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Northwest Atlantic Fisheries Organization

**Serial No. N4974** **NAFO SCR Doc. 04/26**

**SCIENTIFIC COUNCIL MEETING – JUNE 2004**

Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2003

by


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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 2003 has shown some broad scale changes from previous years. Cool conditions tended to dominate the Scotian Shelf and to a lesser extent the eastern Gulf of Maine in 2003. Mean annual sea-surface temperature at Boothbay Harbor was 2.4°C above normal, the 7th warmest in 98 years. St. Andrews was 0.6°C below normal, ranking 47th in 83 years from warmest to coldest. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by 0.1 to 0.3°C. Salinities were generally 0-0.6 above normal throughout the year. Halifax sea surface temperature was 1.8°C below normal, making 2003 the 4th coldest in 78 years. At Halifax Station 2, 0-100 m temperature anomalies were 0 to –2°C; salinity was typically 0-0.5 above normal. Sydney Bight, Misaine Bank and Emerald Basin (to 75 m) featured anomalies of –1 to –2°C. At depths greater than 75 m, Emerald Basin temperatures were about 0.5°C above normal. Lurcher Shoals temperature anomalies were varied but slightly above normal for the year. Georges Basin showed an anomaly reversal like Emerald Basin with temperatures about 1°C below normal 0-100 m and 0.5°C above normal deeper. Eastern Georges Bank temperature anomalies varied through the year, negative early, positive late with amplitudes less than 1°C. Standard sections in April, July, October and December on the Scotian Shelf support the overall conclusion of temperatures ~2°C below normal, salinities ~0.5 above normal and a more intense and extensive cold intermediate layer on the shelf. Cabot Strait deep-water (200-300 m) temperatures were near normal. The temperatures from the July groundfish survey were exceptional with the outstanding feature being a very broad cold intermediate layer with below normal temperatures. The July surface temperatures were generally 0°-3°C above normal for the survey region except for the Bay of Fundy where below normal temperatures by up to 2°C prevailed. However, at the deeper layers of 50 m, 100 m and at the bottom below normal temperatures of up to 3°C, 2°C and 1°C dominated. Break-up of the strong stratification pattern established in the late 20th and early 21st century continued in 2003. Though overall stratification was slightly above normal for the Scotian Shelf region, there was considerable variability at small spatial scales. The Shelf/Slope front and the Gulf Stream moved in opposite directions in 2003 with the former moving onshore on average by 22 km compared to its position in 2002 and the latter offshore by 32 km.


**Introduction**

This paper describes temperature and salinity characteristics during 2003 of the waters on the Scotian Shelf and in the Gulf of Maine (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 (AFAP) database (http://www.mar.dfo-mpo.gc.ca/ science/ocean/database/data-query.html), which is updated monthly from the data archive at the Marine Environmental Data Service (MEDS) in Ottawa. The analyses in this paper use data up to and including the 4 February 2004 update; only data up to and including 2003 are discussed. Additional hydrographic data were obtained directly from DFO fisheries personnel. 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 expressing oceanographic conditions as monthly deviations from their long-term means (called anomalies). Where possible, long-term monthly and annual means have been standardized to a 30-year average, using the base period 1971-2000 in accordance with the convention of the recommendations of the Northwest Atlantic Fisheries Organization (NAFO, 1983) and DFO's Fisheries Oceanography Committee (FOC). Meteorological, sea ice and satellite-derived sea-surface temperature information for eastern Canada during 2003 are described in Petrie *et al*. (2004). Of particular relevance for the Scotian Shelf and the Gulf of Maine was that air temperatures were below normal for the first half of the year and above normal for the second; sea surface temperatures, available only for January to June 2003, were below normal for the Scotian Shelf and the Gulf of Maine. March ice cover for the Scotian Shelf approached the long-term maximum.

## COASTAL SEASURFACE TEMPERATURES

Monthly averages of coastal sea surface temperature (SST) for 2003 were available at Boothbay Harbor (Maine), St Andrews (New Brunswick) and for February-December at Halifax (Nova Scotia). The monthly mean temperature anomalies relative to the 1971-2000 long-term averages at each site for 2002 and 2003 are shown in Fig. 2.

