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Northwest Atlantic Fisheries Organization

Serial No. N4250 **NAFO SCR Doc. 00/21**

SCIENTIFIC COUNCIL MEETING – JUNE 2000

OVERVIEW OF ENVIRONMENTAL CONDITIONS IN THE NORTHWEST ATLANTIC IN 1999

K.F. Drinkwater[1], E. Colbourne[2] and D. Gilbert[3]

[1]Department of Fisheries and Oceans, Bedford Institute of Oceanography
P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2

[2]Department of Fisheries and Oceans, Northwest Atlantic Fisheries Centre
P.O. Box 5667, St. John's, Newfoundland A1C 5X1

[3]Ministère des Pêches et des Océans, Institut Maurice-Lamontagne
C.P. 1000, Mont-Joli, Québec G5H 3Z4

Abstract

A review of environmental conditions in the northwest Atlantic during 1999 is presented. The large-scale atmospheric circulation, as reflected in the North Atlantic Oscillation (NAO) index intensified significantly over 1998 values and reached levels equivalent to those of the early 1990s. In spite of this, air temperatures over the shelf waters off the eastern U.S. and Canada were warmer-than-normal by as much as 2°C, setting new record highs in locations from southern Labrador to the Gulf of Maine. It was a very light ice year in 1999, similar to 1998, as ice generally appeared late and left early. Only 22 icebergs reached the Grand Banks in 1999, the lowest number since 1980, and a significant decline from over a thousand in 1998. Ocean temperatures were warm throughout most of the region. Temperatures over much of Labrador, northern Newfoundland shelves and the Grand Banks continued to be above normal. The CIL volume over the northern Newfoundland Shelf was at its lowest level in over 20 years. Near-bottom temperatures on St. Pierre Bank reached above normal values for the first time since the mid-1980s. In the Gulf of St. Lawrence, CIL waters were colder-than-normal but did warm considerably over 1998 levels. As a consequence, near-bottom waters on the Magdalen Shallows warmed. On the Scotian Shelf, the cold Labrador Slope Water that lay off the shelf edge in 1998 and subsequently penetrated onto the shelf, disappeared in 1999 and was replaced by Warm Slope Waters. The cold shelf waters observed in 1998 also were eventually replaced by warmer waters. Temperatures in the deep region of Emerald Basin rose by 2°-3°C although by the end of 1999 they were near their long-term mean. In the northeastern Scotian Shelf, subsurface waters moderated and reached above normal values for the first time since the mid-1980s. Strong near surface stratification continued on the Scotian Shelf. While the slope/shelf front moved closer inshore than normal in 1999, the Gulf Stream remained seaward of its long-term mean position.

Introduction

This paper examines the atmospheric, sea ice and hydrographic conditions in the Northwest Atlantic during 1999 and continues the series of annual reviews presented to NAFO that began in 1982. It is based upon selected sets of oceanographic and meteorological data. Environmental conditions are compared with those of the preceding year as well as in terms of deviations from their long-term means, called anomalies. Unless otherwise stated, these means have been averaged over a standardized 30-yr base period (1961-90) in accordance with the convention of the World Meteorological Organization and recommendation of the NAFO Scientific Council.

Meteorological Observations

Air Temperatures

The German Weather Service publishes annual and monthly air temperature anomalies (relative to 1961-90) for the North Atlantic Ocean in their publication *Die Grosswetterlagen Europas* (Deutscher Wetterdienstes, 1999). Similar to 1998, warmer-than-normal temperatures dominated the northwest Atlantic during 1999 (Fig. 1). The maximum annual anomalies exceeded 2°C off southern Newfoundland, eastern Nova Scotia and in the southern Gulf of St. Lawrence. Elsewhere in the shelf regions from the northern tip of Labrador to the central Middle Atlantic Bight annual air temperature anomalies exceeded 1°C. Colder-than-normal conditions were observed only in a region stretching from the southern tip of Greenland across the Labrador Sea Baffin Island, in most of Baffin Bay and in a relatively small region south of Iceland.

Monthly data show that in January, warm air covered the continental shelves from southern Labrador through to the southern United States, with the maximum positive anomaly (> 3°C) located south of Cape Hatteras (Fig. 2). In contrast, over the Labrador Sea and Baffin Bay, temperatures in January were below normal by upwards of 4°C. Mild conditions continued for the remainder of the winter over the region south of Labrador to the Middle Atlantic Bight with anomalies between 2°-3°C during February and 3°-6°C in March. In February, the Labrador Sea was again covered by a colder-than-normal air mass but gave way to warm conditions in March. Temperatures were only slightly above normal over most of the northwest Atlantic in April but the pattern of warm over southern Canada and cold over most of the Labrador Sea returned in May. In June through September, this same pattern persisted with only slight modifications. Only in July, October and November, did the majority of the Labrador Sea, including the Labrador Shelf and coastal regions, experience colder-than-normal conditions. In contrast, the West Greenland side of the Labrador Sea was colder-than-normal throughout the year, with the exception in March. The warmest temperature anomalies were observed in September with values of 3°-4°C centered over the Scotian Shelf and the Gulf of St. Lawrence.

Monthly air temperature anomalies for 1998 and 1999 relative to their 1961-90 mean at eight sites in the northwest Atlantic from Godthaab in Greenland to Cape Hatteras on the eastern coast of the United States are shown in Fig. 4 (see Fig. 3 for locations). Data from the Canadian sites were available from the Environment Canada website and for non-Canadian locations from *Monthly Climatic Data for the World* (NOAA, 1999). March and April temperatures from Godthaab were estimated using regressions with Egedesminde. The predominance of warmer-than-normal air temperatures over most of eastern Canadian waters during 1999, noted above, is clearly evident (Fig. 3). At Sable Island, all months were above normal, on the Magdalen Islands all months but one (October), and at Cartwright and St. John’s all but two (October and November). Boston and Cape Hatteras had colder-than-normal means in three months. Not only was there a majority of months with above average monthly mean air temperatures, but also the amplitude of the anomalies were high. Anomalies of +3° to 4°C were common. In contrast to these warm conditions, Godthaab temperatures were colder-than-normal for 6 months of year and the amplitude of the anomalies during the warmer-than-normal months was small.

The annual mean air temperature anomalies for 1999 were also calculated at all eight sites. For all sites except Godthaab, the annual anomalies were above normal. The maximum anomaly was recorded on the Magdalen Islands (2.4°C) where it set a new high for the 66-year time series, eclipsing last year’s record by 0.9°C. New record highs were also recorded at Sable Island (1999 anomaly of 2.1°C; an 85-year record), St. John’s (1.9°C; 126-year record), and Cartwright (1.9°C; 65-year record). The time series of the annual anomalies are shown in Fig. 5. The high air temperature anomalies in 1999 are clearly evident. At St. John’s, the Magdalen Islands and Sable Island the annual anomaly rose above 1998 values by approximately 1°C and at Cartwright by 0.7°C. At the remaining sites they were similar to 1998 except at Godthaab where the anomaly declined by 1.2°C. Note that the interannual variability in air temperatures since 1960 at Godthaab, Iqaluit, Cartwright, and, to a lesser extent, St. John’s, have been dominated by large amplitude fluctuations with minima in the early 1970s, early to mid-1980s and the early 1990s, suggesting a quasi-decadal period. Indeed, the recent rise in temperature is consistent with a continuation of this near decadal pattern. Unlike previous years, monthly temperature anomalies at the Magdalen Islands and Sable Island were generally of higher amplitude than those to the north. These two sites also contain some decadal fluctuations with minima in the early 1970s (both sites), the mid-1980s (Sable Island only) and in the 1990s (Magdalen Islands only). Air temperatures at Boston and Cape Hatteras have generally been out of phase with the temperature fluctuations in the Labrador region. Thus, for example, when the temperatures were very cold in Labrador during the early 1990s, they were relatively warm along the US seaboard (Fig. 5). Also note that all sites where data are available, cold conditions (relative to the 1961-90 mean) existed throughout the late

1800s and early 1990s. Temperatures rose to above normal values between the 1910s and 1950s, the actual timing being site-dependent.

Sea Surface Air Pressures

Climatic conditions in the Labrador Sea area are closely linked to the large-scale pressure patterns and atmospheric circulation. Monthly mean sea-surface pressures over the North Atlantic are published in *Die Grosswetterlagen Europas*. The long-term seasonal mean pressure patterns are dominated by the Icelandic Low centred between Greenland and Iceland and the Bermuda-Azores High centred between Florida and northern Africa (Fig. 6). Winds rotate counter clockwise around the Low and clockwise around the High. The strength of the wind is larger where the pressure contours are closer together (pressure gradients are steeper). The strengths of the Low and High vary seasonally from a winter maximum to a summer minimum. Seasonal anomalies of the sea-surface pressure for 1999, relative to the 1961-90 means, are shown in Fig. 7. Winter includes December 1998 to February 1999, spring is March to May, and summer is June to August. Autumn (September to November) data were not available at the time of writing.

In winter, a strong dipole pattern was established with negative air pressure anomalies in the northern North Atlantic and with positive anomalies over most of the southern North Atlantic. The largest negative anomalies (below -7 mb) were located northeast of Iceland and the largest positive anomalies (>5 mb) were centred over the Azores. These high anomalies extended across the entire width of the Atlantic Ocean. This pattern indicates a strengthening of the atmospheric circulation with an intensification of both the Iceland Low and the Azores High. It also represents a return to the anomaly patterns observed in the first half of the 1990s and different from those observed during the past three years when the circulation had weakened. Strong westerly winds across the northern North Atlantic accompany this pressure pattern with the maximum wind anomalies over Western Europe. Over eastern Canada the pressure field implied slightly stronger-than-normal westerly winds while in the Labrador Sea they were more northwesterly. The latter are consistent with the colder-than-normal air temperatures during the winter over West Greenland. Note that the anomalous High extended into southeastern Canada as far north as southern Labrador. This contributed to the warm temperature anomalies in this region.

In the spring of 1999, a relatively strong negative pressure anomaly (> 2 mb) developed over the northeastern Atlantic, with its center to the north of Scotland. Two smaller and weaker negative anomalies also formed, one off the eastern United States and another over northern Africa. A positive anomaly was centred over Davis Strait and northern Greenland (3-5 mb) with a ridge of higher-than-normal pressures extending from southern Labrador through to Africa. In eastern Canada, the geostrophic winds associated with these anomaly pressure fields would be predominantly from the east.

As is typical in most years, the pressure anomaly fields during the summer of 1999 were generally weaker than in the other seasons. Slightly lower pressures than normal covered most the North Atlantic. There were several local maxima, all of which were slightly above 2 mb. These were found over the Labrador coast, over Baffin Island, west of Ireland and over northern Africa. The geostrophic winds accompanying this pressure anomaly field were also relatively weak.

NAO Index

The North Atlantic Oscillation (NAO) Index is the difference in winter (December, January and February) sea level atmospheric pressures between the Azores and Iceland and is a measure of the strength of the winter westerly winds over the northern North Atlantic (Rogers, 1984). A high NAO index corresponds to an intensification of the Icelandic Low and Azores High. Strong northwest winds, cold air and sea temperatures and heavy ice in the Labrador Sea area are usually associated with a high positive NAO index (Colbourne et al. 1994; Drinkwater 1996). The annual NAO index is derived from the measured mean sea level pressures at Ponta Delgada in the Azores minus those at Akureyri in Iceland. The small number of missing data early in the time series was filled using pressures from nearby stations. The NAO anomalies were calculated by subtracting the 1961-90 mean.

In 1999, the NAO anomaly was well above normal (+14.3 mb) and had increased significantly from the 1998 value which was +1.1 mb (Fig. 8). Indeed, the 1999 index returned to a level similar to that observed during the first half of the 1990s and was above the lower-than-average indices registered in 1996 and 1997. These changes in the NAO index fit the pattern of quasi-decadal variability that has persisted since the 1960s.

Sea Ice Observations

Information on the location and concentration of sea ice is available from the daily ice charts published by Ice Central of Environment Canada in Ottawa. The long-term median, maximum and minimum positions of the ice edge (concentrations above 10%) based on the composite for the years 1962 to 1987 are taken from Coté (1989). The location of the ice edges are constantly in motion due to the action of the winds and the ocean currents, hence rapid changes can occur from day to day. We also include an analysis of the time of onset, duration and last presence of sea ice in the Gulf of St. Lawrence and on the Scotian Shelf based upon the sea-ice database maintained at the Bedford Institute of Oceanography (Drinkwater et al., 1999). The weekly concentration and types of ice within 0.5º latitude by 1º longitude areas were recorded through the ice season. The dates of the first and last appearance of ice within these areas, as well as the duration of ice, were determined. The database begins in the early 1960s and continues to the present. Long-term means (30-years, 1964-1993) of each variable were determined (using only data during the years ice was present) and subtracted from the 1999 values to obtain anomalies. Last year we also included a similar analysis for the southern Labrador and northern Newfoundland shelves based upon the database maintained by Peterson and Prinsenberg (1990). However, as of the time of writing these data were unavailable for 1999.

Newfoundland and Labrador

At the end of 1999, sea ice lay off the southern Labrador coast in the vicinity of Hamilton Inlet resulting in an area coverage that matched closely the long-term median for that time of the year (Fig. 9a). This was aided by below normal air temperatures and strong northwest winds during the latter half of December. By mid-January, the ice had spread past the southern tip of Labrador and into White Bay on the northern Newfoundland coast, still remaining near its long-term median position. During the latter half of January light west to northwest winds prevailed and air temperatures were generally 1º-3°C above normal. By the first of February, the ice edge extended south to Notre Dame Bay and the ice extent and thickness were near normal. In spite of the warmer-than-normal air temperatures (3°-5°C) and light winds during February, by 1 March, the southern most ice edge still lay close to the long-term median position. However, the ice did not extend as far offshore as normal resulting in less ice extent than normal. This was in part due to the persistent northeast winds during the second half of February, which pushed ice shoreward. Winds from the southwest and above normal air temperatures during most of March resulted in an early retreat of the ice and by 1 April, the ice edge was inshore of its long-term median position on the northern Newfoundland shelf, although near it off southern Labrador (Fig. 9b). Warm air temperatures continued throughout April with the result that the ice continued to retreat faster-than-normal. By 1 May, the ice was restricted to the nearshore areas off northern Newfoundland and the inner Labrador Shelf. The ice edge lay well inshore of the long-term median location. On 1 June, the ice had retreated to the Labrador Shelf region north of Hamilton Inlet. The ice edge was near its normal position but the ice thickness was less than normal. By 1 July all traces of ice had disappeared from southern Labrador.

The time series of the areal extent of ice on the Newfoundland and southern Labrador shelves (between 45-55^{o}N; I. Peterson, personal communication, Bedford Institute) show that the peak extent during 1999 was close to but slightly below that observed in 1998 and the lowest since 1978 (Fig. 10). The average ice area during the period of general advancement (January to March) rose slightly relative to 1998 but during the period of retreat (April to June) it declined compared to the previous year. During both advance and retreat periods, the average ice area was below the long-term mean and was much less than the early 1990s. The monthly means of ice area show that in 1999 coverage was above that in 1998 in December and January but below for February to April (Fig. 11). In May to July the ice area was similar to the previous year. Except for January, the monthly mean ice area was below the long-term mean (1963-1990). In summary, 1999 was generally a lighter-than-average ice year on the Labrador and Newfoundland shelves. Variations of ice area generally reflect changes in ice volume as the two are reasonably well correlated based on studies carried out in the Gulf of St. Lawrence (Drinkwater et al., 1999).

Icebergs

The International Ice Patrol Division of the United States Coast Guard monitors the number of icebergs that pass south of 48^{o}N latitude each year. Since 1983, data have been collected with SLAR (Side-Looking Airborne Radar). During the 1998/99 iceberg season (October 1998 to September 1999), a total of only 22 icebergs were spotted south of 48^{o}N. The monthly totals for March to July were 1, 2, 11, 5, and 3, respectively (Fig. 12). No icebergs were spotted between October 1998 and February 1999, inclusive, or in August or September 1999. In 1999, all of the icebergs were observed during the primary iceberg season of March to July, which is higher than the 1983-99 mean of 91.6%. Half of the icebergs during the 1998/99 season penetrated south of 48^{o}N in May but the low number of icebergs overall makes this statistic less meaningful than in recent years. The total number of icebergs in 1999 was down dramatically from the 1384 icebergs recorded in 1998 and was the 11th fewest in the 120-year record (Fig. 12). The low number of icebergs in 1999 is consistent with reduced sea ice coverage and warm air temperatures off southern Labrador and northern Newfoundland. This is believed to be due to increased melting caused by the warmer air temperatures and greater deterioration of the icebergs from breaking waves when there is less sea ice (Marko et al., 1994). Warm air temperatures and reduced ice coverage off Labrador and Newfoundland usually occur in years when the NAO index is low, however this was not the case in 1999.

Gulf of St. Lawrence

At the end of December 1998, ice was only present in nearshore regions in the Gulf of St. Lawrence including within the St. Lawrence Estuary, along the northshore of Quebec, in the Baie des Chaleur, Miramichi Bay and in Northumberland Strait (Fig. 13). Air temperatures during the first half of January were generally below normal by 1°-2°C. This resulted in the ice covering the eastern half of the Gulf and along the northshore of Quebec by mid-month. The ice was near to, but slightly greater than, its normal extent. During the latter half of January, air temperatures rose above normal. The areal extent continued to expand so that by 1 February the ice coverage was again near to but slightly greater than the long-term median. The very high air temperature anomalies during February lead to little further advancement of the ice edge on 1 March over that recorded at the beginning of February. Again the ice thickness was less than normal at this time. During March the continuing high air temperature anomalies caused a rapid retreat so that there was much less ice than normal by 1 April. Ice was confined to the southeastern Gulf, off eastern Cape Breton and in the vicinity of the Strait of Belle Isle at this time. The small amount of ice gradually disappeared through April so that by May 1, the only ice left was in the Strait of Belle Isle region. This ice may have been advected into the Gulf from the Labrador Shelf.

During 1999 within the Gulf (landward of Cabot Strait), ice formation ranged from late December in the St. Lawrence Estuary and in the eastern region of the Magdalen Shallows to early February (after day 30) off southwestern Newfoundland (Fig. 14). This represented a slightly earlier-than-normal appearance of ice, usually within 10 days of the typical date (Fig. 15). The date of last appearance shows the standard pattern of ice lasting longest over the southern Magdalen Shallows and along the north shore of Quebec through to the Strait of Belle Isle (Fig. 14). In 1999, the anomaly in the date of last presence varied throughout the Gulf, with ice leaving earlier-than-normal in much of region but still significant portions where it left later (Fig. 15). For the former, the magnitude of the anomalies tended to be longer, upwards of 40 days early off southwest Newfoundland. The duration of ice ranged from less than 20 days off southwestern Newfoundland to over 130 days in the Strait of Belle Isle (Fig. 16). Relative to the long-term mean, using only years when ice was present, ice duration was less than normal throughout much of the Gulf, exceptions being in the vicinity of Anticosti Island and the western region of the Magdalen Shallows around Prince Edward Island and extending through to the Gaspe Peninsula. Near Cabot Strait and off southwest Newfoundland, the duration of ice was more than 40 days less than the long-term mean.

Scotian Shelf

Sea ice is generally transported out of the Gulf of St. Lawrence through Cabot Strait, pushed by northwest winds and the mean ocean currents. In 1999, ice first appeared seaward of Cabot Strait during mid-January (Fig. 14), which is typical. It maintained a relatively constant presence through into early March on the Newfoundland side of the Strait and mid-April off northern Cape Breton. This ice was primarily restricted to the Sydney Bight area with little ice reaching the Scotian Shelf proper. Most of this ice had disappeared by the end of March or in early April (Fig. 14). This departure was about 10 days earlier-than-normal (Fig. 15). The duration of ice south of Cabot Strait ranged from 70 days off northern Cape Breton Island to 10 days or less off southeastern Cape Breton Island. This was less than the long-term mean by 10 to over 40 days (Fig. 16). Note that a duration of less than 10 days is not plotted in Fig. 16.

The monthly estimates of the ice area seaward of Cabot Strait since the 1960s show that only small amounts of ice were transported onto the Scotian Shelf during 1999 compared to the long-term mean but were similar to 1998 (Fig. 17, 18). There were fewer days than usual when ice was present seaward of Cabot Strait and the integrated ice area (summation of the area times the number of days) was the fourth lowest on record (Fig. 17). In summary, 1999 was the second consecutive year of very light ice conditions seaward of Cabot Strait. Note that based upon data collected since the 1960s, the furthest south that the ice penetrates is along the Atlantic coast of Nova Scotia to just past Halifax. Historical records prior to 1960, albeit incomplete, suggest that during heavy ice years, it occasionally penetrated much further south, for example in the late 1800s sea ice was observed in the Gulf of Maine (A. Ruffman, Geomarine Associates Ltd., Halifax, personal communication).

Oceanographic Observations

Newfoundland and Labrador

Station 27

Temperature and salinity have been monitored since 1946 at Station 27 located approximately 10 km off St. John's, Newfoundland. This site lies within the inshore branch of the Labrador Current but is considered to be representative of hydrographic conditions at long periods (interannual to decadal) over the continental shelf from southern Labrador to the Grand Banks (Petrie et al., 1992). The station was visited 45 times in 1999, with a monthly maximum of 8 in May. No measurements were taken in February. The data were collected at, or linearly interpolated to, standard depths (0, 10, 20, 30, 50 75, 100, 125, 150 and 175 m) and monthly means were calculated for each depth.

During 1999, the water column cooled from January to March reaching temperatures just above 0°C in the surface layers and below –1°C in the subsurface waters. The latter extended through to November with the maximum vertical extension occurring in August (Fig. 19). These very cold subsurface waters were likely advected into the region from the north. Upper layer (generally < 50 m) temperatures were below 0°C until April when they began to rise steadily and reached a peak of over 13°C at the surface in August before autumn cooling set in. The August mean surface temperature was similar to that recorded in 1998. Note the propagation of surface layer heat down into the lower layers in the late autumn. From January to August, temperatures were above normal with the maximum temperature anomalies occurring in the near surface waters in June and July (>2°C). By September, below normal temperatures appeared at mid-depths and spread to encompass approximately the upper 100 m of the water column for the remainder of the year. These may have been the result of southward advection of the cold anomalies observed off the Labrador coast in summer. Near bottom temperatures remained above the long-term mean through out the year (Fig. 19).

In 1999, near surface salinities at station 27 were maximum (> 32.2) in late February to early March, then declined steadily reaching a minimum of < 30.8 in September (Fig. 20). The autumn salinity minimum has been related to the arrival of summer ice melt from the Labrador Shelf (Myers et al. 1990; Petrie et al. 1991). The maximum salinities (>33) appeared near bottom. Salinities during 1999 were saltier-than-normal in the surface waters until March and in the bottom waters until July. Thereafter the waters were fresher than usual except during the last month or two in the upper half of the water column. The largest negative salinity anomaly (-0.4) was in the surface waters during July and August indicating a possible earlier-than-normal arrival of the ice melt. The warmer and fresher anomalies in the early summer indicate stronger stratification.

The time series of monthly temperature anomalies at Station 27 at 0, 50, 100, 150 and 175 m for 1970-1998 are shown in Fig. 21. Note that the temperature scales differ with depth. At the surface and 50 m there is large, short-term variability reflecting atmospheric heating and cooling. Warmer-than-normal temperatures were observed throughout 1999 at 150 and 175 m, continuing a trend that began in 1996. This warming has followed more than a decade of cold conditions. Note that the coldest periods roughly correspond to those identified from the air temperature anomalies, i.e. the early 1970s, the mid-1980s and the 1990s. In contrast to the deepest depths, at mid-depth (50 and 100 m), conditions were near normal with a slight tendency towards cool conditions. In spite of the high variability at the surface, the slow warming trend that began around 1992 appears to be continuing.

The depth-averaged temperature, which is proportional to the total heat content within the water column, also shows large amplitude fluctuations at near decadal time scales with cold periods during the early 1970s, mid- 1980s and early 1990s (Fig. 22). The total heat content of the water column, which fell to a record low in 1991 increased sharply in 1996 reaching a level only matched during the warm 1950s and 1960s. The heat content decreased to slightly below the long-term mean in 1997 and 1998. In 1999 the heat content again rose. The 0 to 50 m depth-averaged summer salinity is also plotted in Fig. 22. The low salinity values of the early 1990s are comparable to values experienced during the Great Salinity Anomaly of the early 1970s (Dickson et al., 1988). In 1997, salinities rose to near-normal values, up from the very low salinities of 1995 and remained close to their long-term mean in 1998. The 1999 values again declined indicative of fresher conditions.

CIL

On the continental shelves off eastern Canada from Labrador to the Scotian Shelf, intense vertically mixing and convection during winter produce a near homogeneous cold upper layer that overlays a warmer deeper layer or occasionally may extend to the bottom in shallow areas. With spring heating, ice melt and increased river runoff, a warm low-saline surface layer develops. The strong stratification in this upper layer inhibits heat transfer downwards, and the waters below remain cold throughout the spring and summer. The latter are called the cold intermediate layer (CIL) waters.

Three standard hydrographic transects (Hamilton Bank, off Bonavista Bay and along 47^{o}N to Flemish Cap) have been occupied during the summer and autumn by the Northwest Atlantic Fisheries Centre in St. John's, Newfoundland in most years since 1950. The areal extent of the CIL in summer along each transect (as defined by waters <0^{o}C) is plotted in Fig. 23. The annual variability in the cross-sectional areas of the CIL are highly correlated between transects (Petrie et al., 1992). In 1999, the summertime CIL area along all three transects was below normal and declined relative to 1998 with the largest drop at Seal Island. On the Seal Island and Bonavista transects the area of CIL waters have been below normal for the past 5 years while on the Flemish Cap 1999 was the first year that it dropped below its long-term mean since the mid-1980s. In general, periods of warmer-than-normal core temperatures are correlated with smaller-than-normal CIL areas. The minimum temperature observed in the core of the CIL along the Seal Island transect during the summer of 1998 was about -1.33^{o}C compared to a normal of -1.57°C. Core temperatures along the Bonavista transect were -1.58^{o}C compared to a normal of -1.63^{o}C and along the Flemish Cap transect were at -1.45^{o}C, below the normal of about -1.51^{o}C. These minimum temperatures warmed compared to 1998 levels along all three transects.

Estimates of the volume of CIL water (<0^{o}C) over the 2J3KL area are available since 1980 (Fig. 24). A description of the analysis method can be found in Colbourne and Mertz (MS 1995). The long-term (1980-1994) mean volume of the CIL of just over 4 x 10^4 km^3 is roughly one-third the total volume of water on the shelf. The volume in autumn shows similar interannual trends to those of summer but its absolute value is about half. The CIL is eroded through the summer due to mixing with warmer waters both at the surface and near bottom. In terms of interannual variability, maximum CIL volumes tended to occur during the cold periods of the mid-1980s and early 1990s. In 1990, the summertime volume began to decrease and by 1995 was similar to that recorded in the early 1980s and again in the later 1980s. Since then the CIL volume has remained relatively low. In the autumn of 1999, the CIL volume in both summer and the autumn declined relative to 1998 and is at its lowest level since the records began.

Horizontal Temperature Distributions Near-Bottom in 2J3KL

Extensive groundfish surveys run out of the Northwest Atlantic Fisheries Centre in St. John's Newfoundland cover Divs. 3LNO in the spring and 2J, 3K and 3LNO in the autumn. All surveys show similar patterns with almost exclusively warmer-than-normal bottom temperatures in 1999 (Fig. 25-27). Temperature anomalies over most of the Grand Banks exceeded 1^oC with a suggestion that the temperature anomalies were increasing from the spring to the autumn. Only in the very nearshore and at the shelf edge were temperatures colder than the long-term mean. This pattern contrasts with the early 1990s when negative temperature anomalies dominated. Although bottom temperature anomalies were also positive in 1998, temperatures in 1999 were warmer and less of the bottom was covered by temperatures $<0^oC$ (Colbourne, MS 2000). Indeed, the average temperatures in each of the surveys conducted in the autumn were the warmest in the over 20-yr record and in the spring were near to warmest in the shallow regions (depths < 100m) in the spring. In addition, the area covered by bottom waters $<-0.5^oC$ tended to be lowest on record or near the lowest.

Hydrographic Conditions on Hamilton Bank

The time series of monthly mean temperature and salinity anomalies (relative to 1961-90 means) from 1950 to 1999 on Hamilton Bank at standard depths of 0, 50, 75 and 150 m are shown in Figs. 28 and 29, respectively. These anomalies were smoothed. This suppresses the high frequency variations and provides a representation of the long-term trends. Note that the monthly averages consist of a variable number of observations.

The smoothed time series are characterized by variations with amplitudes ranging from approximately $\pm 1^oC$ and with periods of a year or two to a decade or more. The cold periods of the early 1970s, the mid-1980s and to a lesser extent the early 1990s are present, however, the amplitude of these anomalies vary considerably with depth. Temperatures on Hamilton Bank have generally been warming since 1994, particularly in the deeper layers. There the waters were below normal from the early 1980s to 1994, similar to conditions further south at Station 27. During 1999, temperature anomalies gradually declined from the high in 1998 to near normal values by the end of the year. Subsurface temperatures were above their long-term means. 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. Salinity anomalies have generally been on the rise since the lows of the mid-1990s and were above normal during much of 1999 except at the surface. In spite of these saltier-than-normal salinities, at the end of the year there was a significant drop in the salinity anomaly at all subsurface depths.

Hydrographic Conditions on Flemish Cap

Three major cold periods are evident from the temperature anomalies over the top 100 m on Flemish Cap; most of the 1970s, the mid-1980s and the late 1980s to early 1990s (Fig. 30). The cold conditions beginning around 1971 continued until 1977 in the upper layers. From 1978 to 1984, temperature anomalies showed a high degree of variability in the upper water column with a tendency towards positive anomalies. By 1985, negative temperature anomalies had returned in the top 100 m of the water column. This cold period moderated briefly in 1987 but returned again by 1988 and continued into the early 1990s. Since 1995 upper layer temperatures have been warming in the top 100 m to above normal conditions. While temperatures at 20 and 100 m remained high throughout 1999, at the surface and 50 m temperature anomalies declined by the end of the year to near normal.

Fresher-than-normal salinities persisted on Flemish Cap from 1971 to 1976 and from 1983 to 1986 in the upper 100 m of the water column with peak amplitudes reaching 0.6 psu below normal (Fig. 31). Salinity during the early 1990s ranged from slightly above normal at the surface to below normal at 50 and 100 m depth and about normal at 200 m depth. During the past few years, salinities at Flemish Cap have been increasing and are now saltier-than-normal in the top 100 m. In general, the temperature and salinity trends are similar to those at Station 27 and elsewhere on the continental shelf over similar depth ranges.

Hydrographic Conditions on St. Pierre Bank

Monthly temperature anomalies from 1950 to 1998 on St. Pierre Bank bounded by the 100 m isobath were computed at standard depths of 0, 20, 50 and 75 m (Fig. 32). These temperature time series are characterized by large variations with amplitudes ranging from ±3°C. The smoothed time series reveal amplitudes generally less than ±1°C with periods from a couple of years to decadal. The cold periods of the mid-1970s and the mid-1980s in the upper water column are coincident with severe meteorological and ice conditions in the Northwest Atlantic and colder and fresher oceanographic anomalies over most of the Newfoundland continental shelves. During the cold period beginning in 1984-1985, temperatures decreased by up to 2°C in the upper water column and by 1°C in the lower water column. These below normal conditions continued until 1994 in the upper water column. Since 1994 the temperatures have been warmer than normal over the top 20 m but remained below average at 50 and 75 m depth until 1998-1999. By the end of 1999 temperatures throughout the top 75 m were above normal.

The 1999 bottom temperature anomaly map for the spring (April) within 3Ps and 3Pn shows most of the bottom covered by above normal temperatures (Fig. 33). This represents the warmest conditions in approximately 20 years and indicates that the warming observed over the last few years continued into 1999. Maximum temperature anomalies exceeded 1°C.

Gulf of St. Lawrence

Cabot Strait Deep Temperatures

Bugden (1991) investigated the long-term temperature variability in the deep waters of the Laurentian Channel in the Gulf of St. Lawrence from data collected between the late 1940s to 1988. The variability in the average temperatures within the 200-300 m layer in Cabot Strait was dominated by low-frequency (decadal) fluctuations with no discernible seasonal cycle. A phase lag was observed along the major axis of the channel such that events propagated from the mouth towards the St. Lawrence Estuary on time scales of several years. The updated time series show that temperatures declined steadily between 1988 and 1991 to their lowest value since the late 1960s (near 4.5°C and an anomaly exceeding -0.9°C; Fig. 34). Then temperatures rose dramatically reaching 6°C (anomaly of 0.6°C) in 1993. By 1994 temperatures had begun to decline although anomalies remained positive. Temperatures continued to fall in 1995 and 1996 towards near normal. In 1999, temperatures rose significantly reaching near record highs during the middle of the year but declined thereafter. Temperatures at the end of 1999 were still over 6°C, however, and up over those observed in 1998.

CIL

The cold intermediate layer (CIL) in the Gulf of St. Lawrence has a maximum thickness in the northeast and a minimum (where depths exceed 100 m) in Cabot Strait and the St. Lawrence Estuary. During 1999, the CIL thickness (defined by waters <0°C) decreased by over 50% relative to 1998. Gilbert and Pettigrew (1997), in a study of the CIL layer, produced a Gulf-wide index of core temperatures for mid-July based upon available observed data and the mean measured warming rate. Their index shows temperature anomalies having an approximate 5-8 year periodicity prior to 1985 (Fig. 35). Since 1985, temperatures in the CIL have remained below normal with minima in the late 1980s and early 1990s. Since 1994 temperatures have been warming (with the exception of 1998) and 1999 being the warmest since the mid-1980s. The mid-summer core CIL temperature in 1999 was -0.15°C (representing an anomaly of -0.17°C), and was warmer than 1998 by 0.56°C. Gilbert and Pettigrew (1997) found high correlations between the variability in the CIL core temperatures and air temperatures along the coast of western Newfoundland, suggesting the possible importance of atmospheric forcing in determining the temperature and extent of the CIL waters in the Gulf. These air temperatures were above normal throughout 1999 and may explain the accompanying warmer temperatures of the CIL waters.

Bottom Temperatures on the Magdalen Shallows

Canada has carried out annual groundfish surveys of the Magdalen Shallows in the southern Gulf of St. Lawrence during September since 1971. Bottom temperatures during the 1999 survey ranged between <0°C to over 10°C (Fig. 36). The majority of the bottom is covered by temperatures of <3°C with the coldest waters (<0°C) limited to a small region to the north of Prince Edward Island (PEI). Most of the Shallows (50-80 m) are covered by temperatures <1°C. From there, bottom temperatures tend to increase towards the shallower, near shore regions and towards the deeper Laurentian Channel. This is because in the Gulf of St. Lawrence during summer, cold temperatures are found at intermediate depths (50-150 m), sandwiched between warm solar-heated upper layer waters and the relatively warm, salty deep waters in the Laurentian Channel which originate from the slope water region off the continental shelf. As in Newfoundland, these cold waters are known as the cold intermediate layer (CIL). In winter, the CIL merges with the upper layer as the latter cools. The origin of the waters in the CIL is thought to be from atmospheric cooling of the water within the Gulf of St. Lawrence in winter as well as by advection of cold Labrador Shelf water through the Strait of Belle Isle. In 1999, the warmest near-bottom temperatures and anomalies in the southern Gulf were in its shallowest regions, in particular in Northumberland Strait, St. Georges Bay and Chaleur Bay. Temperature anomalies on the western half of the Shallows were primarily near to or below normal except in Chaleur Bay where temperatures were above normal. The coldest waters were located between western Prince Edward Island and the Gaspe. On the eastern half of the Shallows, temperatures were generally above normal except around the Magdalen Islands and a small area off eastern Prince Edward Island. The warmest anomalies (above 2°C) were located in Northumberland Strait, St. Georges Bay and along southwestern Cape Breton Island. Relative to 1998, bottom temperatures over most of the central region increased slightly. This differs from the cooling observed from 1997 to 1998 but reverts to the warming trend observed over the previous several years.

Swain (MS 1993) developed an index of near bottom temperature defined as the area of the Magdalen Shallows covered by waters <0°C and <1°C. These two indices show strong similarity (Fig. 37). In 1999, these areal indices declined significantly. Waters with temperatures <0°C almost disappeared from the Magdalen Shallows. The area covered by waters <1°C was the lowest in the past 11 years and dropped below the long-term mean for the first time since 1988.

Bottom Temperatures in the Northern Gulf

A groundfish survey is also conducted in the northern Gulf of St. Lawrence in August by the Institute Maurice Lamontagne. Bottom temperatures follow closely the topography (Fig. 38). In the Laurentian Channel and its offshoots to the northeast and around Anticosti Island are covered by temperatures of 4° of over 5°C. In the shallower depths along the Quebec north shore and off western Newfoundland, temperatures generally range from 0° to 4°C, although temperatures in the very shallow and protected coastal regions of Newfoundland reached upwards of 8°C in 1999. The temperature anomalies relative to the long-term (1961-90) means show generally near normal conditions over most of the region. The cool waters to the northeast of Anticosti Island along the Quebec north shore may be due to onshore movement of water through wind-induced upwelling. The western coast of Newfoundland experienced warmer-than-normal bottom temperatures.

Summer Temperature and Salinity Fields

The hydrographic data collected during groundfish surveys on the Magdalen Shallows and the northern Gulf were combined to estimate mean temperatures over the entire Gulf within specified layers (30-100, 100-200 and 200-300 m) (Fig. 39). In the 30-100 m layer, 1999 temperatures were generally colder-than-normal but increased significantly from 1998. This layer temperature mirrors closely the variability in the CIL core temperature (Fig. 35). Temperatures in the 100-200 m layer also rose in 1999, exceeding the long-term mean for the first time since the mid-1980s. In the deep layer (200-300 m), temperatures were near normal continuing the trend that has persisted throughout the 1990s.

Scotian Shelf and Gulf of Maine

Background

Last year's overview (Drinkwater et al., 2000a) reported the southward extension of Labrador Slope water along the edge of the Scotian Shelf through to the Middle Atlantic Bight from the autumn of 1997 to the spring of 1998. Slope water occupies the region between the shelf water and the Gulf Stream. Two types of slope water were identified by Gatien (1976), one being Warm Slope Water with temperatures typically 8°-12°C and the other being Labrador Slope Water with temperatures 4°-8°C. During most of the past thirty years, the former has occupied the region seaward of the shelves north to the Laurentian Channel. The source of this water is from the south and tends to be of slightly higher salinity than Labrador Slope Water. The latter, as the name suggests, is derived from the deep (100-300 m) Labrador Current. It dominated along the shelf edge of the Scotian Shelf through to at least Georges Bank through most of the 1960s and is believed to appear in years of higher-than-normal transports of the Labrador Current (Petrie and Drinkwater, 1993). This, in turn, is believed to be related to the strength of the large-scale atmospheric circulation patterns over the North Atlantic as reflected in the North Atlantic Oscillation (NAO) index.

The colder, lower salinity slope water that appeared along the continental slope in the autumn of 1997 began to penetrate through the channels and gullies of the southwestern Scotian Shelf in later 1997 and by February of 1998 had flushed all of Emerald Basin. It eventually replaced most of the lower-layer waters on the southwestern Shelf as evidenced by the data from the 1998 groundfish survey, which recorded the lowest temperatures in the 29 year time series for NAFO Subarea 4X. The effects were not restricted to the Scotian Shelf. In January of 1998, the cold Labrador Slope water had reached the entrance to the Gulf of Maine in the Northeast Channel. By spring it had replaced the deep waters of Georges and Crowell basins. Fishermen reported cold waters on Georges Bank at this time and felt that they were affecting the catchability of lobster. The Labrador Slope water did not penetrate further shoreward in the Gulf of Maine until the summer of 1998. Unlike in the basins where the bottom waters were completed replaced, in the inner reaches of the Gulf, the Labrador Slope water appeared to mix with the resident waters. This event has been described in detail by Drinkwater et al. (2000b).

