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Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2006

Conditions océanographiques physiques sur le plateau néo-écossais et dans le golfe du Maine en 2006

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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 2006 indicates that the temperatures were generally ~1^{o}C above normal. This contrasts with 2005 when cooler conditions prevailed. St. Andrews sea surface temperature was 1.31^{o}C above normal making 2006 the warmest in 86 years. At Prince 5, which is 90 m deep, monthly mean temperatures were generally above normal by about 1.1 to 1.3^{o}C. The annual temperatures at 0 and 90 m were the second warmest and warmest in 82 years. Salinities anomalies were -0.02 (0 m) and 0.14 (90 m). Halifax sea surface temperature was 0.3^{o}C above normal, making 2006 the 17th warmest in 81 years. At Halifax Station 2 from 0 to 140 m, temperature anomalies were generally 1^{o}C above normal; salinity anomalies were near normal. Sydney Bight and Misaine Bank had typical temperature anomalies of 1.3 and 0.7^{o}C in the upper 100 m; Emerald Basin, 0.8^{o}C from 0-250 m, Lurcher Shoals, 1.4^{o}C from 0-50 m, Georges Basin, 0.6^{o}C from 0-300 m, and eastern Georges Bank, 0.1^{o}C from 0-50 m all showed positive anomalies at most depths. Observations from standard sections in April and October on the Scotian Shelf support the overall conclusion of generally above normal temperatures over the shelf. Cabot Strait deep-water (200-300 m) temperatures were near normal. The overall temperature for the combined areas of 4Vn,s, 4W and 4X from the July groundfish survey was 0.74^{o}C, an increase of 2.1^{o}C from the record cold values in 2004 and the third warmest year in 37. The overall stratification was above normal for the Scotian Shelf region in 2006. The Shelf/Slope front and the Gulf Stream were about 8 km south and 6 km north of their mean positions. A composite index for the region indicates that 2006 was the warmest of the past 37 years.

RÉSUMÉ

L'examen des conditions océanographiques physiques en 2006 sur le plateau néo-écossais, dans le golfe du Maine et dans les secteurs hauturiers adjacents montre que les températures étaient en général de ~1°C au dessus des normales, ce qui est bien différent de 2005, alors que les températures étaient plus froides. La température de surface de la mer à St. Andrews a été de 1,31 °C supérieure à la normale, ce qui fait de 2006 l'année la plus chaude en 86 ans. À la station Prince 5, qui atteint 90 m de profondeur, les températures mensuelles moyennes ont généralement été de 1,1 à 1,3 °C supérieures à la normale. Les températures annuelles à 0 et à 90 m ont été respectivement la deuxième plus chaude et la plus chaude en 82 ans. Les anomalies de salinité étaient de -0,02 (0 m) et de 0,14 (90 m). À la station Halifax, la température de surface de la mer était de 0,3 °C au dessus de la normale, faisant de 2006 la 17e plus chaude en 81 ans. À la station Halifax 2, les anomalies de température des profondeurs 0 à 140 m étaient généralement supérieures à la normale de 1 °C, tandis que les anomalies de salinité étaient près des normales. Le Sydney Bight et le banc de Misaine ont présenté des anomalies de température types de 1,3 et de 0,7 °C dans la couche de 0 à 100 m de profondeur; le basin d'Émeraude, de 0,8 °C entre 0 et 250 m, les hauts-fonds Lurcher, de 1,4 °C entre 0 et 50 m, le bassin Georges, de 0,6 °C entre 0 et 300 m et l'est du banc Georges, de 0,1 °C entre 0 et 50 m. Tous affichaient des anomalies positives à la plupart les profondeurs. Des profils standard établis en avril et en octobre sur le plateau néo-écossais appuient la conclusion générale selon laquelle les températures ont été généralement supérieures à la normale sur le plateau. Les températures de l'eau profonde (200-300 m) du détroit de Cabot ont été près de la normale. La température globale pour les divisions combinées 4Vn,s, 4W et 4X selon le relevé des poissons de fond de juillet étaient de 0,74 °C, soit une hausse de 2,1 °C par rapport à la température froide record de 2004, faisant de 2006 la troisième année la plus chaude en 37 ans. La stratification générale était supérieure à la normale dans la région du plateau néo-écossais en 2006. Le front plateau-talus et le Gulf Stream se trouvaient à environ 8 km au sud et à 6 km au nord de leur position moyenne. Un indice agrégatif pour la région montre que 2006 était la plus chaude des 37 dernières années.

Introduction

This paper describes temperature and salinity characteristics of Scotian Shelf and Gulf of Maine waters during 2006 (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[1], which is updated monthly from the national archive at the Marine Environmental Data Service (MEDS) in Ottawa. Our analyses use data updated to 22 January 2007; only data up to the end of 2006 are discussed. Additional hydrographic data were obtained directly from DFO fisheries surveys. 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. In some cases, we use the standardized anomaly (anomaly/standard deviation). 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 (SST) information for eastern Canada during 2006 are described in Petrie et al. (2007). The monthly air temperature anomalies for the Scotian Shelf were consistently above normal during 2006 with an annual value of 1.41^{o}C for Sable Island and 1.81^{o}C for Shearwater (Halifax); the monthly values were variable in the Gulf of Maine with annual anomalies of 1.09^{o}C for Yarmouth, 1.62^{o}C for Saint John and 0.81^{o}C for Boston. Annually averaged SSTs were above normal for the eastern and central Scotian Shelf by 1.2^{o}C to 1.6^{o}C, the western Scotian Shelf to Bay of Fundy by 0.4 to 1.1^{o}C and Georges Bank by only 0.1^{o}C. Ice cover for the Scotian Shelf was substantially below normal in 2006, in fact it was the 3rd lowest ice cover for the Jan-April period in 38 years.

Coastal Sea Surface Temperatures

Monthly averages of coastal sea surface temperature (SST) for 2006 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 2005 and 2006 are shown in Fig. 2.

At St. Andrews, all months featured positive anomalies with the largest anomaly (relative to the monthly standard deviations) in February, 2.6 standard deviations above normal. The 2006 annual anomaly was 1.31^{o}C, the warmest in 86 years. The monthly anomalies at Halifax were a mixture of positive and negative

[1] http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html

values with an overall annual mean of 0.3°C (0.66 SD), making 2006 the 17th warmest in 81 years.

The time series of annual anomalies have changed remarkably at both sites since 2004: the annual average surface temperature at St. Andrews has increased by 2.1°C, while at Halifax temperatures warmed by 1.3°C.

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 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 features are likely 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 2006, monthly mean temperatures ranged from a minimum in March of 3.4°C at the surface to a maximum in October of 12.4°C (Fig. 3, 4). Monthly temperature anomalies were positive throughout the mid-year especially at the start and end. The monthly anomalies followed a similar pattern at 90 m but with weak negative values in August and September. The annual mean temperatures have high interannual variability with evidence of strong long-term trends at the surface and 90 m (Fig. 4). In 2006, the annual temperature anomalies at 0 and 90 m were about 1.07°C and 1.21°C. At 0 m, 2006 was the 2nd warmest in the 82 year record, surpassed only by 1951; at 90 m, it was the warmest in 82 years. Note that an October value is missing at 90 m and the annual anomaly at this depth was based on the average of 11 monthly anomalies. Using the other months in 2006 at 0 and 90 m to estimate the missing value gives an even higher annual anomaly at 90 m.

The salinity at Prince 5 had a broad minimum in the spring at the surface (~30.6 in June) and at 90 m (31.97 in June; Fig. 3, 5). The salinity anomalies were variable through most of 2006 and had typical amplitudes of 0.2. The annual salinity anomalies were slightly negative from 0-70 m but became positive near the bottom;

the anomaly was -0.02 at the surface and 0.14 at 90 m. These values represent an increase of the average annual salinity by 0.3-0.4 since 2004. The density (sigma-t) variability was strongly linked to temperature. Density was below normal at all depths though the anomaly near the bottom was very small.

Halifax Line Station 2

As part of the Atlantic Zone 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 19 occupations of H2 in 2006 3 more than in 2005, the year with the fewest samples since the AZMP program started.

Surface temperatures at H2 ranged from 0.3°C in March to 18.4°C in July and August 2006 (Fig. 6). Near-bottom (140 m) temperatures were between 4.25°C and 9.46°C throughout the year with an average value of 7.3°C, a higher range of values than observed in 2005. Relative to the long-term means, annual average temperatures were above normal at all depths by 0.3°C to 1°C. The Cold Intermediate Layer (CIL), which was thicker than usual at H2 in 2005 (Petrie et al. 2006), was not as extensive in 2006, forming an ~60 m layer during the late spring to fall period. The CIL typically has a temperature range from about 1°C to 6°C depending on the time of the year.

Salinity anomalies were small in 2006 with a mixture of above and below normal values in the upper 100 m through the year and generally above normal values from 100 m to the bottom. The largest annual anomaly was about 0.25 at 150 m.

In the surface layers, stratification began to develop in June increasing in intensity through to August-September. During autumn, the warmer and fresher surface layer was gradually mixed down to ~35 m, before sampling ended. Density anomaly variations alternated between negative and position values from the surface to the bottom.

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 2006 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 2006 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°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 the mid-1980s to 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 2006 (Fig. 8) and as time series plots for a selected depth in each region (Fig. 9).

The majority of monthly profiles for the six areas had positive temperature anomalies during 2006. This was particularly so for the Scotian Shelf sites. In Sydney Bight (area 1, Fig. 7) off eastern Cape Breton, the annual profile had above normal temperature anomalies from 0.3°C to 2.1°C (Fig. 8). Misaine Bank annual temperature anomalies were in the range of 0.1°C to 1.3°C. With profiles in all months, Emerald Basin annual values were from 0.4°C to 1.7°C; anomalies were generally higher at shallow depths and decreased towards bottom. Lurcher Shoals had above normal temperatures from 0.8°C to 1.8°C. The Georges Basin annual anomaly profile featured a mid-depth maximum and an overall range of -0.1 at the surface, the only depth with a negative value, to 1.0°C. Georges Bank anomalies also had negative values and small anomalies ranging from -0.1°C to 0.4°C.

Figure 9 shows the time series of temperature anomalies for one depth from each of the 6 regions. There has been a remarkable change since 2004, a year with generally colder than normal conditions and having the lowest composite index for the region since 1970. For five of the six time series, the annual temperature anomalies have increased since 2004. The 100 m depth temperature anomalies for Sydney Bight and Misaine Bank have risen by about 1.25°C (difference of 2006 minus 2004). The Emerald Basin 250 m record reflects the influence of slope water on the Scotian Shelf and was the only exception to the overall trend – between 2004 and 2006 the 250 m temperature fell by 0.1°C. Lurcher Shoals temperature anomalies (50 m) increased by 2.2°C, the largest change of the six sites. The temperature change was more modest, 0.34°C in Georges Basin. Even though the annual anomaly was slightly negative on eastern Georges Bank in 2006, it represented an increase of nearly 1.5°C from its 2004 value.

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 213 CTD stations were taken during the 2006 survey and an additional 86 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 analysis. Thus the warmest area often ends up in Sydney Bight. On the other hand, the 1971-2000 July 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 2006 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 2006 featured the warmest waters in Sydney Bight (18°C) that extended, with slightly decreasing values, over the eastern half of the Shelf to Halifax; the coldest temperatures (11-13°C) were found near the mouth of the Bay of Fundy, and represent an increase of about 2°C from 2005 (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 2006 were dominated by warmer than normal values over the entire survey area (Fig. 11a).

The temperatures at 50 m ranged from 2°C to over 10°C with the coldest waters in the northeast and the warmest waters off Browns Bank and in the Gulf of Maine and Bay of Fundy (Fig. 10a). The lower temperatures over the inner half of the shelf mark the CIL, similar to the one seen in 2005 but not as extensive. 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. Similar to the near-surface temperatures, the 50 m anomalies were predominantly positive, ranging from 0°C to >3°C above normal (Fig. 11b). The largest anomalies (~2-3°C) occurred over the central Shelf and Browns Bank.

The temperatures at 100 m ranged from <2°C on the northeastern Scotian Shelf to 10°C along the shelf break (Fig. 10b). The warmer waters encroach onto the shelf with strong NE-SW horizontal gradients evident on the eastern Shelf. The temperatures are elevated as well in the eastern Gulf of Maine. This pattern contrasts to the one from the 2005 survey which featured strong temperature gradients along the shelf break rather than across the shelf. The 2006 anomaly pattern at 100 m, like the two shallower depths, was dominated by positive values.

Near-bottom temperatures ranged from ~3°C on Misaine Bank in the northeastern Scotian Shelf to ~9°C in Emerald Basin and 10°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 with a small patch of slightly colder than normal water off southwestern Nova Scotia (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 bottom temperatures in all 4 NAFO divisions in 2006 compared to 2005. This is seen in the diagrams as a downward slope of the lines defining the areas in each temperature range. A downward slope means that the areas corresponding to lower temperatures are decreasing. In 4Vn, most of the bottom is covered by waters <6°C and about 39% is <5°C, down from 54% in 2005. For 4Vs, 65% is <5°C, again down from 74% in 2005 (Fig. 12a). In 4W, 28% and in 4X, 8% of the bottom is covered by temperatures <6°C, reduced from 41% and 21% in 2005 (Fig. 12b). In all 4 regions, bottom waters were substantially warmer in 2006 than in 2005, and substantially reduced from 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 2006 featured average bottom temperatures that were well above the 1971-2000 norms. Areas 4Vn and 4Vs were 0.64°C (1.3 standard deviations) and 0.58°C (0.8 SD) above normal and the 5th and 8th warmest in 37 years. Areas 4W and 4X were 0.84 (1.3 SD) and 0.78°C (1.1 SD) above normal, in both cases the 4th warmest in 37 years. Combining the 4 NAFO areas (accounting for the different area sizes), we find an overall bottom temperature anomaly of 0.74°C (1.37 SD), the 3rd warmest year in 37. In 2004, the overall bottom temperature anomaly was -1.35°C (-2.5 SD), the coldest year from 1970 to present.

Standard Sections

The hydrographic observations from the Cabot Strait, Louisbourg, Halifax and Browns Bank lines (Fig. 1) from the spring and fall are shown in Fig. 14a-e. 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 3-6°C across the Browns Bank and the Halifax sections to the shelf break (Fig. 14a). Temperature anomalies were mostly positive on all 4 sections with the larger values over the slope on the Halifax and Browns Bank sections. Salinities anomalies were divided more evenly between positive and negative values with the highest values over the slope on the Halifax section and evidence of spillover into Emerald Basin (Fig. 14b).

In June a repeat occupation of the Halifax section shows that changes have occurred (Fig. 14c). The major difference is found over the shelf break and slope in the form of strong negative temperature and salinity anomalies in the upper 100 m. Shelf waters, marked by the 33 isohaline, have moved offshore from their position in the May survey.