At Boothbay Harbor in 2003, winter temperatures were slightly below normal but by early spring SST anomalies were positive and grew to ~3$^{o}$C by summer. Positive anomalies continued in the fall. The anomalies equalled or exceeded 2 standard deviations (SD, based upon the years 1971-2000) in 4 months (July-October) with September exceeding 4 SD. The annual anomaly was 2.4$^{o}$C, the 7$^{th}$ highest in the 98 year record. At St. Andrews, March-May featured negative anomalies that exceeded 1 standard deviation, with only October having a positive anomaly that exceeded 1 SD. The 2003 annual anomaly was -0.6$^{o}$C , ranking 47$^{th}$ in 83 years from warmest to coldest. The monthly anomalies at Halifax were generally negative with the August value, -4.93$^{o}$C, more than 6 SD below normal; it was a major contributor to the overall annual anomaly of –1.8$^{o}$C. Thus, 2003 was the 4$^{th}$ coldest in 78 years.

Time series of annual anomalies show that the surface temperature at Boothbay Harbor continued above its long-term mean, whereas, in 2003 St. Andrews and Halifax anomalies were below normal. This continues the recent downturn at both of these sites.

## 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 but since 1998, multiple occupations per month have been taken. For months with multiple measurements, an arithmetic average was used to estimate the monthly mean temperature and salinity. A single observation, or even three per month (especially in the surface layers in the spring or summer 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 2003, monthly mean temperatures ranged from a minimum in March of 0.92$^{o}$C at the surface to a maximum in October of 12.1$^{o}$C (Fig. 3, 4). Monthly temperature anomalies were mostly negative throughout the year with positive anomalies from January to mid-February and from mid-September to mid-November (Fig. 3). Negative anomalies were greatest (-1.5$^{o}$C) in early spring. The highest positive anomalies were about 1°C. The annual mean temperatures exhibited 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 2003, the annual temperature anomalies at all depths were negative and ranged from about –0.1 to –0.3°C. These negative anomalies oppose the long-term warming trend that began in the early-1990s.

The salinity at Prince 5 showed a typical annual cycle with lowest values in the spring (May) at the surface (~31) and the highest values (>33) near bottom in the autumn (Fig. 3, 5). The salinity anomalies were predominantly positive throughout the year (Fig. 3). Maximum anomalies (>0.6) occurred between 25 and 75 m at the beginning of the year. Annual salinity anomalies in 2003 were above their long-term means at all depths by 0.14 to 0.23. There have been large interannual salinity fluctuations, but the longer-term trends show a general freshening from the late-1970s to the mid-1990s. The lowest salinities on record at Prince 5 occurred in 1996. These changes paralleled events in the deep waters of Jordan and Georges Basin and appear to have been related to advection from areas farther north (Smith *et al*., 2001; Drinkwater *et al.*, 2003b). Salinities rose above normal by 1999 and have remained there with slightly lower values in 2003 compared to 2002.

*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 collected. We report the hydrographic data. The long-term monthly means of temperature, salinity and density (sigma-t) were discussed in Drinkwater *et al*. (2000).

Surface temperatures at H2 ranged from <0°C to >16°C in 2003 (Fig. 6). Near-bottom temperatures were highest (>8°C) in January, February, and from mid-May to mid-August. Relative to the long-term means, surface to ~100 m temperatures were predominantly below normal for most of the year. Deeper than 100 m, the anomalies varied between positive and negative values. Maximum positive temperature anomalies were on the order of 4°C from 100 m to the bottom in mid-February; the minimum anomalies were below -2°C centered around 50 m in early October. The temperature anomaly pattern suggests that there was more Cold Intermediate Layer (CIL) water than usual at H2 in 2003. The CIL off Halifax typically has a temperature range from about 1°C to 6°C depending on the time of the year.

Sea-surface salinities were relatively uniform during 2003 with short periods during winter and late summer when values were less than 31. Deeper salinities increased from the beginning of the year to late summer, reaching maximum values >34 near the bottom. Relative to the long-term means, salinities were primarily saltier-than normal, with fresher conditions occurring from mid-March to mid-April.

In the surface layers, stratification began around May increasing in intensity through to August-September. During autumn, the warmer and fresher surface layer was gradually mixed down to 30 m and deeper. Density anomalies were concentrated in the upper 30 m from June to October.

