Northwest Atlantic Fisheries Organization

Serial No. N4682 **NAFO SCR Doc. 02/69**

SCIENTIFIC COUNCIL MEETING – JUNE 2002

Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2001

K. Drinkwater and B. Petrie

Department of Fisheries and Oceans, Maritimes Region
Ocean Sciences Division, Bedford Institute of Oceanography
Box, 1006, Dartmouth, N.S. B2Y 4A2

Abstract

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2001 is presented. Surface temperatures varied depending upon location. Higher-than-normal temperatures were recorded in the Gulf of Maine and from the central and northeastern portions of the Scotian Shelf. In the southwestern shelf and along the coast of Nova Scotia, sea surface temperatures were negative. Subsurface temperatures also varied spatially. Colder conditions occurred in the northeastern portions of the Scotian Shelf declined to below normal values, reversing the warming trend of the past decade. This followed 2 years of above normal temperatures. Waters in the deep basins both on the Shelf and in the Gulf of Maine indicate continuance of the warm conditions re-established in 1999 after the cold water event of 1998. Mid-depth temperatures over Emerald Basin were much colder-than-normal, ~1°C from 50 to 150 m. Near-bottom temperatures throughout the Scotian Shelf were generally below normal in 2001 and the area of bottom covered by cold temperatures increased significantly. There was some evidence to suggest the return of Cold Slope Water along the Scotian Shelf during 2001. While the vertical stratification in the upper water column (between surface and 50 m) over the Scotian Shelf generally weakened in 2001 relative to 2000, it remained higher than normal. The Shelf/Slope front and the Gulf Stream moved seaward of their positions during 2001. This resulted in the Shelf/Slope front being seaward of its normal position but the Gulf Stream still remained shoreward of its normal position.

Introduction

This paper describes temperature and salinity characteristics of the waters on the Scotian Shelf and in the Gulf of Maine during 2001 (Fig. 1). The results are derived from data obtained at coastal sea surface stations and long-term monitoring stations, along standard transects, on annual groundfish surveys, and from ships-of-opportunity and research cruises. Most of the data are available in the BIO historical temperature and salinity (AFAP) database, which is updated monthly from the data archive at the Marine Environmental Data Service (MEDS) in Ottawa. The analyses in this paper use data up to and including the March 2002 update. Additional hydrographic data were obtained directly from the DFO fisheries personnel. This represents the third year that the environmental reviews for the FOC are being presented as part of the Atlantic Zonal Monitoring Program (AZMP).

In order to detect long-term trends in the hydrographic properties, we have removed the potentially large seasonal cycle by expressing oceanographic conditions as monthly deviations from their long-term means (called anomalies). Where possible, these long-term monthly means, as well as the long-term annual means have been standardized to a 30-yr average using the base period 1971-2000 in accordance with the convention of the World Meteorological Organization and recommendations of the Northwest Atlantic Fisheries Organization (NAFO, 1983). This is a change to previous reviews that used the period 1961-1990. Meteorological, sea ice and satellite-derived sea-surface temperature information for eastern Canada during 2001 is described in Drinkwater and Petrie (2002). Of particular relevance was that air temperatures and sea surface temperatures over most of the northwest Atlantic during 2001 were warmer-than-normal and in most regions there was less ice. This includes the Scotian Shelf region.

Coastal Sea Surface Temperatures

Monthly averages of coastal sea surface temperature (SST) for 2001 were available at Boothbay Harbor in Maine and Halifax in Nova Scotia. Data from St. Andrews in New Brunswick were not available at the time of writing. The monthly mean temperature anomalies relative to the 1971-2000 long-term averages at each site for 2000 and 2001 are shown in Fig. 2.

At Boothbay Harbor in 2001, warmer-than-normal temperatures dominated as indicated by eleven monthly means with positive temperature anomalies. This continues the warm conditions of the past few years. The anomalies equalled or exceeded 2 standard deviations (based upon the years 1971-2000) in 4 months at Boothbay Harbor (May, June, August and September) and one standard deviation in 3 other months (July, October and December). In contrast to the warm conditions at Boothbay Harbor, Halifax temperatures were mostly below normal (9 out of the 12 months). Temperatures in two months during 2001 at Halifax equalled or exceeded 2 standard deviations (June and July) and in another three months (April, August and December) they exceed one standard deviation. Except for December, these monthly anomalies were negative. The maximum monthly anomaly at Boothbay was in June, 2.1^{o}C. At Halifax the largest anomaly was a negative 3.2^{o}C in July.

Time series of annual anomalies show that the surface temperature at Boothbay Harbor has been above its long-term mean in recent years and generally has been increasing since a minimum in the late 1980s (Fig. 2). The annual mean temperature in 2001 at Boothbay was 10.0^{o}C and 1.2^{o}C above the 1971-2000 mean. These temperatures are near the warmest since the mid-1950s. At Halifax the annual average for 2001 was 7.2^{o}C and 0.6^{o}C below its long-term mean. This reverses the warming trend that had been observed at this site over the last several years.

Fixed Stations

Prince 5

Temperature and salinity measurements have been taken since 1924 at Prince 5, a station off St. Andrews, New Brunswick, near the entrance to the Bay of Fundy (Fig. 1). It is the longest continuously operating hydrographic monitoring site in eastern Canada. Prior to the 1990s, data were obtained using reversing thermometers and water bottles. Since then data have been collected with a CTD (Conductivity, Temperature, Depth) profiler. Up to and including 1997, there was only one observation per month but since 1998, multiple occupations per month have been taken. For months with multiple measurements, an arithmetic average was used to estimate the monthly mean temperature and salinity. A single observation, or even three per month, especially in the surface layers in the spring or summer, may not necessarily produce results that are representative of the true monthly "average" conditions 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 2001, monthly mean temperatures ranged from a minimum in March of 2.6^{o}C throughout most of the water column to a maximum in September of 11.9^{o}C near surface (Fig. 3, 4). Monthly temperature anomalies were dominated by positive values during the first half of the year while in the second half they were principally negative anomalies (Fig. 3). The highest positive anomalies (>1.5°C) occurred in March near the surface and were >1°C throughout most of the water column. The maximum negative anomalies (lower than -1°C) were observed near bottom in summer. The annual mean temperatures exhibit high year to year variability with evidence of strong longer-term trends (Fig. 4). The temperature patterns at both the surface and 90 m are similar. These include colder-than-normal temperatures prior to 1945, throughout the 1960s and again in the mid-1980s to mid-1990s. The later years of the 1990s exhibited positive anomalies. In 2001, the annual temperature anomalies at the surface (and the top 50 m) were positive while at 90 m (representing 50-90 m) they were negative. At both depths the anomalies declined relative to 1999 and 2000. The maximum annual temperatures at this site occurred in the early 1950s and the minimum in the mid-1960s.

The salinity at Prince 5 showed a typical annual cycle with lowest values in the spring (May) at the surface (>31) and the highest values (>32.5) near bottom in the autumn (Fig. 3, 5). In terms of anomalies, they vary between positive and negative values, with a slight prevalence of the former especially in the upper layers (Fig. 3, 5). Maximum anomalies (>0.4) occurred in May and November (Fig. 5). The former is the time of minimum salinities and is probably the result of less runoff from the St. John River or perhaps the path of the river plume is further offshore than usual. Annual salinity anomalies in 2001 were near the long-term means below the near surface layer (top 10 m) with the highest values at the surface (0.15). 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. These 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 (Smith *et al*., 2001). Salinities rose above normal by 1999 and have remained there through 2001 but near bottom they fell to near normal in 2001.

Halifax Line Station 2

As part of the AZMP, a standard monitoring site was established in 1998 on the Scotian Shelf. Based on representativeness and logistic considerations, the selected site was Station 2 on the Halifax Line (Fig. 1). This station, hereafter referred to as H2, is situated approximately 30 km off the entrance to Halifax Harbour in about 150 m of water at the inner edge of Emerald Basin. It was felt that it was far enough offshore to avoid contamination by high frequency upwelling and downwelling but close enough to shore to be able to be monitored on a monthly basis using small vessels if necessary. Hydrographic measurements are taken using a CTD. In addition, nutrient and biological sampling are conducted. In this paper we only report on the hydrographic information. The long-term monthly means of temperature, salinity and density (sigma-t) were discussed in Drinkwater *et al.* (2000).

Surface temperatures at H2 ranged from less than 0°C to over 18°C in 2001 (Fig. 6). Near bottom temperatures, as is typical, rose to its highest level in the summer reaching over 6°C. Relative to the long-term means, surface waters were predominantly above normal throughout the year. In subsurface waters, there were mostly positive temperature anomalies during the winter, upwards of 2°C at mid-depths (50-100 m). Below the surface layer, there were negative anomalies for the remainder of the year with maximum values just below the surface layer in the summer (-4°C) and at deeper depths in the autumn (-1°C). This suggests that there was more cold intermediate layer water than usual at this site in 2001.

Sea surface salinities were highest during the spring with the lowest (<31) sustained values during the winter, which is typical. At subsurface depths, salinities rose during the summer, reaching maximum values (>34) near bottom. This also is typical of the seasonal pattern and is believed to be associated with coastal upwelling. Relative to the long-term means, waters varied throughout the year between fresher and saltier-than-normal with no strong overall pattern.

In the surface layers, stratification began around May increasing in intensity through to August-September. During autumn, the surface layer heat and low salinity waters were gradually mixed down to 30 m and deeper resulting in a decrease in the depth of the isopycnals (lines of constant density or sigma-t). Sigma-t anomalies indicated large variability but generally near normal stratification in the upper layers during the spring and higher stratification than usual in the autumn. Near normal stratification was also observed in the winter and summer.

Deep Emerald Basin Temperatures

Emerald Basin is located in the central Scotian Shelf. The waters in the deep layers of the Basin underwent rapid cooling in 1998 in response to the appearance of cold Labrador Slope Water at the shelf edge in the autumn of 1997 and its subsequent transport onto the shelf (Drinkwater *et al*., 2000). In 1999, warm temperatures reappeared in the Basin as the Labrador Slope Water retracted northward and was replaced by Warm Slope Water. The time series of temperature anomalies at 250 m shows this cooling and subsequent warming (Fig. 7). Dominant in the time series are the cool period of the 1960s and the relatively warm periods of the 1970s to the 1990s. In 2001, the water was warmer-than-normal by approximately 0.5°C. This is similar to 2000 but below the values recorded through earlier years of the 1990s. While the 250 temperature anomalies are usually representative of the lower layers from 100 m to the bottom, this was not the case in 2001. The annual anomalies at the standard depths in Emerald Basin and their error of the means were estimated from the available monthly values. They show much colder-than-normal temperatures (by upwards of -1°C) at 75 m to 125 m (Fig. 7) in contrast to the near bottom conditions. These cold temperatures were principally due to conditions in the latter half of the year, consistent with measurements at

Halifax Station 2 (Fig. 6). Note that the surface layers in Emerald Basin were warmer-than-normal in 2001 of around 1°C.

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. 8). Petrie *et al.* (1996) published a more recent atlas using these same areas but containing all available hydrographic data. In this report we produce monthly mean conditions for 2001 at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compare them to the long-term averages (1971-2000). 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. 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 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). From the mid-1990s, temperatures at these depths have been warming, eventually reaching above normal values throughout the region by 2000 (Drinkwater *et al*., 2000). Below, we describe temperature conditions in several representative areas of the Scotian Shelf and Gulf of Maine.

On Sydney Bight (area 1 in Fig. 8) off eastern Cape Breton, mean profiles from 5 months show highly variable temperature anomalies in the near surface layers being highest in July and lowest in January (Fig. 9). Below about 50 m, however, there were predominantly negative anomalies of upwards of –1.5°C. At 100 m, the high temperature anomalies in the 1950s 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 remained below normal through 1998, but were slowly rising from the early-1990s. Above normal temperatures were reached in 1999 and continued through into 2000. Temperature anomalies in 2001 declined significantly compared to 2000 (Fig. 9).

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 8) were collected in 8 months during 2001. They show primarily warmer-than-normal temperatures throughout the water column in January but declined thereafter (Fig. 10). From May on, temperature anomalies were primarily negative below 50 m. Surface anomalies tended to vary tremendously with the highest positive anomalies in November and largest negative anomalies in September. The time series of the 100 m shows a decline in 2001 from positive anomalies in 2000 to below normal values (Fig. 10). This follows two years of positive anomalies. This had contrasted with the predominantly negative anomalies over the previous 15 years (Fig. 10). As in 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 below normal and reached a record sustained minimum of around -1°C in the first half of the 1990s. From the early-1990s to 2000, as on Sydney Bight, temperatures slowly but steadily increased.

Lurcher Shoals is located off Yarmouth, Nova Scotia (area 24 in Fig. 8). This area exhibited principally colder-than-normal temperatures in 2001 in the 6 months of 2001 when data were available (Fig. 11). The coldest anomalies were in August with values between -1° and -2°C. The warmest month was in October with anomalies of

0.5°-1°C. The time series at 50 m clearly shows a large decline in 2001 to below normal anomalies. This compares to the positive temperature anomalies in 1999 and 2000. 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 in the northeastern Scotian Shelf, temperatures declined by the mid-1980s to below normal reaching 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. 8) and is connected to the offshore slope water through the Northeast Channel. Data were collected during 2001 in 7 months between April and November. As in Emerald Basin there were large differences in the temperature anomalies with depth. Annual anomalies were predominantly colder-than-normal with significant negative means from 50 m to 175 m whereas from 200 to 300 m they were near normal. Temperatures in the deep regions (200 m) of Georges Basin (Fig. 12) show a striking similarity to those near bottom in Emerald Basin (Fig. 7) including the very cold conditions in 1998, warm in 1999 through 2001. 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. 8). Data were available in 9 months of 2001 between February and November. Temperatures tend to exhibit higher variability than at many of the other sites (Fig. 13), in large part because of their 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 the near bottom of Georges Basin and Emerald Basin. These again include the low temperatures in the 1960s, the higher-than-average conditions in the 1970s into the 1990s. In 2001, temperatures tended to be above normal as was observed in 1999 and 2000.

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 209 CTD stations were taken during the 2001 survey and an additional 154 bottom temperature stations were obtained as part of the ITQ (Individual Transferable Quota) fleet survey. The ITQ survey 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° 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. 14). Maximum depths for the interpolated temperature field were limited to 1 000 m off the shelf. The 2000 temperature anomalies relative to the July 1971-2000 means were also computed at the same four depth levels (Fig. 15).

The broad spatial pattern of near-surface temperatures in July 2001 was similar to past years with the warmest waters (17°C) off the northeastern coast of Nova Scotia and the coldest (<10°C) in the Gulf of Maine/Bay of Fundy region (Fig. 14a). The cooler surface temperatures in the Gulf of Maine compared to the Scotian Shelf are due to the intense bottom-generated vertical mixing caused by the high tidal currents. The surface temperatures in 2001 were warmer than the long-term average throughout the northeastern Scotian Shelf and a large portion of the western Gulf of Maine. The maximum anomaly was just over 2°C in the Gulf. The positive anomalies contrast with the central and southeastern regions of the Shelf and the Bay of Fundy where temperatures were colder-than-normal (Fig. 15a). The maximum negative anomaly was over 3°C below normal off the southwest tip of Nova Scotia. Relative to 2000, the surface temperatures in 2001 generally decreased with the maximum decline in the southwest. This appears related to more intense upwelling and a larger spreading out of the upwelled waters in 2001 than in 2000.

The temperatures at 50 m ranged from 1°C to over 8°C with the coldest waters in the northeast and the warmest waters in the Bay of Fundy (Fig. 14a). Temperature gradients are weak over the Scotian Shelf proper, generally varying between 1°-3°C except around Sable Island due to the extreme shallowness of the area. Emerald Basin tends to be slightly warmer than most of the rest of the shelf. Temperature anomalies at 50 m (Fig. 15a) were predominantly negative over the Shelf (mostly 0° to -1°C). The largest negative anomalies appeared along the shelf break in the southwest and around Sable Island. The former must be regarded cautiously, however, due to the limited data in this region.

The spatial pattern of the 100 m temperatures resembles that at 50 m although the actual temperatures generally are slightly higher (Fig. 14b). The temperatures at 100 m ranged from 1-2°C in the northeast to over 7°C offshore of Browns Bank and in Emerald Basin. Temperature anomalies at this depth were again generally negative, mostly ranging from 0° to -2°C over the Shelf and into the Gulf of Maine (Fig. 15b). The highest anomalies (>5°C) occurred along the outer shelf off Emerald Basin suggesting the possibility of a penetration of colder than normal slope waters in through the Scotian Gulf towards the Basin.

