Fisheries and Oceans Canada — Pêches et Océans Canada

Science — Sciences

C S A S — S C C S

Canadian Science Advisory Secretariat

Secrétariat canadien de consultation scientifique

Research Document 2006/040

Document de recherche 2006/040

Not to be cited without permission of the authors *

Ne pas citer sans autorisation des auteurs *

Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2005

Conditions océanographiques physiques sur le plateau néo-écossais et dans le golfe du Maine en 2005

B. Petrie, R. G. Pettipas, W. M. Petrie and V. 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

ISSN 1499-3848 (Printed / Imprimé)

Canada

ABSTRACT

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2005 has shown the temperature conditions were generally from 0 to 1°C below normal. This contrasts with 2004 when cooler conditions prevailed. St. Andrews sea surface temperature was 0.07°C below normal making 2005 the 49th coldest in 85 years. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by about 0.3 to 0.4°C. Salinities were 0.42 (0 m) and 0.17 (90 m) below normal. Halifax sea surface temperature was 1.0°C below normal, making 2005 the 8th coldest in 80 years. At Halifax Station 2, 0-140 m temperature anomalies were generally within 1°C of normal; salinity was slightly below normal values. Sydney Bight and Misaine Bank had typical temperature anomalies of 0.5 and 0°C; Emerald Basin, Lurcher Shoals, Georges Basin and eastern Georges Bank profiles featured typical anomalies of –0.5°C at most depths. Standard sections in April and October on the Scotian Shelf support the overall conclusion of near normal temperatures in the upper 100m. Cabot Strait deep-water (200-300 m) temperatures were near normal. The temperatures from the July groundfish survey increased substantially from the record cold values in 2004. The overall anomaly for the combined areas of 4Vn,s, 4W and 4X was -0.07°C. The overall stratification was slightly above normal for the Scotian Shelf region in 2005. The Shelf/Slope front and the Gulf Stream were about 6 and 8 km south of their mean positions.

RÉSUMÉ

L'examen des conditions océanographiques physiques en 2005 sur le plateau néo-écossais, dans le golfe du Maine et dans des zones extracôtières adjacentes montre que les conditions de température ont généralement été de 0,0 °C à 1 °C sous la normale. Cela contraste avec les conditions plus fraîches qui ont prévalu en 2004. La température de la surface de la mer à St. Andrews a été de 0,07 °C sous la normale, ce qui a fait de 2005 la 49e année la plus froide en 85 ans. À la station Prince 5, les températures mensuelles moyennes de 0 m à 90 m de profondeur ont généralement été de 0,3 °C à 0,4 °C environ sous la normale. Les salinités ont été de 0,42 (0 m) et de 0,17 (90 m) sous la normale. À Halifax, la température de la surface de la mer a été de 1,0 °C sous la normale, ce qui a fait de 2005 la 8e année la plus froide en 80 ans. À la station Halifax 2, les anomalies de température de 0 m à 140 m de profondeur n'ont généralement pas été supérieures à 1 °C, et la salinité a été légèrement sous les valeurs normales. La baie de Sydney et le banc de Misaine ont présenté des anomalies de température typiques de 0,5 °C et de 0 °C, tandis que les profils du bassin d'Émeraude, du haut-fond Lurcher, du bassin Georges et de l'est du banc Georges ont présenté des anomalies typiques de -0,5 °C à la plupart des profondeurs. Des sections standard établies en avril et en octobre sur le plateau néo-écossais appuient la conclusion générale selon laquelle les températures dans les 100 m supérieurs ont été près de la normale. Les températures en eau profonde (de 200 à 300 m) du détroit de Cabot ont été près de la normale. Les températures mesurées lors du relevé du poisson de fond de juillet ont augmenté de façon importante par rapport aux valeurs froides records de 2004. L'anomalie générale pour les zones combinées 4Vn, 4Vs, 4W et 4X a été de -0,07 °C. La stratification générale a été légèrement au-dessus de la normale pour la région du plateau néo-écossais en 2005. Le front plateau/talus et le *Gulf Stream* ont été de 6 à 8 km environ au sud de leur position moyenne.

Introduction

This paper describes temperature and salinity characteristics of the waters on the Scotian Shelf and in the Gulf of Maine during 2005 (see Fig. 1 for the study area). The results are derived from data obtained at coastal 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 temperature and salinity (CLIMATE) database (http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html), which is updated monthly from the national archive at the Marine Environmental Data Service (MEDS) in Ottawa. Our analyses use data up to and including the 12 January 2006 update; only data up to and including 2005 are discussed. Additional hydrographic data were obtained directly from DFO fisheries cruises. We also provide information on the position of the Gulf Stream and the boundary between the shelf waters and the offshore slope waters.

In order to detect long-term trends, we have removed the potentially large seasonal cycle by determining the monthly differences, i.e. the anomalies, from the long-term means. Where possible, long-term monthly and annual means have been calculated for the base period 1971-2000. This follows the recommendations of the Northwest Atlantic Fisheries Organization (NAFO, 1983) and the Fisheries Oceanography Committee of DFO. Meteorological, sea ice and satellite-derived sea-surface temperature information for eastern Canada during 2005 are described in Petrie et al. (2006). The air temperature anomalies for the Scotian Shelf and the Gulf of Maine were variable during 2005 with annual values of 0.70°C (Sable Island) and -0.36°C (Boston); sea surface temperatures (SST) were above normal for the eastern and central Scotian Shelf by 1.1°C and 0.6°C; the western Scotian Shelf SST were normal while Lurcher Shoal, the Bay of Fundy and Georges Bank had annual values of 0.2-0.9°C below normal. Ice cover for the Scotian Shelf was below normal in 2005.

Coastal Sea Surface Temperatures

Monthly averages of coastal sea surface temperature (SST) for 2004 were available at St Andrews (New Brunswick) and Halifax (Nova Scotia). The monthly mean temperature anomalies relative to the 1971-2000 long-term averages at each site for 2004 and 2005 are shown in Fig. 2. We have discontinued reporting the Boothbay Harbor time series because of unresolved problems with the data.

At St. Andrews, 7 months featured negative anomalies with the largest anomaly (relative to the standard deviation) in July, ~0.8 standard deviations below normal. The 2005 annual anomaly was -0.07°C (-0.14 SD), the 49th coldest in 85 years. The monthly anomalies at Halifax were generally negative with June-August values ~2 SD below normal; the annual anomaly was –1.0°C, making 2005 the 8th coldest in 80 years.

Time series of annual anomalies shows that the surface temperatures in 2005 at St. Andrews warmed to near normal; Halifax anomalies were below normal at the same level as in 2004.

Fixed Stations

Prince 5

Temperature and salinity measurements have been taken since 1924 at Prince 5, a station near St. Andrews, New Brunswick, adjacent to 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 a CTD (Conductivity, Temperature, Depth) profiler has been used. Up to and including 1997, there was one observation per month; 1998-2003 had multiple occupations per month; in 2004 sampling was been reduced to once per month because of financial and personnel restrictions. For months with multiple measurements, the arithmetic mean was used to estimate the monthly mean temperature and salinity. A single or even several observations per month (especially in the surface layers in the spring or summer when some stratification can develop) may not necessarily produce results that are representative of the true monthly "average" conditions. While this is less of a problem in such a well-mixed area as the Bay of Fundy, still 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 depth is due to the strong tidal mixing within the Bay of Fundy.

In 2005, monthly mean temperatures ranged from a minimum in March of 1.7^{o}C at the surface to a maximum in September of 11.3^{o}C (Fig. 3, 4). Monthly temperature anomalies were negative throughout the mid-year especially in July and August by as much as -2^{o}C. The annual mean temperatures have high interannual variability with evidence of strong long-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 2005, the annual temperature anomalies at 0 and 90 m were about –0.4^{O}C and -0.3^{o}C. At 0 m, 2005 was the 31st coldest year in 81; at 90 m, it was the 39th coldest year. This represents a warming at both depths relative to 2004.

The salinity at Prince 5 had a broad minimum in the spring and summer at the surface (~30.2 in May) and at 90 m (31.58 in June; Fig. 3, 5). The salinity anomalies were negative in most of 2005 and had typical amplitudes of -0.4. The annual salinity anomalies were about -0.42 at 0 m and -0.17 at 90 m. These values represent a moderate freshening since 2004.

Halifax Line Station 2

As part of the Atlantic Zonal Monitoring Program (AZMP), a standard monitoring site was established in 1998 on the Scotian Shelf at Station 2 on the Halifax Line (Fig. 1). This station, hereafter referred to as H2, is about 150 m deep and is situated approximately 30 km off the entrance to Halifax Harbour at the northern edge of Emerald Basin. Hydrographic measurements are taken using a CTD; nutrient and biological samples are also collected. We present only the hydrographic data. The long-term monthly means of temperature, salinity and density (sigma-t) were discussed in Drinkwater et al. (2000). There were fewer occupations of H2 in 2005 than in any other full year since the AZMP program started.

Surface temperatures at H2 ranged from ~0°C to ~17.8°C in 2005 (Fig. 6). Near-bottom temperatures were between 2.2°C and 7.7°C throughout the year, a much broader range of values than observed in 2004. Relative to the long-term means, 0-140 m temperatures were roughly equally divided between above and below normal values in 2005. A ~15 m deep near-surface layer had above normal temperatures in the fall, above a layer of stronger, below normal anomalies. As in 2004, the temperature anomaly pattern suggests that there was a thicker Cold Intermediate Layer (CIL) than usual at H2 in 2005. The CIL off Halifax typically has a temperature range from about 1°C to 6°C depending on the time of the year.

Salinity anomalies were small in 2005 with a mixture of above and below normal values in the upper 50 m through the year and generally below normal values between 50 m and the bottom. Peak anomaly magnitude was about 1.

In the surface layers, stratification began to develop in May increasing in intensity through to August-September. During autumn, the warmer and fresher surface layer was gradually mixed down to ~50 m, before sampling ended. Density anomaly variations followed the same pattern as the salinity anomalies.

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. 7). Petrie et al. (1996) updated the report using these same areas and all available hydrographic data. We present monthly mean conditions for 2005 at standard depths for 6 selected areas (averaging data by month within these areas) and compare them to the long-term averages (1971-2000). Data are not available for each month in each area; in some areas, the 2005 annual means are based upon as few as 3 monthly averaged profiles. As a result, the series can have short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1-2^{o}C. The spikes represent high frequency temporal or spatial variability and most often show little similarity between regions. These data must be interpreted carefully and appropriate weight given to any individual mean. The long period trends often show similarity over several areas. To better show the trends, we have estimated the annual mean anomaly based on all available means within the year at selected depths.

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. At intermediate depths of 50 m to approximately 150 m, they found that temperatures had declined steadily from approximately the mid-1980s into the 1990s. On Lurcher Shoals off Yarmouth, on the offshore banks and 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, on St. Pierre Bank off southern Newfoundland (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., 2001).

We describe temperature conditions in Sydney Bight, Misaine Bank, Emerald Basin, Lurcher Shoal, Georges Basin and eastern Georges Bank, representative areas of the Scotian Shelf and Gulf of Maine. The results are displayed as monthly and annual (the average of the monthly anomalies) anomalies in 2005 (Fig. 8) and as time series plots for a selected depth in each region (Fig. 9).

In Sydney Bight (area 1, Fig. 7) off eastern Cape Breton, the monthly profiles overall showed predominantly above normal temperature anomalies for depths greater than 50 m (Fig. 8). Misaine Bank profiles, on the other hand, had temperature anomalies that were close to normal except for the upper 50 m where the variability was large but generally not significantly different from 0^{o}C. With profiles in all months except May and December, Emerald Basin featured a mixture of above normal temperatures of ~1^{o}C at the surface, a transition to predominantly below normal values from 75 to 200 m with a maximum annual anomaly of nearly -2^{o}C at 100 m. The annual anomaly crossed 0^{o}C between 225 and 250 m and was slightly above normal at 250 m. Lurcher Shoals had only 3 monthly average profiles in 2005. There was a tendency to below normal temperatures from 50 to 100 m. Georges Basin generally had below normal temperatures from the surface to 300 m, with a maximum at about 100 m, similar to Emerald Basin. Georges Bank anomalies were mostly negative, with a maximum value of about -1^{o}C at 75 m.

Figure 9 shows the time series of temperature anomalies for one depth from each of the 6 regions. The tendency was for the 3 eastern series to have a positive annual anomaly while the 3 western regions had a negative anomaly at the given depths. The 100 m depth temperature anomalies for Sydney Bight and Misaine Bank are quite similar with a cold period from the mid-1980s to the late 1990s, followed by a short warm period until 2003 when temperatures were below normal. The Sydney Bight and Misaine Bank 100 m temperatures in 2005 were 1 and 0.1^{o}C above normal. The Emerald Basin 250 m record reflects the influence of slope water on the Scotian Shelf. The intrusion of Labrador Slope Water onto the shelf in 1998 is very prominent. This event was followed by a period of slightly above normal temperatures which continued at depth in 2003; in 2005 the temperature was ~0.2^{o}C above normal. Lurcher Shoals temperature anomalies (50 m) follow a similar pattern as the Misaine Bank series but with 2005 having below normal temperatures by -0.3^{o}C. Since 1975 the filtered time series from Georges Basin has had quasi-periodic fluctuations of less than 1^{o}C; the Labrador Slope Water intrusion of 1998 was observed but had a shorter duration than in Emerald Basin. The annual anomaly at 200 m in 2005 was -0.22^{o}C. On the other hand, the filtered temperature anomaly series from eastern Georges Bank had been almost flat for 30 years until 2003 when values were below normal, a tendency that continued in 2004 and in 2005 with an anomaly of -1.1^{o}C.

Temperatures during the Summer Groundfish Surveys

The broadest spatial coverage of the Scotian Shelf is obtained during the annual DFO groundfish survey, usually in July. A total of 216 CTD stations were taken during the 2005 survey and an additional 185 bottom temperature stations were obtained as part of the ITQ (Individual Transferable Quota) fleet survey. The groundfish survey takes 1 month to complete with the area west of Halifax sampled first and the area east of Halifax sampled second. The observations are plotted without taking the time of sampling into account. This means that the Sydney Bight area sampled at the end of the survey has had about a month longer solar heating than the area to the west of Halifax sampled at the start of the survey. This is not accounted for directly in the data displays. Thus the warmest area often ends up in Sydney Bight. On the other hand, the 1971-2000 temperature climatology is dominated by these surveys which are conducted in the same way every year. Thus we expect the anomalies to be largely unaffected by this temporal sampling bias. The ITQ survey fills in gaps in the DFO survey for the Bay of Fundy, off southwest Nova Scotia and on the southwestern Scotian Shelf. The temperature data from the ITQ survey were obtained using Vemco Minilogs© attached to the trawl. These data are quality controlled during processing at the Bedford Institute of Oceanography.

The 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" with a horizontal length scale of 30 km and a vertical length scale of 15 m in the upper 30 m and 25 m at deeper depths. Data near the interpolation grid point are weighted proportionately more than those farther away. Temperatures were optimally estimated for 0, 50, 100 m and near bottom (Fig. 10). Maximum depths for the interpolated temperature field were limited to 1000 m off the shelf. The 2005 temperature anomalies relative to the July 1971-2000 means were also computed at the same four depths (Fig. 11).

The broad spatial pattern of near-surface temperatures in July 2005 featured the warmest waters near the shelf break south of the eastern Scotian Shelf (>18°C) that penetrated well onto the shelf, and the coldest (<9°C) near the mouth of the Bay of Fundy (Fig. 10a). The cooler surface temperatures in this region compared to the Scotian Shelf are due in part to the intense bottom-generated vertical mixing caused by the strong tidal currents. The surface temperatures in July 2005 were warmer than normal over most of the eastern Shelf and along the coast of SW Nova Scotia, but were as much as 2 to 3°C cooler than normal off western Nova Scotia in the Gulf of Maine (Fig. 11a).