## 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 2003 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 at each area and in some areas the monthly means are based upon only one profile. As a result, the series are characterized by short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1-2°C. The spikes represent 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 such trends we have estimated the annual mean anomaly based on all available means within the year and then calculated the 5-year running mean of the annual values 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 in the northeastern Scotian Shelf, the temperature minimum in this period approached or matched the minimum observed during the very cold period of the 1960s. This cold water was traced through the Gulf of Maine from southern Nova Scotia, along the coast of Maine and into the western Gulf. Cooling occurred at approximately the same time at Station 27 off St. John's, Newfoundland, 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 2003 (Fig. 8) and as time series plots for a selected depth in each region (Fig. 9). For the 6 regions, the months with data were: Sydney Bight, May-August and October; Misaine Bank, March-May, July, September and October; Emerald Basin, January-November; Lurcher Shoals, January, April, May, July, August; Georges Basin, January, April-November; and eastern Georges Bank, January, February, April, May, August and November.

In Sydney Bight (area 1 in Fig. 7) off eastern Cape Breton, the 5 monthly anomaly profiles overall showed temperature anomalies of about $1^{o}$C below normal with strong variability in the upper 30 m (Fig. 8). Misaine Bank profiles were similar to those in Sydney Bight – temperatures were 1-$1.5^{o}$C below normal and more variable at shallow depths. With profiles in 11 months of the year, Emerald Basin featured below normal temperatures by 1-$2^{o}$C in the upper 50 m, reversing at about 75 m, and positive anomalies of about $0.5^{o}$C between 100 m and the bottom. The split between the negative and positive anomalies is related to the predominance of shelf water in the upper layer of the basin and slope water in the deeper layer. Lurcher Shoals anomalies were highly variable with a tendency to above normal temperatures but within a standard error of average conditions. Georges Basin exhibits an anomaly structure similar to Emerald Basin, perhaps also reflecting the influence of slope water at depth. The 10 months of data in 2003 show a tendency for the upper 100 m to have below normal temperatures by about $1^{o}$C and the deeper waters to be about $0.5^{o}$C above normal. Georges Bank anomalies are generally negative in the early part of the year and positive in the latter half.

Figure 9 shows the time series of temperature anomalies for one depth from each of the 6 regions. 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 Emerald Basin 250 m record reflects the influence of slope water on the Scotian Shelf. The incursion of Labrador Slope Water onto the shelf in 1998 is very prominent. This event has been followed by a period of slightly above normal temperatures which continued at depth in 2003. Lurcher Shoals temperature anomalies at 50 m follow a similar pattern as the Misaine Bank series; however, in the past 5 years there have been large fluctuations in the monthly values that average to give low frequency variability that is near the long-term mean. Since 1975 the filtered times 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. Above normal anomalies were recorded in 2003. On the other hand, the filtered temperature anomaly series from eastern Georges Bank has been almost flat with a tendency of slightly below normal values in 2003.

The monthly time series of Fig. 9 are qualitatively different with, for example, the Emerald Basin series showing a predominantly low frequency (periods longer than 1 year) variability, whereas, the Lurcher Shoals record has most of its variance in month-to-month changes. This is indicated in the table below where 95 percent of the temperature anomaly variance is associated with periods longer than 1 year for Emerald Basin and 82% for periods less than 1 year for the Lurcher Shoals record. The records from Sydney Bight, Misaine Bank and Georges Bank are dominated by higher frequency variability; Georges Basin at 200 m has the variance nearly evenly split between the 2 bands.

***Distribution of temperature anomaly variance with period***

| Std. Dev. ($^oC$) | Sydney Bight 100 m | Misaine Bank 100 m | Emerald Basin 250 m | Lurcher Shoals 50 m | Georges Basin 200 m | Georges Bank 50 m |
|---|---|---|---|---|---|---|
| **Monthly series** | 0.83 | 0.77 | 1.25 | 1.13 | 1.01 | 1.29 |
| **Periods>Annual** | 0.46 | 0.35 | 1.22 | 0.48 | 0.66 | 0.67 |
| **Periods<Annual** | 0.69 | 0.69 | 0.27 | 1.02 | 0.76 | 1.10 |
| **Percent Variance, Periods<annual** | 69 | 79 | 5 | 82 | 58 | 73 |

Another important characteristic feature of the variability is the rate at which its autocorrelation decreases as lag increases. The autocorrelation function is a measure of the frequency dependence of the variability, e.g. a slow (rapid) decrease indicates that longer (shorter) period changes dominate. It also indicates how well the current temperature can forecast a future value. In Fig. 10, the autocorrelations for the monthly and annual time series for the 6 records show rapid declines: the e-folding times for the correlations of the monthly (annual) times series are 2-3 months (< 1 year) for Sydney Bight, 6-7 months (<1 year) for Misaine Bank, ~10 months (~3 years) for Emerald Basin, 2-3 months (<1 year) for Lurcher Shoals, > 12 months (3-4 years) for Georges Basin and ~1 month (3-4 years) for eastern Georges Bank.