Coastal Sea Surface Temperatures

Monthly averages of sea surface temperature (SST) for 1999 were available at Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia (see Fig. 40 for locations). The Halifax averages are based on a continuous recording thermistor submerged just below low water on the wharf in Halifax Harbour by the Maritime Museum of the Atlantic. They replace the twice a day measurements taken during weekdays from the DFO Halifax Laboratory wharf, which ended in August 1998. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each site for 1998 and 1999 are shown in Fig. 41.

The dominant feature in 1999 at Boothbay Harbor and St. Andrews was the above normal temperatures throughout most of the year (12 months and 11 months, respectively). The 1999 anomalies equalled or exceeded one standard deviation (based upon the years 1961-90) in 7 months at Boothbay Harbor (February, April-September) and in 9 months at St. Andrews (April to December). The maximum monthly anomalies were in June, 3.3°C (over 4 standard deviations from the long-term mean) at Boothbay and 2.2°C at St. Andrews (over 2 standard deviations). At Halifax sea surface temperature anomalies showed high variability in 1999 with 6 of the available 12 months being warmer-than-normal, one normal (October) and 5 colder-than-normal (Fig. 41).

Time series of annual anomalies show that the surface temperature at both Boothbay Harbor and St. Andrews have been above their long-term means in recent years and generally on the increase since a minimum in the late 1980s (Fig. 41). That minimum was as low as one in the mid-1960s at St. Andrews but at Boothbay Harbor the minimum was only slightly below normal. Consistent with the recent trends, the 1999 annual mean temperature at these two sites was above normal (mean of 8.2°C and 1.1°C above normal at St. Andrews and 9.9°C and 1.4°C above normal at Boothbay). At both sites the temperature rose relative to 1998 and exceeded the recent peak observed in 1995 (Fig. 41). At St. Andrews, it was the 5th warmest year in the 79-year record while at Boothbay Harbor it was the 6th warmest year in the 94-year record. In contrast to these two stations, Halifax had an annual mean sea surface temperature that was normal.

Prince 5

Since 1924, monthly temperature and salinity measurements have been taken near the entrance to the Bay of Fundy, at Prince 5, a station off St. Andrews, New Brunswick (Fig. 40). It is the longest continuously operating hydrographic monitoring site in eastern Canada. Up to and including 1997, there was only one observation per month but since 1998 multiple occupations have been taken whenever possible. In 1999 there were 3 measurements during December, 2 in January and April-October and 1 in February, March and November. For months with multiple measurements, an arithmetic average was used to estimate the monthly mean temperature and salinity. A single, or even three observations per month, especially in the surface layers in the spring or summer, may not necessarily produce results that are representative of the true "average" conditions for the month and therefore the interpretation of the anomalies must be viewed with some caution. No significance should be placed on any individual monthly anomaly but persistent anomaly features are likely to be real. The general vertical similarity in temperatures over the 90 m water column is due to the strong tidal mixing within the Bay of Fundy.

In 1999, monthly mean temperatures ranged from a minimum of around 2.5°C throughout most of the water column in March to a maximum of over 13°C near the surface in September (Fig. 42,43). Following below normal temperatures in January, the monthly temperature anomalies for the remainder of the year were positive. The highest positive anomalies (>2°C) occurred in December below 10 m depth. In most months the anomalies exceeded or were near +1°C. The annual mean temperatures exhibit high year-to-year variability (Fig. 43). In 1999, they were above normal throughout the water column with the anomalies being approximately 1.2°C except at the surface where the anomaly was 0.9°C. This represents a large increase relative to 1998 at both the surface and near bottom. The surface values are the warmest since 1994 and at the bottom they are warmest in over 20 years (since 1976). With the exception of the negative temperature anomalies in the early 1990s, temperatures at Prince 5 have generally been warmer than the long-term mean since the mid-1970s at the surface and since the late 1960s near bottom. The maximum annual temperatures at this site occurred in the early 1950s and the minimum in the mid-1960s.

Salinities at Prince 5 during 1999 were fresher-than-normal during the first 4-5 months of the year and generally saltier-than-normal for the remainder of the year (Fig. 42, 44). The lowest salinities (<31 psu) occurred in the upper half of the water column during April and the highest salinities (>33 psu) appeared near bottom in the autumn. The arrival of higher salinity waters in autumn is typical. The largest negative anomalies (between 0.25 and 0.5 psu) were observed throughout most of the water column in January and February and in the upper half of the water column in April. Time series show that the annual salinity anomalies in 1999 rose by approximately 0.4-0.5 relative to 1998 values at both the surface and 90 m (Fig. 44). There have been large fluctuations in salinity but the longer-term trends show that salinities generally freshened from the late 1970s to at least the late-1990s with the lowest salinities on record at Prince 5 occurring in 1996. The salinity changes parallel events in the deep waters of Jordan and Georges Basin and appear to be related to advection from areas further to the north (P. Smith, BIO, personal communication). Whether the increase in salinity in 1999 is part of a high frequency fluctuation or if the high salinities will remain is unclear.

Gulf of Maine Temperature Transect

The Northeast Fisheries Science Centre in Narragansett, Rhode Island, has collected expendable bathythermograph (XBT) data approximately monthly from ships-of-opportunity since the late 1970s. The XBTs are dropped along a transect in the Gulf of Maine from Massachusetts Bay to the western Scotian Shelf as part of their continuous plankton recorder program. We grouped the available data into 10 equally spaced boxes along the transect, and then averaged by month any data within these boxes at standard depths. Data for 1999 were available for 9 months of the year.

Data from February and August 1999 are shown together with the site locations (centre of the boxes) in Fig. 45. The upper layer temperatures in January increase from the Scotian Shelf towards the western Gulf of Maine but cool again inshore. In August there is strong thermal stratification although the increase in surface temperature from east to west across the Gulf with cooling inshore to the west was still evident. Bottom layer temperatures ranged between 5° and 10°C. The cool subsurface waters in August is most likely the out flowing “cool pool” waters formed from in situ cooling in winter. Temperatures in 1999 were generally warmer than their long-term means. The highest anomalies were in the surface waters in August (+4 °C) with high subsurface values at stations 7 and 8 (upwards of 3°C above normal). The surface anomalies are consistent with the high air temperatures while the subsurface anomalies are most likely due to an influx of warmer-than-usual slope water. The pattern of warm subsurface temperature anomalies in the east persisted throughout the other months of 1999 where data were available.

Halifax Line Station 2

As part of Canada's new Atlantic monitoring program (called the Zonal Monitoring Program or ZMP), a standard monitoring site was established in 1998 on the Scotian Shelf off Halifax (at Station 2 on the Halifax Line; H2 in Fig. 40). Hydrographic, nutrient and biological measurements are taken on a monthly basis.

The monthly mean temperature, salinity and density (sigma-t) for 1961-90 are shown in Fig. 46. The site is vertically mixed to 50 to 100 m during most of the winter. Minimum temperatures (<0°C) occur in the upper 40 m or so in March. The waters begin to stratify through the spring and reach maximum stratification in September. Surface layer temperatures warm to a maximum of around 16°C in September. Through the autumn, surface temperatures decline due to atmospheric cooling but also the surface layer heat is distributed down into the water column, probably by increased wind mixing. Surface layer salinities decline in the late spring reaching a minimum in late summer but remain low through into the winter. The later is related to the influence of the outflow of low salinity waters from the Gulf of St. Lawrence. In the waters below 100 m, there is evidence of higher density waters moving slowly upwards and reaching their shallowest levels in the late summer to early autumn. Accompanying this, lower layer temperatures and salinities both increase.

At the beginning of 1999, temperatures and salinities were warmer and saltier-than-normal at H2 (Fig. 47). In March there was a rapid deepening of the isotherms such that 2°C waters extended to about 125 m where previously it was shallower than 50 m. This was accompanied by deepening of the isohalines and the isopycnals as well. These relatively cool, fresh waters remained until early June when below 50 m they were replaced by warmer, saltier waters and returned to above normal conditions. No waters with temperatures less than 2°C were observed after early June. Through the summer, the temperature and salinities of the deep waters increased. Cooling of these waters began around September and continued throughout the remainder of the year. With the exception of the 50-75 m depth range, temperature and salinity anomalies were mostly positive. In the surface layers, stratification began around May increasing in intensity through to August. At this time, surface layer temperatures exceeded 18°C with salinities <31. Similar low salinities were first observed in late spring and continued into the summer through to the late autumn. During autumn, the surface layer heat and low salinities were gradually mixed down to 50 m and deeper. At the same time surface temperatures decreased and salinities increased. From mid-spring into the early autumn, the temperatures and salinities in the surface layer were generally warmer and fresher-than-normal. These conditions extended to depths of 50 m in the early autumn and occupied the top 50 m of H2 for most of the remainder of the year.

Deep Emerald Basin Temperatures

Emerald Basin is located in the central Scotian Shelf. As discussed in the Background Section above, the waters in the Basin were very cold in 1998. Details of the temperature changes from 1997 to late-1999 show the large decline in the early months of 1998 at all depths from 100 m to 250 m, a minimum in the spring of 1998, a slow recovery and a return to the warm temperatures prior to the event between early to mid-1999 (Fig. 48). The largest temperature changes were at 100 to 150 m, which corresponds to the sill depth separating Emerald Basin from the offshore slope waters. This is consistent with the offshore slope waters being the source of the large temperature deviations in the Basin. In 1999 the cold Labrador Slope Water that had occupied the edge of the shelf retracted northward to be replaced by the Warm Slope Water. The latter then flowed onto the shelf and gradually flushed Emerald Basin. The time series of temperature anomalies at 250 m, which is reasonably representative of the lower layers from 100 m and deeper, also shows this cooling and subsequent warming (Fig. 49). Dominant in the time series are the cool period of the 1960s and the relatively warm periods of the 1970s to the 1990s.

Other Scotian Shelf and Gulf of Maine Temperatures

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities from available bottle data for irregularly shaped areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins (Fig. 50). A more recent atlas containing all available hydrographic data has been published by Petrie et al. (1996). In this report we produce monthly mean conditions for 1999 at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compared them to the long-term averages (1961-90). Unfortunately, data are not available for each month at each area and in some areas the monthly means are based upon only one profile. As a result the series are characterized by short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1-2°C. The spikes represent noise and most often show little similarity between regions. Thus care again must be taken in interpreting these data and little weight given to any individual mean. The long period trends often show similarity over several areas, however. To better show such trends we have estimated the annual mean anomaly based on all available means within the year and then calculated the 5-year running mean of the annual values. This is similar to our treatment of the Emerald Basin data.

Drinkwater and Pettipas (1994) examined long-term temperature time series for most of the areas on the Scotian Shelf and in the Gulf of Maine. They showed that the temperatures in the upper 30 m tended to vary greatly from month to month, due to atmospheric heating and cooling. Also, at intermediate depths of 50 m to approximately 150 m, temperatures had declined steadily from approximately the mid-1980s into the 1990s. On Lurcher Shoals off Yarmouth, on the offshore banks and in the northeastern Scotian Shelf the temperature minimum in this period approached or matched the minimum observed during the very cold period of the 1960s. This cold water was traced through the Gulf of Maine from southern Nova Scotia, along the coast of Maine and into the western Gulf. Cooling occurred at approximately the same time at Station 27 off St. John's, Newfoundland, off southern Newfoundland on St. Pierre Bank (Colbourne 1995) and in the cold intermediate layer (CIL) waters in the Gulf of St. Lawrence (Gilbert and Pettigrew 1997). Data since 1994 indicate warming of the intermediate layers in the Gulf of Maine but a continuation of colder-than-normal water on most of the Scotian Shelf (Drinkwater et al. 2000a).

The warming referred to above has continued into 1999 and on the northeastern Scotian Shelf temperature anomalies have risen above normal for the first time in approximately 15 year. Below, we describe temperature conditions in several representative areas of the Scotian Shelf.

On Sydney Bight (area 1 in Fig. 50) off eastern Cape Breton, mean profiles from 3 months show near to or above normal temperatures throughout most of the water column (Fig. 51). In July surface temperatures were over 3°C warmer-than-usual. The time series of the 100 m temperature anomalies show high temperature anomalies in the 1950s that fell to a minimum around 1960 and then rose steadily through the 1960s. Temperatures remained relatively high during the 1970s. By the 1980s temperatures began to decline and by the mid-1980s dropped to below normal with a minimum anomaly around -1°C in the early 1990s. Temperatures in recent years have generally remained below normal but increased slowly with several monthly anomalies of above normal being observed since 1995. The 1999 anomalies at 100 m were on average above normal although two of the three available months show slightly below normal temperatures.

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 50) are available for 8 months during 1999. They show primarily warmer-than-normal temperatures in the upper 100 m (Fig. 52). The only exception is cold conditions in the top 30 m in October. Below 100 m the temperatures tend to be near or slightly below normal.

Note that in July at 200 m there is a slight positive temperature anomaly. The time series of the 100 m temperature anomalies show consistent positive values in 1999, which contrast with the predominantly negative anomalies over the last 15 years (Fig. 52). As at Emerald Basin, temperatures were relatively high in the 1950s. Temperatures then declined and at Misaine Bank reached a minimum around 1960, several years earlier than areas further to the southwest. Temperatures were near normal from the late-1960s to the mid-1970s before rising to a maximum in the late 1970s. By the late-1980s, temperatures fell to below normal and reached a record sustained minimum of around -1°C in the first half of the 1990s. Since then, as on Sydney Bight, temperatures have been slowly but steadily increasing.

Lurcher Shoals is located off Yarmouth, Nova Scotia (area 24 in Fig. 50). This area exhibited warmer-than-normal temperatures in 1999 in the 7 months of 1999 when data were available (Fig. 53). This contrasts with the very cold temperatures observed during 1998. Anomalies in July, August, September and November exceeded +1°C. The time series at 50 m clear shows high temperature anomalies in 1999 relative to the cold conditions over most of the past 15 years. Temperatures over Lurcher Shoals tended to be high in the late 1940s and early 1950s, declined to a mid-1960s minimum, rose rapidly into the 1970s and remained above normal into the mid-1980s. As on the northeastern Scotian Shelf, temperatures declined to below normal by the mid-1980s and reached a long-term minimum in the early 1990s. Although there had been some positive monthly temperature anomalies, annual mean temperatures and most monthly means remain below normal through the 1990s until 1999.

Georges Basin is located near the southeastern entrance to the Gulf of Maine (area 26 in Fig. 50) and is connected to the offshore slope water through the Northeast Channel. The time series of temperature in the deep regions (200 m) of Georges Basin (Fig. 54) shows a striking similarity to that of Emerald Basin including the very cold conditions in 1998 and warm in 1999 (Fig. 49). Also, the low values in the mid-1960s, rising sharply to a peak in the early 1970s and varying slightly but generally remaining above the long-term (1961-90) mean until 1998 are similar in the two basins. This is not surprising given that the source of the waters for both is primarily the offshore slope waters (Petrie and Drinkwater, 1993).

Temperature conditions were also examined on eastern Georges Bank (area 28 in Fig. 50). The Georges Bank 50 m temperatures exhibit higher variability than many of the other sites, in large part because of its shallowness. In spite of this, the long-term trend as revealed by the 5-year running mean at 50 m, shows many similarities to those in Georges Basin and in areas on the Scotian Shelf (Fig. 55). These again include the low temperatures in the 1960s, the higher-than-average conditions in the 1970s into the 1990s. In 1999, temperatures were generally above normal while in 1998 they were below normal.

Temperatures during the Summer Groundfish Surveys

The most extensive temperature coverage over the entire Scotian Shelf is obtained during the annual DFO groundfish survey, usually undertaken in July. A total of 200 CTD stations were taken during the 1999 survey and an additional 186 temperature stations were obtained as part of a fishing fleet survey. The latter fills in gaps in the DFO survey for the Bay of Fundy, off southwest Nova Scotia and in the southwestern Scotian Shelf. Temperatures from both surveys were combined and interpolated onto a 0.2 by 0.2 degree latitude-longitude grid using an objective analysis procedure known as optimal estimation. The interpolation method uses the 15 "nearest neighbours" and a horizontal length scale of 30 km and vertical length scale of 15 m in the upper 30 m and 25 m below that. Data near the interpolation grid point are weighted proportionately more than those further away. Temperatures were optimally estimated onto the grid for depths of 0, 50, 100 m and near bottom (Fig. 56). Maximum depths for the interpolated temperature field were limited to 1000 m off the shelf. The 1999 temperature anomalies were also computed relative to the July 1961-90 means (Fig. 57).

The pattern of near-surface temperatures in July 1999 was similar to past years. They ranged from 19°C off the northeastern coast of Nova Scotia to 10°C off the southwestern shore (Fig. 56a). The latter may be related to wind-induced upwelling by the predominantly southwesterly winds in summer. The cooler temperatures in the Gulf of Maine are due to the intense bottom-generated vertical mixing caused by the high tidal currents. The 1999 surface temperatures were generally much warmer than the long-term averages with a maximum anomaly of over 6°C off southern Cape Breton and >3°C over the entire northeastern Scotian Shelf (Fig. 57a). This is consistent with the satellite imagery that has shown high sea surface temperature anomalies throughout the Scotian Shelf during much of 1999 (Petrie and Mason, 2000). These warm conditions contrast with the colder-than-normal temperatures off southwestern Nova Scotia, which again are believed to be due to wind-induced upwelling. As such, it may have been a short-lived phenomenon and not represented of the average surface conditions for the month. Relative to 1998, the surface temperatures generally increased. The maximum increase was off southern Cape Breton by upwards of 4ºC. The major exception is off southwestern Nova Scotia, in the area of suspected upwelling. The very warm surface waters over most of the Scotian Shelf in 1999 are most likely related to atmospheric heating. This is consistent with the above normal-air temperatures (Drinkwater et al., 2000a). Part of the excess amount of heat in the atmosphere is expected to be transferred to the ocean.

The temperatures at 50 m ranged from <2°C to over 10°C with the coldest waters in the northeast and the warmest waters in the deep Gulf of Maine (Fig. 56a). There appears to be penetration of warmer waters (>6°C) towards Emerald Basin from offshore. Temperature anomalies at 50 m (Fig. 57a) were predominantly positive in the northeastern region of the Shelf (mostly <1°C) and from Browns Bank to the Bay of Fundy including the eastern Gulf of Maine (1°-3°C). To the east of Browns the survey encountered slightly colder-than-normal temperatures (mostly between 0 and -1°C).

The temperature pattern at 100 m resembles that at 50 m although the actual temperatures were higher in the former (Fig. 56b). The temperatures at 100 m ranged from <3°C to over 10°C offshore between 63°-64°W and in the central Gulf of Maine. Most of the Scotian Shelf had anomalies not significantly different from normal being between -1°C and 1°C (Fig. 57b). As observed at 50 m the central Gulf of Maine appeared very warm being upwards of 3°C warmer-than-normal.

The near-bottom temperatures over the Scotian Shelf had a similar range to that at 100 m, from 3°C in the northeast to over 10°C in the Gulf of Maine/Bay of Fundy and in the Scotian Gulf seaward of Emerald Basin (Fig. 56b). The pattern of colder temperatures in the northeastern Shelf and warmest in the Gulf of Maine with relatively warm waters in the deep basins of the central Shelf is typical. The former is derived largely from the Gulf of St. Lawrence while in the deep basins of the Scotian Shelf the waters mainly originate from the offshore slope waters. The warm waters around Sable Island are in large part due to the shallowness, with the bottom depths being near to the surface mixed layer. Elsewhere on the shelf the bottom depths lay below the mixed surface layer. Relative to the long-term mean, the near bottom temperatures are predominantly near to or warmer-than-normal (Fig. 57b). The largest deviation from the mean (warmer by over 2°C) is off southwestern Nova Scotia and in the Browns Bank region. Another region of above normal temperatures is in the Scotian Gulf seaward of Emerald Basin. These temperatures represent much warmer conditions than the previous year, upwards of 4°C in the Browns Bank region and 2°-3°C over most of the southwestern Scotian Shelf. This is related to the replacement of cold Labrador Slope Water by the Warm Slope Water. In the northwest, near-bottom temperatures also warmed producing above normal temperatures in the region for the first time in almost 15 years. The mechanism here is thought to be a combination of atmospheric forcing and advection from the Gulf of St. Lawrence or off southern Newfoundland.

Standard Sections

As part of the Canada's new Zonal Monitoring Program, seasonal sampling along the historical standard sections was reinstituted in 1998. On the Scotian Shelf this included the Cape Sable Line, the Halifax Line, the Louisbourg Line and the Cabot Strait Line (Fig. 40). While four occupations per section has been the goal, this has not been achieved for all sections due primarily to budgetary constraints. Similar to the standard stations, the data collected usually include CTDs, nutrient and chemical sampling and plankton. Only the hydrographic data are discussed in the present paper. Anomalies relative to the 1961-90 means were only estimated for the Halifax Line. At the other sections, the data were considered of insufficient quantity to determine reliable means for this time period.

Cape Sable   Extending south from Cape Sable off the southwestern tip of Nova Scotia across Browns Bank to the entrance of the Northwest Channel into the Gulf of Maine, this section was occupied three times in 1998 (April, October and November) and twice in 1999 (April and November). In 1998, the main feature was the presence of the cold Labrador Slope Water (temperatures 4°-8°C) offshore (Fig. 58). By April 1999 the offshore was occupied by Warm Slope Water (temperatures >8°C), which was still there in October of 1999 (Fig. 59). Comparison between the April 1998 and 1999 show only minor changes on the inner shelf regions but over the offshore edge of Browns, the presence of the warm, salty offshore Slope Waters is seen in 1999. In contrast, there are large differences in the shelf water properties in October. In 1998, below 50 m there are few temperatures >6°C whereas in 1999 there are no waters colder than 6°C. Salinities too differed, being mostly >32 in 1998 and mostly >33 in 1999. Density on the other hand changed only slightly as the temperature and salinity changes compensated in terms of their effect on density.

Halifax Line   The standard Halifax Line was occupied 5 times in 1998 and in 1999 (April, June, July, October, and November in both years). Contours of temperature, salinity and sigma-t across the section and their anomalies for June 1998 and 1999 are shown in Fig. 60 and 61, respectively. In 1998, we again see the cold Labrador Slope Water characteristics off the Shelf and in the deeper reaches of Emerald Basin, which lead to the negative anomalies (cold and fresh) below 100 m. Temperature anomalies were upwards of 2°-3°C below normal and salinities >0.5 fresher-than-normal. This contrasts with 1999, when temperatures were much warmer and the temperature anomalies in the deep waters (>100 m) were all positive. Salinity anomalies offshore also had switched from negative to positive from 1998 to 1999 although in the inner Emerald Basin the salinities remained negative. Sigma-t anomalies in both years were predominantly negative indicating lighter water than normal. From the other occupations of the Halifax Line, the gradual warming of the Basin through 1998 as seen in Fig. 47 can be detected. The largest change offshore occurs between November 1998 and April 1999 when the Labrador Slope Water is replaced by Warm Slope Water. Temperature anomalies reach over 6°C and salinities over 2 in the outer reaches of the Halifax Line in the upper 50 m in April 1999.

Louisbourg Line   This line runs southeast off Louisbourg, across Banquereau Bank and out into the Slope Water region. It was occupied twice in 1998 (April and October) and four times in 1999 (March, April, July and October). The temperature, salinity and sigma-t contours for July (Fig. 62) show strong surface stratification with high temperatures (>18°C) and low salinities (< 31). Below approximately 50 m, the waters are between 2-4°C and salinities mainly between 32-33. The surface temperatures are high but consistent with the satellite imagery, which show anomalies of about 1°C above normal.

Cabot Strait Line   This line extends from northern Cape Breton to southwestern Newfoundland and was occupied twice in 1998 (April and October) and three times in 1999 (April, August and October). The August transect of 1999 is representative (Fig. 63). The coldest waters generally are found between about 50 m and 150 m on the Cape Breton side. These are the cold intermediate (CIL) waters exiting the Gulf of St. Lawrence. The lowest salinities are also usually on the Cape Breton side near the surface. The >6°C waters in the 200 to 300 m layer are consistent with the Cabot Strait temperature index (Fig. 34). Also of note are the very warm waters in the near surface layer, with temperatures exceeding 20°C.

Density Stratification

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. The extent of the stratification can affect the extent of vertical mixing, the vertical structure of the wind forcing, the timing of the spring bloom, vertical nutrient fluxes and plankton speciation to mention just a few. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper, lower layers. Last year we examined the variability in stratification for the first time by calculating the density (sigma-t) difference between 0 and 50 m. The density difference was based on a monthly mean density profile calculated for each area in Fig. 49. The long-term monthly mean density gradients for the years 1961-90 were estimated and these then subtracted from the monthly values to obtain monthly anomalies. Annual anomalies were estimated by averaging all available monthly means within a calendar year. A 5-yr running mean of the annual anomalies was then calculated. The monthly and annual means show high variability but the 5-yr running means show some distinctive trends. The density anomalies are presented in g/ml/m. A value of 0.1 represents a difference of 0.5 a sigma-t unit over the 50 m. As reported previously (Drinkwater et al., 2000a), the dominant feature is the higher stratification during recent years throughout the Scotian Shelf (Fig. 64a,b). The 5-year running mean began to increase steadily around 1990 and the most recent values are at or near the highest values in the approximate 50-year records in most areas. The 1999 values confirm a continuation of high stratification. There is surprising consistency from area to area, through most of the Scotian Shelf. This higher-than-average stratification does not extend into the Gulf of Maine region and it was absence or weak in the Laurentian Channel and Sydney Bight areas. One expects the anomalies in density stratification in the Gulf of Maine to be lower than on the Scotian Shelf due to the more intense tidal mixing in the former. Examination of the temperature and salinity characteristics reveal that the primary cause of the increased stratification was due to changes in surface salinity, although in 1999 the warm surface layer also contributed.

Frontal Analysis

Shelf/Slope Front

The waters on the Scotian Shelf and in the Gulf of Maine have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters offshore. The relatively narrow boundary between the shelf and slope waters is regularly detected in satellite thermal imagery. Positions of this front and of the northern boundary of the Gulf Stream between 50°W and 75°W for the years 1973 to 1992 were assembled through digitization of satellite derived SST charts (Drinkwater et al., 1994). From January 1973 until May 1978, the charts covered the region north to Georges Bank, but in June 1978 the areal coverage was extended to include east to 55°W and eventually 50°W. Monthly mean positions of the shelf/slope front in degrees latitude at each degree of longitude were estimated. NOAA updated this data set until the termination of the satellite data product in October 1995. A commercial company has continued the analysis but did not begin until April 1996. Even then, the initial charts did not contain data east of 60°W. Data for 1999 have been digitized, estimates of monthly means positions determined and anomalies relative to the 20-year period, 1978 to 1997, were calculated.

The overall mean position of the Shelf/Slope front together with the 1999 annual mean position is shown in Fig. 65. The average position is close to the 200 m isobath along the Middle Atlantic Bight separates slightly from the shelf edge off Georges Bank and then runs between 100-300 km from the shelf edge off the Scotian Shelf and the southern Grand Bank. It is generally furthest offshore in winter and onshore in late summer and early autumn. During 1999, the shelf/slope front was shoreward of its long-term mean position from 74°W to 60°W and east of 60°W it was seaward of the mean. The largest deviations from the mean position occurred near Georges Bank and the entrance to the Northeast Channel around 65°W. The time series of the annual mean position (averaged over 55°W-75°W) shows the front was at a maximum seaward location in 1985 and again in 1993. Since 1993, the front moved steadily seaward approximately 40 km, reaching its most southerly position in 1997. During the 1998 and 1999, the frontal position has been moving northward again with the largest change occurring in 1999.

Gulf Stream

The position of the northern boundary or "wall" of the Gulf Stream was also determined from satellite imagery by Drinkwater et al. (1994) up to 1992 and has been updated in a manner similar to that for the shelf/slope front. Thus, the time series consists of the monthly position at each degree of longitude from 55°W to 75°W. The average position of the north wall of the Stream and the 1999 annual mean is shown in Fig. 66. The Stream leaves the shelf break near Cape Hatteras (75°W) running towards the northeast. East of approximately 62°W the average position lies approximately east-west. During 1999, the average position of the Stream was near the long-term mean position at most degrees of longitude. The stream was slightly seaward of the mean between 63° to 66°W and farthest shoreward at 56°W. The Stream was located south of its mean position during the late-1970s and 1980, near the long term mean through most of the 1980s and north of it during the late-1980s and into the first half of the 1990s (Fig. 66). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed a rapid decline in 1996 and remained low through 1997 and 1998. The 1996 position is not well defined, however, since it is based upon only three months of the data (October to December). The decline does match the large decline in the NAO index in 1996 and is consistent with the finding of a significant positive correlation between the Gulf Stream position and the NAO. In 1999, the average position of the front moved shoreward but remained south of the mean.

Summary

During 1999, the NAO index increased to a level well above its long-term mean indicating an intensification of the Icelandic Low and Azores High relative to 1996-98 and near that of the early 1990s. As during the past several years, the largest changes in the air pressure fields occurred on the eastern side of the Atlantic. Air temperatures over most of the northwest Atlantic were above normal continuing the warming trend of the past 3 years. Indeed, from the Labrador coast, through Newfoundland and the Gulf of St. Lawrence, to the Gulf of Maine, 1999 ranked as the warmest year on record. The exception to these warm temperatures was on the eastern side of the Labrador Sea and along Western Greenland where temperatures were near to or colder than normal. The warmer-than-normal winter temperatures resulted in less ice than normal off Newfoundland and Labrador, and in the Gulf of St. Lawrence. Ice typically arrived late and left early, causing fewer days of ice in most areas. Little to no ice reached the Scotian Shelf proper. The number of icebergs that reached the northern Grand Banks increased fell to its lowest level since 1980.

During 1999, ocean temperature indices suggested that most of the water off southern Labrador, northern Newfoundland and on the Grand Banks was warmer-than-normal, continuing a trend that began in 1996. This was seen at Hamilton Bank, on Flemish Cap, and in the near bottom temperatures during the annual surveys (spring on the Grand Banks and during the autumn from the Grand Banks to southern Labrador), and at Station 27 throughout the year. As well, the CIL volume both in summer and autumn were well below normal. At shallower depths at Station 27, temperatures were warmer-than-normal from January to September but during the remainder of the year temperatures in the upper half of the water column were relatively cool compared to the long-term means. Salinities in the upper layer at Station 27 were fresher than normal except during the first three months of the year and in the upper water column during November-December. On St. Pierre Bank, temperatures in the bottom waters continued to moderate with the result that most of the area experienced above normal temperatures for the first since the mid-1980s.

In the Gulf of St. Lawrence, the CIL waters generally decreased in depth while the core temperature warmed. This meant a return to the warming trend observed since the mid-1990s after the reversal to colder temperatures in 1998. Earlier studies had found a relationship with air temperatures off western Newfoundland with warmer winters resulting in less and warmer CIL waters. This is consistent with the warming of the CIL waters observed in 1999, as the winter of 1998/99 was relatively mild. The warming of the CIL and its shrinking resulted in less of the bottom of the Magdalen Shallows being covered by colder waters (<0° and <1°C) than observed in 1998 and the smallest area since the mid to late-1980s. In the 200-300 m deep layer in the Gulf (i.e. within the Laurentian Channel), temperatures were near their long-term mean.

The cold, Labrador-type Slope Water that was observed along the shelf edge in 1998, disappeared in 1999 to be replaced by Warm Slope Water. Subsequently, the cold slope water that had penetrated onto the shelf through channels and gullies in 1998 was replaced by warm slope water in the deep basins such as Emerald Basin and Georges Basin. Temperature changes in the deep region of Emerald Basin were of order 2°-3°C warmer than last year and was near its long term mean. In the northeastern Scotian Shelf, waters continued to experience warming resulting in above normal temperatures is a significant portion of the region for the first time since the mid-1980s. The presence of the cold waters in the northeastern Scotian Shelf is believed to have been due to a combination of advection from the Gulf of St. Lawrence and off the Newfoundland Shelf and *in situ* cooling during the winter although the relative importance has not been established. Also of significance is the continued strong stratification on the Scotian Shelf that has persisted through most of the 1990s. Indeed, stratification in recent years has been at its maximum in the approximate 50-year record. This high stratification was not observed in the Gulf of Maine.

ACKNOWLEDGEMENTS

We wish to thank those who provided data, especially to I. Peterson of the Bedford Institute for the monthly areal ice extent data for the Newfoundland region, the Bigelow Laboratory for providing Boothbay Harbor temperature data; F. Page and R. Losier of the Biological Station in St. Andrews, for providing St. Andrews and Prince 5 data, J. McRuer for the Scotian Shelf July groundfish survey data; B. Petrie of the BIO for the Halifax sea surface temperature data, D. Swain for the Gulf of St. Lawrence September survey data, Brian Petrie and Victor Soukhovtsev for the data and plots of the data from the standard sections and the standard station on the Halifax Line and G. Bugden of the BIO for his Cabot Strait temperature data. Special thanks to L. Petrie, R. Pettipas, C. Lafleur and D. Foote for their analytical and technical assistance.

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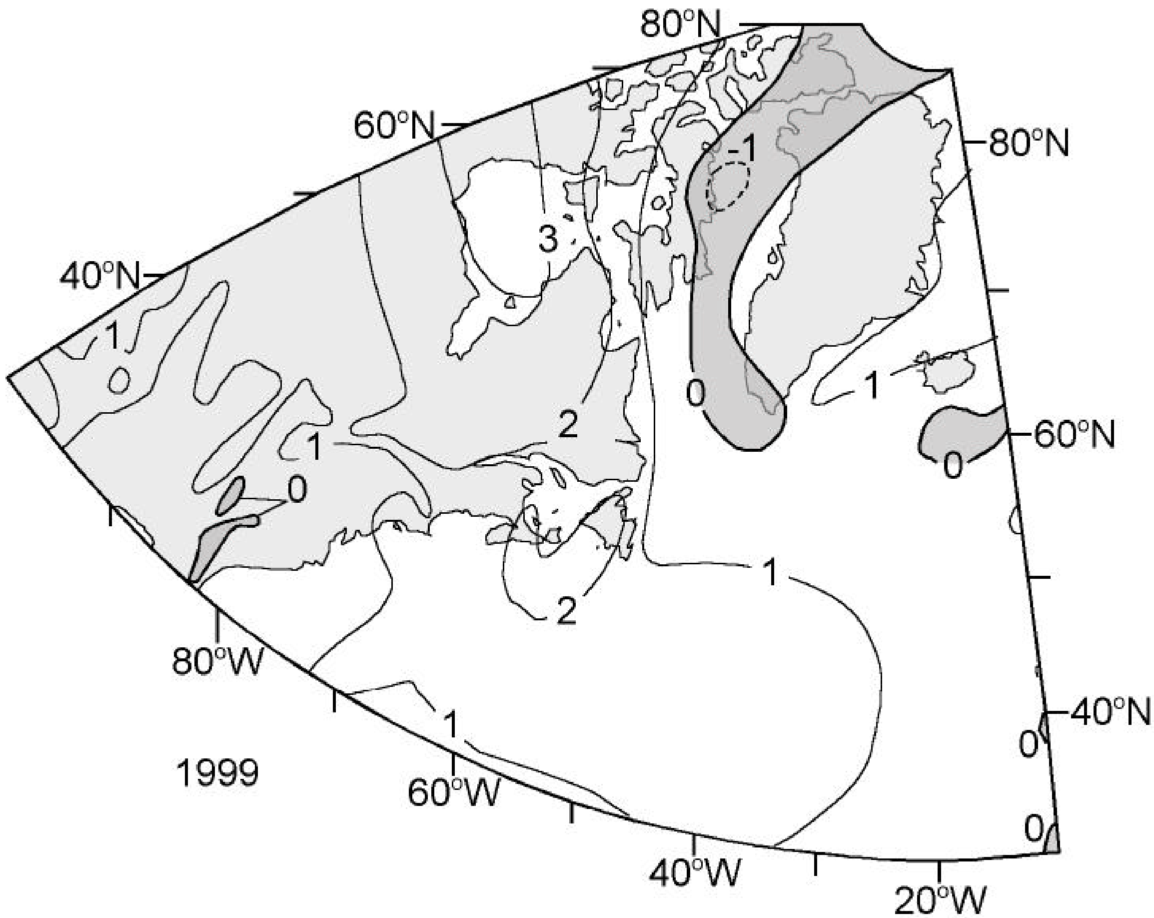


Fig. 1. Annual air temperature anomalies (in °C) over the northwest Atlantic in 1999 relative to the 1961-90 means (taken from Grosswetterlagen Europas). The darker shaded anomalies indicate areas of colder-than-normal temperatures.