In October, except for the outer shelf, slope area on the Halifax section, the temperature anomalies were generally positive (Fig. 14d). In particular, the Browns Bank section featured a large area with temperatures 2-3°C above normal. 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 CIL on the Halifax section was confined to the inner 2 stations; over the shelf break there was a large area of low temperature, low salinity water characteristic of Gulf of St. Lawrence outflow (Fig. 14d, e). Except for the outer shelf, shelf break and slope on the Halifax section, the salinities tended to be above normal.

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 a range of about 2.5^{o}C, 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 ~7 years. More recent work by Gilbert (2004) agrees qulitatively with that of Bugden (1991) but with a shorter propagation time of about 3-4 years along the Laurentian Channel. In 2006, the temperature was 0.09^{o}C above the long-term mean, nearly the same as in 2005 (Fig. 15).

Density Stratification

Stratification of the near surface layer influences physical and biological processes in the ocean. 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 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-year 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 are highly variable but the 5-yr running means feature some distinctive trends. The units of the density gradient anomalies are 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 weak stratification in the 1960s and the stronger stratification during the 1990s throughout the Scotian Shelf (Fig. 16a, b). In 2006, there was considerable spatial variability of the stratification index in the region: stronger stratification was generally found on the eastern and western shelf, weaker stratification in the central region and Lurcher Shoal area. The average stratification parameter for areas 4-23 was above normal in 2006 (Fig. 17) and slightly higher than in 2005.

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 is measured with respect to a fixed reference point om land. Consequently, relative sea level consists of two major components: one due to true changes of sea level and a second caused by any motion of the land such as sinking or rising. In Atlantic Canada, the area roughly south (north) of the north shore of the Gulf of St. Lawrence is sinking (rising) in response to glacial retreat; this gives rise to an apparent rise (fall) of sea level. Relative sea level at Halifax (1990-2006) 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 (1990-2006) has a positive slope of 31.6 (±8.1) 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 1990-2006 by only ~9 cm/century. In 2006 relative sea level was about 0.7 cm higher than in 2005.

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 charts did not contain data east of 60°W but within a year were extended east to 55°W. Data for 2006 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. In 2006, it was extended again to 50W.

The overall mean position of the Shelf/Slope front and the 2006 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 2006, the shelf/slope front was slightly southward, 8.1 km, of its long-term mean position. This was mainly due to a large southward displacement south of Newfoundland. In 2006, the front moved about 2.4 km offshore from its mean position in 2005.

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 2006 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. In 2006, the Gulf Stream showed only minor deviations from its long-term mean position. Overall in 2006, it moved onshore by 14 km from its 2005 position, about 6 km north of its average location.

Summary

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2006 indicates that the temperatures were generally ~1°C above normal. This contrasts with 2005 when cooler conditions prevailed. St. Andrews sea surface temperature was 1.31°C above normal making 2006 the warmest in 86 years. At Prince 5, which is 90 m deep, monthly mean temperatures were generally above normal by about 1.1 to 1.3°C. The annual temperatures at 0 and 90 m were the second warmest and warmest in 82 years. Salinities anomalies were -0.02 (0 m) and 0.14 (90 m). Halifax sea surface temperature was 0.3°C above normal, making 2006 the 17th warmest

in 81 years. At Halifax Station 2 from 0 to 140 m, temperature anomalies were generally 1^{o}C above normal; salinity anomalies were near normal. Sydney Bight and Misaine Bank had typical temperature anomalies of 1.3 and 0.7^{o}C in the upper 100 m; Emerald Basin, 0.8^{o}C from 0-250 m, Lurcher Shoals, 1.4^{o}C from 0-50 m, Georges Basin, 0.6^{o}C from 0-300 m, and eastern Georges Bank, 0.1^{o}C from 0-50 m all showed positive anomalies at most depths. Observations from standard sections in April and October on the Scotian Shelf support the overall conclusion of generally above normal temperatures over the shelf. Cabot Strait deep-water (200-300 m) temperatures were near normal. The overall temperature for the combined areas of 4Vn,s, 4W and 4X from the July groundfish survey was 0.74^{o}C, an increase of 2.1^{o}C from the record cold values in 2004 and the third warmest year in 37. The overall stratification was above normal for the Scotian Shelf region in 2006. The Shelf/Slope front and the Gulf Stream were about 8 km south and 6 km north of their mean positions. A composite index for the region indicates that 2006 was the warmest of the past 37 years.

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 below normal. In 2006, all variables except Georges Bank 50 m temperature 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. The overall index value for 2006 make it the warmest year in the 37 year record. Moreover the change that has occurred since 2004 is striking.

This last plot is an attempt to derive an overall climate index for the area. 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 (4Vn,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°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.

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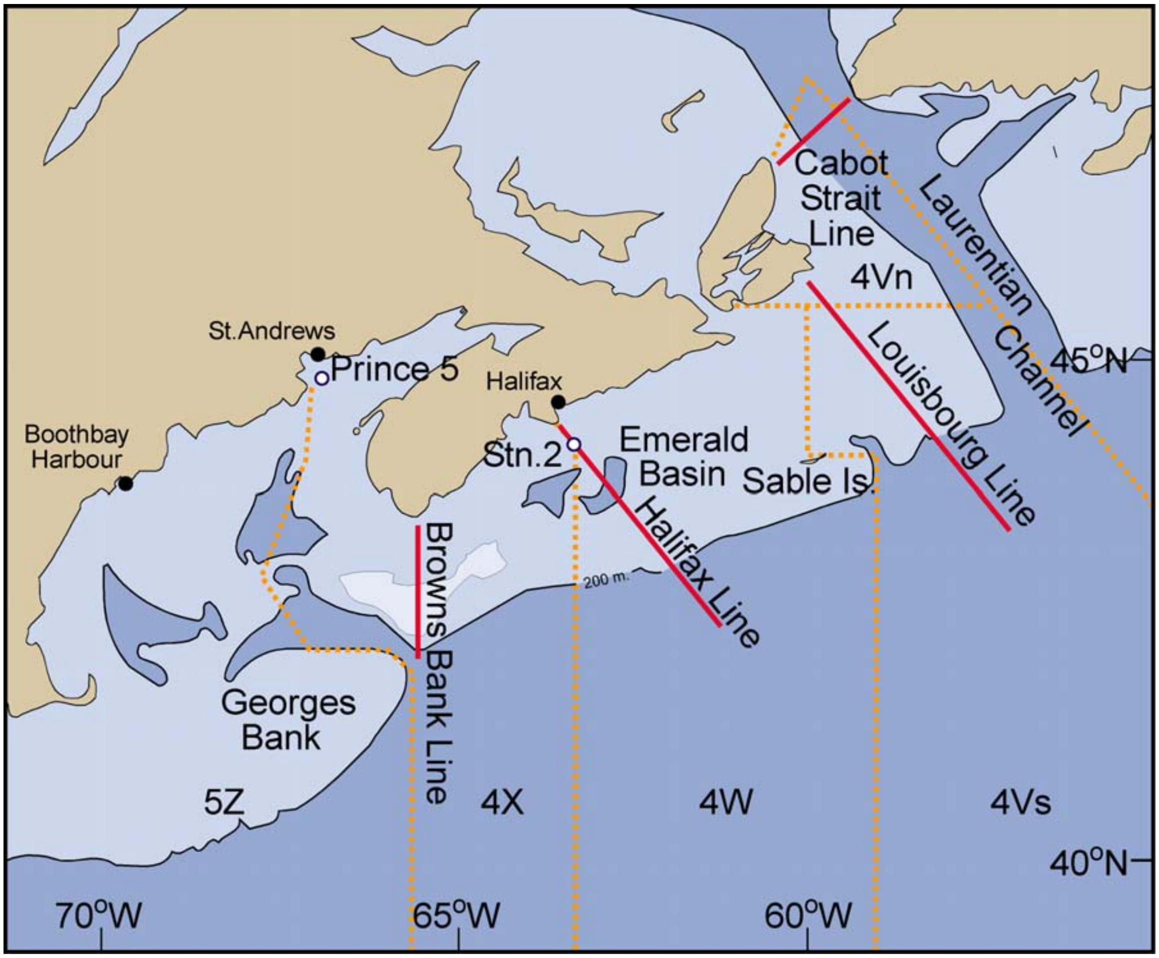


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

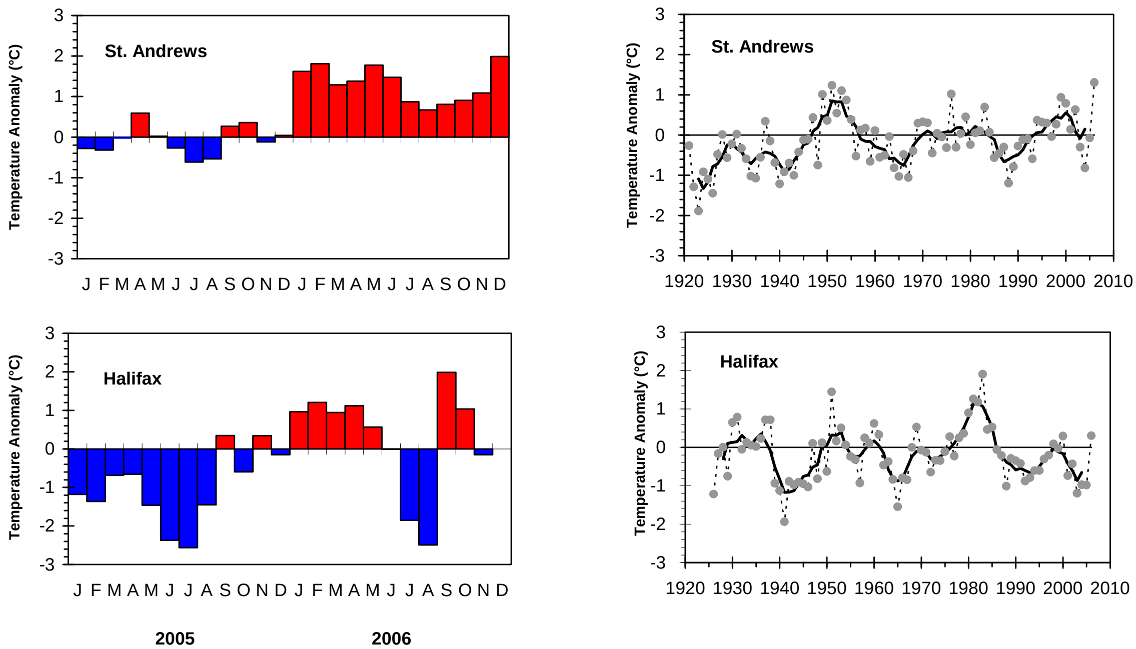


Fig. 2. The monthly sea surface temperature anomalies during 2005 and 2006 (left) and the annual temperature anomalies and their 5-year running means (right) for St. Andrews and Halifax Harbour. Anomalies are relative to the 1971-2000 means.

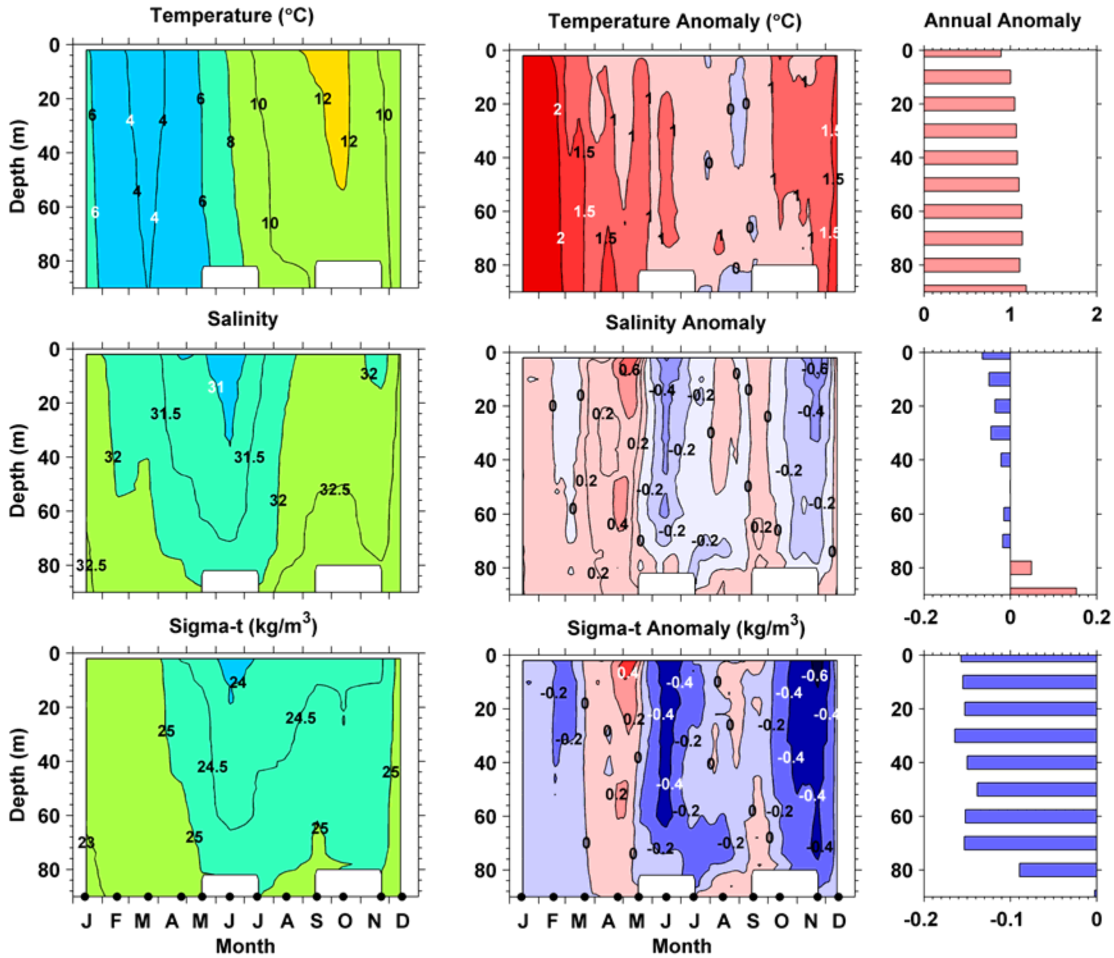


Fig. 3. Contours of temperature, salinity and sigma-t and their anomalies at Prince 5 as a function of depth during 2006 relative to the 1971-2000 means. Blue (red) indicates below (above) normal anomalies. The bar chart shows the annual anomalies.