## 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 215 CTD stations were taken during the 2003 survey and an additional 136 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 from Vemco Minilogs© attached to the trawl. These data are quality controlled during processing at the Bedford Institute of Oceanography.

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 below that. Data near the interpolation grid point are weighted proportionately more than those farther away. Temperatures were optimally estimated onto the grid for depths of 0, 50, 100 m and near bottom (Fig. 11). Maximum depths for the interpolated temperature field were limited to 1000 m off the shelf. The 2003 temperature anomalies relative to the July 1971-2000 means were also computed at the same four depths (Fig. 12).

The broad spatial pattern of near-surface temperatures in July 2003 was similar to past years with the warmest waters (>18°C) off eastern Cape Breton and the coldest (<11°C) in the Gulf of Maine/Bay of Fundy region (Fig. 11a). The cooler surface temperatures in the Gulf of Maine compared to the Scotian Shelf are due in part to the intense bottom-generated vertical mixing caused by the high tidal currents. The surface temperatures in July 2003 were warmer-than-normal over most of the Shelf but as much as $3^oC$ cooler than normal at the mouth of the Bay of Fundy (Fig. 12a). Note the small patch of below normal temperatures off Halifax agreeing with the Halifax coastal (Fig. 2) and H2 (Fig. 6) observations. The anomaly pattern in 2003 was approximately the reverse of the pattern in 2002.

The temperatures at 50 m ranged from 2°C to over 8°C with the coldest waters in the northeast and the warmest waters in the Gulf of Maine and Bay of Fundy (Fig. 11a). The lower temperatures over the inner half of the shelf indicate a cold, broad intermediate layer in 2003. 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. Temperature anomalies at 50 m (Fig. 12a) were below normal nearly everywhere by as much as 5°C. Compared to 2002, temperatures decreased over most of the Shelf and Gulf of Maine regions.

The temperatures at 100 m ranged from <1-2°C in the northeast to over 8°C offshore and in Northeast Channel (Fig. 11b). Temperature anomalies were predominantly negative, ranging from 1°C to 2°C below normal over the Shelf and close to normal in the Gulf of Maine (Fig. 12b). The largest anomalies (about -4°C) occurred along the outer shelf off Sable and Banquereau Banks suggesting the presence of colder-than-normal slope waters. Relative to 2002, temperatures at 100 m fell in 2003.

Near-bottom temperatures over the Scotian Shelf ranged from <1°C in the northeastern Scotian Shelf to over 9°C in Emerald Basin and in the Bay of Fundy (Fig. 11b). In Emerald Basin, the high temperatures are due to the penetration of Warm Slope Water into the Basin, 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 their long-term means (1971-2000), the near-bottom temperatures were predominantly colder-than-normal from Sydney Bight to Halifax and southwest Nova Scotia into the Bay of Fundy; the shelf-wide area from Halifax to Shelburne had above normal bottom temperatures (Fig. 12b).

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. 13a,b. Several points are noteworthy. First is the generally higher temperature as one moves southwestward from 4Vs/4Vn towards 4W and 4X. In 4Vn, most of the bottom is covered by waters <6°C and almost 50% is <5°C. For 4Vs, 80-90% is <6°C and 75% is <5°C (Fig. 13a). In 4W <50% and in 4X <20% of the bottom is covered by temperatures <6°C (Fig. 13b). The time series for 4Vn and 4Vs show an increase during the late-1980s and early-1990s in the amount of 0°-1°C waters and especially those <3°C (Fig. 13a). Also in 4Vs there are waters <1°C during this colder period. In 4W there is an increase in the area of the waters <3°C, but it is of smaller amplitude than in 4V. In 4X there is an increase in waters <4°C, but it is not as large an amplitude as in the other regions (Fig. 13b).

The interannual variability of the bottom temperature areas can be summarized by determining the average bottom temperatures in each of the regions (Fig. 14). Three of the areas in 2003, 4Vn, 4Vs and 4W featured average bottom temperatures below the 1971-2000 normals. Area 4Vn was –0.29°C (0.6 standard deviations) below normal and the 11th coldest in 34 years. Area 4Vs and 4W were –1.1 (1.4 standard deviations) and 0.81°C (1.3 standard deviations) below normal, the 4th and 3rd coldest years in 34. However 4X, perhaps influenced by the Warm Slope Water in Emerald and LaHave Basins was 0.09°C above normal (0.1 standard deviations), ranking 21st coldest in 34 years.