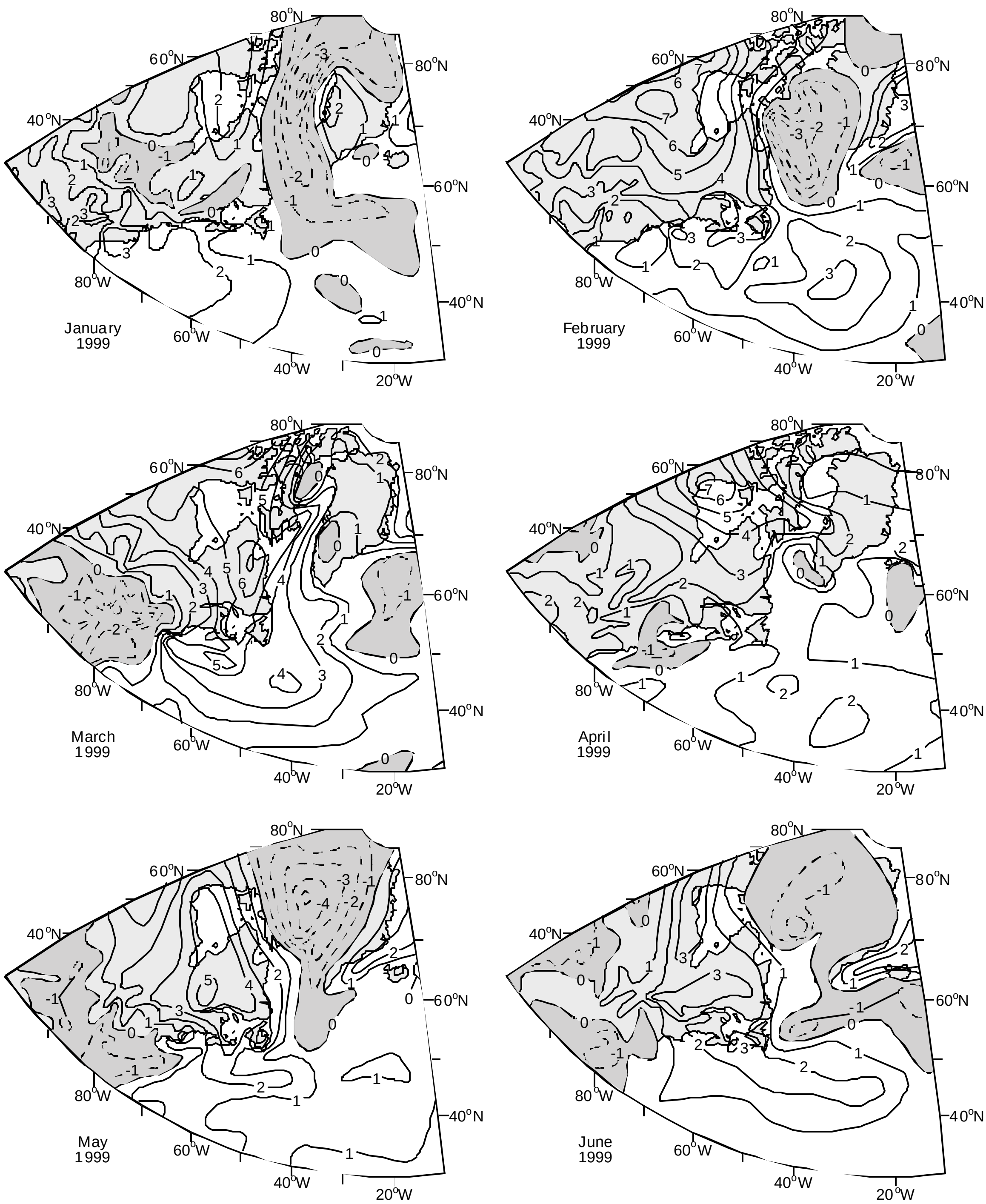


Fig. 2. Monthly air temperature anomalies (January-June; in °C) over the Northwest Atlantic and eastern Canada in 1999 relative to the 1961-90 means. Shaded areas are colder-than-normal. (From *Grosswetterlagen Europas*)

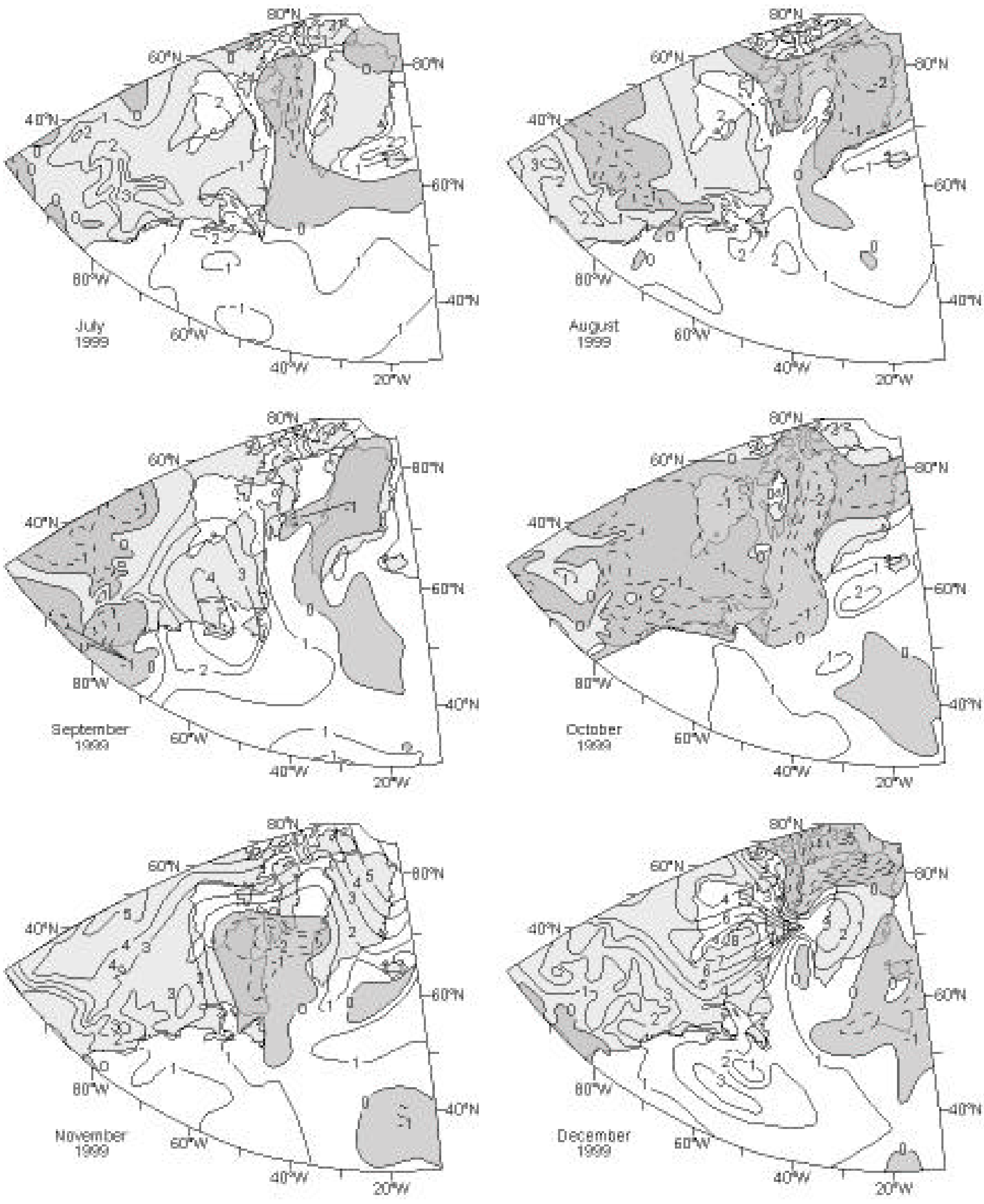


Fig. 2 (continued). Monthly air temperature anomalies (July-December; in °C) over the Northwest Atlantic and eastern Canada in 1999 relative to the 1961-90 means. Shaded areas are colder-than-normal. (From *Grosswetterlagen Europas*)

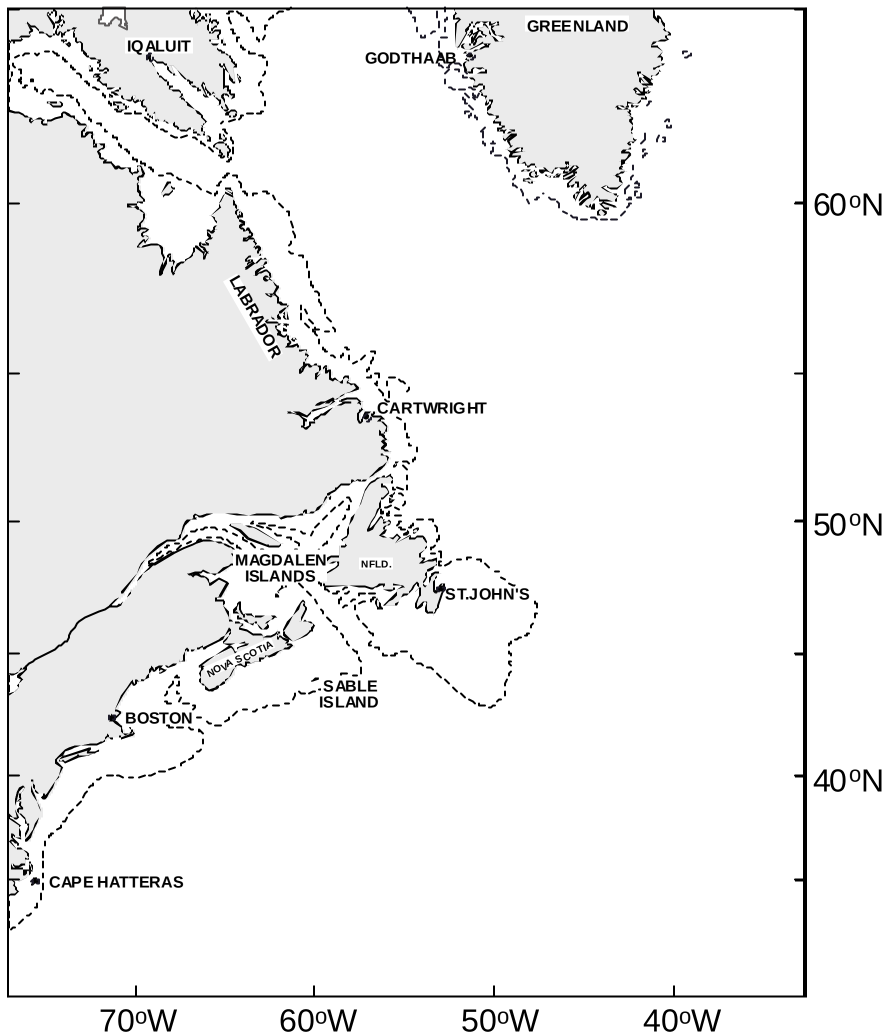


Fig. 3. Northwest Atlantic showing coastal air temperature stations.

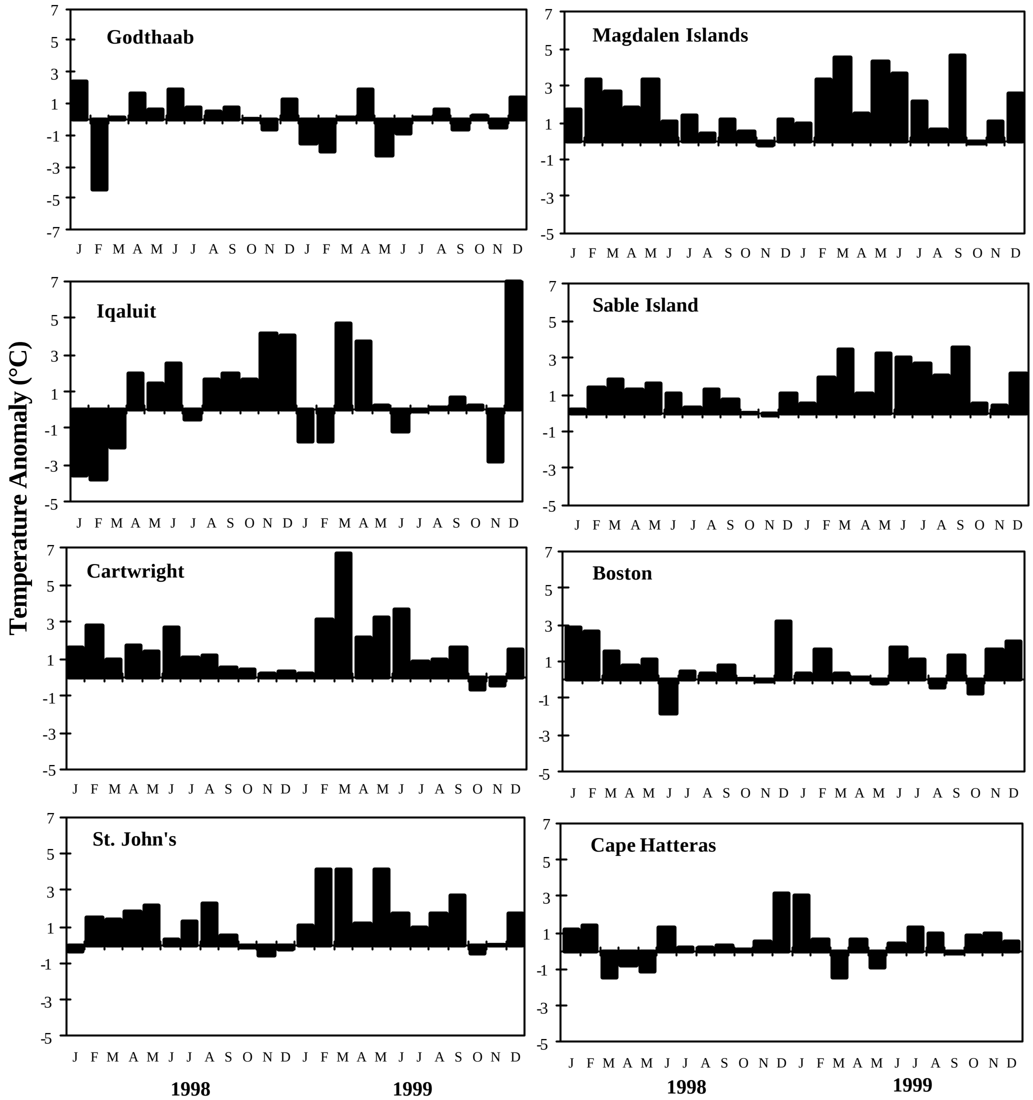


Fig. 4. Monthly air temperature anomalies in 1998 and 1999 at selected coastal sites (see Fig. 3 for locations).

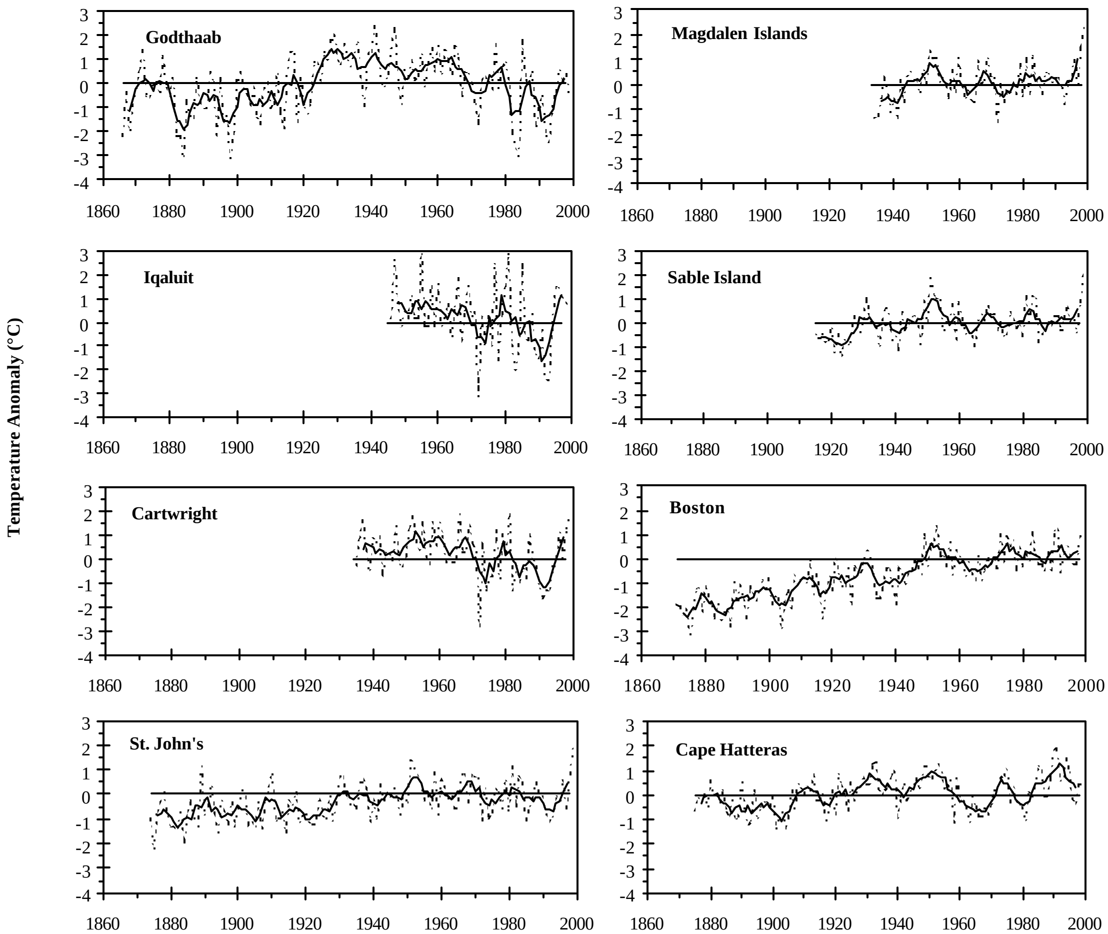


Fig. 5. Annual air temperature anomalies (dashed line) and 5-yr running means (solid line) at selected sites.

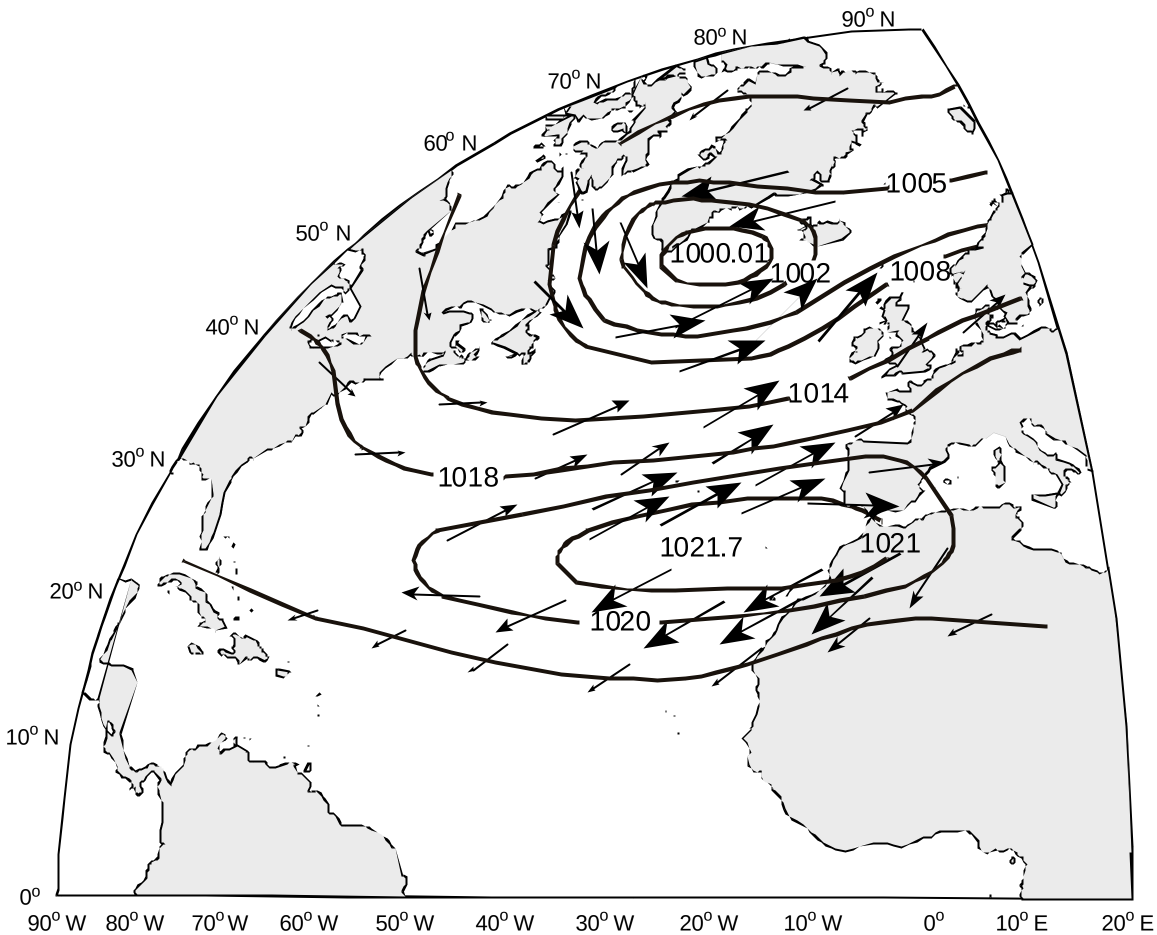


Fig. 6. The long-term (1961-90) mean sea surface pressures during winter (average of December, January and February). A schematic of the associated wind field is also shown.

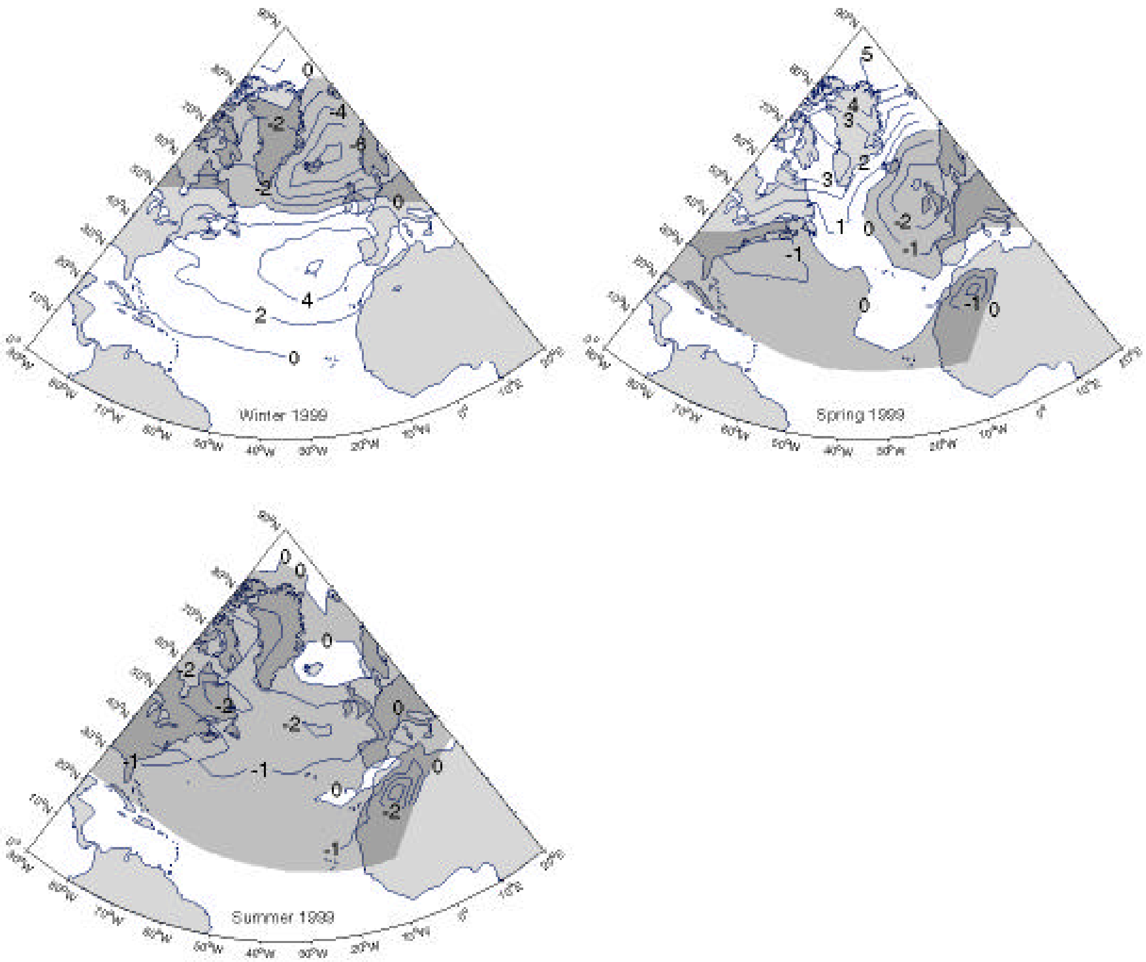


Fig. 7. Seasonal sea-surface air pressure anomalies (mb) over the North Atlantic in 1999 relative to the 1961-90 means.

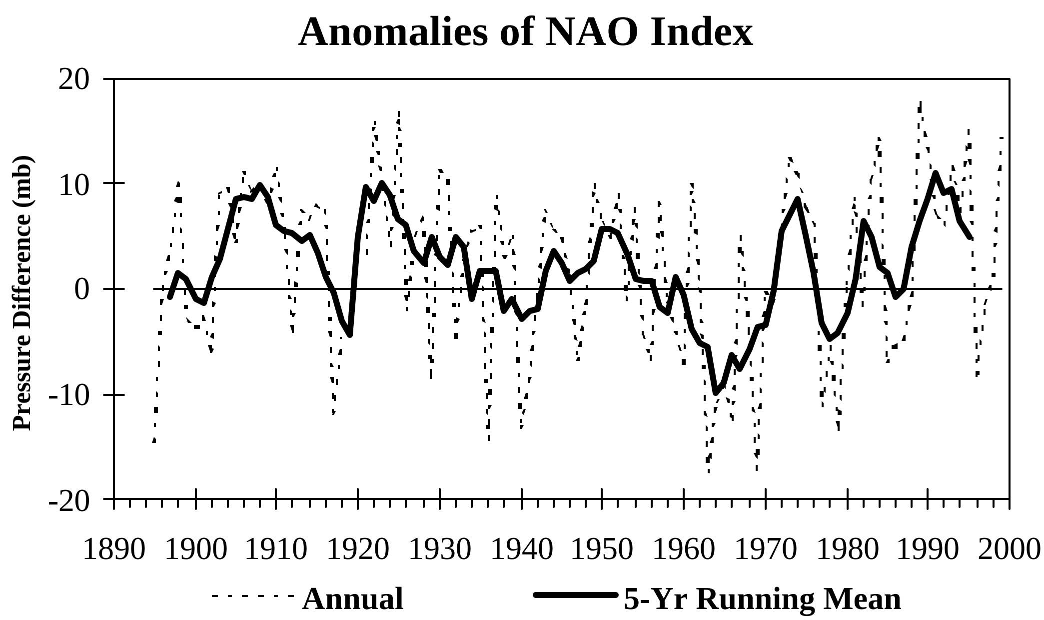


Fig. 8. Anomalies of the North Atlantic Oscillation Index, defined as the winter (December, January, February) sea level pressure at Ponta Delgada in the Azores minus Akureyri in Iceland, relative to the 1961-90 mean.

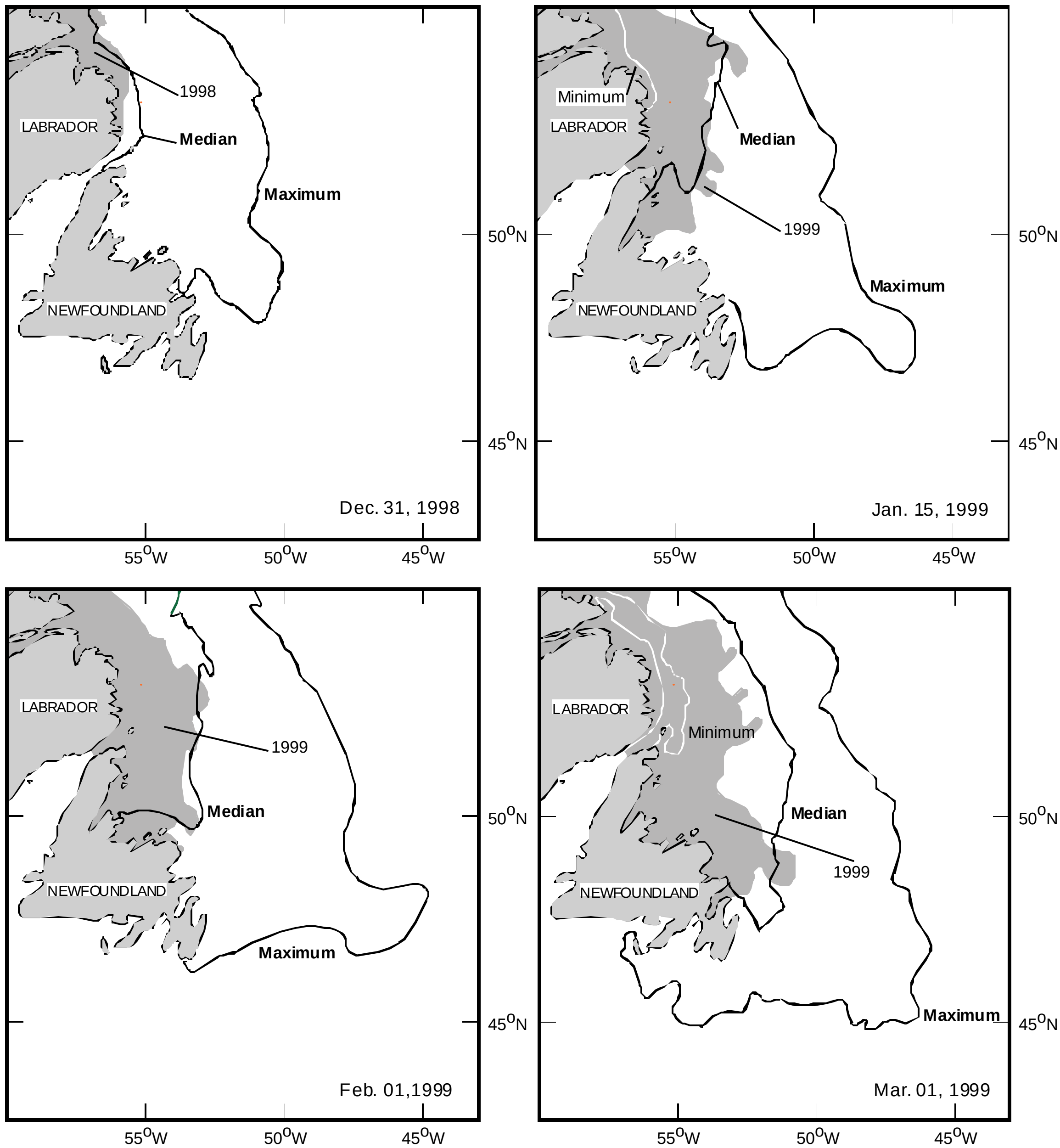


Fig. 9a. The location of the ice (shaded area) between December 1998 and March 1999 together with the historical (1962-1987) minimum, median and maximum positions of the ice edge off Newfoundland and Labrador.

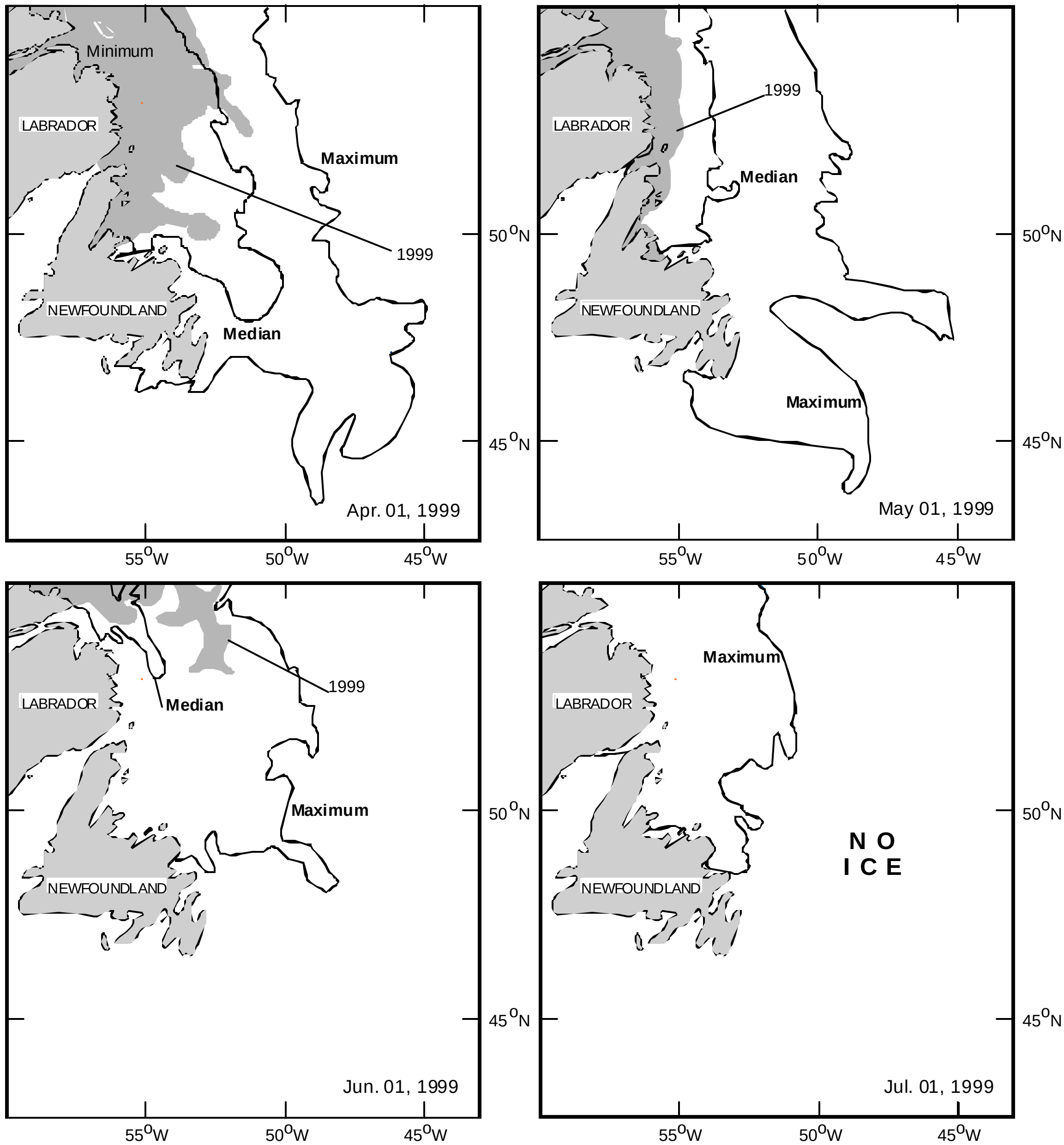


Fig. 9b. The location of the ice (shaded area) between April and July 1999 together with the historical (1962-1987) minimum, median and maximum positions of the ice edge off Newfoundland and Labrador.

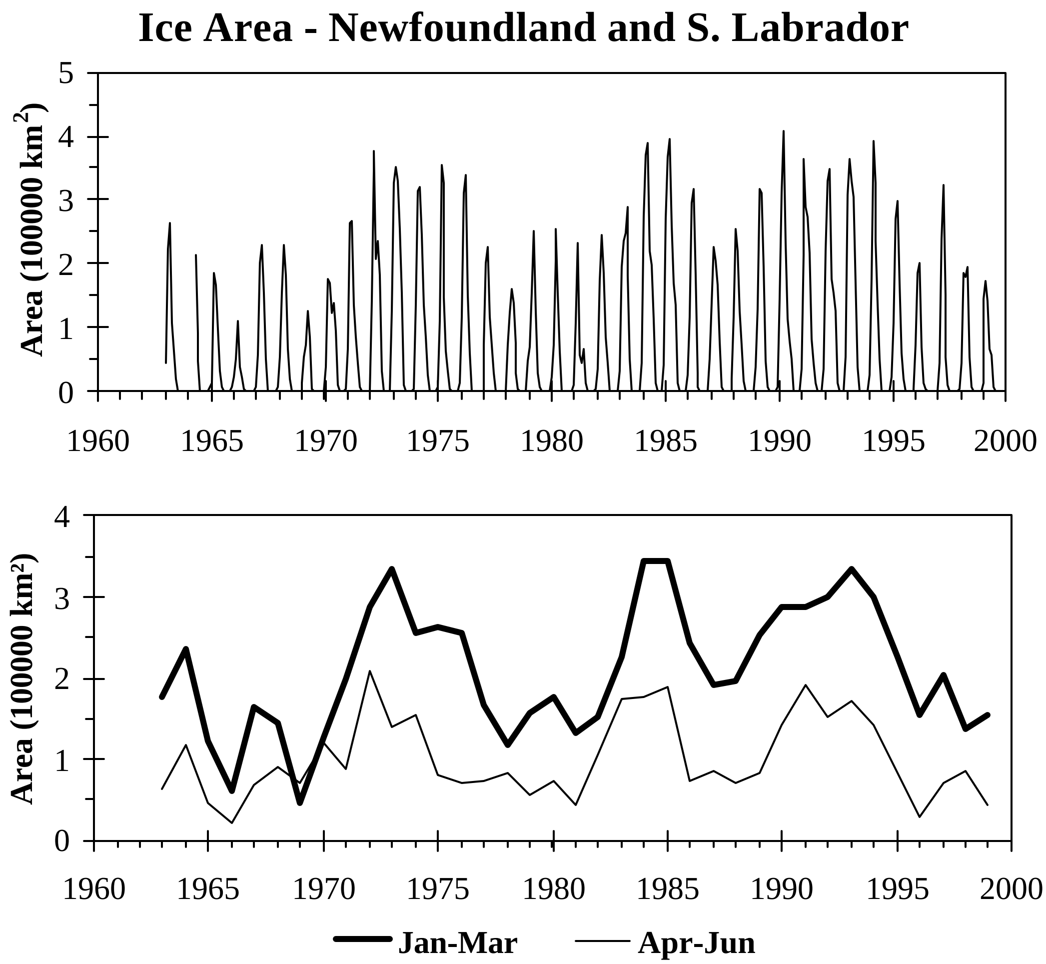


Fig. 10. Time series of the monthly mean ice area off Newfoundland and Labrador between 45°N- 55°N (top panel) and the average ice area during the normal periods of advancement (January-March) and retreat (April-June) (bottom panel).

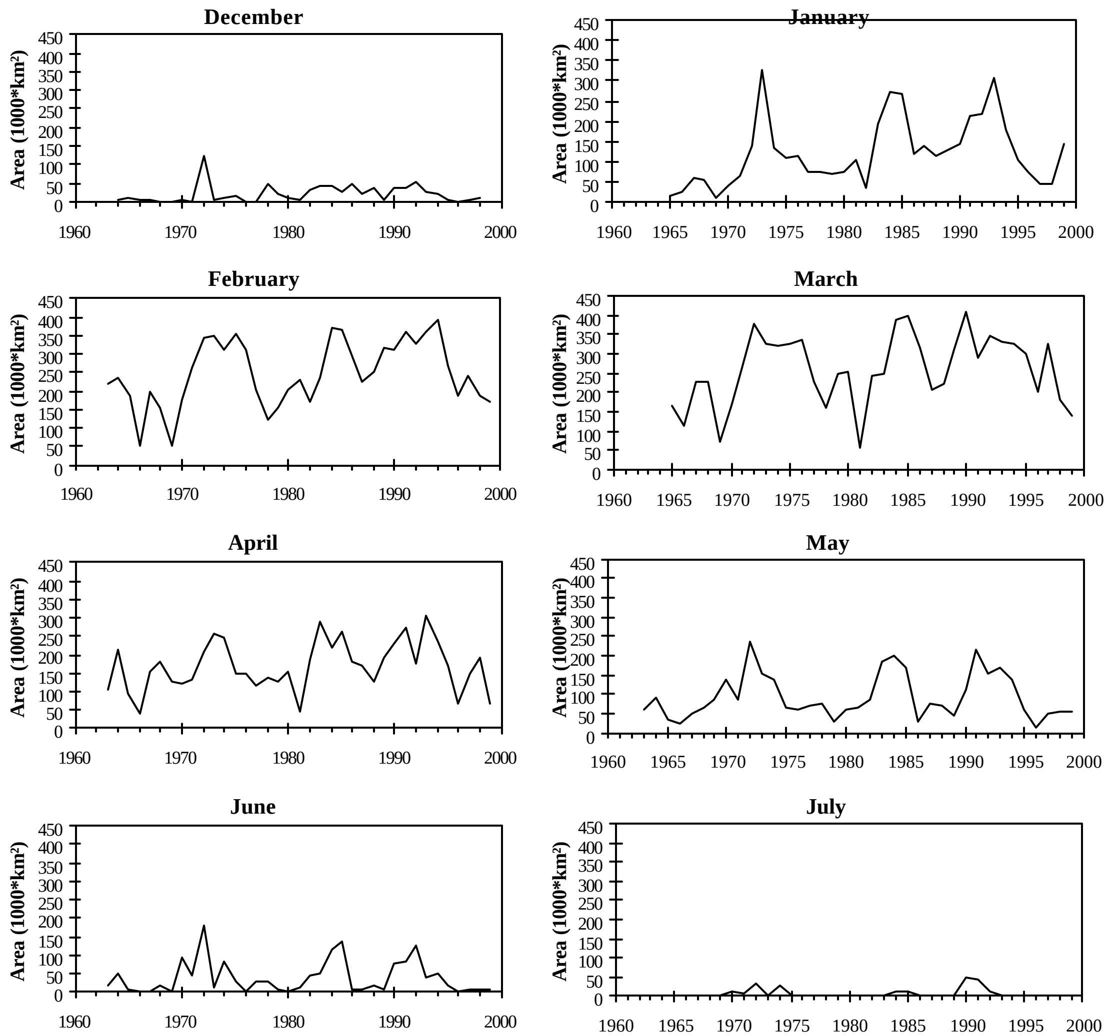


Fig. 11. The time series of ice area off Newfoundland and Labrador, by month.