The temperatures at 50 m ranged from 2°C to over 8°C with the coldest waters in the northeast and the warmest waters at the shelf break and in the Gulf of Maine and Bay of Fundy (Fig. 10a). The lower temperatures over the inner half of the shelf indicate a cold, broad intermediate layer similar to the one seen in 2004 but not as cold. The higher temperatures towards the outer edge of the Shelf in the central region reflect the influence of Slope Waters. The higher temperatures at 50 m in the Gulf of Maine compared to the Scotian Shelf are, in part, due to the increased importance of tidal mixing. Anomalies were predominantly positive, ranging from 0°C to 4°C above normal over the Scotian Shelf and mostly negative in the western region of the survey (Fig. 11b). The largest anomalies (~4°C) occurred along the outer shelf off Banquereau, Western and Emerald Banks suggesting the presence of warmer-than-normal slope waters.

The temperatures at 100 m ranged from <1-2°C in the northeastern Scotian Shelf to over 11°C along the shelf break (Fig. 10b). The warmer waters encroach onto the outer shelf with strong horizontal gradients evident at mid-shelf. The temperatures are elevated as well in the eastern Gulf of Maine. This pattern is a considerable contrast to the one from the 2004 survey which featured very cold 100 m temperatures over most of the shelf. Consequently the anomaly pattern is quite different: in 2004 negative anomalies to -4°C were found; in 2005 there was a mixture of above and below normal anomalies.

Near-bottom temperatures over the Scotian Shelf ranged from ~2°C in the northeastern Scotian Shelf to ~9°C in Emerald Basin and 7°C in the upper Bay of Fundy (Fig. 10b). In Emerald Basin, the high temperatures are due to the penetration of Warm Slope Water, while in the Bay of Fundy and other parts of the Gulf of Maine they are, in part, due to the intense vertical mixing by the tides.

The pattern of colder temperatures in the northeastern Shelf and warmer in the Gulf of Maine and in the deep basins of the central Shelf is typical of most years. The colder waters are largely derived from the Gulf of St. Lawrence. Relative to the 1971-2000 means, the near-bottom temperatures were predominantly warmer than normal over the Scotian Shelf and colder than normal in western part of the region; -1°C was a representative anomaly (Fig. 11b).

We also estimated the area of the bottom covered by each one degree temperature range (e.g. 1-2°C, 2-3°C, 3-4°C, etc.) within NAFO Subareas 4Vn, 4Vs, 4W and 4X (Fig. 1). The areas were obtained from the optimally estimated temperature distributions from the July groundfish and ITQ surveys. The time series for each NAFO Subarea are shown in Fig. 12a, b. There were generally higher temperatures towards the southwest, from 4Vs/4Vn to 4W and 4X. In 4Vn, most of the bottom is covered by waters <6°C and about 54% is <5°C. For 4Vs, 74% is <5°C (Fig. 12a). In 4W, 41% and in 4X, 21% of the bottom is covered by temperatures <6°C (Fig. 12b). In all 4 regions, bottom waters were substantially warmer in 2005 than in 2004, the coldest year overall.

The interannual variability can be summarized by determining the average bottom temperatures in each region (Fig. 13). All areas in 2005 featured average bottom temperatures close to the 1971-2000 norms. Areas 4Vn and 4Vs were 0.27°C (0.6 standard deviations) and 0.26°C (0.4 SD) above normal and the 23rd and 25th coldest in 36 years. Areas 4W and 4X were 0.23 (0.4 SD) and 0.09°C (0.1 SD) below normal, in both cases the 18th coldest in 36 years. Combining the 4 NAFO areas we find an overall bottom temperature anomaly of -0.02°C (-0.03 SD) and a ranking of the 21st coldest year in 36, that is to say, 2005 was about as close to an average year as possible. In 2004, the overall anomaly was -1.35°C (-2.5 SD), the coldest year for bottom temperatures from 1970 to 2005.

Standard Sections

The hydrographic observations from the Cabot Strait, Louisbourg, Halifax and Browns Bank lines run in April and October are shown in Fig. 14a-d. The anomalies corresponding to these data were calculated for the date on which they were collected. In April-May, 0-100 m temperatures were 0-2°C across the Cabot Strait and Louisbourg sections, and 2-4°C across the Browns Bank and the Halifax sections to the shelf break (Fig. 14a). Temperature anomalies were near 0°C for all depths on the Cabot Strait section, and between 0 and -1°C for most of the 3 other sections. Salinity was ~31-33 over the shelf, approximately equal to the long-term mean for most areas but with anomalies of up to ~0.5 for mid-shelf on the Halifax and Browns sections (Fig. 14b).

In October there was an extensive subsurface cold layer with temperatures 0-2°C below normal on the western side of Cabot Strait; below 100 m there were above normal temperatures by 0-1°C (Fig. 14c). A remnant cold intermediate layer (CIL) from 50 m to the bottom and extending from the coast to offshore of the shelf break is evident on the Louisbourg section. The upper 50 m of this section is warmer than normal with anomalies reaching 6°C near the coast. The CIL on the Halifax section is only seen at the inner 2 stations; temperatures over the continental slope are above normal by as much as 8°C in the upper 100 m. Except at the shelf break, temperatures on the Browns Bank section were generally above normal by 1-2°C. Salinity anomalies showed considerably small scale variability over all sections (Fig. 14d); in general, anomalies were positive on the Cabot, Louisbourg and Halifax sections and negative on the Browns Bank section.

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 from 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 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 late 1991 to their lowest value since the late 1960s (about 4.5°C, giving an anomaly exceeding -0.9°C; Fig. 15). The temperature increased reaching 6°C (anomaly of 0.6°C) by late 1993. During the remainder of the 1990s, temperatures oscillated about the long-term mean with a slight tendency towards positive values. In 2005, the temperature was 0.06°C above the long-term mean, just 0.1°C cooler than 2003 and 2004.

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 ocean's response to wind forcing, the timing of the spring bloom, vertical nutrient fluxes and plankton speciation. 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 between 0 and 50 m. The density differences were based on monthly mean density profiles calculated for each area in Fig. 7. The long-term monthly mean density gradients for 1971-2000 were estimated; these were subtracted from the individual monthly values to obtain monthly anomalies. Annual anomalies were estimated by averaging all available monthly anomalies within a calendar year. This could be misleading if, in a particular year, most data were collected in months when stratification was weak, while in another year, sampling was in months when stratification was strong. However, initial results, whereby the observations were normalized by dividing the anomalies by the monthly standard deviation, were qualitatively similar to the plots presented here. The 5-yr running means of the annual anomalies were then calculated for subareas 4-23 on the Scotian Shelf (Fig. 16, 17). These anomalies were weighted by the surface areas of the subareas. The monthly and annual means show high variability but the 5-yr running means feature some distinctive trends. The density anomalies are presented in g/ml/m. A value of 0.01 represents a difference of 0.5 of a sigma-t unit over the 50 m.

The dominant feature of the 5-year means is the higher stratification during the 1990s throughout the Scotian Shelf (Fig. 16a, b). In 2005, there was considerable spatial variability of the stratification index throughout the region. For example, in the Sydney Bight to Misaine Bank area (top panel, Fig. 16a), the tendency is for above normal values of the parameter. On the other hand, in the central shelf region (Emerald Bank to LaHave Basin, Fig. 16a, bottom panel), the opposite situation prevails. The average stratification parameter for areas 4-23 showed increased stratification in 2005 (Fig. 17).

Sea Level

Sea level is a primary variable in the Global Ocean Observing System. On Canada's east coast, two gauges, one at Halifax and the other on the Labrador coast, are part of Canada's proposed contribution to this global effort. Relative sea level at Halifax (1990-2005) is plotted as monthly means and as a filtered series using a 12-month running-mean filter (Fig. 18). The linear trend of the monthly mean data (1990-2005) has a positive slope of 29.0 (±8.8) cm/century, lower than the value of 36.7 cm/century (1897-1980) given by Barnett (1984) but within the standard error (note Barnett does not give a standard error). Despite the long-term rising trend, relative sea level generally decreased at Halifax from 1998-2003. The trend is referenced to a benchmark fixed on the land and therefore is not an absolute value of the sea level rise. The green line in the figure is a model estimate of the sea level trend, 23 cm/century at Halifax, caused by post-glacial rebound (Tushingham and Peltier, 1991). The observed trend exceeds the model's prediction for the period 1990-2005 by only 6.0 cm/century. In 2005 relative sea level was the same as in 2004.

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 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 2005 have been digitized, estimates of monthly mean positions determined, and anomalies relative to 1973-2000 were calculated. Since May 2005, we have been downloading front positions from the U.S. Naval Oceanographic Office. During the past several years, the analysis only extends east to 56°W due to inconsistencies in the data at 55°W.

The overall mean position of the Shelf/Slope front and the 2005 annual mean position are shown in Fig. 19. 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 100-200 km from the shelf edge off the Scotian Shelf and the southern Grand Bank. It is generally farthest offshore in winter and onshore in late summer and early autumn. During 2005, the shelf/slope front was slightly southward, 5.7 km, 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 shoreward location in 1985 with another maximum in 1993. Since 1993, the front moved steadily seaward approximately 40 km, reaching its most southerly position in 1996. In 2005, the front moved about 13 km onshore from its mean position in 2004.

Gulf Stream

The position of the northern boundary of the Gulf Stream was 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. The time series consists of the monthly position at each degree of longitude from 56°W to 75°W. The average position of the northern edge of the Gulf Stream and the 2005 annual mean is shown in Fig. 20. The Gulf Stream leaves the shelf break near Cape Hatteras (75°W) running towards the northeast. East of approximately 62°W, the average position is oriented approximately east-west. The time series of the position shows the Gulf 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. 20). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed by a rapid southward movement in 1996. By 2000 the position of the Gulf Stream was again shoreward of its long-term mean and has remained so through to 2002. In 2004, the Gulf Stream was about 20 km south of its mean position. In 2005, it moved onshore by 12 km, about 8 km south of its long-term mean position.

Summary

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2005 has shown the temperature conditions were generally from 0 to 1°C below normal. This contrasts with 2004 when cooler conditions prevailed. St. Andrews sea surface temperature was 0.07°C below normal making 2005 the 49th coldest in 85 years. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by about 0.3 to 0.4°C. Salinities were 0.42 (0 m) and 0.17 (90 m) below normal. Halifax sea surface temperature was 1.0°C below normal, making 2005 the 8th coldest in 80 years. At Halifax Station 2, 0-140 m temperature anomalies were generally within 1°C of normal; salinity was slightly below normal values. Sydney Bight and Misaine Bank had typical temperature anomalies of 0.5 and 0°C; Emerald Basin, Lurcher Shoals, Georges Basin and eastern Georges Bank profiles featured typical anomalies of –0.5°C at most depths. Standard sections in April and October on the Scotian Shelf support the overall conclusion of near temperatures in the upper 100m. Cabot Strait deep-water (200-300 m) temperatures were near normal. The temperatures from the July groundfish survey increased substantially from the record cold values in 2004. The overall anomaly for the combined areas of 4Vn,s, 4W and 4X was -0.07°C. The overall stratification was slightly above normal for the Scotian Shelf region in 2005. The Shelf/Slope front and the Gulf Stream were about 6 and 8 km south of their mean positions.

A graphical summary of many of the time series already shown indicates that the periods 1987-1993 and 2003-2004 were predominantly colder than normal and 1999-2000 was warmer than normal (Fig. 21, upper panel). The period 1979-1986 also tends to be warmer than normal but, except for 1984, not as dominantly so as 1999-2000. In this figure, annual anomalies based on the 1971-2000 means have been normalized by dividing by the 1971-2000 standard deviations for each variable. The results are displayed as the number of standard deviations above (red) and below (blue) normal. During predominantly warmer or colder than normal periods, there are sometimes systematic exceptions to the overall pattern. For example, for the eastern and central Scotian Shelf (Misaine, Emerald, 4Vn, 4Vs), temperatures in 2005 were above normal whereas most other variables were above normal. The mosaic plot can be summarized as a combination bar and line-scatter plot (Fig. 21, lower panel). The bar components are colour coded by variable so that for any year the contribution of each variable can be determined and systematic spatial variability seen. The height of each variable’s contribution to the bar depends on its magnitude. The positive components are stacked on the positive side, the negative components on the negative side. The sum of the normalized anomalies (difference between the positive and negative stacks) is shown as a black line connecting grey circles. This is a measure of whether the year tended to be colder or warmer than normal and can serve as an overall climate index. The cold periods of 1987-1993 and 2003-2004 and the warm period of 1999-2000 are apparent. Systematic differences from the overall tendency as noted

above are also apparent. This last plot is an attempt to derive an overall climate index for the area, a draft index you might say. In the manifestation presented in Fig. 21, we have selected “profiles” for the eastern (Misaine), central (Emerald) and western (Lurcher) Scotian Shelf, the Bay of Fundy (Prince 5) and Georges Bank. In addition, we have included the spatially comprehensive but temporally limited July groundfish survey bottom temperatures (4, Vn,s, 4W and 4X) and surface temperatures for Halifax and St. Andrews because of their long-term nature. It may be that some of the series should be consolidated or others added, e.g. a volumetric estimate of the amount of water with a temperature less than $4^{o}C$ from the July groundfish survey, before summing to get an overall climate index. We shall continue to experiment with the development of an index over the next year.

Acknowledgements

We wish to thank the many individuals who provided data or helped in the preparation of this paper, including: Don Spear, Mathieu Ouellet and Scott Tomlinson of the Marine Environmental Data Service in Ottawa; F. Page and R. Losier of the Biological Station in St. Andrews, for providing St. Andrews and Prince 5 data; G. Bugden of BIO and D. Gilbert of IML for their Cabot Strait temperature data; and J. Jackson and D. Gregory for their maintenance of the BIO hydrographic database. We also thank Eugene Colbourne and Denis Gilbert for their comments which improved the document.

References

Barnett, T. 1984. The estimation of “global” sea level change: a problem of uniqueness. J. Geophys. Res. 89, 7980-7988.

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. 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. 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., 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.

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., B. Petrie and P. C. Smith 2003. Climate variability on the Scotian Shelf during the 1990s. ICES Mar. Sci. Symp. Ser. (in press).

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., 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.

Petrie, B., R. Pettipas, W. Petrie and K. Drinkwater 2004. An overview of meteorological, sea ice and sea-surface temperature conditions off eastern Canada during 2003. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/047, 37 p.

Tushingham, A. and R. Peltier 1991. Ice 3-G: a new global model of late Pleistocene deglaciation based on geophysical predictions of post-glacial relative sea level change. J. Geophys. Res. 96, 4497-4523.