## STANDARD SECTIONS

Hydrographic data for on the Cabot Strait (October), Louisbourg (April, October), Halifax (April, July, October, December) and Browns Bank (April, October) sections are shown in Fig. 15a-f. The anomalies corresponding to these data were calculated for the time the observations were collected. In April temperatures were <2°C across the entire Louisbourg and Halifax (0-50 m) sections and to the shelf break on the Browns Bank line (Fig. 15a). Temperatures on the shelf were 1-2°C below normal. Salinity was 32-33 over the shelf, approximately equal to the long-term mean (Fig. 15b). The isopycnal slopes (not shown) indicate a southwestward flow at the shelf break on the Louisbourg and Browns Bank sections and at the coast on the Halifax line.

The July Halifax section had 50-75 m thick cold intermediate layer extending about 150 km offshore, with temperatures 1-2°C below normal and salinities 0-0.5 above normal (Fig. 15c). Over the slope, subsurface temperatures were up to 3°C above normal and salinities up to 1 above normal.

In October there was an extensive subsurface cold layer with temperatures 0-1°C below normal at Cabot Strait and 2-6°C below normal along the Louisbourg line (Fig. 15d,e). A remnant cold intermediate layer 50 m thick at the coast and extending 80 km offshore was observed at the Halifax section. Temperatures were up to 2°C below normal. An intense warm anomaly by up to 6°C was intruding from the slope onto the outer shelf. Browns Bank temperatures were close to the long-term normal values for October. Salinities were generally above normal in all sections.

The Halifax section in December featured a strong warm anomaly of up to 8°C over the slope with salinities as much as 1.5 above normal (Fig. 15f). Temperatures were near normal over the shelf but salinities were about 0.5 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 between the late-1940s to 1988. The variability in the average temperatures within the 200-300 m layer in Cabot Strait was dominated by low-frequency 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 (near 4.5°C and an anomaly exceeding -0.9°C; Fig. 16). Then temperatures rose dramatically reaching 6°C (anomaly of 0.6°C) in late-1993. During the remainder of the 1990s, temperatures oscillated about the long-term mean with a slight tendency towards positive values. In 2003, temperatures in the deep waters of Cabot Strait were close to the long-term mean, slightly cooler than in 2002.

## DENSITY STRATIFICATION

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. Stratification can affect the extent of vertical mixing, the vertical structure of the wind forcing, the timing of the spring bloom, vertical nutrient fluxes and plankton speciation to mention just a few. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper, lower layers. We examined the variability in stratification by calculating the density (sigma-t) difference nominally between 0 and 50 m. The density difference was based on a monthly mean density profile calculated for each area in Fig. 7. The long-term monthly mean density gradients for the years 1971-2000 were estimated and these then subtracted from the monthly values to obtain monthly anomalies. Annual anomalies were estimated by averaging all available monthly means within a calendar year. This could lead to misinterpretation if in one year most data were collected in months when stratification is weak while in another year sampling was during months when stratification was strong. However, initial results of transforming the observations by dividing by the monthly standard deviation and calculating the mean annual stratification anomaly in standard deviation units were qualitatively similar to the plots presented here. A 5-yr running mean of the annual anomalies was then calculated. The monthly and annual means show high variability but the 5-yr running means show some distinctive trends. The density anomalies are presented in g/ml/m. A value of 0.01 represents a difference of 0.5 of a sigma-t unit over the 50 m.

As reported in previous overviews, the dominant feature of the 5-year means is the higher stratification during the 1990s throughout the Scotian Shelf (Fig. 17a, b, 18). Fig. 18 shows the stratification anomaly contoured for all of the areas. The 5 year running mean filtered values were used for 1970-2001; the individual year values were used for 2002 and 2003. The anomalies began to increase around 1990 with the peak in the mid to late-1990s. There is surprising consistency in the stratification trends from area to area, over the Scotian Shelf. The higher-than-average stratification during the 1990s did not extend into the Gulf of Maine region and tended to be weaker in the Laurentian Channel and Sydney Bight areas. The primary cause of the increased stratification was a decrease in surface salinities that were advected from the Newfoundland area (Drinkwater *et al.*, 2003). The 2002 stratification values in most areas fell below average continuing the general decrease during the past three years. This is clearly seen in the annual values of the stratification averaged over the entire Scotian Shelf (Areas 4-23, Fig. 7) in Fig. 18. However, in 2003, areas 4-23 overall showed increased stratification (Fig. 19) although there was strong spatial variability (Fig. 18).