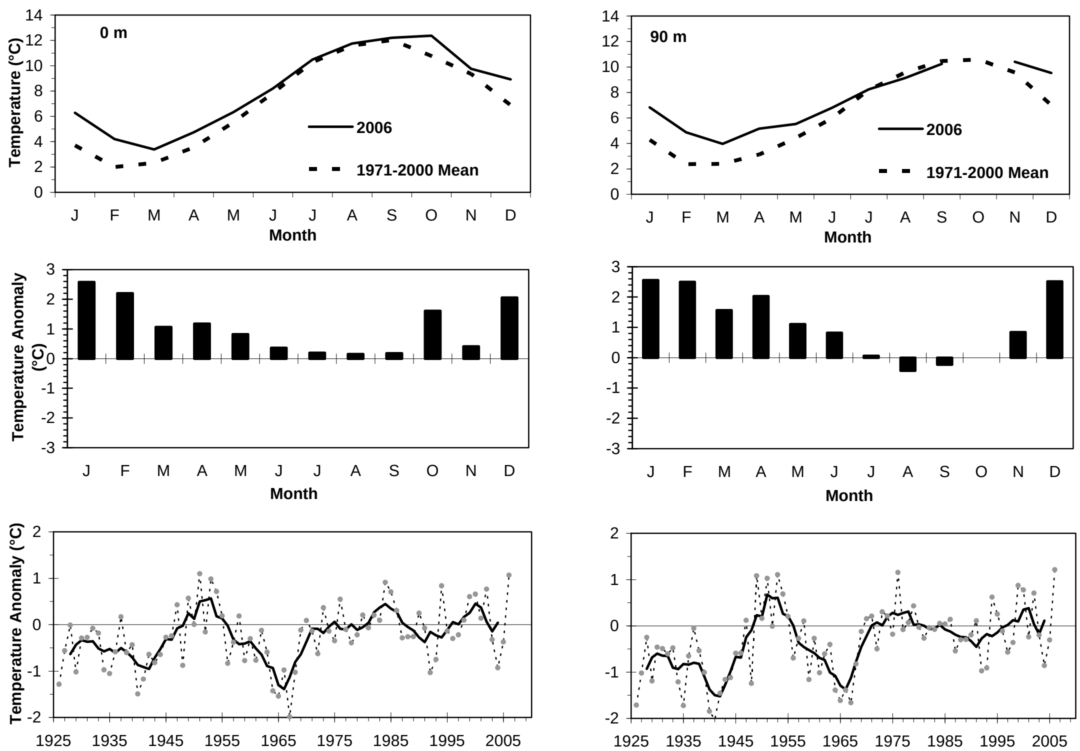


Fig. 4. The monthly mean temperatures for 2006 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

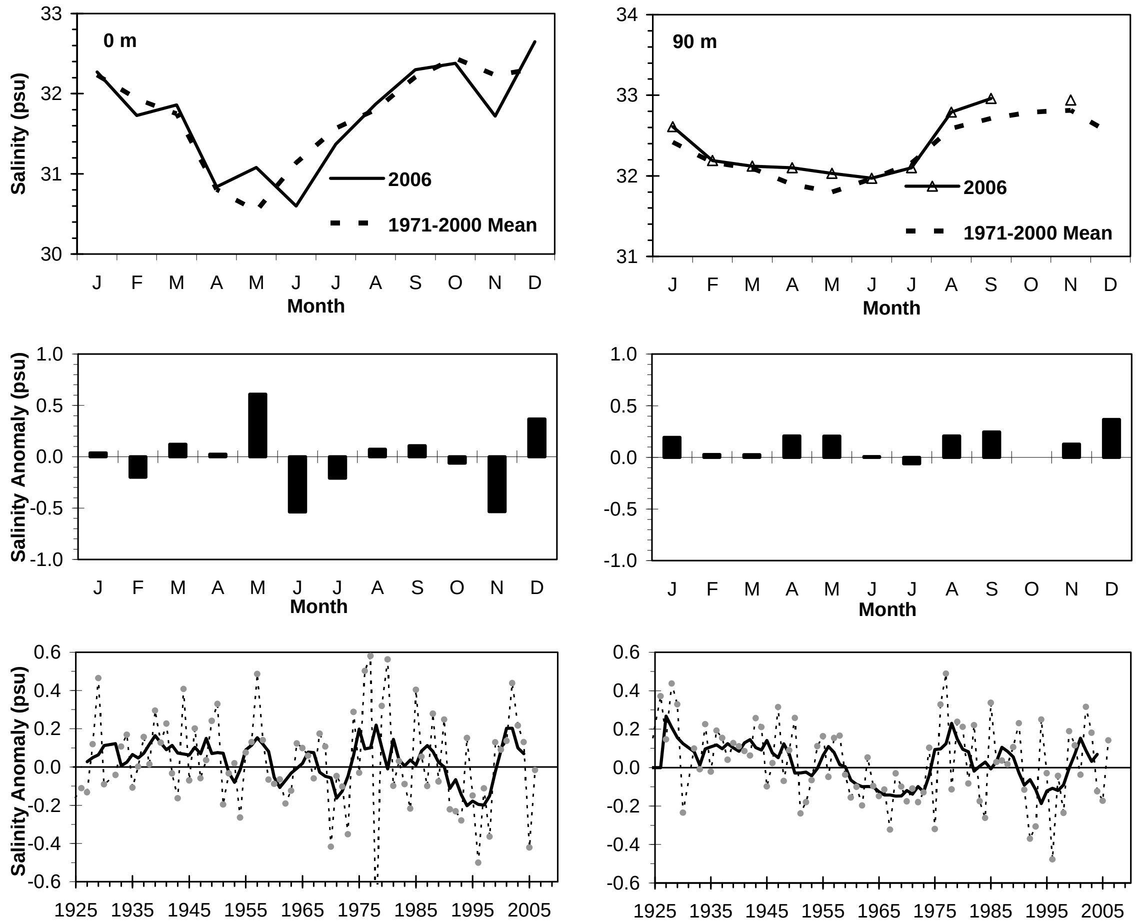


Fig. 5. The monthly mean salinities for 2006 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

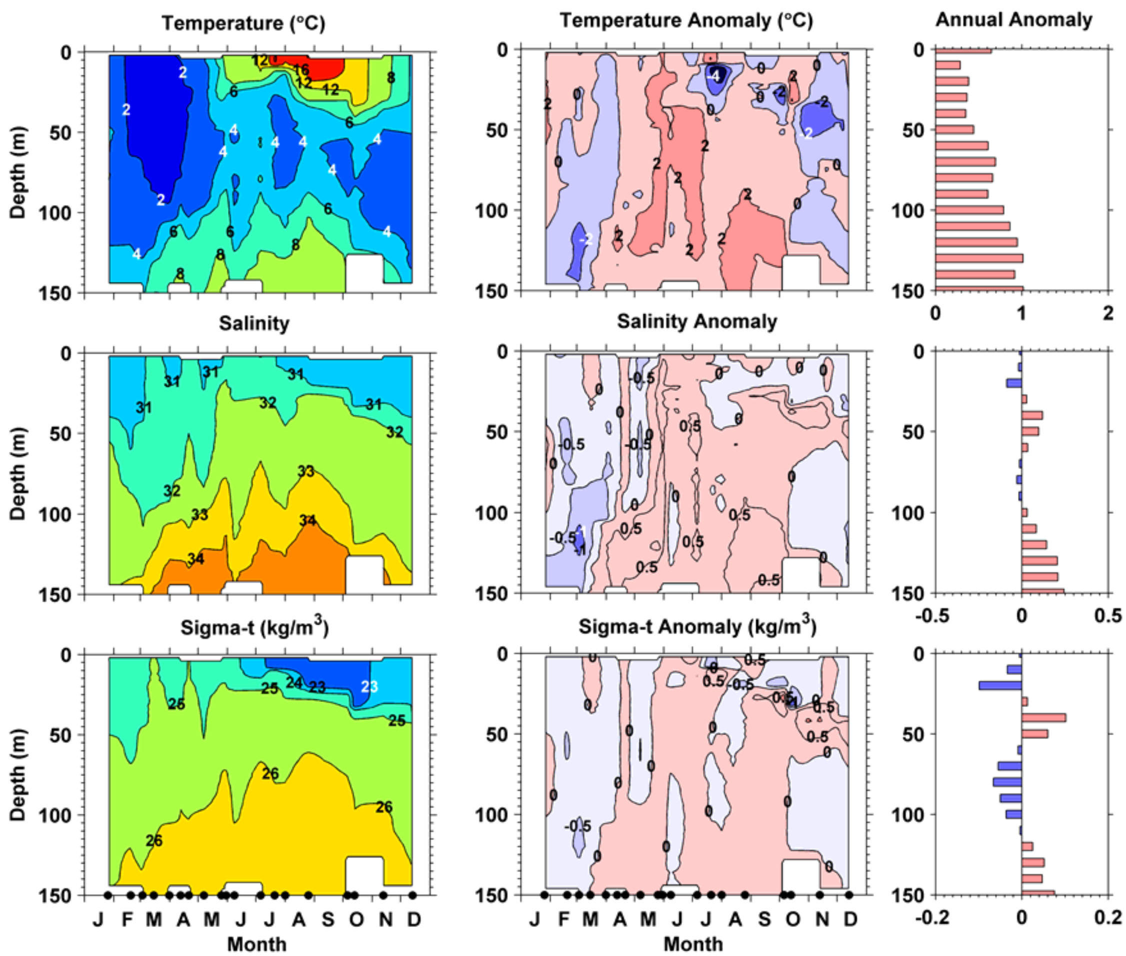


Fig. 6. Contours of the 2006 temperature, salinity and density (sigma-t) (left) and their anomalies (right) at the fixed station Halifax Section Station 2. Blue (red) indicates below (above) normal anomalies. The bar chart shows the annual anomalies.

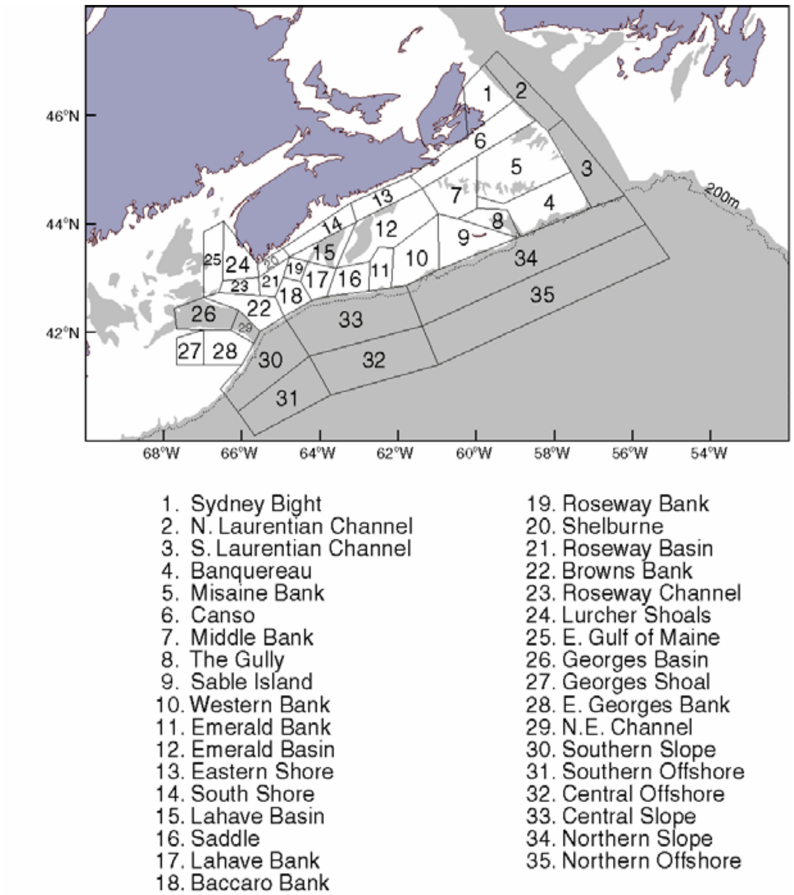


Fig. 7. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

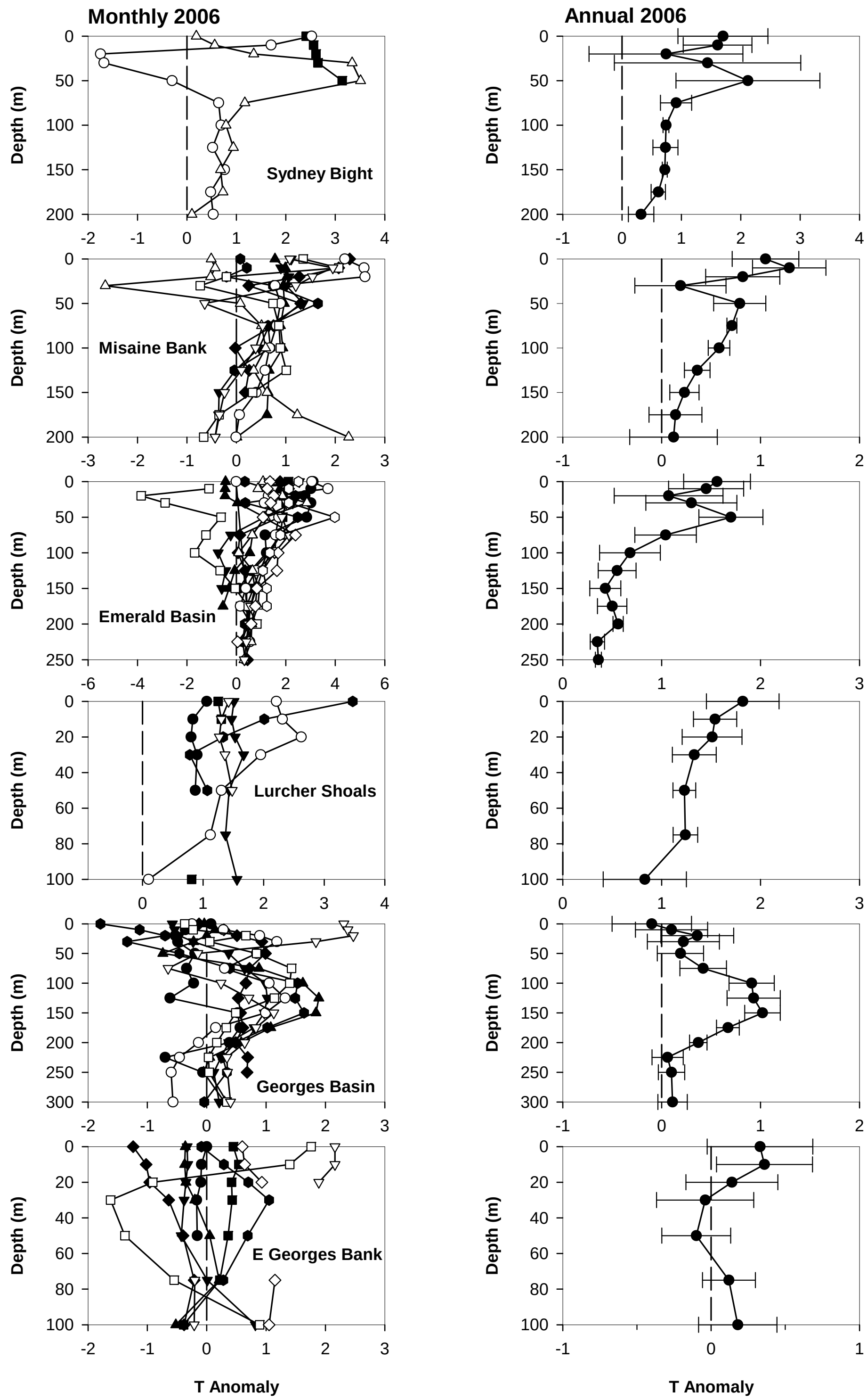


Fig. 8. Monthly (left) and annual (±std. error, right) temperature anomaly profiles for selected locations. Symbol order for monthly profiles is filled dot, square, up triangle, down triangle, diamond, hexagon for January-June,, then open symbols in the same order for July-December.

