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Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2000

Conditions océanographiques physiques en 2000 sur la plate-forme Scotian et dans le golfe du Maine

K. Drinkwater, B. Petrie, R. Pettipas, L. Petrie and V. Soukhovtsev

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

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Abstract

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2000 is presented. Warm conditions dominated the region at all depths. Coastal sea surface temperatures, fisheries surveys, transect data, fixed monitoring sites and other CTD stations all indicate that surface temperatures were well above normal throughout the year. Subsurface temperatures in the northeastern portions of the Scotian Shelf continued their warming trend, were above normal and rose slightly relative to 1999. This followed nearly 15 years of below normal temperatures with the minimal temperatures recorded in the early to mid-1990s. 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. Near bottom temperatures throughout the Scotian Shelf were also above normal in 2000 and the area of bottom covered by cold temperatures decreased significantly. The cold intermediate layer waters emulating from the Gulf also were warmer-than-usual. Warm Slope Water was located offshore and there was no evidence of Cold Slope Water along the Scotian Shelf or off the Gulf of Maine during 2000. While the vertical stratification in the upper water column (between surface and 50 m) over the Scotian Shelf generally weakened in 2000 relative to 1999, it remained higher than normal. The Shelf/Slope front and the Gulf Stream were well shoreward of their normal positions. For the Gulf Stream it was the 2nd most shoreward position in the 29-year record.

Resumé

Une étude des conditions océanographiques physiques en 2000 sur la plate-forme Scotian et dans le golfe du Maine, ainsi que dans les zones hauturières avoisinantes, est présentée. Des températures chaudes dominaient dans la région, et ce, à toutes les profondeurs. Les températures superficielles côtières de la mer, les relevés des pêcheries, les données de récoltes manuelles le long d'un transect, ainsi que les stations de surveillance fixes et autres stations de CTP, indiquent toutes que les températures superficielles étaient largement supérieures à la normale pendant toute l'année. Dans les zones du nord-est de la plate-forme Scotian, la tendance au réchauffement des eaux sous-marines s'est poursuivie, les températures étant supérieures à la normale et légèrement plus élevées que celles de 1999. Cette situation survient après une période d'une quinzaine d'années où les températures étaient inférieures à la normale, les températures minimales ayant été enregistrées entre le début et le milieu des années 1990. Les mesures effectuées en eaux profondes, sur la plate-forme comme dans le golfe du Maine, indiquent que les températures élevées, qui ont suivi l'épisode d'eaux froides de 1998, se poursuivent. Les températures près du fond, sur toute la plate-forme Scotian, étaient aussi supérieures à la normale en 2000 et la partie du fond couverte par les eaux froides a sensiblement diminué. Les eaux froides des couches intermédiaires provenant du golfe du Maine étaient aussi plus chaudes que d'habitude. Les eaux chaudes du talus continental étaient situées au large et il n'y avait aucune indication d'eaux froides du talus continental le long de la plate-forme Scotian ou au large du golfe du Maine en 2000. Bien que, dans la colonne d'eau supérieure (entre la surface et 50 m de profondeur) située au-dessus de la plate-forme Scotian, a généralement diminué en 2000, par rapport à la situation en 1999, elle était tout de même plus importante que la normale. Le front plate-forme/talus et le Gulf Stream étaient situés beaucoup plus près du rivage que d'habitude. Dans le cas du Gulf Stream, sa position était la deuxième plus rapprochée du rivage de toutes les observations effectuées en 29 ans.

Introduction

This paper describes temperature and salinity characteristics of the waters on the Scotian Shelf and in the Gulf of Maine during 2000 (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 2001 update. Additional hydrographic data were obtained directly from the DFO fisheries personnel. This represents the second 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 1961-1990 in accordance with the convention of the World Meteorological Organization and recommendations of the Northwest Atlantic Fisheries Organization (NAFO, 1983). Meteorological, sea ice and satellite-derived sea-surface temperature information for eastern Canada during 2000 is described in Drinkwater et al. (2001). Of particular relevance was that air temperatures and sea surface temperatures over most of the northwest Atlantic during 2000 were warmer-than-normal.

Coastal Sea Surface Temperatures

Monthly averages of coastal sea surface temperature (SST) for 2000 were available at Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each site for 1999 and 2000 are shown in Fig. 2.

The dominant feature in 2000 at all sites was the above normal temperatures (in all 12 months at Boothbay Harbor and St. Andrews and in 9 of the 12 months at Halifax). The anomalies equalled or exceeded one standard deviation (based upon the years 1961-90) in 10 months at Boothbay Harbor (all months but February and December) and at St. Andrews (all months but September and December). Four months equalled or exceeded one standard deviation at Halifax (Jan, March, July and August). Exceeding one standard deviation means the data are approximately within the top or bottom 16% of the time series. The maximum monthly anomaly at Boothbay was in July, 2.6°C (over 3 standard deviations from the long-term mean) with June to September all having anomalies >2 °C. At St. Andrews the maximum positive anomaly was 1.2°C in January. A similar amplitude anomaly but negative was observed in September but this was less than 1 standard deviation from the long-term mean for this month.

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. 2). 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. In 2000, the annual mean temperature at these two sites was above normal (mean of 8.1°C and 1.0°C above normal at St. Andrews and 10.1°C and 1.6°C above normal at Boothbay). At Boothbay the temperature rose relative to 1999, was the 4th warmest year in the 95-year record and is at its highest level since 1954 (Fig. 2). At St. Andrews, the annual mean temperature fell below the 1999 value, but was still the 7th warmest year in the 80-year record. Halifax had an annual mean sea surface temperature anomaly of only 0.3 °C but rose compared to 1999.

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. In 2000, there were 3 measurements during March and November, 2 in May-September and December and 1 in January, February, April and October. 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 2000, monthly mean temperatures ranged from a minimum in February of around 2.8°C throughout most of the water column to a maximum in August of 12.4°C near surface (Fig. 3,4). Monthly temperature anomalies were positive except in the upper 50 m in January. The highest positive anomalies (>2°C) occurred in May throughout most of the water column and in April at the bottom. From March to October, temperature anomalies were over 1°C above normal. This represents the third consecutive year of relatively warm temperatures. The annual mean temperatures exhibit high year to year variability (Fig. 4). In 2000, annual anomalies were approximately 1°C through the water column and were similar to those recorded in 1999. With the exception of the negative anomalies in the early

1990s, temperatures at Prince 5 have generally been warmer than their long-term means since the early-1970s at the surface and 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 2000 were saltier-than-normal except in April and May (Fig. 3, 5). The lowest salinities (<29 psu) occurred at the surface in April and the highest salinities (>33 psu) appeared near bottom in the autumn. The former represented an anomaly of –2. This could be a result of an early arrival or greater quantity of St. John River runoff or perhaps the path of the river plume is closer to shore. The arrival of higher salinity waters near bottom in autumn is typical. Annual salinity anomalies in 2000 were positive and although similar to 1999 values at both the surface and 90 m, they fell slightly (Fig. 5). 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, 2001). Salinities rose above normal by 1999.

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 (1961-90) monthly means of temperature, salinity and density (sigma-t) for 1961-90 were discussed in Drinkwater et al. (2000).

Temperatures at H2 ranged from less than 2°C to over 18°C in 2000 and were predominantly warmer-than-normal (Fig. 6). Only intermediate layer waters during the last three months of the year were colder than their long-term averages. Upper layer waters in the spring and early summer were upwards of 2°-4°C warmer-than-usual. Similar amplitude anomalies were observed in the subsurface waters (deeper than 50 m), especially during the late winter and spring. This suggests that there was less cold intermediate layer water than usual at this site in 2000, being replaced by waters with characteristics more similar to Slope Water. For example, salinities in the subsurface waters were generally saltier-than-normal (by upwards of 0.5-1). Salinities ranged from <31 to >34. Averaged over the upper 20 m salinity was highest during April to June and lowest at the end of the year, which is typical. Relative to the long-term means, waters generally were fresher-than-normal in late winter and early spring and again during the last few months of the year. At subsurface depths, salinities rose during the summer, which is again typical, and are most likely related to coastal upwelling. 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 50 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 less dense water than normal in the surface waters during the first four months of the year and through much of the summer and autumn. These lower-than-normal densities also extended through the water column in the latter half of the year but at this time were not much below normal. Higher than usual densities were observed even in the surface waters in May and June. The density anomalies in 2000 indicate stronger stratification during the winter and early spring and the summer with weaker stratification than normal in the late spring.

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, which is reasonably representative of the lower layers from 100 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 2000, the water was warmer-than-normal by approximately 0.5°-1°C. This is up from 1999 and 1998 but below the values recorded through earlier years of 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. 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 2000 at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compare 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. 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 3 months show predominantly above normal temperatures throughout most of the water column (Fig. 9). The exception was below 100 m in July where they were slightly below normal. In August surface temperatures were over 4°C warmer-than-usual and in July over 2°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.

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 8) were collected in 7 months during 2000. They show primarily warmer-than-normal temperatures throughout the water column (Fig. 10). The only real exceptions were in the deepest layers in April, June and October. Surface anomalies tended to be high in all months with positive values of 1°-2°C. The time series of the 100 m temperature anomalies show 2000 to be the second consecutive year of positive values and contrast 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. 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. 8). This area exhibited warmer-than-normal temperatures in 2000 in the 6 months of 2000 when data were available (Fig. 11). The warmest month was April when temperatures were approximately 2.5°C above normal throughout the water column. Anomalies in 4 months exceeded +1°C. The time series at 50 m clearly shows high temperature anomalies in 1999 and 2000 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 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. Temperatures in the deep regions (200 m) of Georges Basin (Fig. 12) show a striking similarity to that of Emerald Basin (Fig. 7) including the very cold conditions in 1998 and warm in 1999 and 2000. 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). They exhibit higher variability than 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 Georges Basin and in areas on the Scotian Shelf. These again include the low temperatures in the 1960s, the higher-than-average conditions in the 1970s into the 1990s. In 2000, temperatures were above normal as was observed in 1999.

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 218 CTD stations were taken during the 2000 survey and an additional 202 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 1000 m off the shelf. The 2000 temperature anomalies relative to the July 1961-90 means were also computed at the same four depth levels (Fig. 15).

The broad spatial pattern of near-surface temperatures in July 2000 was similar to past years with the warmest waters (17°C) off the northeastern coast of Nova Scotia and the coldest (<11°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 2000 were warmer than the long-term average throughout the northeastern Scotian Shelf whereas in the central and southeastern region of the Shelf the temperatures varied above and below normal (Fig. 15a). The maximum anomaly was over 4°C above normal off southern Cape Breton. Surface temperatures off southwest Nova Scotia were also warmer-than-usual by upwards of 2°C. This contrasts with the colder-than-normal temperatures in the Bay of Fundy, Northeast Channel and the outer central Shelf region. The generally warm conditions are consistent with the satellite imagery which has shown high sea surface temperature anomalies throughout the Scotian Shelf during much of 2000 (Drinkwater et al., 2001). Relative to 1999, the surface temperatures in 2000 generally decreased. This is not surprising given the extremely warm sea surface temperatures experienced during 1999, which in turn were due to record high air temperatures. This excess heat in the atmosphere would have led to increased heat flux from the air to the ocean. Although air temperatures in 2000 were also generally above their long-term means, they were not as warm as in 1999. One exception to the cooler waters in 2000 compared to 1999 was off the southwest coast of Nova Scotia. In 1999, this was an area of active upwelling. The warmer-than-normal waters in 2000 suggest that there was less upwelling than normal.

The temperatures at 50 m ranged from 2-3°C to over 9°C with the coldest waters in the northeast and the warmest waters in the deep Gulf of Maine and the Bay of Fundy (Fig. 14a). There appears to be some penetration of warmer offshore waters (>6°C) in towards Emerald Basin. Temperature anomalies at 50 m (Fig. 15a) were predominantly positive over the Shelf (mostly 1°-2°C). Slightly below normal temperatures appeared along the shelf break. These 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 are higher (Fig. 14b). The temperatures at 100 m ranged from 2-3°C in the northeast to over 9°C in the Northeast Channel and Emerald Basin. The analysis also suggests the possibility of 10°C water along the shelf break but again data in this region must be viewed cautiously. Temperature anomalies at this depth were typically 0°-1°C in the northeast and 1°-2°C over most of the rest of the Shelf (Fig. 15b). The highest anomalies (>3°C) occurred along the inner shelf off the Nova Scotia coast near Halifax. This would appear to be due to a greater than usual inshore penetration of slope waters and is consist with the data collected at the Halifax 2 Station (Fig. 6).

Near-bottom temperatures over the Scotian Shelf ranged from 3°-4°C in the northeastern Scotian Shelf to over 10°C in the Bay of Fundy (Fig. 14b). High temperatures (>9°C) were also observed in the Northeast Channel and in Emerald and LaHave Basins. 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 while in the deep basins of the Scotian Shelf and the Gulf of Maine, the waters mainly originate from the warmer offshore slope waters. The warm waters around Sable Island are due to the shallow depths and hence the close proximity to the warm surface mixed layer. Elsewhere on the shelf the bottom depths lay well below the mixed surface layer. Relative to the long-term mean (1961-90), the near bottom temperatures were predominantly warmer-than-normal (Fig. 15b). Similar to 100 m, the temperature anomalies on the northeastern Scotian Shelf were generally 0°-1°C and over the rest of the region were 1°-2°C. The largest deviation from the long-term mean (warmer by around 2°C) occurred just off the mainland coast of Nova Scotia, on Middle Bank in the northeast and at a couple of locations near the shelf edge.

A more detailed analysis of both the temperature and salinity characteristics during the 2000 Scotian Shelf groundfish survey examined in the context of the survey strata are provided by Losier et al. (2001).

We also estimated the area of the bottom covered by each one degree temperature range (i.e. 1-2°C, 2-3°C, 3-4°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°C and almost 50% <5°C (Fig.

16a). For 4Vs, 80-90% is <6°C and 75% <5°C (Fig. 16a). In 4W <50% and in 4X<20% is covered by temperatures <6°C (Fig. 16b). The time series for 4Vn and 4Vs show an increase in the 0°-1°C and especially <3°C waters during the late 1980s and early 1990s (Fig. 16a). Also in 4Vs there are waters <1°C during this colder period. In 4W there is an increase in the area of the waters <3°C but it is of smaller amplitude than in 4V. In 4X there is an increase in waters <4°C but it is not as large an amplitude as in the other regions (Fig. 16b). During 2000 in all areas there was a significant decrease in the area covered by temperatures in the colder temperature ranges. A similar result was found by Losier et al. (2001) using cumulative frequency diagrams of the bottom temperatures.

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°C and an anomaly exceeding -0.9°C; Fig. 17). Then temperatures rose dramatically reaching 6°C (anomaly of 0.6°C) in 1993. Since then temperatures have remained above normal through most of the rest of the 1990s. Temperatures in 2000 also were above the long-term mean but declined from 1999 values.