## SEA LEVEL

Sea level is a primary variable in the Global Ocean Observing System (GOOS). On Canada's east coast, two gauges, one at Halifax and the other to be established on the Labrador coast, are part of Canada's proposed contribution to the global effort. Relative sea level at Halifax (1990-2003) is plotted as monthly means and filtered using a 12-month running-mean filter (Fig. 20). The linear trend of the monthly mean data (1990-2002) has a positive slope of 33.1 (±12.1) cm/century, in good agreement with the value of 36.7 cm/century (1897-1980) given by Barnett (1984). Note, however, that relative sea level generally has been falling at Halifax for the past 5 years. The trend is relative to a benchmark fixed on the land and therefore is not an absolute value of the sea level rise. The solid 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 1990-2003 by only 1.3 cm; given this single record, the variability at higher frequencies and the assumptions associated with the model, we cannot conclude that absolute sea level is rising, even locally. In 2003 relative sea level continued its downward trend at Halifax, falling to 5 cm below the long term trend plotted to match observed sea level in 1990.

## FRONTAL ANALYSIS

### *Shelf/Slope Front*

The waters on the Scotian Shelf and in the Gulf of Maine have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters offshore. The relatively narrow boundary between the shelf and slope waters is regularly detected in satellite thermal imagery. Positions of this front and of the northern boundary of the Gulf Stream between 50°W and 75°W for the years 1973 to 1992 were assembled through digitization of satellite derived SST charts (Drinkwater *et al.*, 1994). From January 1973 until May 1978, the charts covered the region north to Georges Bank, but in June 1978 the areal coverage was extended to include east to 55°W and eventually 50°W. Monthly mean positions of the shelf/slope front in degrees latitude at each degree of longitude were estimated. NOAA updated this data set until the termination of the satellite data product in October 1995. A commercial company has continued the analysis but did not begin until April 1996. These initial charts did not contain data east of 60°W but within a year were extended east to 55°W. Data for 2003 have been digitized, estimates of monthly mean positions determined, and anomalies relative to 1973-2000, were calculated. 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 together with the 2003 annual mean position is shown in Fig. 21. The average position is close to the 200 m isobath along the Middle Atlantic Bight, separates slightly from the shelf edge off Georges Bank and then runs between 100-300 km from the shelf edge off the Scotian Shelf and the southern Grand Bank. It is generally farthest offshore in winter and onshore in late summer and early autumn. During 2003, the shelf/slope front was slightly northward 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 maxima in 1993. Since 1993, the front moved steadily seaward approximately 40 km, reaching its most southerly position in 1997. During 1998 through 2000, the position of the Shelf/Slope front moved northward with the largest increase recorded in 1999. The front moved southward in 2001 to a position that was approximately 15 km seaward of its long-term mean position. Its location in 2002 was similar to that recorded in 2001. In 2003 it moved northward by about 22 km.

### *Gulf Stream*

The position of the northern boundary or "north wall" of the Gulf Stream was also determined from satellite imagery by Drinkwater *et al.* (1994) up to 1992 and has been updated in a manner similar to that for the shelf/slope front. Thus, the time series consists of the monthly position at each degree of longitude from 56°W to 75°W. The average position of the north wall of the Gulf Stream and the 2003 annual mean is shown in Fig. 22. The Gulf Stream leaves the shelf break near Cape Hatteras (75°W) running towards the northeast. East of approximately 62°W the average position lies approximately east-west. During 2003, the average position of the Gulf Stream was seaward of its long-term mean position. 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. 21). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed by a rapid decline in 1996 and remained low through 1997 and 1998. By 2000 the position of the Gulf Stream was shoreward of its long-term mean and has remained so through to 2002 when the displacement anomaly of the Stream was similar to that recorded in 2001. In 2003, the Gulf Stream front moved about 32 km seaward of its 2003 position.