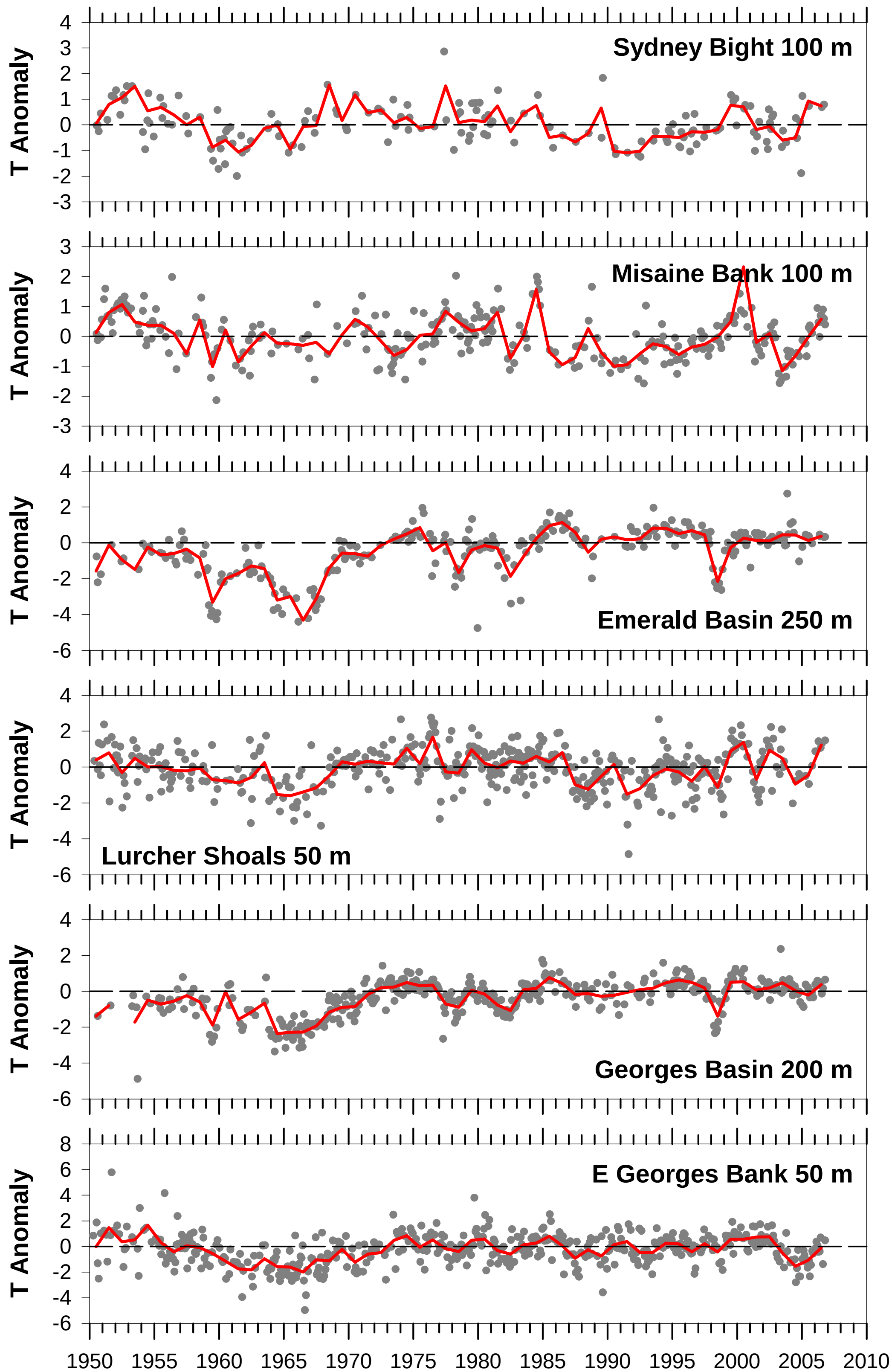


Fig. 9. The monthly mean temperature anomaly time series (grey dots) and the estimated annual anomalies (solid line) at 6 sites on the Scotian Shelf and in the Gulf of Maine (see Fig. 7).

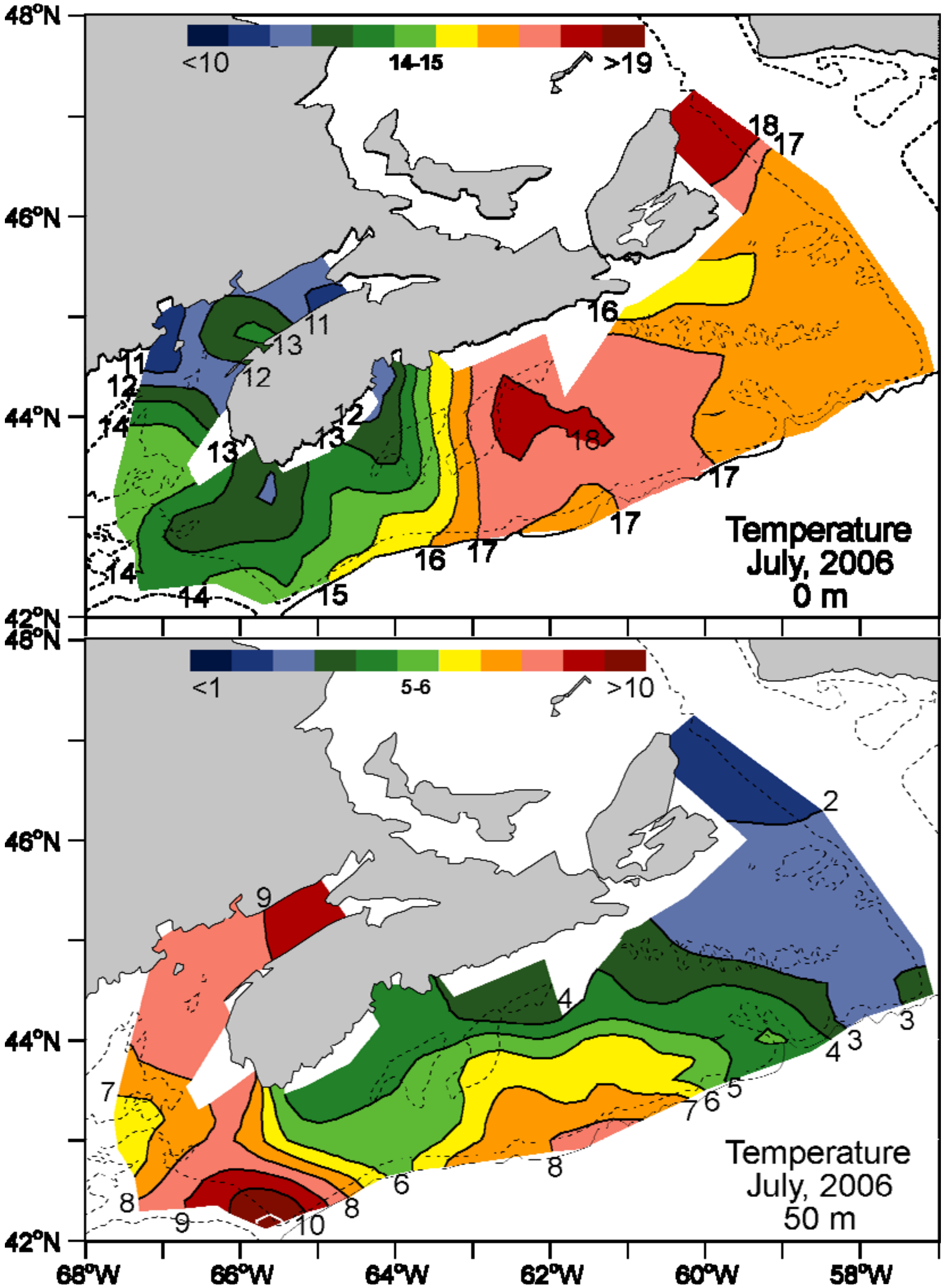


Fig.10a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2006 July groundfish and ITQ surveys.

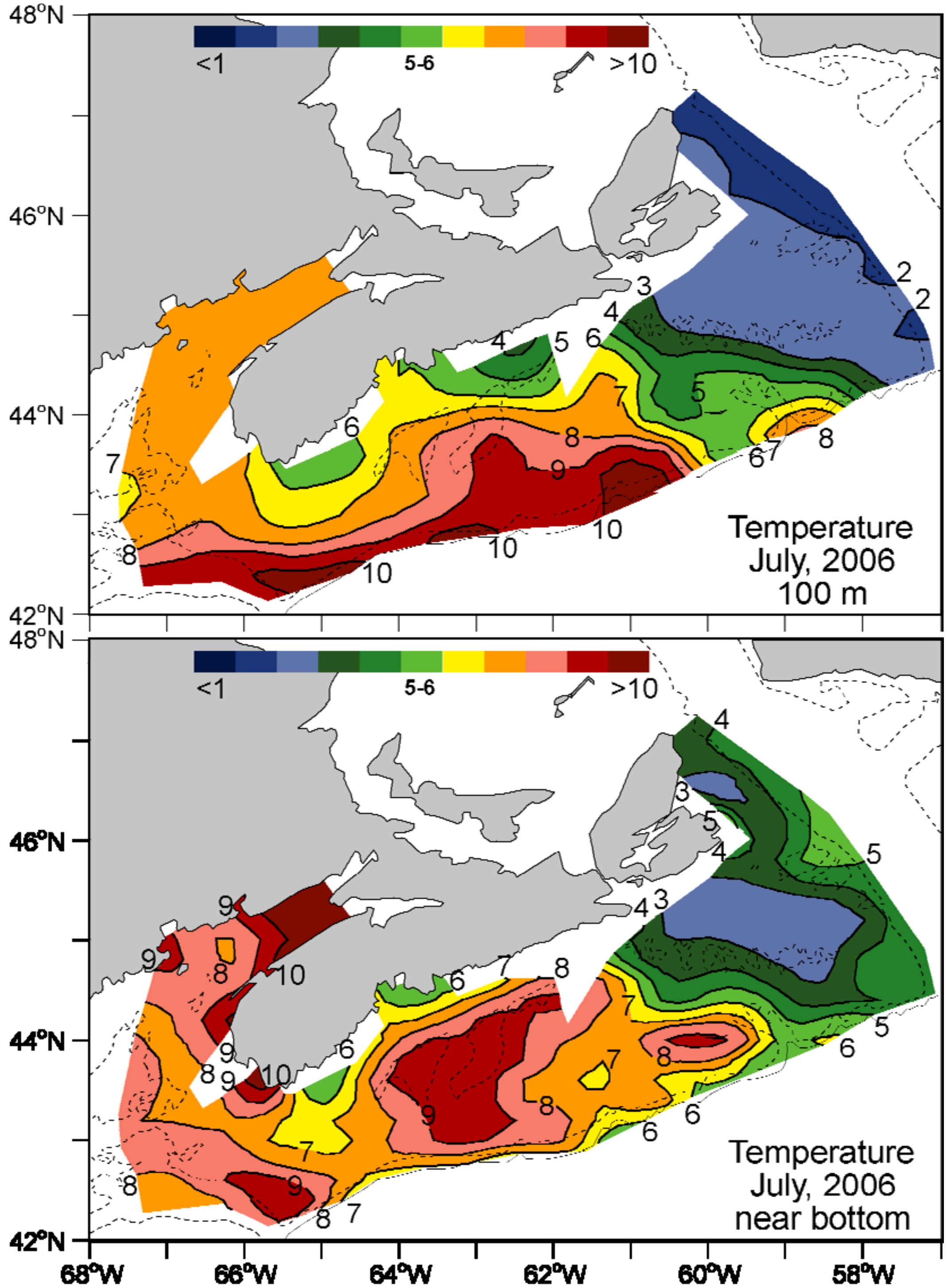


Fig. 10b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2006 July groundfish and ITQ surveys.

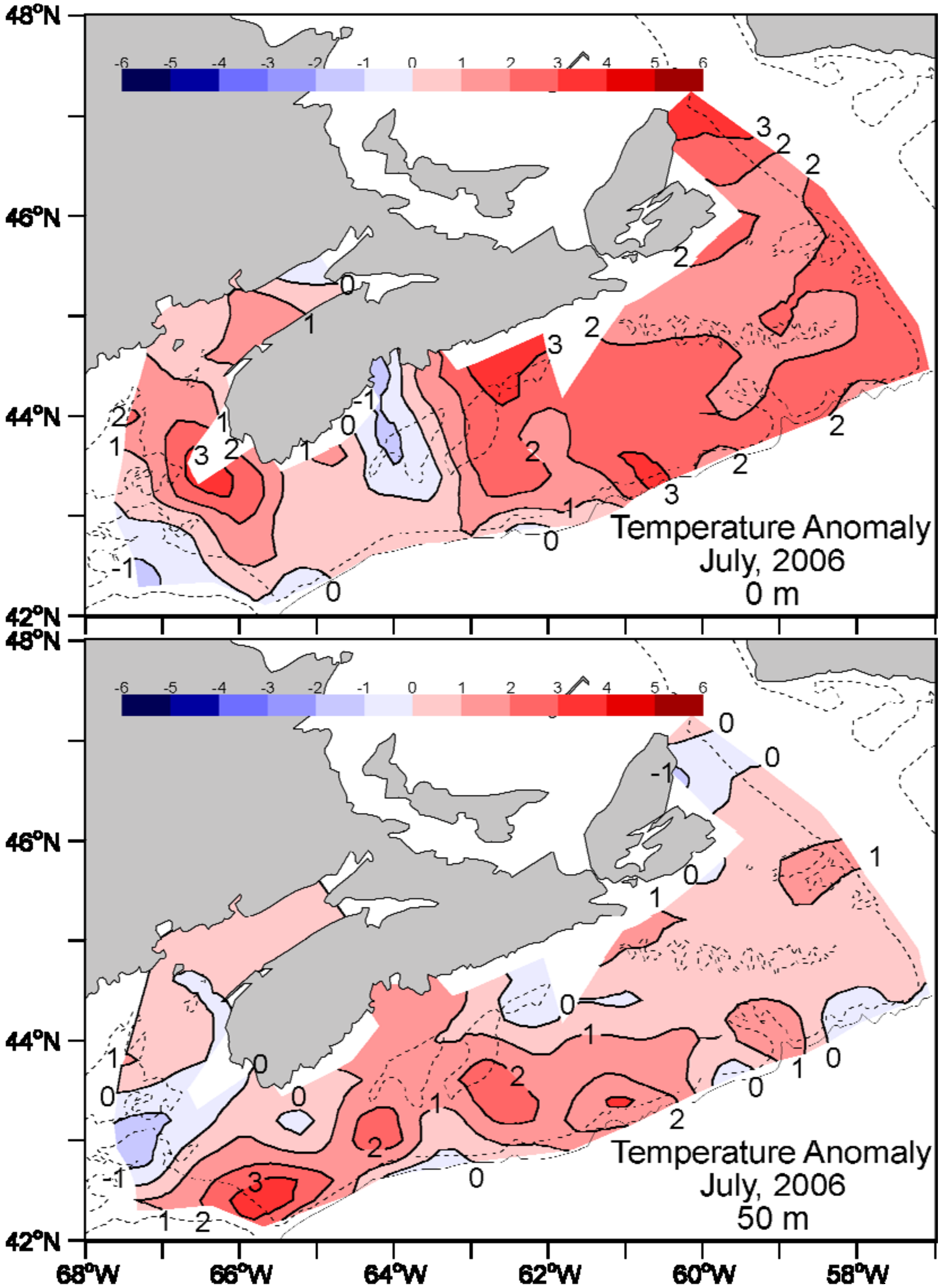


Fig. 11a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2006 July groundfish and ITQ surveys.