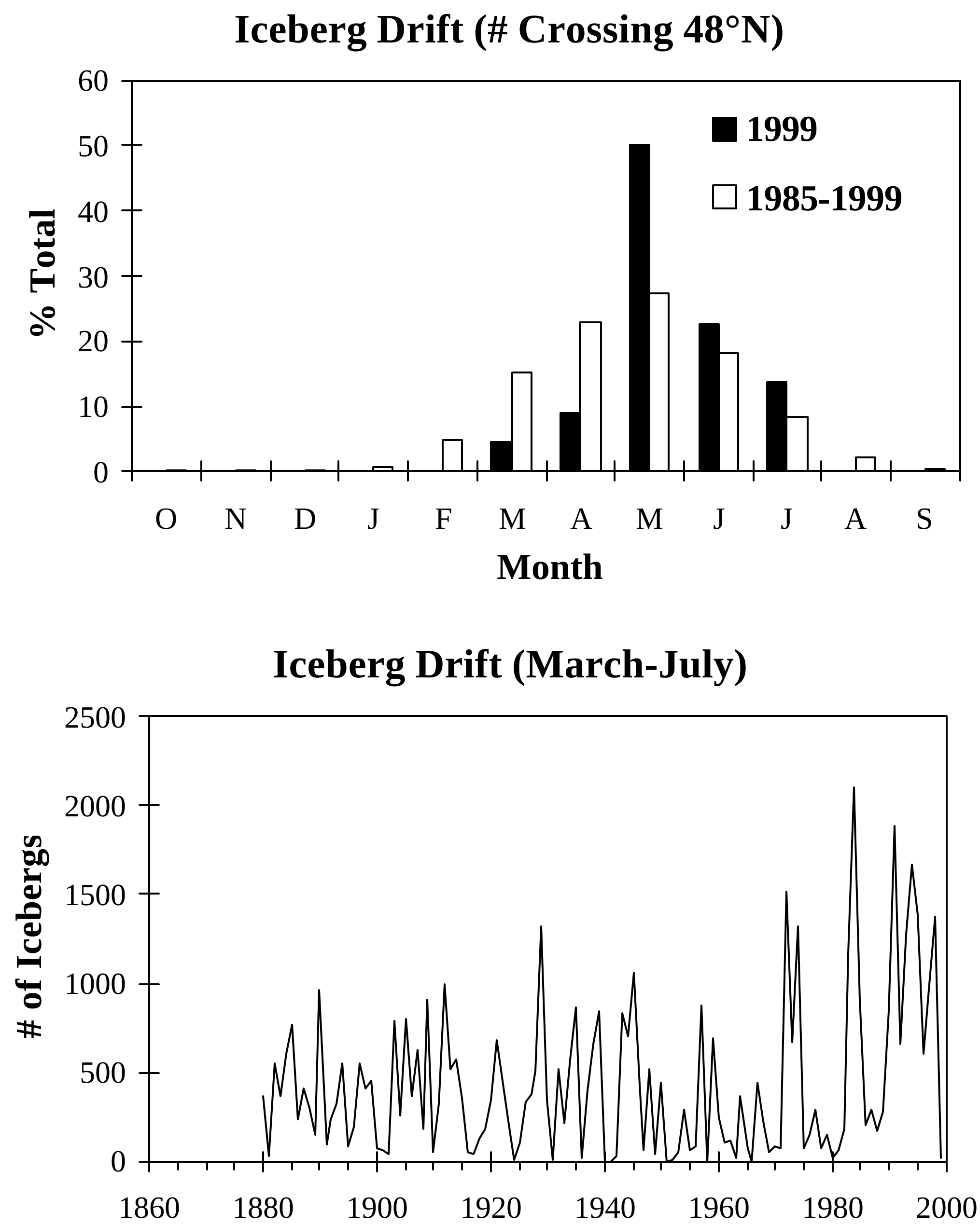


Fig. 12. The number of icebergs crossing south of 48°N during the iceberg season 1998/99 expressed as a percent of the total by month compared to the mean during 1983-99, the years SLAR has been used (top panel) and the time series of total number of icebergs observed during March to July (bottom panel).

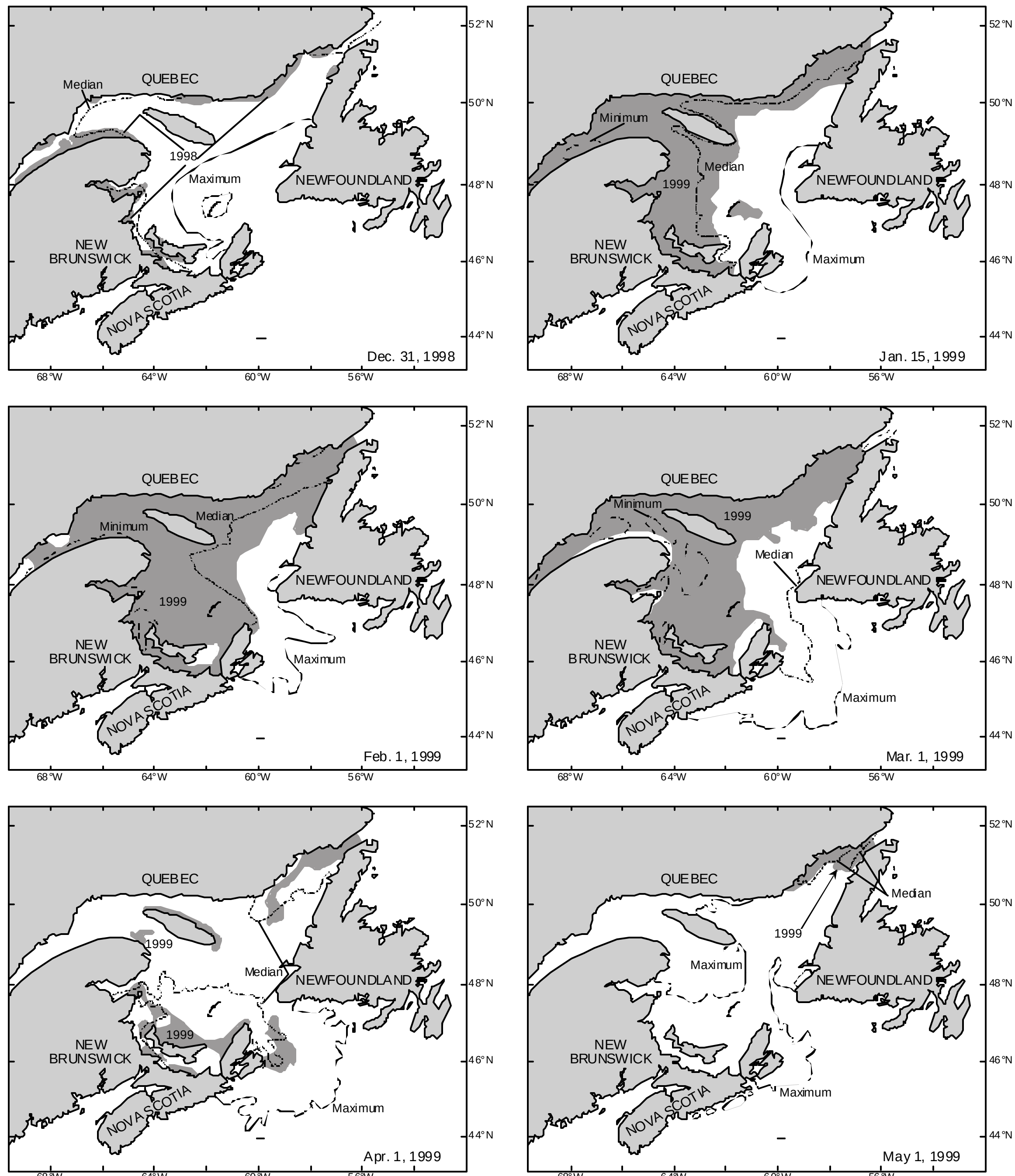


Fig. 13. The location of the ice (shaded area) between December 1998 and May 1999 together with the historical (1962-1987) minimum, median and maximum positions of the ice edge in the Gulf of St. Lawrence.

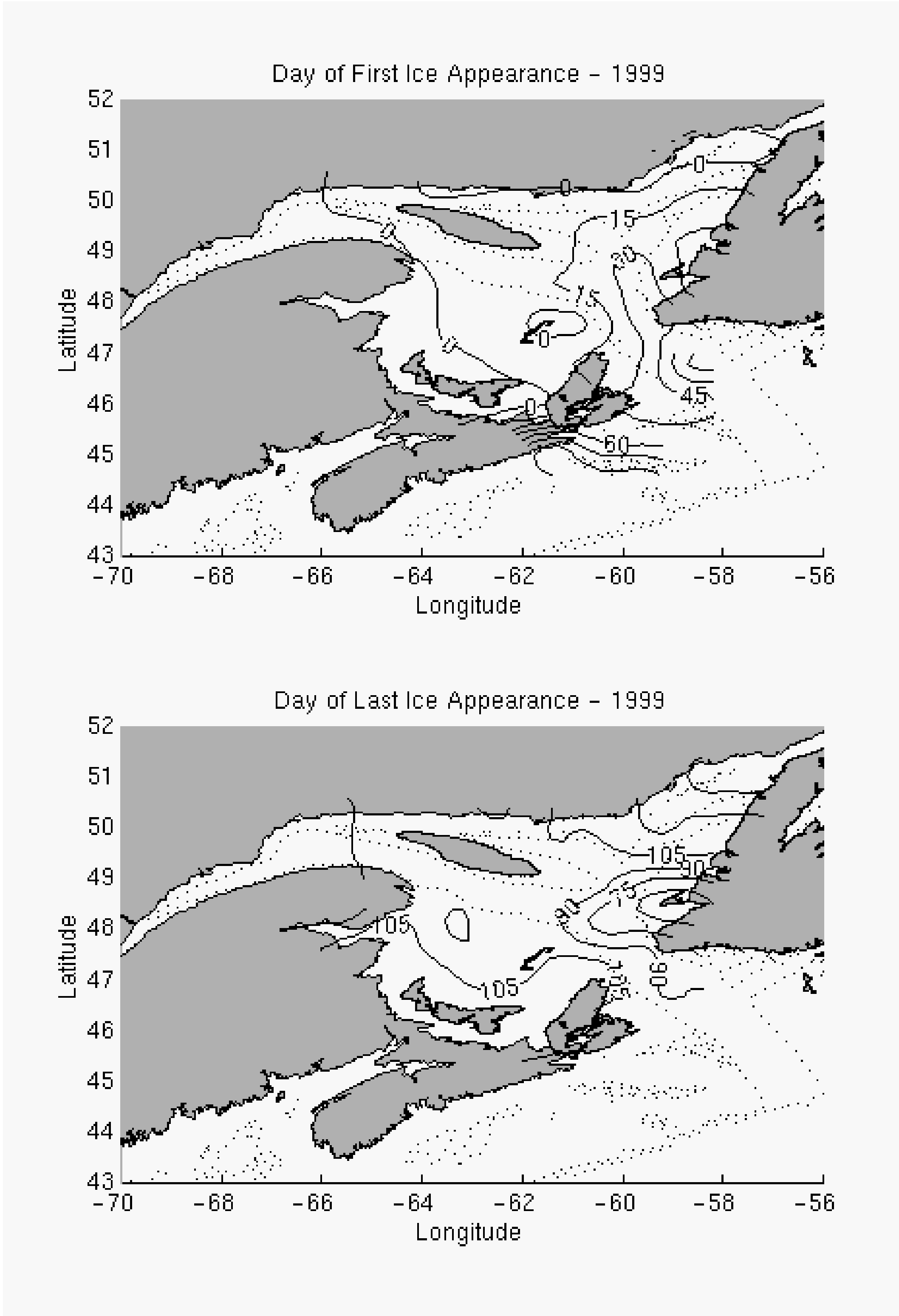


Fig. 14. The time when ice first appeared (top panel) and last appeared (bottom panel) during 1999 in days from the beginning of the year.

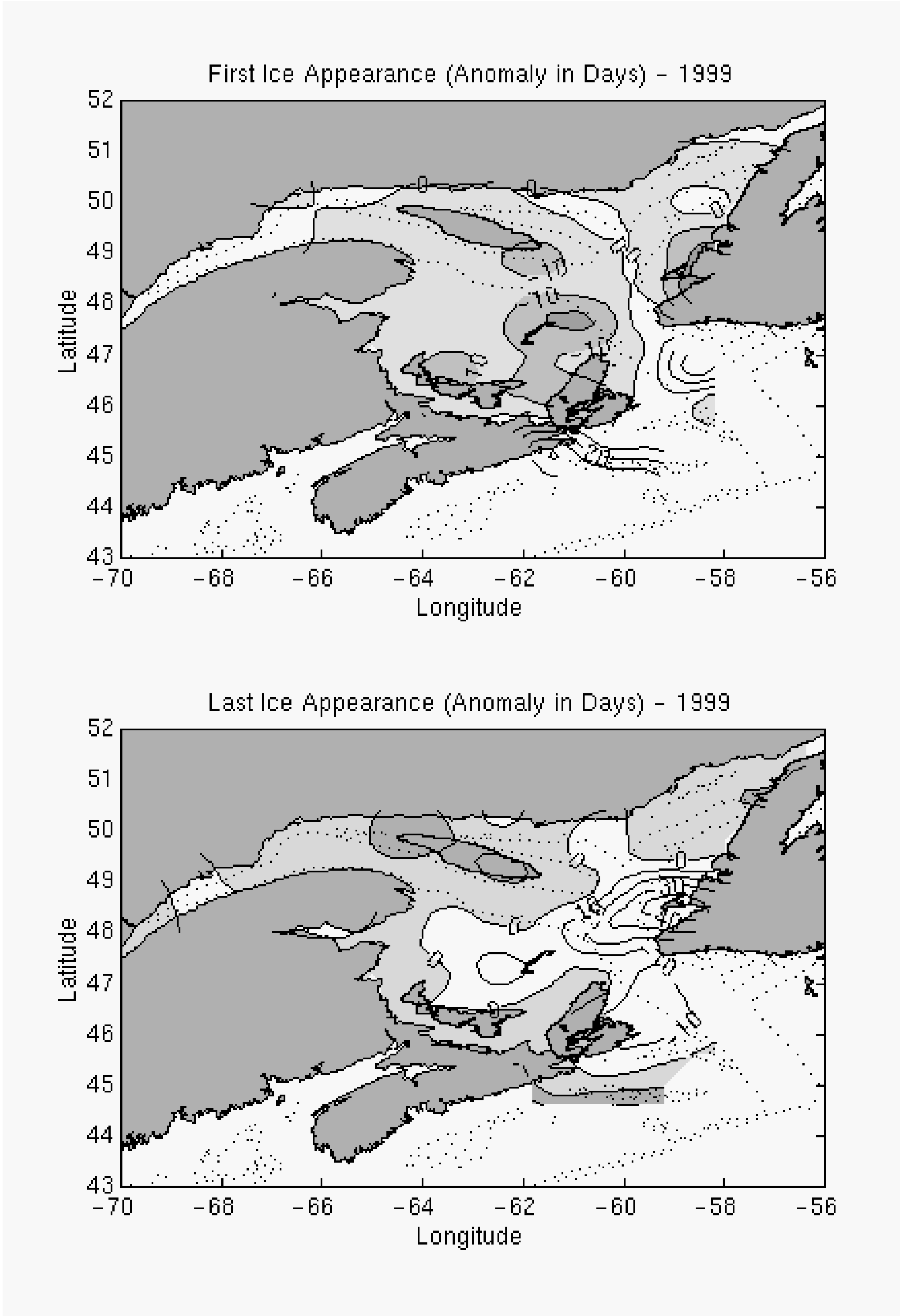


Fig. 15. The anomaly of the time when ice first appeared (top panel) and was last reported (bottom panel) during 1999 in days from the beginning of the year. Negative anomalies indicate earlier-than-normal and positive are later-than-normal. The shaded anomalies indicate conditions generally associated with cold years, i.e. earlier ice appearance and later-than-normal disappearance.

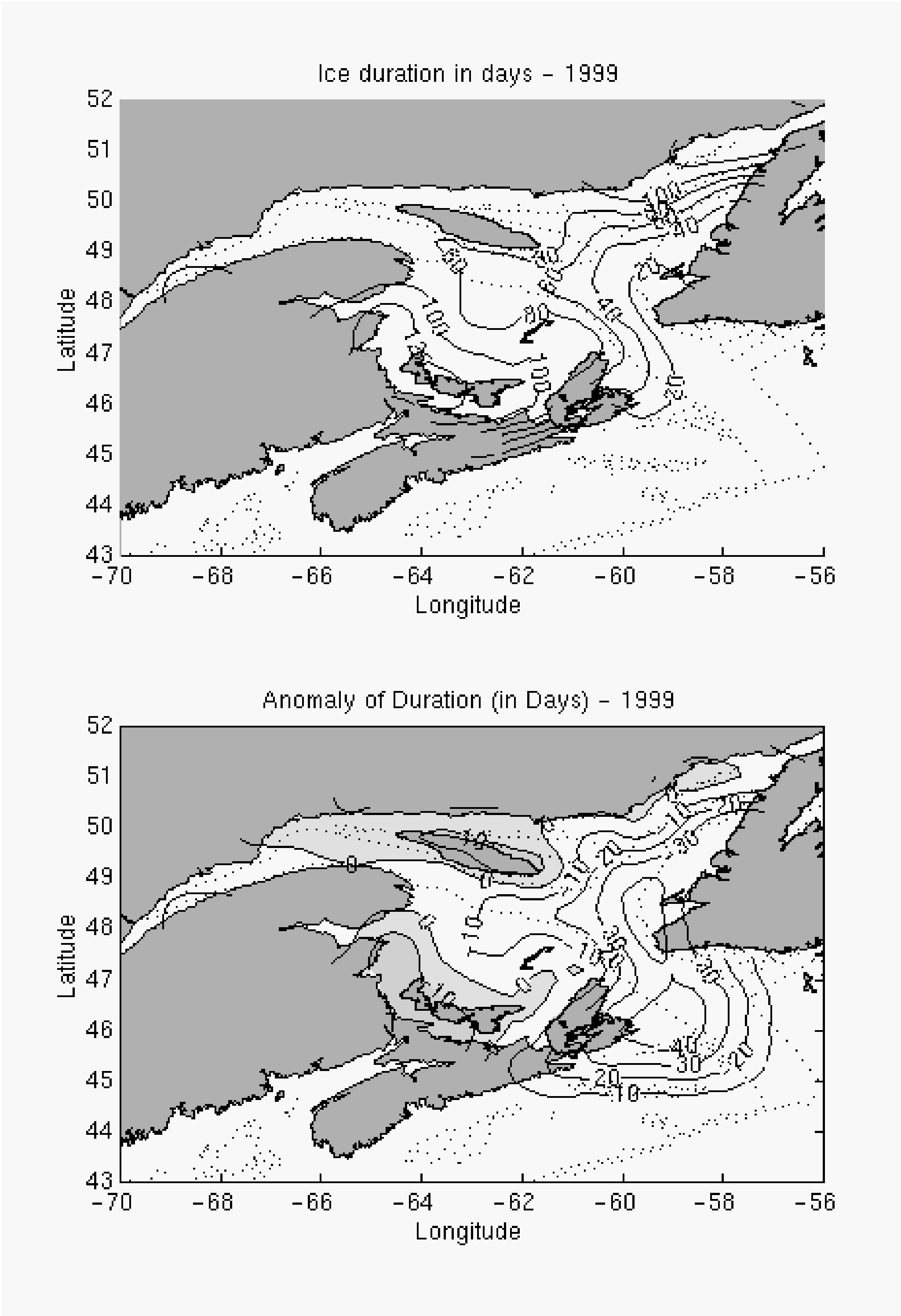


Fig. 16. The duration of ice in days (top panel) and their anomaly from the long term mean in days (bottom panel). The shaded positive anomalies indicate a duration longer than the mean which is generally associated with a cold year.

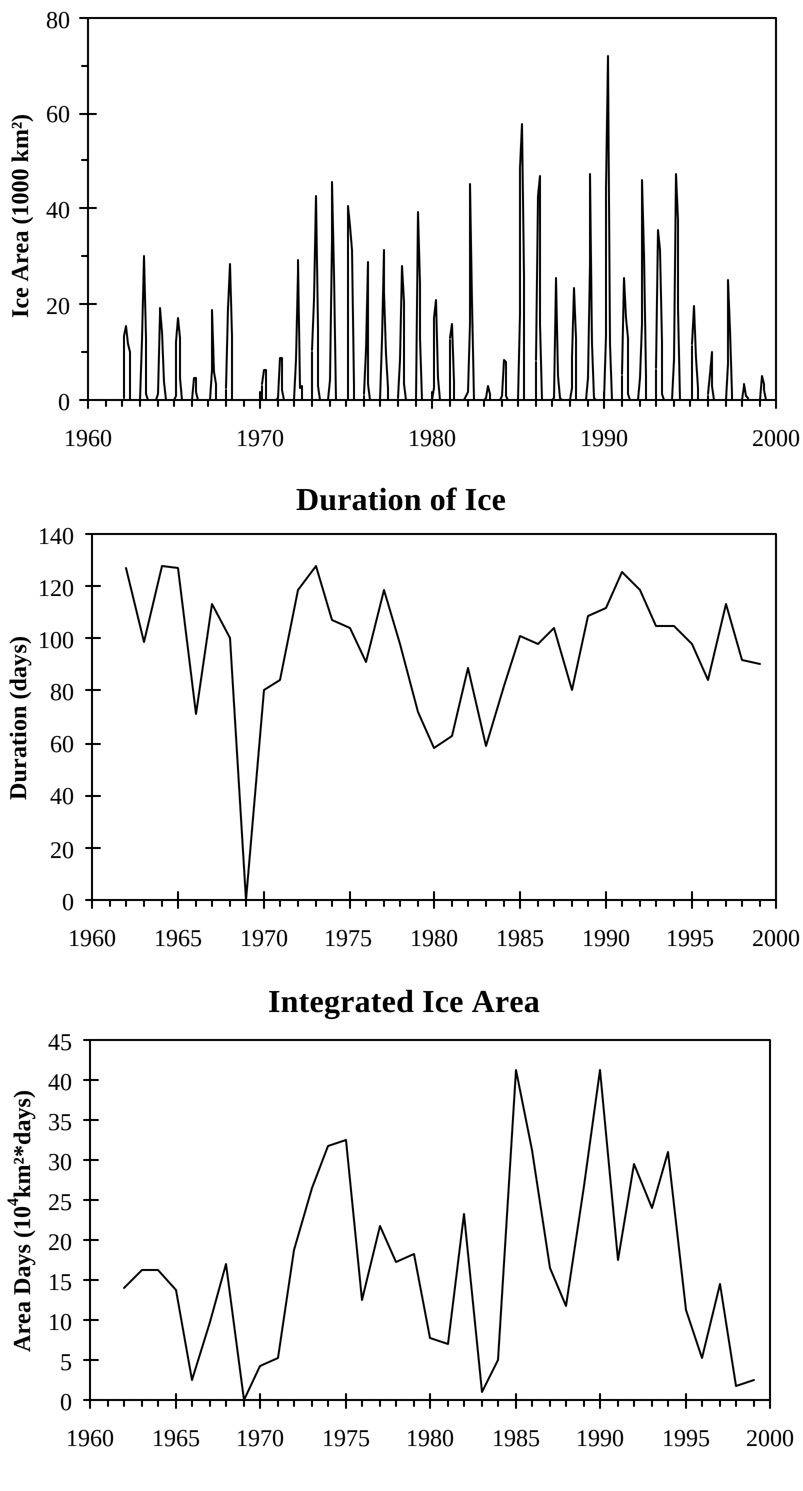


Fig. 17. For the region seaward of Cabot Strait, the time series of the monthly mean ice area (top), the duration of ice (middle) and the annual integrated ice area (summation of the area times the number of days).

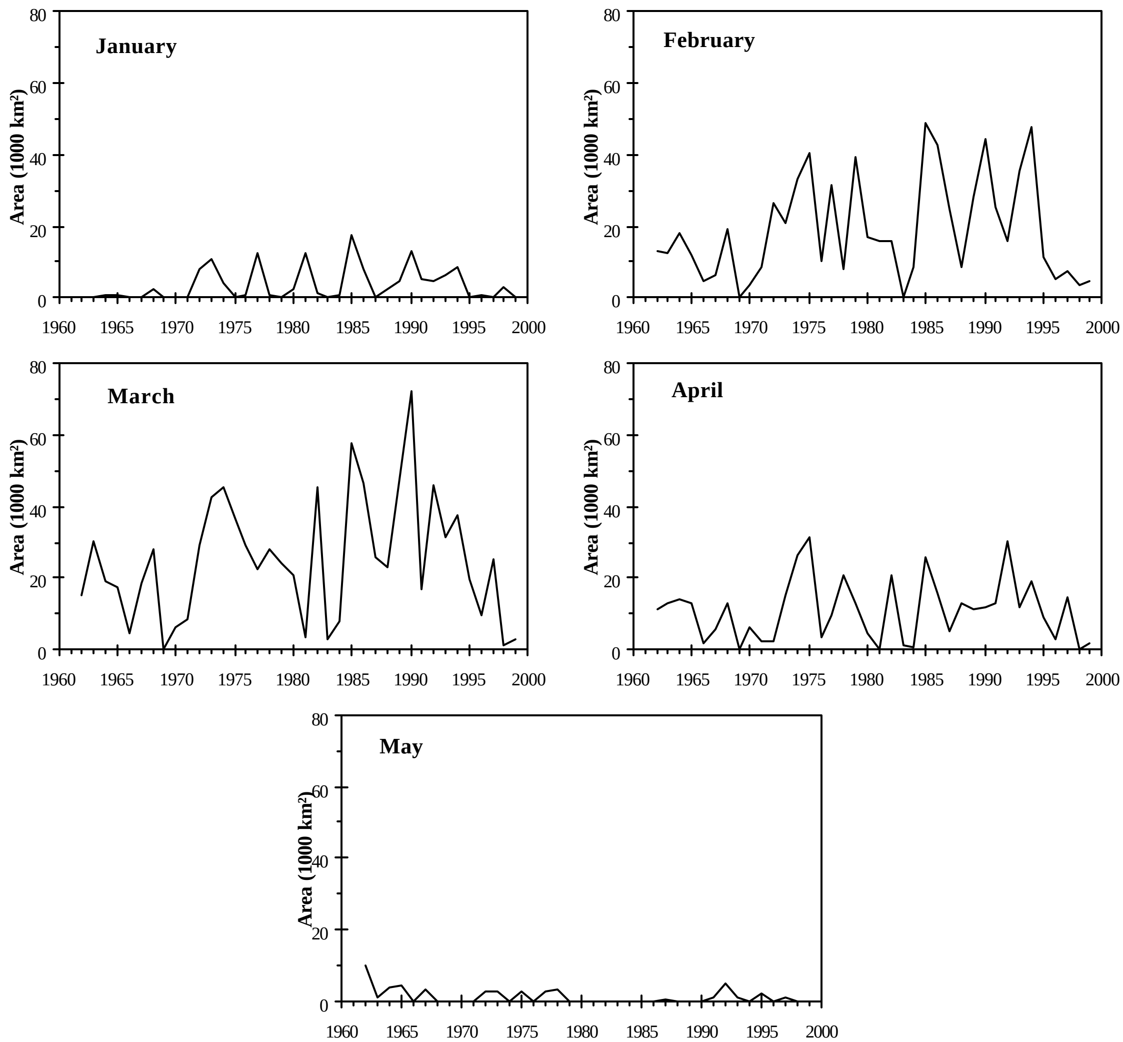


Fig. 18. The time series of ice area seaward of Cabot Strait, by month.

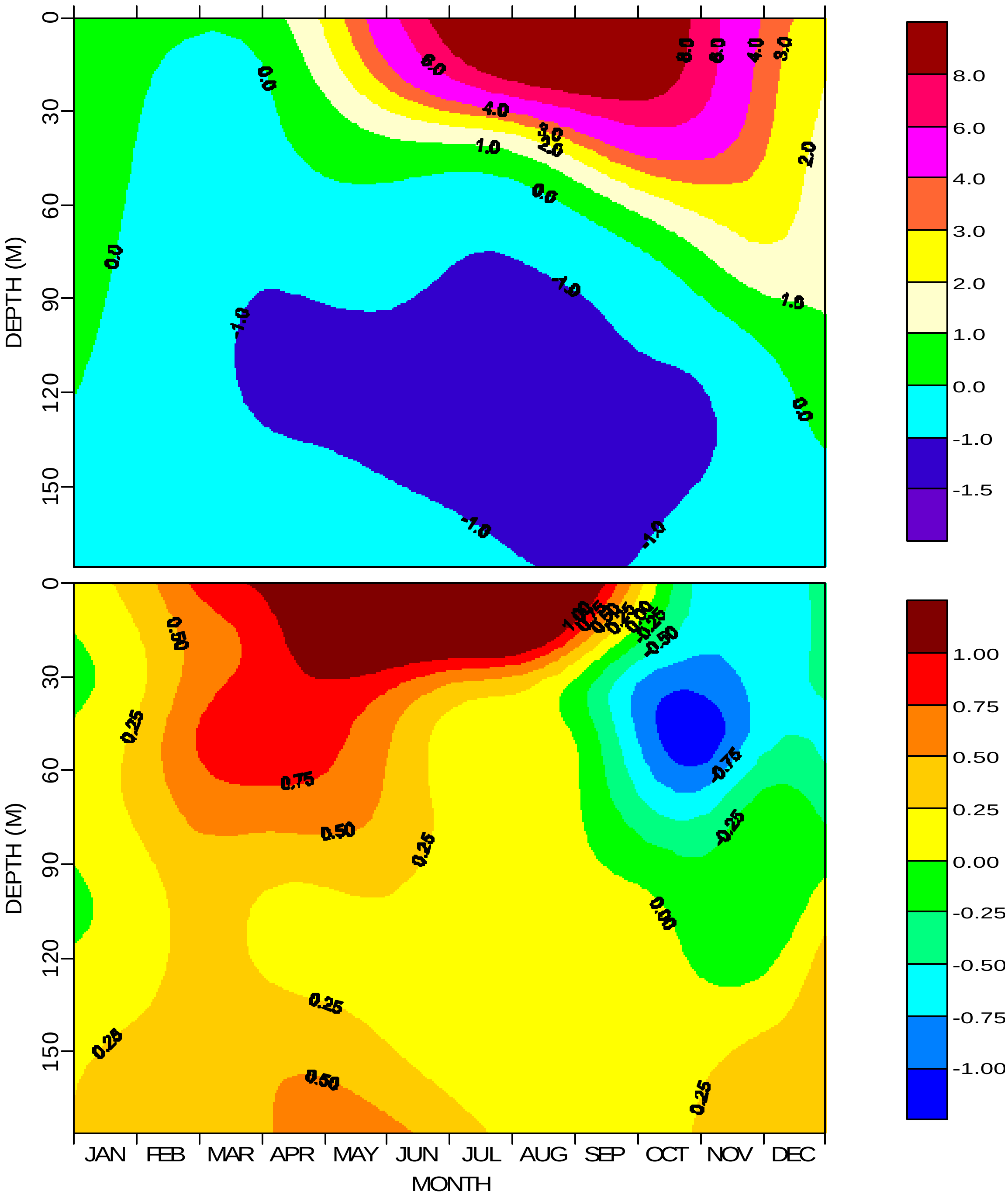


Fig. 19. Monthly mean temperatures and their anomalies (in °C) relative to the 1961-90 long-term average at Station 27 as a function of depth during 1999.

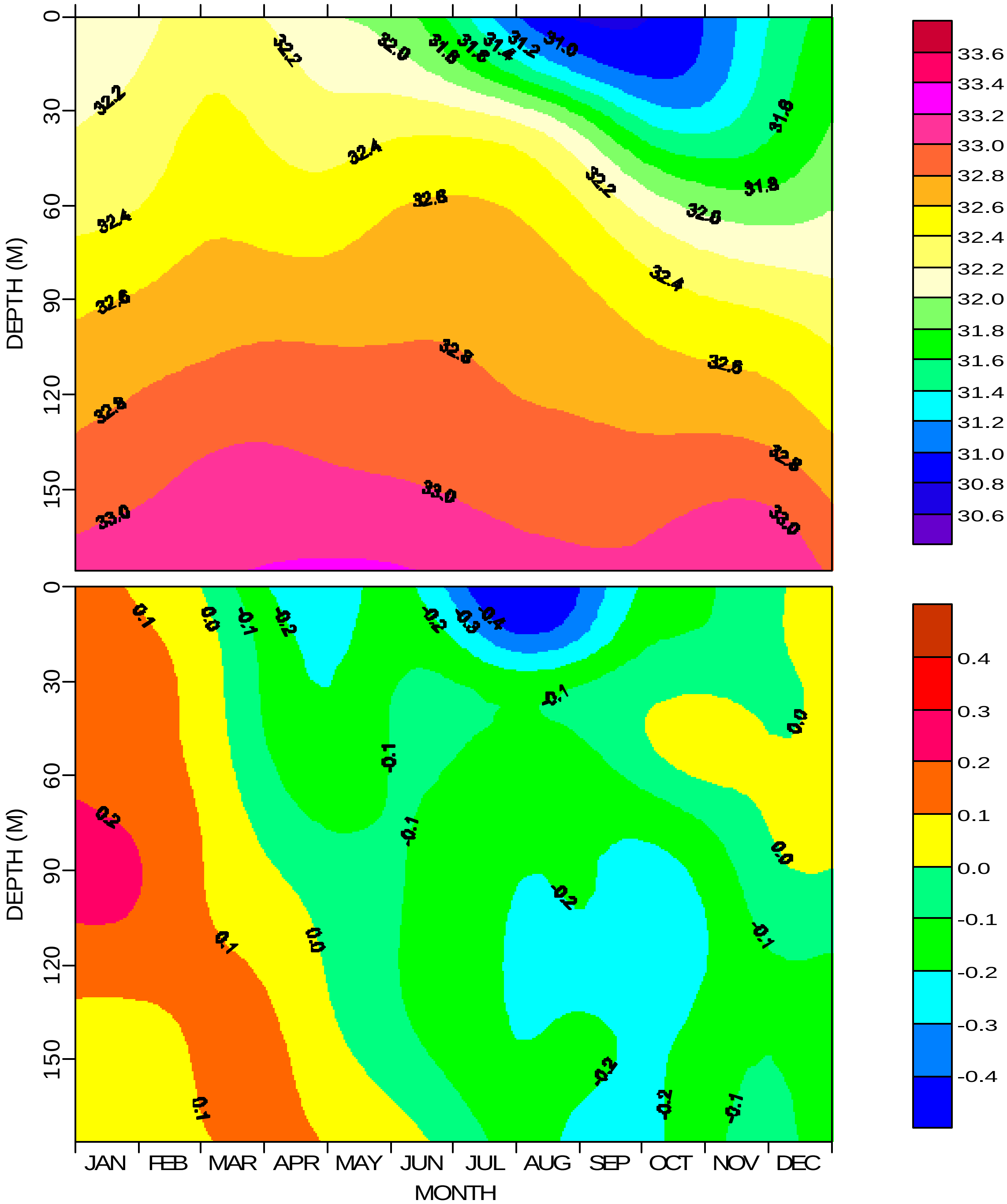


Fig. 20. Monthly mean salinities and their anomalies relative to the 1961-90 long-term average at Station 27 as a function of depth during 1999.

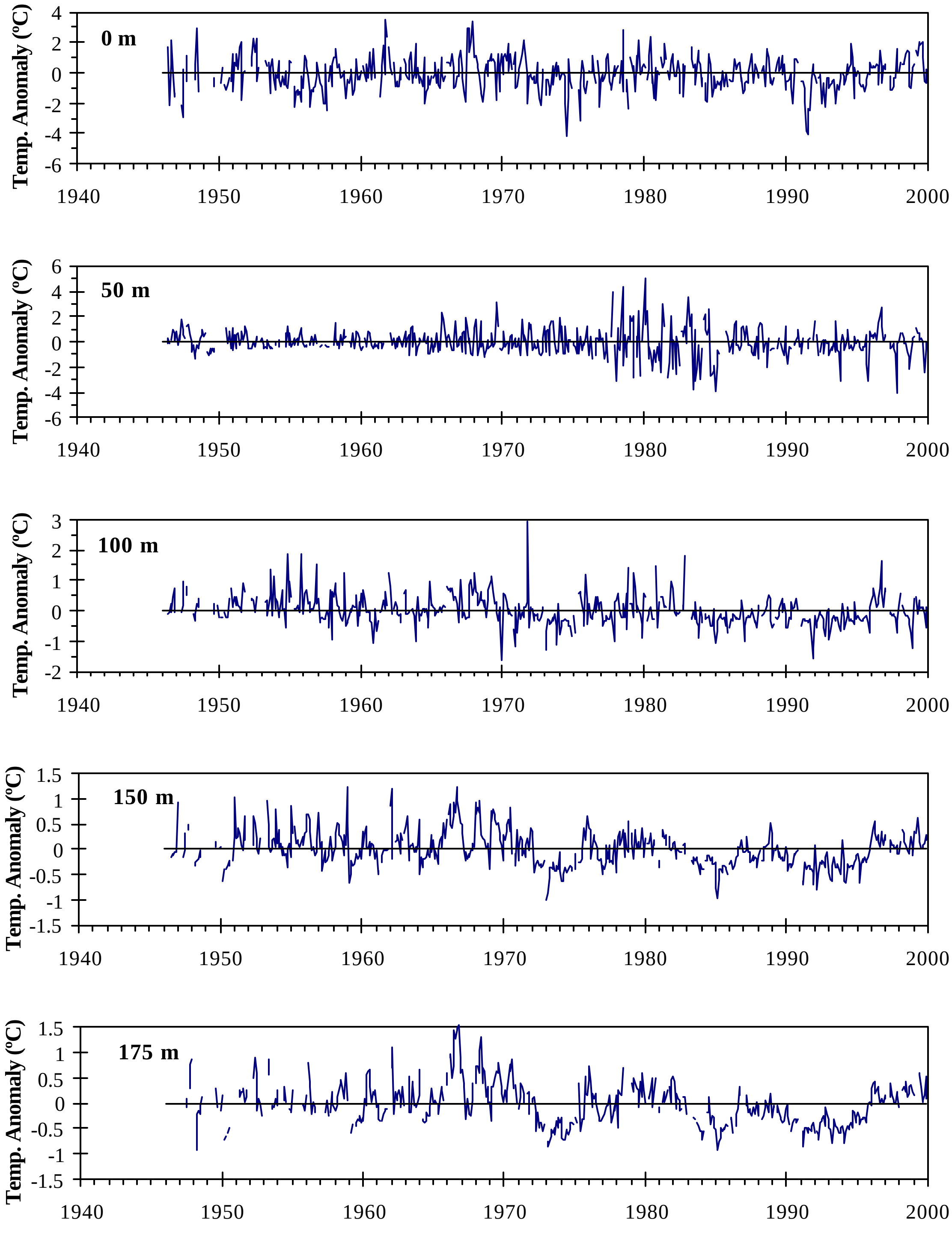


Fig. 21. Monthly mean temperature anomalies at selected depths from Station 27.