Near-bottom temperatures over the Scotian Shelf ranged from <2°C in the northeastern Scotian Shelf to over 9°C in Emerald Basin, around Sable Island and in the Bay of Fundy (Fig. 14b). The source of the high temperatures differs in each case. Around Sable Island the depths are shallow and the high temperatures reflect the surface layer. In Emerald Basin, the high temperatures are due to the penetration of warm slope waters from offshore into the Basin, while in the Bay of Fundy they are due to the intense tidal mixing that tends to mix both surface and deep waters together. 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 colder waters are largely derived from the Gulf of St. Lawrence. Relative to their long-term means (1971-2000), the near bottom temperatures were predominantly colder-than-normal (Fig. 15b). The largest negative anomalies were on the outer Banks to the southwest, including Browns, Emerald and Western. Exceptions to the negative anomalies were around Sable Island, portions of Banquereau Bank and in the northeast adjacent to the Laurentian Channel. These typically were weak (0°-1°C).

We also estimated the area of the bottom covered by each one-degree temperature range (i.e. 1-2^{o}C, 2-3^{o}C, 3-4^{o}C, etc.) within NAFO Subareas 4Vn, 4Vs, 4W and 4X (see Fig. 1 for Subarea boundaries). These were obtained from optimally estimated temperatures from the July groundfish and ITQ surveys. The time series for each NAFO Subarea are shown in Fig. 16a,b. Several points are noteworthy. First is the increase in temperature from 4Vs/4Vn to 4W and 4X. In 4Vn most of the bottom is covered by waters <6^{o}C and almost 50% <5^{o}C (Fig. 16a). For 4Vs, 80-90% is <6^{o}C and 75% <5^{o}C (Fig. 16a). In 4W <50% and in 4X<20% is covered by temperatures <6^{o}C (Fig. 16b). The time series for 4Vn and 4Vs show an increase in the 0^o-1^{o}C and especially <3°C waters during the late 1980s and early 1990s (Fig. 16a). Also in 4Vs there are waters <1^{o}C during this colder period. In 4W there is an increase in the area of the waters <3^{o}C but it is of smaller amplitude than in 4V. In 4X there is an increase in waters <4^{o}C but it is not as large an amplitude as in the other regions (Fig. 16b). During 2001 in all areas there was a significant increase in the area covered by temperatures in the colder temperature ranges.

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 shows that temperatures declined steadily between 1988 and 1991 to their lowest value since the late-1960s (near 4.5^{o}C and an anomaly exceeding -0.9^{o}C; Fig. 17). Then temperatures rose dramatically reaching 6^{o}C (anomaly of 0.6^{o}C) in 1993. During the remainder of the 1990s, temperatures oscillated about the long-term mean with a slight tendency towards positive values. In 2000 and 2001 temperatures were typically above the long-term mean.

Standard Sections

As part of the AZMP, seasonal sampling along the historical standard sections was re-established by the Canadian Department of Fisheries and Oceans in 1998. On the Scotian Shelf this included transects off Cape Sable, Halifax, Louisbourg and across Cabot Strait (Fig. 1). While four occupations per section has been the goal, this has not been achieved for all sections due primarily to budgetary constraints. Dedicated monitoring cruises have provided some of the section data while others have been obtained from fisheries surveys. In 2001, dedicated cruises were run during April and October and some of the sections were derived from data collected during the July survey. 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 and temperature along the Louisbourg Line in November. At the other sections, the historical 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, this section crosses Browns Bank to the entrance of the Northwest Channel (Fig. 1). During May and October, the offshore was occupied by Warm Slope Water (temperatures >8°C; Fig. 18). The waters over the shelf warmed significantly from 2°-4°C in May to 6°-14°C in October. Of particular note is the increase in the temperatures in the lower half of the water column. In the surface waters salinities decreased from May to October, as usually occurs. Also typical, there was an increase in stratification from the spring to the fall. The strongest vertical stratification in both months was observed at the shelf edge. In October the uplifting of the isopycnals are suggestive of upwelling near shore.

Temperatures in spring during 2001 were much colder than in 2000 in spite of being taken almost a month later. They also were slightly fresher. The contrast was less between the years for October but still it was slightly colder in 2001 Stratification was definitely weaker in both months during 2001 relative to 2000.

Halifax Line

The Halifax Line was occupied 3 times in 2001 (early May, May-June and October). Contours of temperature, salinity and sigma-t across the section are shown in Fig. 19, 20 and 21, respectively. In early May, Warm Slope Water (temperatures, >8°C; salinities >34.8) appears along the shelf edge but colder and fresher waters occupy much of the region in May-June and October. This water may represent an increase in the influence of Labrador Slope Water although the 2°C water at the shelf edge in October at around 100 m depth may be derived from outflow from the Gulf of St. Lawrence. Waters in the deep Emerald Basin in all months display temperatures and salinities characteristic of the Warm Slope Water, however. Seasonal warming and freshening are clearly evident in the upper layers, which result in increased stratification from spring through to the summer and into the autumn. Minimum temperatures (<4°C) in the cold intermediate layer extent over the shelf much further than normal. Relative to the long-term means, temperatures were predominantly above normal in the upper 30 to 50 m, during all three periods. In contrast, the subsurface waters were typically colder-than-normal with an indication of these colder waters moving more shoreward through the year. High negative anomalies (0° to -2°C) were observed over Emerald Bank at depth in May (Fig. 19) and upwards of -3°C in both May-June (Fig. 20) and October (Fig. 21). Above Emerald Basin, subsurface temperatures tended to also be below normal but by a lesser amount (0° to -1°C), in May-June and October. Temperatures at the farthest offshore stations were lower-than-normal and salinities fresher-than-normal. However, salinites along the Halifax Line were near normal in early May throughout the water column. In May-June the subsurface waters were generally fresher than normal except over the surface waters where they were saltier than usual. By October, however, salinities had freshened more than usual except near the coast. The density anomalies varied spatially being less than usual in shore and at the seaward extent of the Halifax Line during May and May-June with higher densities than normal in between. In October low density waters occupied most of the Halifax Line except around 50 m at the shelf edge and nearshore.

Compared to 2000, temperatures in Emerald Basin were colder in 2001. Salinities in 2001 tended to be fresher than in 2000. Stratification was generally weaker in 2001, however, in October the mixed layer was deeper in 2001 than in 2000 and the density gradient stronger.

Louisbourg Line

This line runs southeast off Louisbourg, across Banquereau Bank and out into the Slope Water region (Fig. 1). It was occupied twice in 2000 (May and October). Warm Slope Water (8°-12°C) was located off the shelf during October but not in May (Fig. 22). On the shelf, temperatures in April were cold (<2°-3°C) and vertical stratification was weak. Salinities on the shelf were <32 with a small amount of water near the coast <31. These conditions contrast with those during October when there was strong stratification with the near-surface waters being warm (10°-12°C) and fresher (<30-31). Waters below 50 m were generally <2°C.

Compared to 2000, waters in 2001 were of similar temperatures in May but much colder in October, both on the shelf and offshore. Salinites on the shelf were similar in October but slightly saltier in May of 2001. Densities were similar in May in both years but in October were higher during 2001 leading to generally weaker stratification.

Cabot Strait Line

This line extends from northern Cape Breton to southwestern Newfoundland (Fig. 1) and was occupied twice in 2001 (May and October). In May, there was weaker vertical stratification (Fig. 23). Surface temperatures were >2°C but there was a large area of water <2°C and some waters <0°C. These represent the CIL waters. Salinities were lowest (<31) on Cape Breton side. Below 200 m temperatures were >5°C and salinities were 34. By October there was strong stratification, being maximum on the Cape Breton side of the Strait due to the lower salinities. In the surface layers, temperatures were >10° across the Strait while salinities varied between 30 and 32. The CIL still had temperatures <2°C. Below 200 m temperatures and salinities remained near the same between May and October.

Compared to 2000, waters in May and October were colder in 2001 except in the deep layers where they were similar. Near surface salinities and stratification were similar in the two years.

Density Stratification

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. 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. We examined the variability in stratification by calculating the density (sigma-t) difference nominally between 0 and 50 m. The density difference was based on a monthly mean density profile calculated for each area in Fig. 8. The long-term monthly mean density gradients for the years 1971-2000 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 last year (Drinkwater *et al*., 2001), the dominant feature is the higher stratification during recent years throughout the Scotian Shelf (Fig. 24a, 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 2001 values confirm a continuation of high stratification but there has been a general decrease in its strength during the past two years. There is surprising consistency from area to area, over the Scotian Shelf. This higher-than-average stratification does not extend into the Gulf of Maine region and tends to be absent 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 reveals that the primary cause of the increased stratification was due mostly to decreases in surface salinity, although the higher than normal surface temperatures 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. These initial charts did not contain data east of 60°W but within a year were extended east to 55°W. Data for 2001 have been digitized, estimates of monthly mean positions determined and anomalies relative to the 20-year period, 1978 to 1997, were calculated. During the past several years, the charts only extend east to 56°W.

The overall mean position of the Shelf/Slope front together with the 2001 annual mean position is shown in Fig. 25. 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 2001, the shelf/slope front was generally seaward of its long-term mean position. The time series of the annual mean position (averaged over 56°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 1998 through 2000, the position of the Shelf/Slope front moved northward with the largest increased recorded in 1999. The position in 2001 retracted southward from the shoreward anomaly in 2000.

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 56°W to 75°W. The average position of the north wall of the Stream and the 2001 annual mean is shown in Fig. 26. 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 2001, the average position of the Stream was near to or shoreward of its long-term mean position at all degrees of longitude. The time series of the position shows 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. 24). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed by a rapid decline in 1996 and remained low through 1997 and 1998. By 2000 the position of the Gulf Stream was shoreward of its long-term mean and although remaining so through 2001, it moved shoreward relative to 2000. The trend in the Gulf Stream roughly matches that of the NAO index.

Summary

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2001 is presented. Warm conditions dominated the surface layer in many regions although not along the Atlantic coast of Nova Scotia and in the southwestern region of the Scotian Shelf where negative sea surface temperature anomalies were observed. In the subsurface layers, cold conditions generally prevailed over the Shelf, with the exception of the deeper depths of Emerald Basin. This reversed the warming trend in the northeastern portions of the Scotian Shelf. Cause of the cold conditions may be related to reports of Labrador water that penetrated into the Gulf of St. Lawrence through the Strait of Belle Isle. Also, there appears to be an increase in the influence of the cold Labrador Slope Water along the shelf break in 2001. Near bottom temperatures throughout the Scotian Shelf were also below normal in 2000 and the area of bottom covered by cold temperatures increased in all regions. The cold intermediate layer waters emulating from the Gulf also was colder-than-usual. While the vertical stratification in the upper water column (between surface and 50 m) over the Scotian Shelf generally weakened in 2001 relative to 2000, it generally remained higher than normal. The Shelf/Slope front and the Gulf Stream moved further offshore in 2001, being shoreward of its normal position for the Gulf Stream but seaward for the Shelf/Slope front.

Acknowledgements

We wish to thank the many individuals who provided data or helped in the preparation of this paper, including: R. Pettipas and L. Petrie at the Bedford Institute of Oceanography for technical support; the Marine Environmental Data Service in Ottawa; 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; G. Bugden of BIO and D. Gilbert of IML for their Cabot Strait temperature data; and H. Hayden and D. Gregory for their maintenance of the BIO hydrographic database.

References

Bugden, G.L. 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. p. 139-147. In J.-C. Therriault [ed.] The Gulf of St. Lawrence: small ocean or big estuary? Can. Spec. Publ. Fish. Aquat. Sci. 113.

Colbourne, E. 1995. Oceanographic conditions and climate change in the Newfoundland region during 1994. DFO Atlan. Fish. Res. Doc. 95/3, 36 p.

Drinkwater, K.F. and R.G. Pettipas. 1994. On the physical oceanographic conditions in the Scotia-Fundy region in 1993. DFO Atlantic Fish. Res. Doc. 94/37, 31 p.

Drinkwater, K.F. and R.W. Trites. 1987. Monthly means of temperature and salinity in the Scotian Shelf region. Can. Tech. Rep. Fish. Aquat. Sci. 1539: 101 p.

Drinkwater, K.F., E. Colbourne and D. Gilbert. 2001. Overview of environmental conditions in the Northwest Atlantic in 2000. NAFO SCR Doc. 01/36, 84 p. 34 p.

Drinkwater, K.F., R.A. Myers, R.G. Pettipas and T.L. Wright. 1994. Climatic data for the Northwest Atlantic: The position of the shelf/slope front and the northern boundary of the Gulf Stream between 50^{o}W and 75^{o}W, 1973-1992. Can. Data Rept. Fish. Ocean. Sci. 125: 103 pp.

Drinkwater, K.F., R.G. Pettipas and W.M. Petrie. 2000. Physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 1999. Can. Stock Assessment Secretariat Res. Doc. 2000/060, 46 p.

Gilbert, D. and B. Pettigrew. 1997. A study of the interannual variability of the CIL core temperature in the Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. Vol. 54 (Suppl. 1): 57-67.

NAFO. 1983. Scientific Council Reports. Dartmouth, N.S., 151 p.

Petrie, B. and K. Drinkwater. 1993. Temperature and salinity variability on the Scotian Shelf and in the Gulf of Maine, 1945-1990. J. Geophys. Res. 98: 20079-20089.

Petrie, B., K. Drinkwater, A. Sandström, R. Pettipas, D. Gregory, D. Gilbert and P. Sekhon. 1996. Temperature, salinity and sigma-t atlas for the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 178: 256 p.

Smith, P.C., R.W. Houghton, R.G. Fairbanks and D.G. Mountain. 2001. Interannual variability of boundary fluxes and water mass properties in the Gulf of Maine and on Georges Bank: 1993-1997. Deep-Sea Research II:

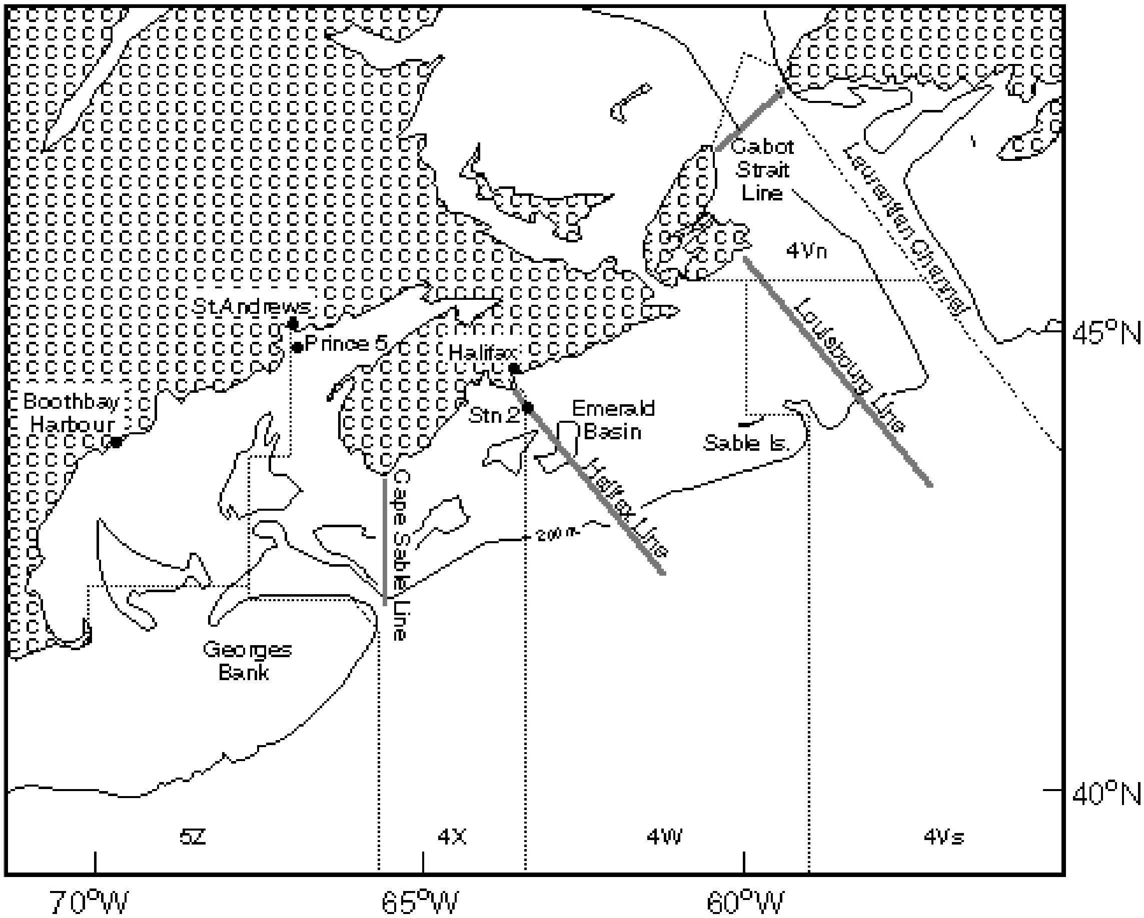


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

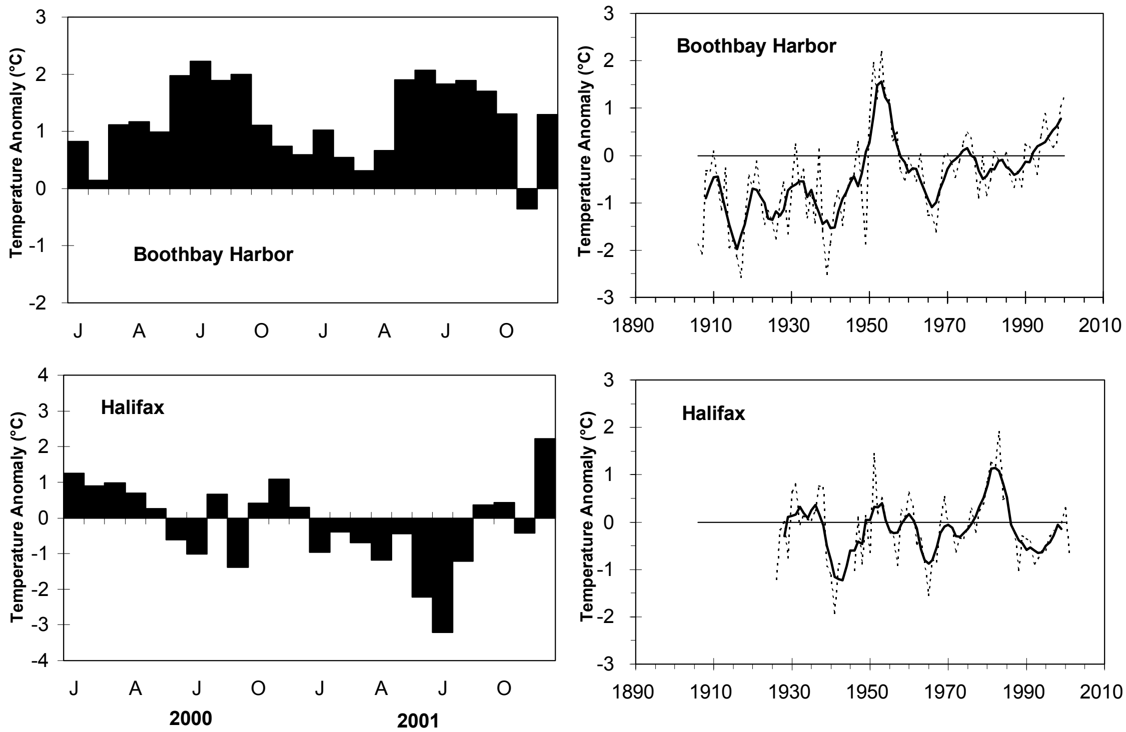


Fig. 2. The monthly sea surface temperature anomalies during 2000 and 2001 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Anomalies are relative to the 1971-2000 means.