Comparing Fig. 21 and 22, we see that there is some similarity between the annual displacements of the two fronts. In fact, they have a correlation of 0.69 with a slope of 0.64 (Shelf/Slope displacement = slope*Gulf Stream displacement + constant). The Gulf Stream and the NAO index are also positively correlated with a value of 0.48.

## SUMMARY

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2003 has shown some broad scale changes from previous years. Cool conditions tended to dominate the Scotian Shelf and to a lesser extent the eastern Gulf of Maine in 2003. Mean annual sea-surface temperature at Boothbay Harbor was 2.4°C above normal, the 7th warmest in 98 years but St. Andrews was 0.6°C below normal ranking 47th in 83 years from warmest to coldest. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by 0.1 to 0.3°C. Salinities were almost always 0-0.6 above normal throughout the year. Halifax sea surface temperature was 1.8°C below normal over the year, making 2003 the 4th coldest in 78 years. At Halifax Station 2, 0-100 m temperature anomalies were 0°C to –2°C; salinity was typically 0-0.5 above normal. Sydney Bight, Misaine Bank and Emerald Basin (to 75 m) featured anomalies of –1 to –2°C. At depths greater than 75 m, Emerald Basin temperatures were about 0.5°C above normal. Lurcher Shoals temperature anomalies were mixed but slightly above normal for the year. Georges Basin showed an anomaly reversal like Emerald Basin with temperatures about 1°C below normal 0-100m and 0.5°C above normal deeper. Eastern Georges Bank temperature anomalies varied through the year, negative early, positive late with amplitudes less than 1°C. Standard sections in April, July, October and December on the Scotian Shelf support the overall conclusion of temperatures ~2°C below normal, salinities ~0.5 above normal and a more intense and extensive cold intermediate layer on the shelf. Cabot Strait deep-water (200-300 m) temperatures were near normal. The temperatures from the July groundfish survey were exceptional with the outstanding feature being a very broad cold intermediate layer with below normal temperatures. The July surface temperatures were generally 0-3°C above normal for the survey region except for the Bay of Fundy where below normal temperatures by up to 2°C prevailed. However, at the deeper layers of 50 m, 100 m and at the bottom below normal temperatures of up to 3, 2 and 1°C dominated. Break-up of the strong stratification pattern established in the late 20th and early 21st century continued in 2003. Though overall stratification was slightly above normal for the Scotian Shelf region, there was considerable variability with small spatial scales. The Shelf/Slope front and the Gulf Stream moved in opposite directions in 2003 with the former moving onshore on average by 22 km compared to its position in 2002 and the latter offshore by 32 km.

## 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; the Bigelow Laboratory for providing Boothbay Harbor temperature data; F. Page and R. Losier of the Biological Station in St. Andrews, for providing St. Andrews and Prince 5 data; J. McRuer for the Scotian Shelf July groundfish survey data; G. Bugden of BIO and D. Gilbert of IML for their Cabot Strait temperature data; and 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.

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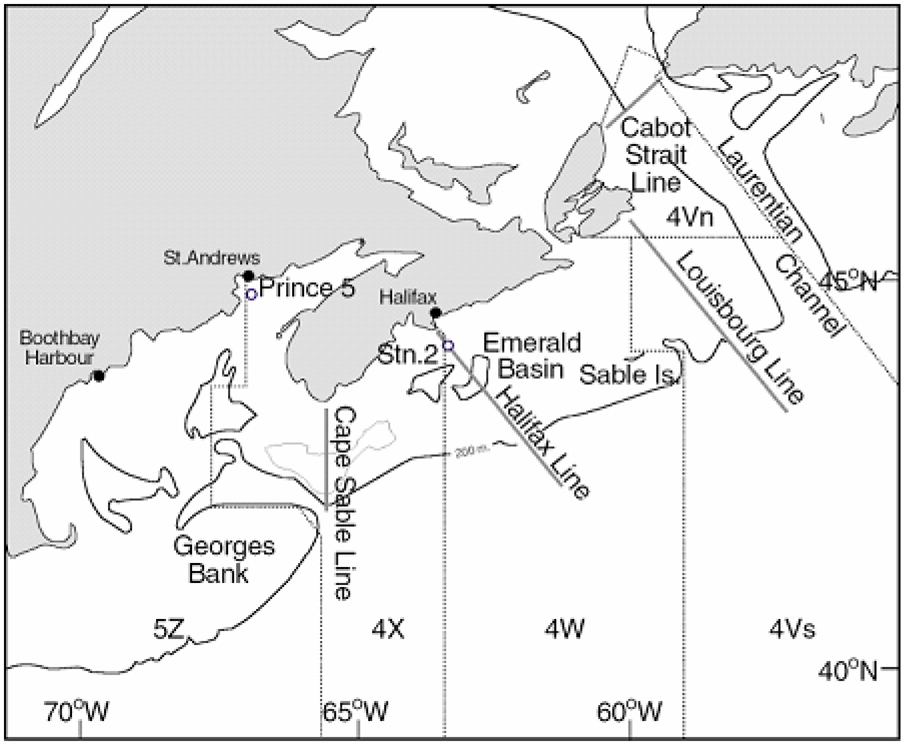