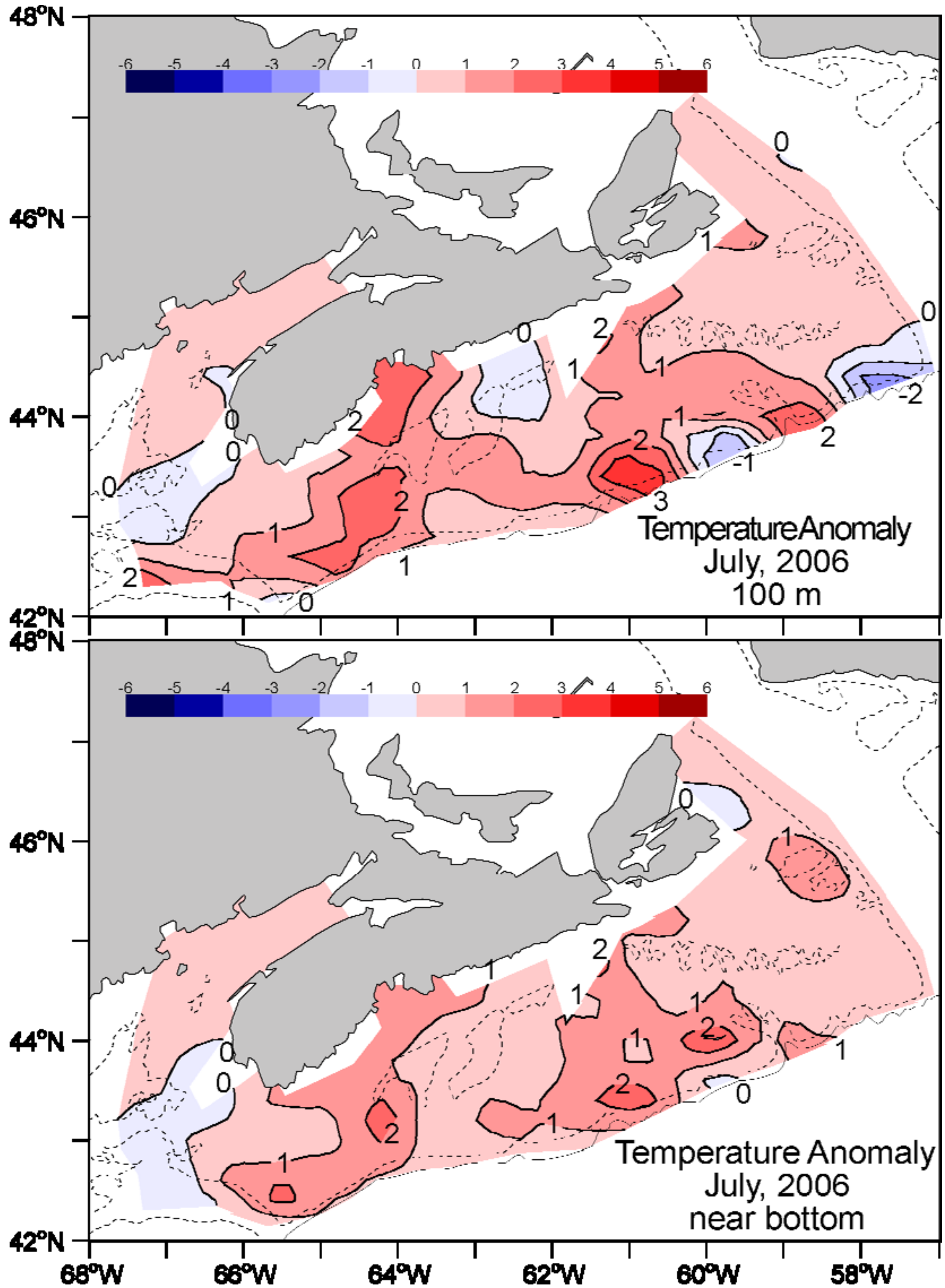
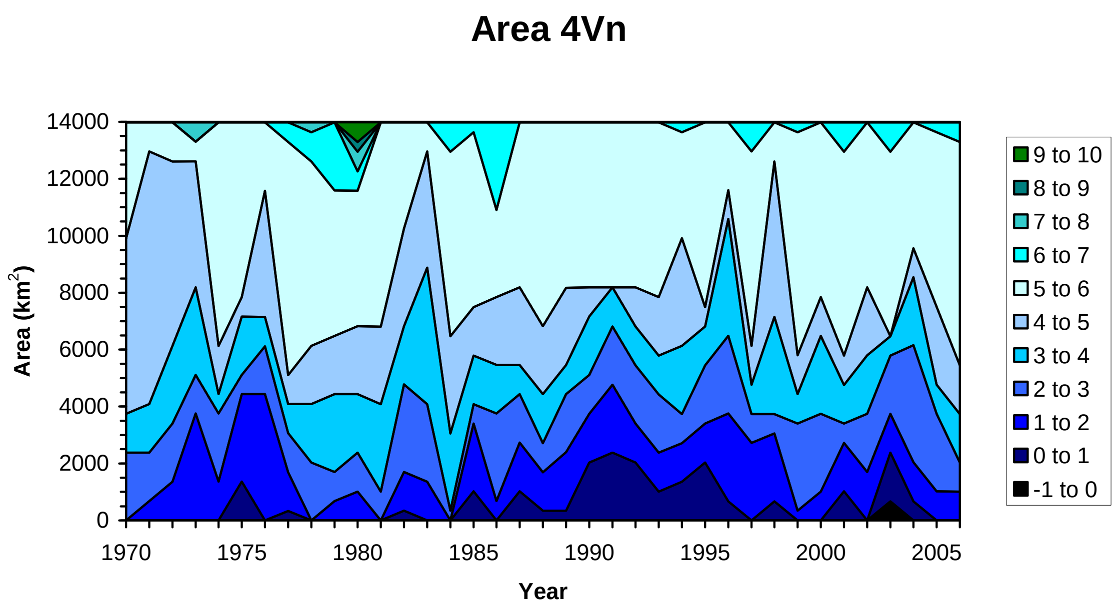


Fig. 11b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2006 July groundfish and ITQ surveys.



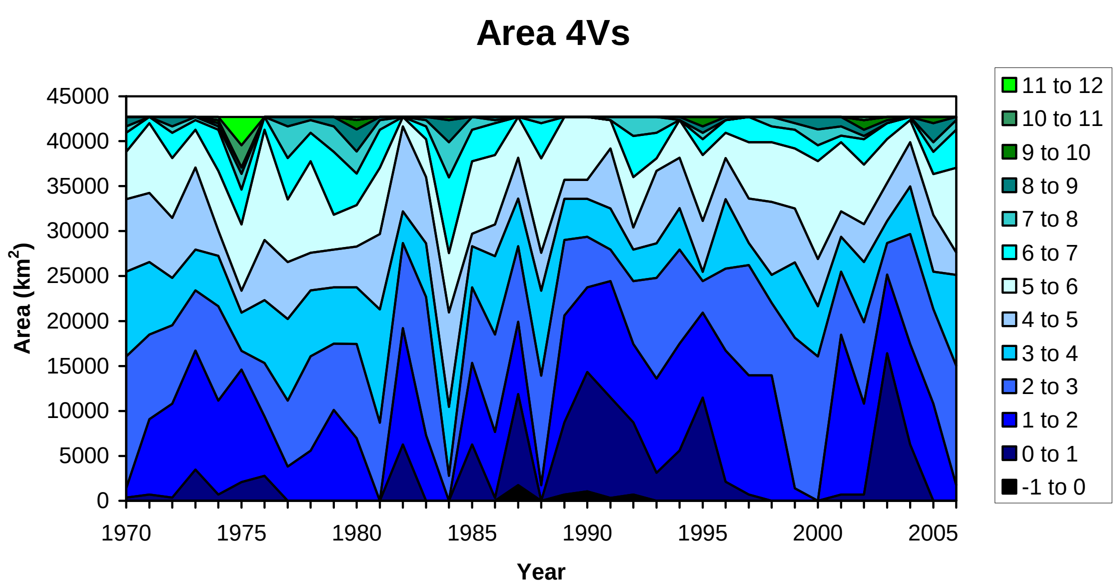
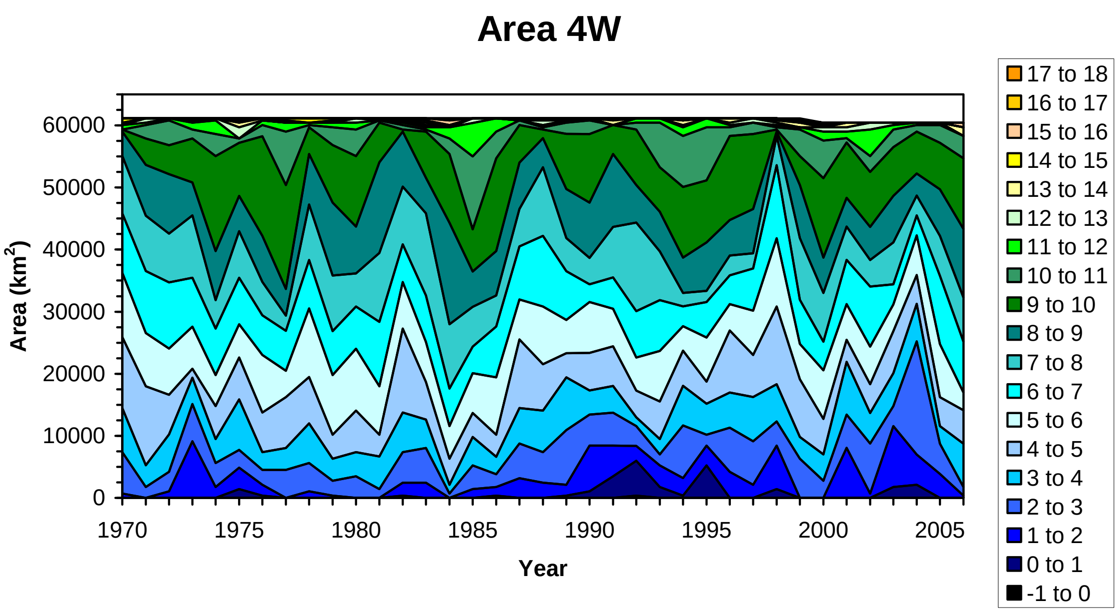


Fig. 12a. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).



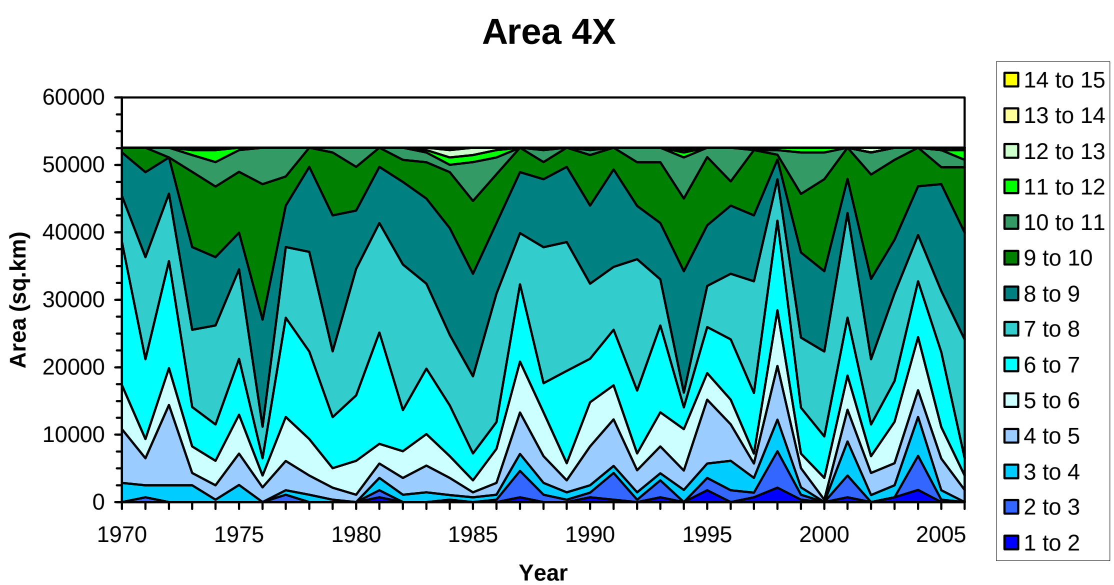


Fig. 12b. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4W (top panel) and 4X (bottom panel).

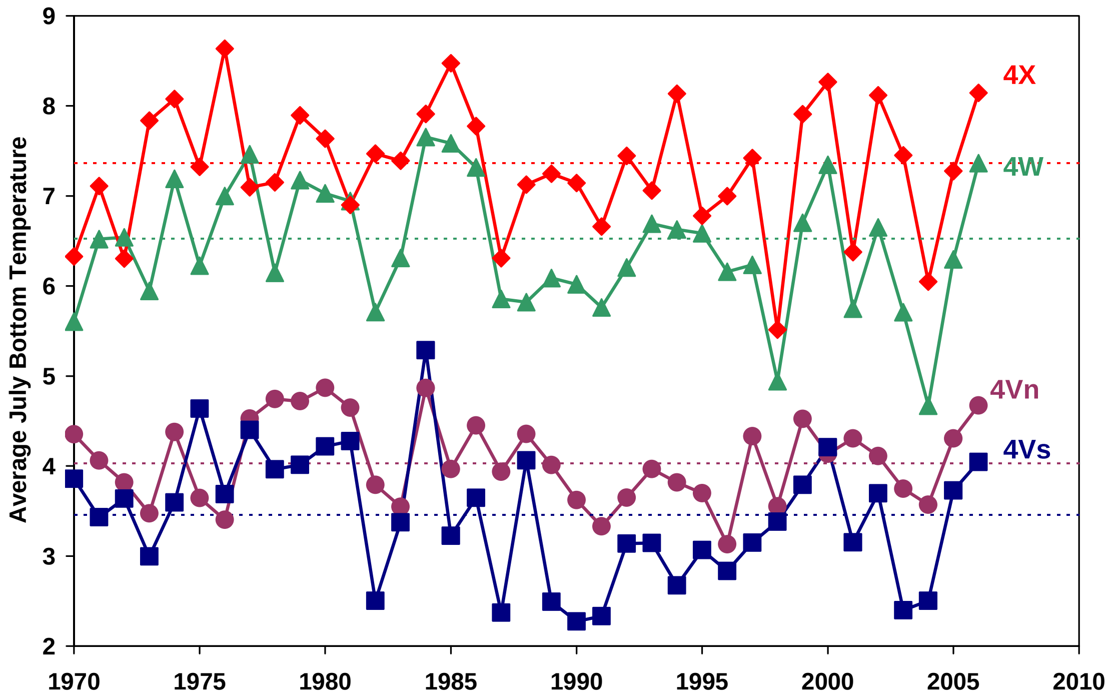


Fig. 13. Time series of annual mean bottom temperatures from areas 4Vn, 4Vs, 4W and 4X. The horizontal lines are the 1971-2000 means.