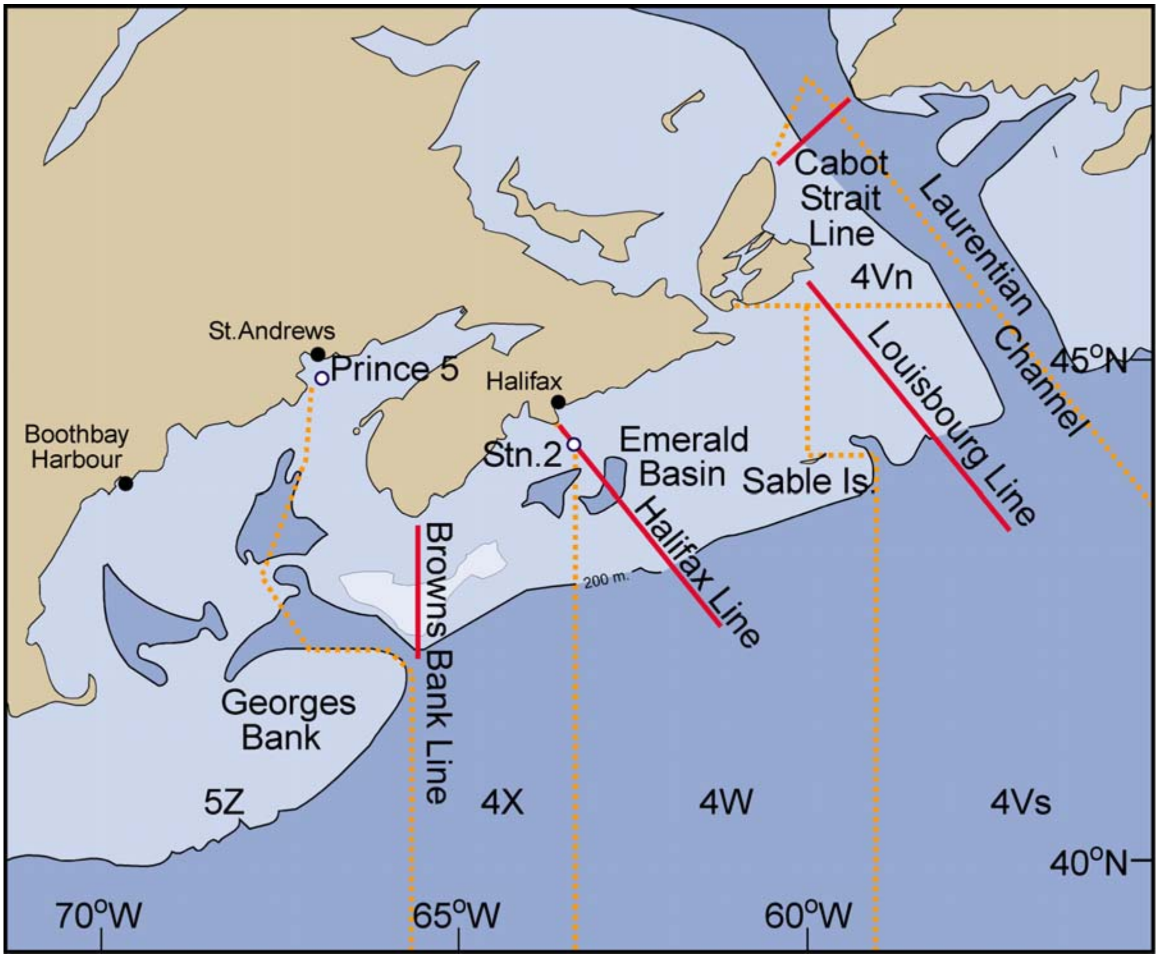


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

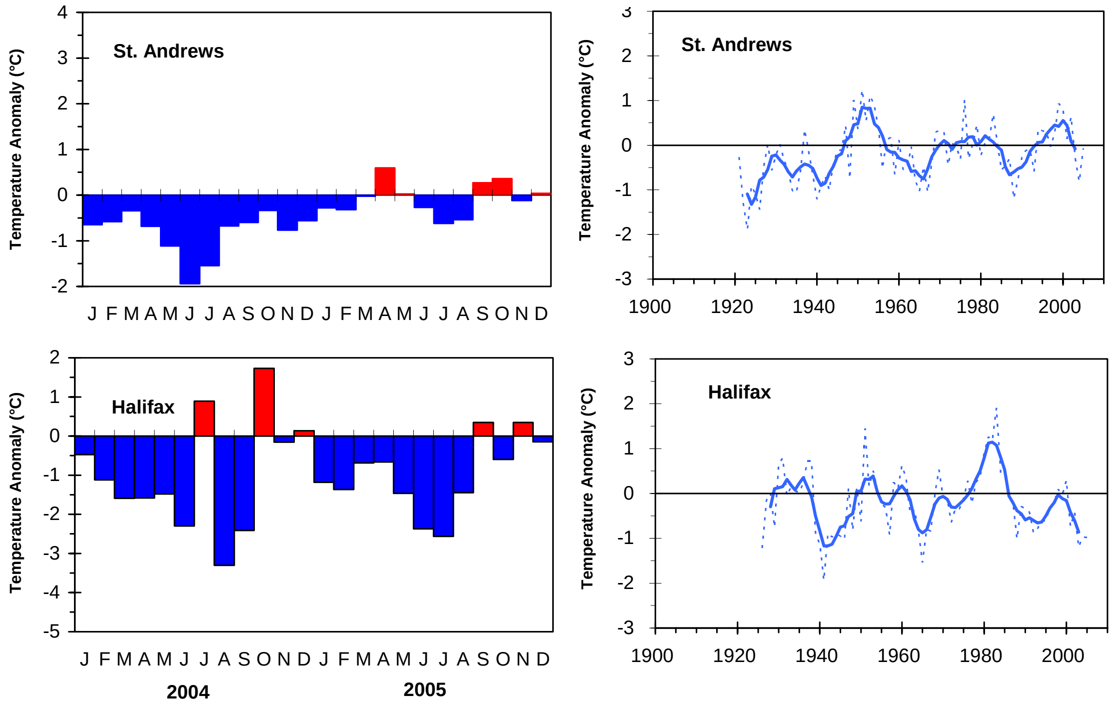


Fig. 2. The monthly sea surface temperature anomalies during 2004 and 2005 (left) and the annual temperature anomalies and their 5-year running means (right) for St. Andrews and Halifax Harbour. Anomalies are relative to the 1971-2000 means.

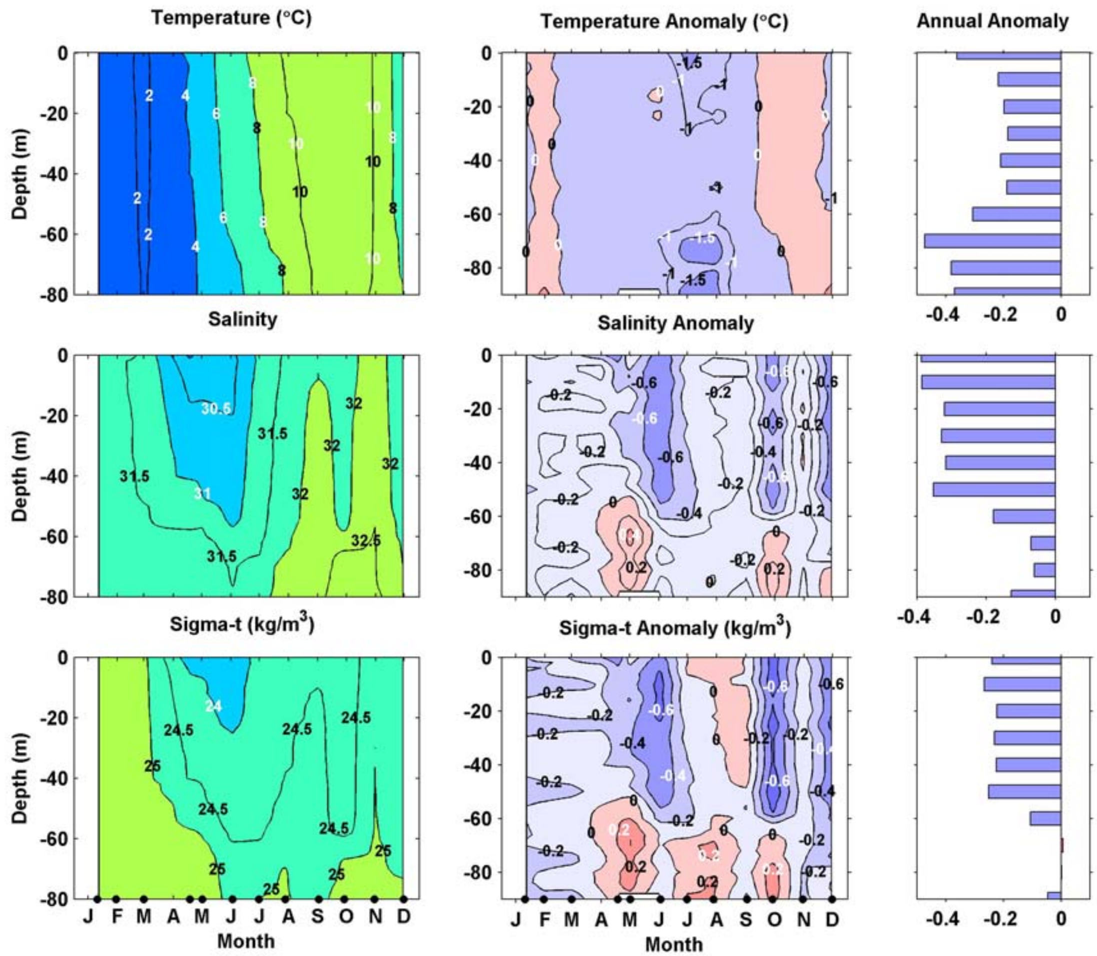


Fig. 3. Contours of temperature, salinity and sigma-t and their anomalies at Prince 5 as a function of depth during 2005 relative to the 1971-2000 means. Blue (red) indicates below (above) normal anomalies. The bar chart shows the annual anomalies.

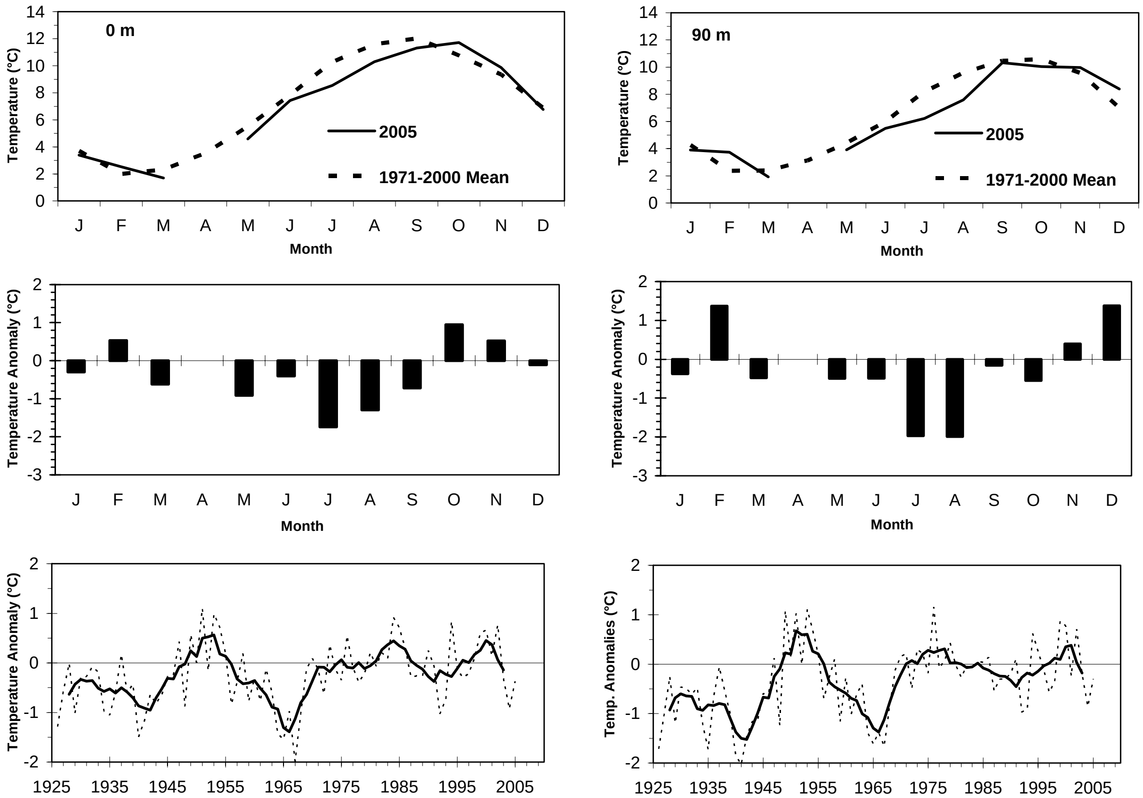


Fig. 4. The monthly mean temperatures for 2005 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

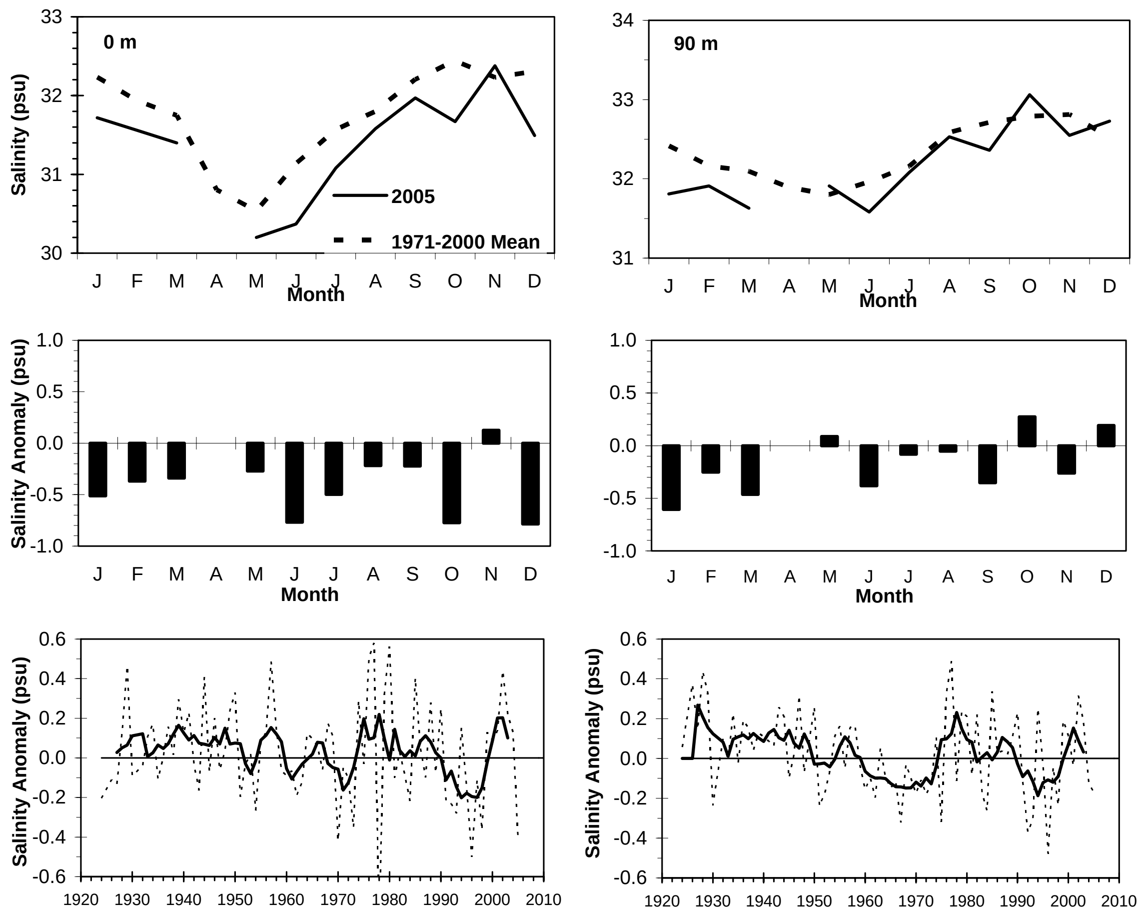


Fig. 5. The monthly mean salinities for 2005 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

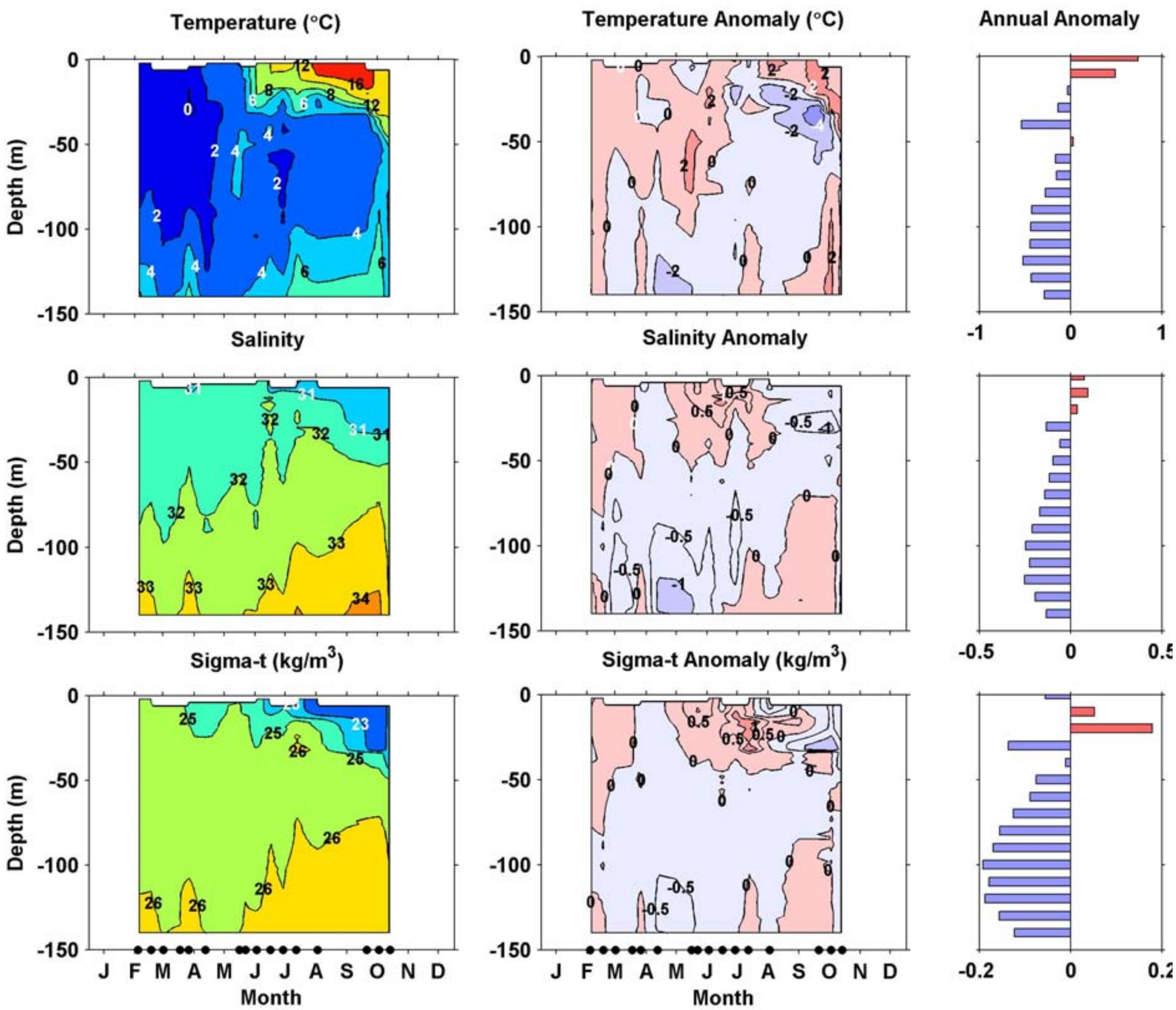


Fig. 6. Contours of the 2005 temperature, salinity and density (sigma-t) (left) and their anomalies (right) at the fixed station Halifax Section Station 2. Blue (red) indicates below (above) normal anomalies. The bar chart shows the annual anomalies.