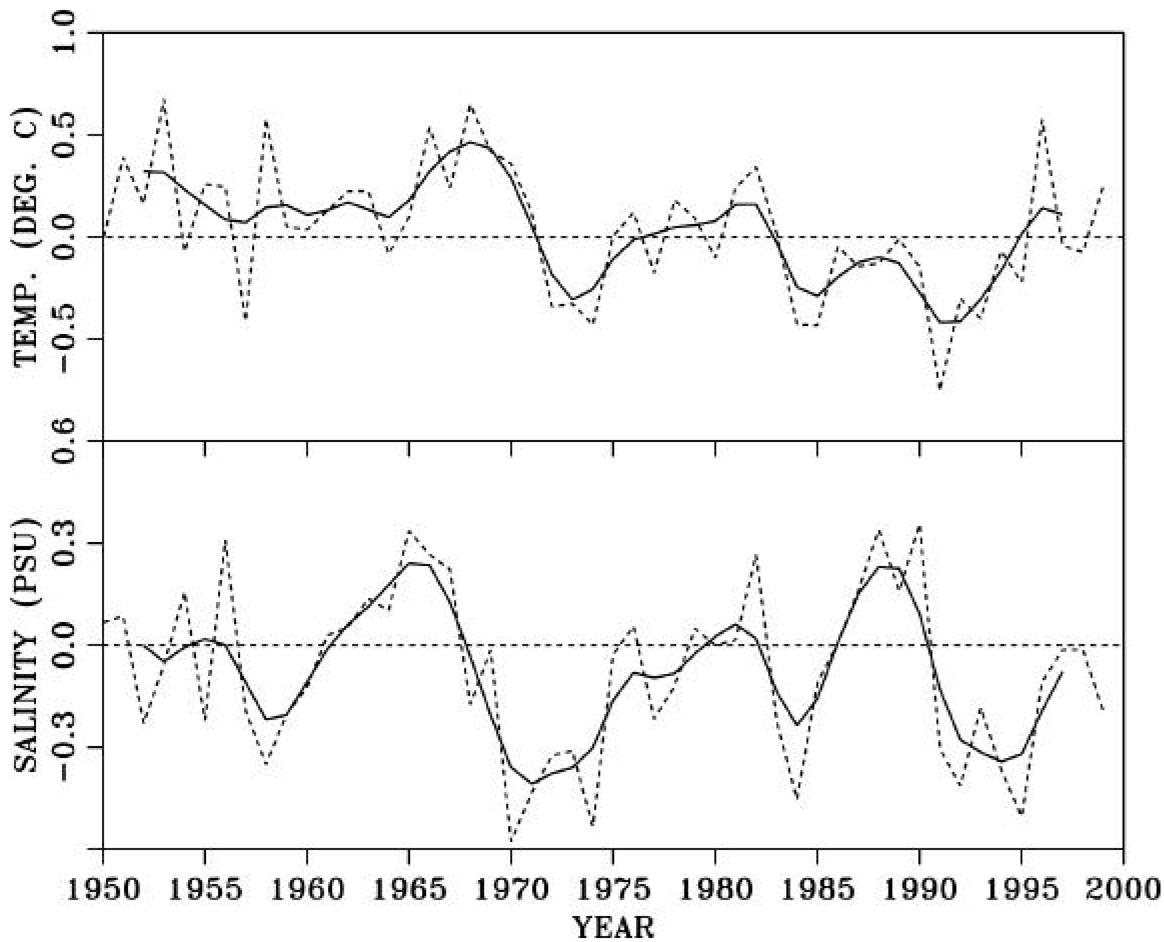


Fig. 22. Vertically averaged (0-176 m) temperature and (0-50) salinity from Station 27. The annual values are designated by the lighter dashed lines and the 5-yr running means by the heavy solid line.

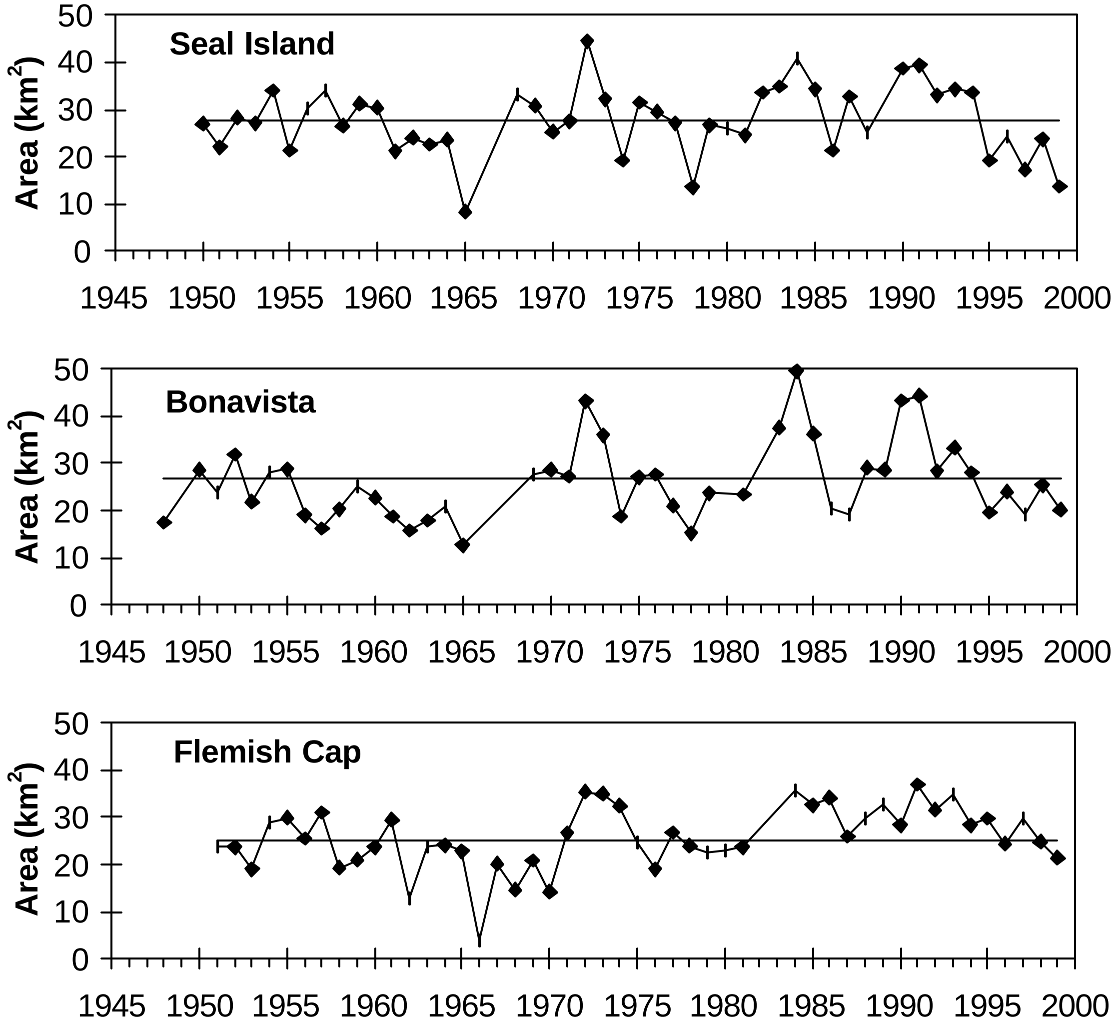


Fig. 23. The CIL area (in km^2) during the summer along standard sections off Seal Island (southern Labrador), Bonavista Bay (northeastern Newfoundland) and Flemish Cap (Grand Banks).

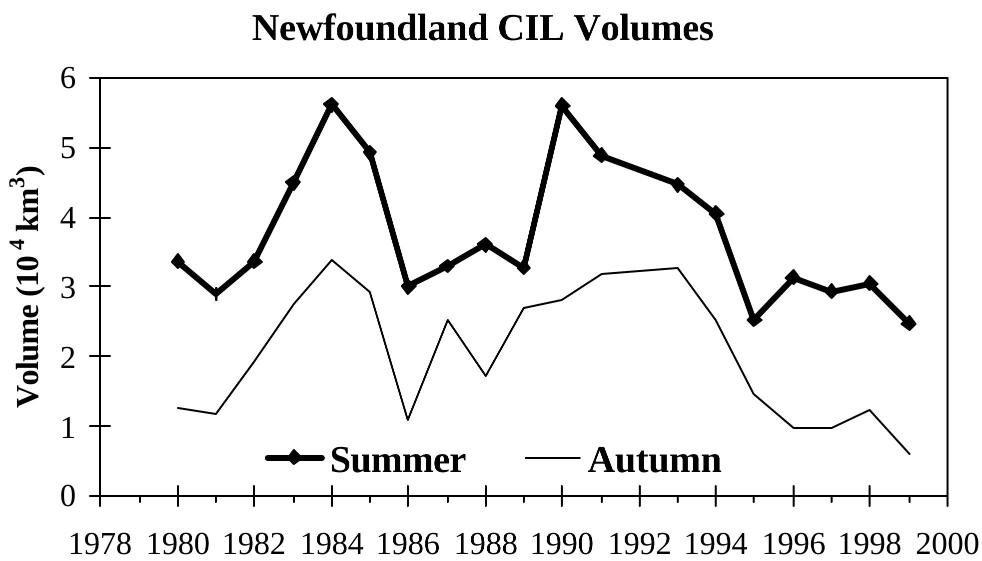


Fig. 24. The CIL volume in the summer and autumn within Divisions 2J and 3KL.

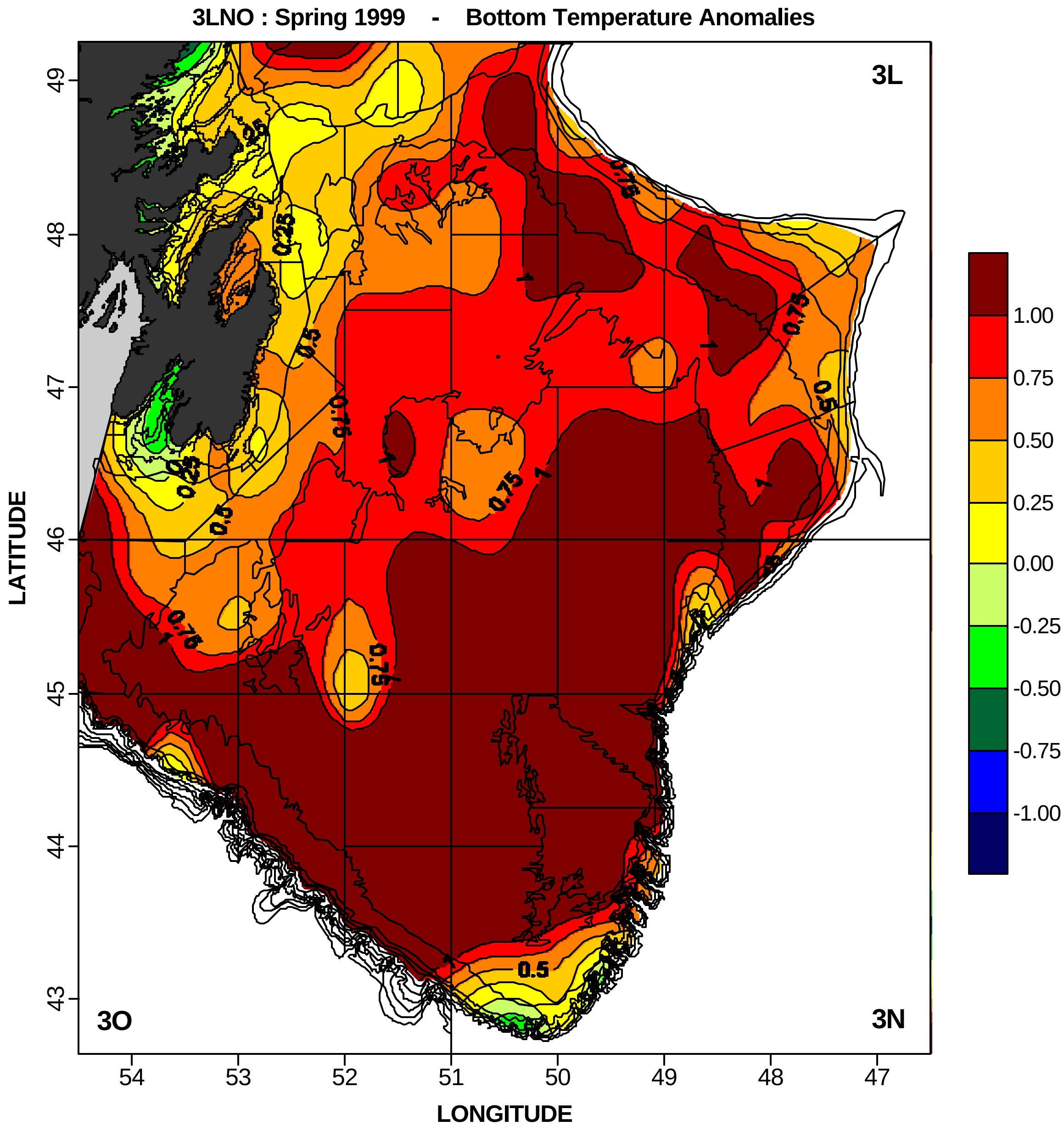


Fig. 25. Bottom temperature anomalies (in °C) during the spring in Divisions 3LNO.

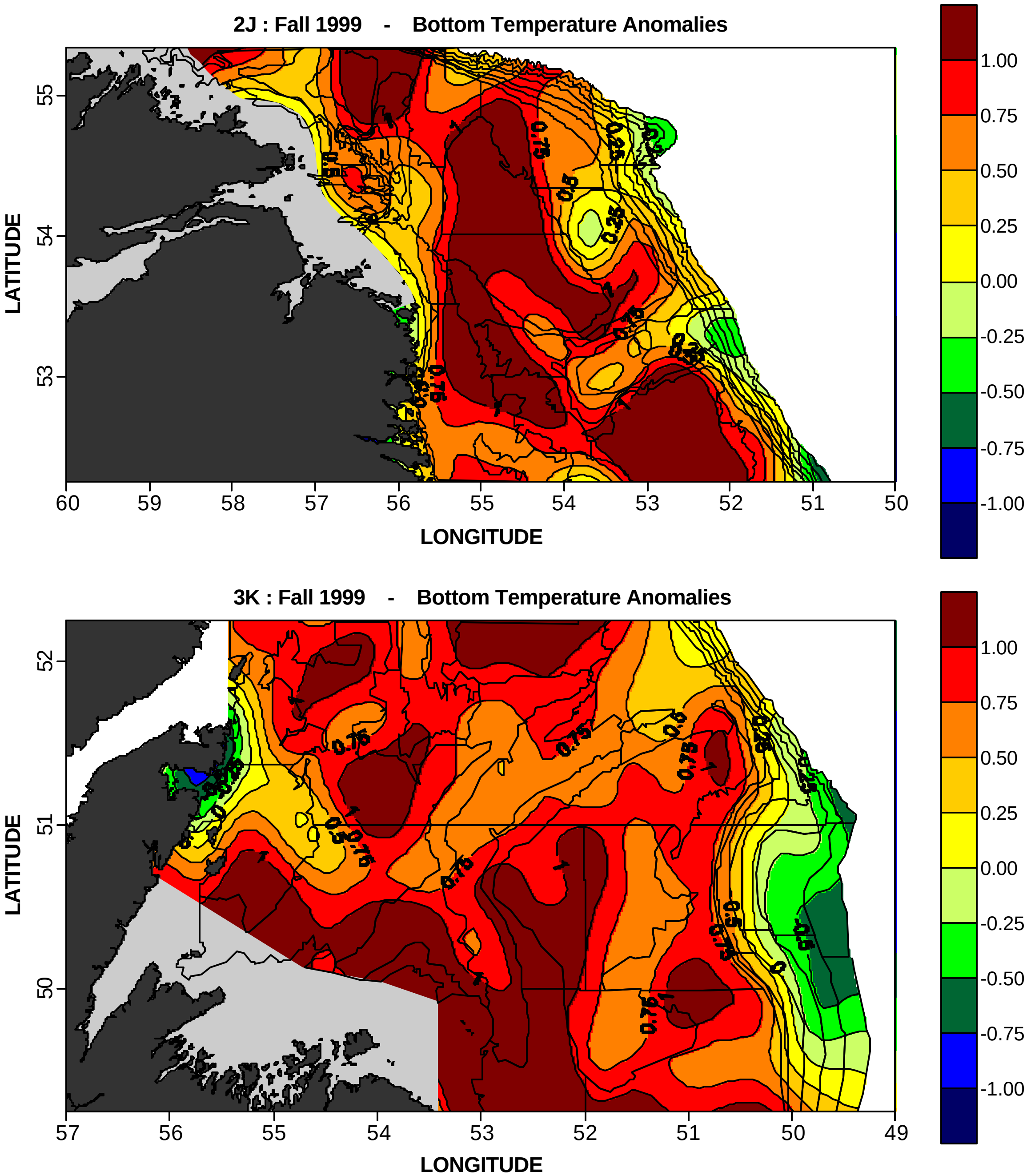


Fig. 26. Bottom temperature anomalies (in °C) during the autumn in Divisions 2J (top panel) and 3K (bottom panel).

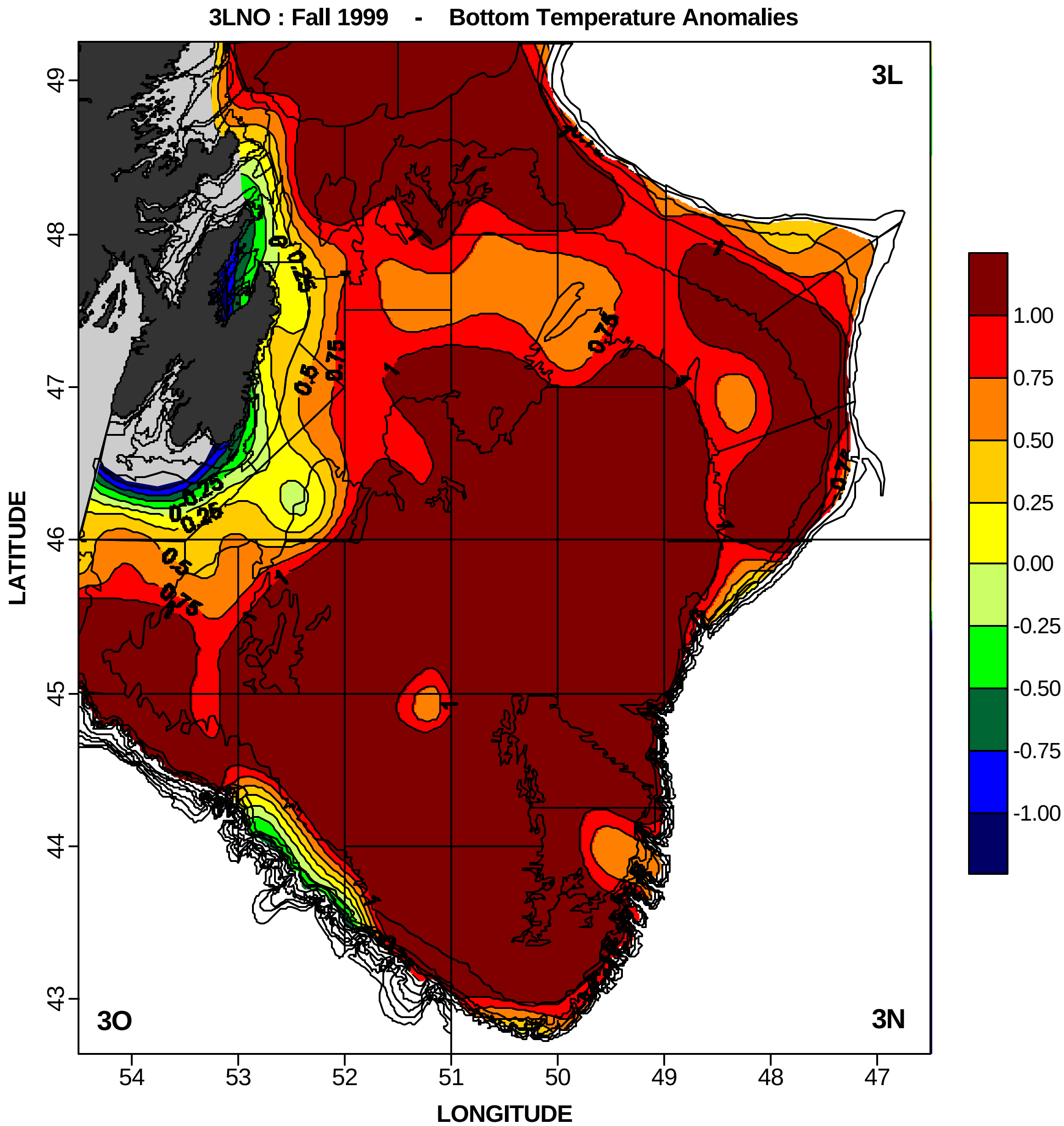


Fig. 27. Bottom temperature anomalies (in °C) during the autumn in Divisions 3LNO.

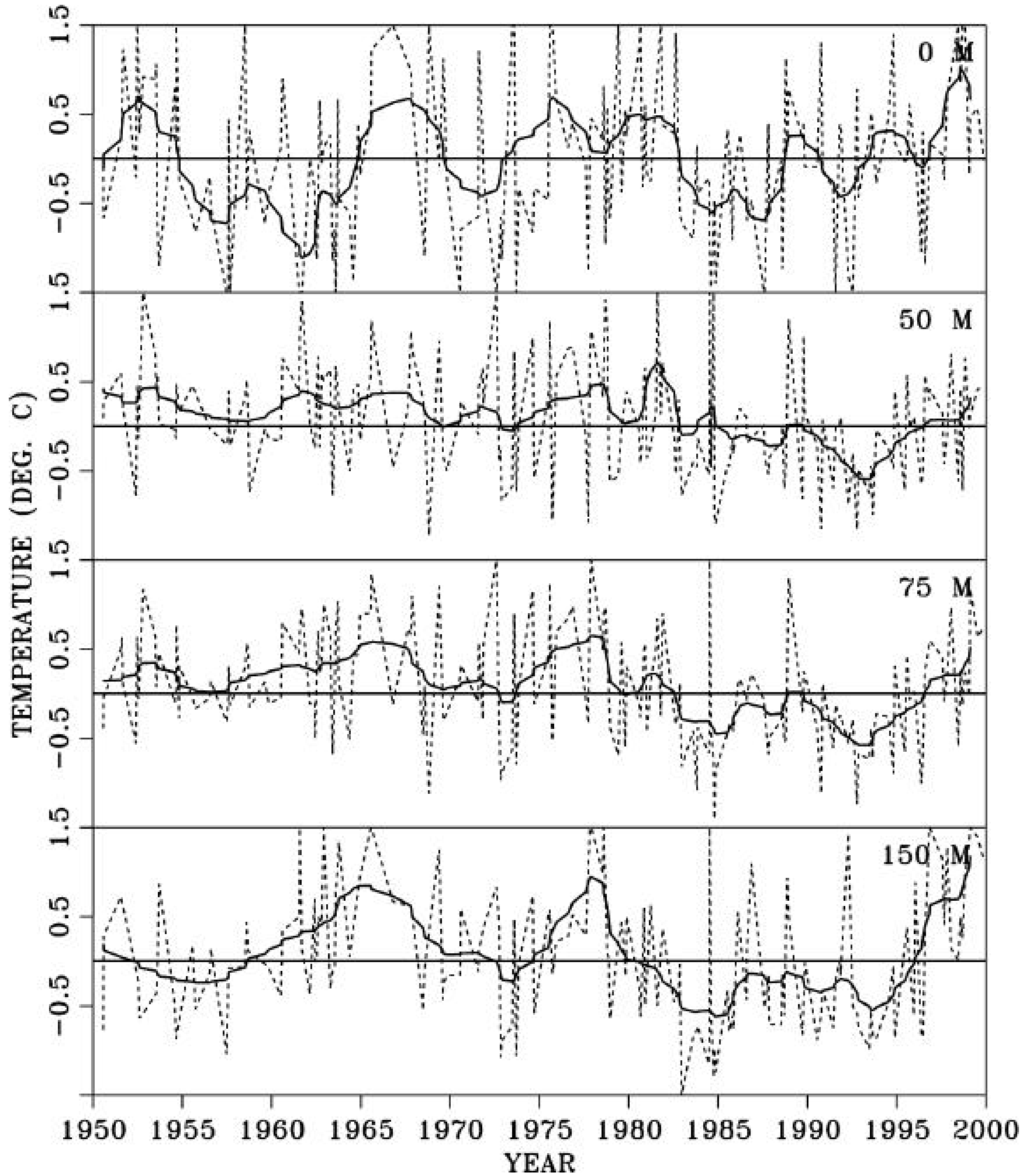


Fig. 28. Monthly mean temperature anomalies at selected depths over Hamilton Bank (Div. 2J). The solid line represents the smoothed temperature anomalies.

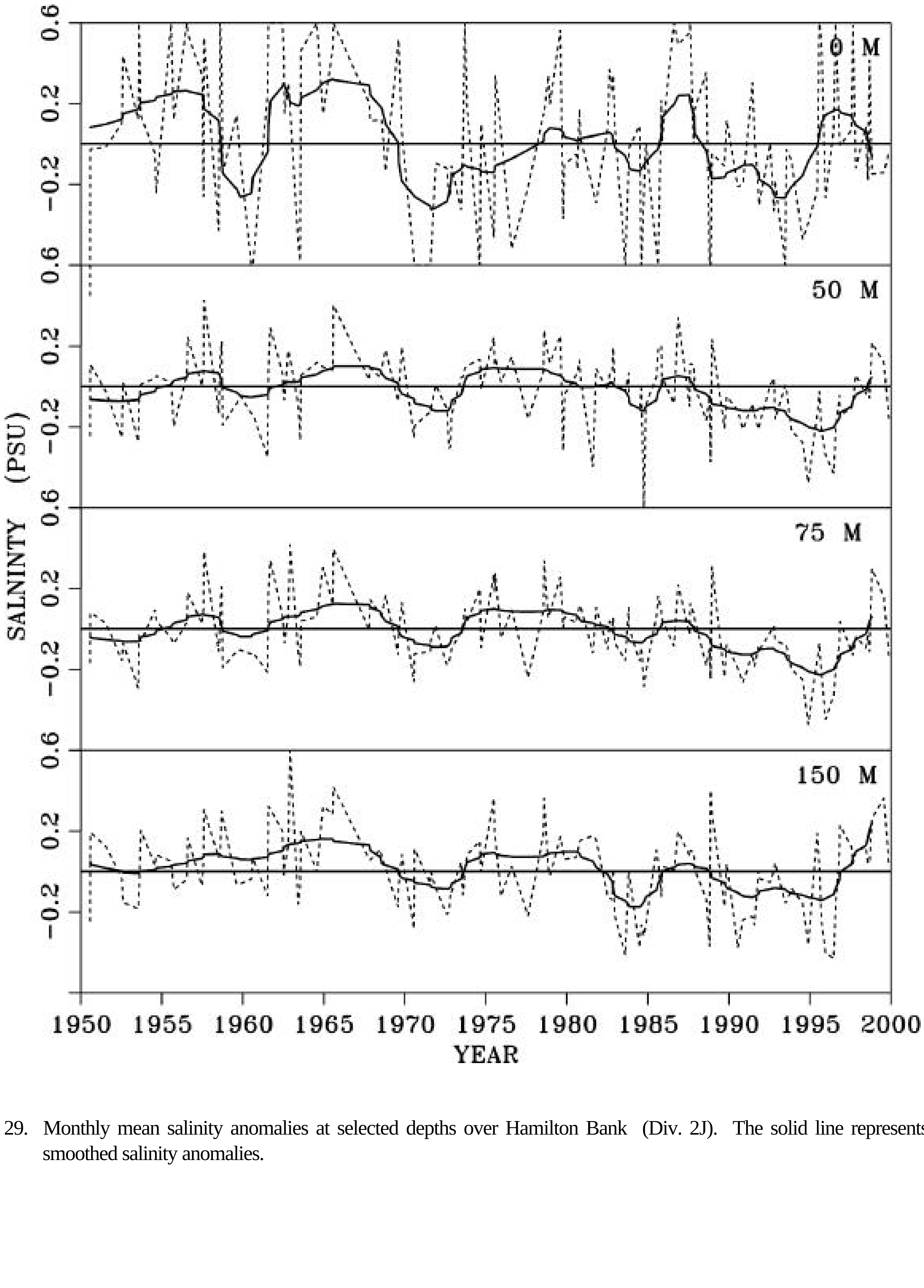


Fig. 29. Monthly mean salinity anomalies at selected depths over Hamilton Bank (Div. 2J). The solid line represents the smoothed salinity anomalies.

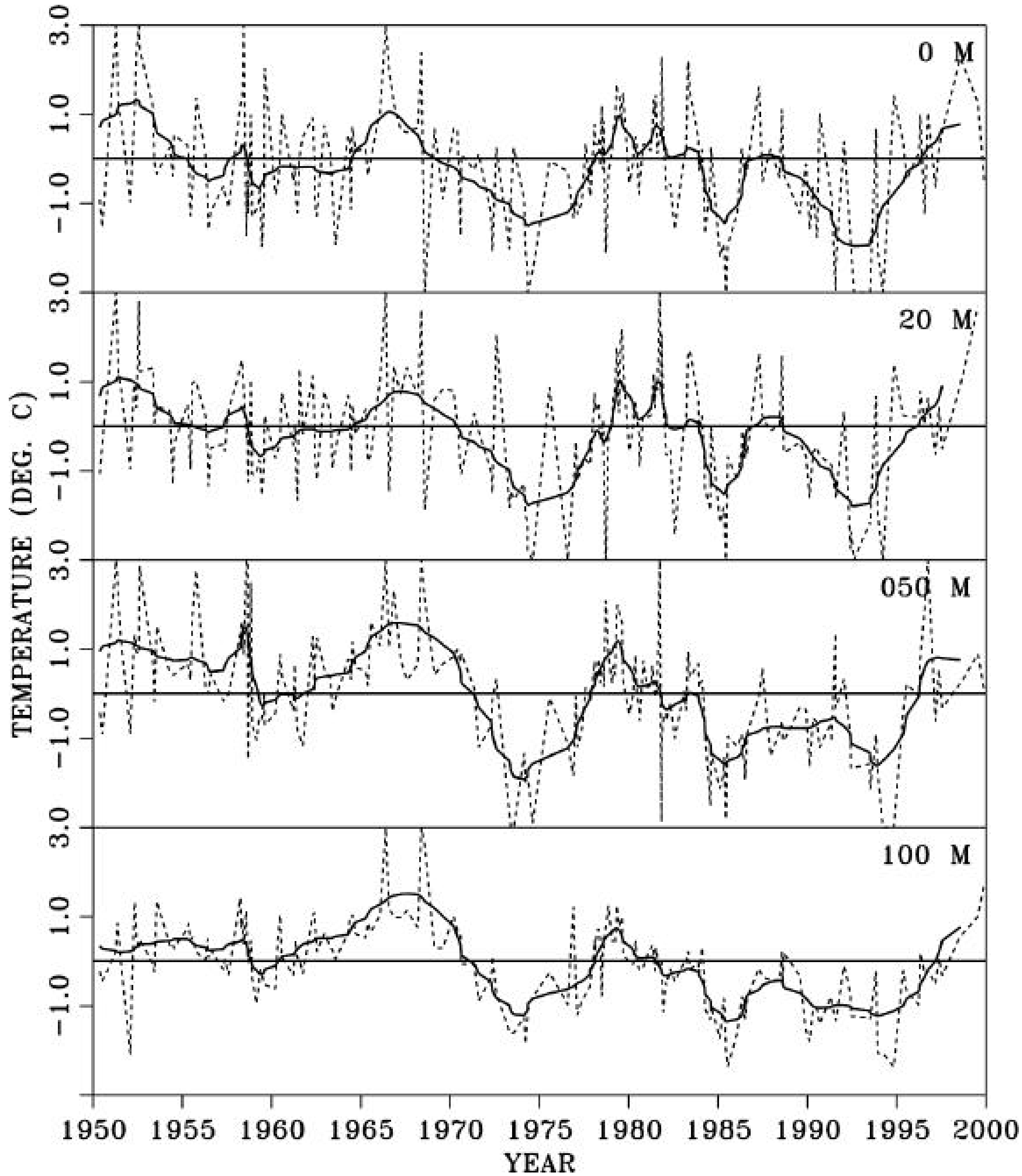


Fig. 30. Monthly mean temperature anomalies at selected depths over Flemish Cap (Div. 3M). The solid line represents the smoothed temperature anomalies.

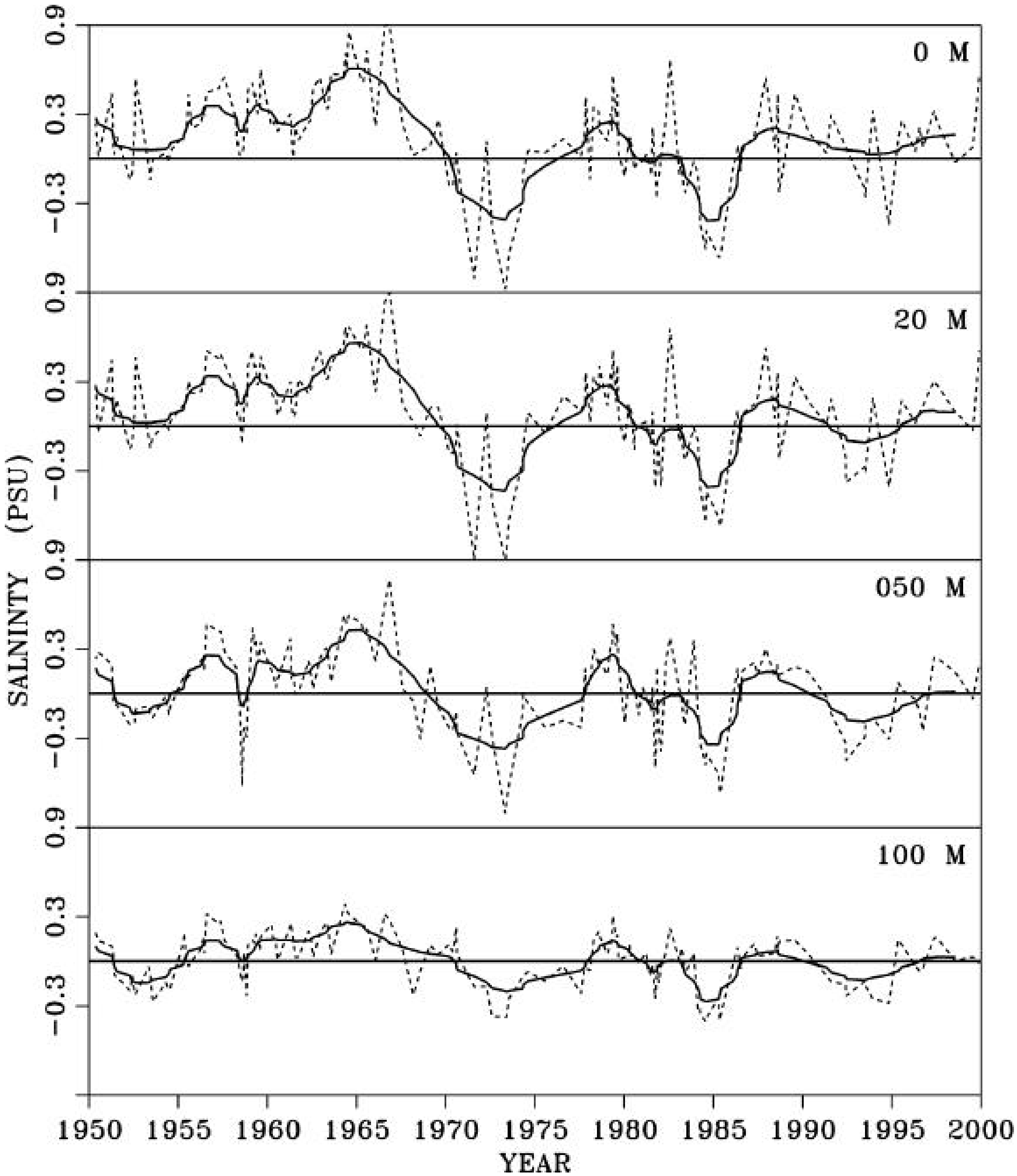


Fig. 31. Monthly mean salinity anomalies at selected depths over Flemish Cap (Div. 3M). The solid line represents the smoothed salinity anomalies.

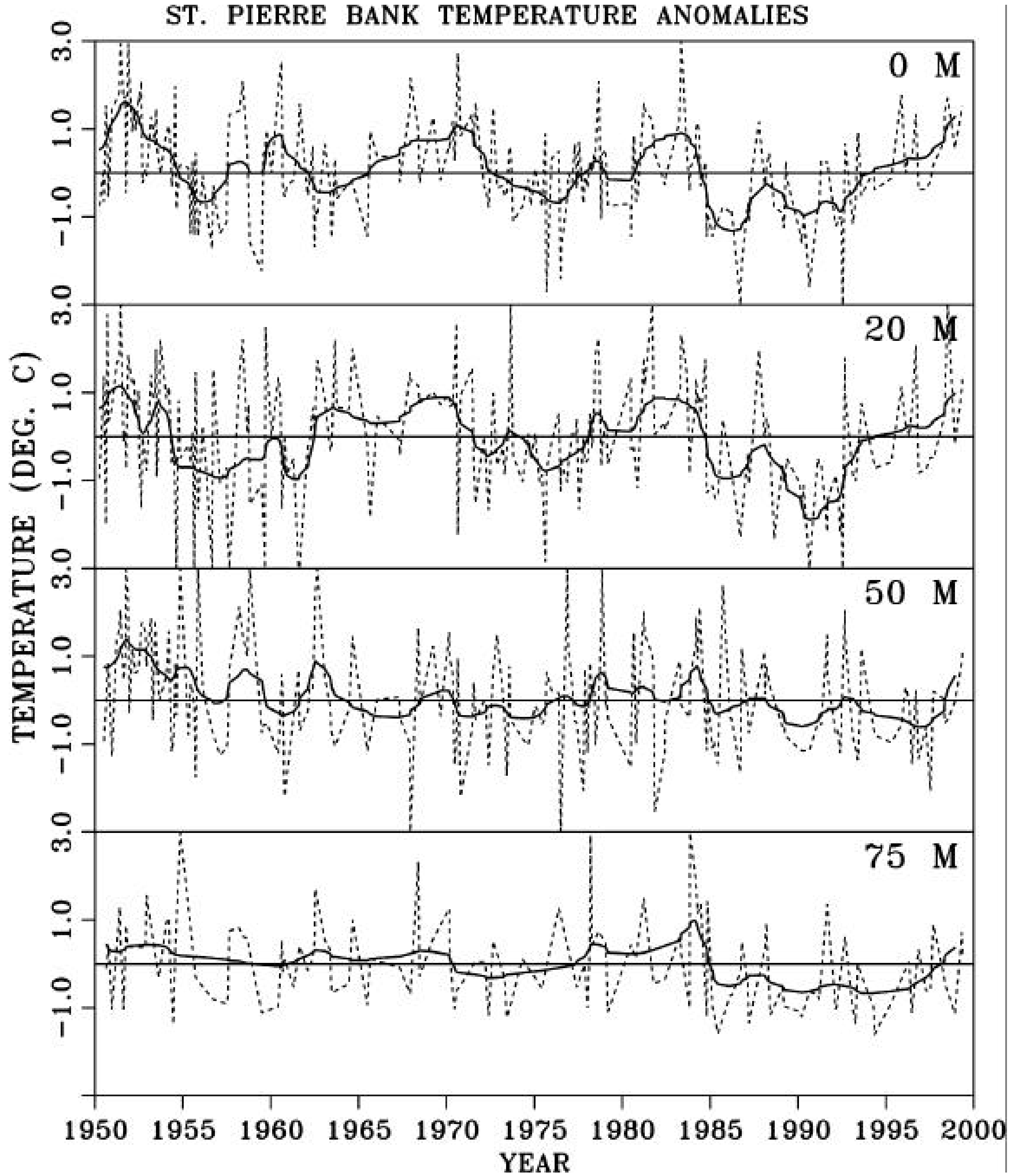


Fig. 32. Monthly mean temperature anomalies at selected depths over St. Pierre Bank (Div. 3Ps). The solid line represents the smoothed temperature anomalies.