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 2000, 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. 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 April and October, the offshore was occupied by Warm Slope Water (temperatures >8°C; Fig. 18). The waters over the shelf warmed significantly from 4°-7°C in April to 7°-14°C in October. Of particular note is the increase in the temperatures in the lower half of the water column. For these deeper waters there was also an increase in salinity consistent with a greater influx of slope water onto the shelf. In the surface waters salinities decreased from April 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.

Compared to the same months of 1999, hydrographic properties in 2000 tended to be slightly warmer and fresher in April but slightly cooler and saltier in October. Stratification was definitely stronger in both months during 2000 relative to 1999.

Halifax Line

The Halifax Line was occupied 3 times in 2000 (April, June and October). Contours of temperature, salinity and sigma-t across the section are shown in Fig. 19, 20 and 21, respectively. In all three months, there is evidence of Warm Slope Water (temperatures, >8°C; salinities >34.8) along the shelf edge. Waters in the deep Emerald Basin in all months display temperatures and salinities characteristic of the Warm Slope Water. Seasonal warming and freshening are also clearly evident in the upper layers, which result in increased stratification from spring through to the summer and into the autumn. Minimum temperatures (<6°C) in the cold intermediate layer are located near shore. Relative to the long-term means, temperatures were predominantly above normal throughout the water column. High positive anomalies (>3°C) occurred over Emerald Basin at depths of 30-100 m in April (Fig. 19), between 20-30 m in June (Fig. 20) and in October (Fig. 21). The only exceptions to the warmer-than-normal conditions appeared near bottom on Emerald Bank in April and June and above Emerald Bank (20-50 m) in October. Also, temperatures at the farthest offshore stations were lower-than-normal and salinities fresher-than-normal. However, salinites along the transect were predominantly saltier-than-normal during 2000. Exceptions in addition to the offshore waters in October were on the outer edge of Emerald Bank in April and June and in the inshore half of the shelf in April (surface only) and October. Lower-than-normal densities dominated in the surface waters and higher-than-normal in the deep waters (>50-100 m). Consequently the vertical stratification was stronger than normal.

Compared to 1999, temperatures in Emerald Basin appear slightly warmer and fresher in 2000. While surface layer temperatures were generally warmer in

1999, at intermediate depths temperatures were warmer in 2000. Salinities in 2000 tended to be fresher than in 1999 in the upper layers but saltier in the deeper layers. Stratification appeared stronger in 1999.

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 (April and October). Warm Slope Water (8°-12°C) was located off the shelf during both of these months (Fig. 22). On the shelf, temperatures in April were cold (<2°-4°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 (14°-16°C) and fresh (<30-31). Waters below 50 m were generally <4°C.

Compared to 1999, waters in 2000 were warmer both on the shelf and offshore. Salinites on the shelf were similar between years but offshore in both months they were saltier in 2000, indicative of more of an influence of Warm Slope Water. Densities were lower in 2000 with generally stronger stratification.

Cabot Strait Line

This line extends from northern Cape Breton to southwestern Newfoundland (Fig. 1) and was occupied twice in 2000 (April and October). In April, there was weak vertical stratification (Fig. 23). Upper layer temperatures were <2°C with some waters <0°C on the Cape Breton side of the Strait. Salinities were lowest (<31) also 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. In the surface layers, temperatures on that side were maximum (>10°) while salinities were a minimum (<30). The cold intermediate layer (CIL) at mid-depths was thickest on the Newfoundland side. It had temperatures <2°C. Below 200 m temperatures had warmed slightly from April with significant quantities of >6°C in October. Salinities remained the same, however.

Compared to 1999, waters in April were warmer in 2000 in the deep layers and slightly colder at the upper layers. In 1999, for example there was no water <0°C. Near surface salinites were higher in 2000 and stratification was weaker. In October conditions in the two years were similar.

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 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 last year (Drinkwater et al., 2000), 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 2000 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 to changes in surface salinity, although in 2000 the high 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 2000 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 2 years, the charts only extend east to 56°W.

The overall mean position of the Shelf/Slope front together with the 2000 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 2000, the shelf/slope front was shoreward of its long-term mean position except at its eastern end. The largest positive deviations occurred just east of Cape Hatteras. 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 2000 was near to but slightly farther north than 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 56°W to 75°W. The average position of the north wall of the Stream and the 2000 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 2000, the average position of the Stream was shoreward of its long-term mean position at all degrees of longitude except 75°W and 64°W. 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. The 1996 position is not well defined, however, since it is based upon only three months of the data (October to December). In 1999, the average position of the front moved shoreward but remained south of the mean. By 2000 the position of the Gulf Stream was shoreward of its long-term mean and was the 2nd highest positive anomaly behind only 1995. The trend 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 2000 is presented. Warm conditions dominated the region at all depths. Coastal sea surface temperatures, fisheries surveys, transect data, fixed monitoring sites and other CTD stations all indicate that surface temperatures were well above normal throughout the year. Subsurface temperatures in the northeastern portions of the Scotian Shelf continued their warming trend, were above normal and rose slightly relative to 1999. This followed nearly 15 years of below normal temperatures with the minimal temperatures recorded in the early to mid-1990s. 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. Near bottom temperatures throughout the Scotian Shelf were also above normal in 2000 and the area of bottom covered by cold temperatures decreased significantly. The cold intermediate layer waters emulating from the Gulf also were warmer-than-usual. Warm Slope Water was located offshore and there was no evidence of Cold Slope Water along the Scotian Shelf or off the Gulf of Maine during 2000. While the vertical stratification in the upper water column (between surface and 50 m) over the Scotian Shelf generally weakened in 2000 relative to 1999, it remained higher than normal. The Shelf/Slope front and the Gulf Stream were well shoreward of their normal positions. For the Gulf Stream it was the 2nd most shoreward position in the 29-year record.

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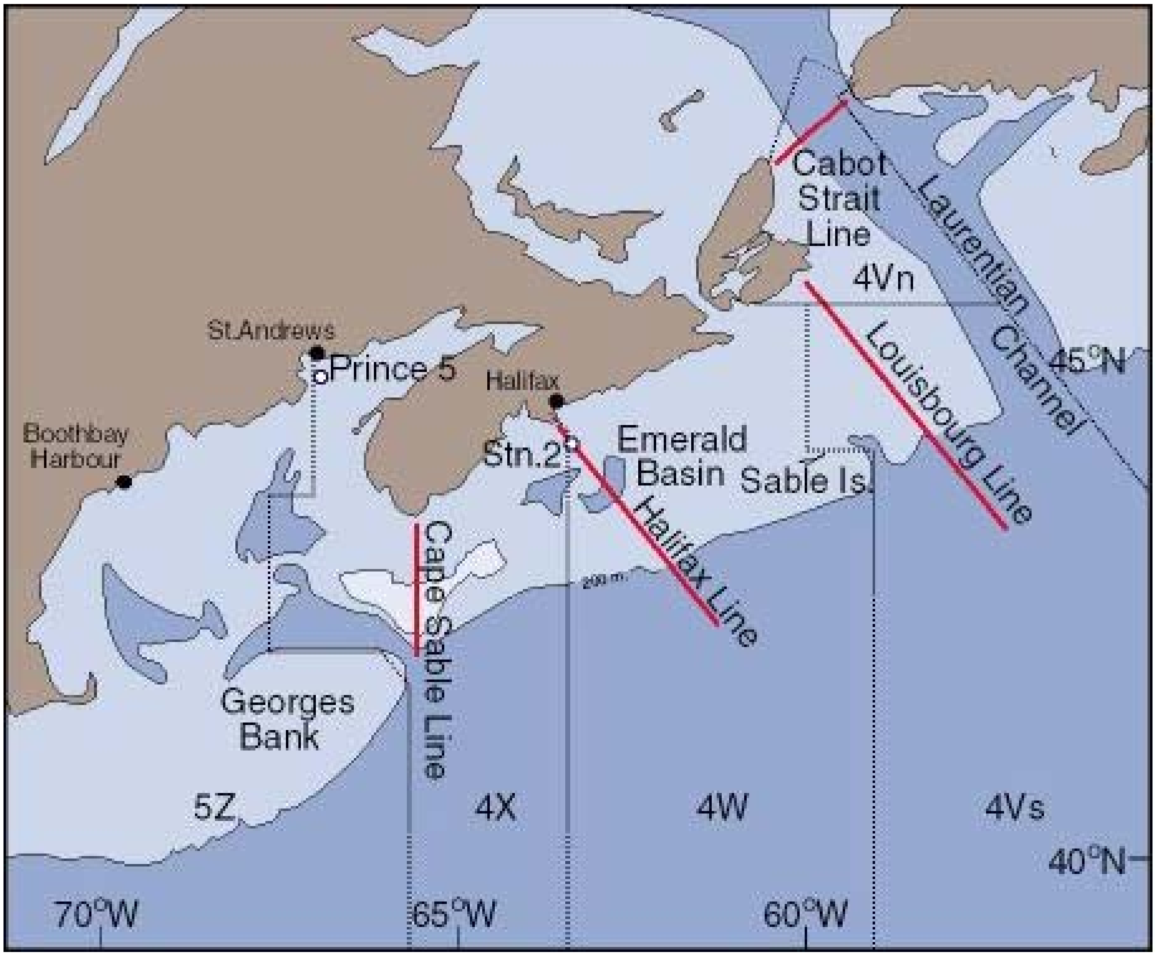


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

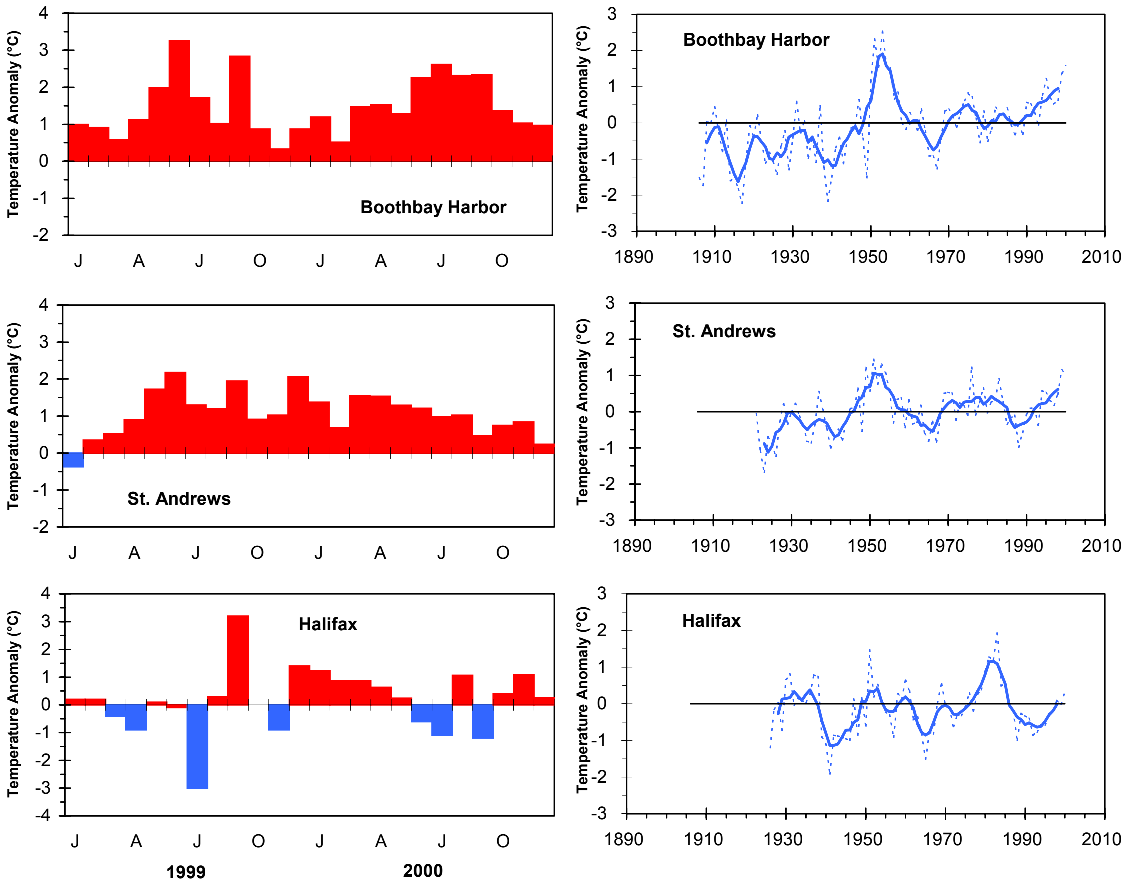


Fig. 2. The monthly sea surface temperature anomalies during 1999 and 2000 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Red bars denote positive anomalies and blue bars, negative anomalies. Anomalies are relative to the 1961-90 means.

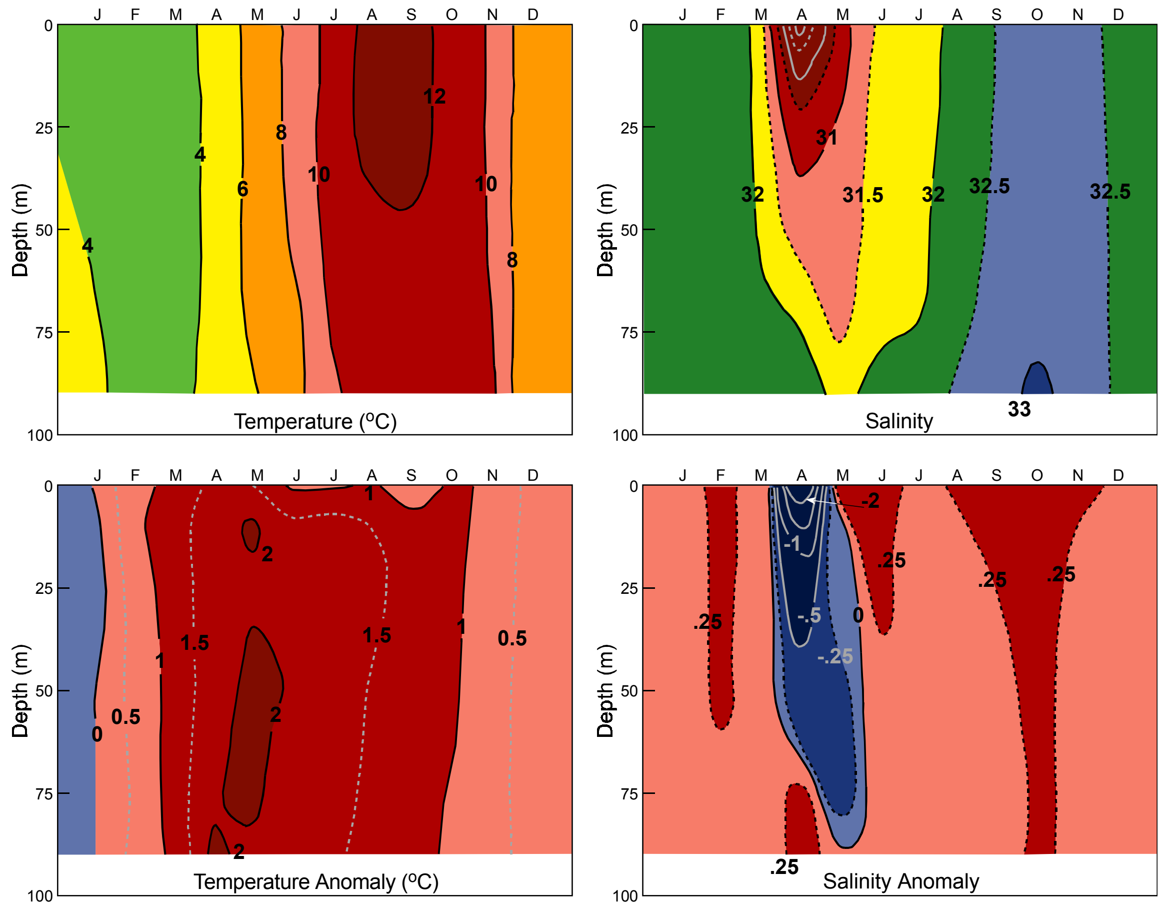


Fig. 3. Contours of monthly mean temperature (left) and salinity (right) and their anomalies (bottom panels) at Prince 5 as a function of depth during 2000 relative to the 1961-90 means. Colder and fresher-than-normal conditions are shaded.