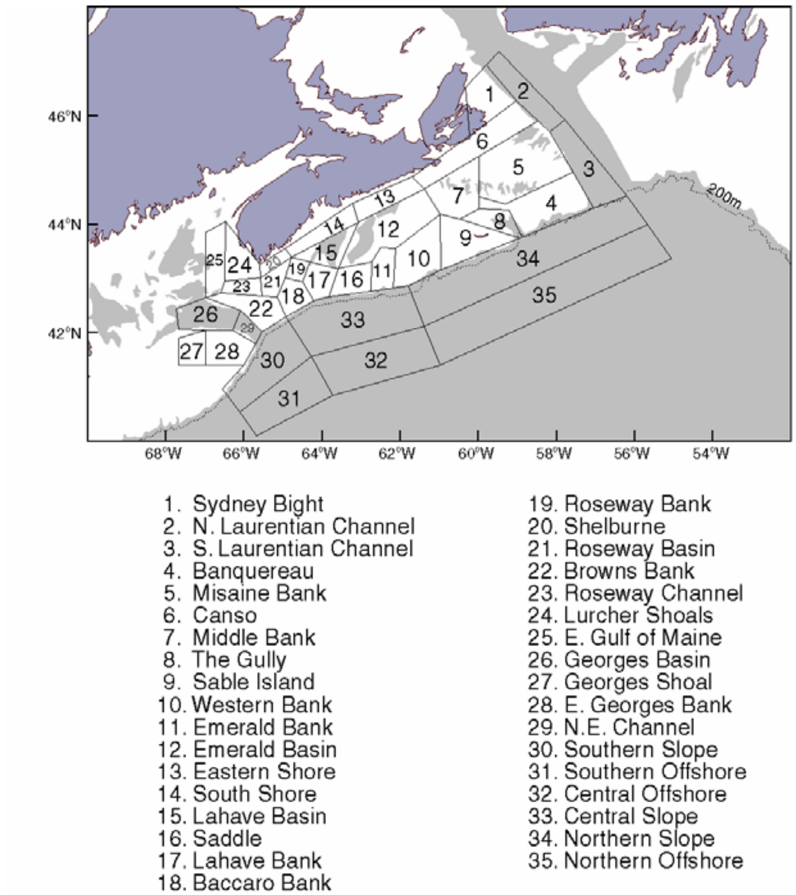


Fig. 7. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

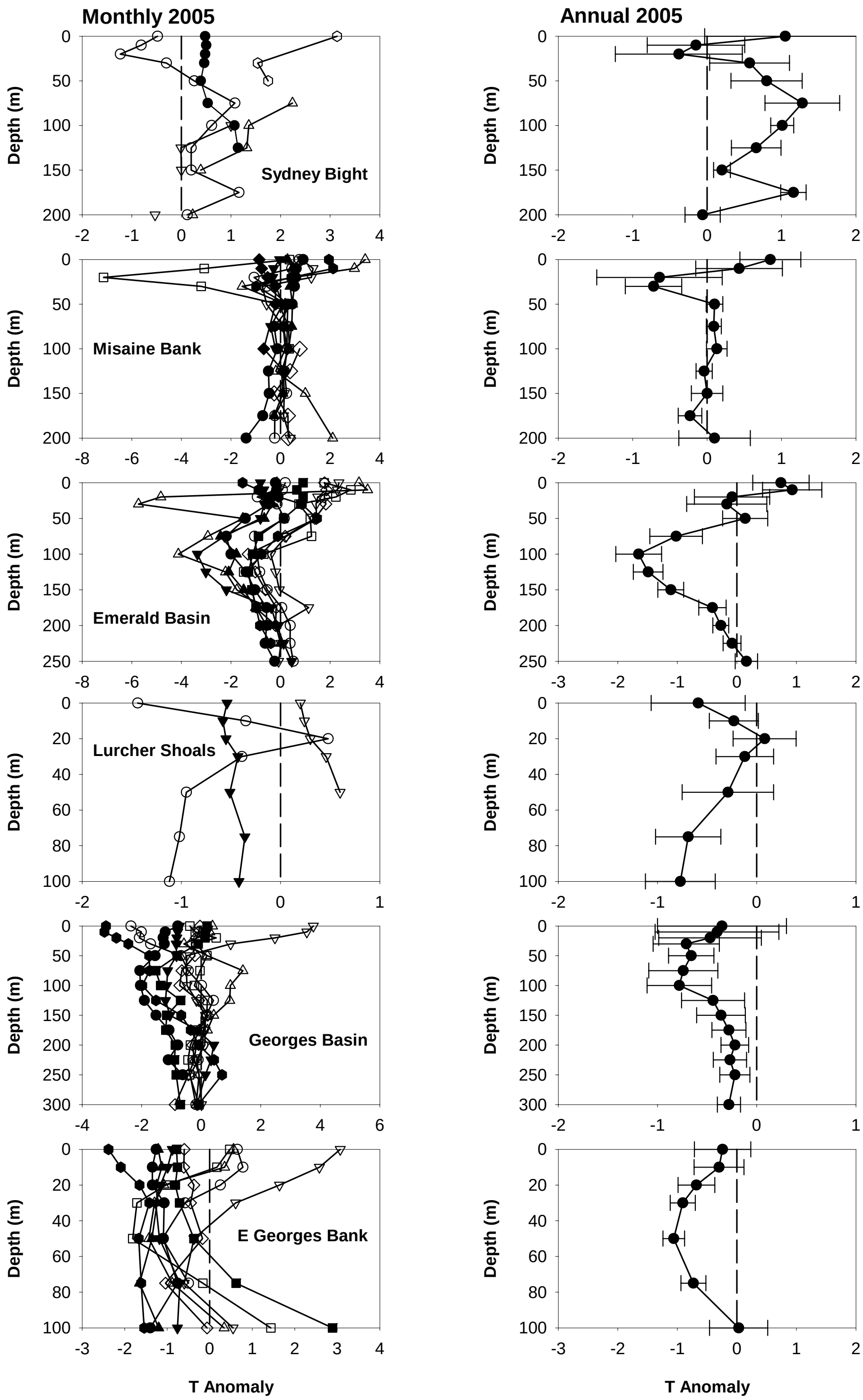


Fig. 8. Monthly (left) and annual (±std. error, right) temperature anomaly profiles for selected locations. Symbol order for monthly profiles is filled dot, square, up triangle, down triangle, diamond, hexagon for January-June,, then open symbols in the same order for July-December.

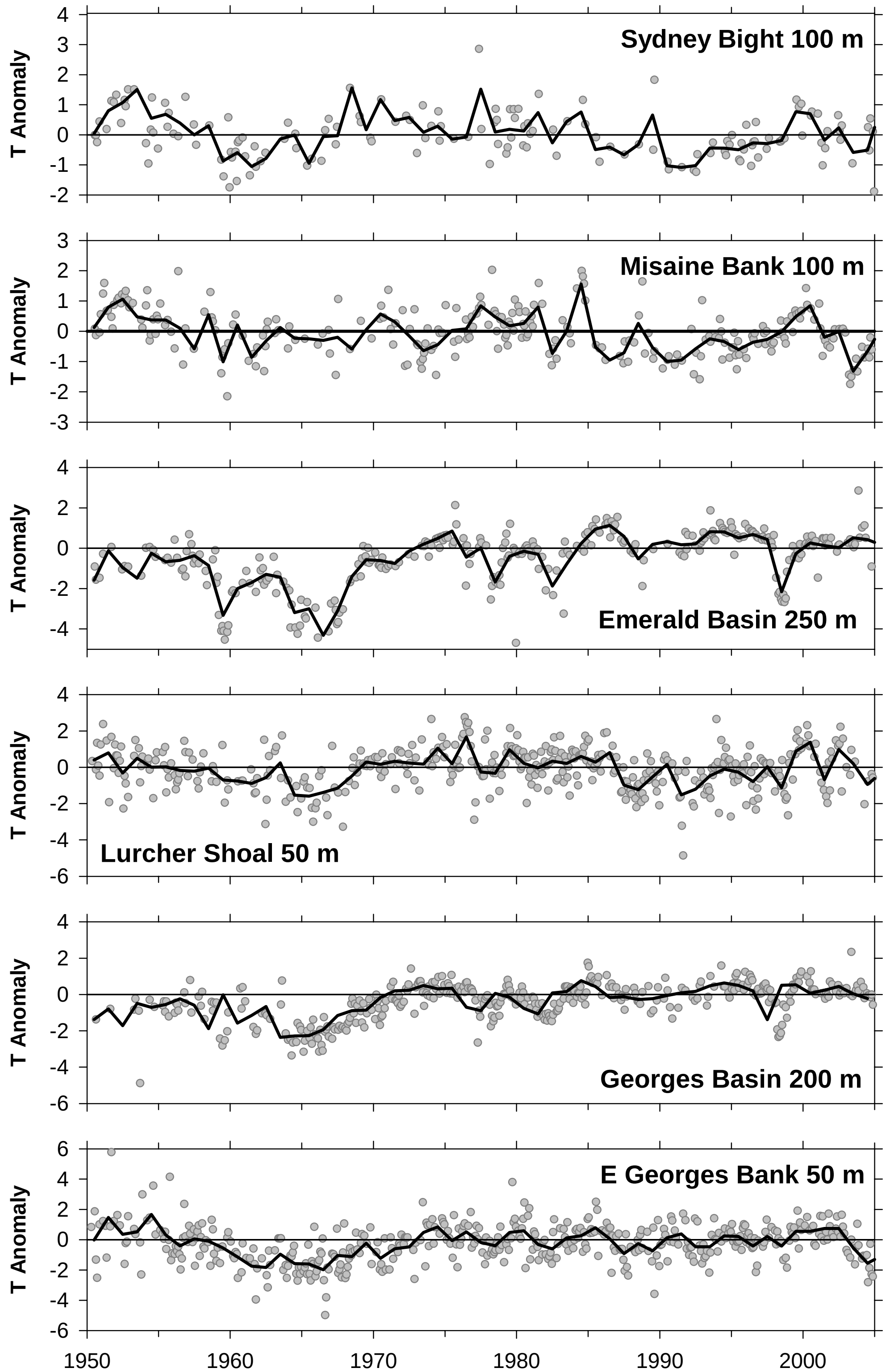


Fig. 9. The monthly mean temperature anomaly time series (grey dots) and the estimated annual anomalies (solid line) at 6 sites on the Scotian Shelf and in the Gulf of Maine (see Fig. 7).

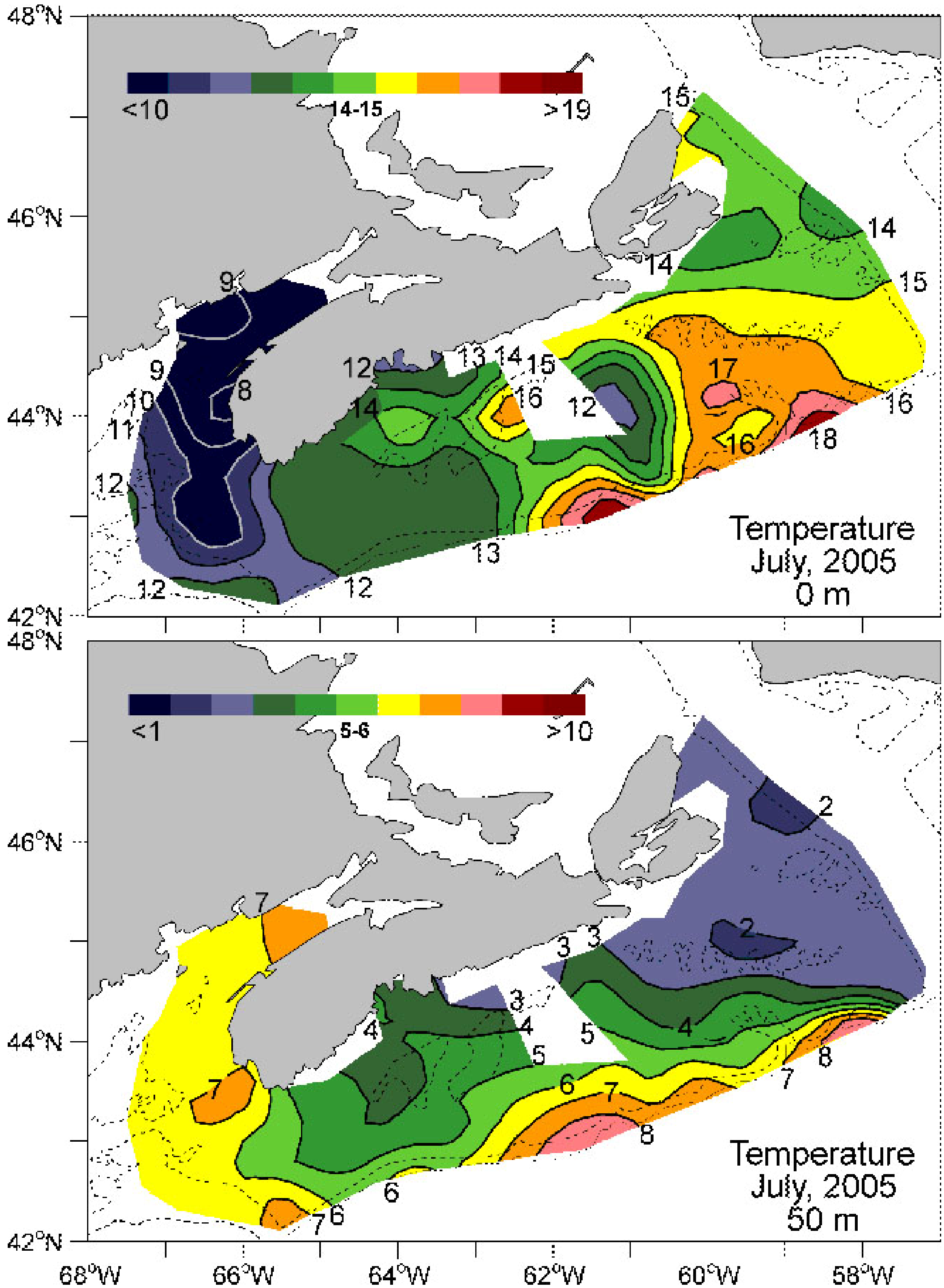


Fig.10a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2005 July groundfish and ITQ surveys.