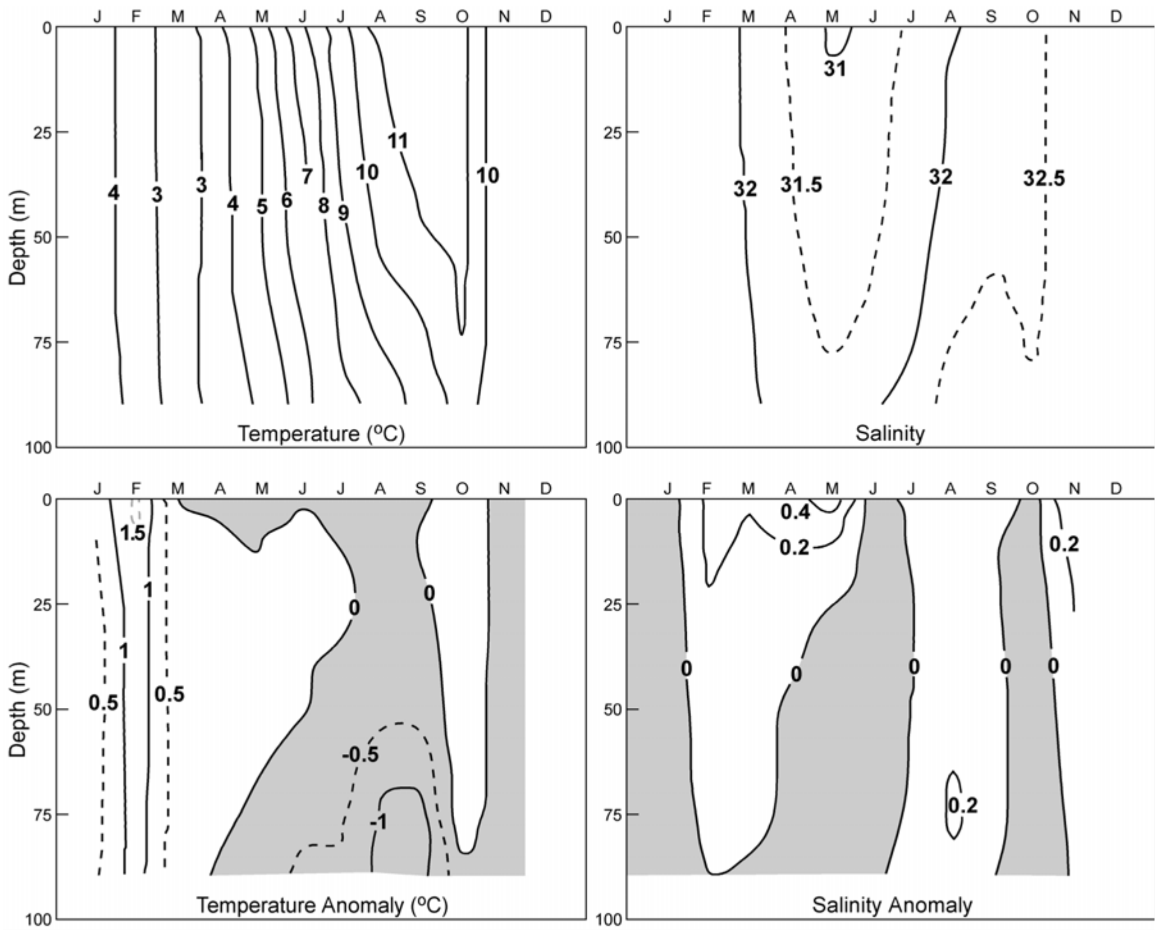


Fig. 3. Contours of monthly mean temperature (left) and salinity (right) and their anomalies (bottom panels) at Prince 5 as a function of depth during 2001 relative to the 1971-2000 means. Colder and fresher-than-normal conditions are shaded.

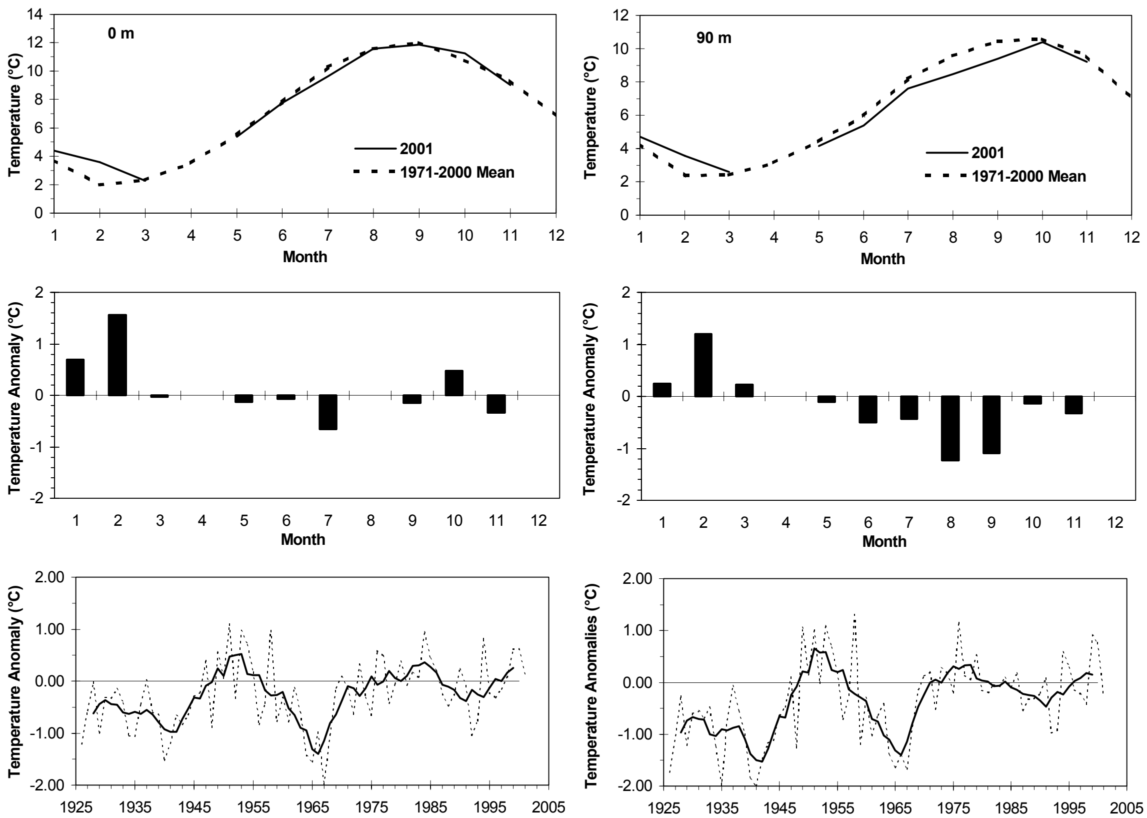


Fig. 4. The monthly mean temperatures for 2001 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

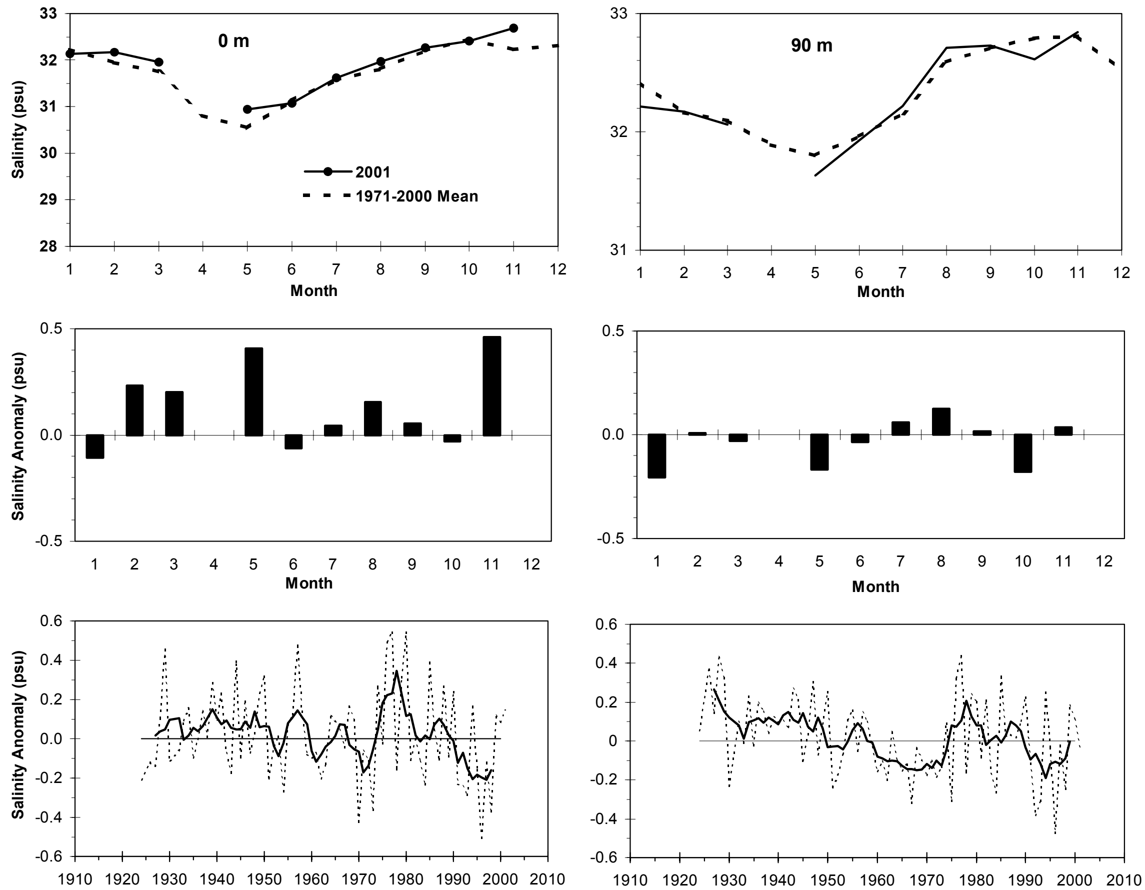


Fig. 5. The monthly mean salinities for 2001 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

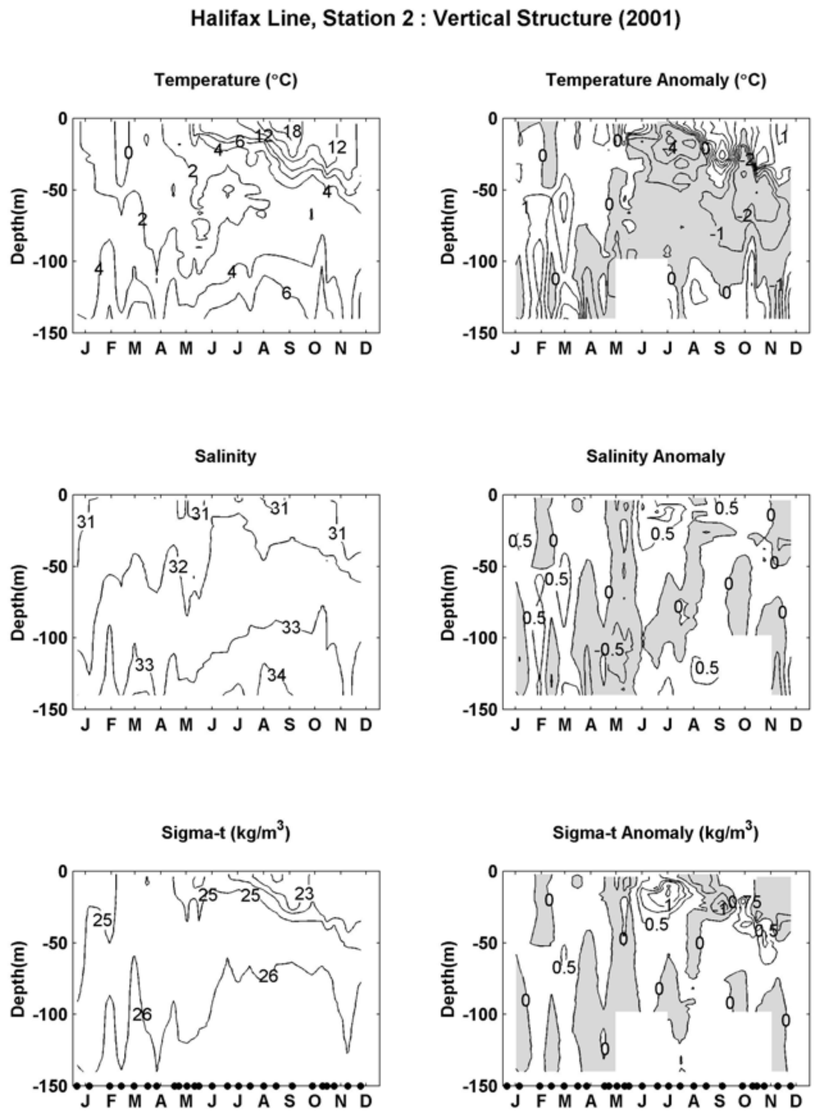


Fig. 6. Contours of temperature, salinity and density (sigma-t) for 2001 (left) and their anomalies (right) at the standard station H2. Negative anomalies are shaded.