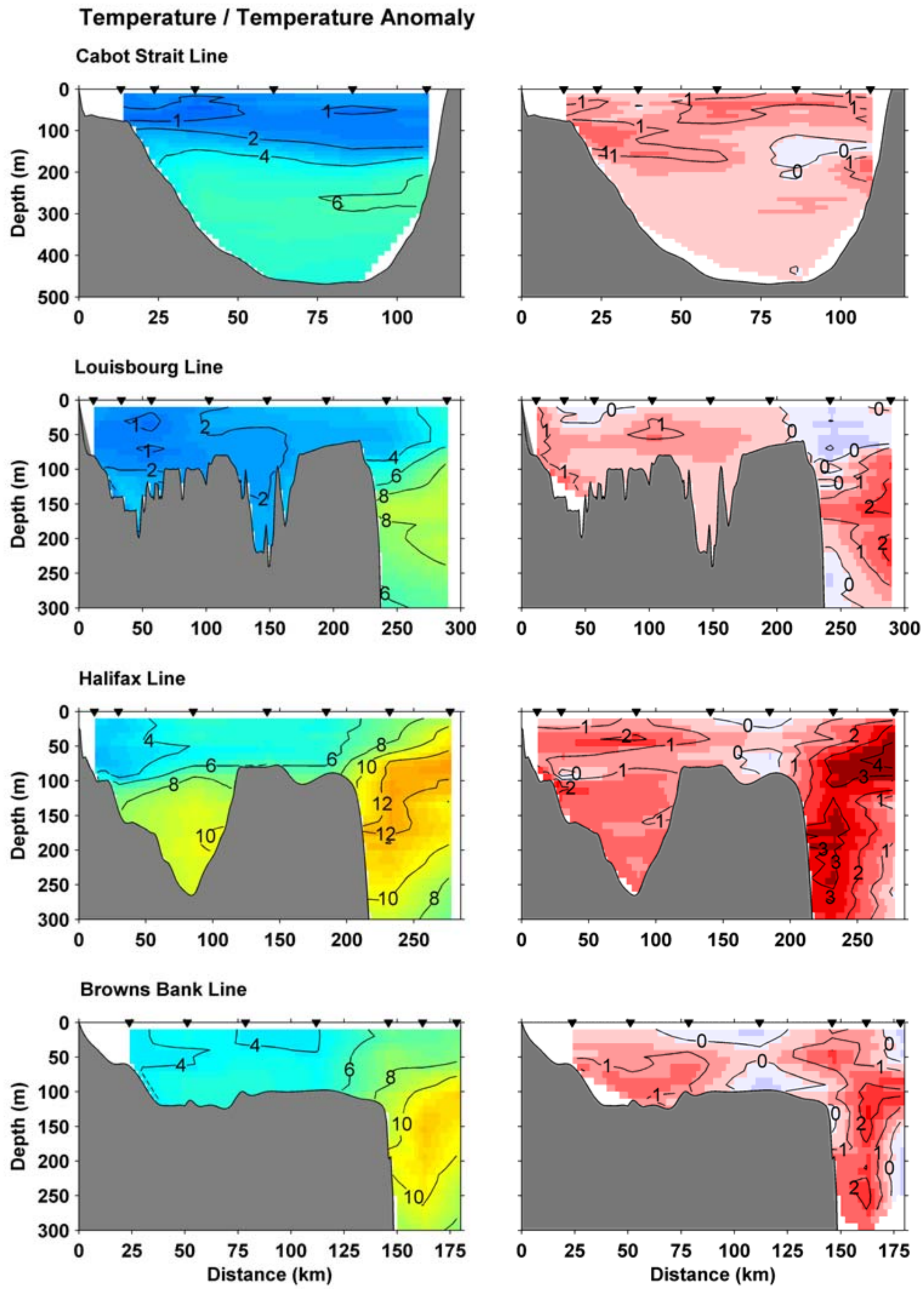


Fig. 14a. Temperature and temperature anomalies for standard Scotian Shelf sections, April-May 2006.

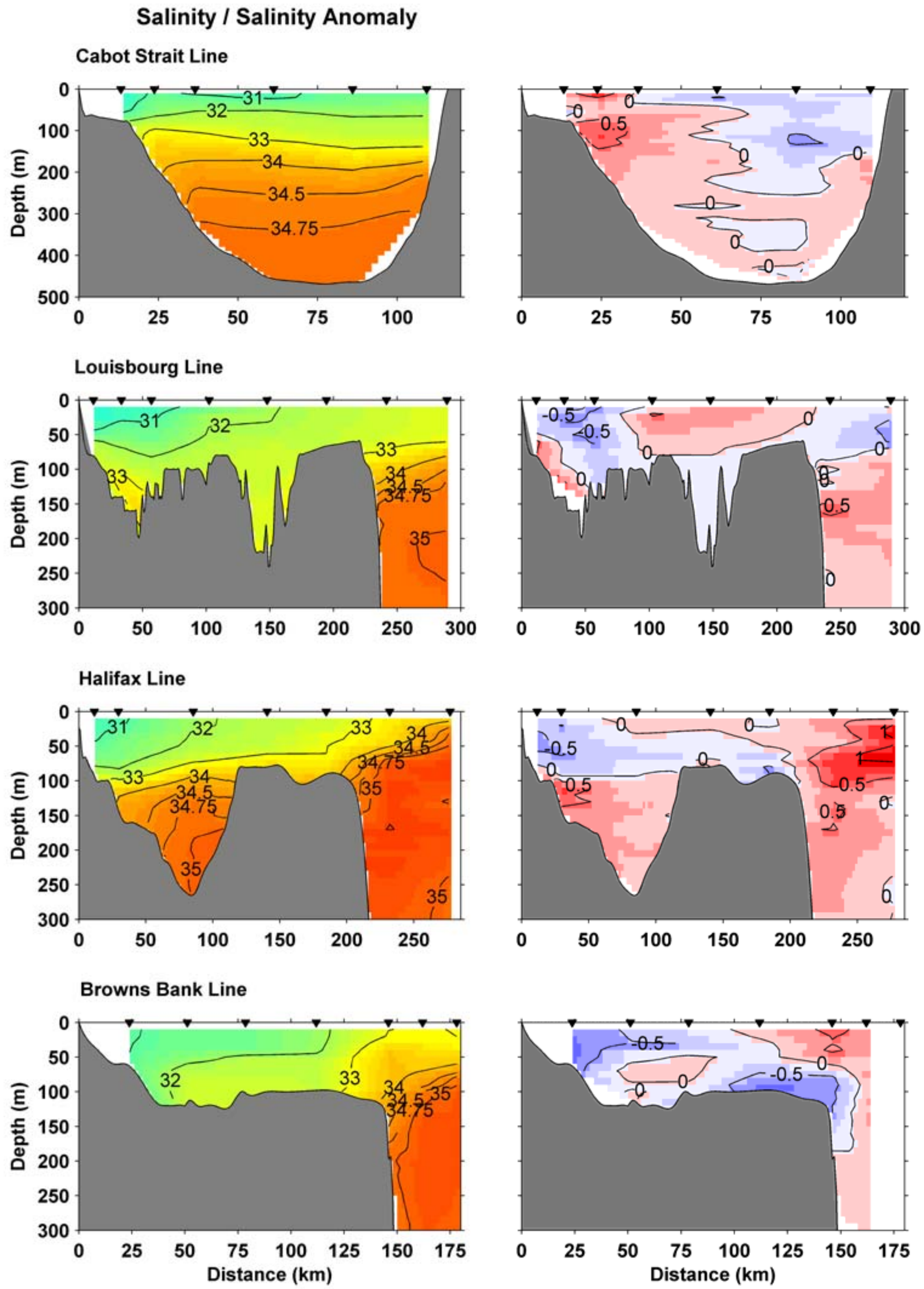


Fig. 14b. Salinity and salinity anomalies for standard Scotian Shelf sections, April-May 2006.

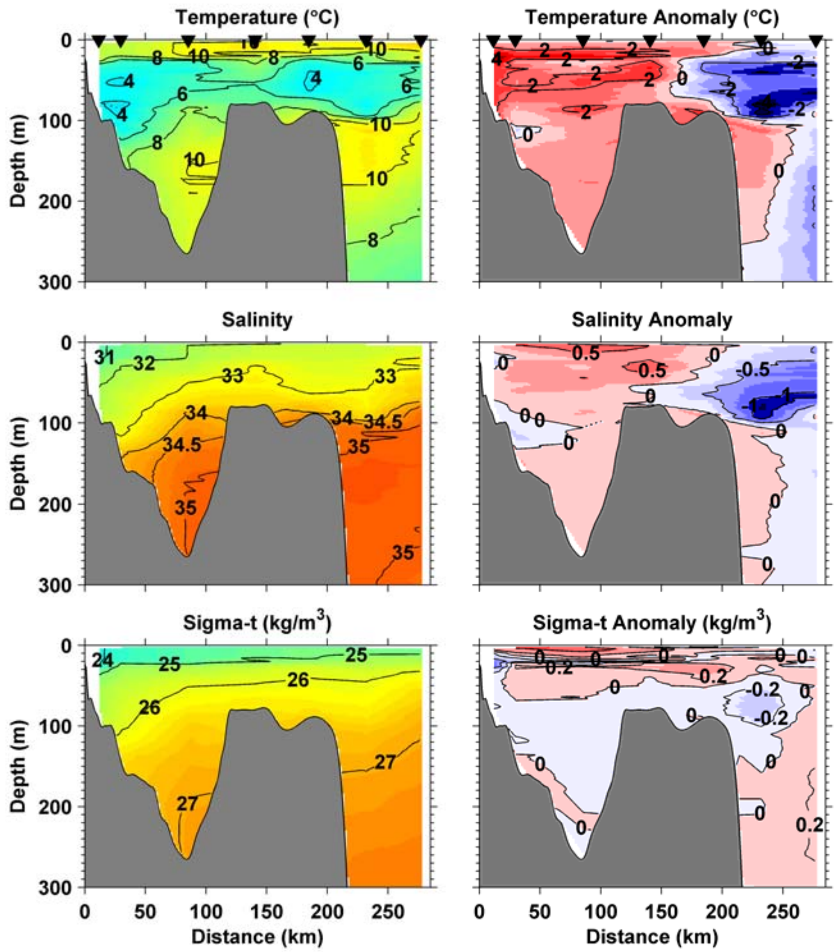


Fig. 14c. Temperature, salinity and sigma-t and their anomalies for the Halifax Section, June 2006.

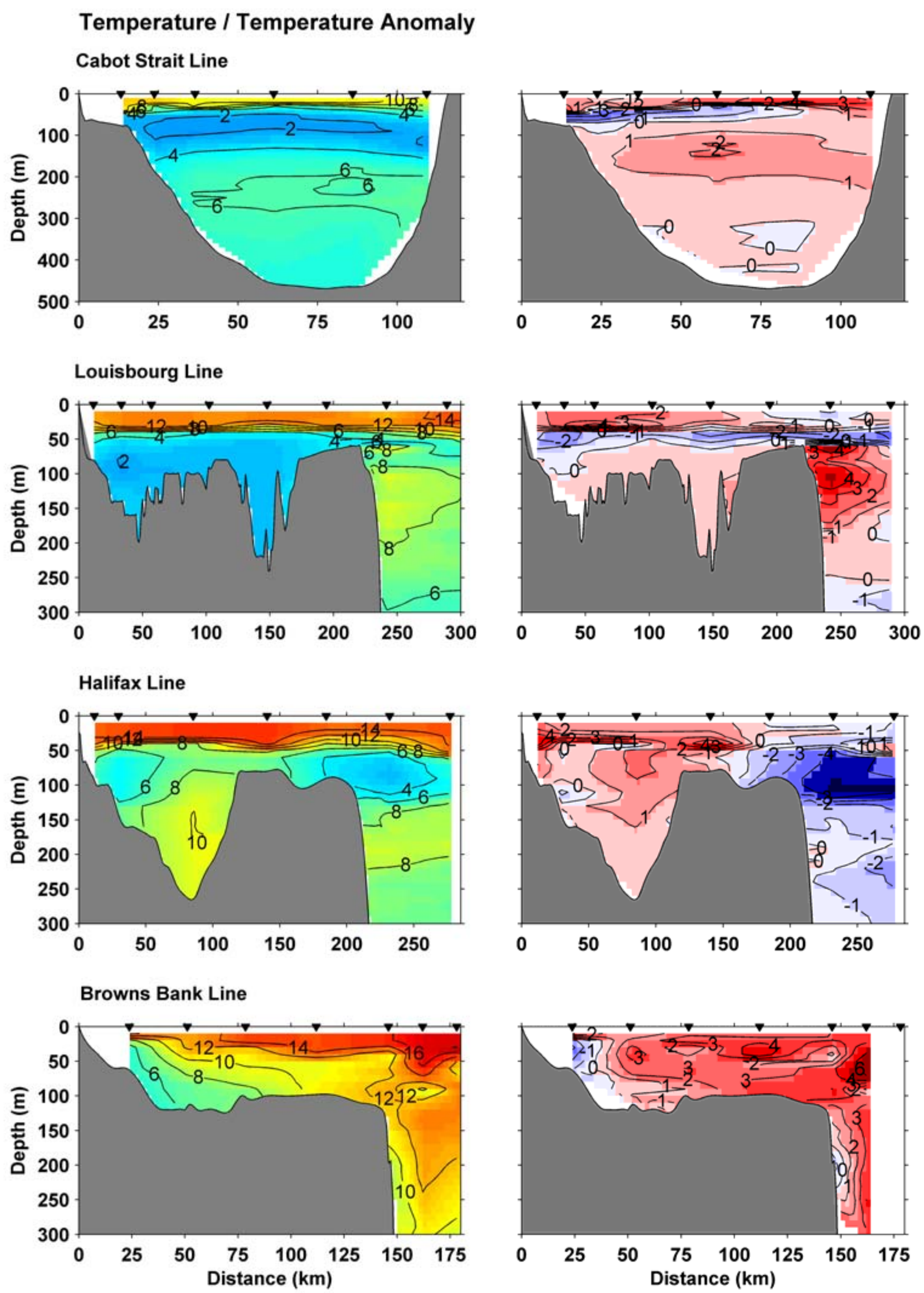


Fig. 14d. Temperature and temperature anomalies for standard Scotian Shelf sections, October 2006.