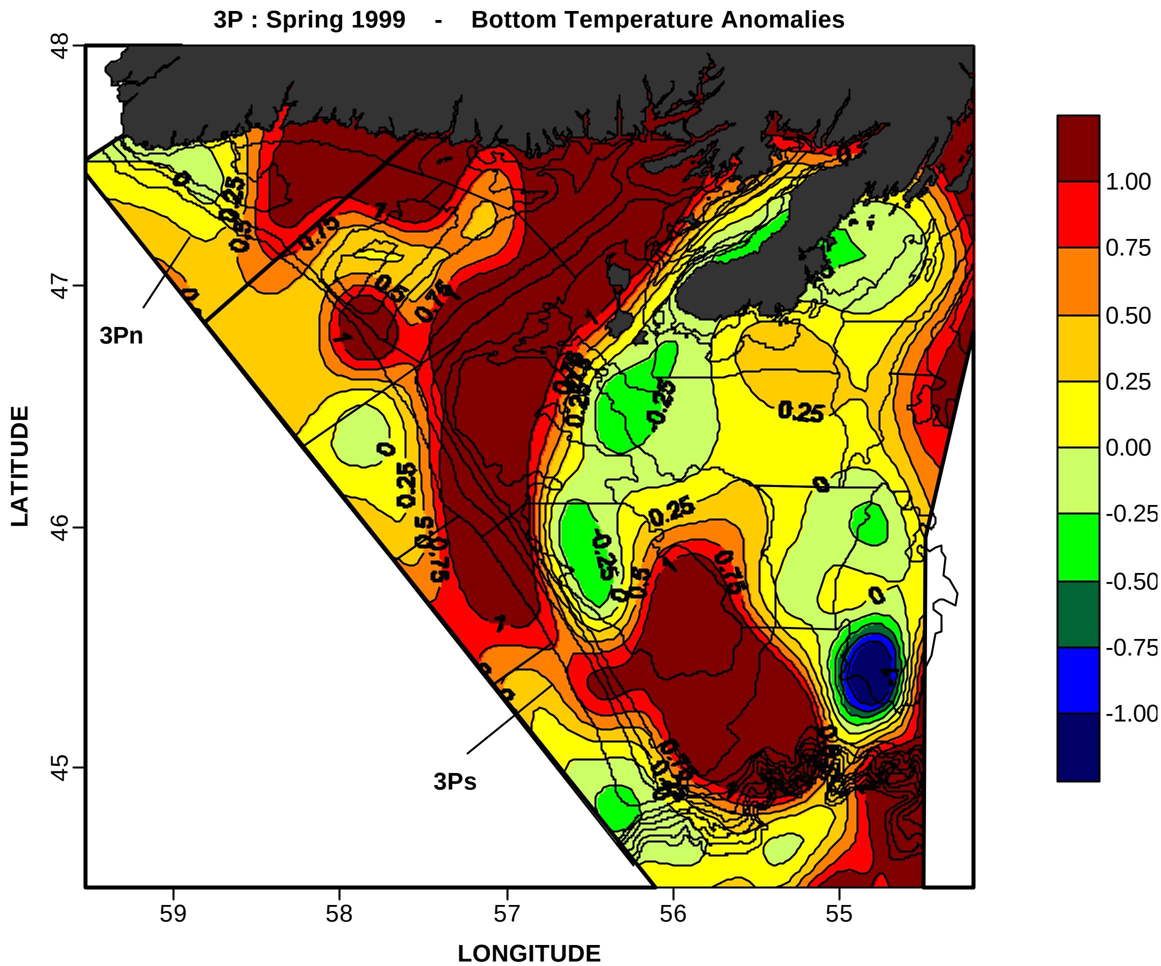


Fig. 33. Bottom temperature anomalies (in °C) during the spring in the vicinity of St. Pierre Bank (Div. 3Ps).

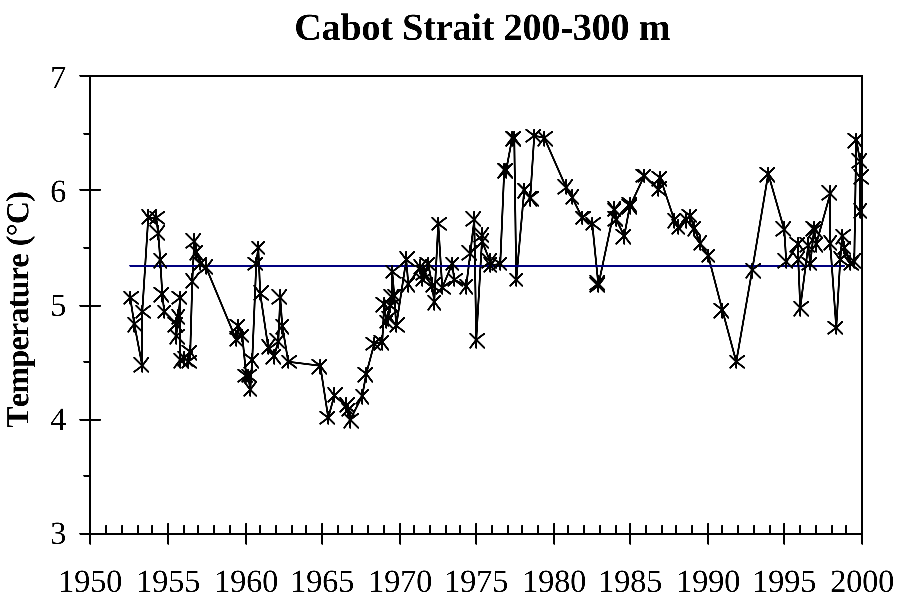


Fig. 34. The average temperature in the 200-300 m layer in Cabot Strait.

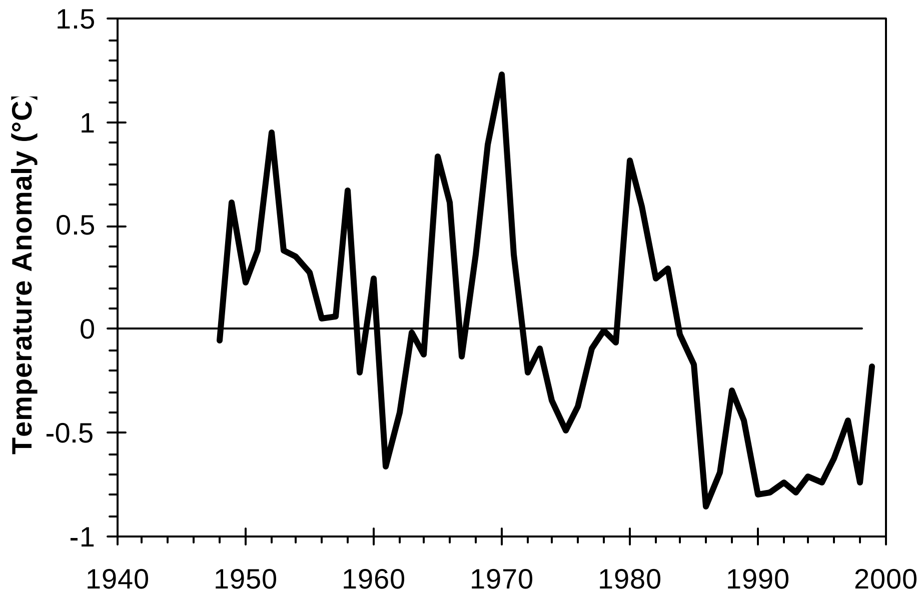


Fig. 35. Anomalies of the CIL core temperatures (extrapolated to July 15) for the Gulf of St. Lawrence.

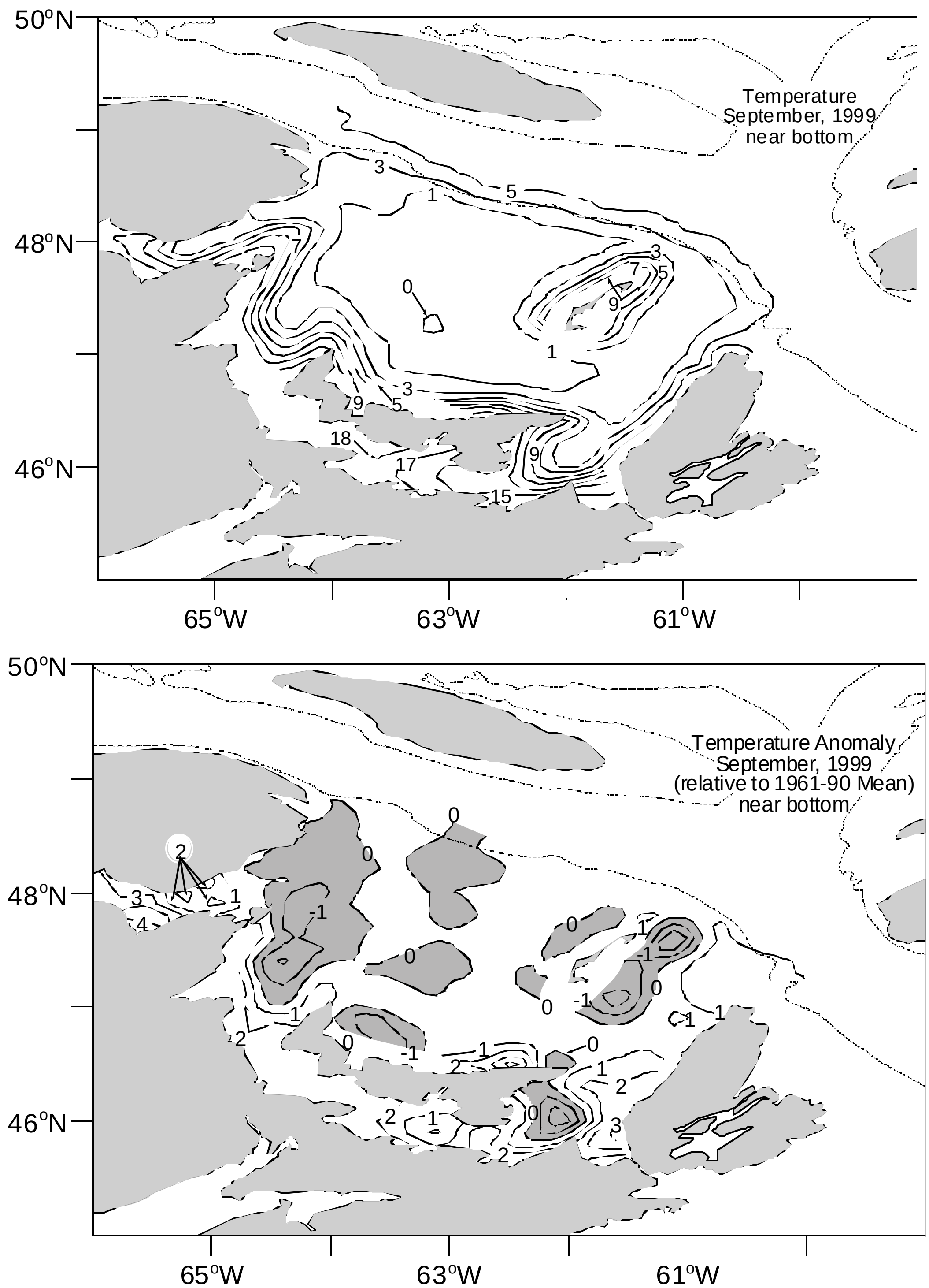


Fig. 36. Near-bottom temperatures (top panel) and their departure from the long-term (1961-1990) means (bottom panel) in the southern Gulf of St. Lawrence during the 1999 September survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

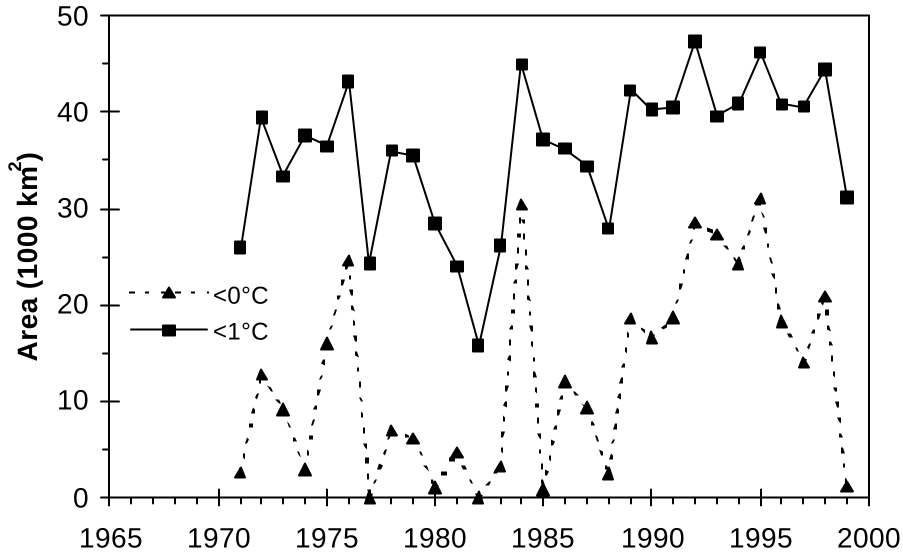


Fig. 37. The area of the Madgalen Shallows with bottom temperatures <0°C and <1°C during September.

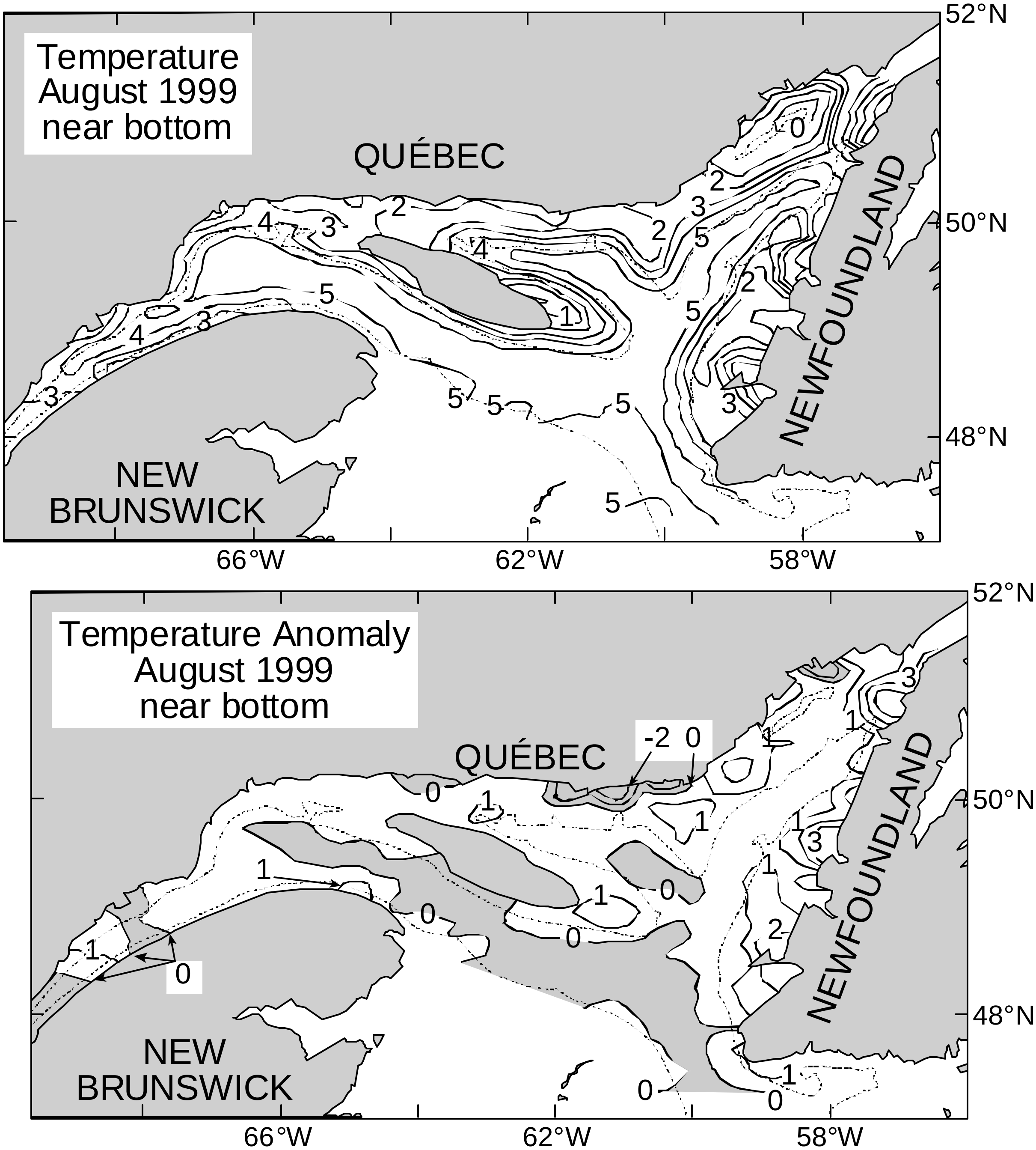


Fig. 38. Near-bottom temperatures (top panel) and their departure from the long-term (1961-1990) means (bottom panel) in the northern Gulf of St. Lawrence during the 1999 August survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

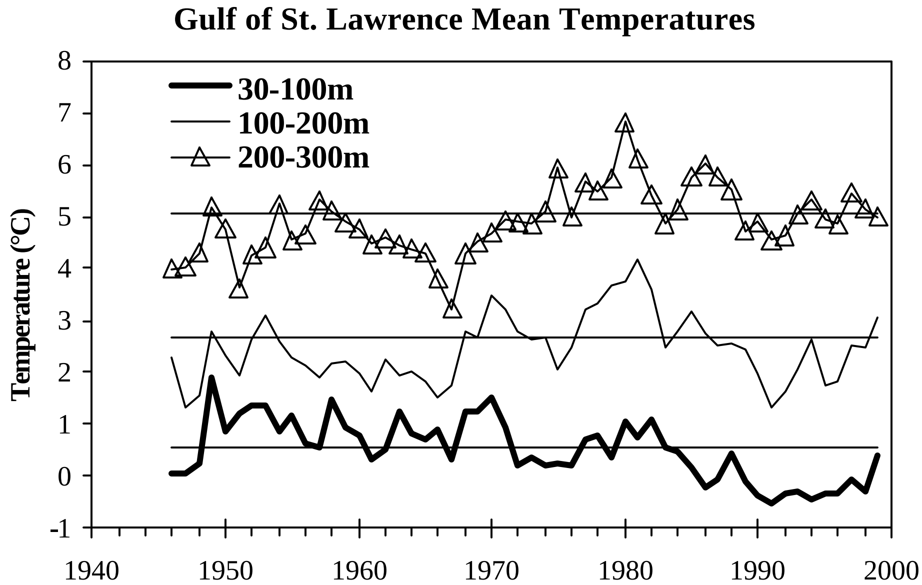


Fig. 39. The temperature of the 30-100 m, the 100-200 m and the 200-300 m layers in the Gulf of St. Lawrence during August-September. The horizontal lines indicate the long-term averages.

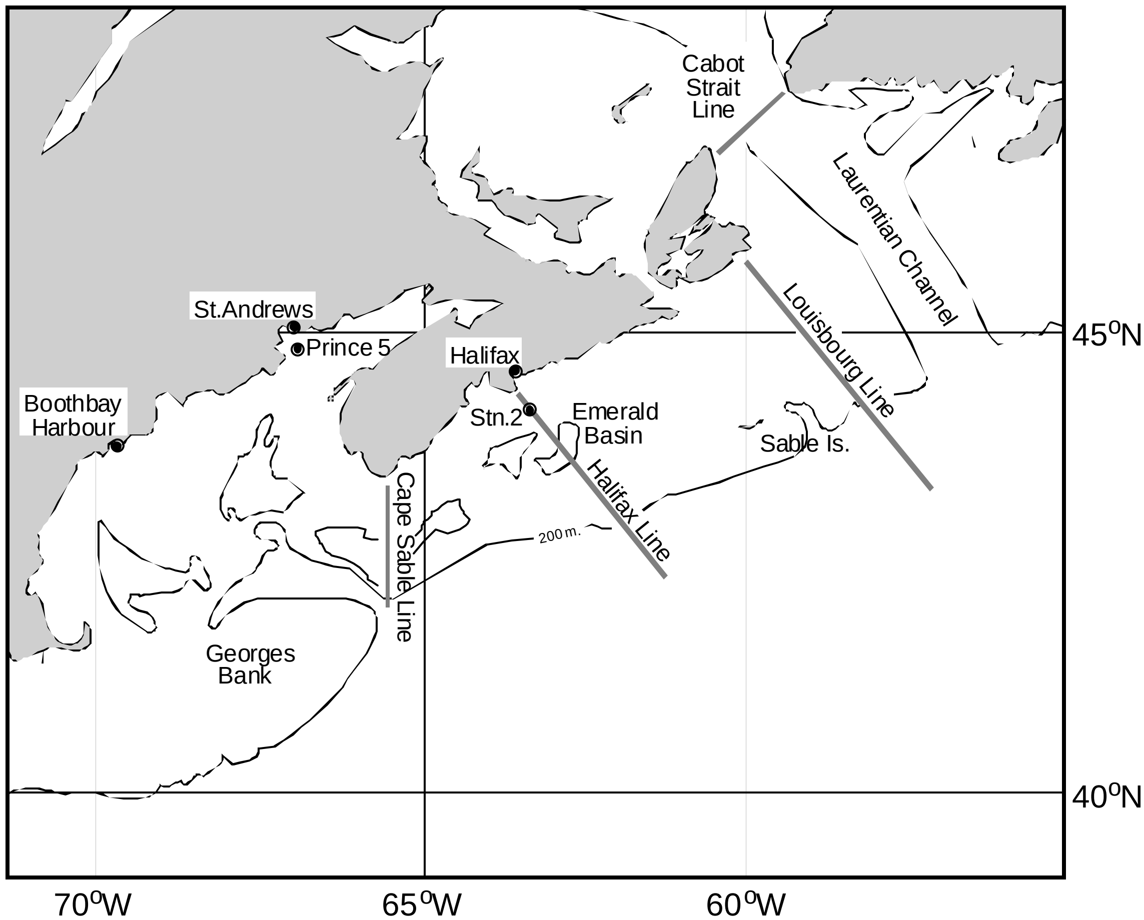


Fig. 40. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features.

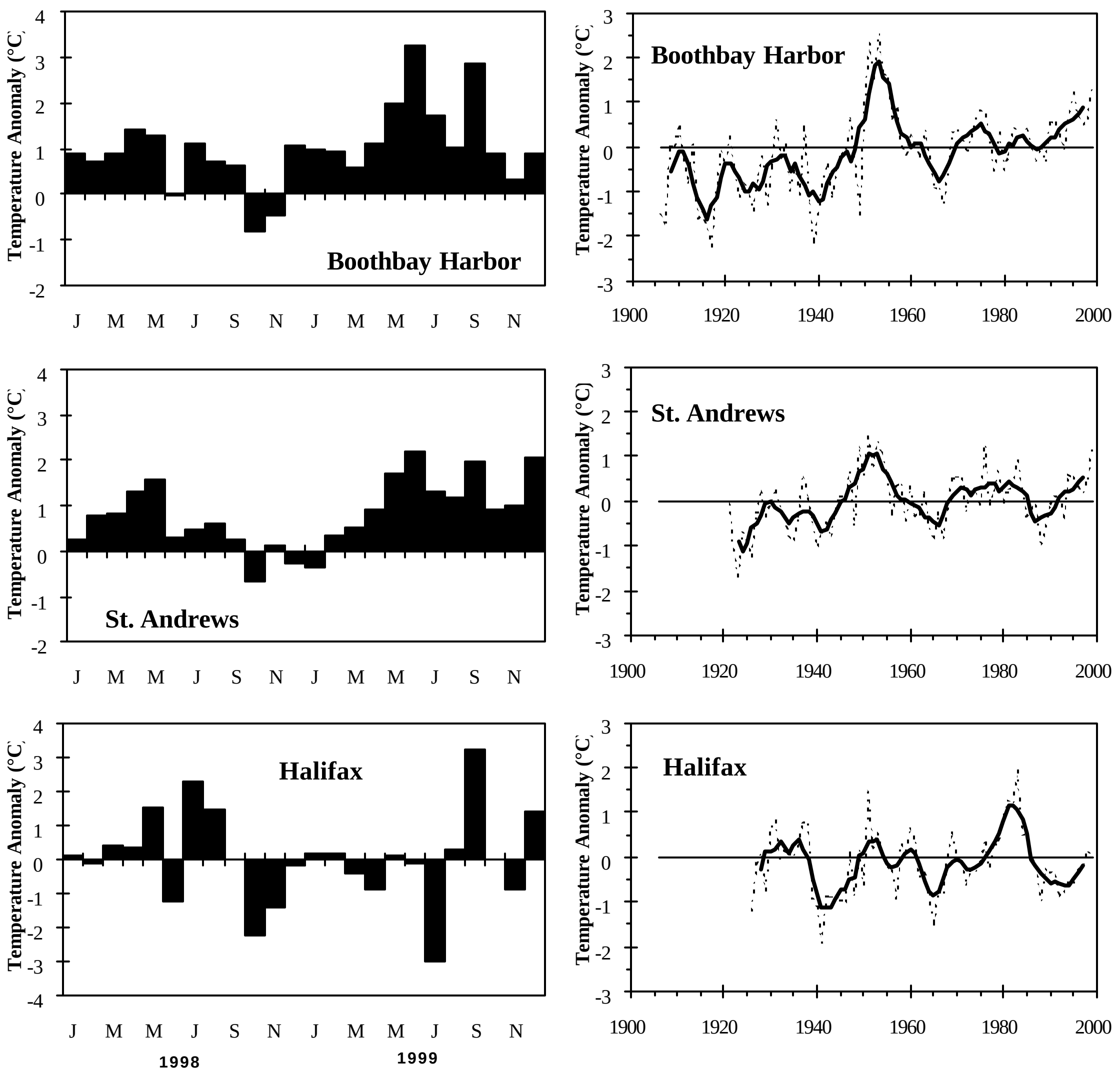


Fig. 41. The monthly sea surface temperature anomalies during 1998 and 1999 (left) and the annual temperature anomlaies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Anomalies are relative to the 1961-90 means.

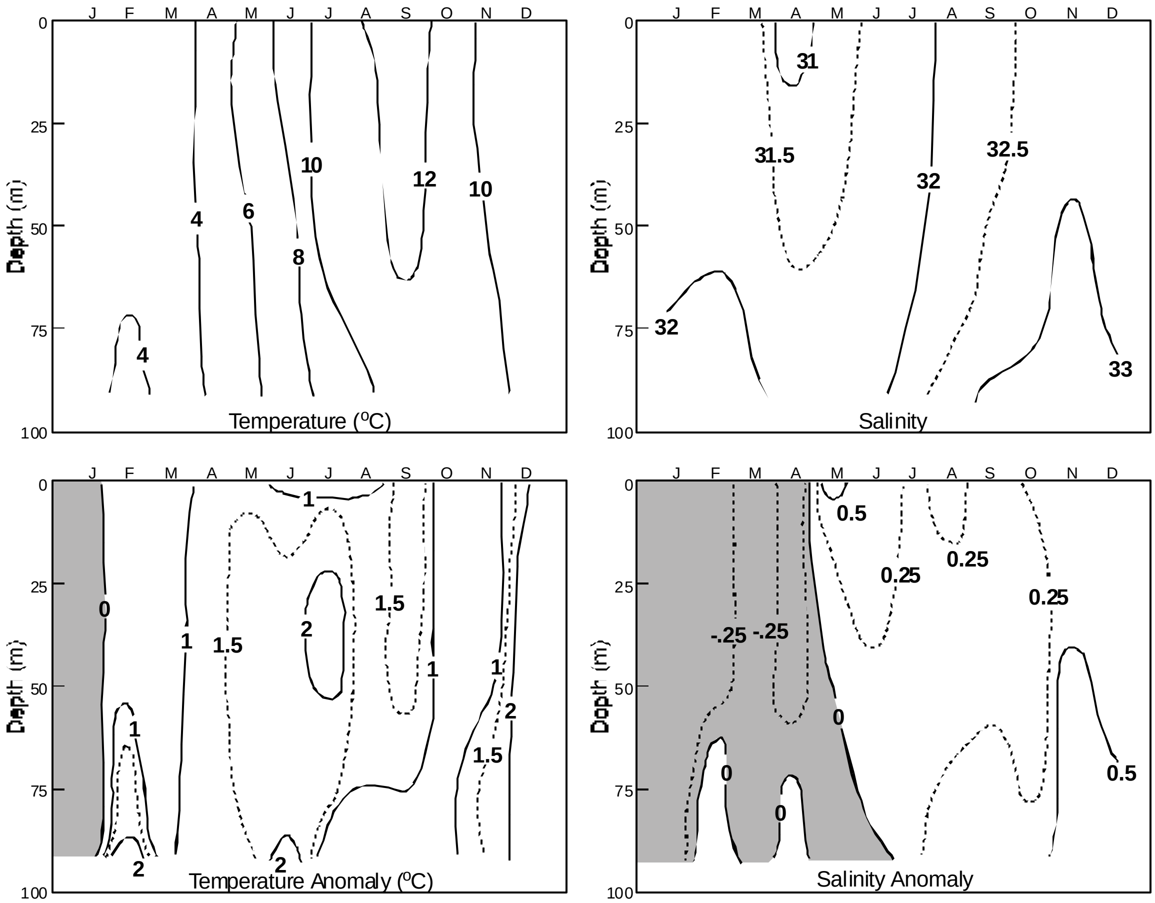


Fig. 42. Contours of monthly mean temperature (left) and salinity (right) and their anomalies (bottom panels) at Prince 5 as a function of depth during 1999 relative to the 1961-90 means. Colder and fresher-than-normal conditions are shaded.

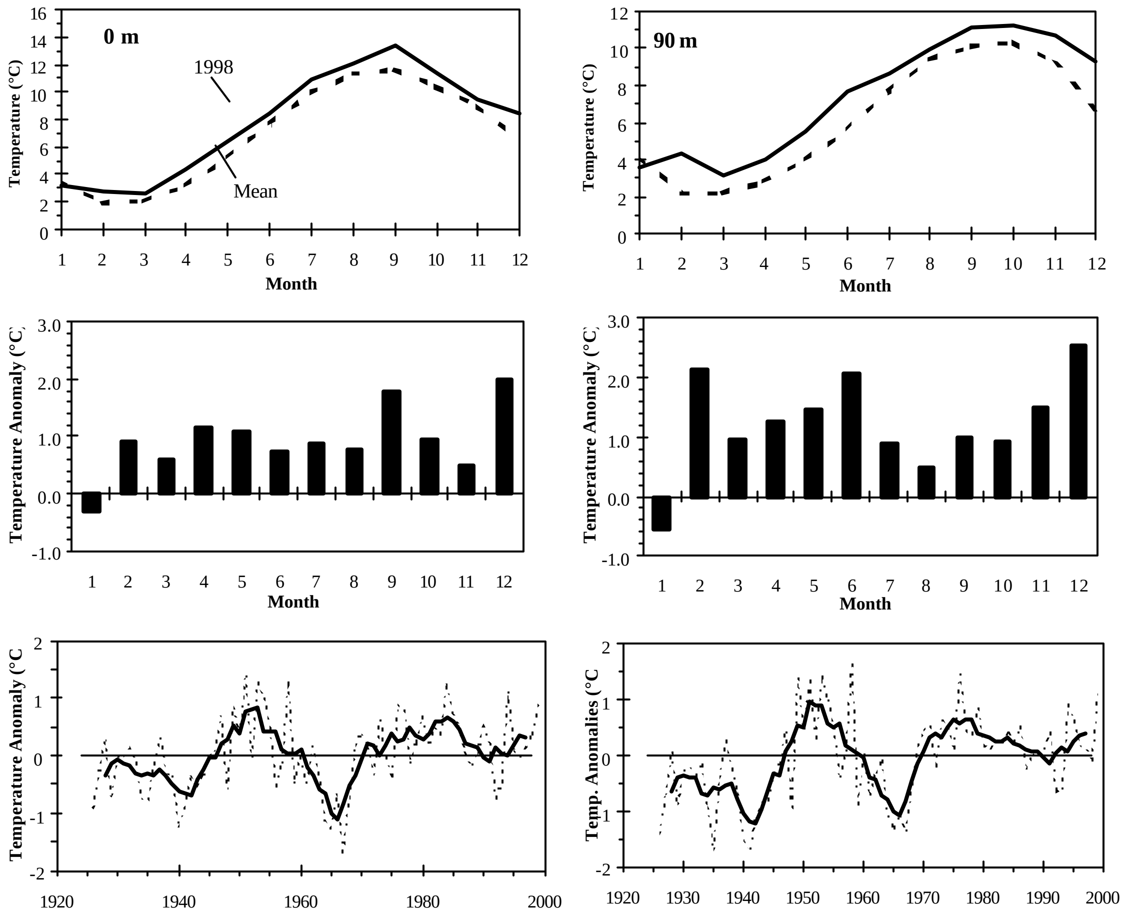


Fig. 43. The monthly mean temperatures for 1999 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

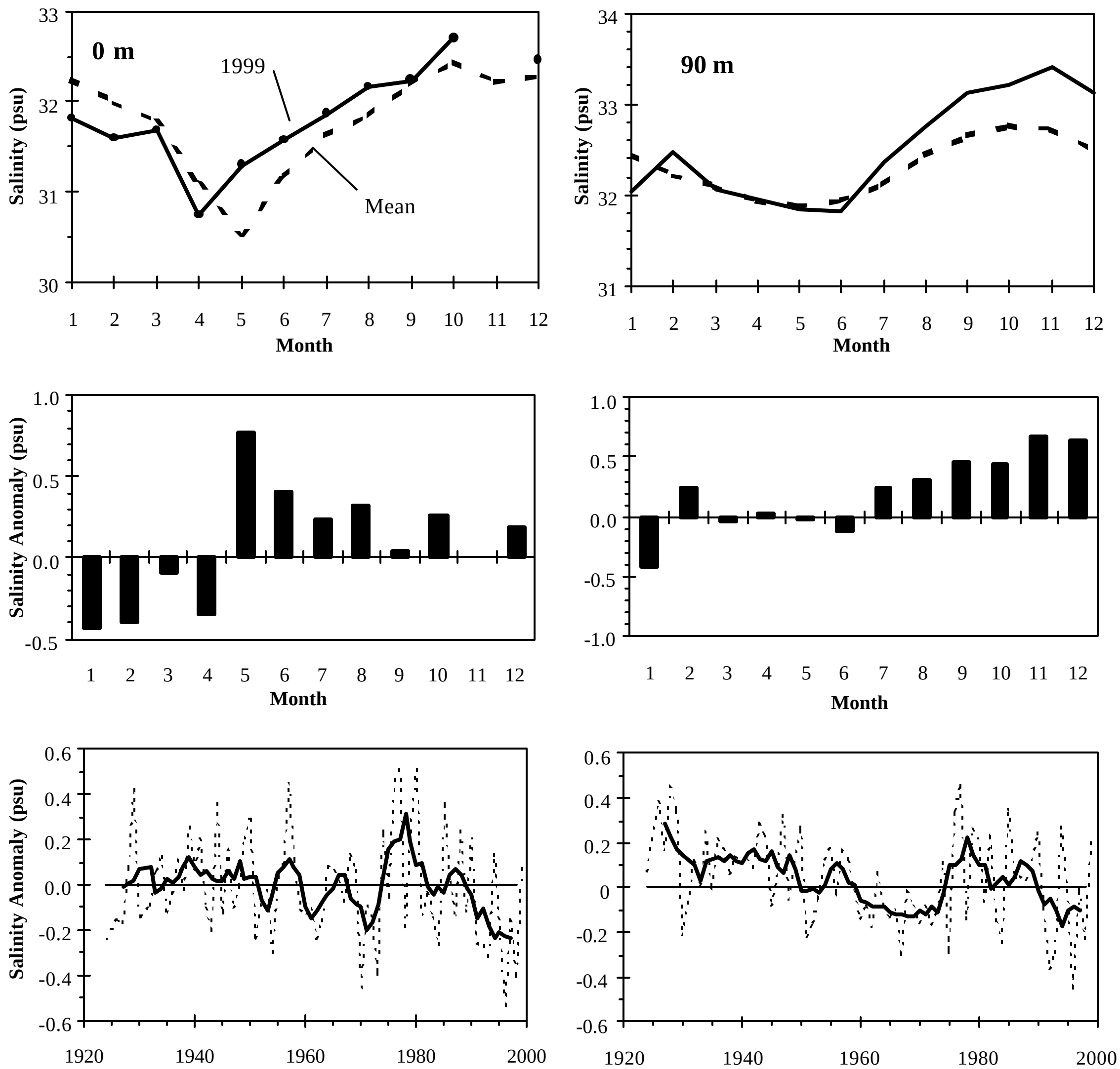


Fig. 44. The monthly mean salinities for 1999 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

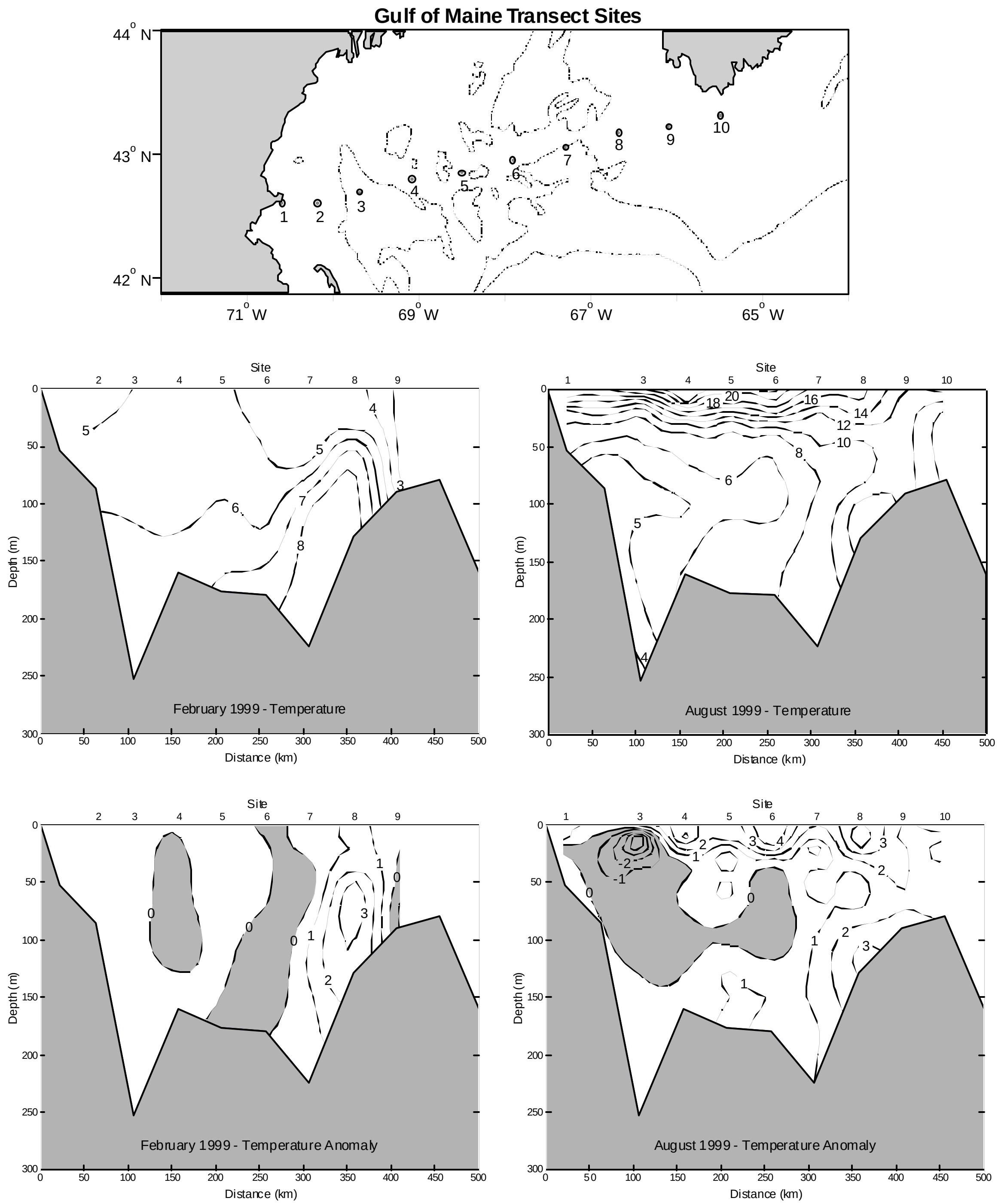


Fig. 45. The temperature (middle panels) and temperature anomalies (bottom panels) in °C along a XBT transect (top panel) across the Gulf of Maine during February and August 1999.