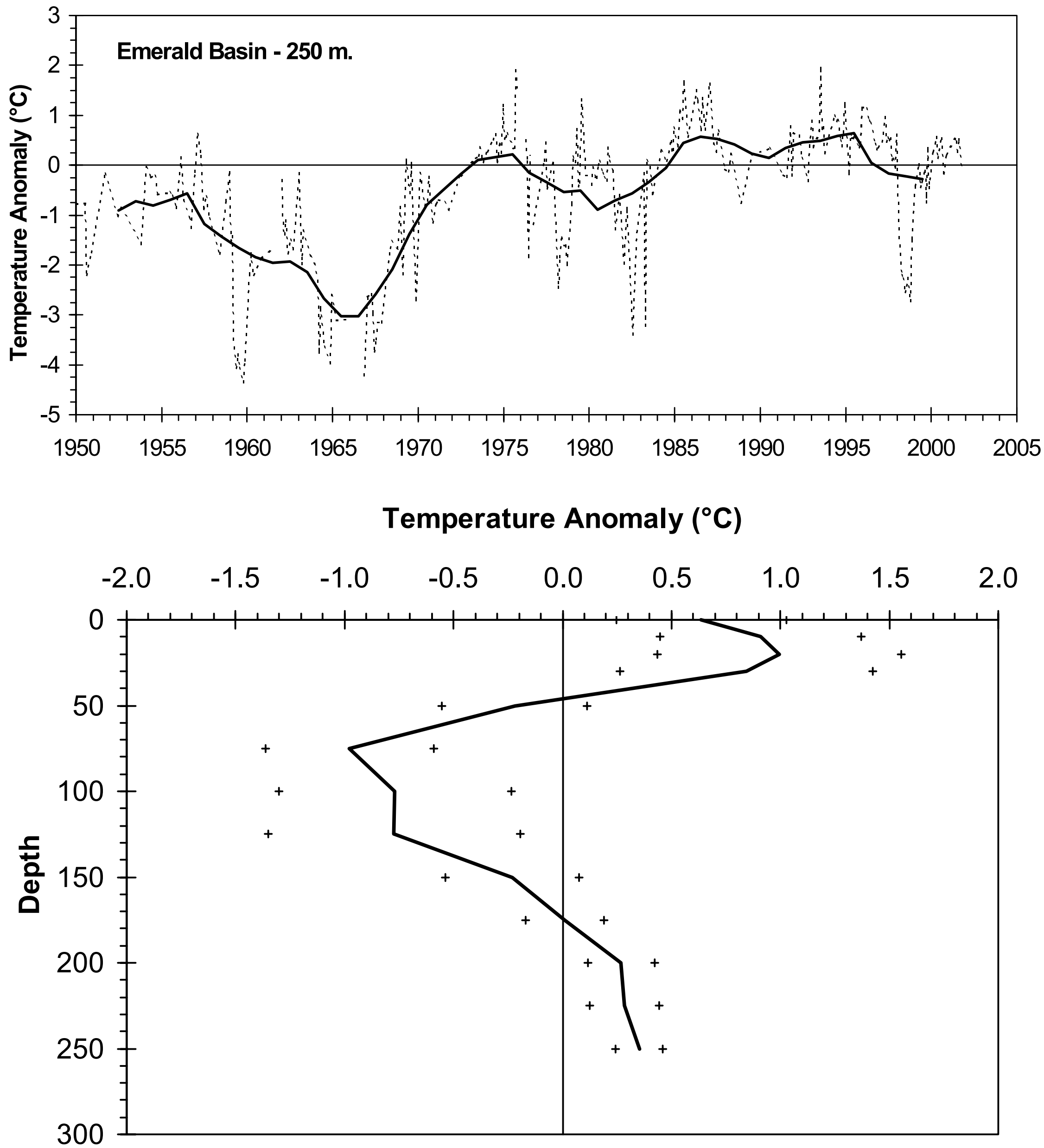
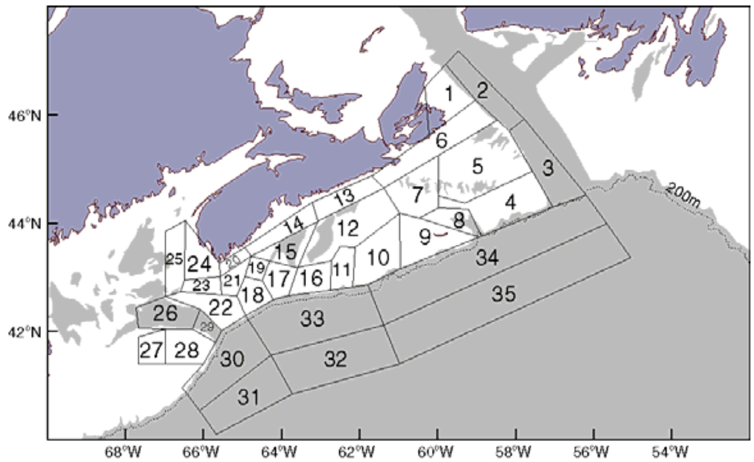
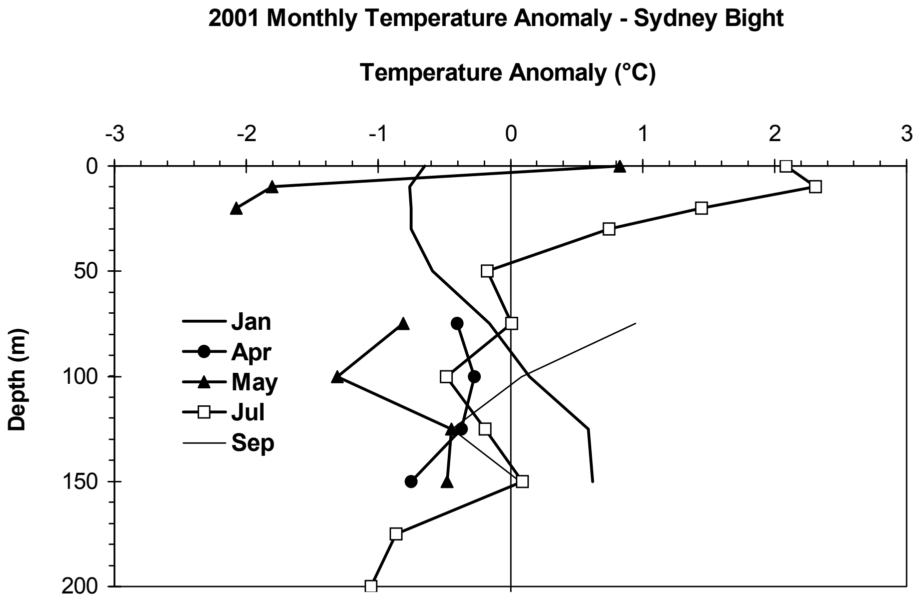


Fig. 7. Time series of available monthly mean temperature anomalies at 250 m in Emerald Basin (dashed line) and their 5-year running means (solid line) in the top panel. The bottom panel shows the annual temperature anomalies for 2002 as a function of depth. The crosses represent standard error of the means based upon the available monthly anomalies.



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



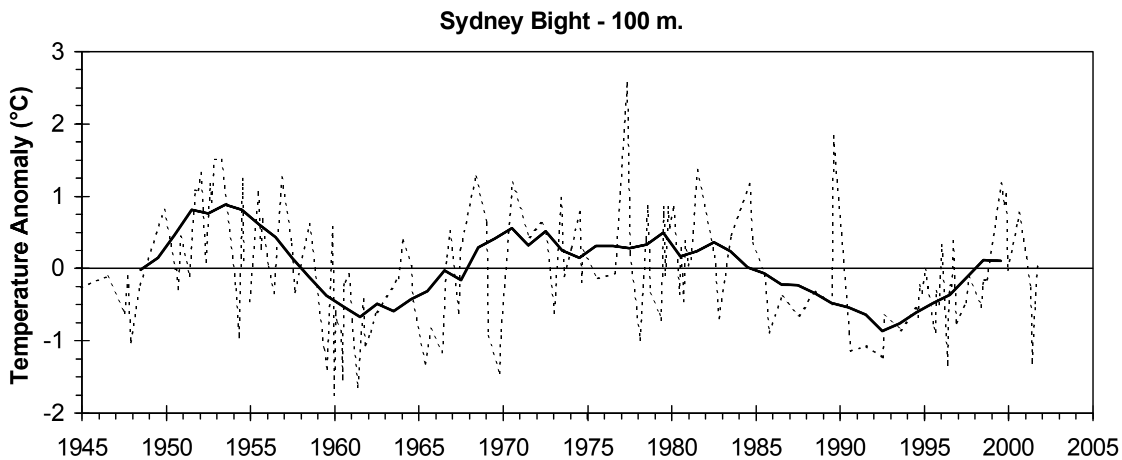


Fig. 9. 2001 monthly temperature anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1-Fig. 8).

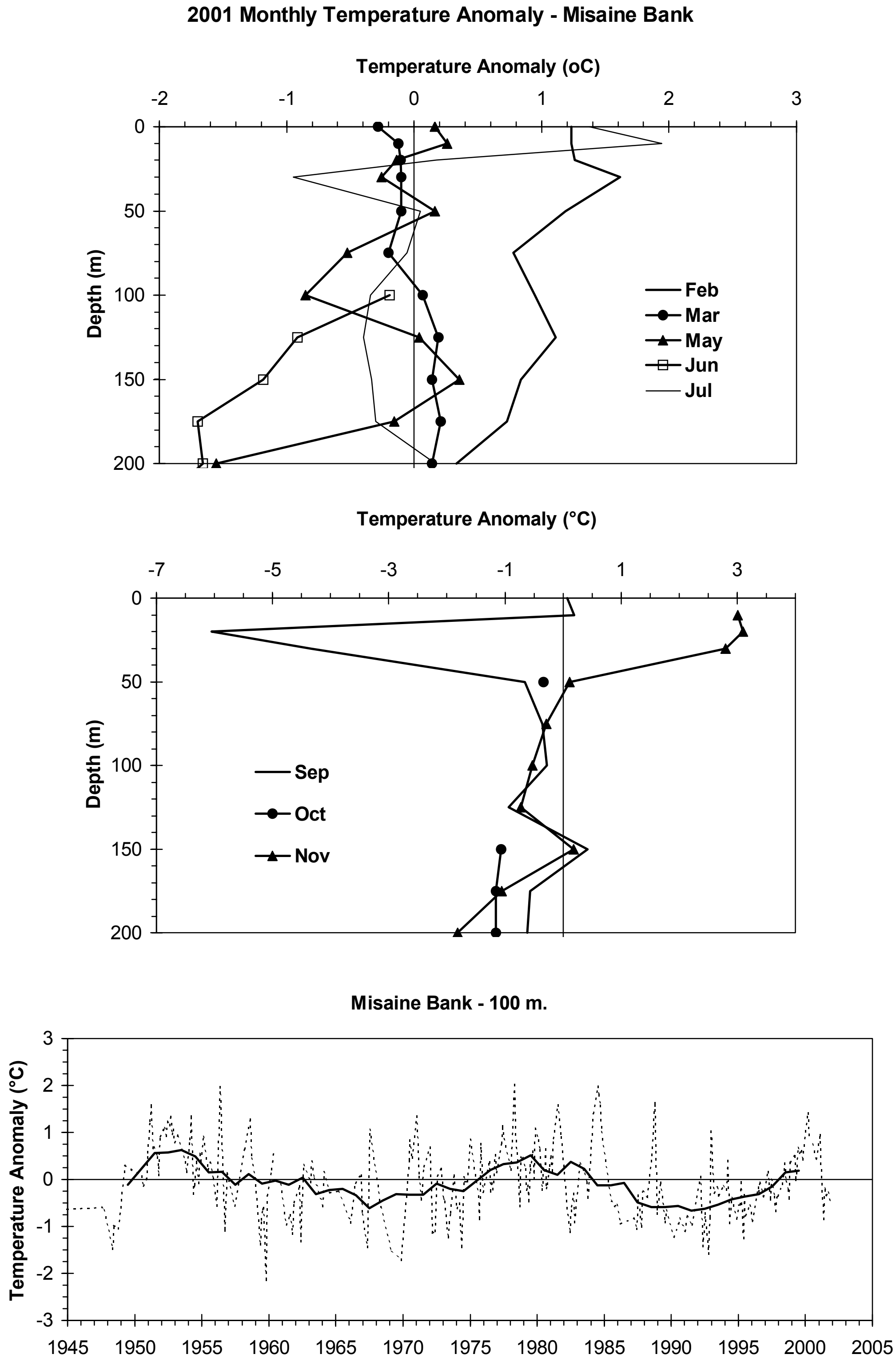


Fig. 10. 2000 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5-Fig. 8).

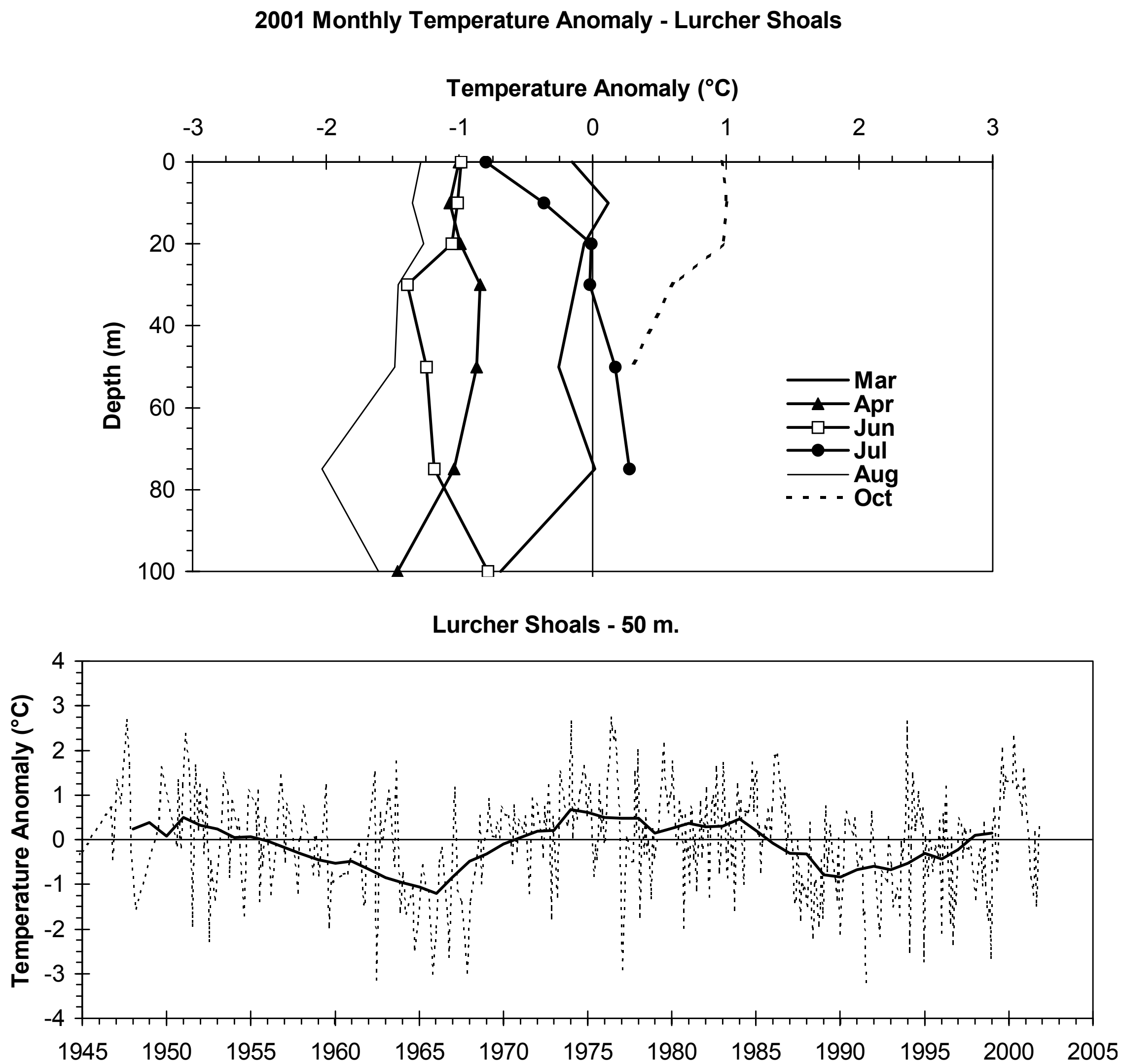


Fig. 11. 2001 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Lurcher (area 24-Fig. 8).