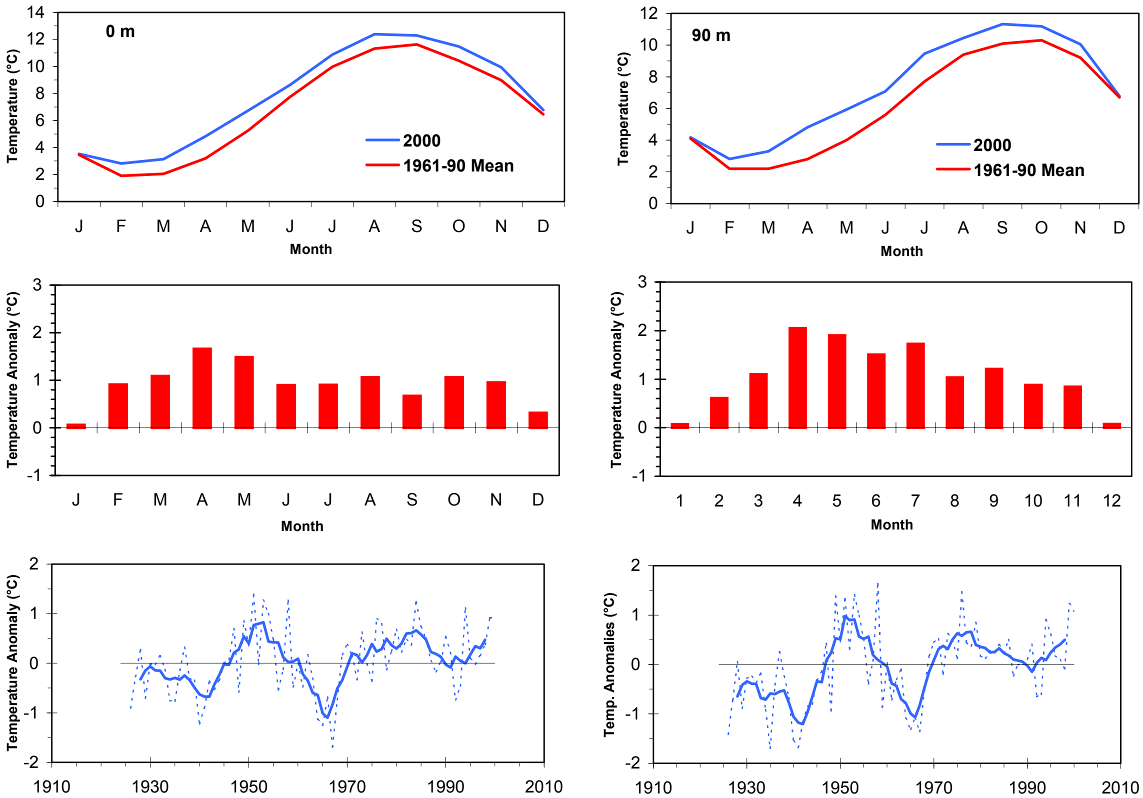


Fig. 4. The monthly mean temperatures for 2000 and their long-term means (top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

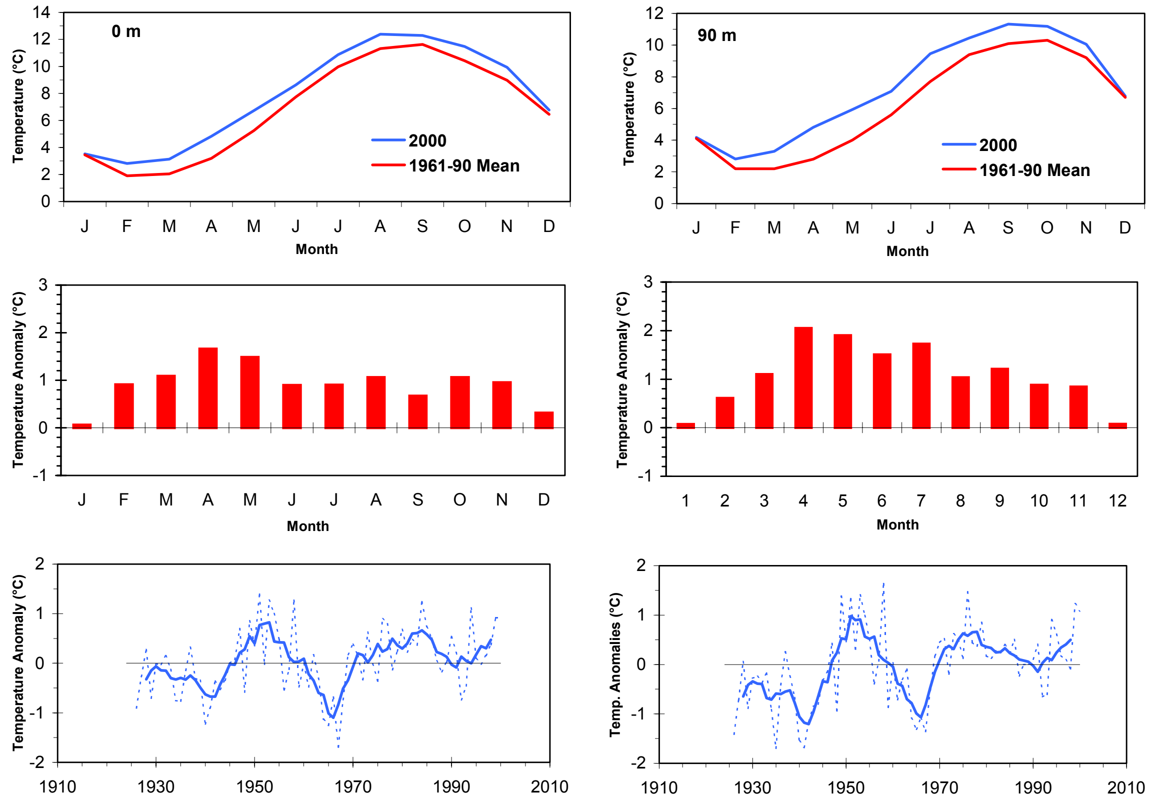


Fig. 5. The monthly mean salinities for 2000 and their long-term means (top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

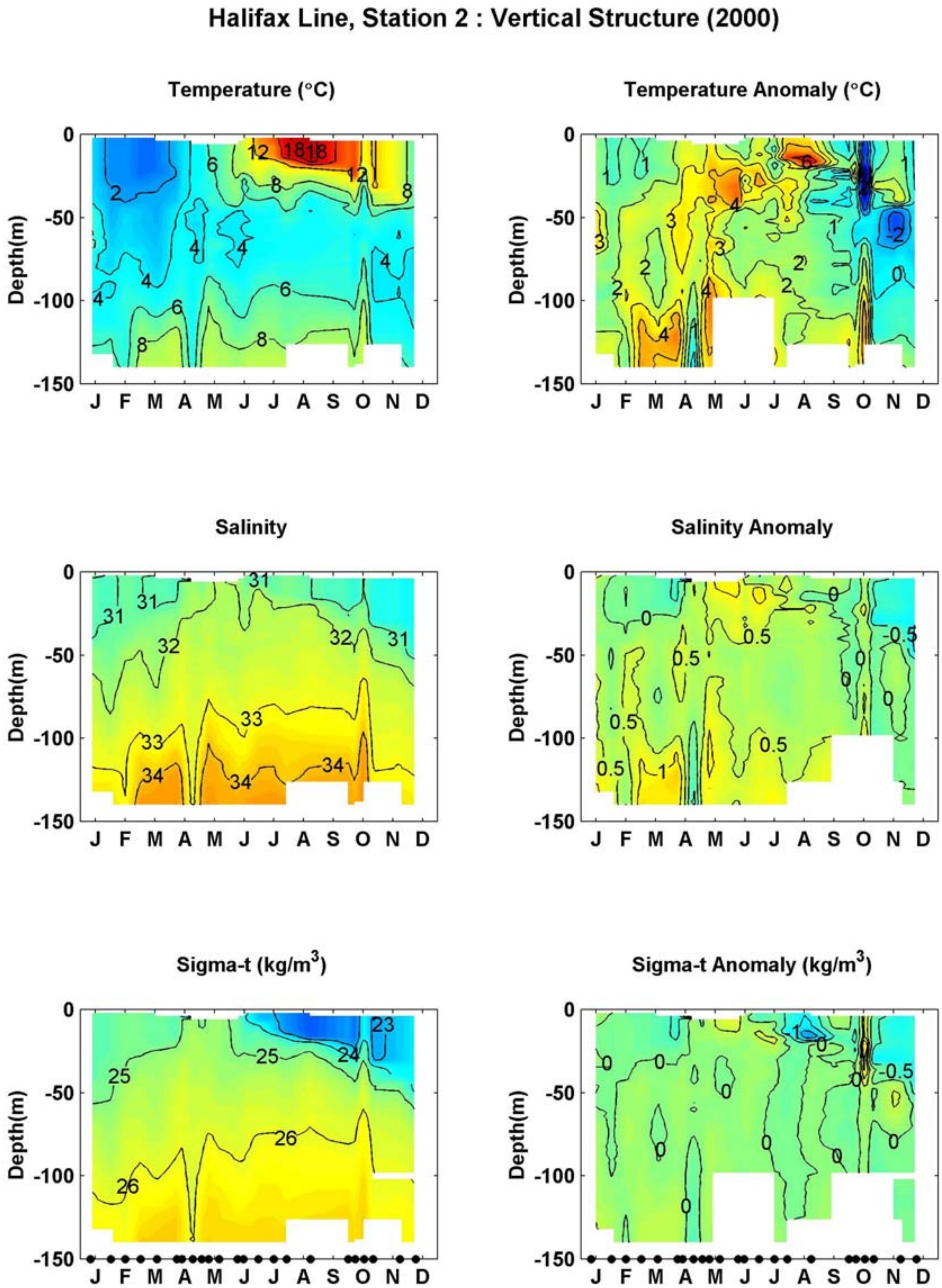


Fig. 6. Contours of temperature, salinity and density (sigma-t) for 2000 (left) and their anomalies (right) at the standard station H2. The dots on the x-axis of the lower panels indicate the dates when measurements were taken.

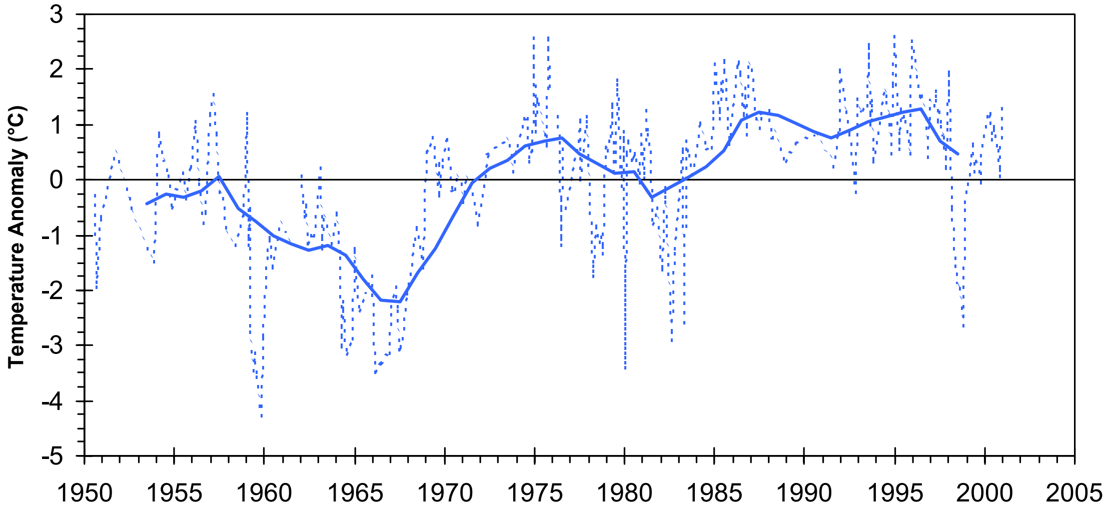
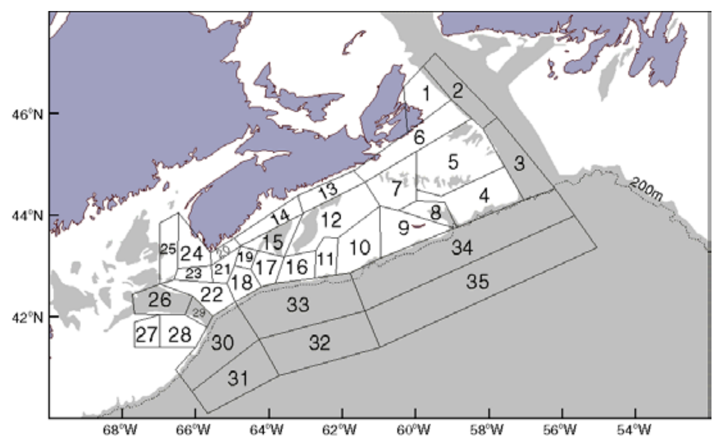


Fig. 7. Time series of available monthly mean temperature anomalies at 250 m in Emerald Basin Bank (dashed line) and their 5-year running means (solid line).



