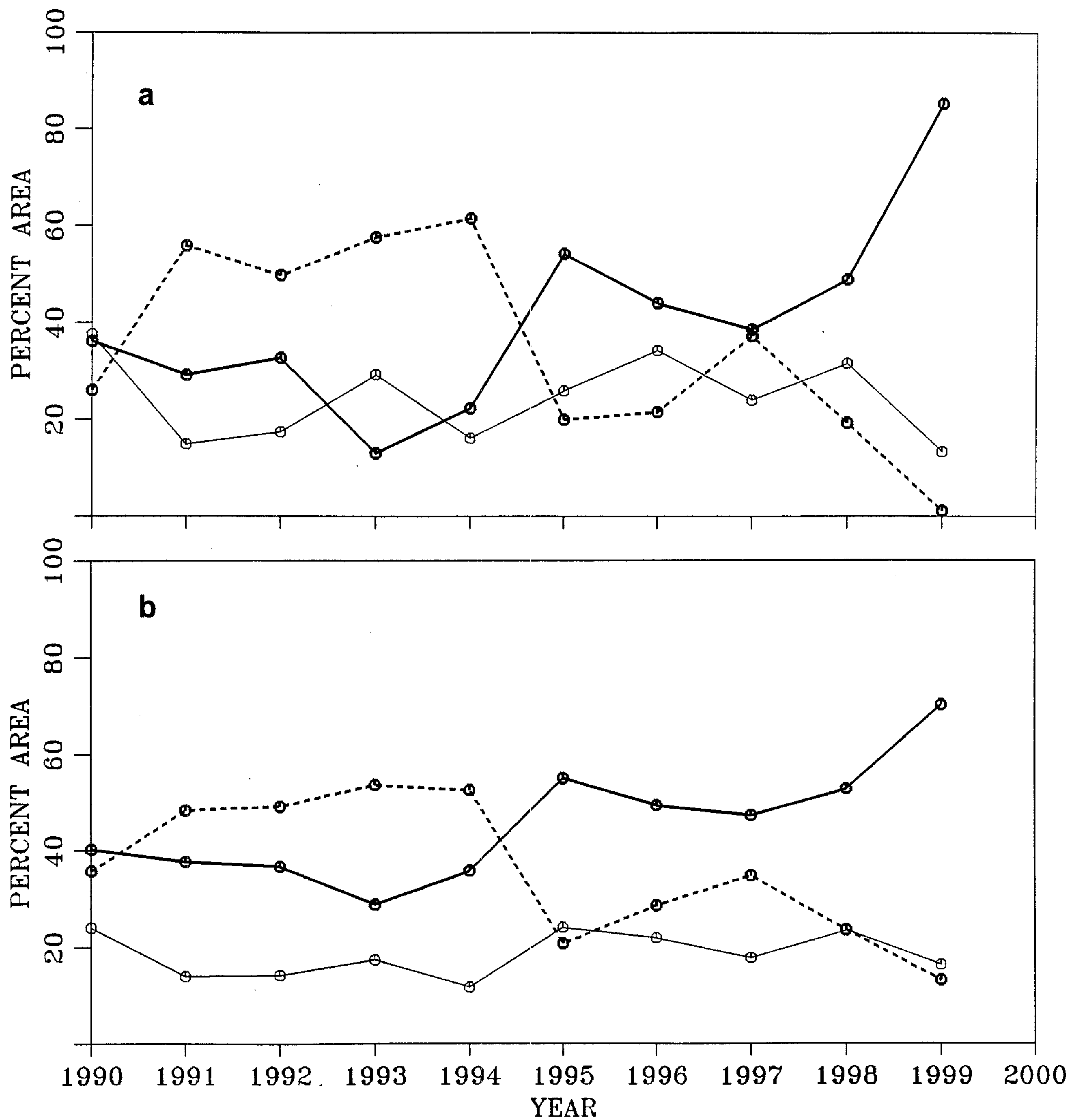


Fig. 30. Time series of the percentage area of Divisions 3LNO covered by water with bottom temperatures ≤ 0°C (dashed line), 0-1°C (light solid line) and ≥1°C (heavy solid line) during fall for (a) strata ≤ 100-m and (b) for all strata.