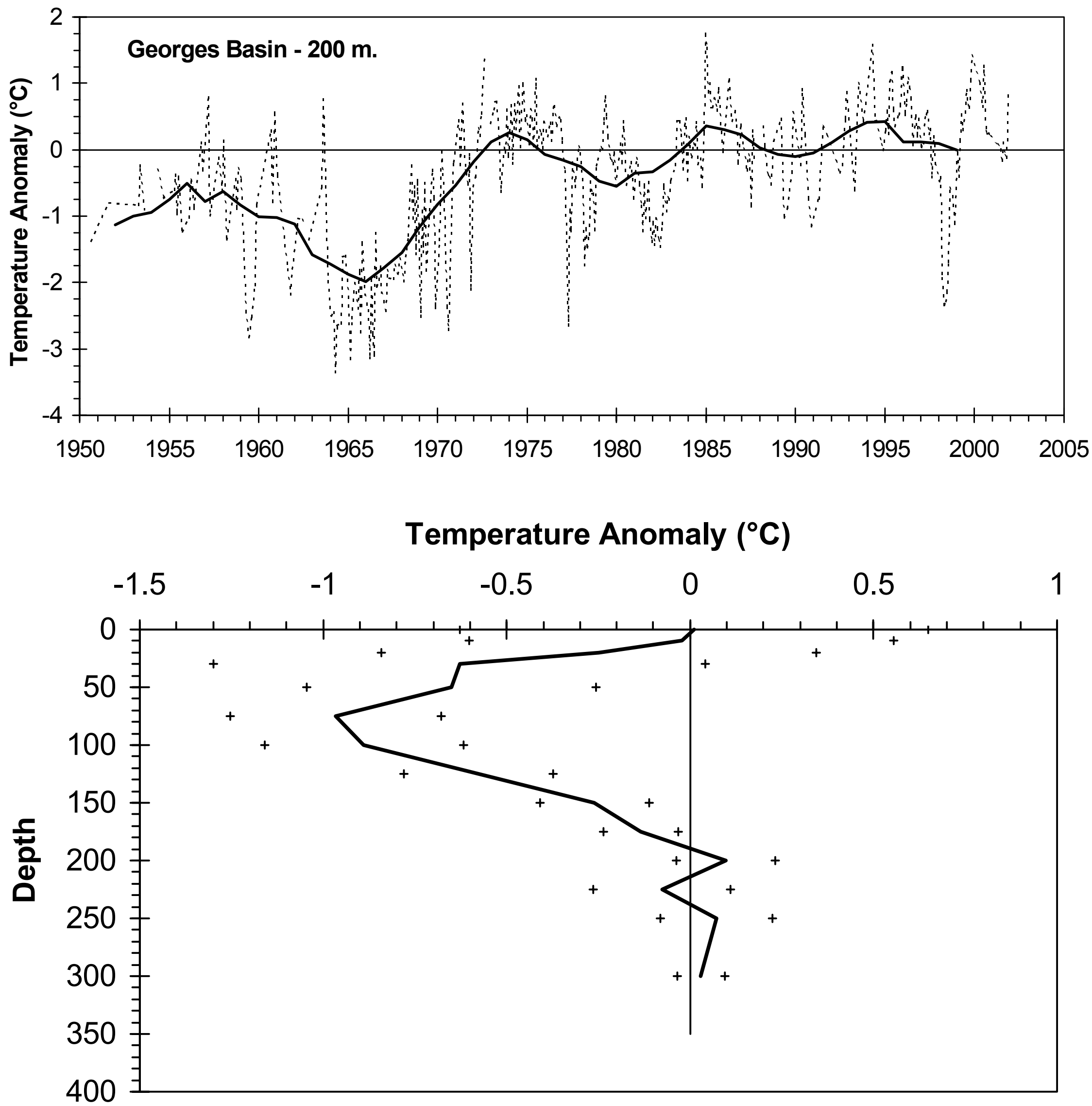


Fig. 12. Time series of available monthly mean temperature anomalies at 200 m in Georges Basin (dashed line) and their 5-year running means (solid line) in the top panel. The bottom panel shows the annual temperature anomalies for 2002 as a function of depth. The crosses represent standard error of the means based upon the available monthly anomalies.

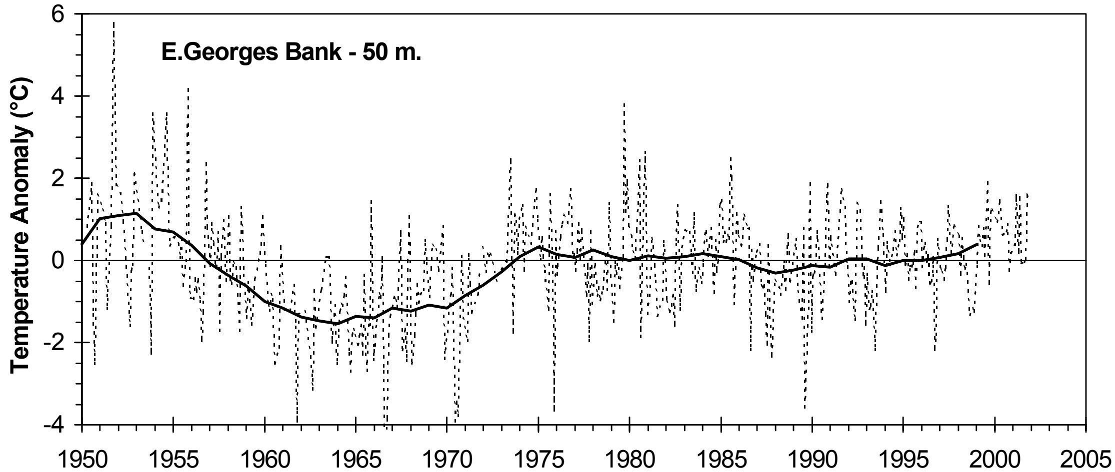


Fig. 13. Time series of monthly mean temperature anomalies at 50 m on eastern Georges Bank (dashed lines) and their 5-year running means (solid line).

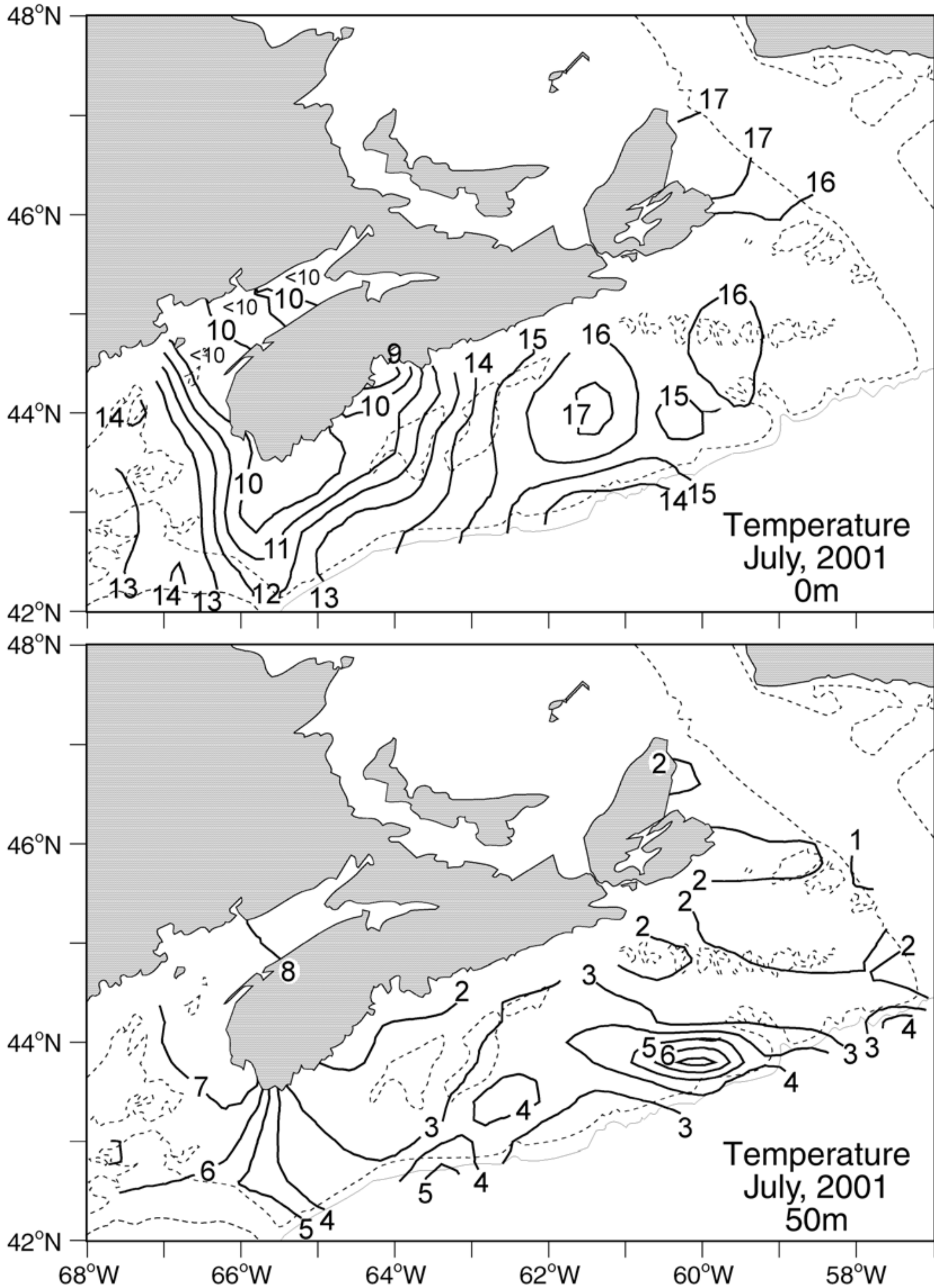


Fig. 14a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2001 July groundfish and ITQ surveys.

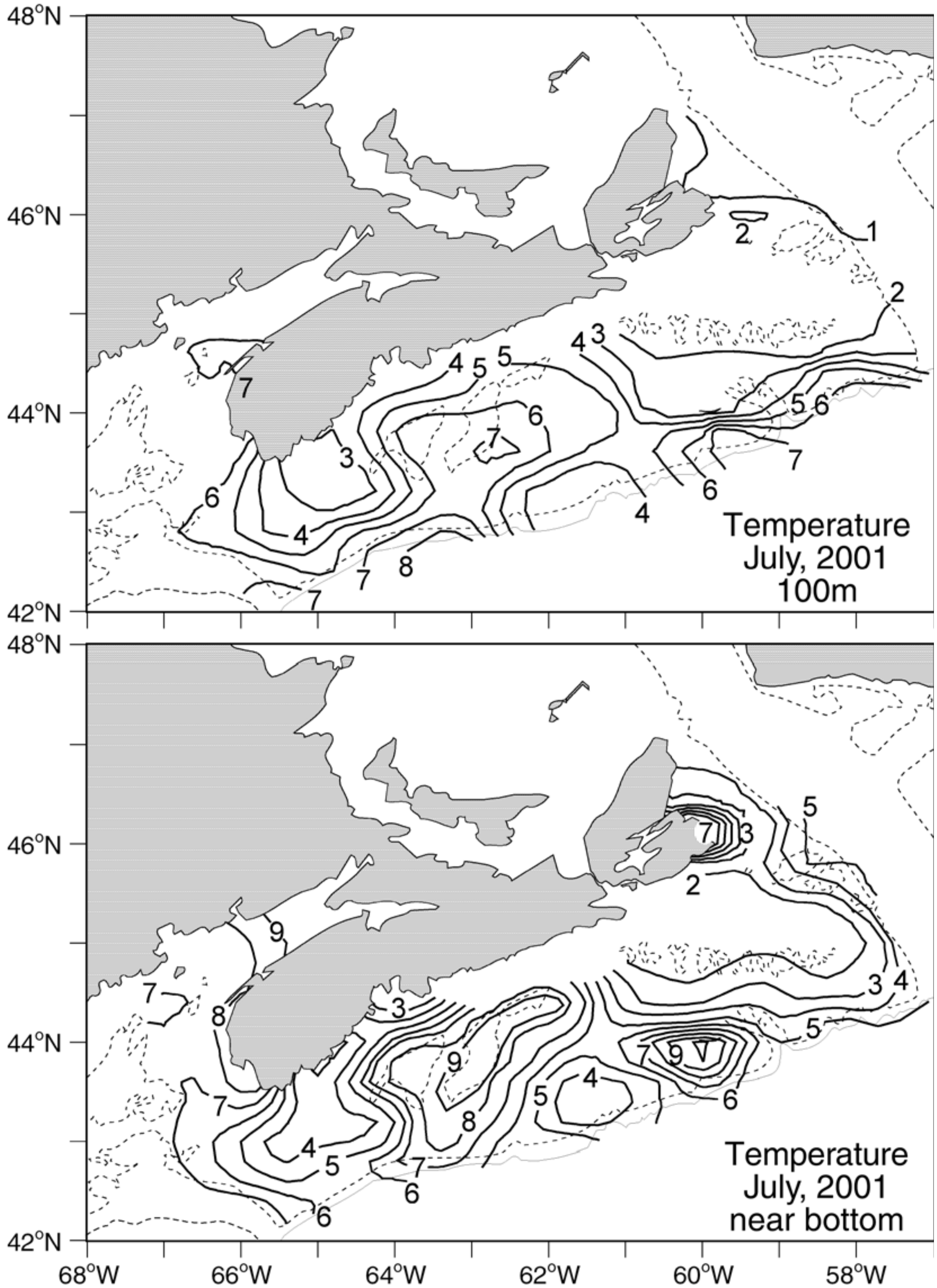


Fig. 14b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2001 July groundfish and ITQ surveys.

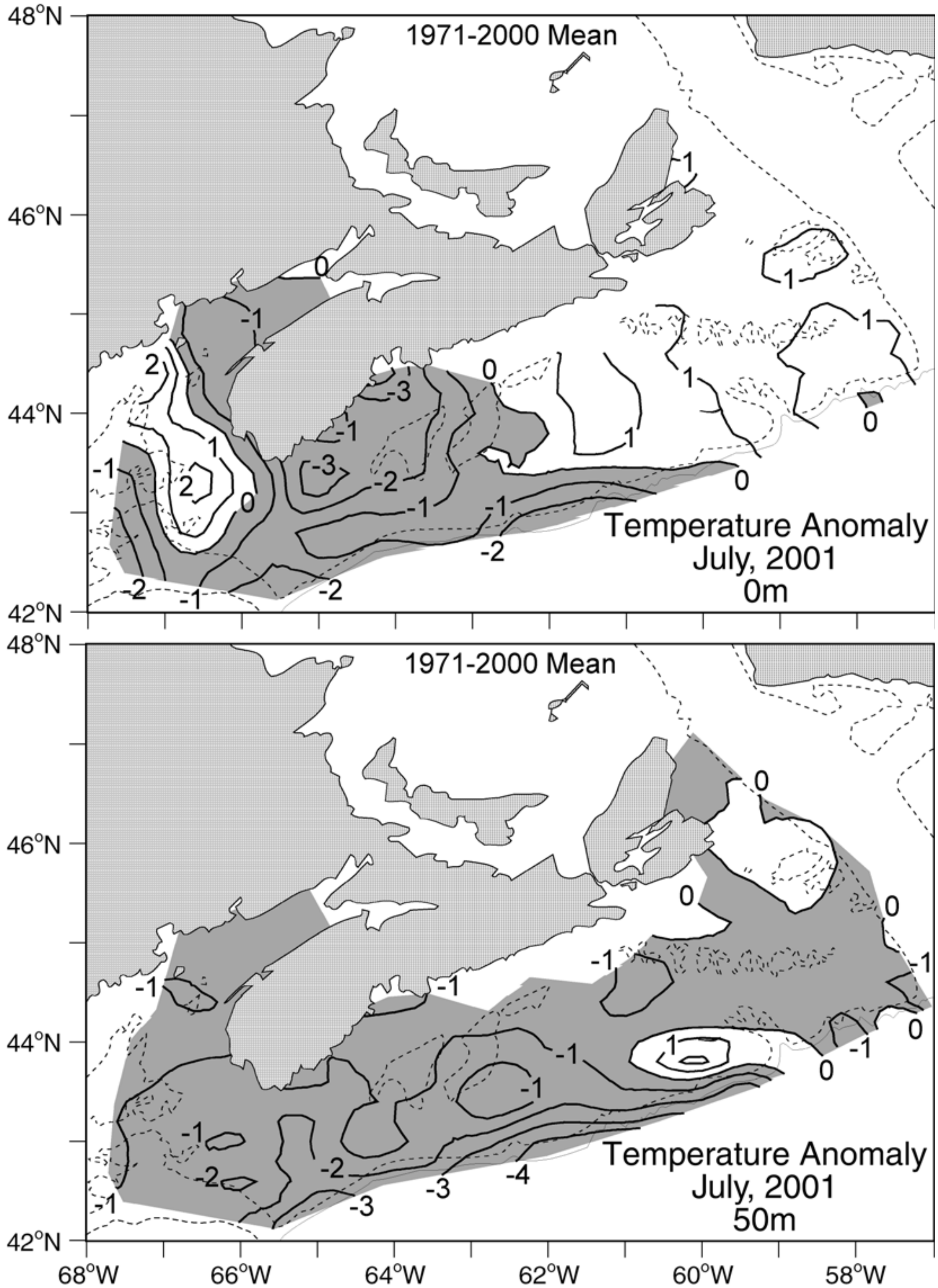


Fig. 15a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2001 July groundfish and ITQ surveys.