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

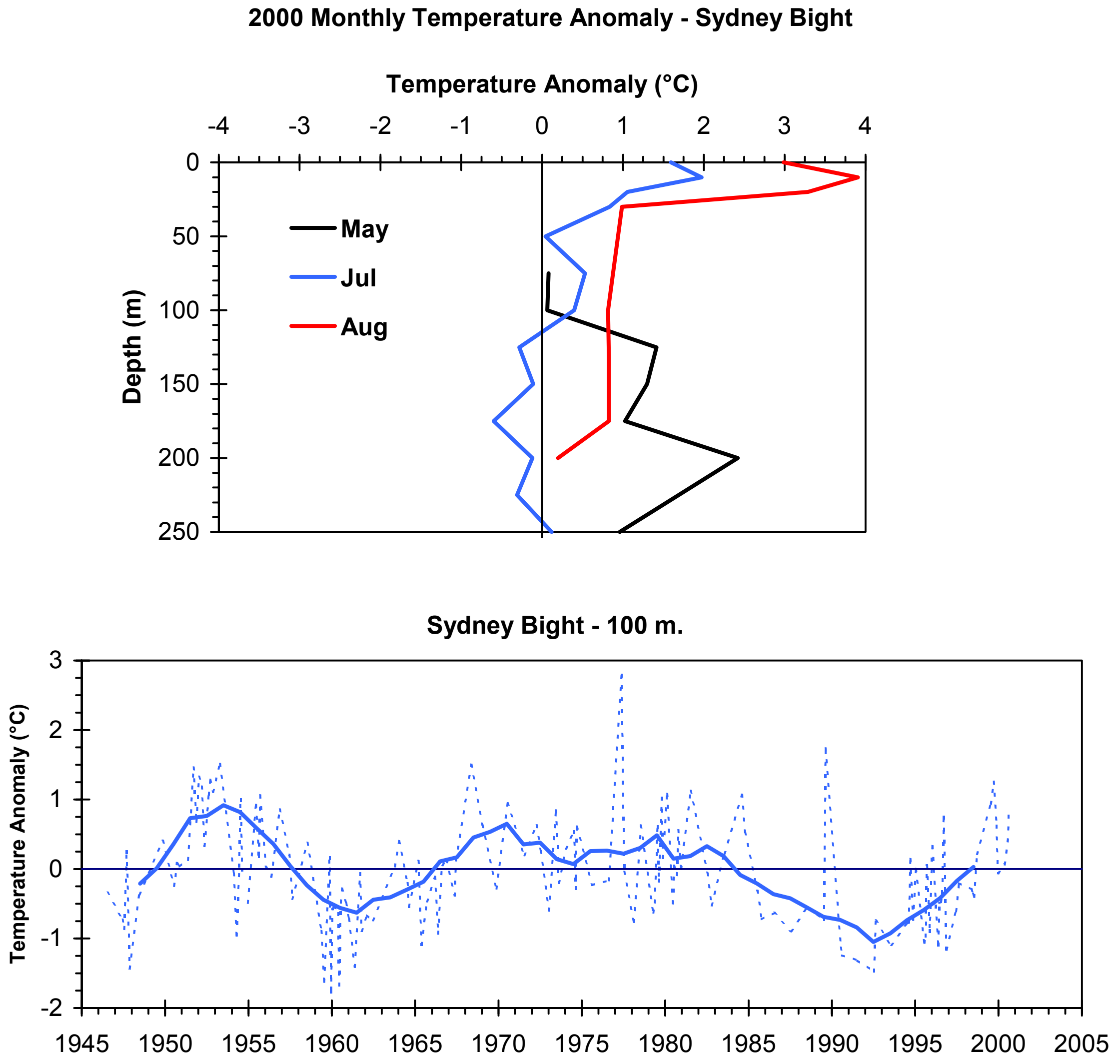


Fig. 9. 2000 monthly temperature anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1-Fig. 8).

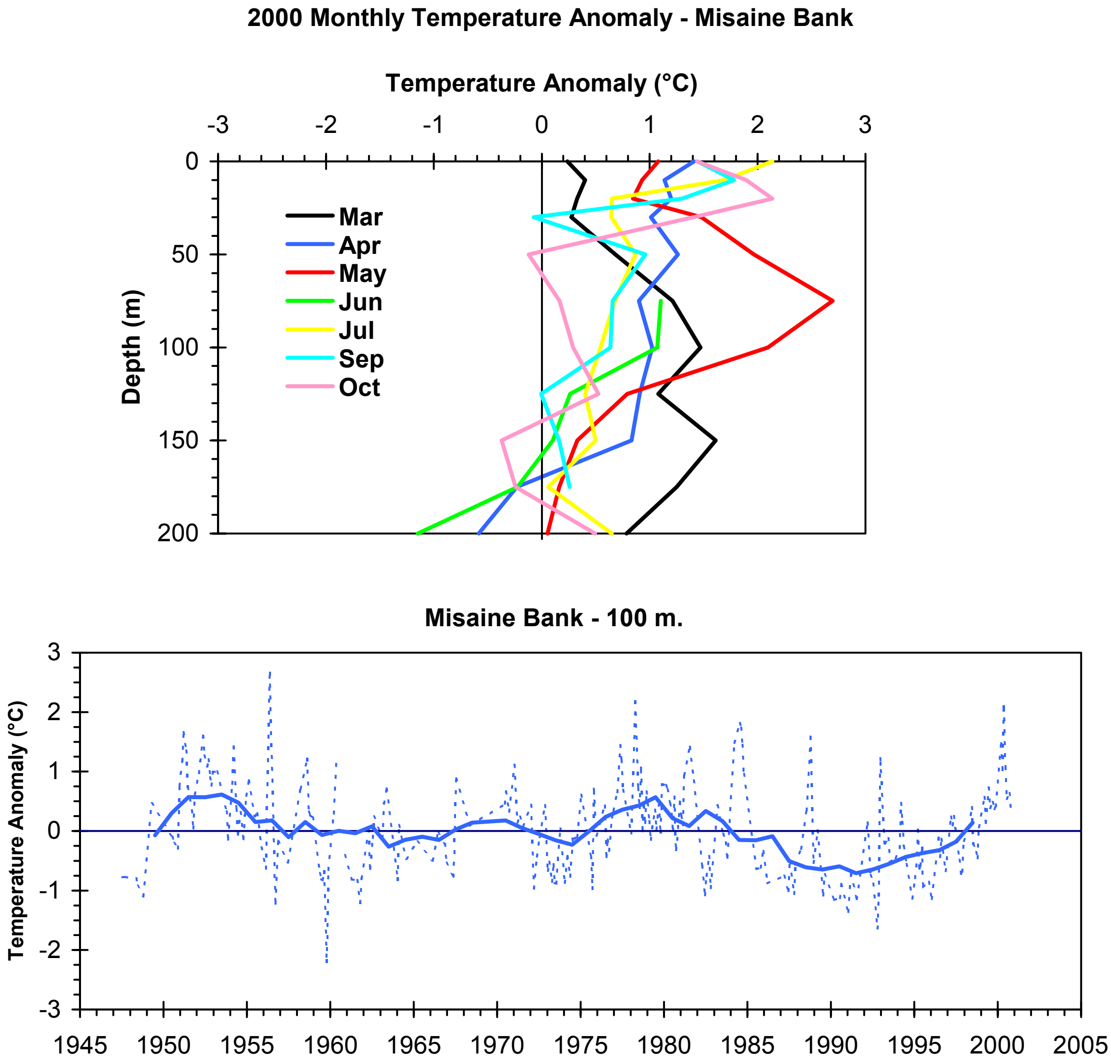


Fig. 10. 2000 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5-Fig. 8).

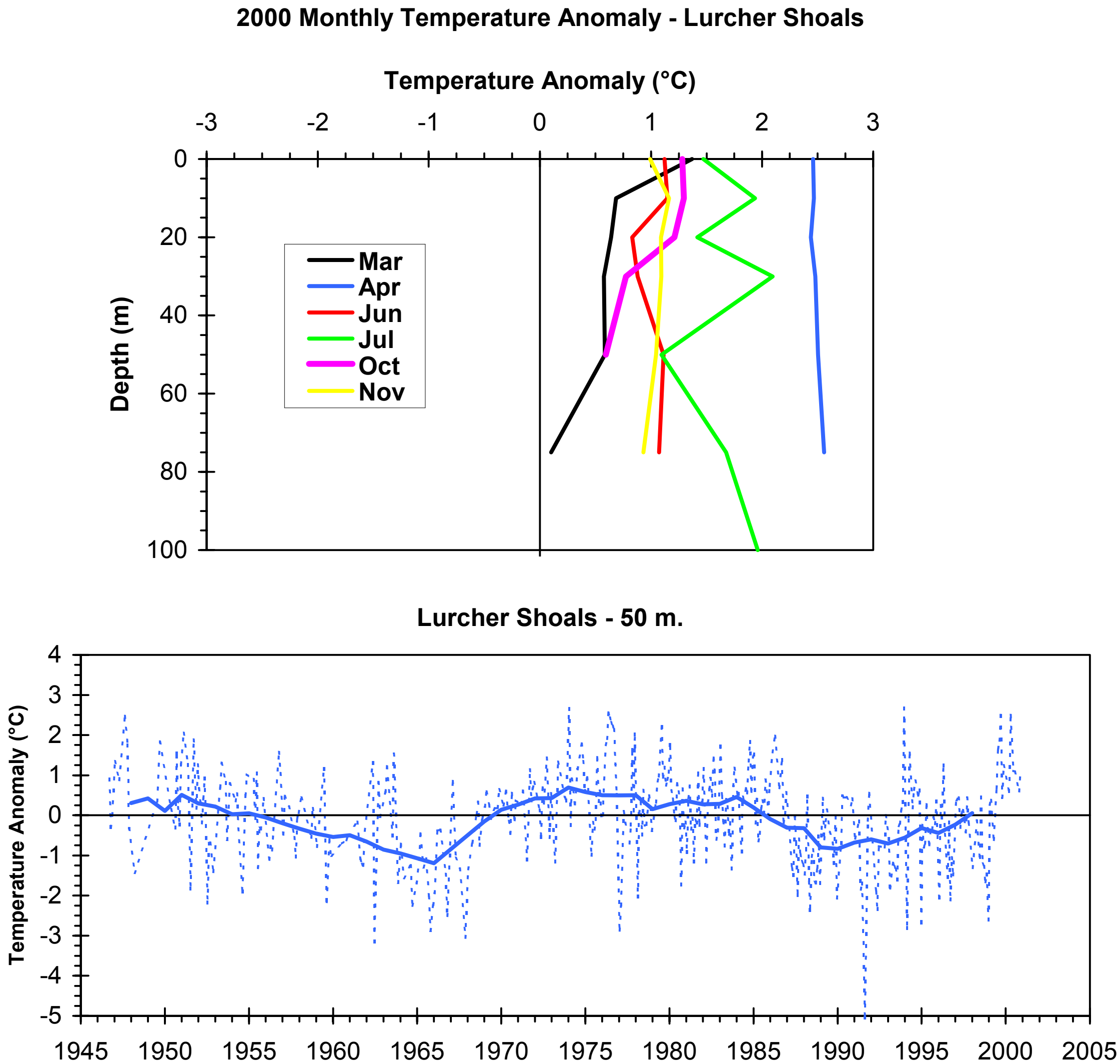


Fig. 11. 2000 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Lurcher (area 24-Fig. 8).

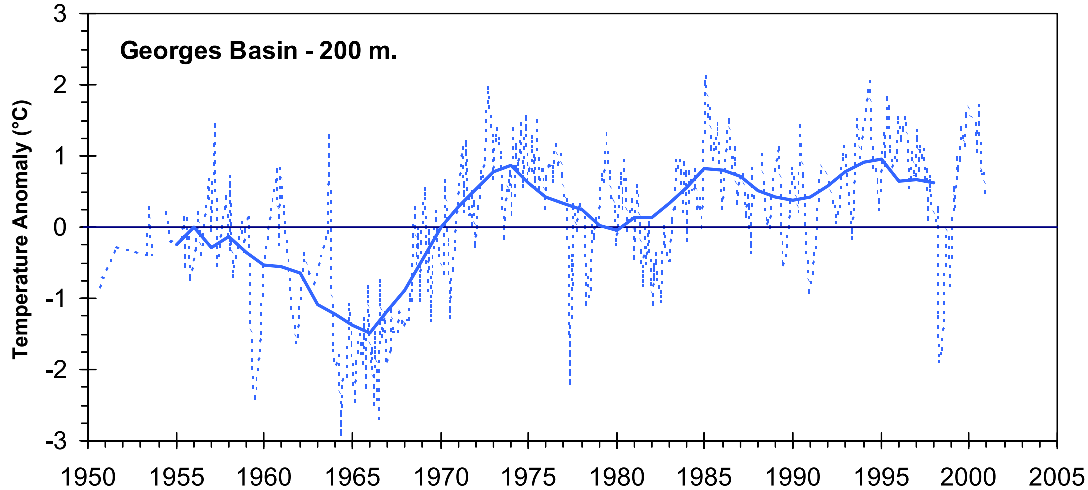


Fig. 12. Time series of monthly mean temperature anomalies at 200 m in Georges Basin (dashed lines) and their 5-year running means (solid line).

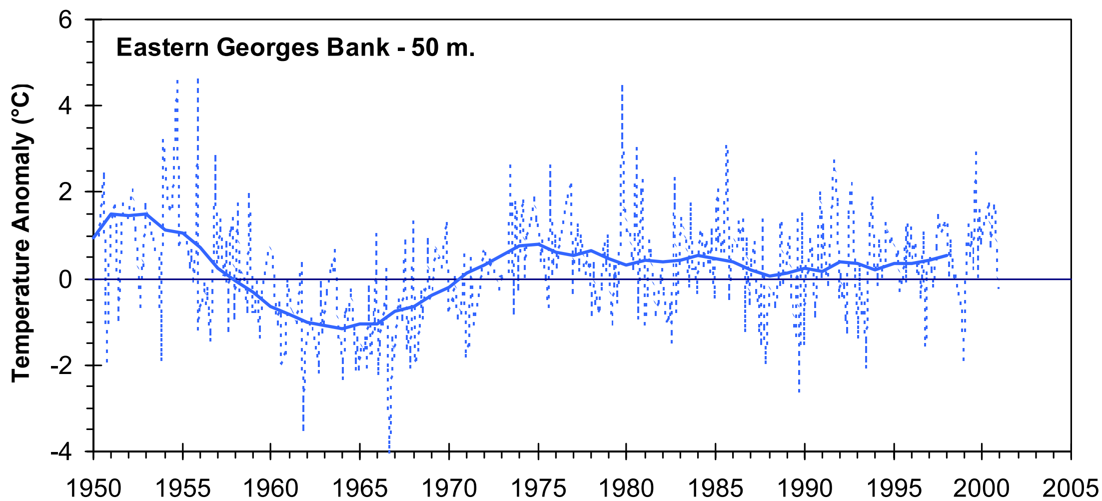


Fig. 13. Time series of monthly mean temperature anomalies at 50 m on eastern Georges Bank (dashed lines) and their 5-year running means (solid line).