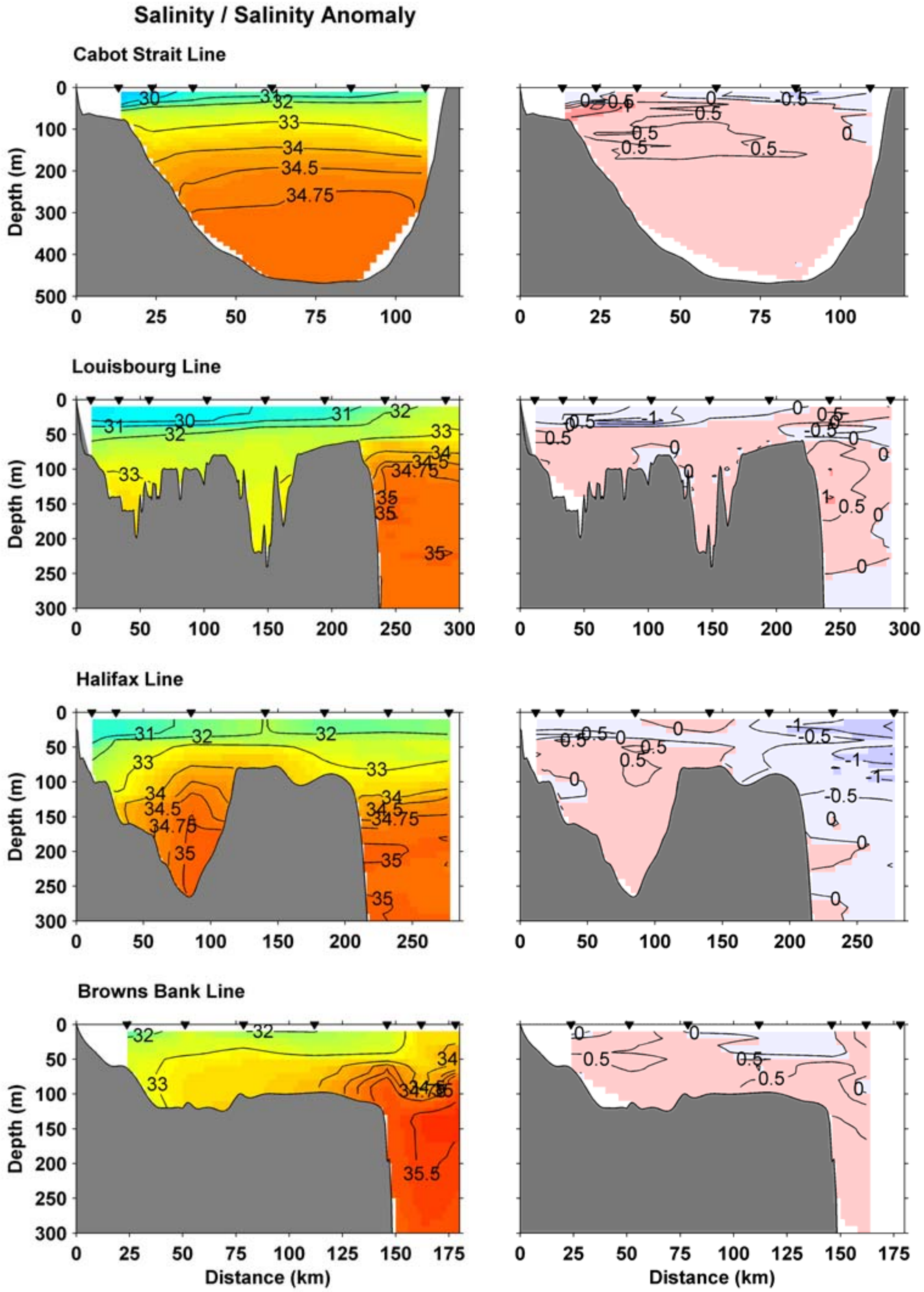


Fig. 14e. Salinity and salinity anomalies for standard Scotian Shelf sections, October 2006

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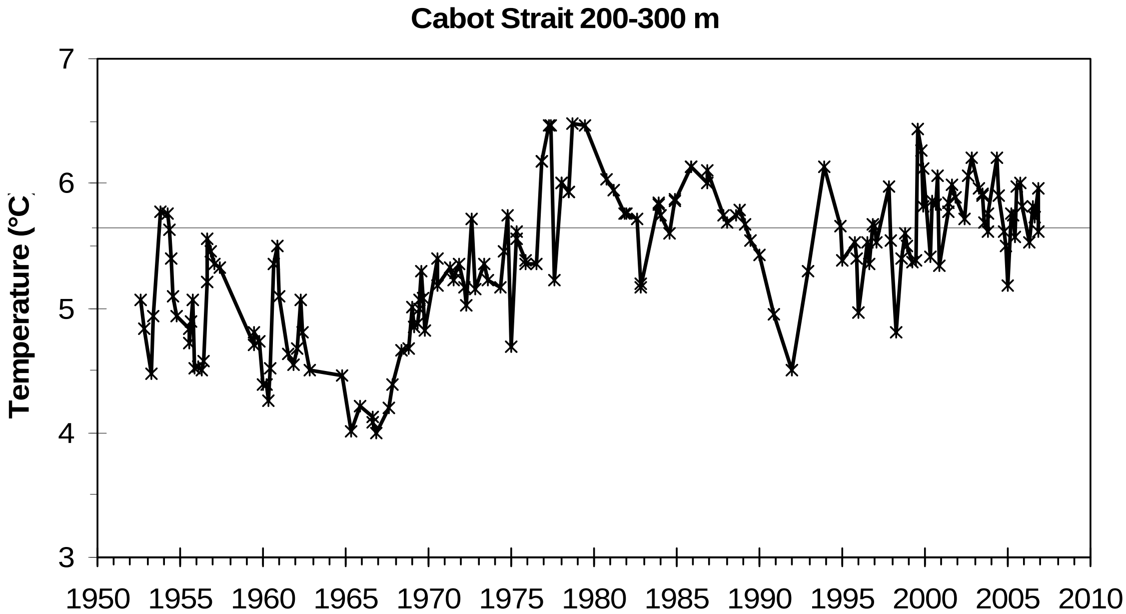


Fig. 15. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the 1971-2000 mean.

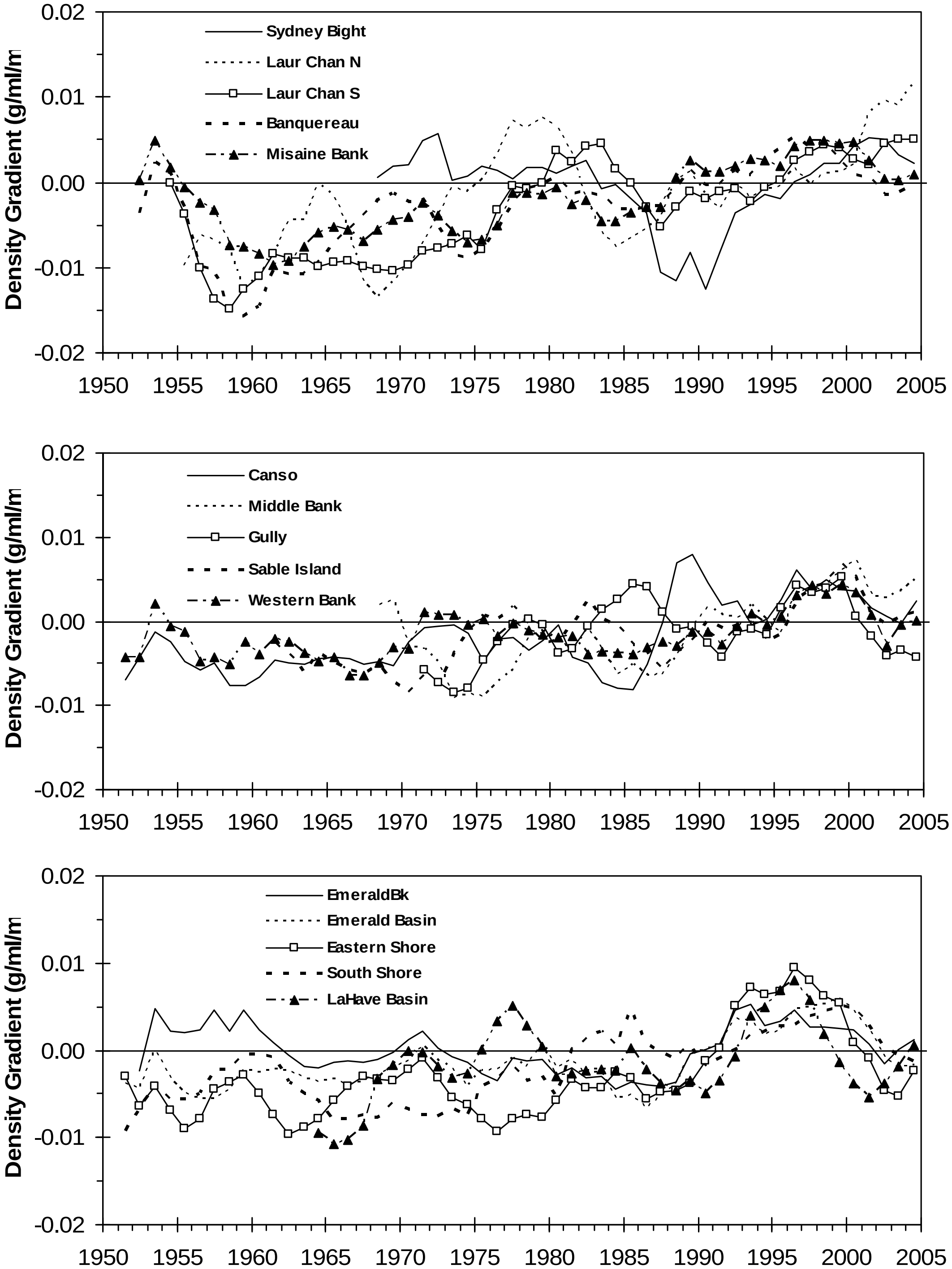


Fig. 16a. Five-year running means of the annual density gradient anomalies between the surface and 50 m calculated for the areas 1-15 in Fig. 7.

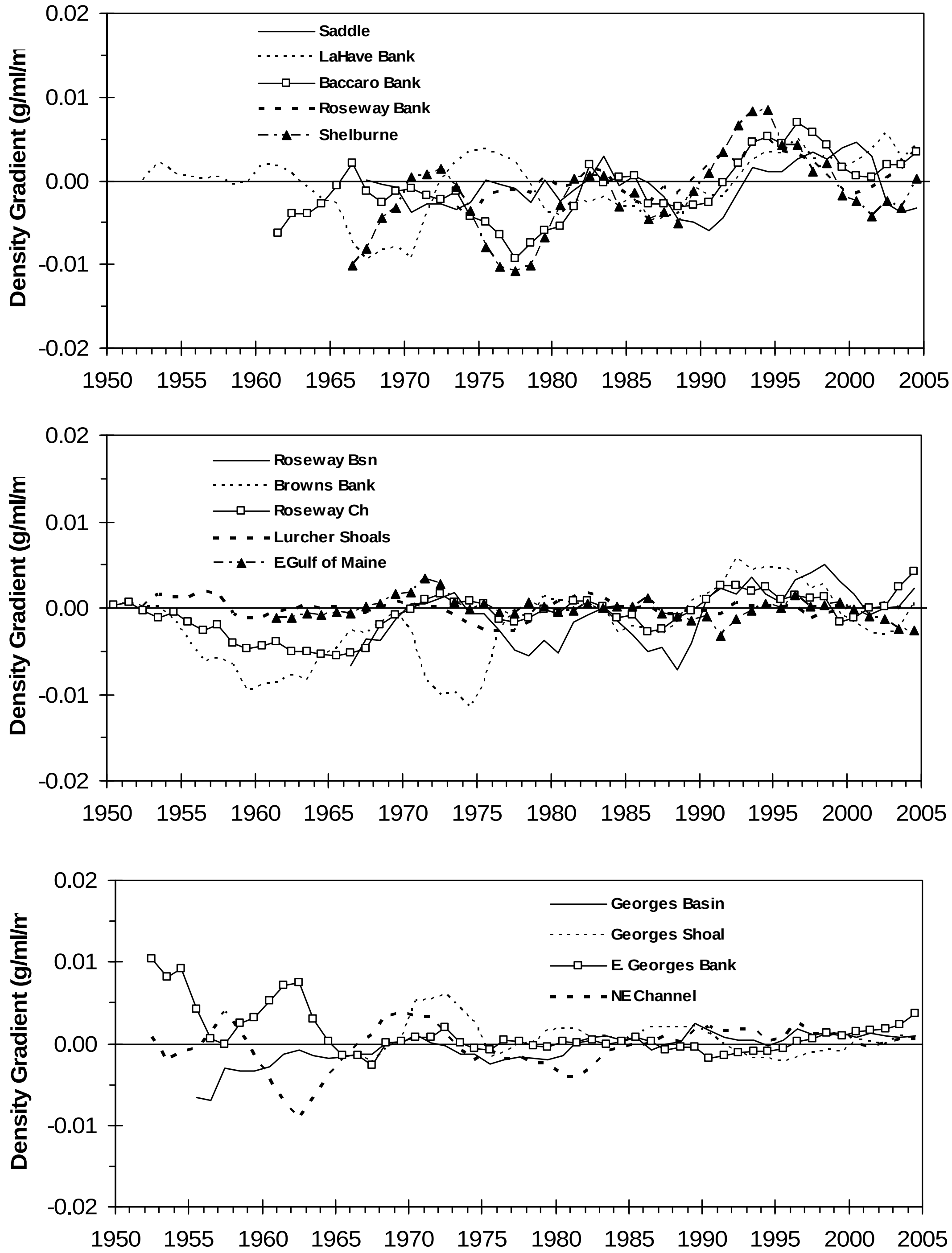


Fig. 16b. Five-year running means annual density gradient anomalies between the surface and 50 m calculated for the areas 16-29 in Fig. 7.