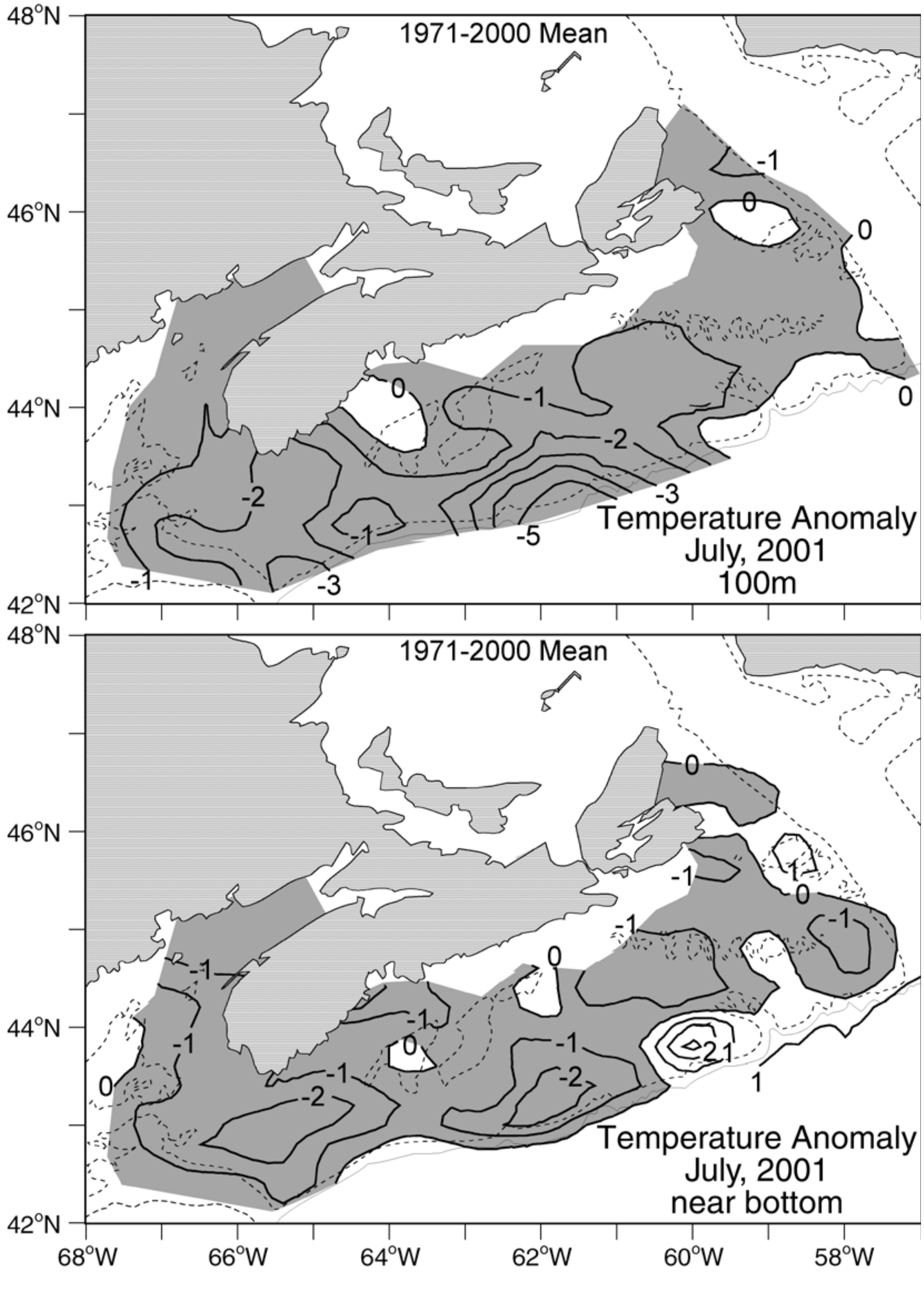
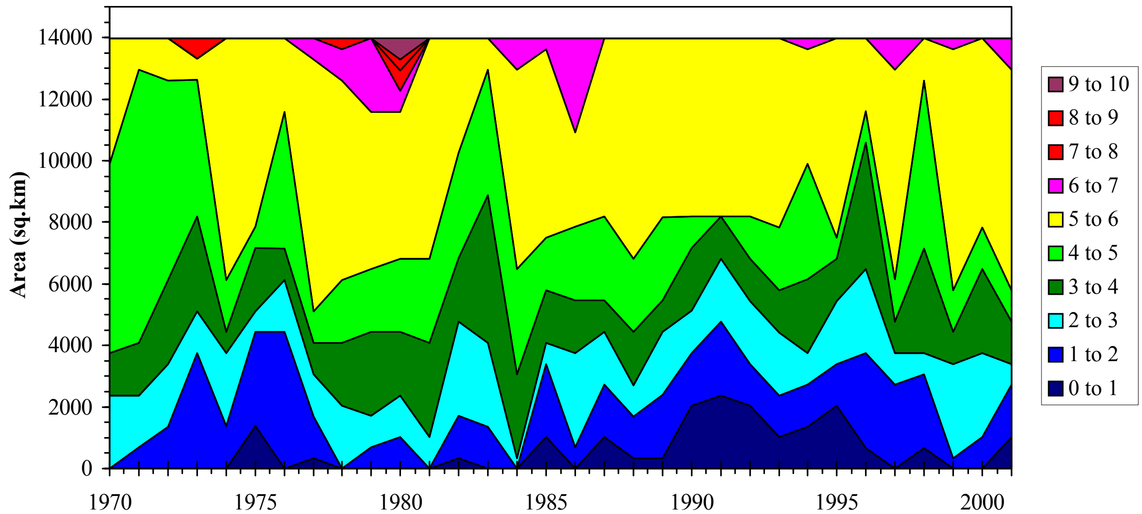


Fig. 15b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2001 July groundfish and ITQ surveys.

Area 4Vn



Area 4Vs

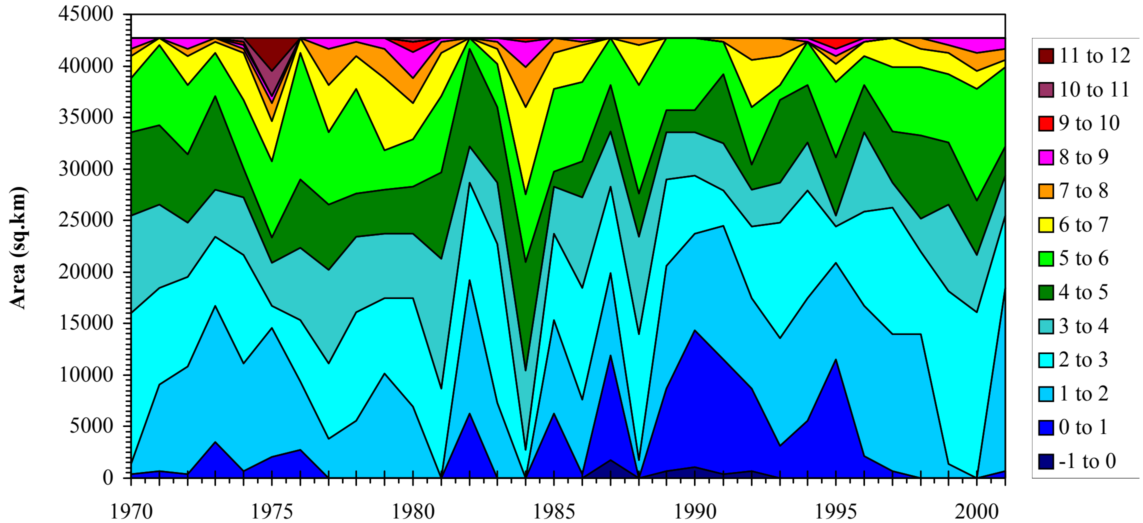
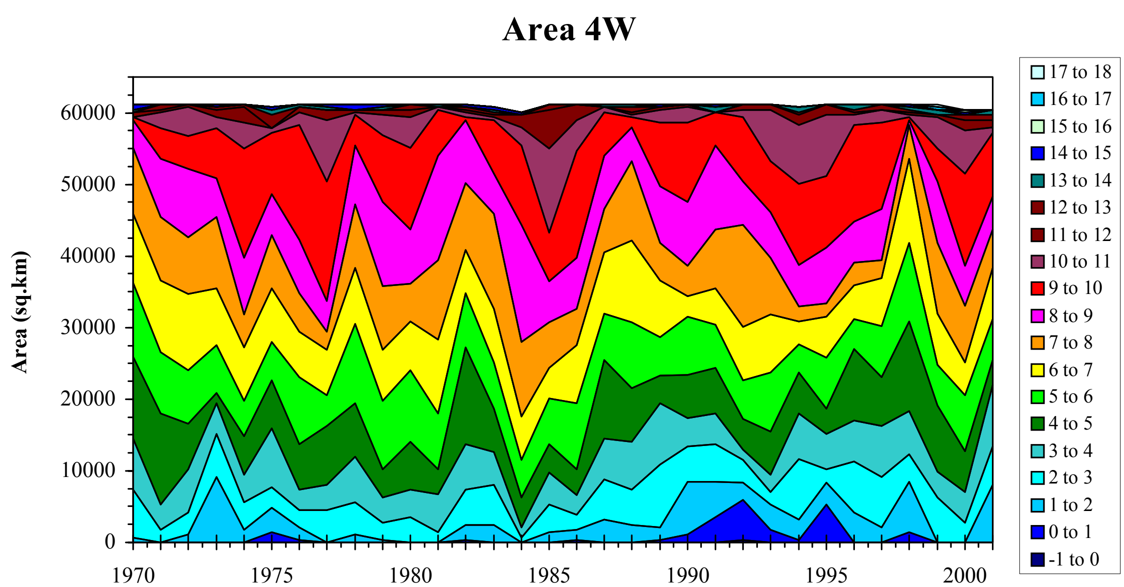


Fig. 16a. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).



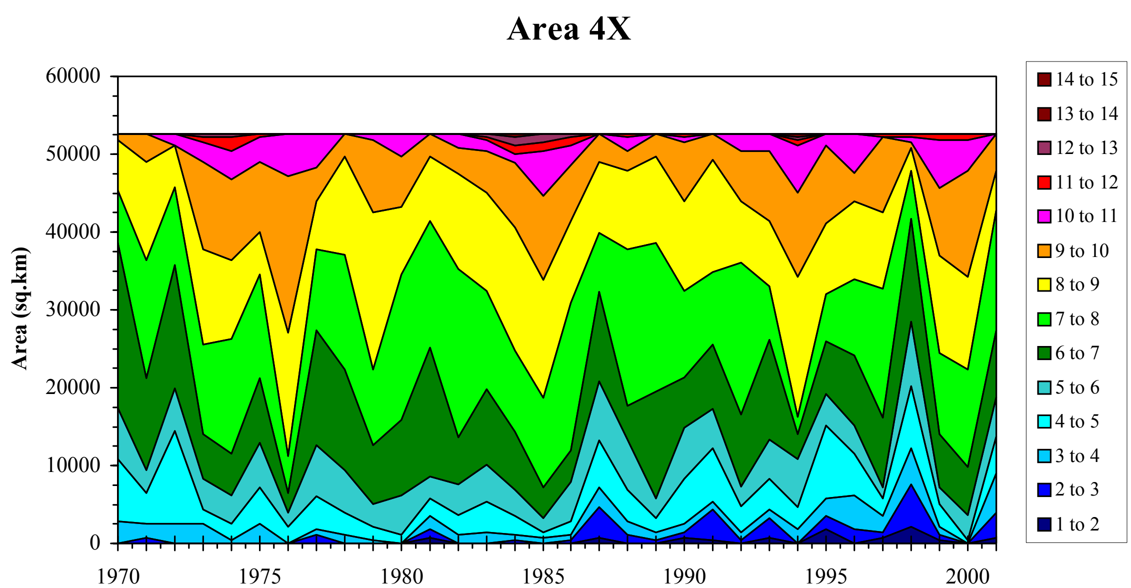


Fig. 16b. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4W (top panel) and 4X(bottom panel).

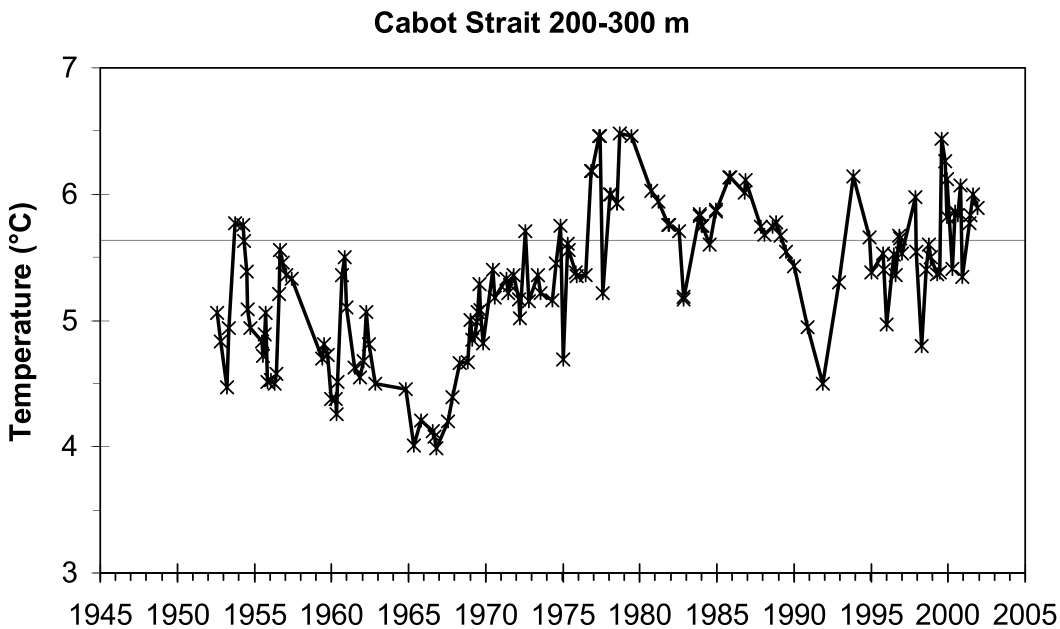


Fig. 17. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the long-term mean during 1971-2000.

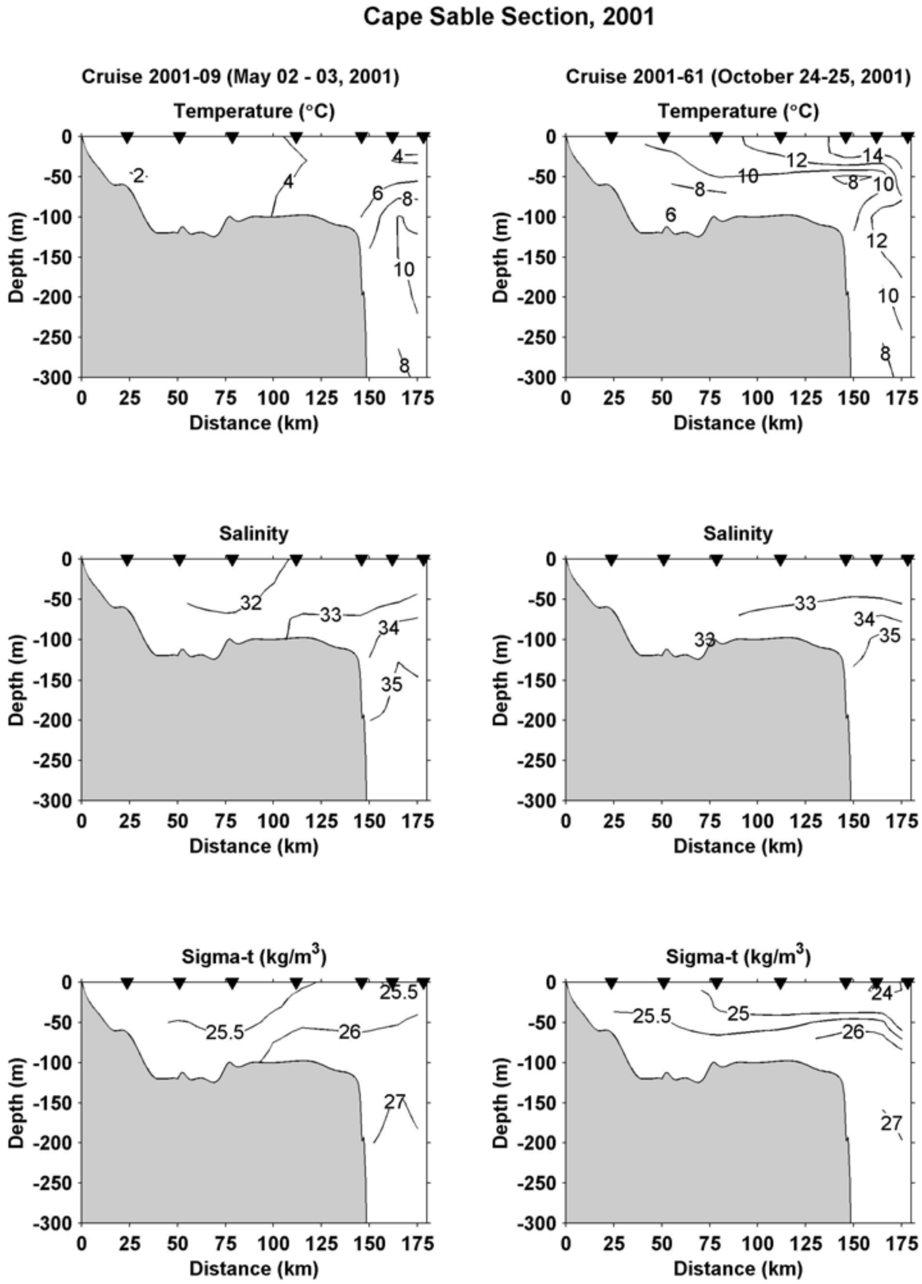


Fig. 18. The temperature, salinity and sigma-t contours along the Cape Sable Section during November of 2001. The triangles denote the location of the CTD profiles.