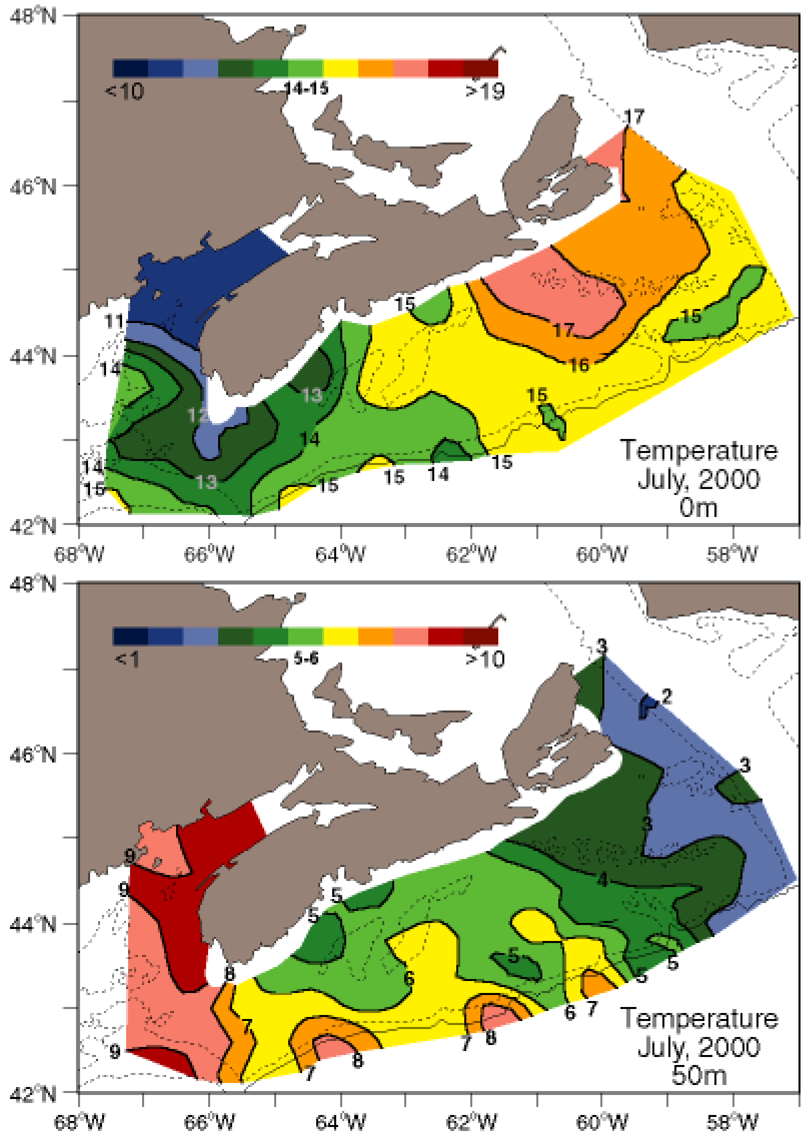


Fig. 14a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2000 July groundfish and ITQ surveys. Note that the colour scale is different for the 2 depths.

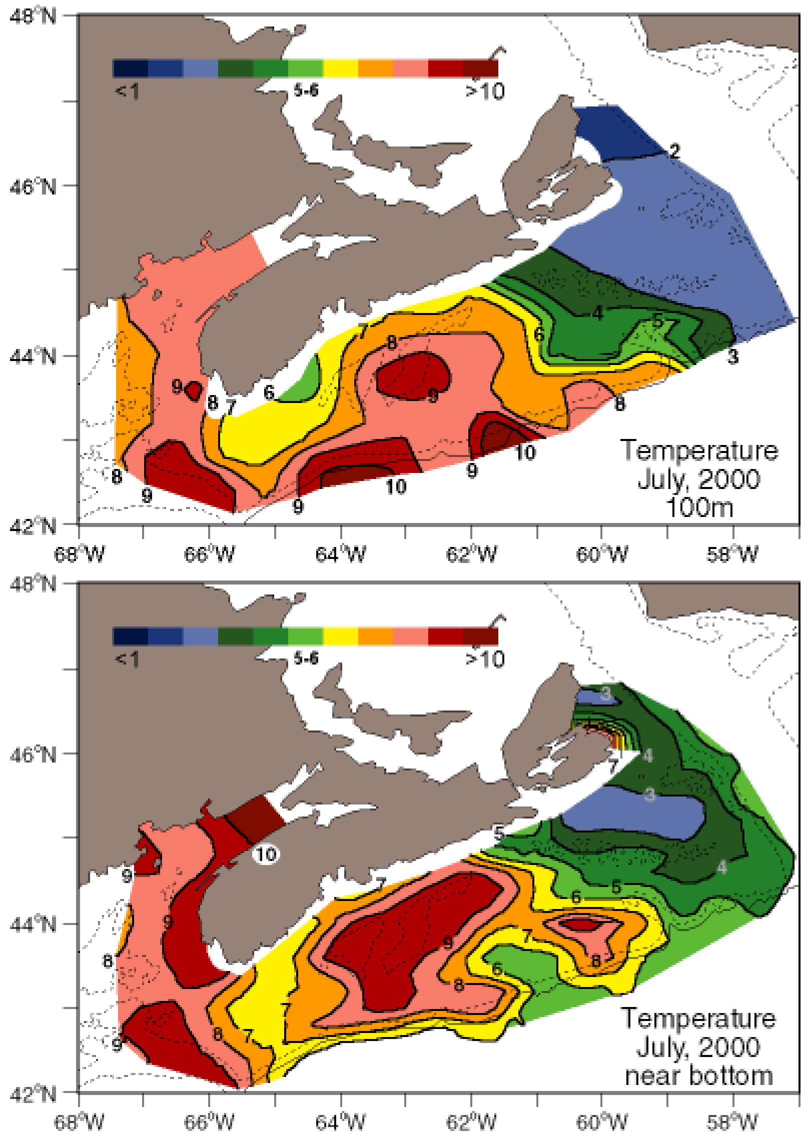


Fig. 14b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2000 July groundfish and ITQ surveys. The colour scale is similar for the two depths.

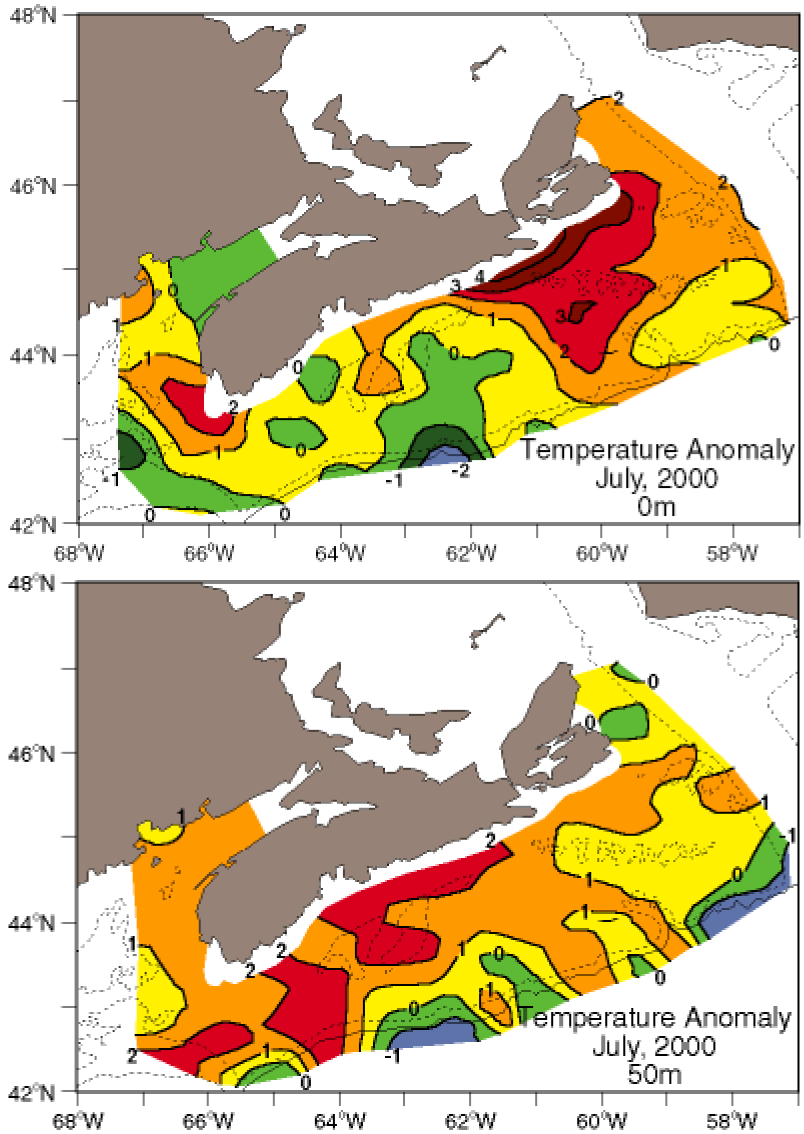


Fig. 15a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2000 July groundfish and ITQ surveys.

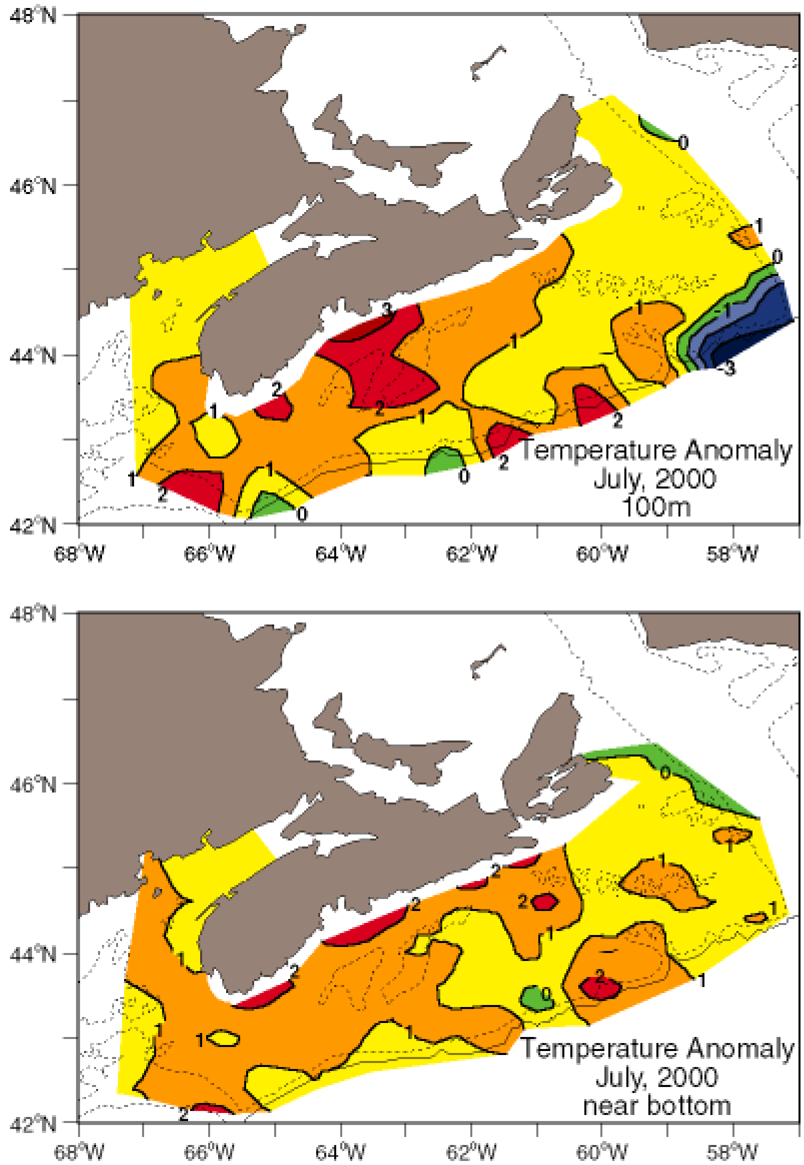


Fig. 15b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2000 July groundfish and ITQ surveys.

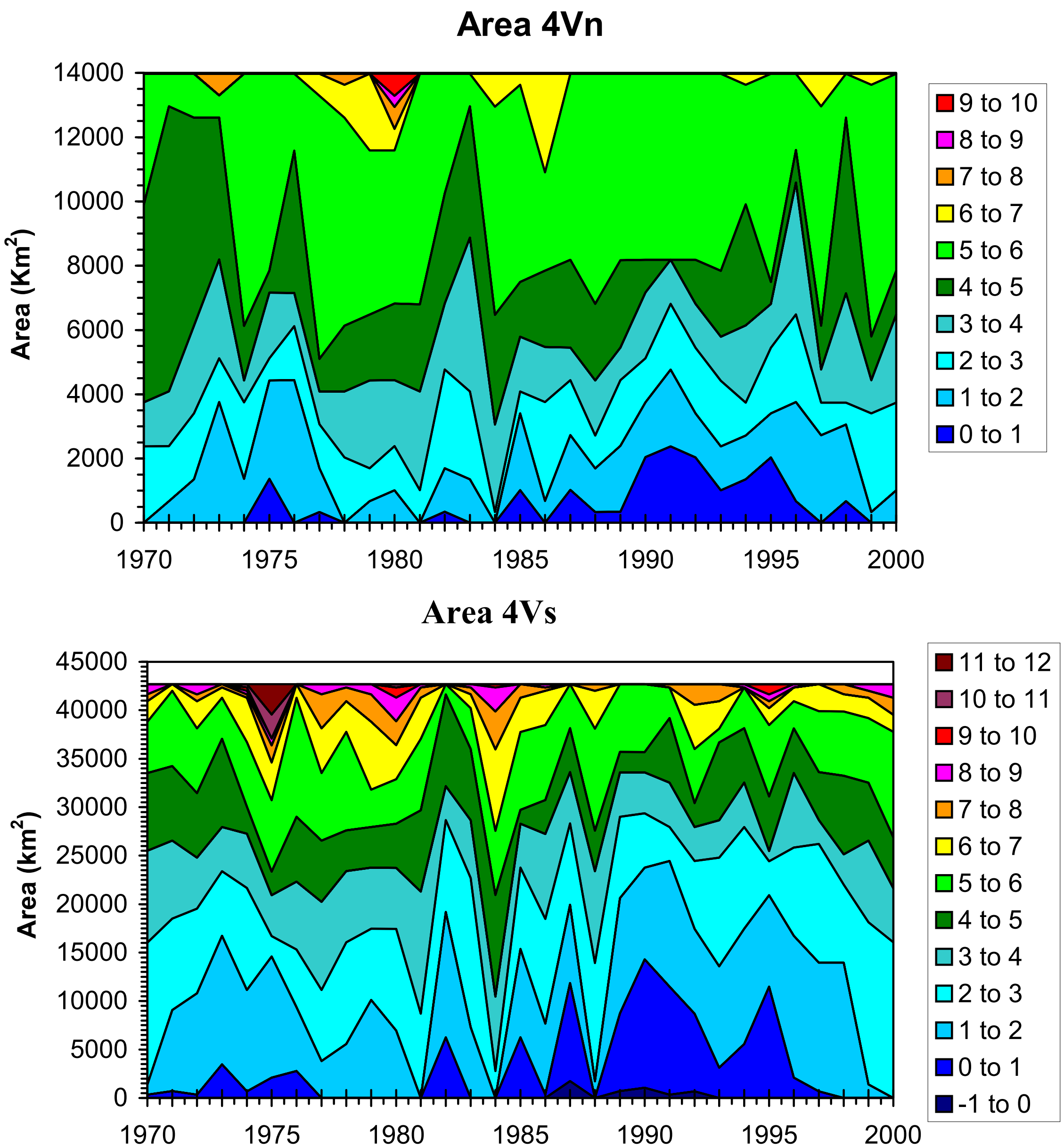


Fig. 16a. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).