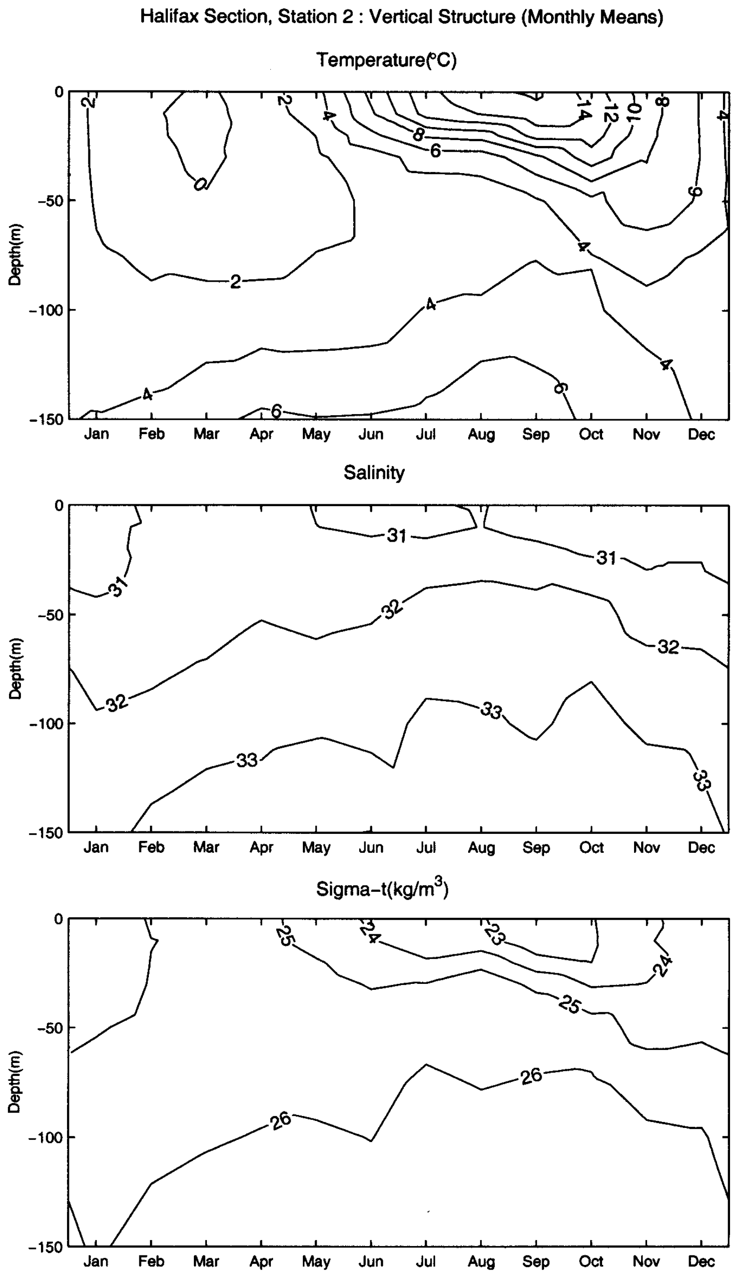


Fig. 46. Contours of the long-term monthly means of temperature, salinity and density (sigma-t) at the standard station H2 (Halifax Line 2).

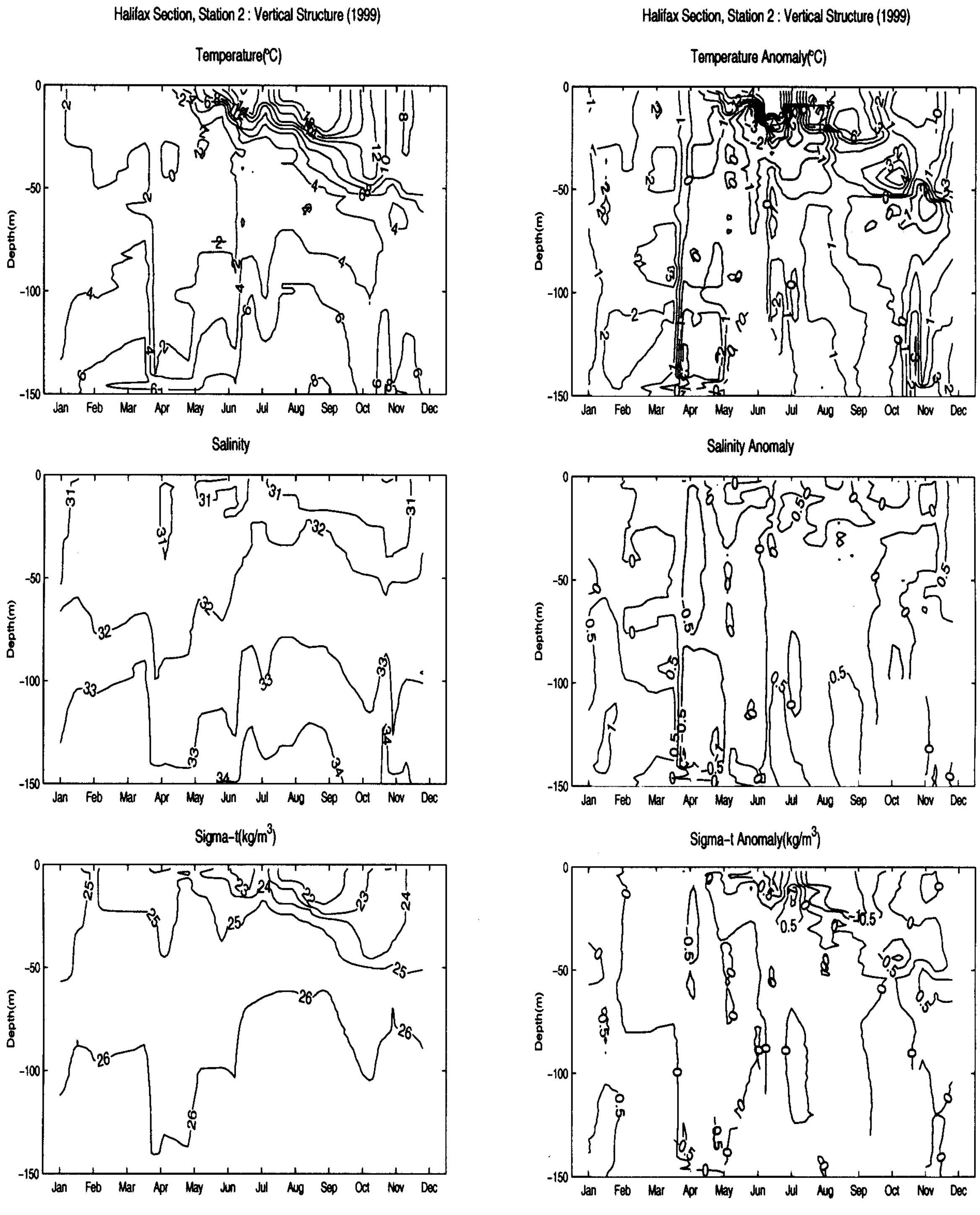


Fig. 47. Contours of temperature, salinity and density (sigma-t) for 1999 (left) and their anomalies (right) at the standard station H2.

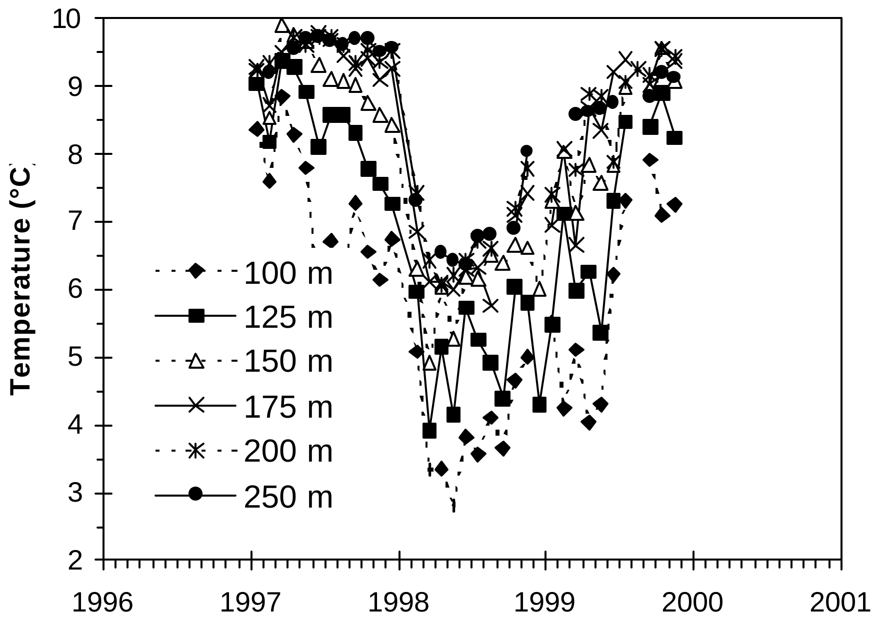


Fig. 48. Time series of temperature by depth in Emerald Basin from available data for 1997 to 1999.

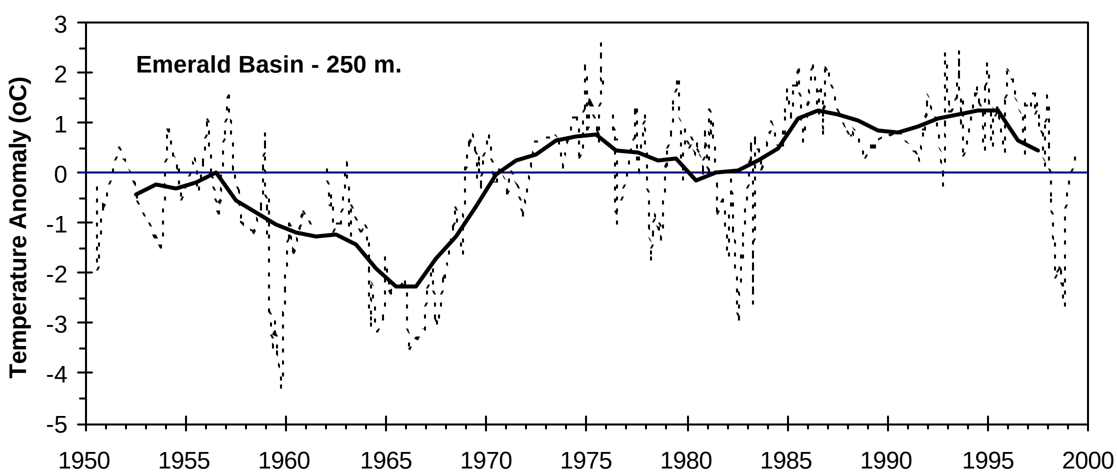
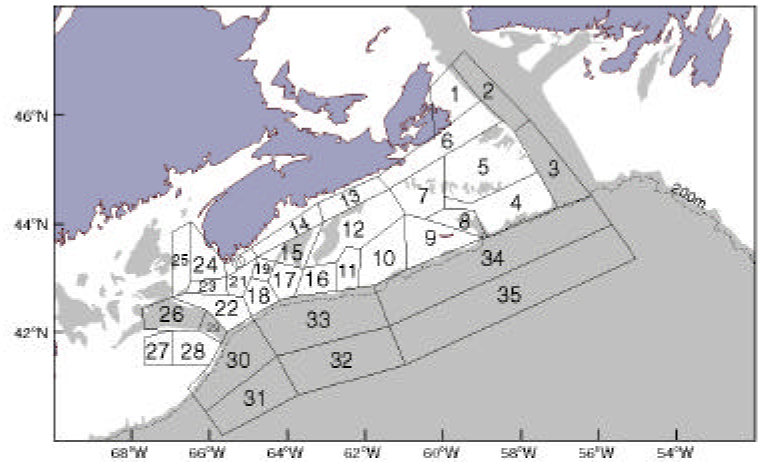
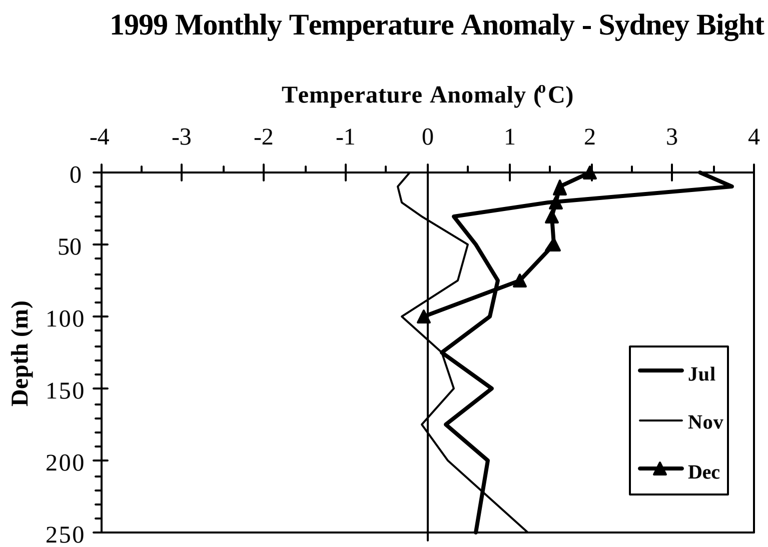


Fig. 49. Time series of available monthly mean temperature anomalies at 250 m in Emerald Basin Bank (dashed line) and their 5-year running means (solid line).



1. Sydney Bight
2. N. Laurentian Channel
3. S. Laurentian Channel
4. Banquereau
5. Misaine Bank
6. Canso
7. Middle Bank
8. The Gully
9. Sable Island
10. Western Bank
11. Emerald Bank
12. Emerald Basin
13. Eastern Shore
14. South Shore
15. Lahave Basin
16. Saddle
17. Lahave Bank
18. Baccaro Bank
19. Roseway Bank
20. Shelburne
21. Roseway Basin
22. Browns Bank
23. Roseway Channel
24. Lurcher Shoals
25. E. Gulf of Maine
26. Georges Basin
27. Georges Shoal
28. E. Georges Bank
29. N.E. Channel
30. Southern Slope
31. Southern Offshore
32. Central Offshore
33. Central Slope
34. Northern Slope
35. Northern Offshore

Fig. 50. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).



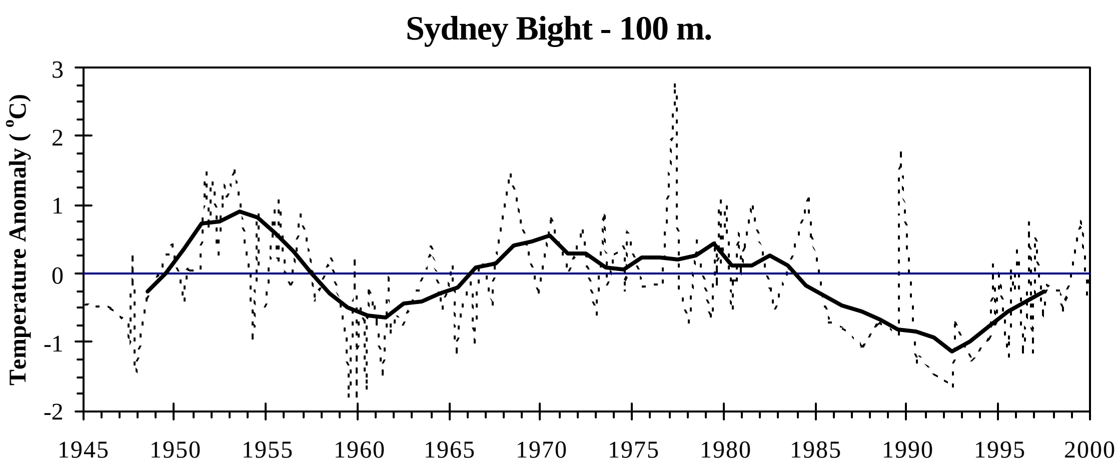
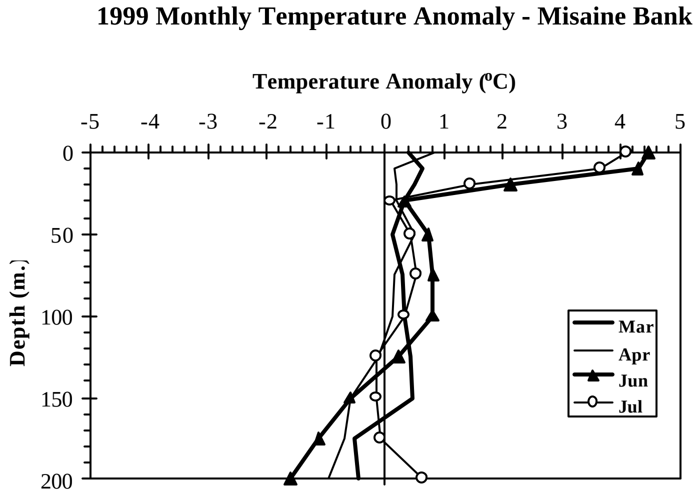
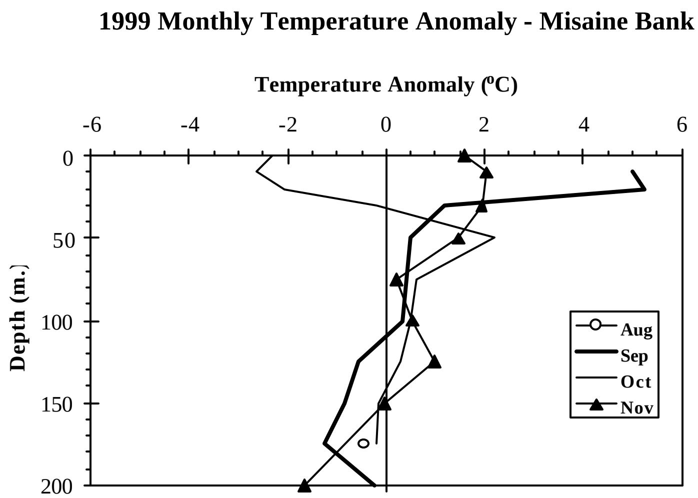


Fig. 51. 1999 monthly temperature anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1-Fig. 50).





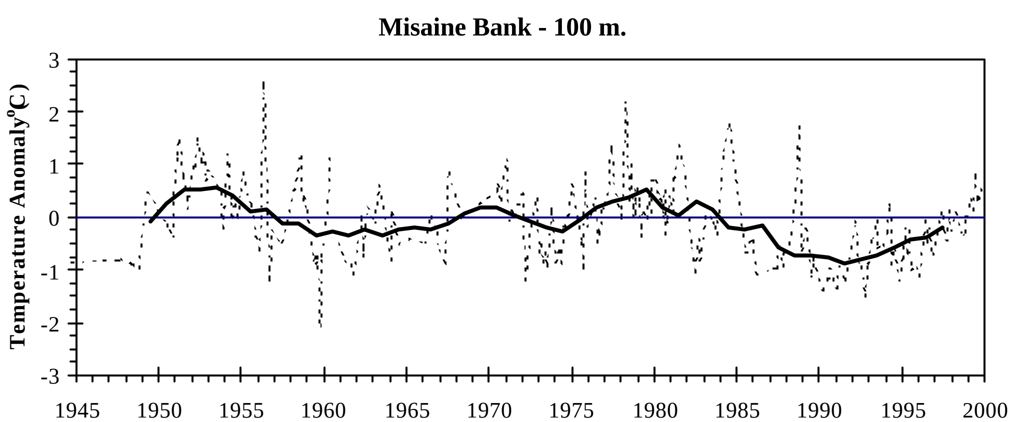


Fig. 52. 1999 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5-Fig. 50).

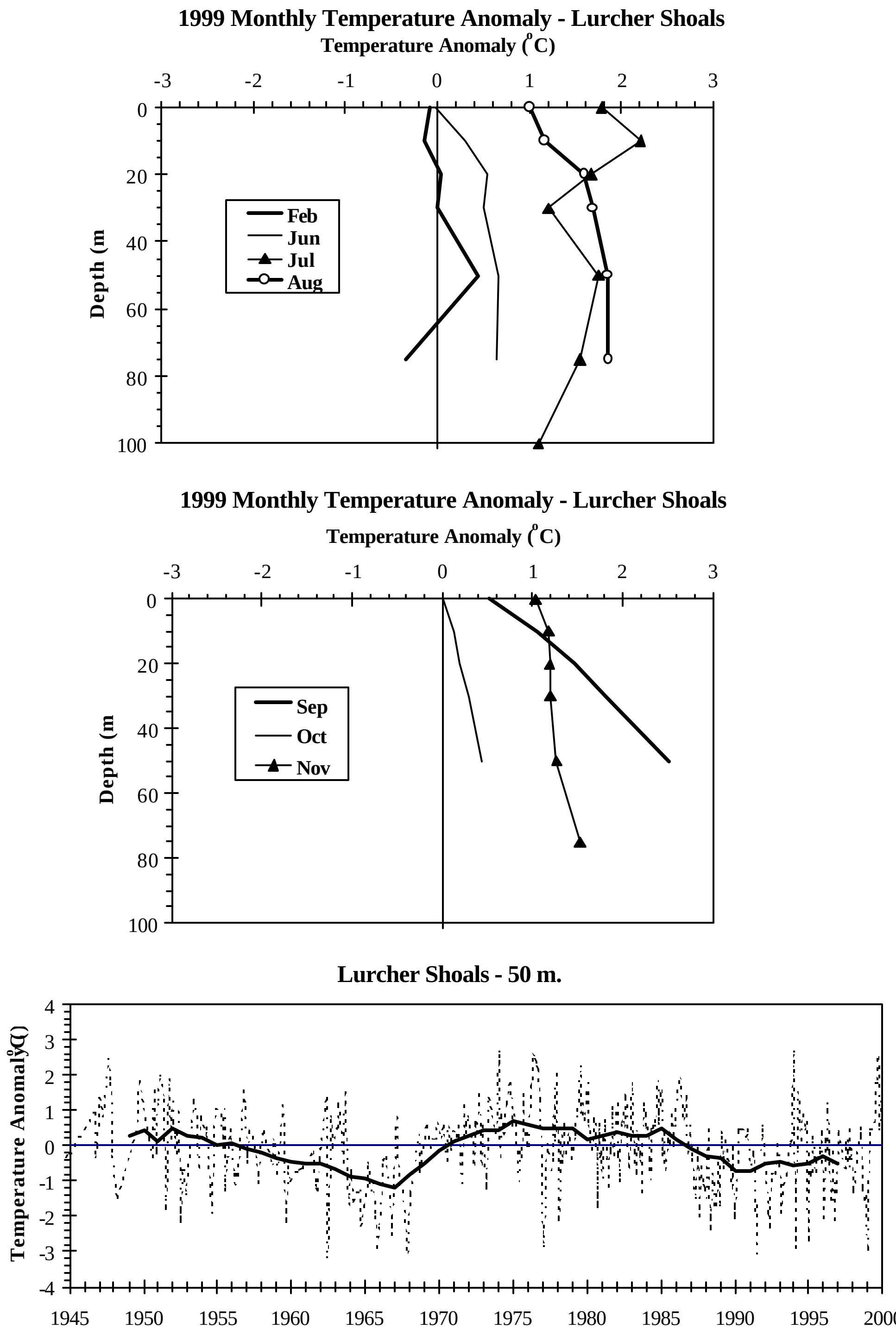


Fig. 53. 1999 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Lurcher (area 24-Fig. 50).

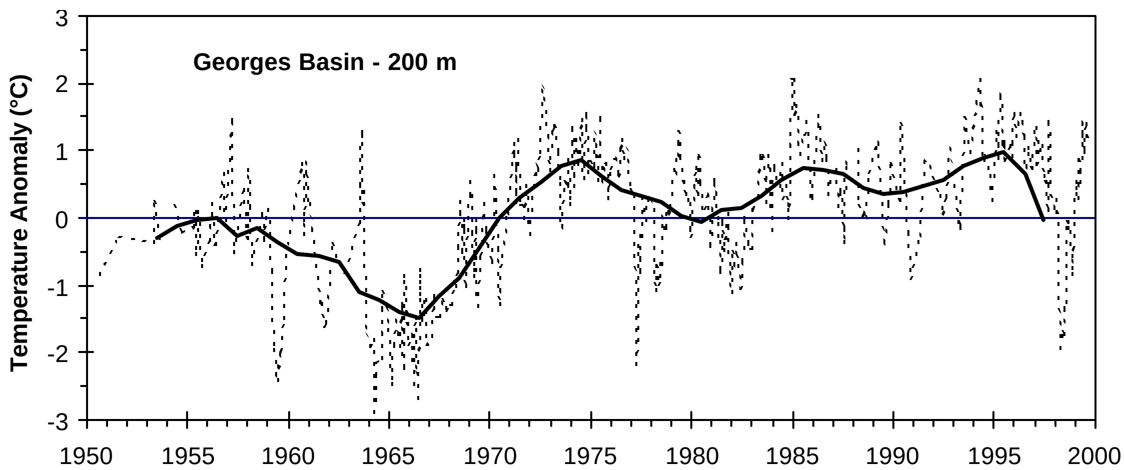


Fig. 54. Time series of monthly mean temperature anomalies at 200 m in Georges Basin (dashed lines) and their 5-year running means (solid line).

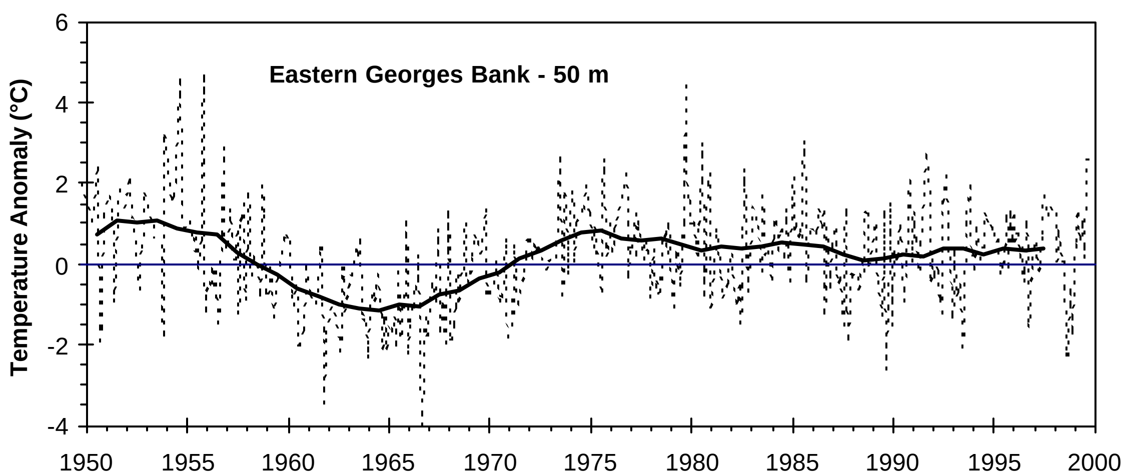


Fig. 55. Time series of monthly mean temperature anomalies at 50 m on eastern Georges Bank (dashed lines) and their 5-year running means (solid line).

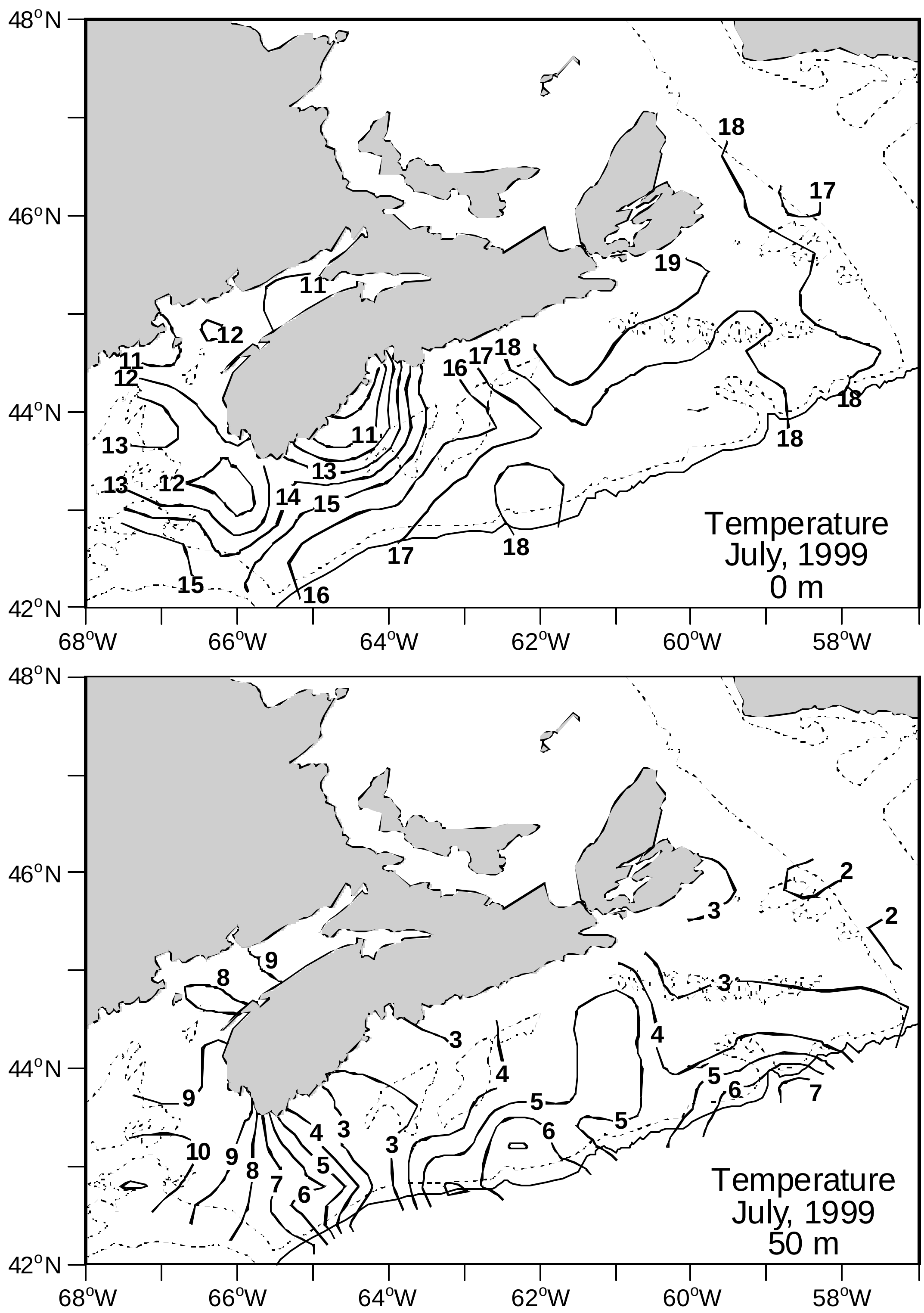


Fig. 56a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 1999 July groundfish surveys.

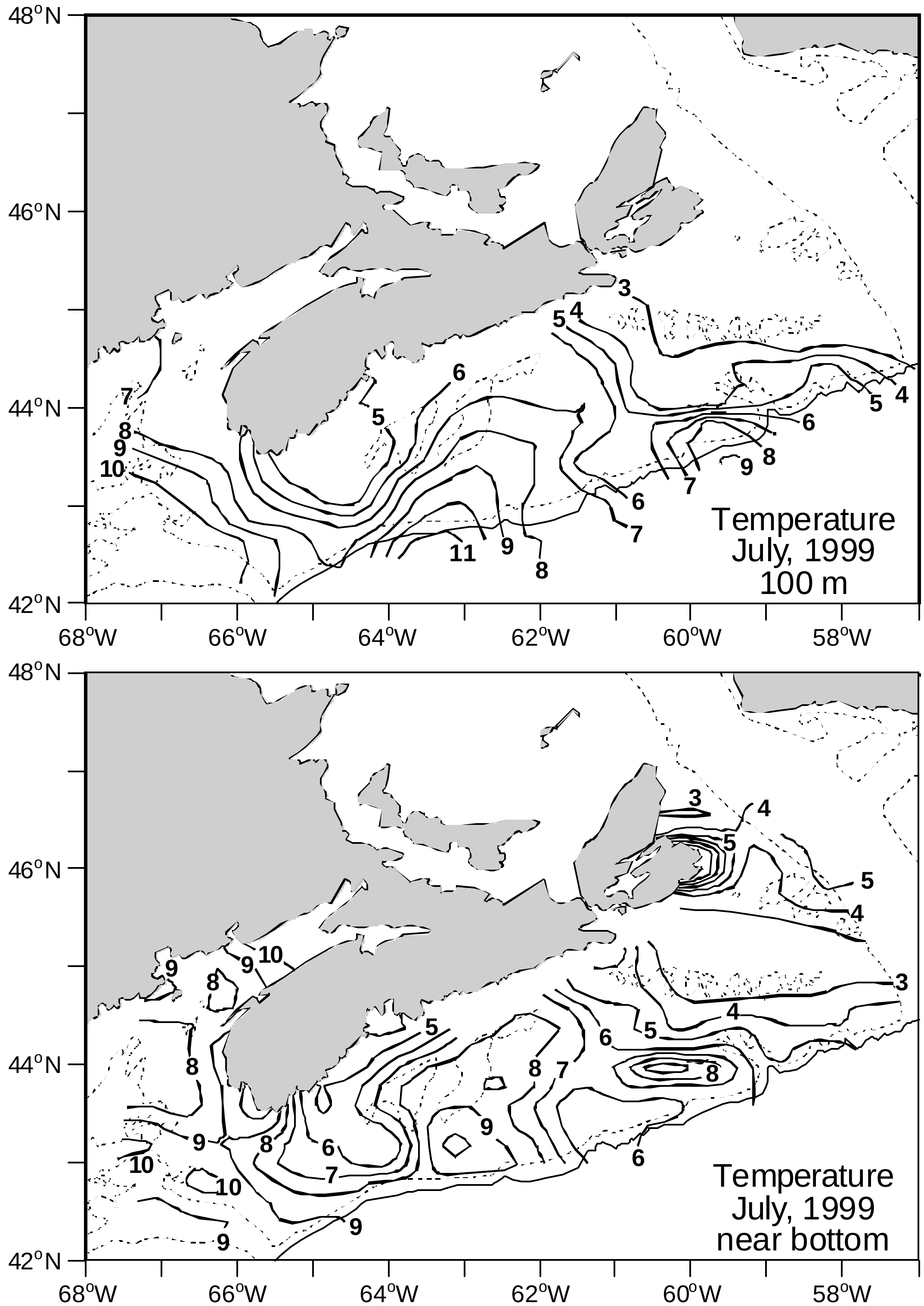


Fig. 56b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 1999 July groundfish surveys.

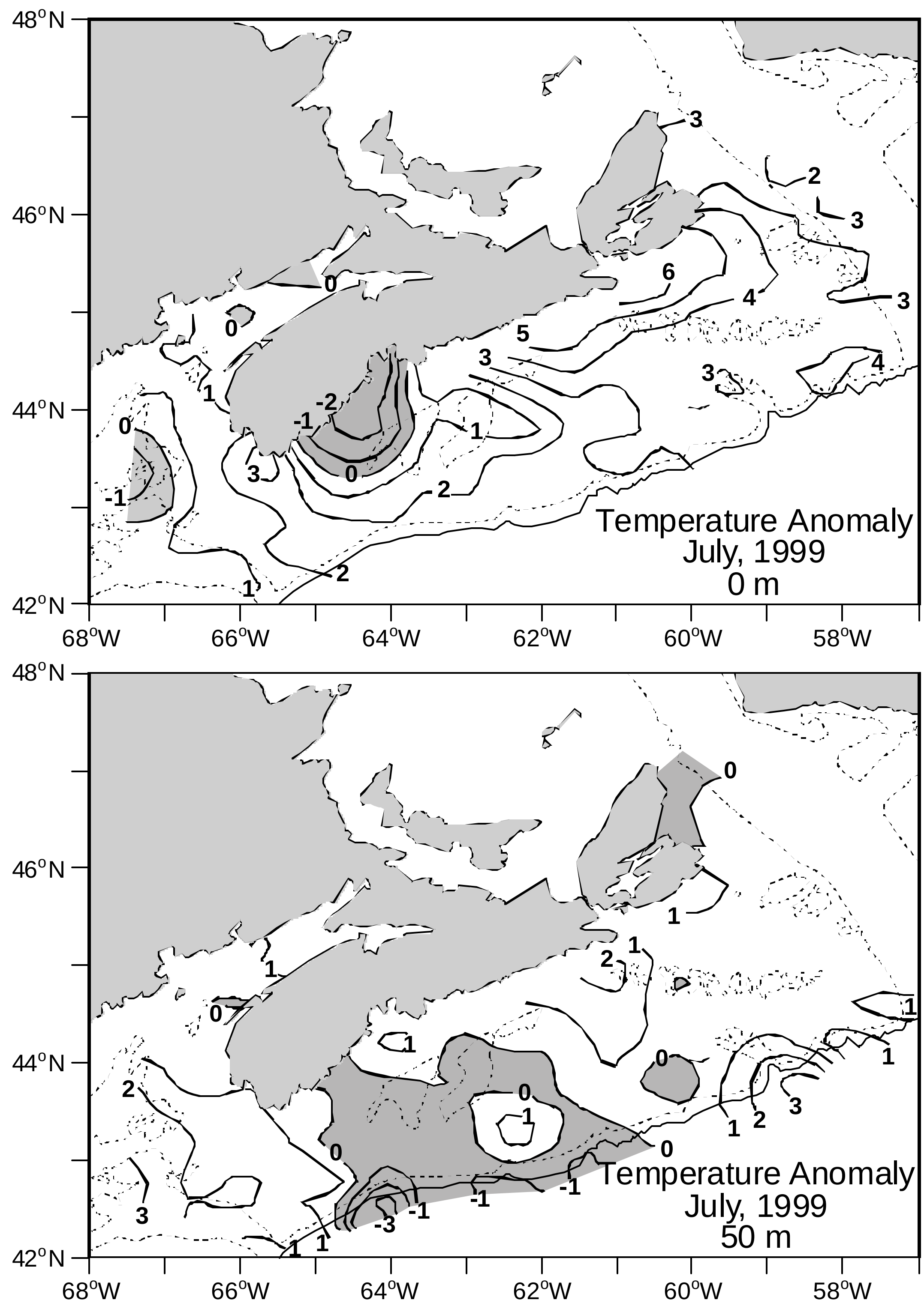


Fig. 57a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 1999 July groundfish surveys.