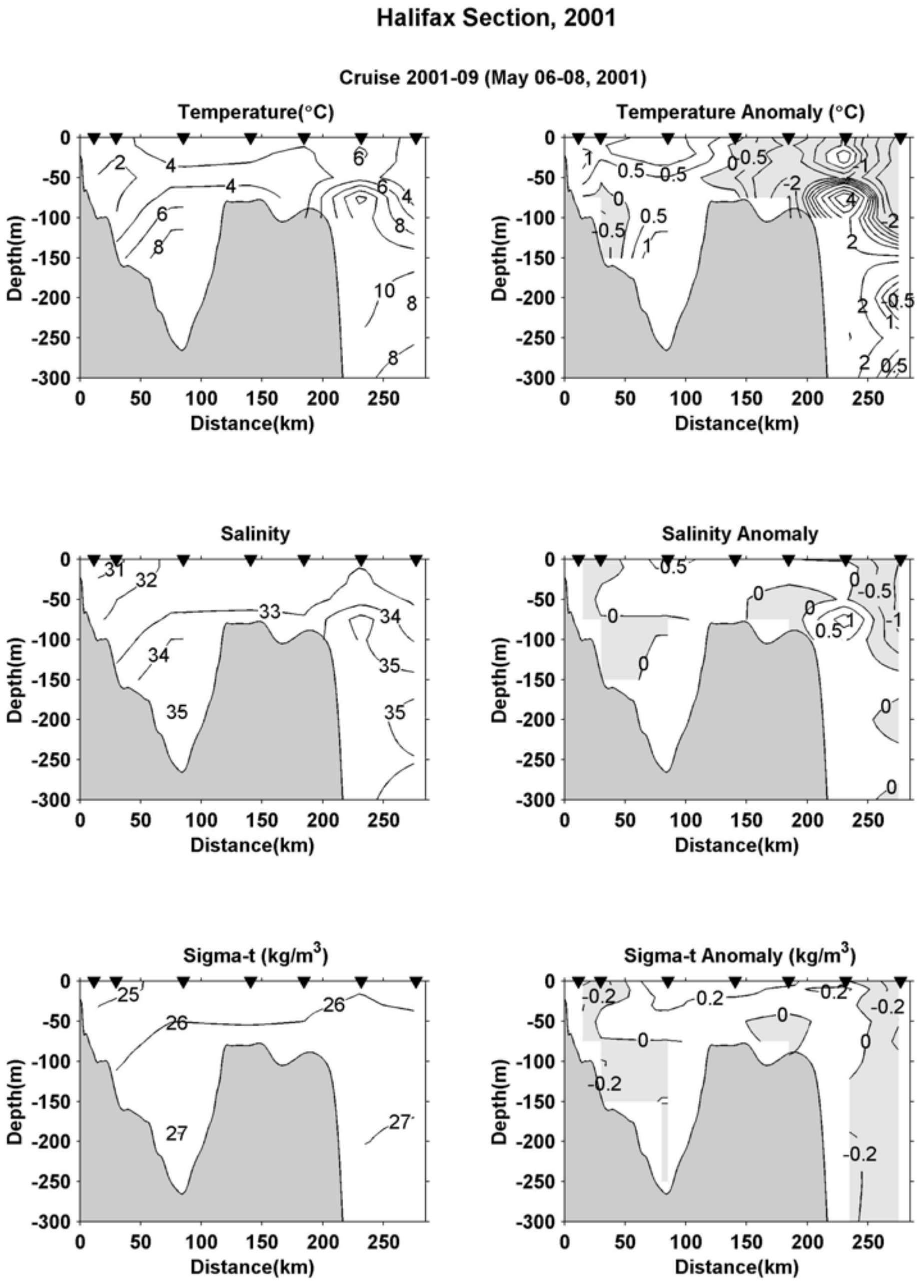


Fig. 19. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during May 2001 (left panels). The triangles denote the location of the standard stations.

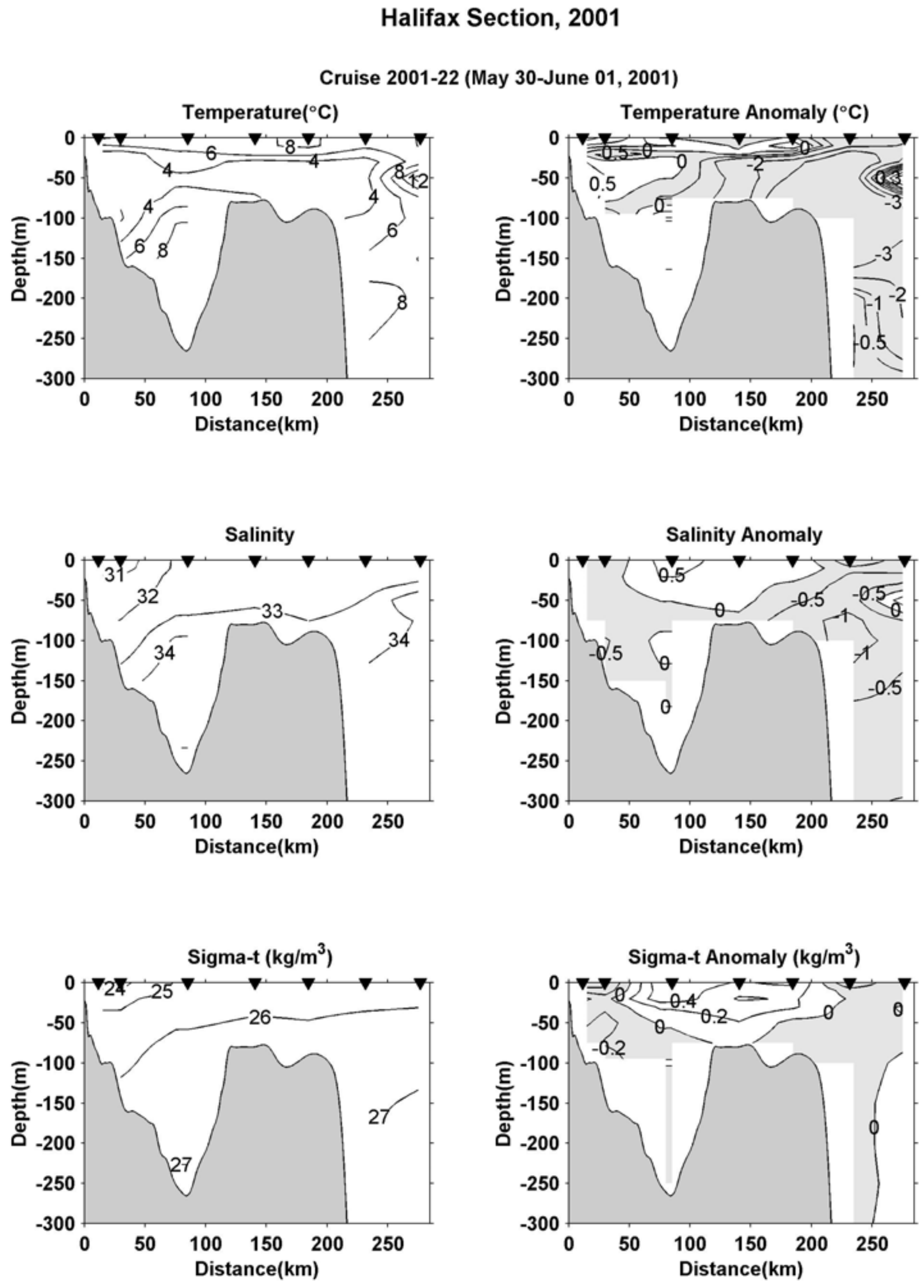


Fig. 20. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during 31 May-1 June 2001 (left panels). The triangles denote the location of the standard stations.

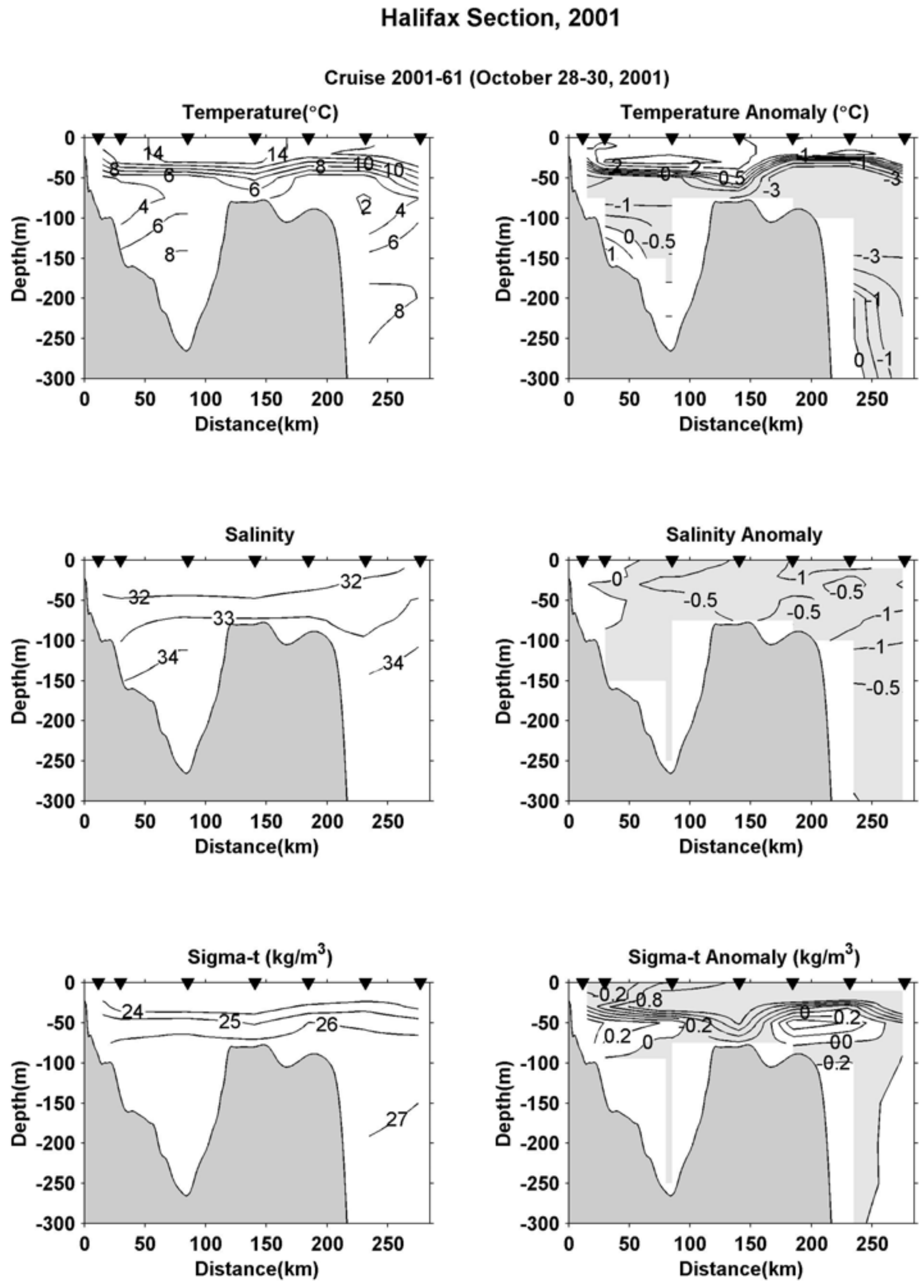


Fig. 21. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during October 2001 (left panels). The triangles denote the location of the standard stations.

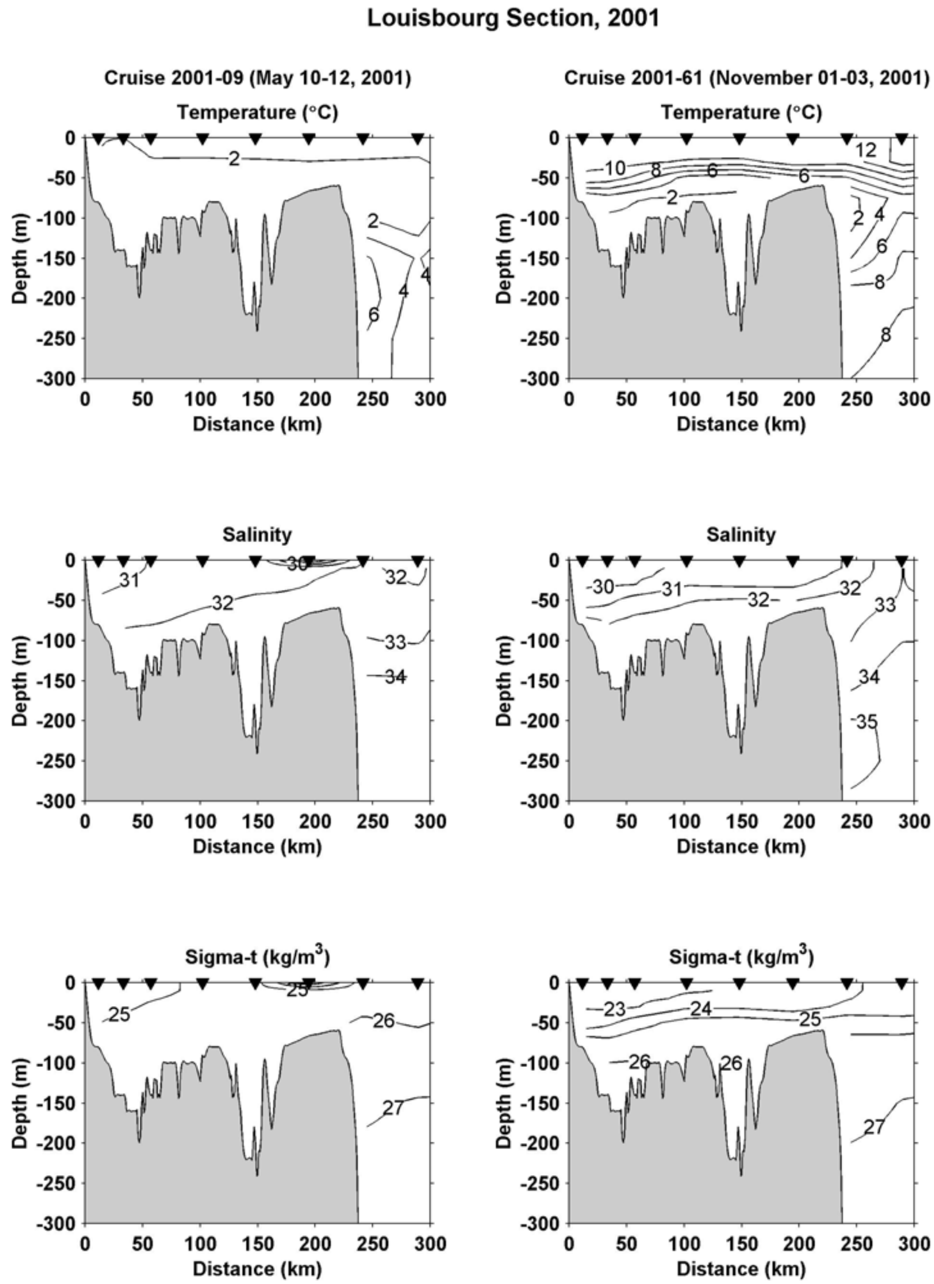


Fig. 22. Contours of the temperature, salinity and sigma-t along the Louisbourg Line during November 2001. The triangles denote the location of the CTD stations. Also shown are the temperature anomalies.

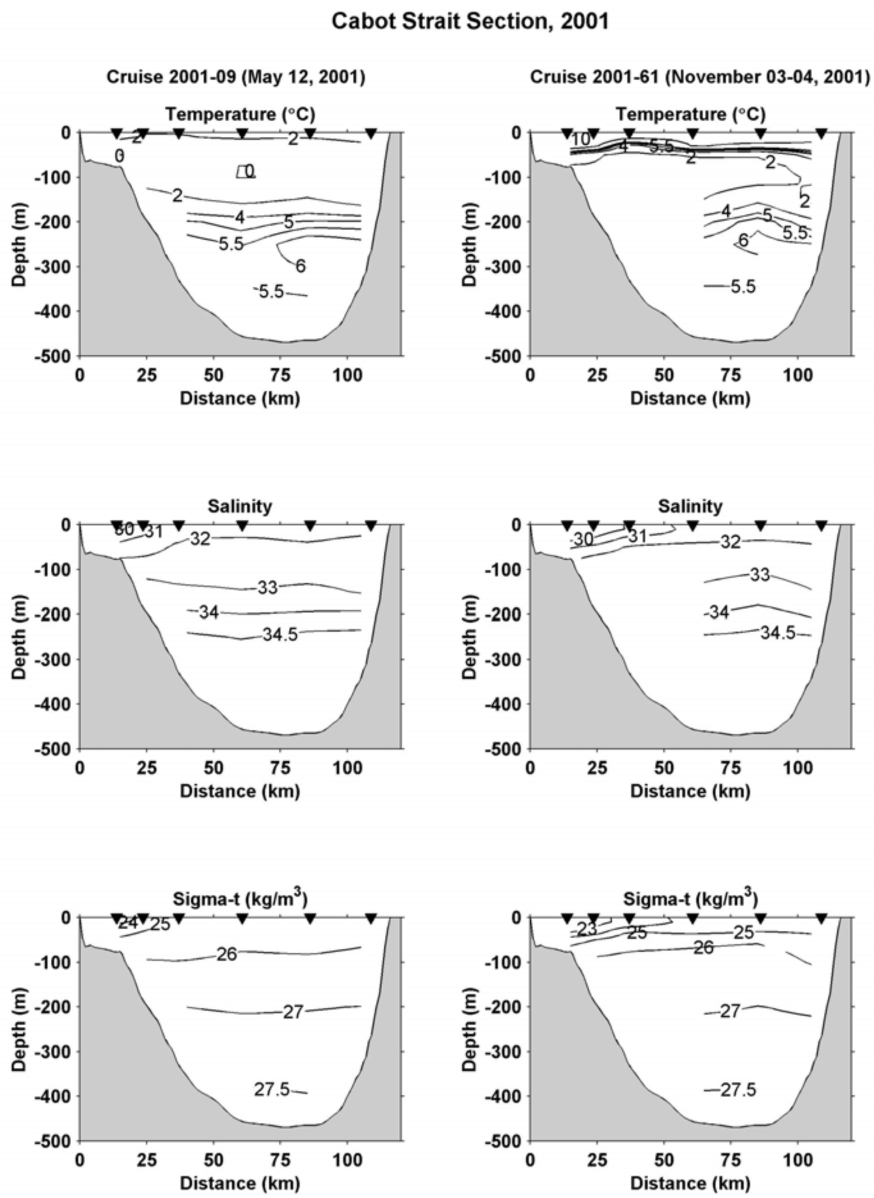


Fig. 23. Contours of the temperature, salinity and sigma-t along the Cabot Strait Line during May and November 2001. The triangles denote the location of the CTD stations.