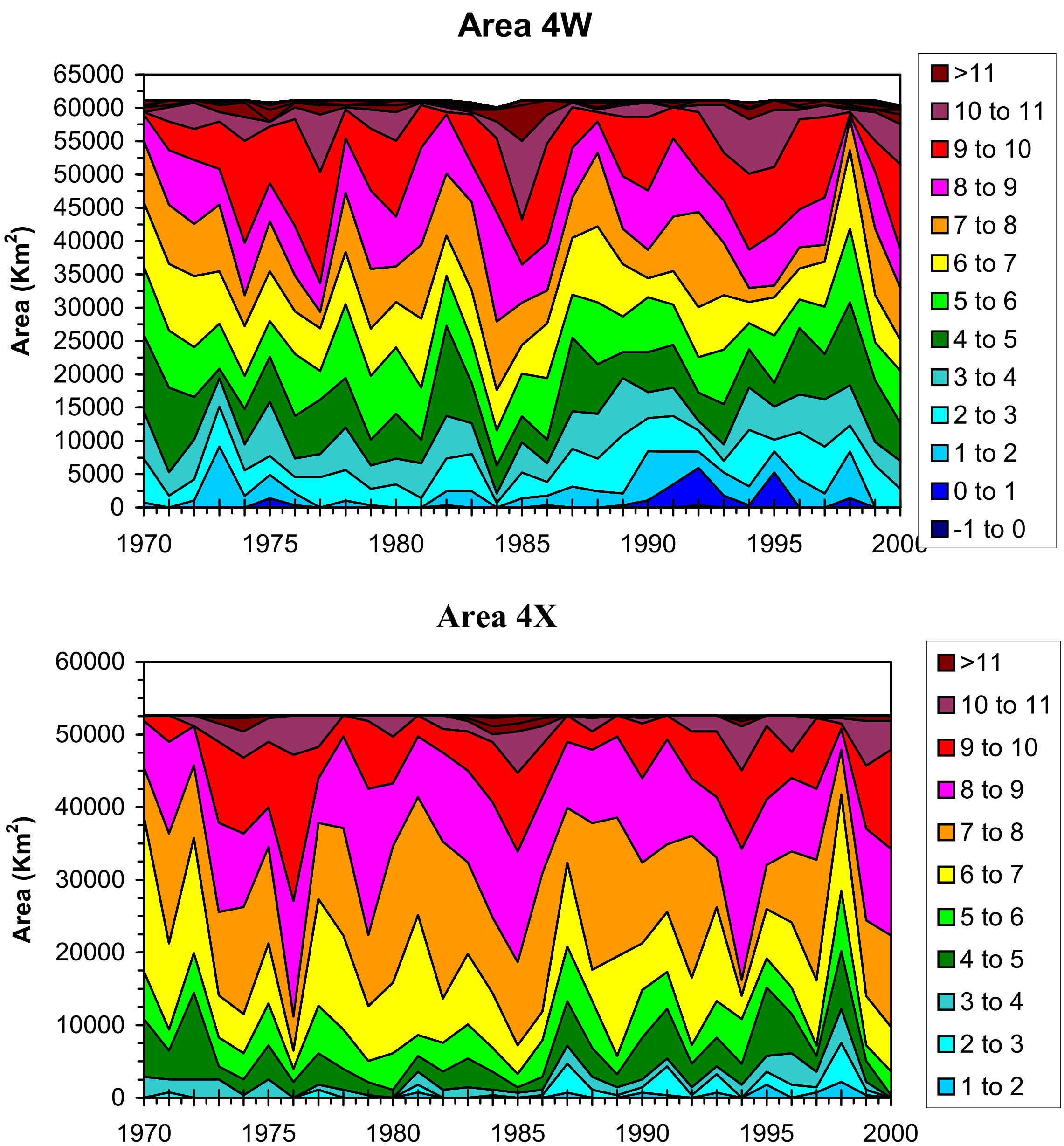


Fig. 16b. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4W (top panel) and 4X(bottom panel).

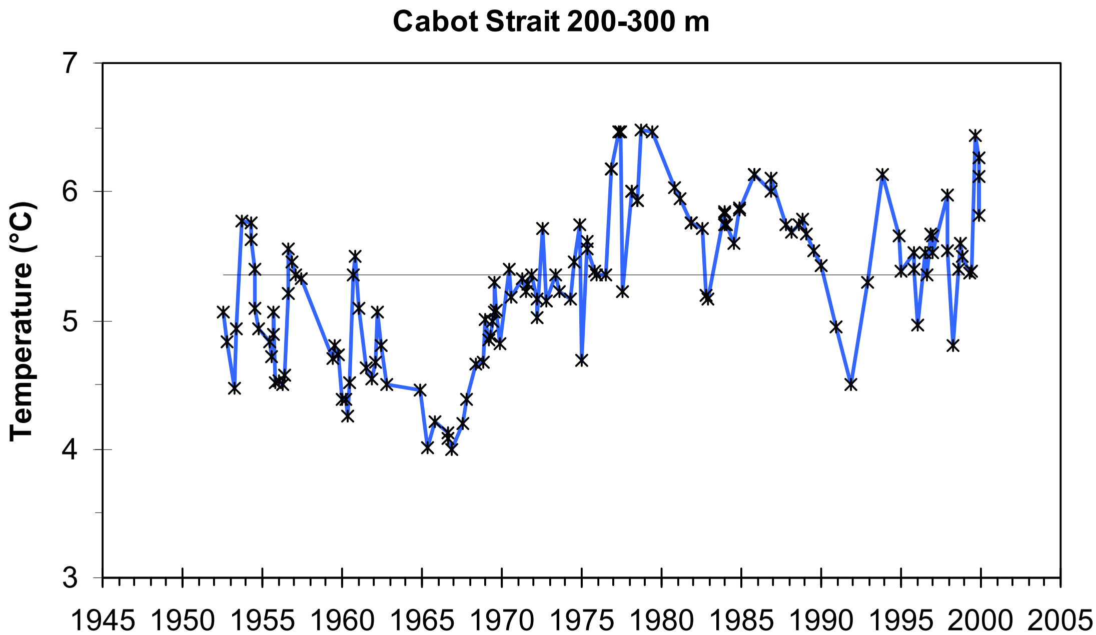


Fig. 17. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the long-term mean during 1961-90.

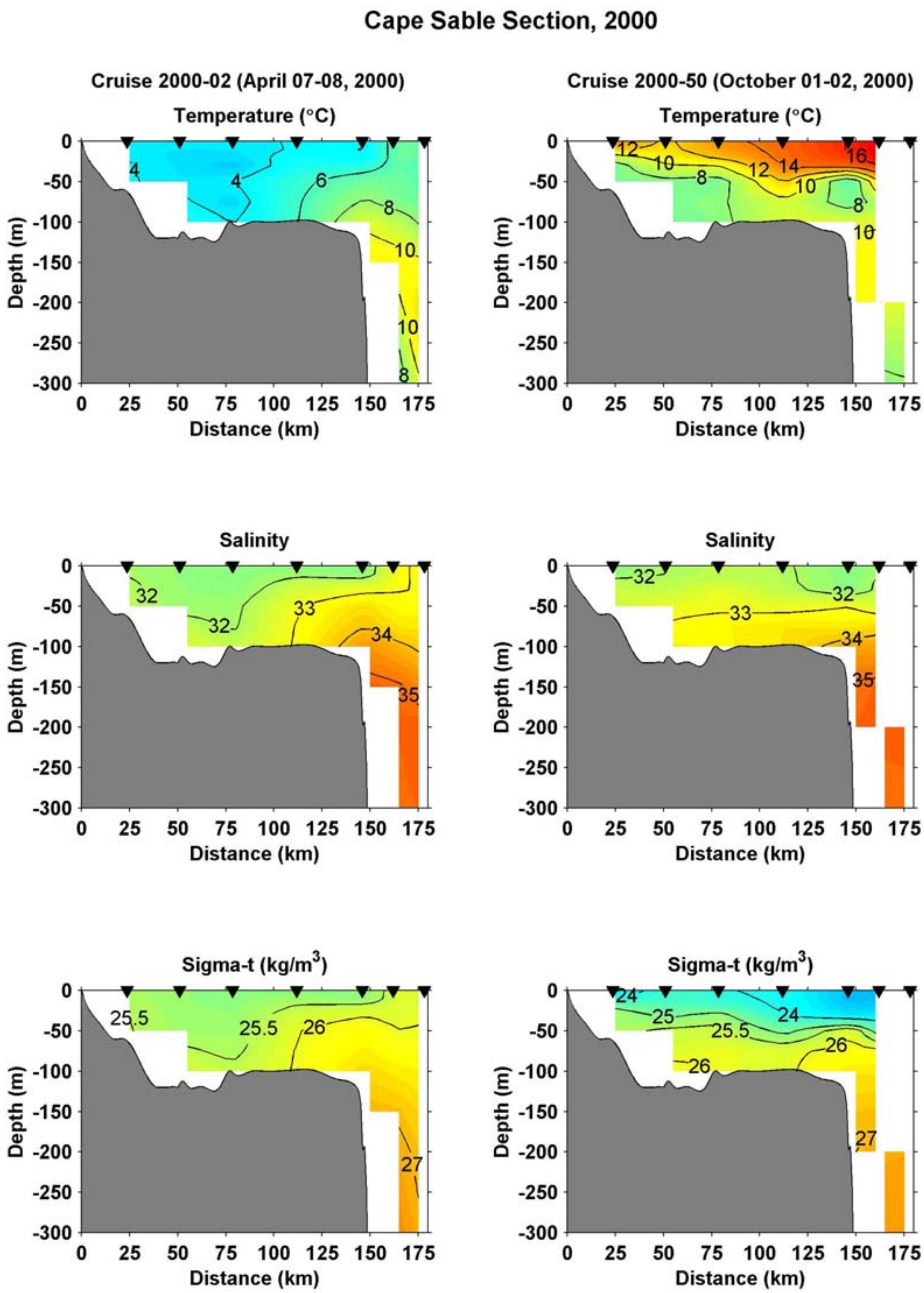


Fig. 18. The temperature, salinity and sigma-t contours along the Cape Sable Section during April (left panels) and October (right panels) of 2000. The triangles denote the location of the CTD profiles.

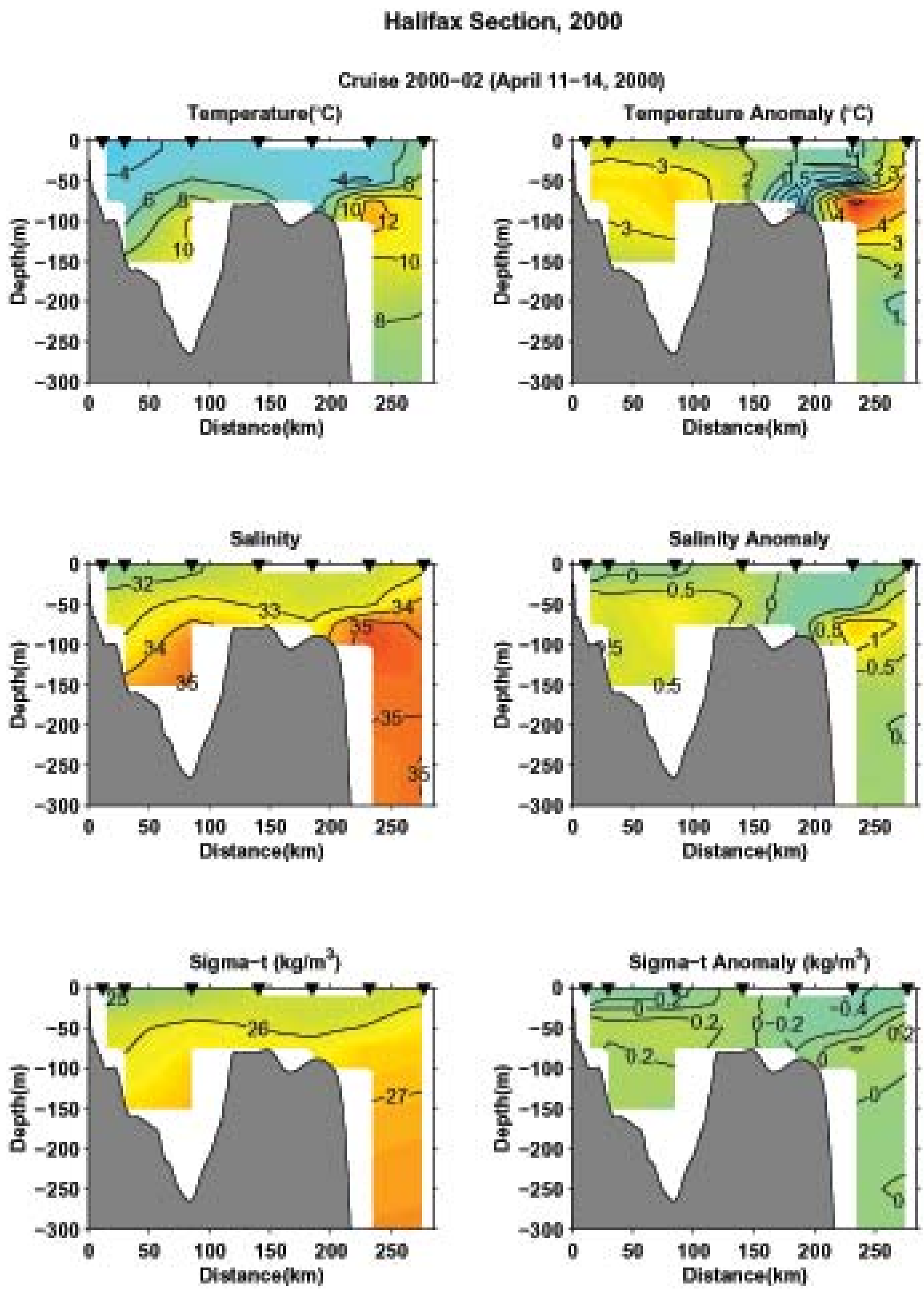


Fig. 19. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during April 2000 (left panels). The triangles denote the location of the standard stations.