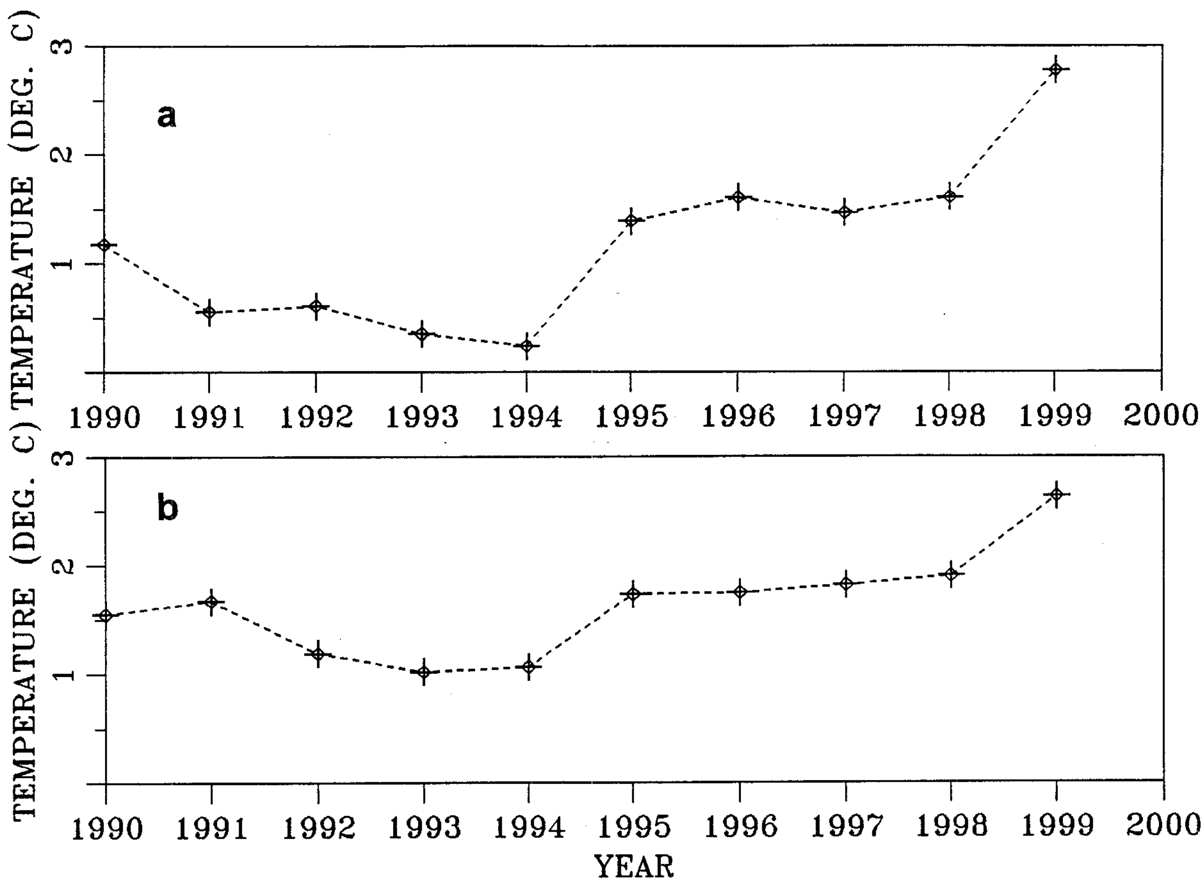


Fig. 31 Time series of mean bottom temperature (in °C) for Divisions 3LNO during fall for (a) strata ≤ 100-m and (b) for all strata.