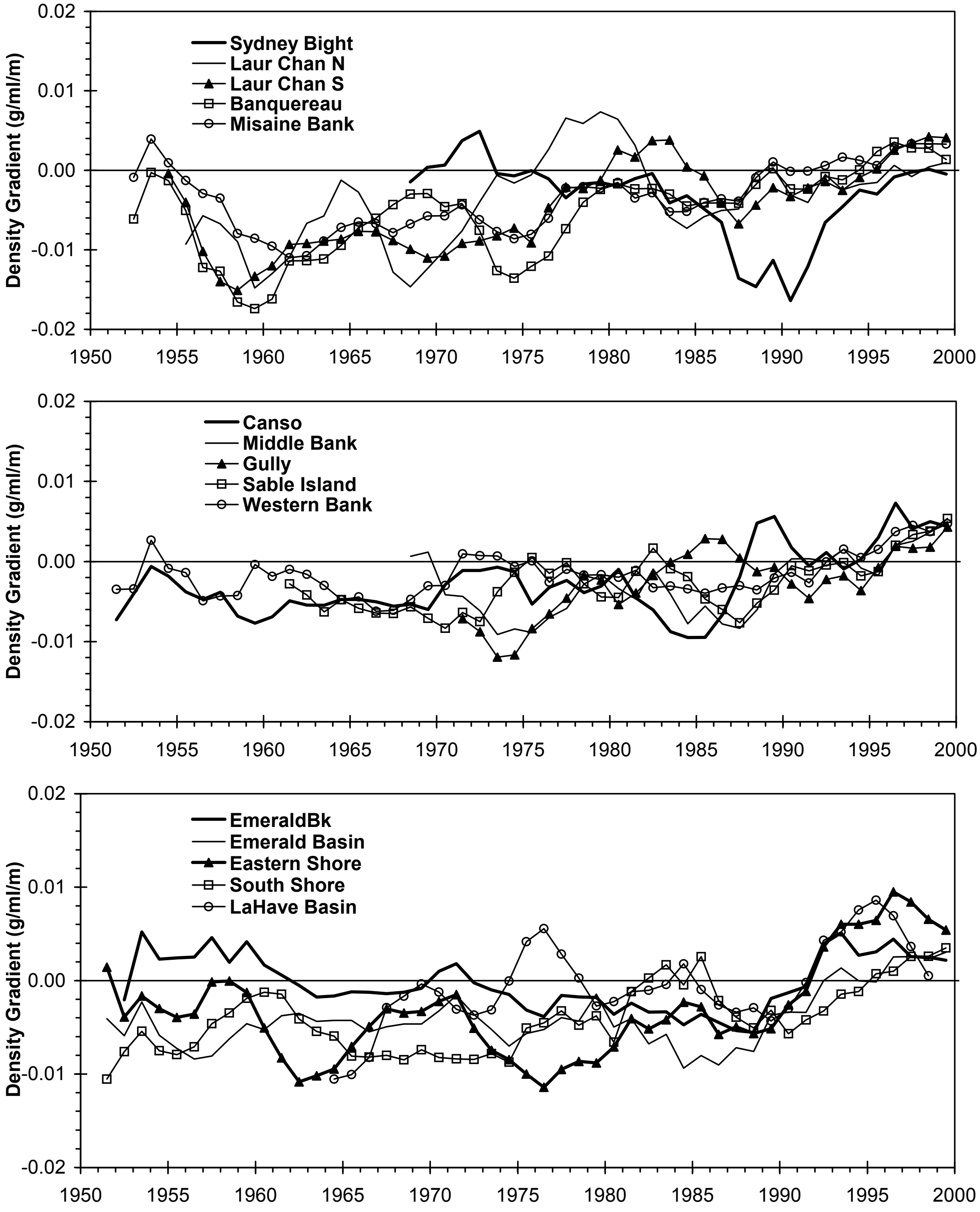


Fig. 24a. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 1-15 in Fig. 8.

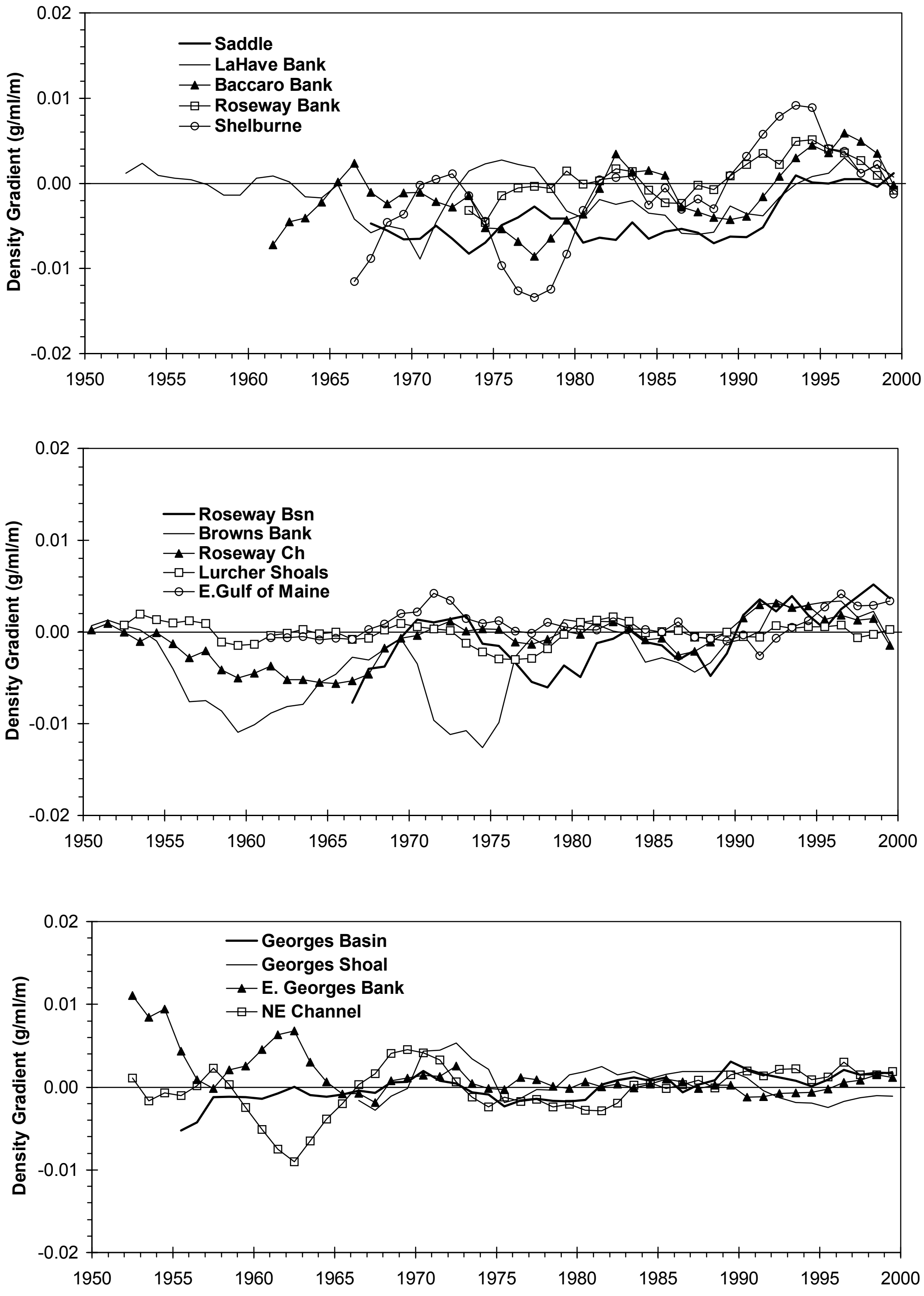


Fig. 24b. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 16-29 in Fig. 8.

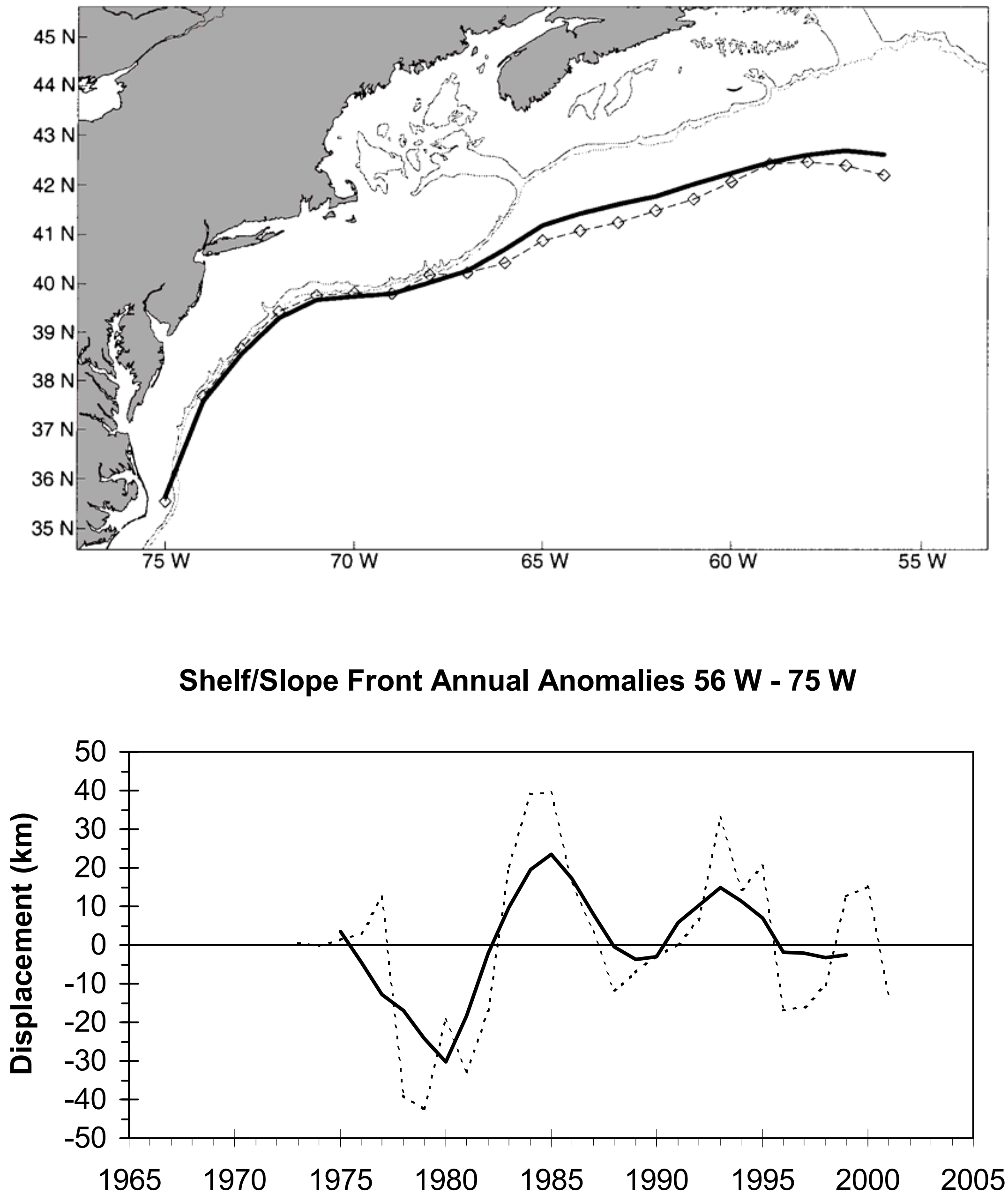


Fig. 25. The 2001 (dashed line) and long-term mean (1973-2000; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).

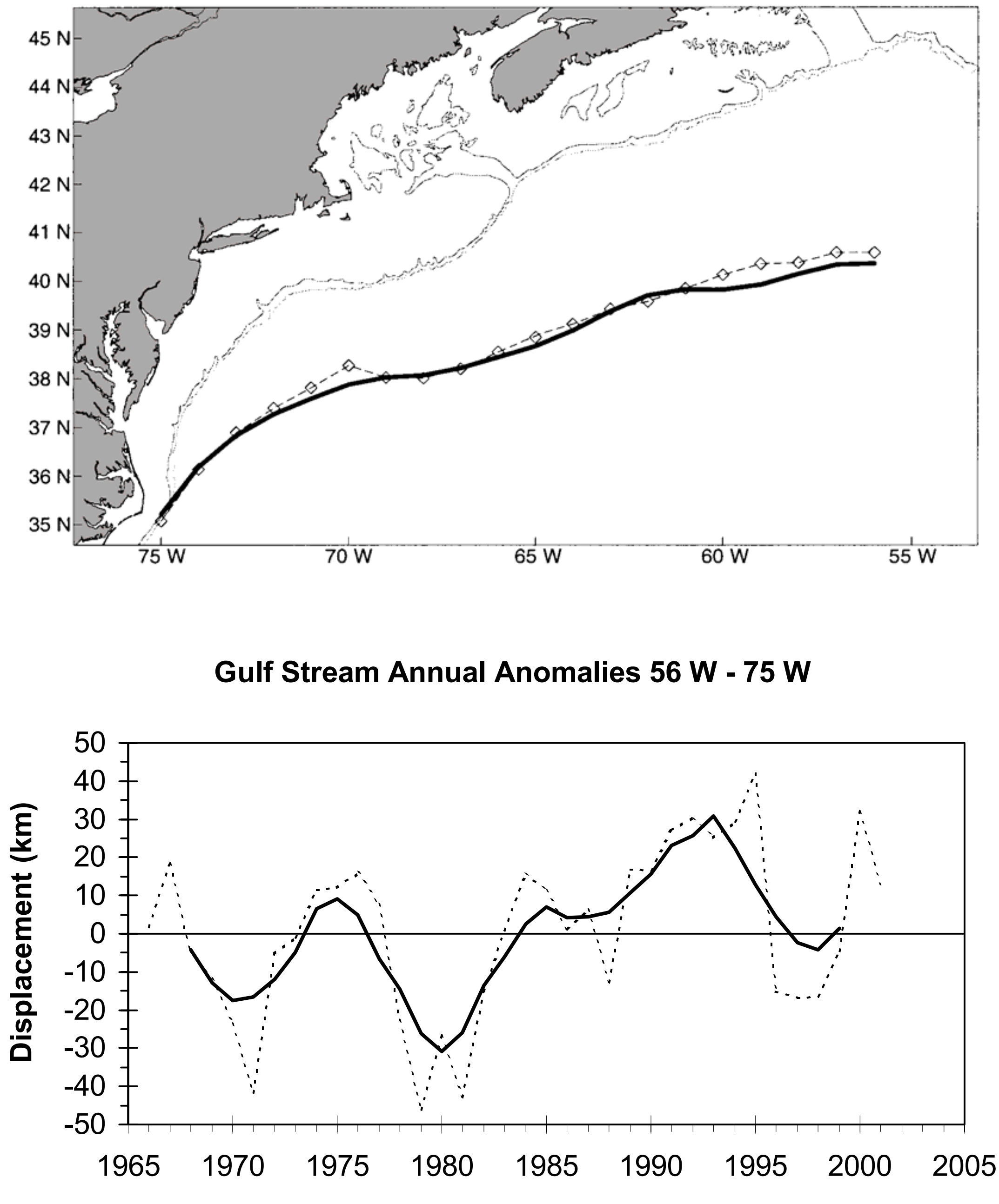


Fig. 26. The 2001 (dashed line) and long-term mean (1973-2000; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).