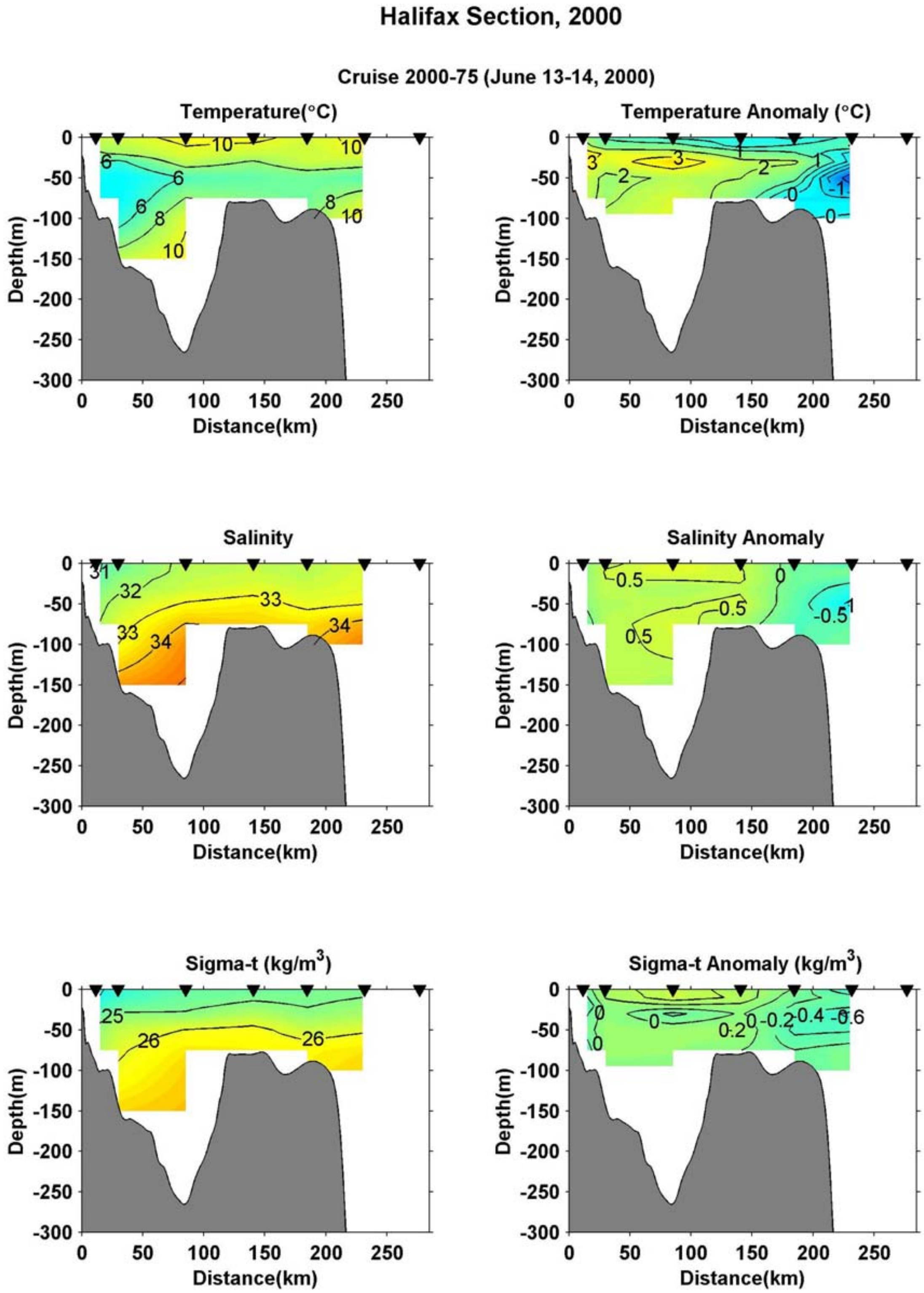


Fig. 20. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during June 2000 (left panels). The triangles denote the location of the standard stations.

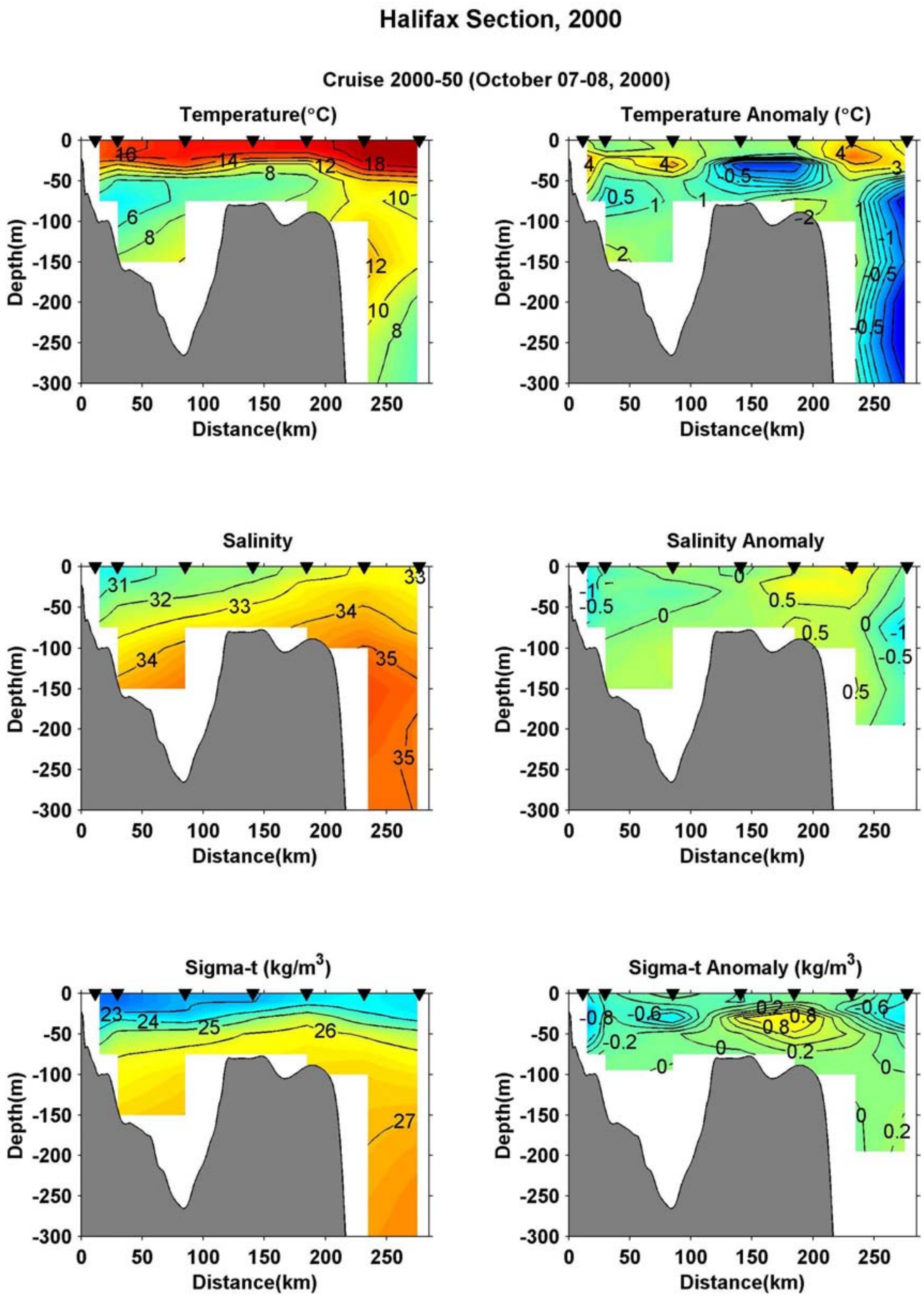


Fig. 21. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during October 2000 (left panels). The triangles denote the location of the standard stations.

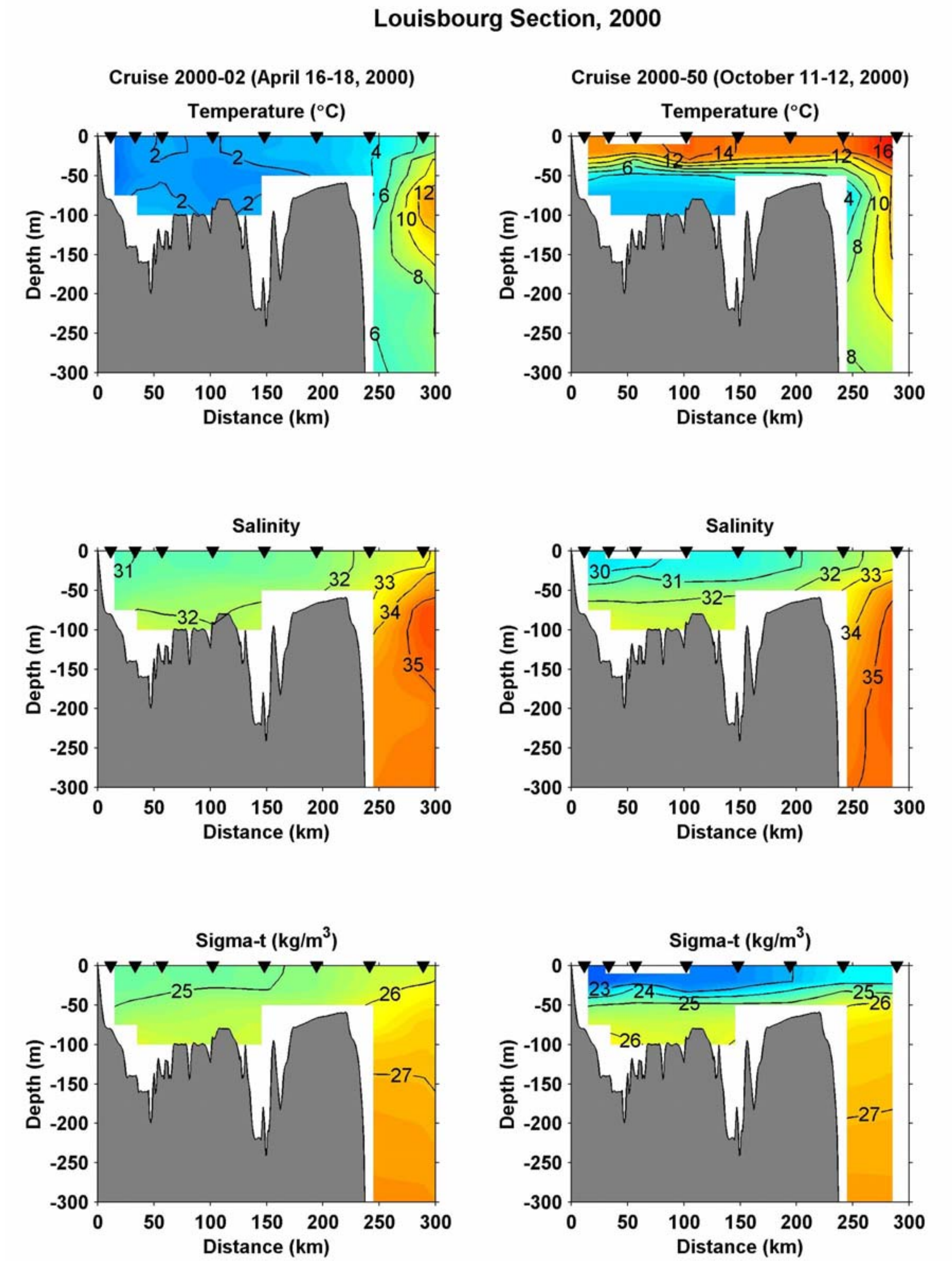


Fig. 22. Contours of the temperature, salinity and sigma-t along the Louisbourg Line during April and October 2000. The triangles denote the location of the CTD stations.

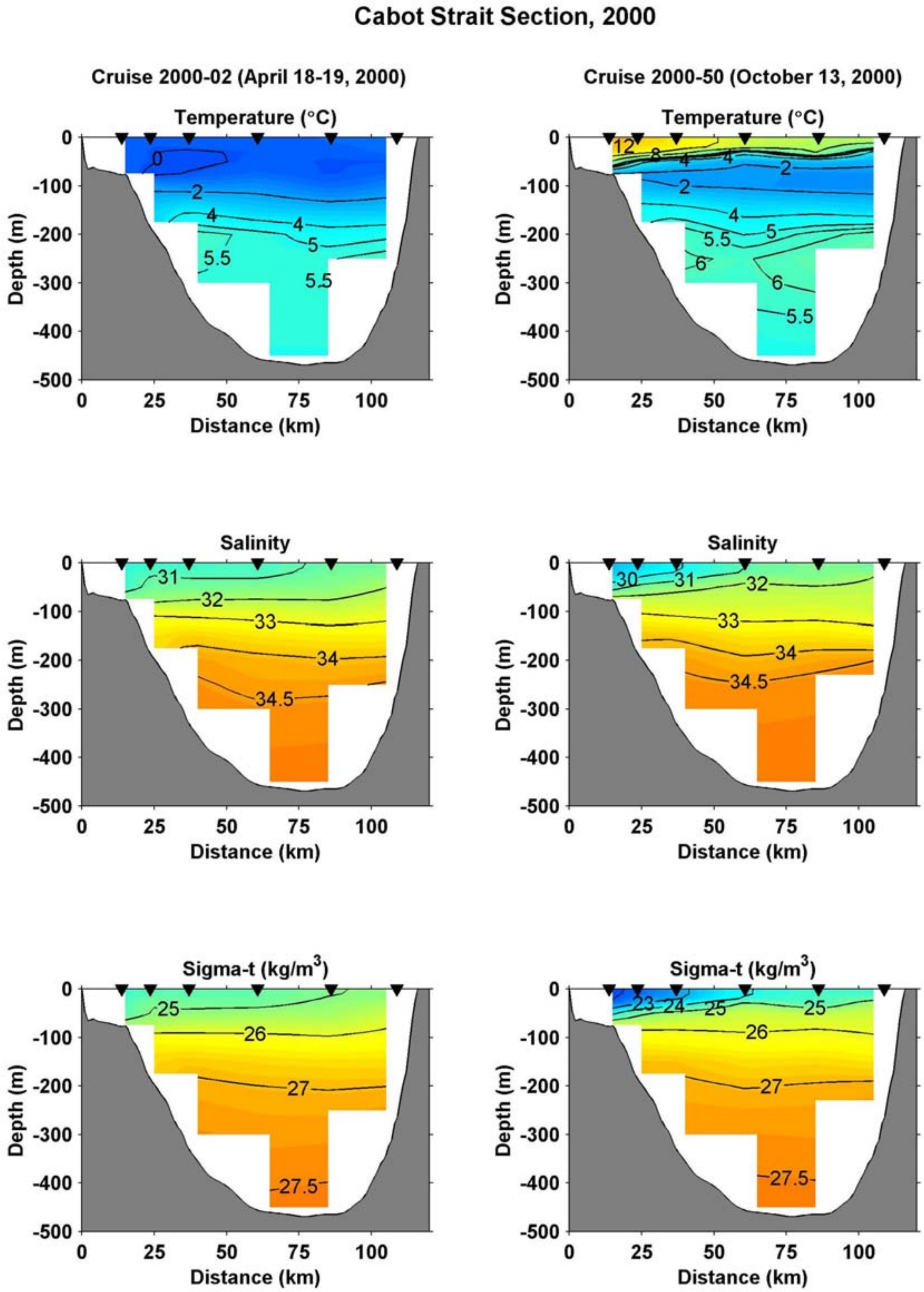


Fig. 23. Contours of the temperature, salinity and sigma-t along the Cabot Strait Line during April and October 2000. The triangles denote the location of the CTD stations.