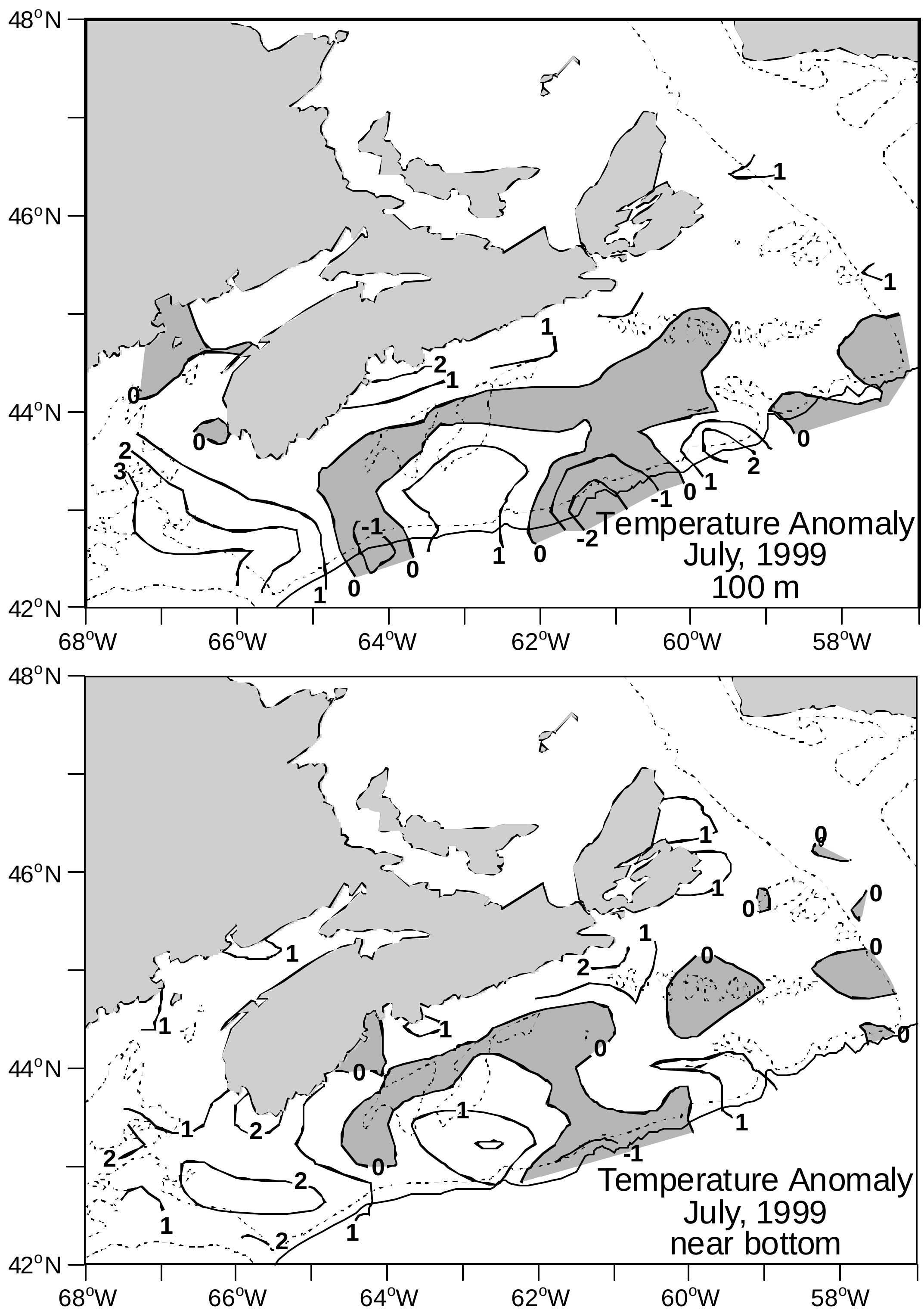


Fig. 57b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 1999 July groundfish surveys.

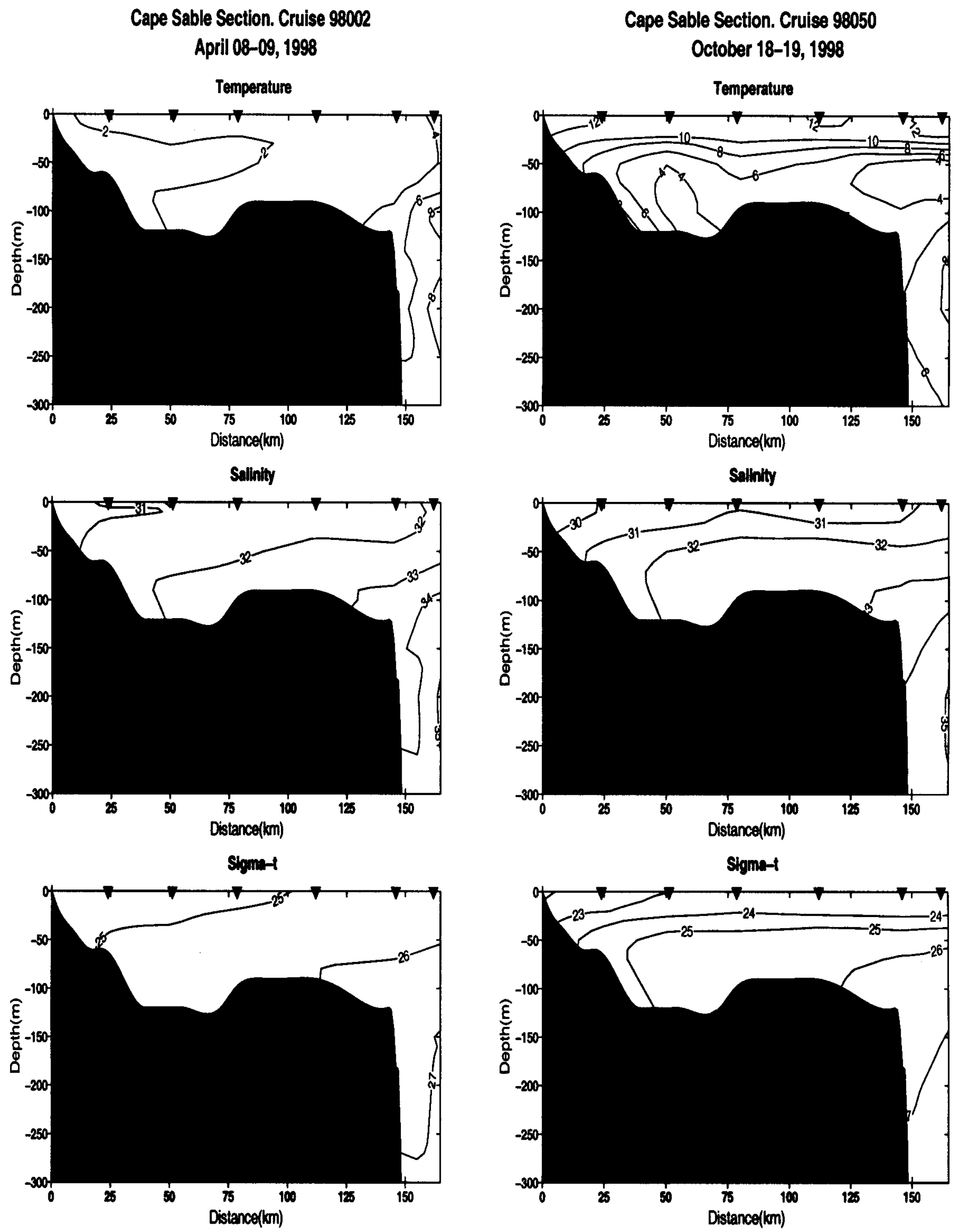


Fig. 58. The temperature, salinity and sigma-t contours along the Cape Sable Section during April (left panels) and October (right panels) of 1998. The triangles denote the location of the CTD profiles.

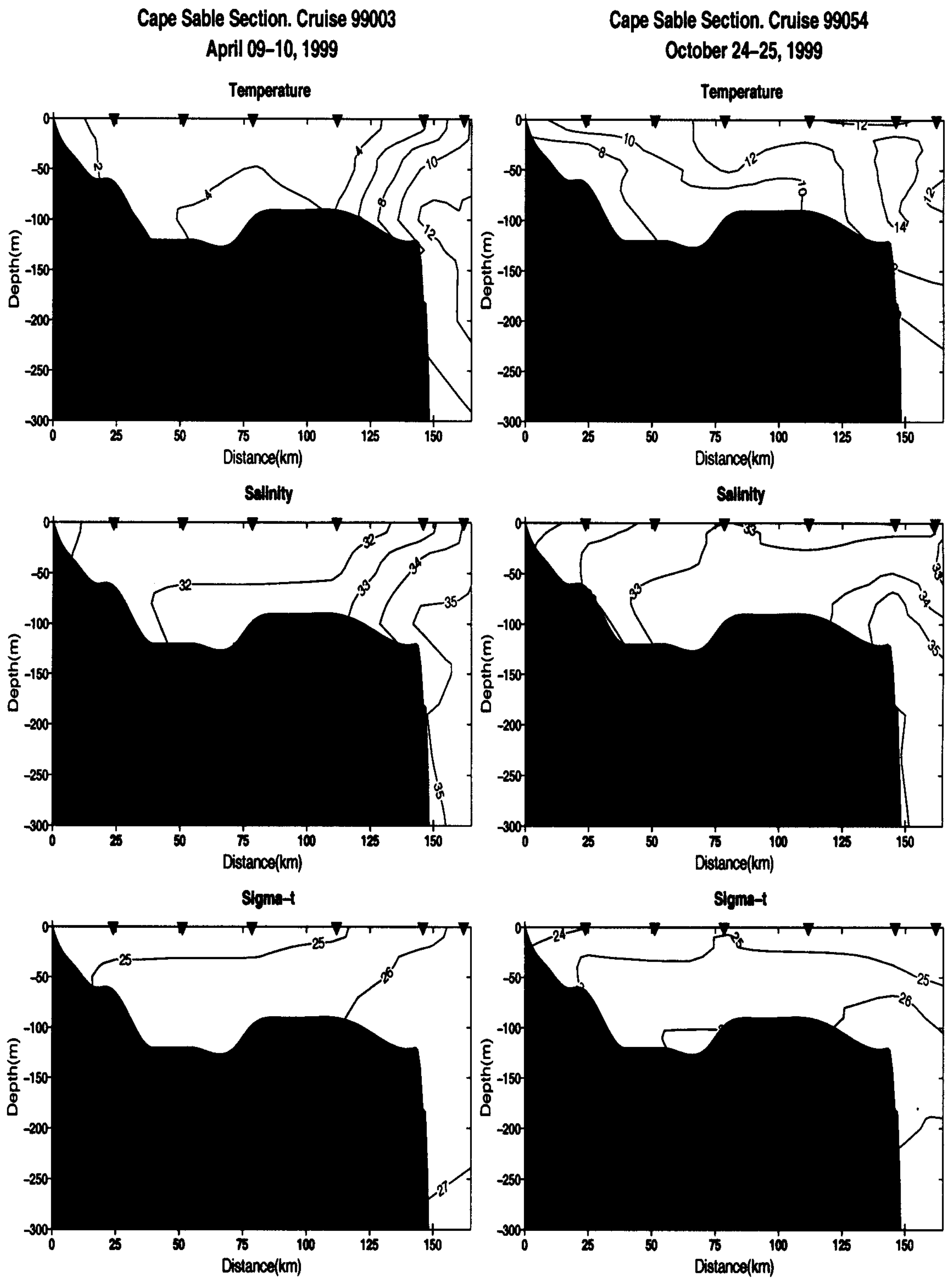


Fig. 59. The temperature, salinity and sigma-t contours along the Cape Sable Section during April (left panels) and October (right panels) of 1999. The triangles denote the location of the CTD profiles.

Halifax Section, 1998

Cruise 98023 (June 22–23, 1998)

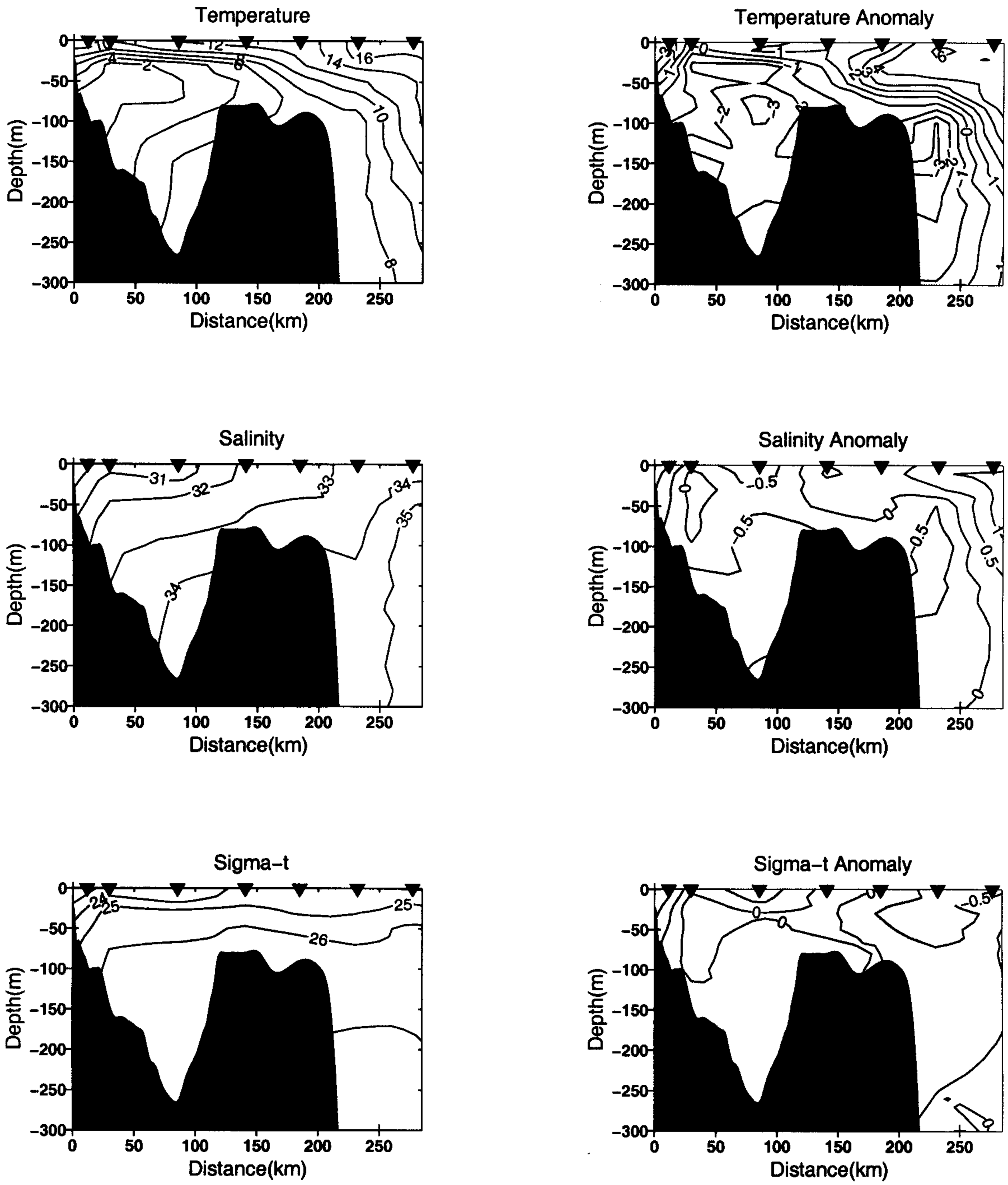


Fig. 60. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during June 1998 (left panels). The triangles denote the location of the standard stations.

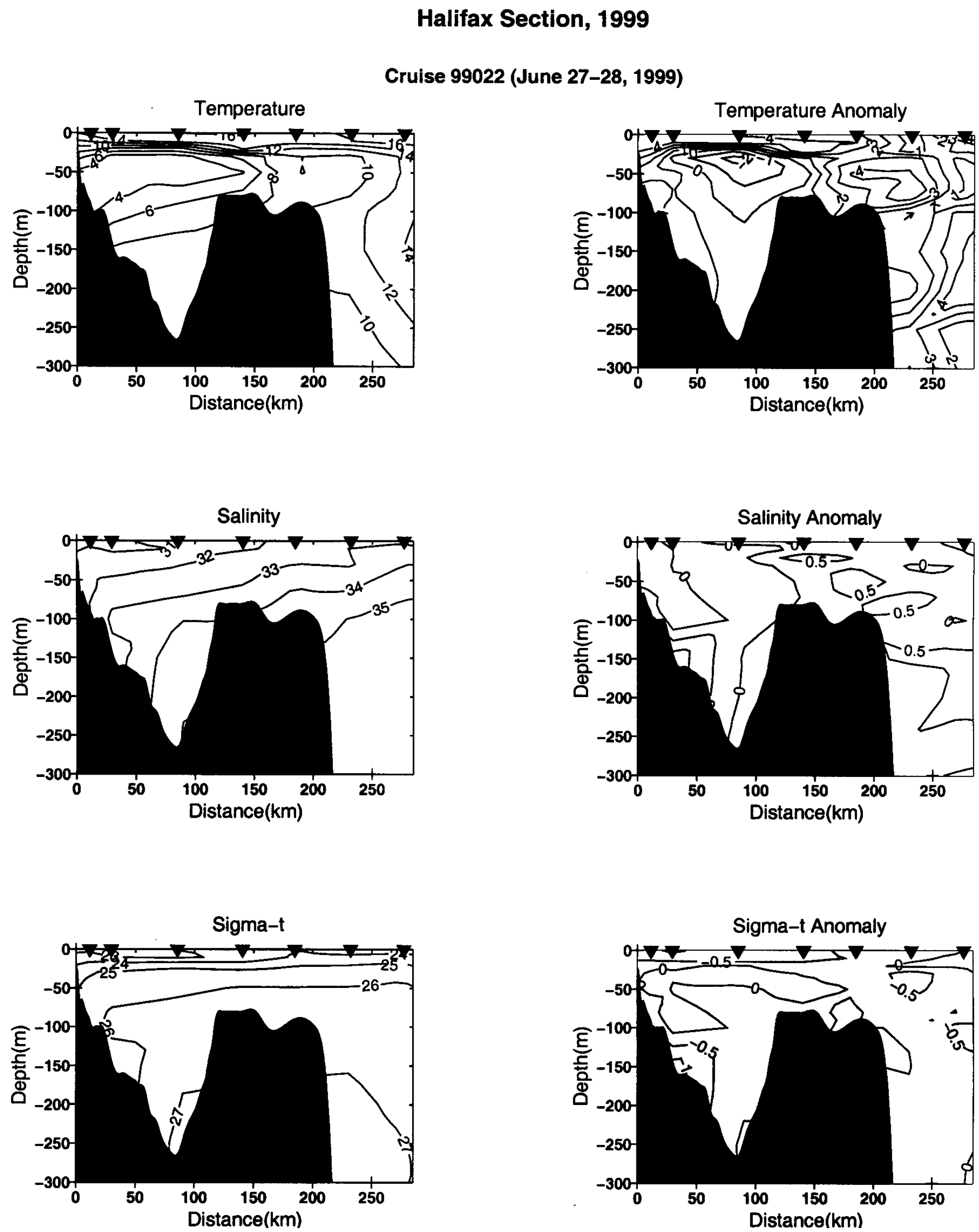


Fig. 61. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during June 1999 (left panels). The triangles denote the location of the standard stations.

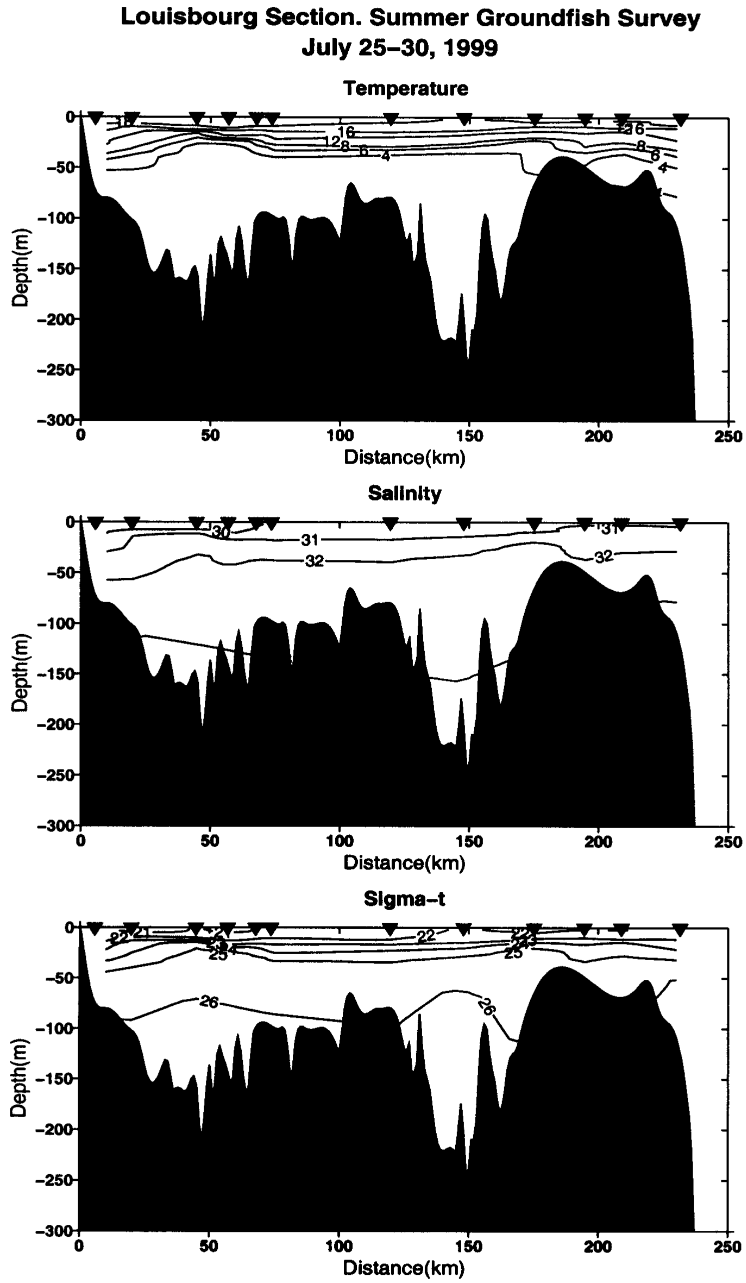


Fig. 62. Contours of the temperature, salinity and sigma-t along the Louisbourg Line during July 1999. The triangles denote the location of the standard stations.

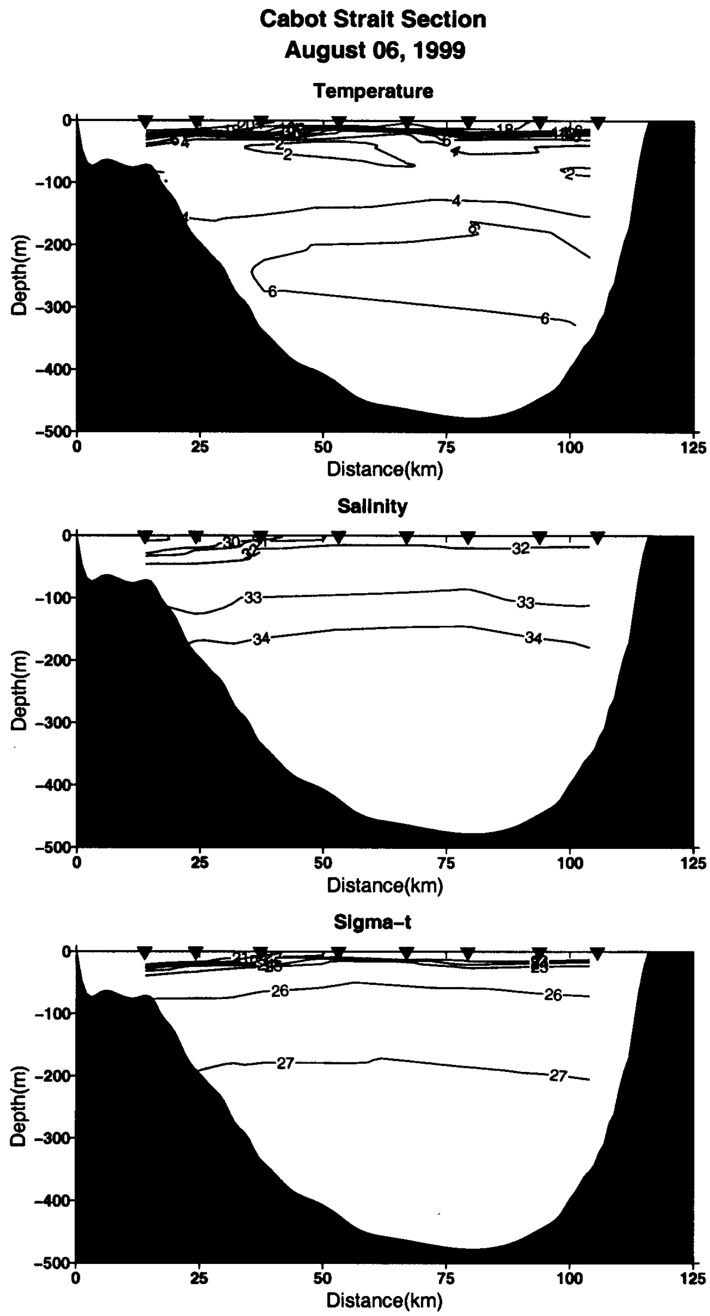


Fig. 63. Contours of the temperature, salinity and sigma-t along the Cabot Strait Line during August 1999. The triangles denote the location of the standard stations.

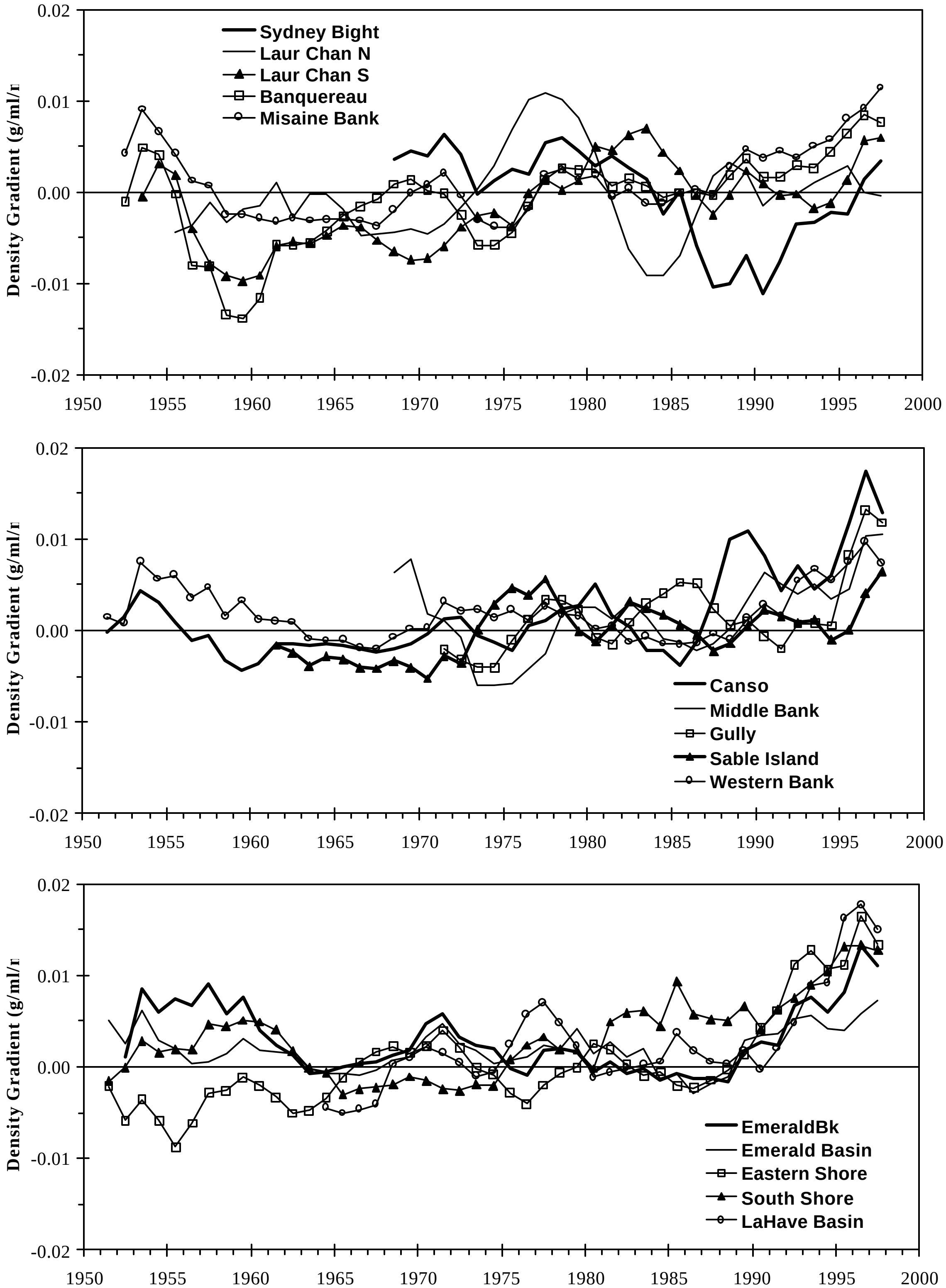


Fig. 64a. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 1-15 in Fig. 49.

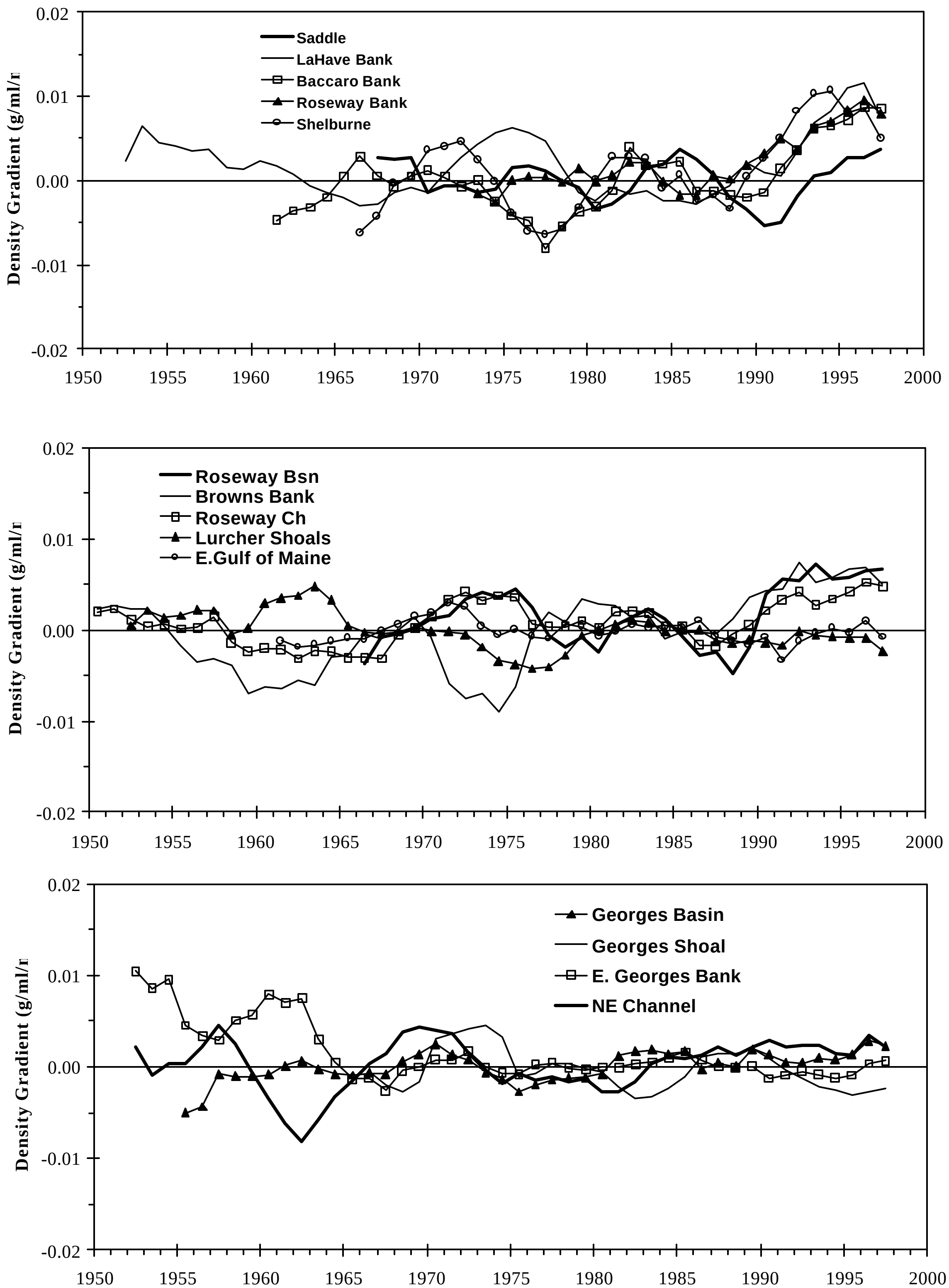
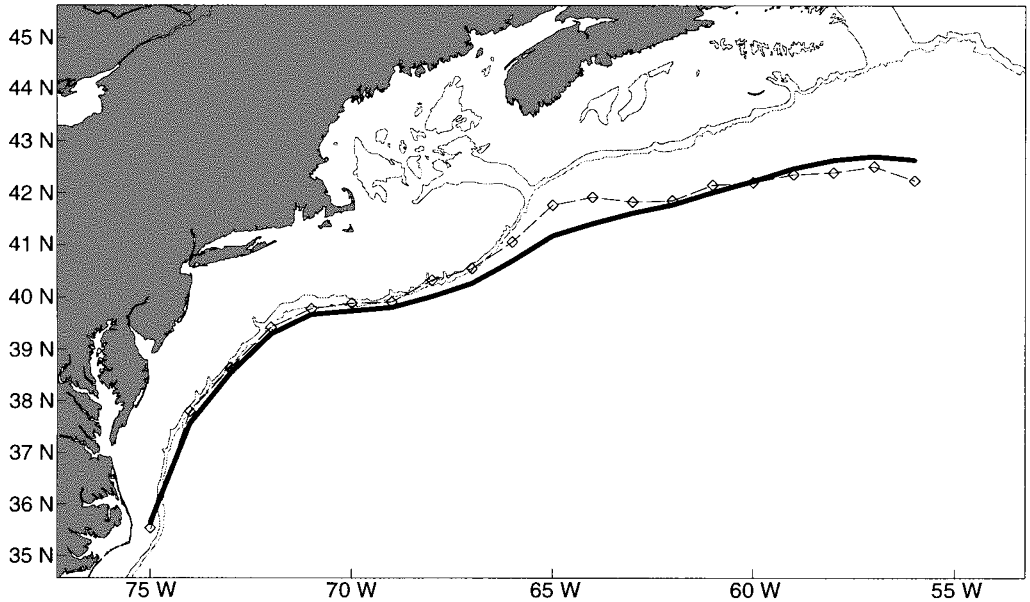


Fig. 64b. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 16-29 in Fig. 49.



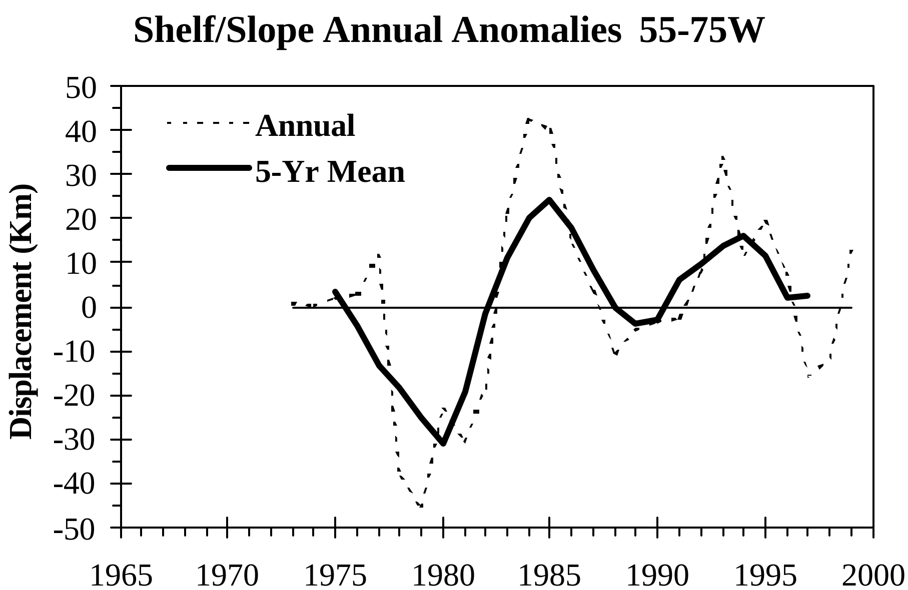
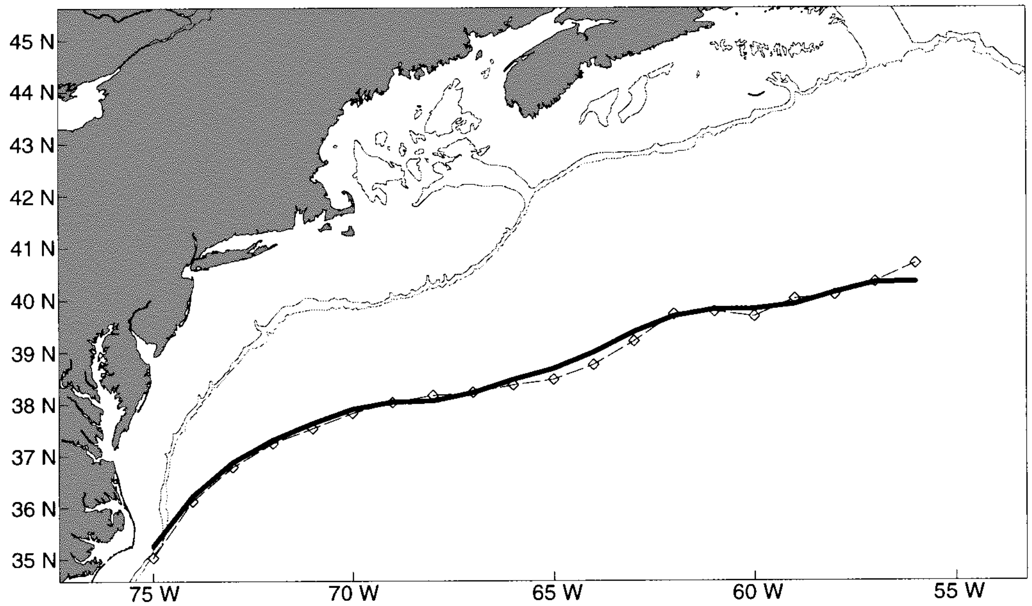


Fig. 65. The 1999 (dashed line) and long-term mean (1973-97; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the shelf/slope front (bottom panel).



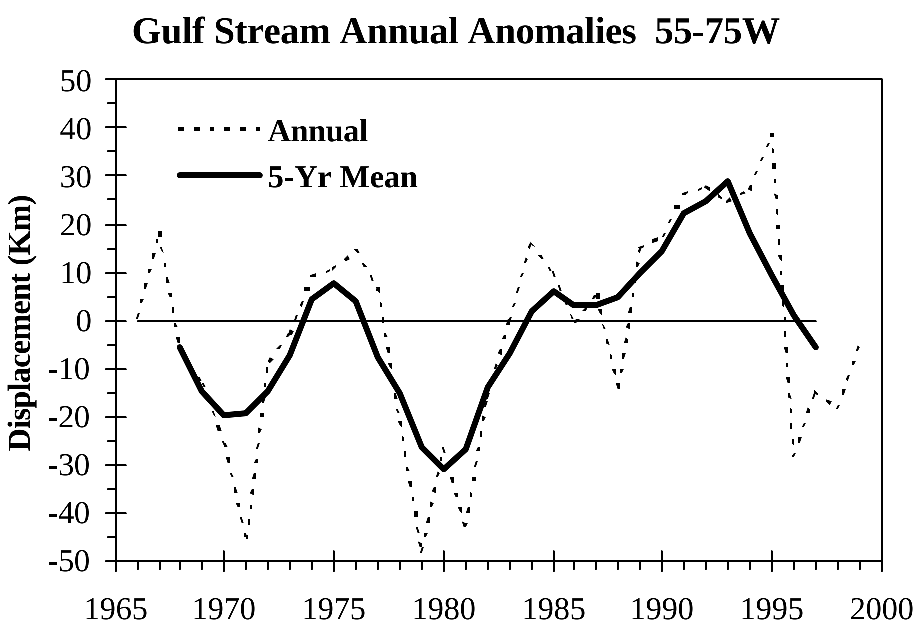


Fig. 66. The 1999 (dashed line) and long-term mean (1973-97; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the Gulf Stream front (bottom panel).