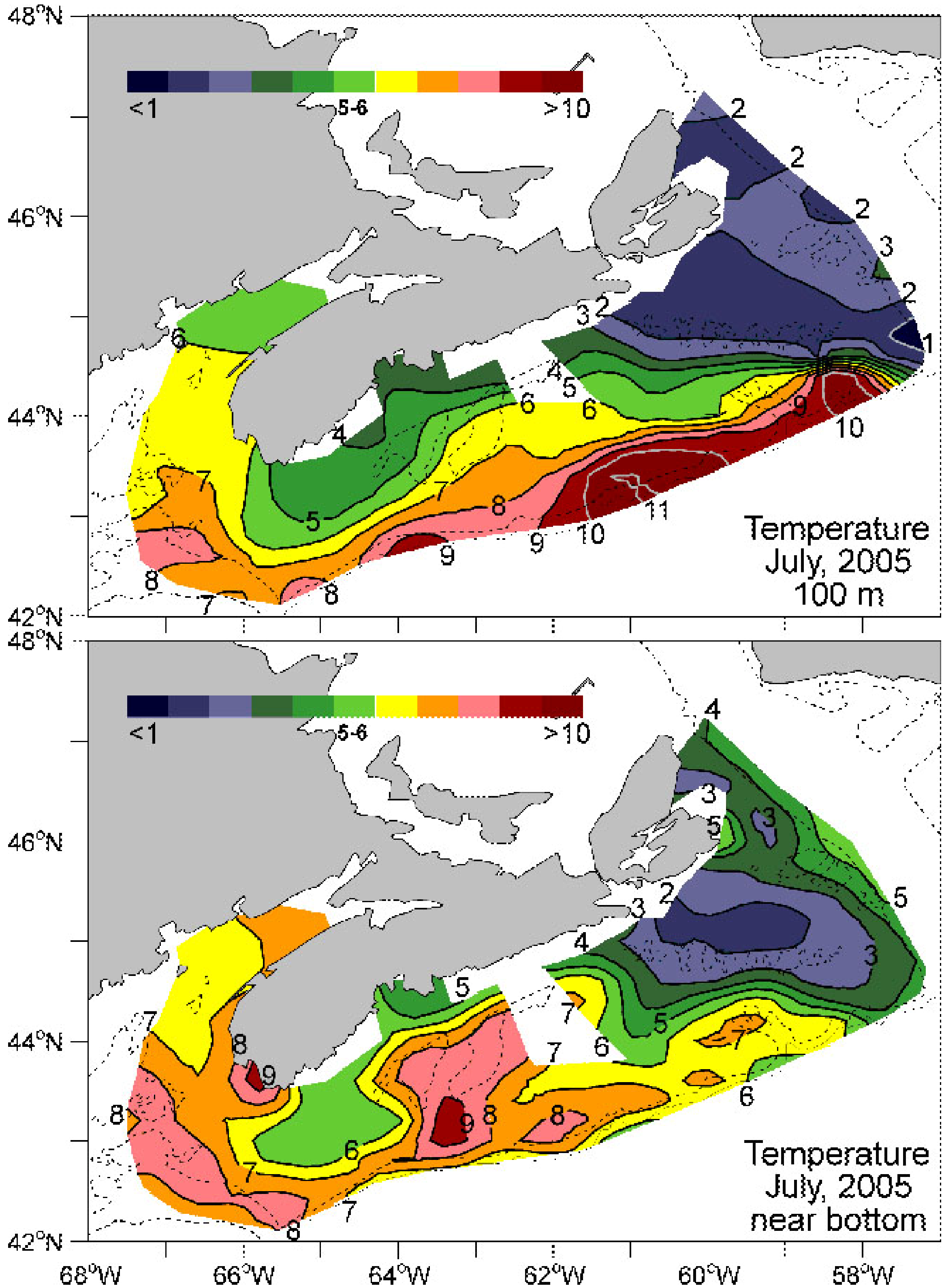


Fig. 10b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2005 July groundfish and ITQ surveys.

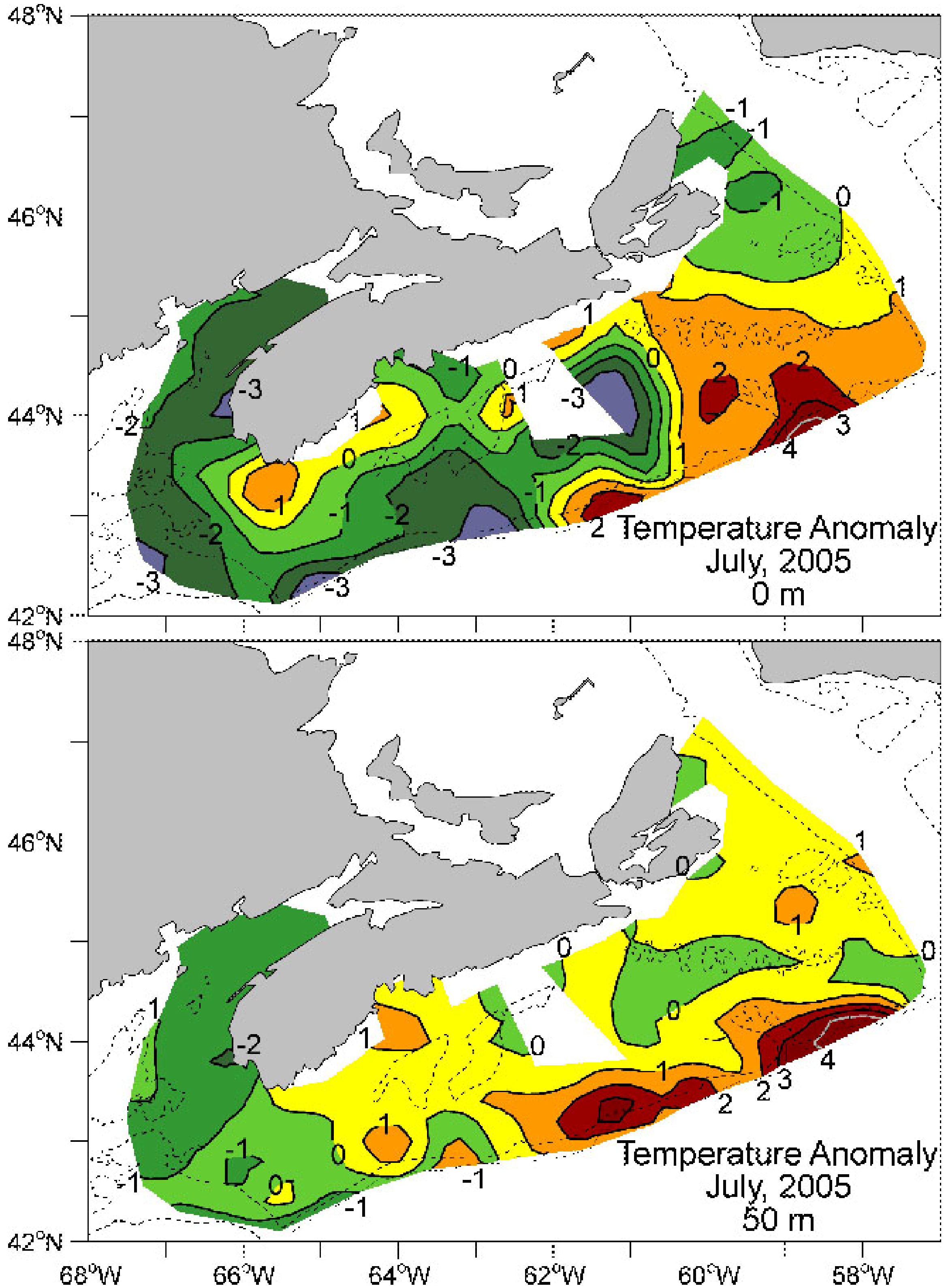


Fig. 11a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2005 July groundfish and ITQ surveys.

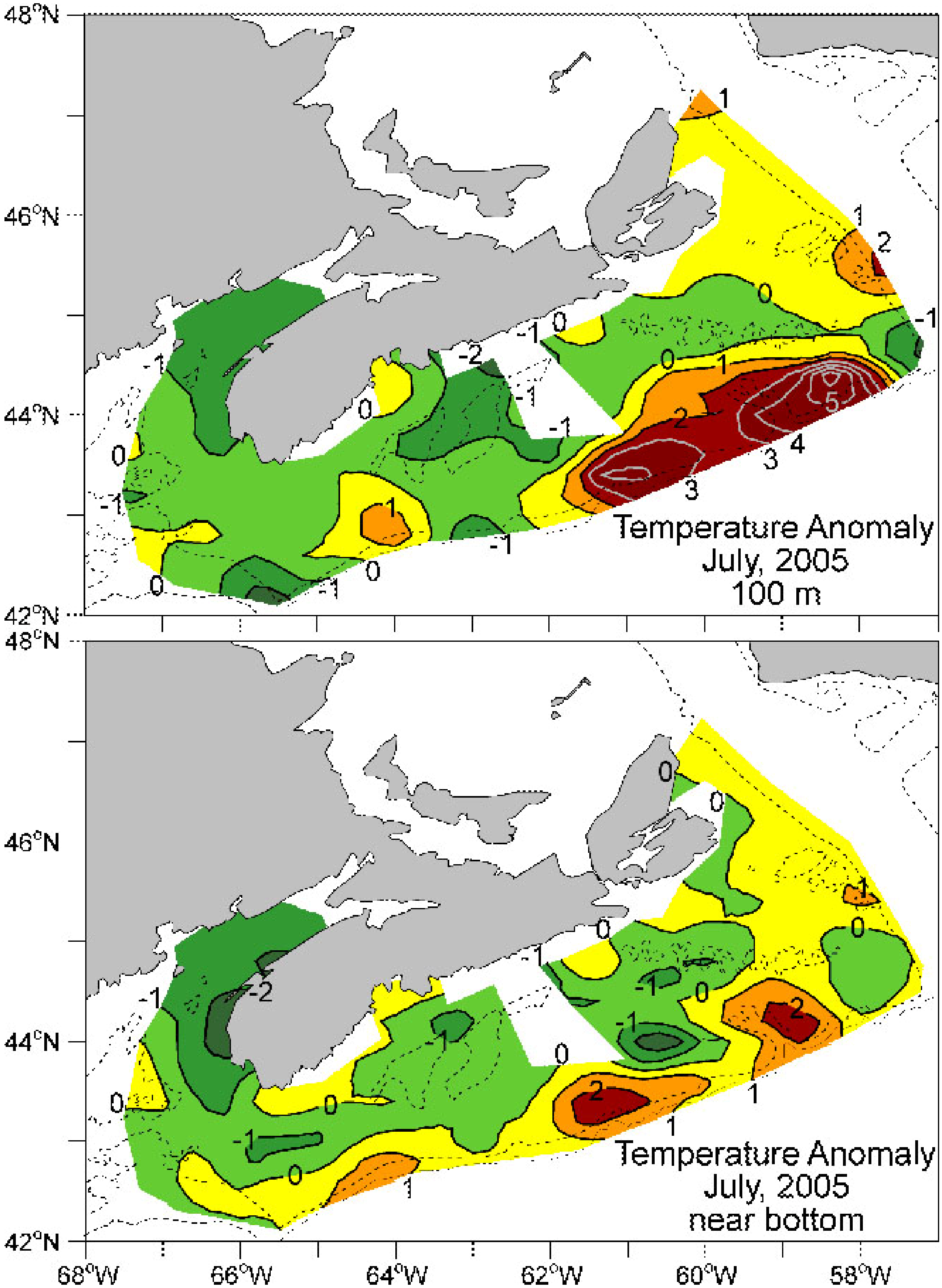
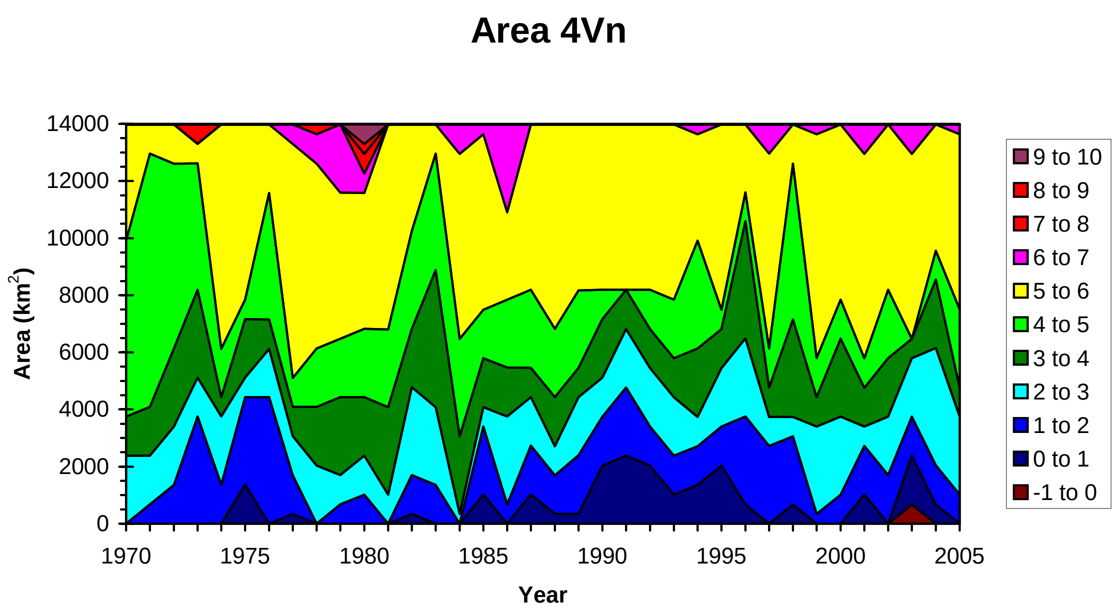


Fig. 11b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2005 July groundfish and ITQ surveys.



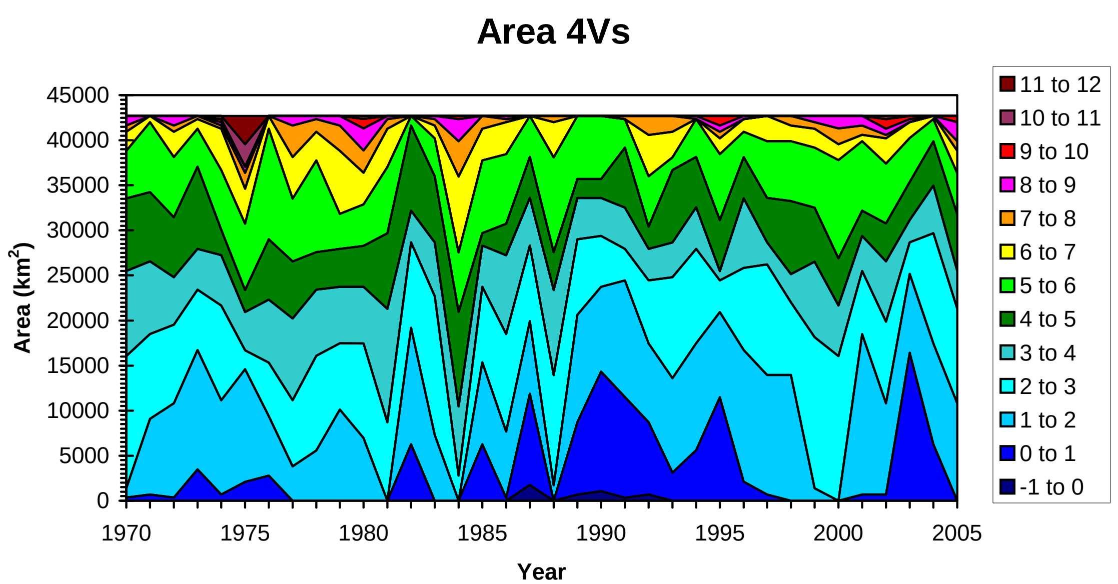
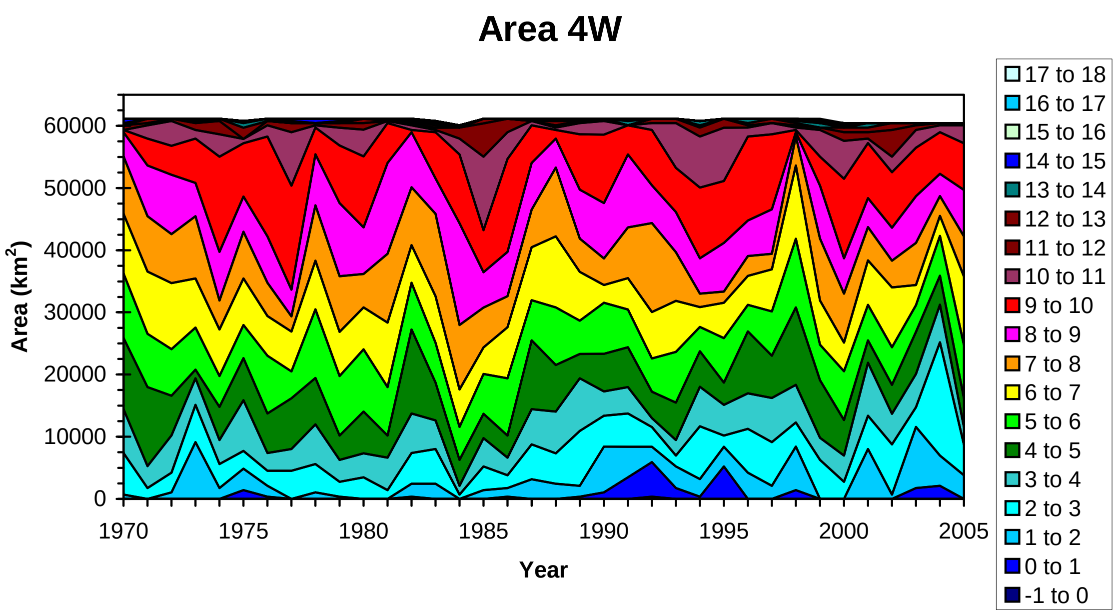


Fig. 12a. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).