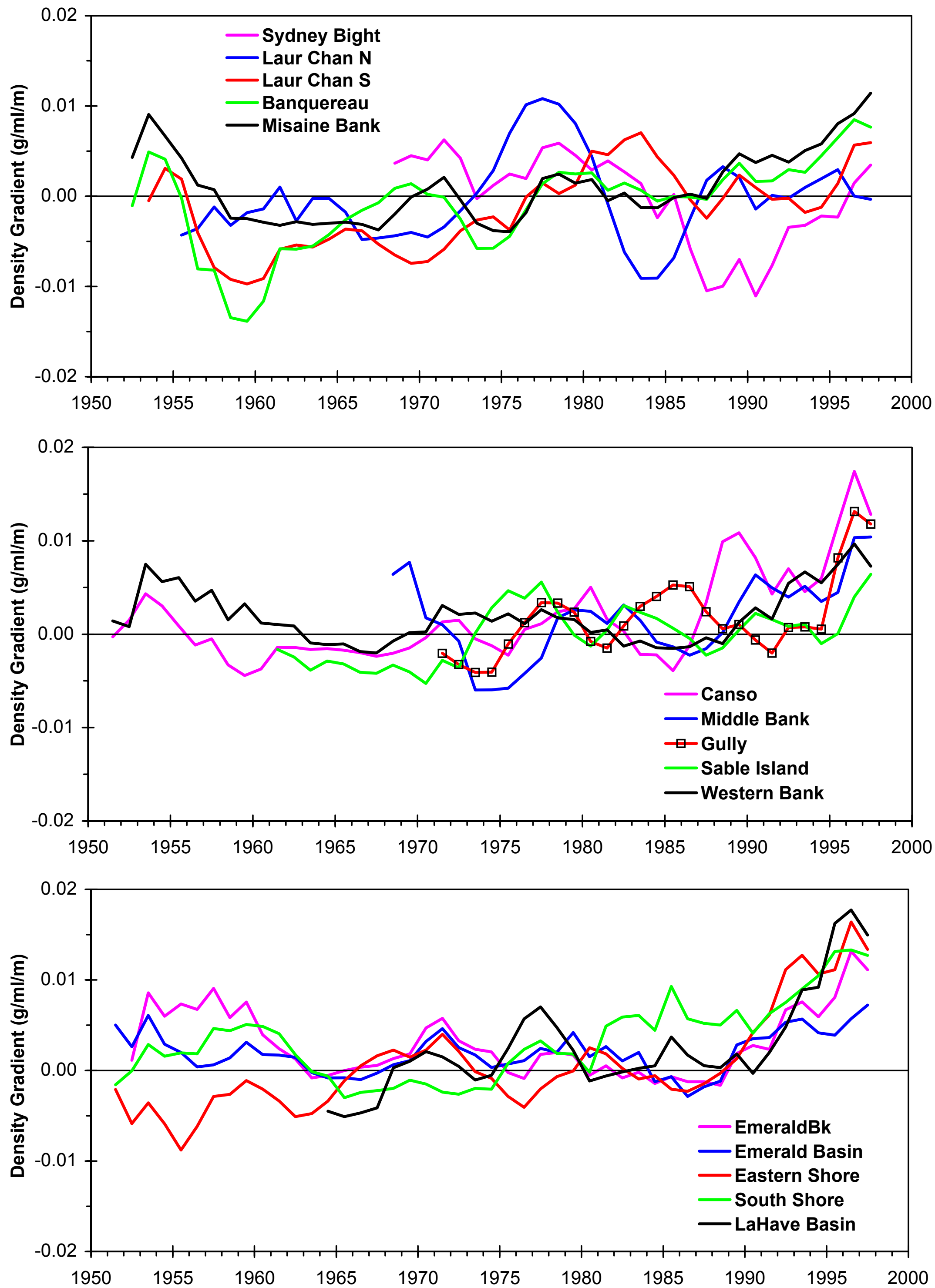


Fig. 24a. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 1-15 in Fig. 8.

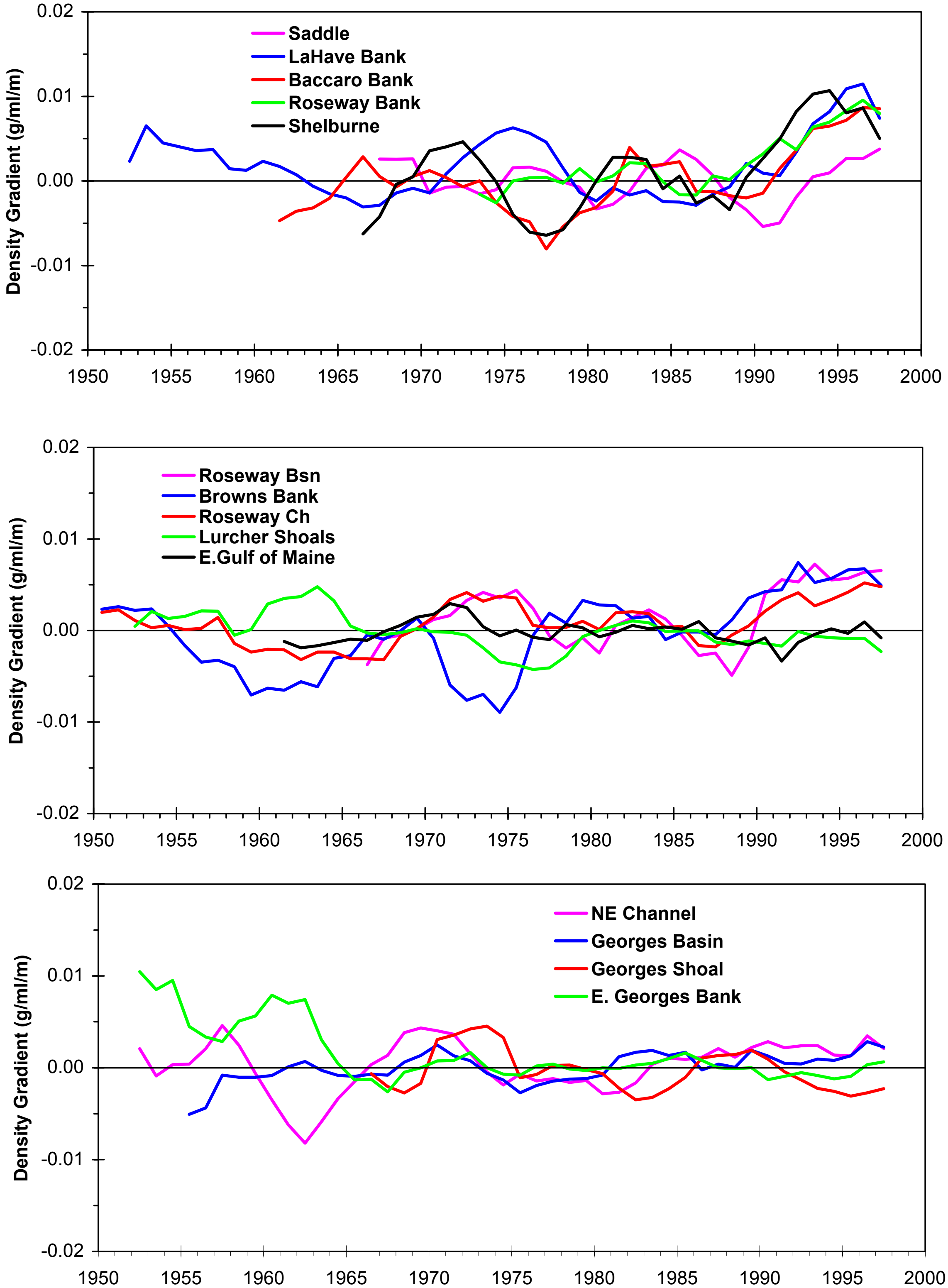


Fig. 24b. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 16-29 in Fig. 8.

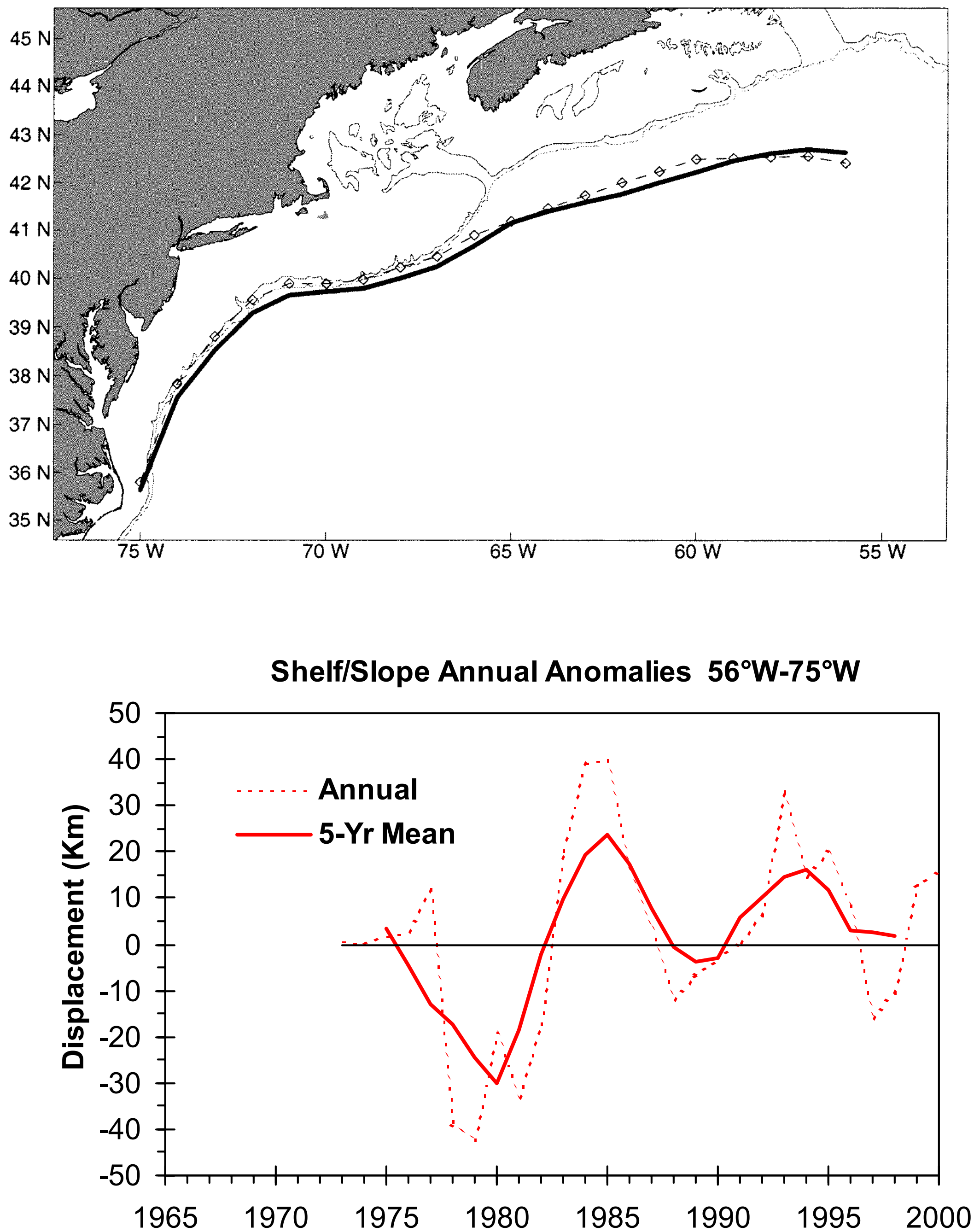


Fig. 25. The 2000 (dashed line) and long-term mean (1973-97; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).

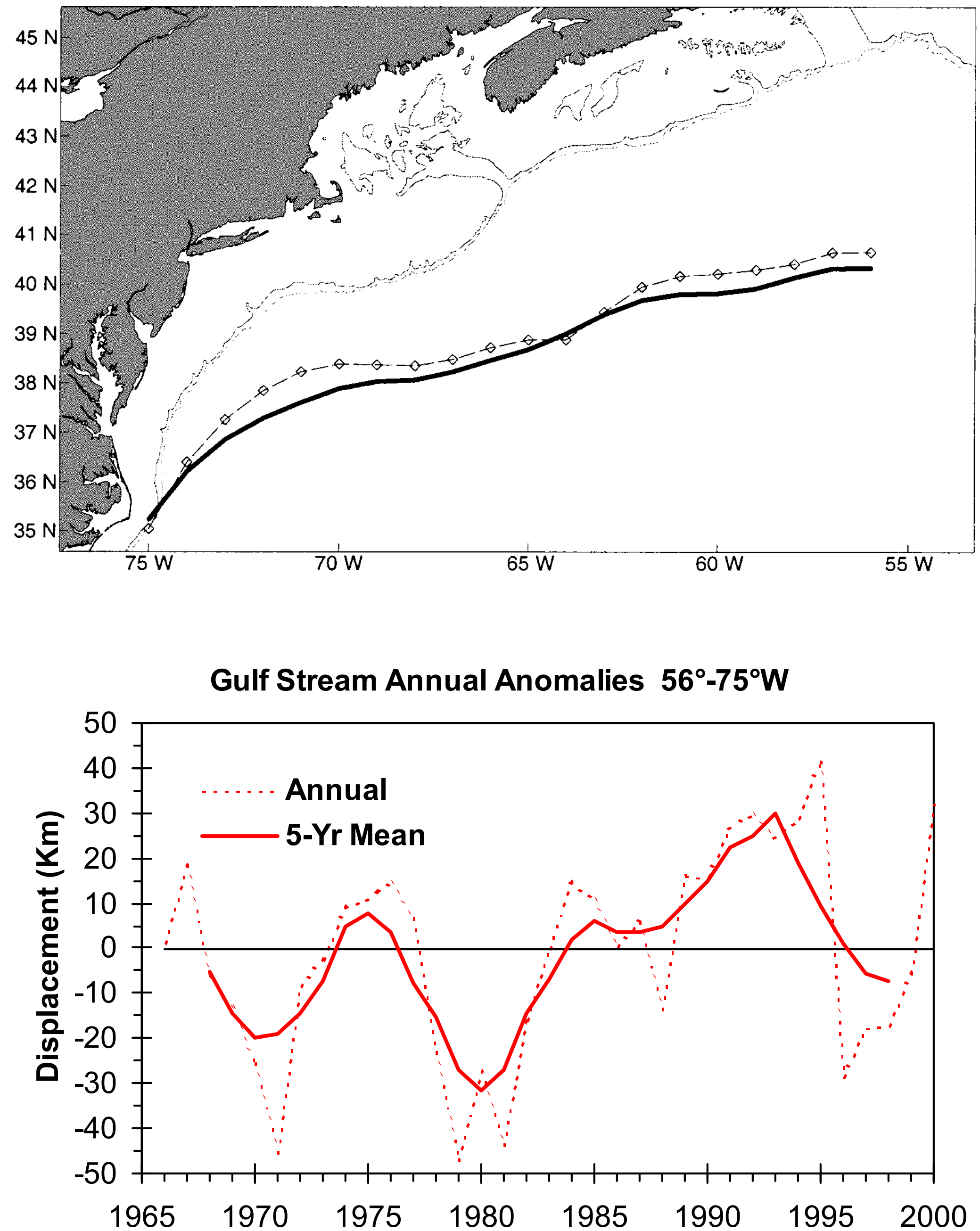


Fig. 26. The 2000 (dashed line) and long-term mean (1973-97; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).