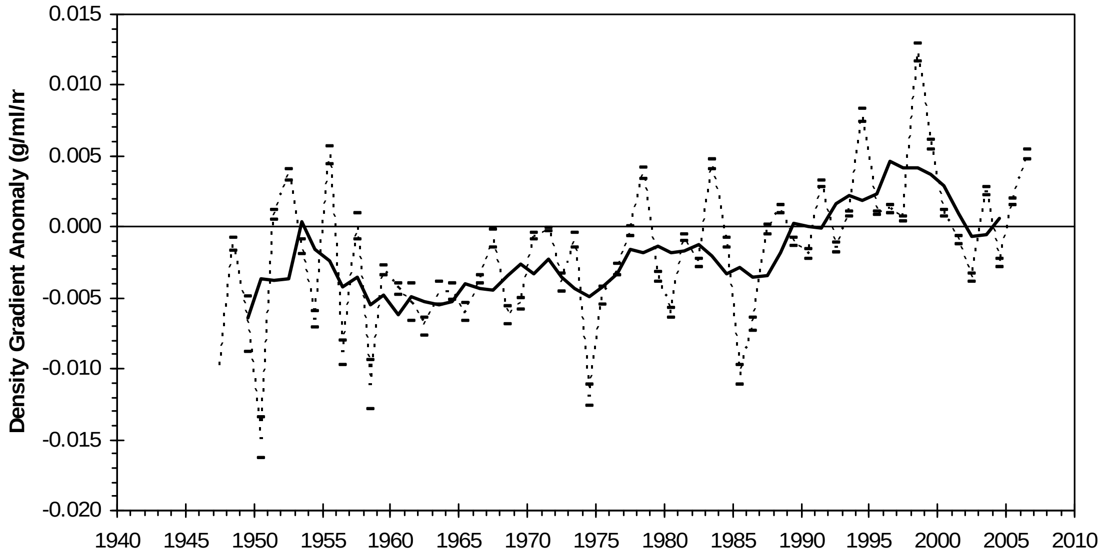


Fig. 17. The mean annual (dashed line) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive). The short horizontal lines for each year represent the standard errors of the different areas.

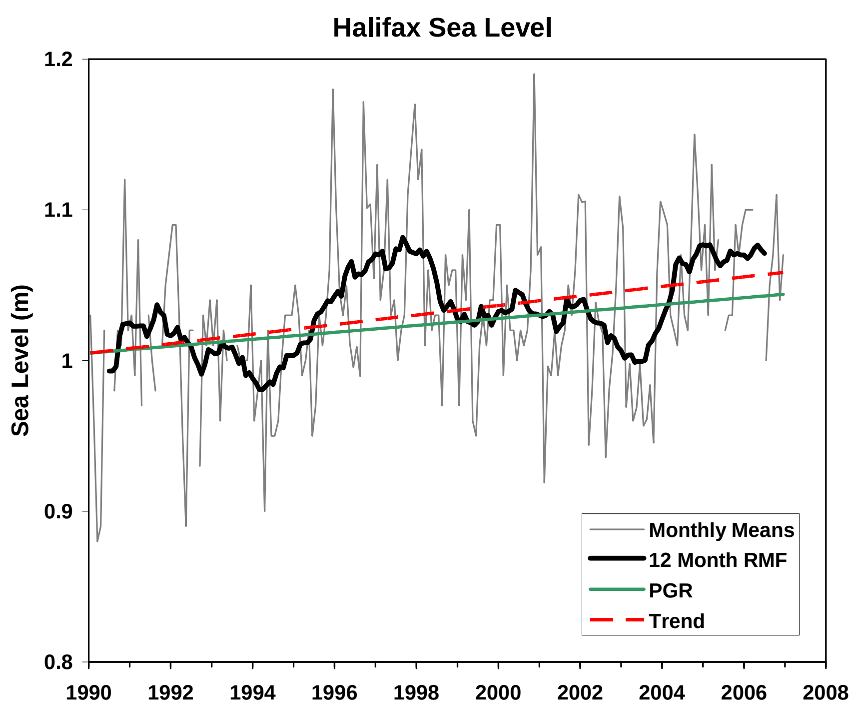


Fig. 18. The time series of the monthly means and a 12 month running mean of the sea level elevations at Halifax, along with the observed linear trend (1990-present) and that predicted by a model from post-glacial rebound.

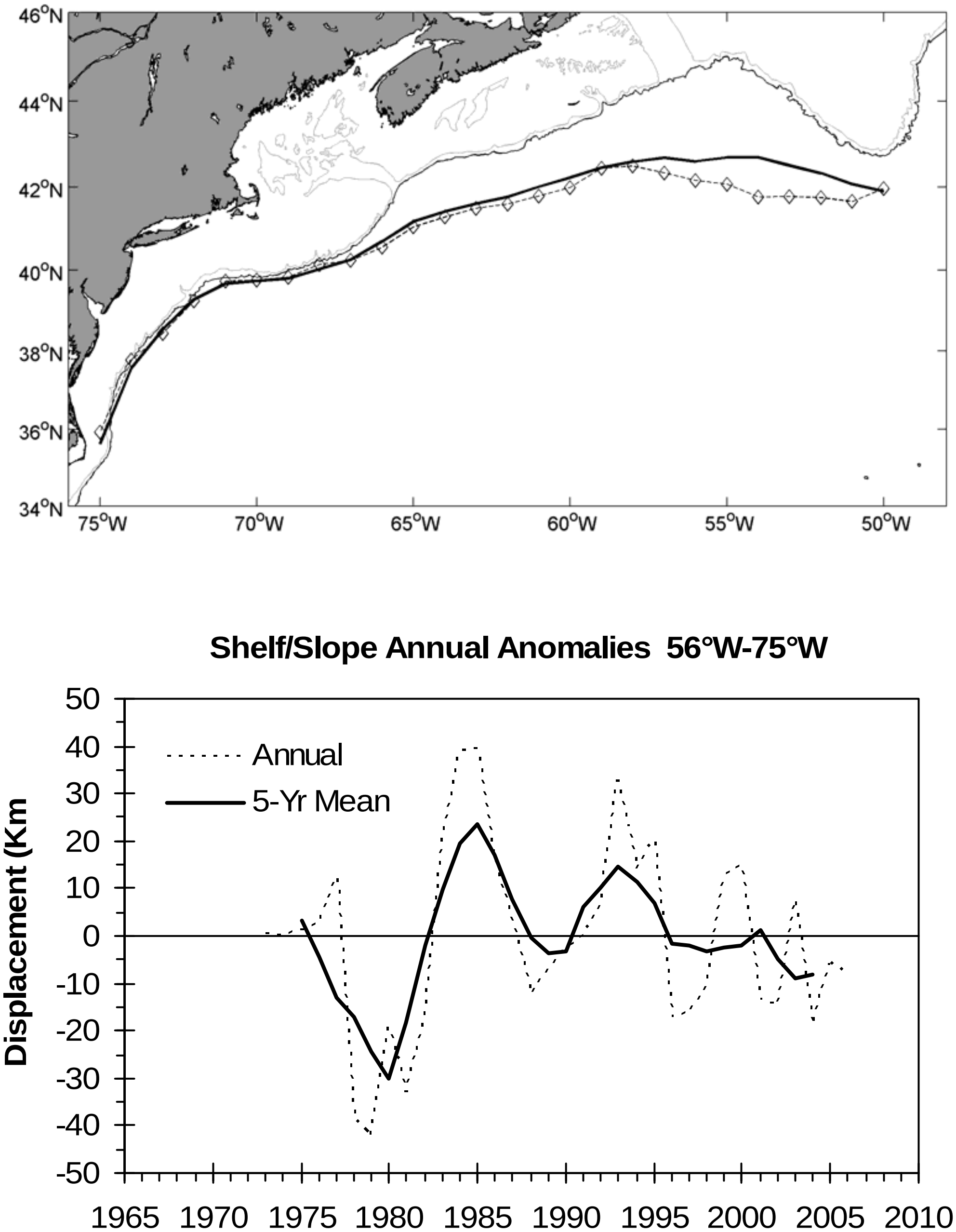
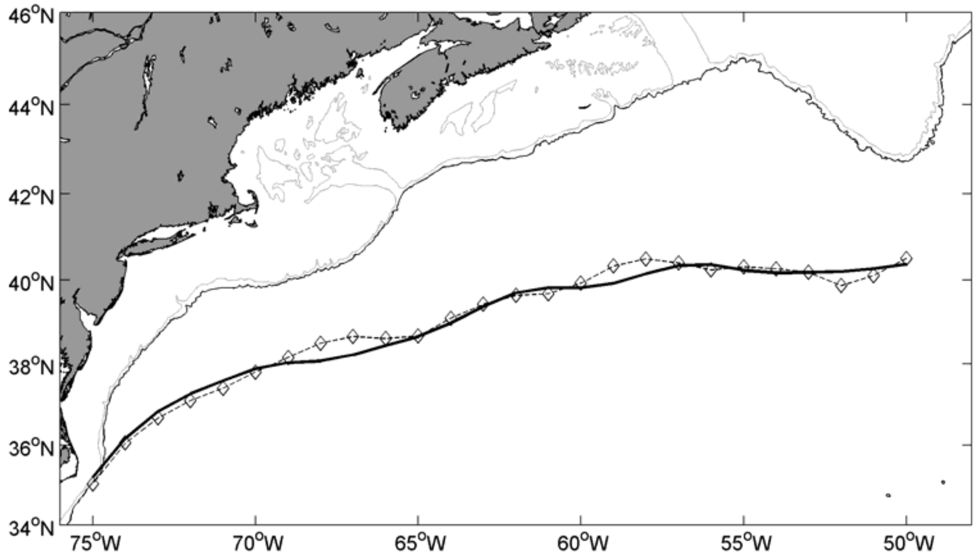


Fig. 19. The 2006 (dashed line) and long-term mean (1973-2000; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).



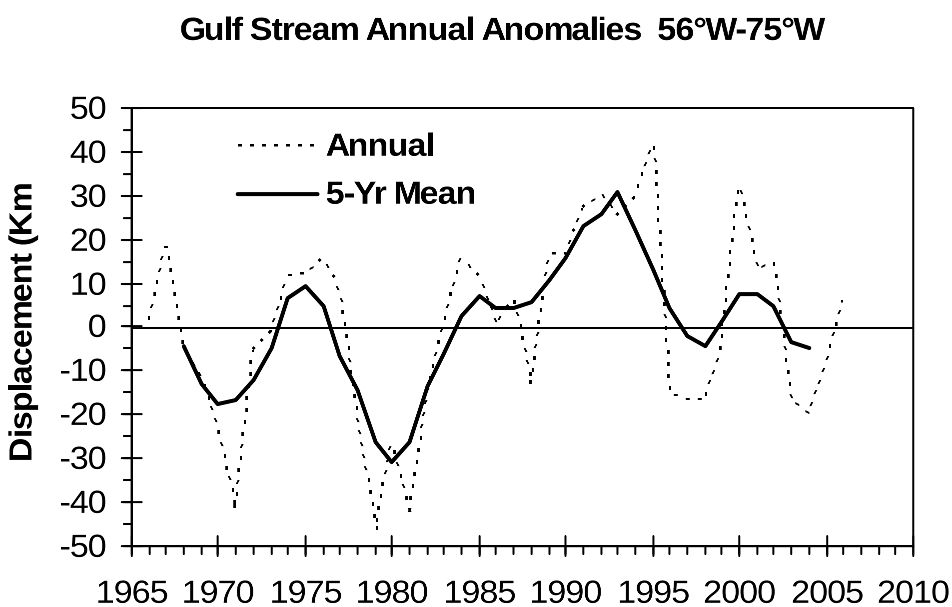


Fig. 20. The 2006 (dashed line) and long-term mean (1973-2000; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).

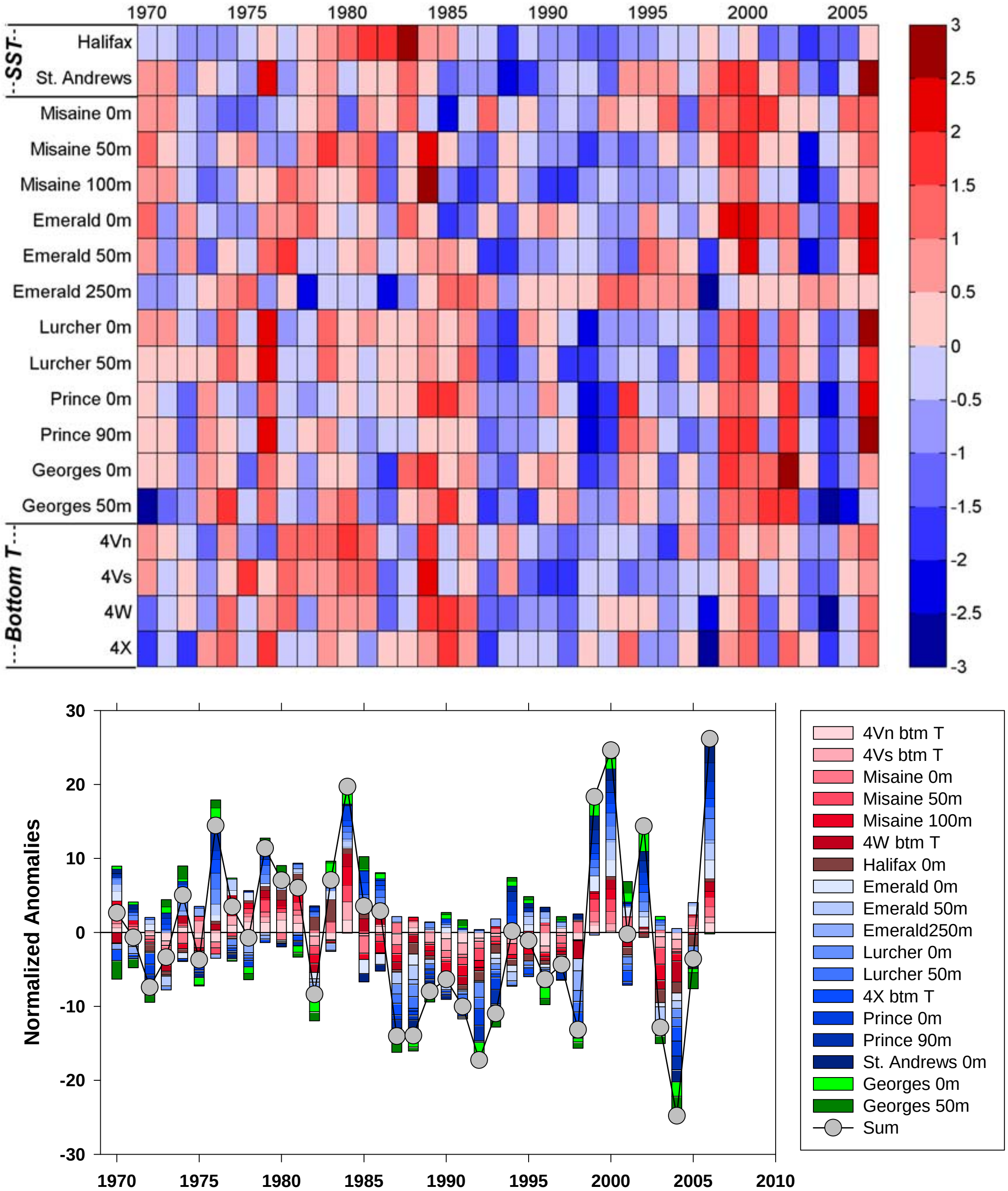


Fig. 21. Normalized annual anomalies of bottom temperatures and temperatures at discrete depths for the Scotian Shelf-Gulf of Maine region (upper panel). The normalized anomalies are the annual anomalies based on the 1971-2000 means, divided by the standard deviation. The scale represents the number 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).