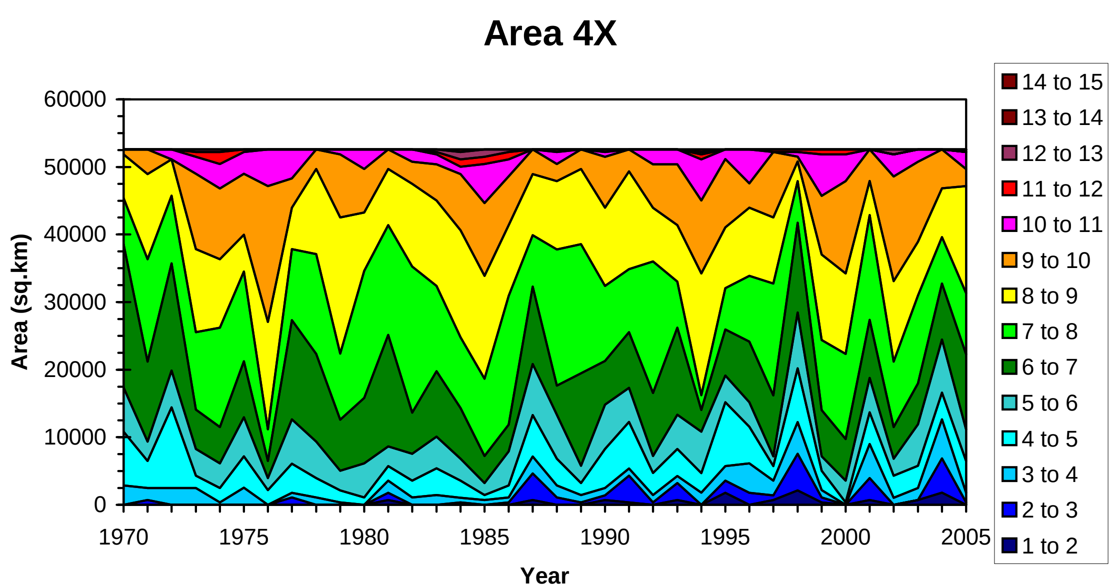


Fig. 12b. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4W (top panel) and 4X (bottom panel).

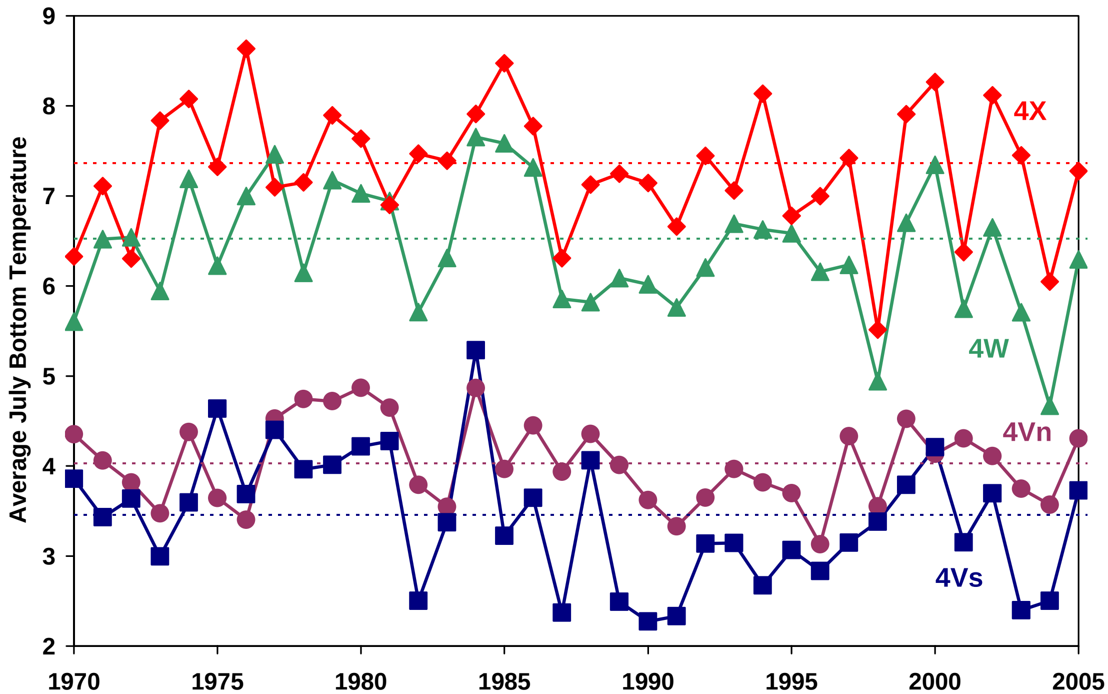


Fig. 13. Time series of annual mean bottom temperatures from areas 4Vn, 4Vs, 4W and 4X. The horizontal lines are the 1971-2000 means.

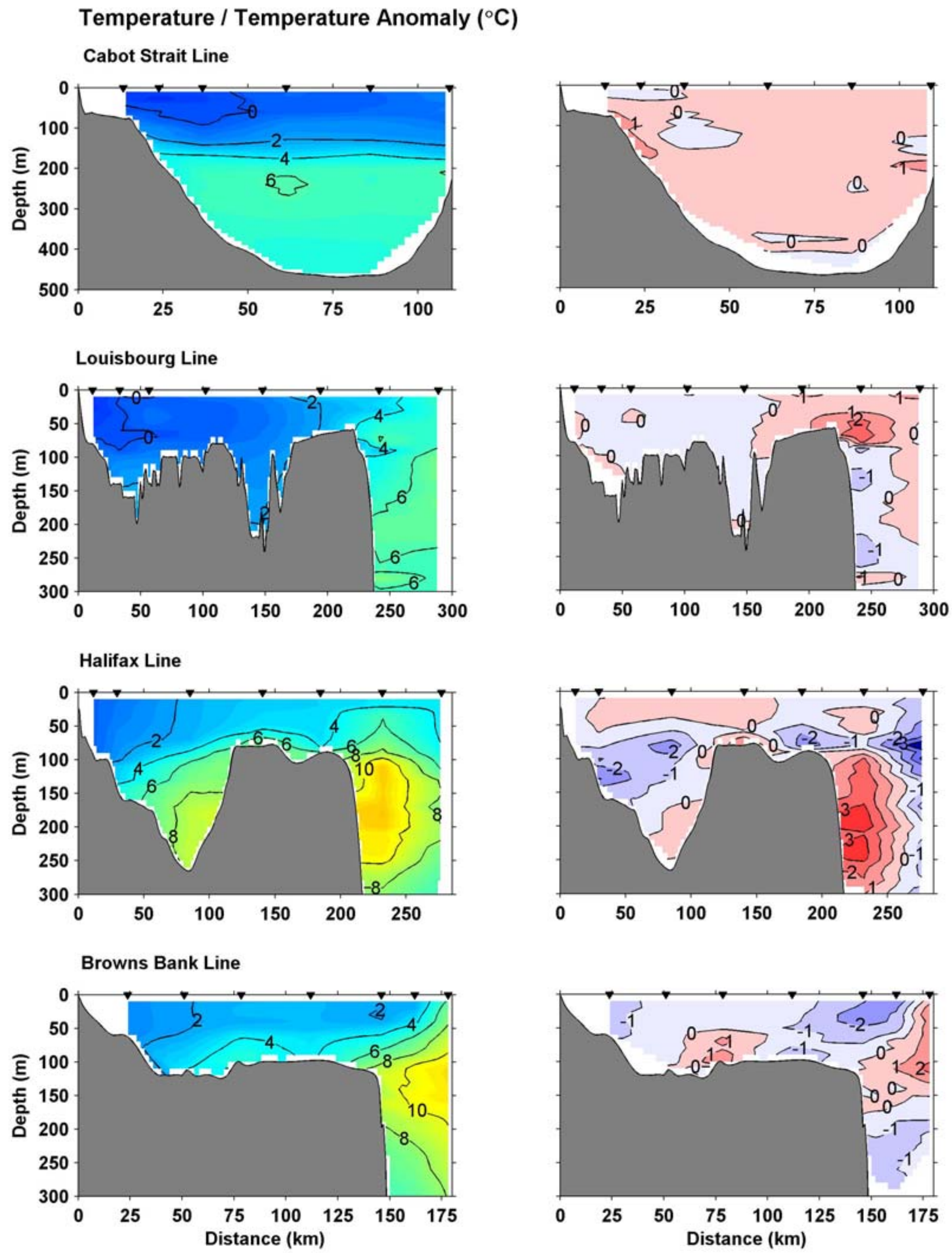


Fig. 14a. Temperature and temperature anomalies for standard Scotian Shelf sections, April 2005.

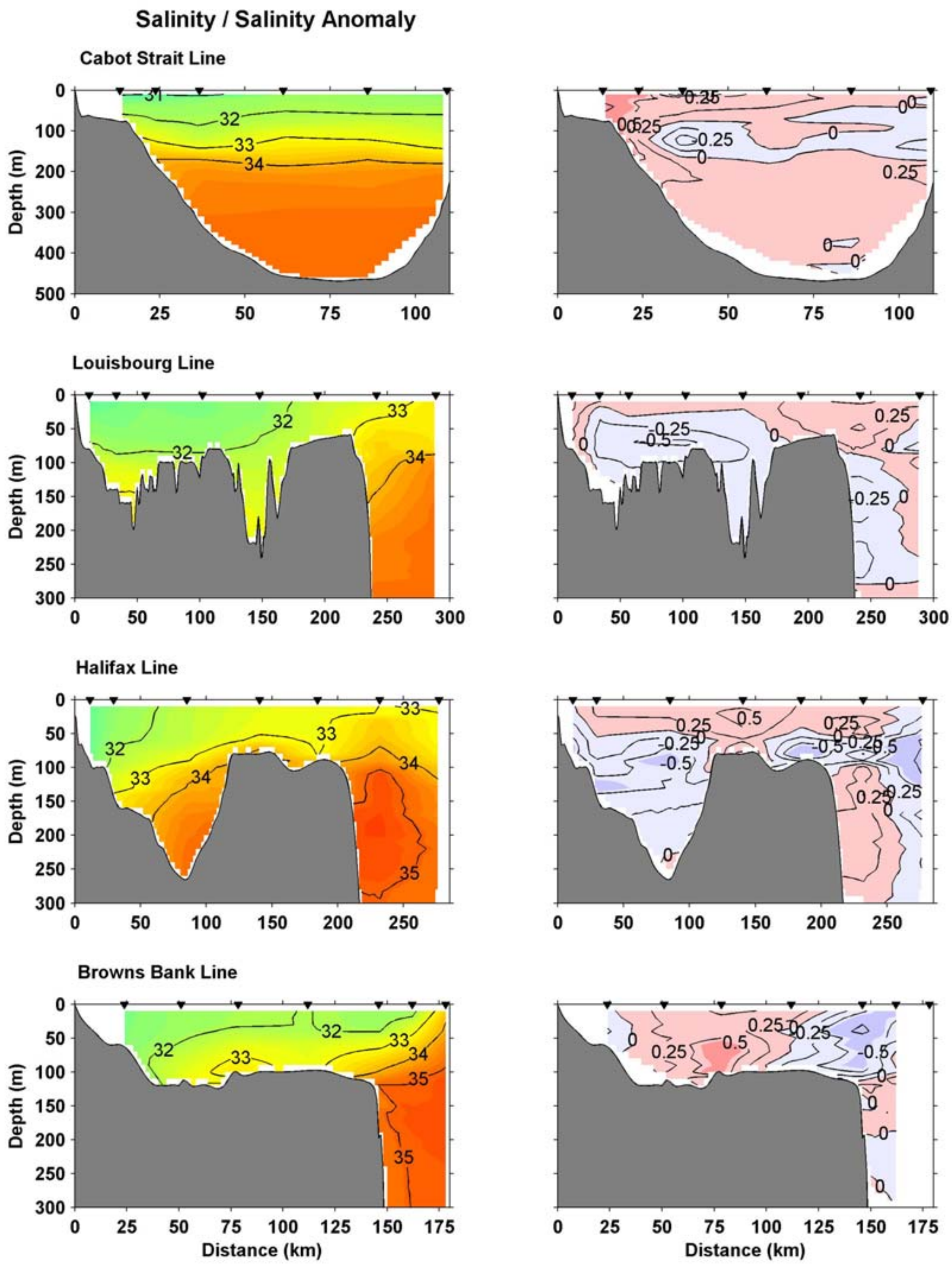


Fig. 14b. Salinity and salinity anomalies for standard Scotian Shelf sections, April 2005.

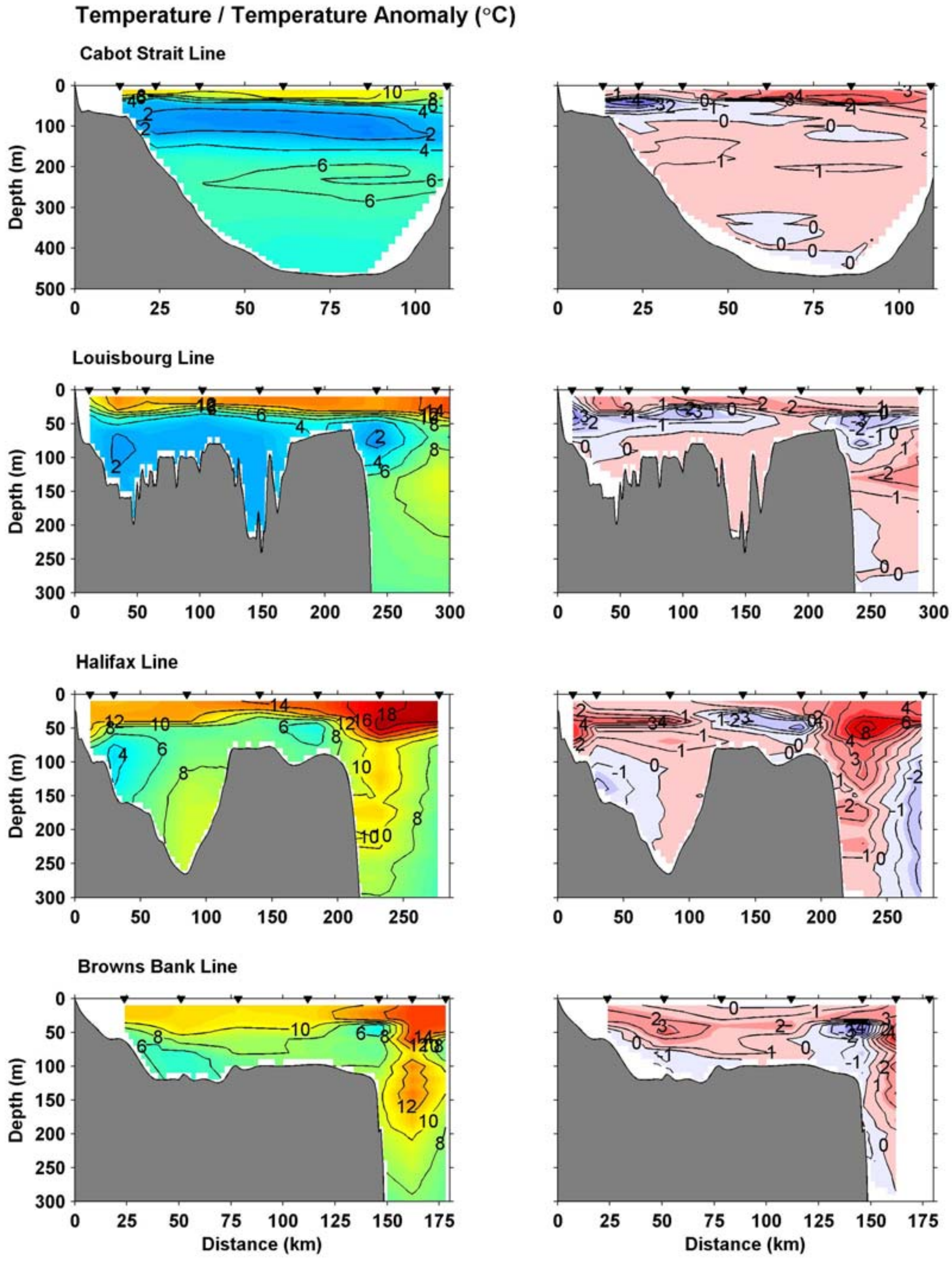


Fig. 14c. Temperature and temperature anomalies for standard Scotian Shelf sections, October 2005.

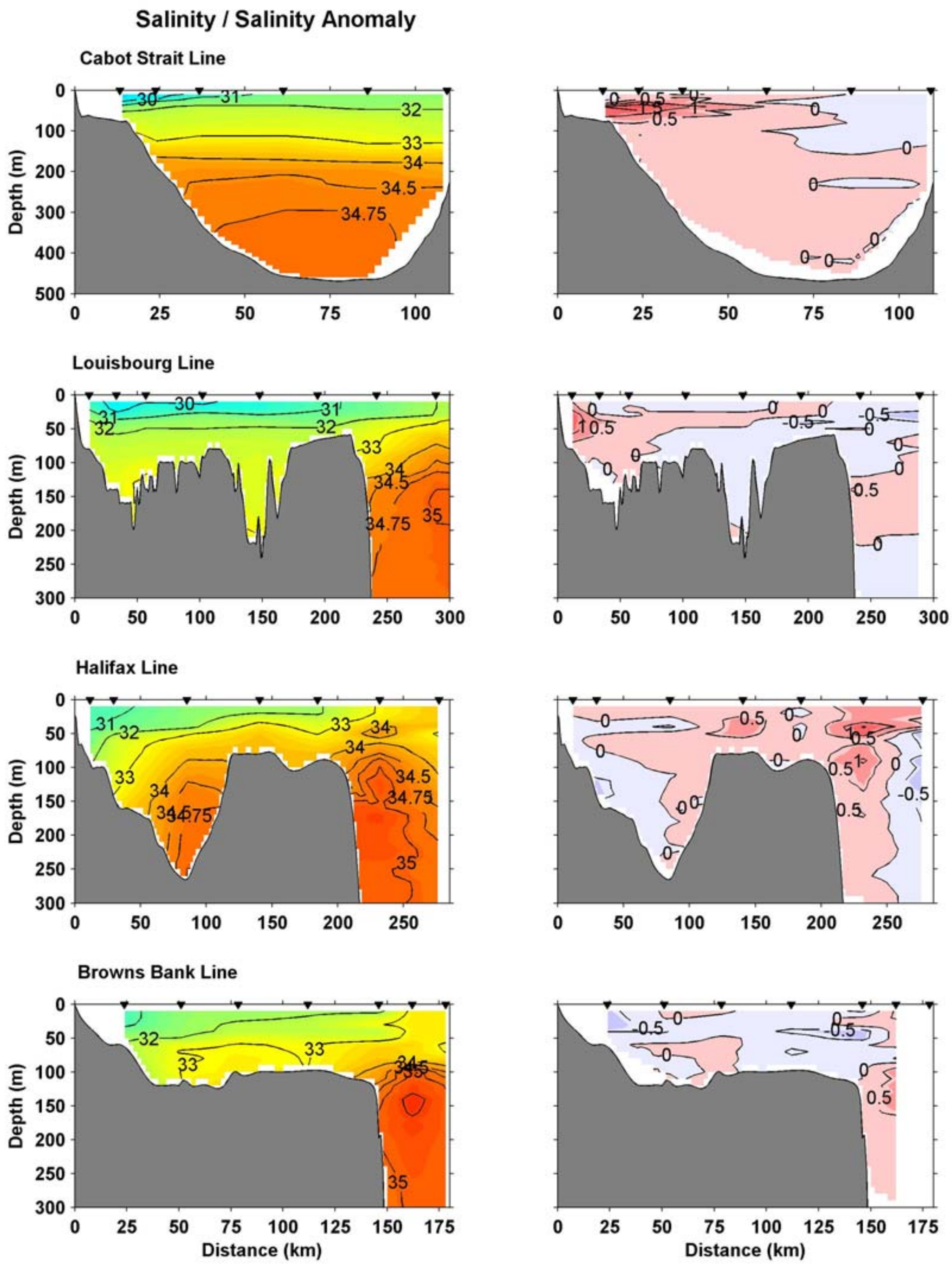


Fig. 14d. Salinity and salinity anomalies for standard Scotian Shelf sections, October 2005.

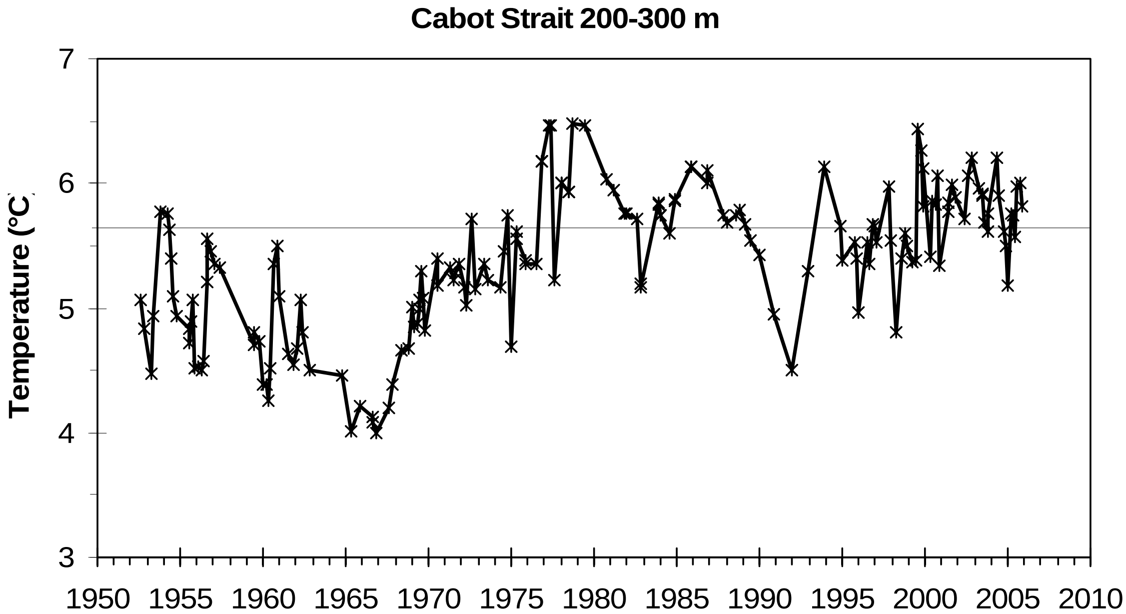


Fig. 15. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the 1971-2000 mean.

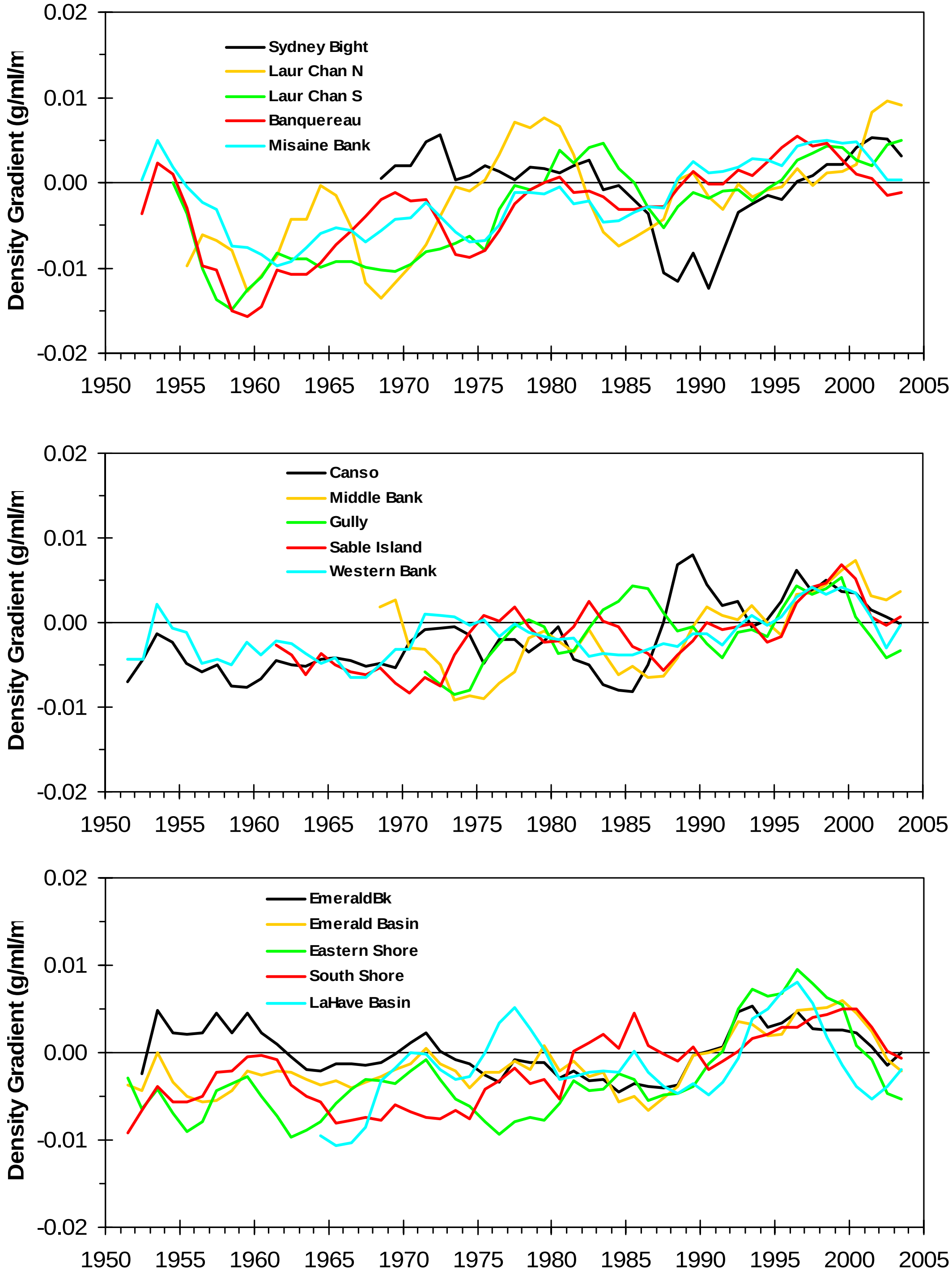


Fig. 16a. Five-year running means of the annual density gradient anomalies between the surface and 50 m calculated for the areas 1-15 in Fig. 7.

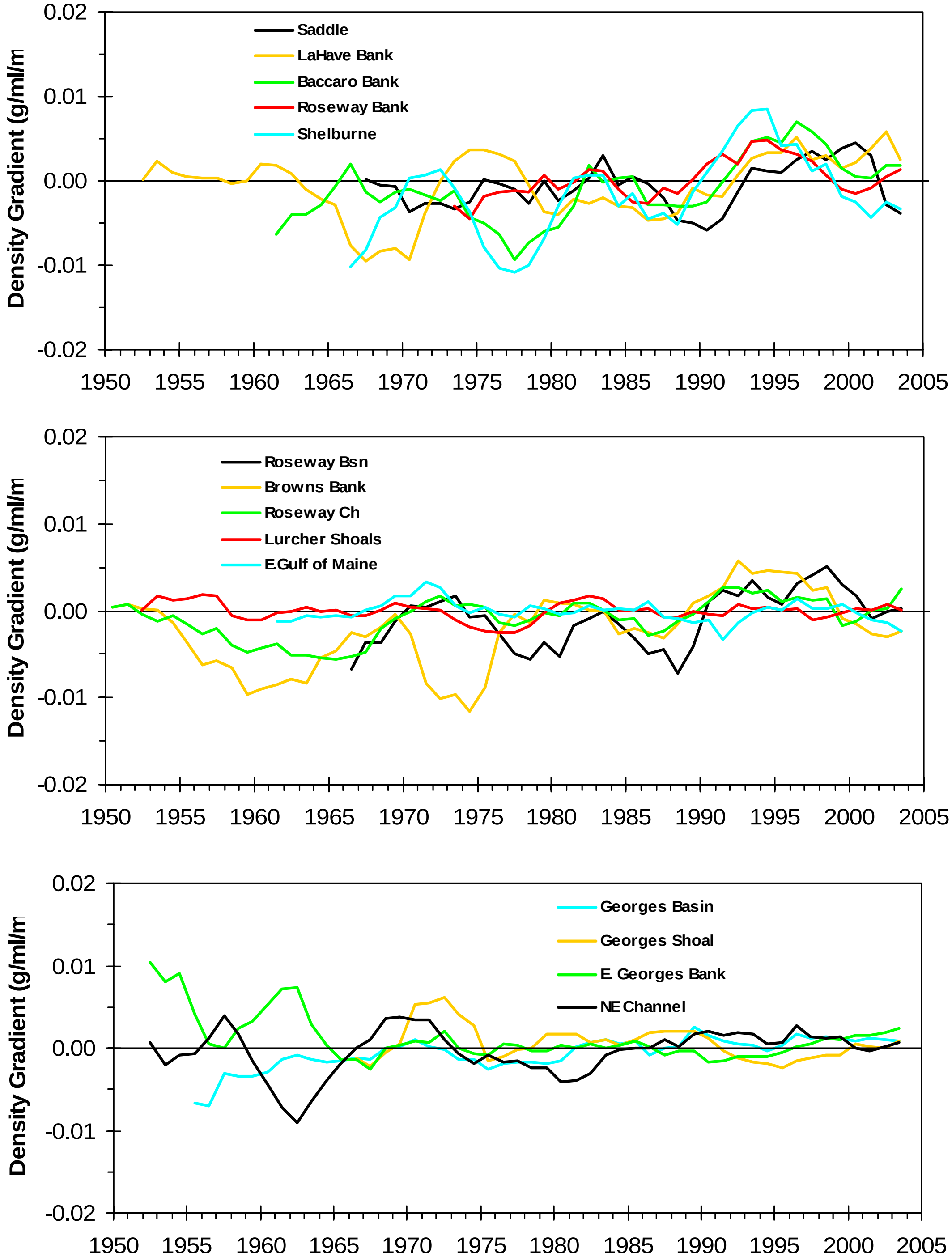


Fig. 16b. Five-year running means annual density gradient anomalies between the surface and 50 m calculated for the areas 16-29 in Fig. 7.

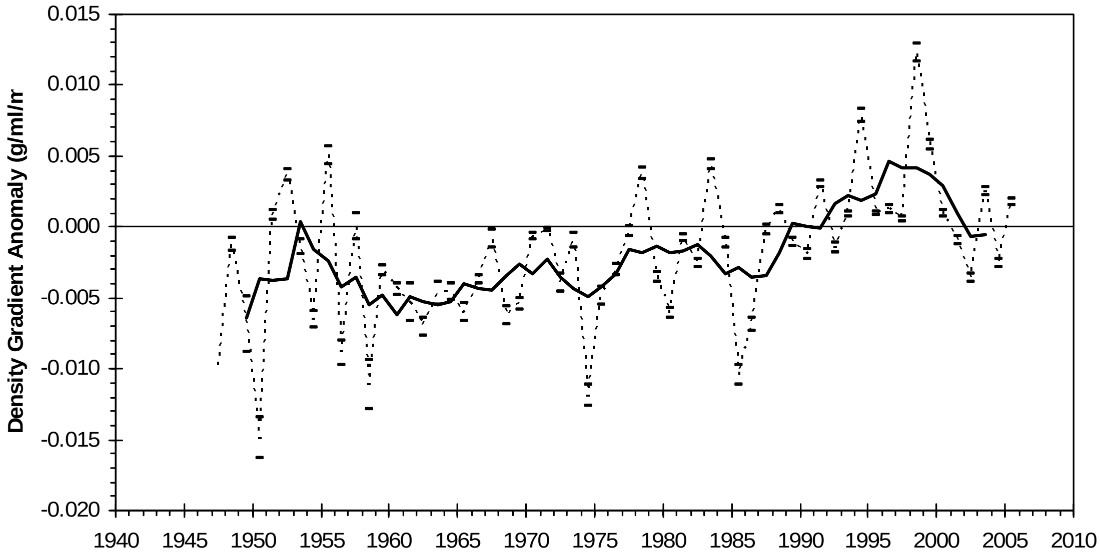


Fig. 17. The mean annual (dashed line) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive). The short horizontal lines for each year represent the standard errors of the different areas.

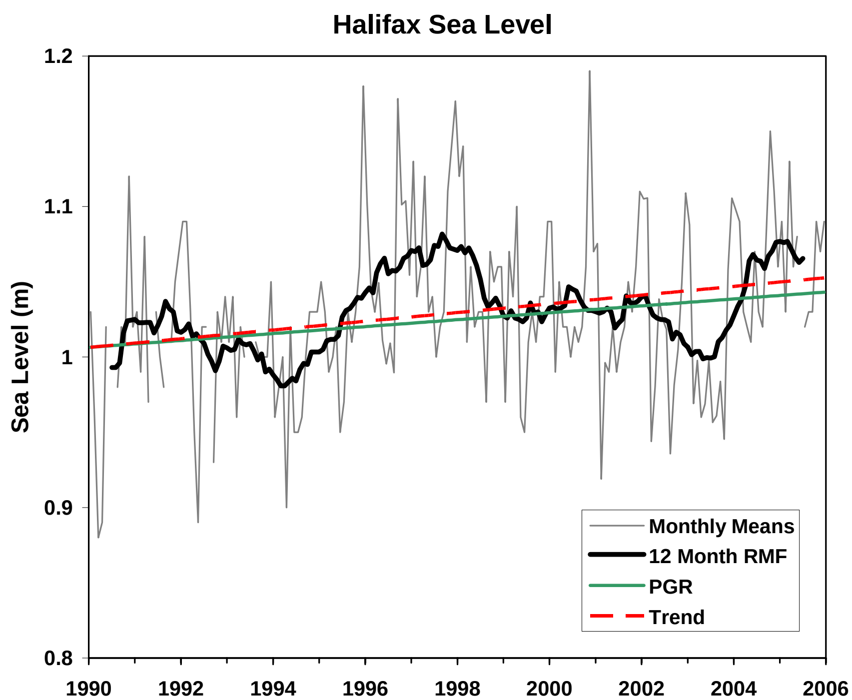
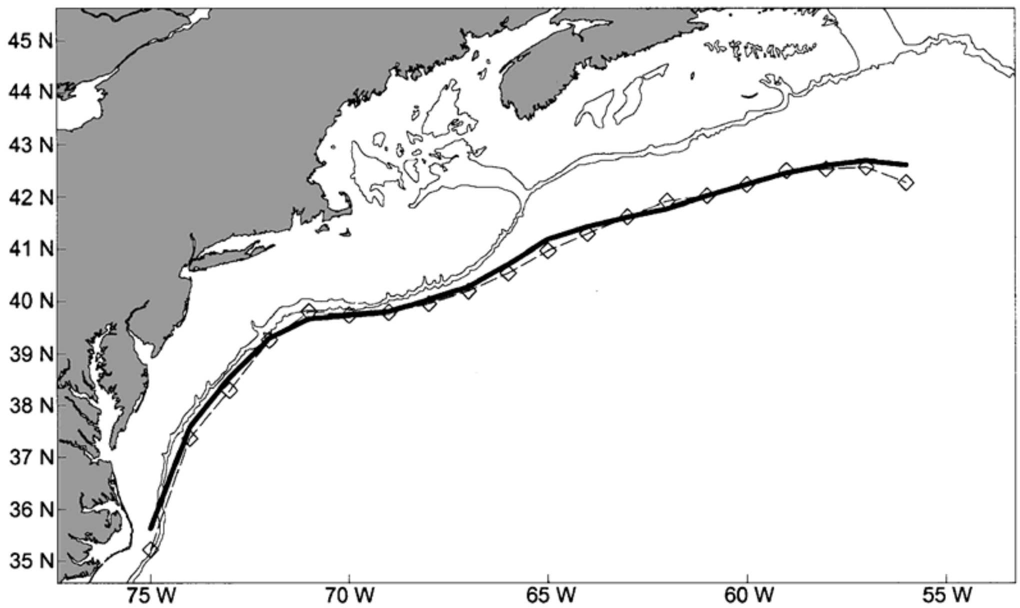


Fig. 18. The time series of the monthly means and a 12 month running mean of the sea level elevations at Halifax, along with the observed linear trend and that predicted by a model from post-glacial rebound.



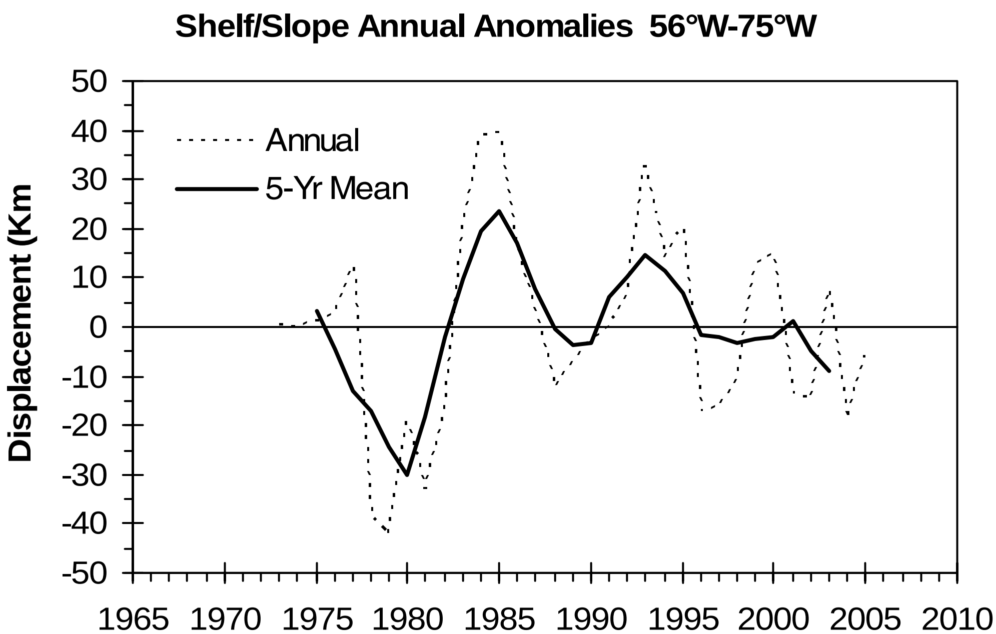
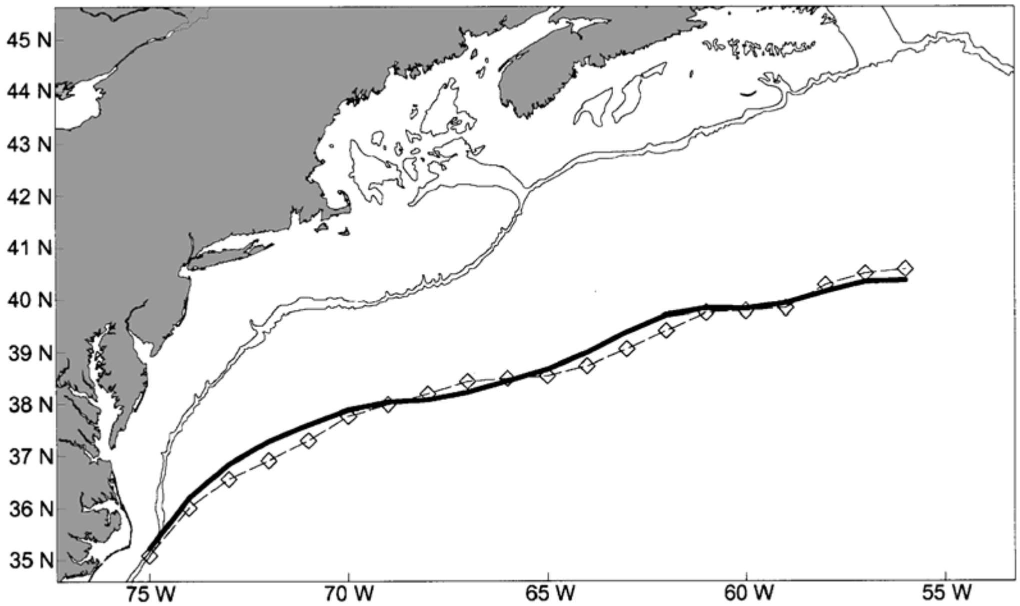


Fig. 19. The 2005 (dashed line) and long-term mean (1973-2000; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).



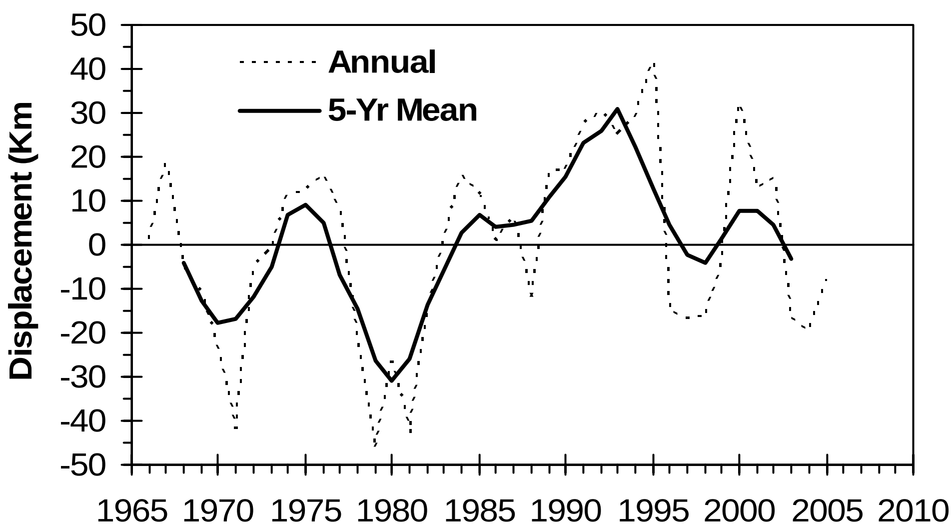


Fig. 20. The 2005 (dashed line) and long-term mean (1973-2000; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).

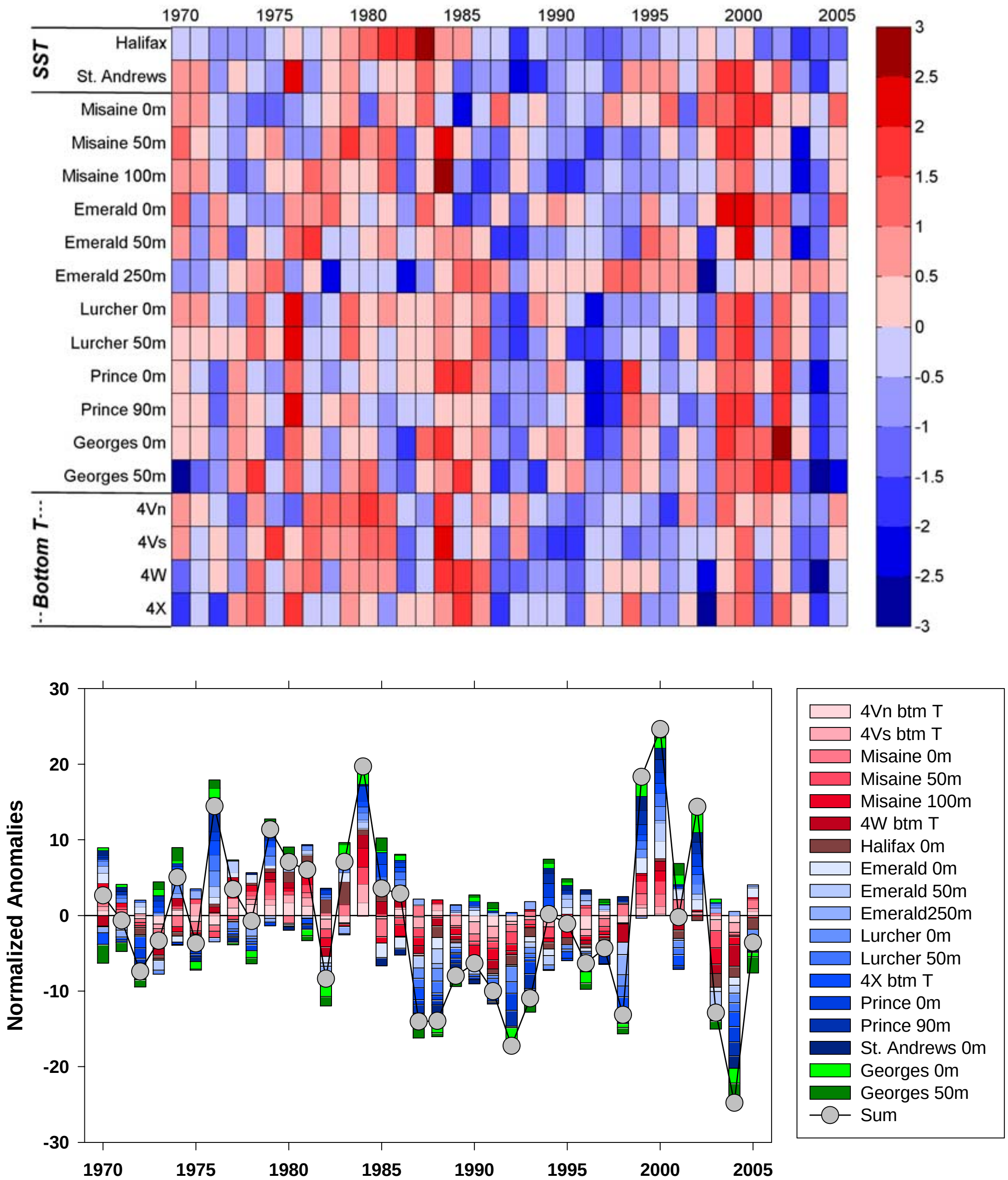


Fig. 21. Normalized annual anomalies of bottom temperatures and temperatures at discrete depths for the Scotian Shelf-Gulf of Maine region (upper panel). The normalized anomalies are the annual anomalies based on the 1971-2000 means, divided by the standard deviation. The scale represents the number of standard deviations an anomaly is from normal; blue indicates below normal, red above normal. The contributions of each of the normalized anomalies are shown as a bar chart and their summation as a time series (grey circles, black line; lower panel).