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

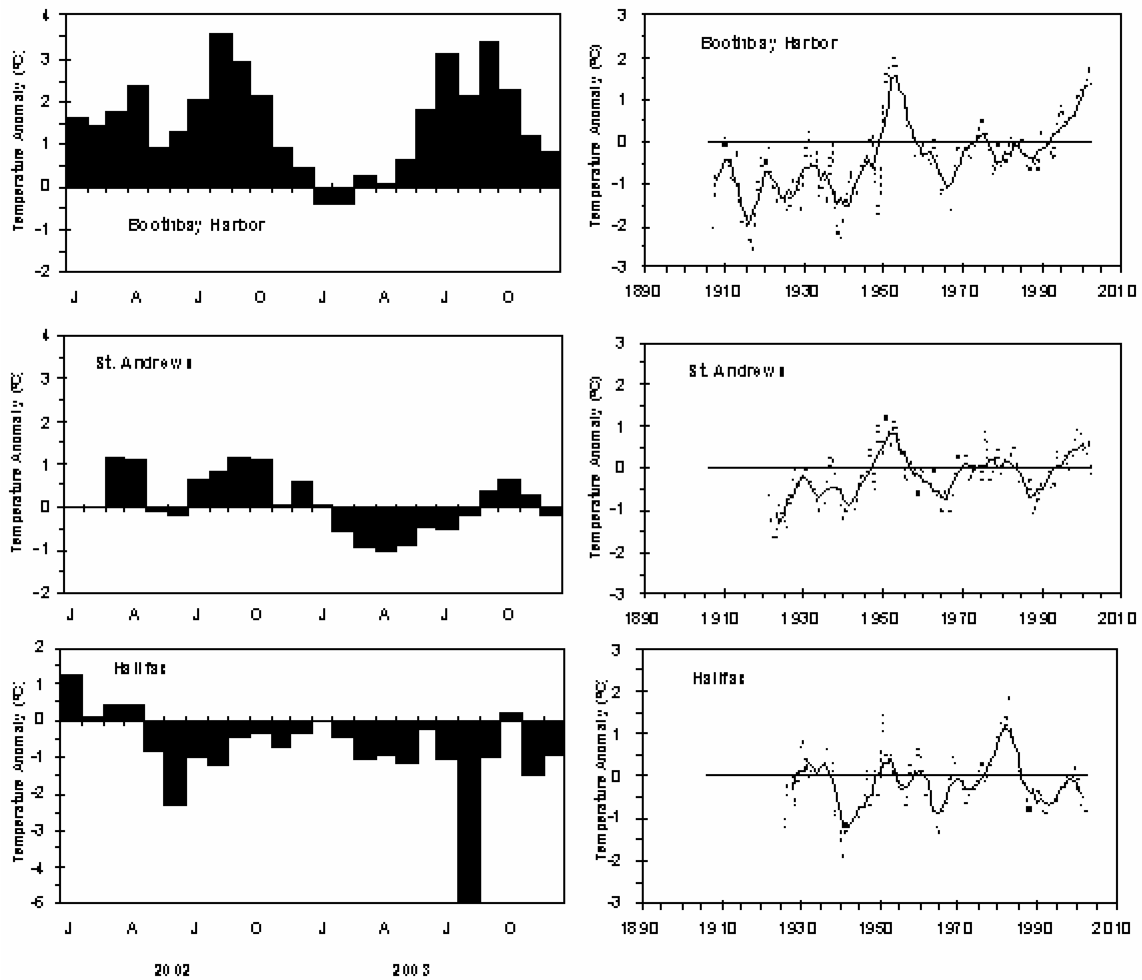


Fig. 2. The monthly sea surface temperature anomalies during 2002 and 2003 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Anomalies are relative to the 1971-2000 means.

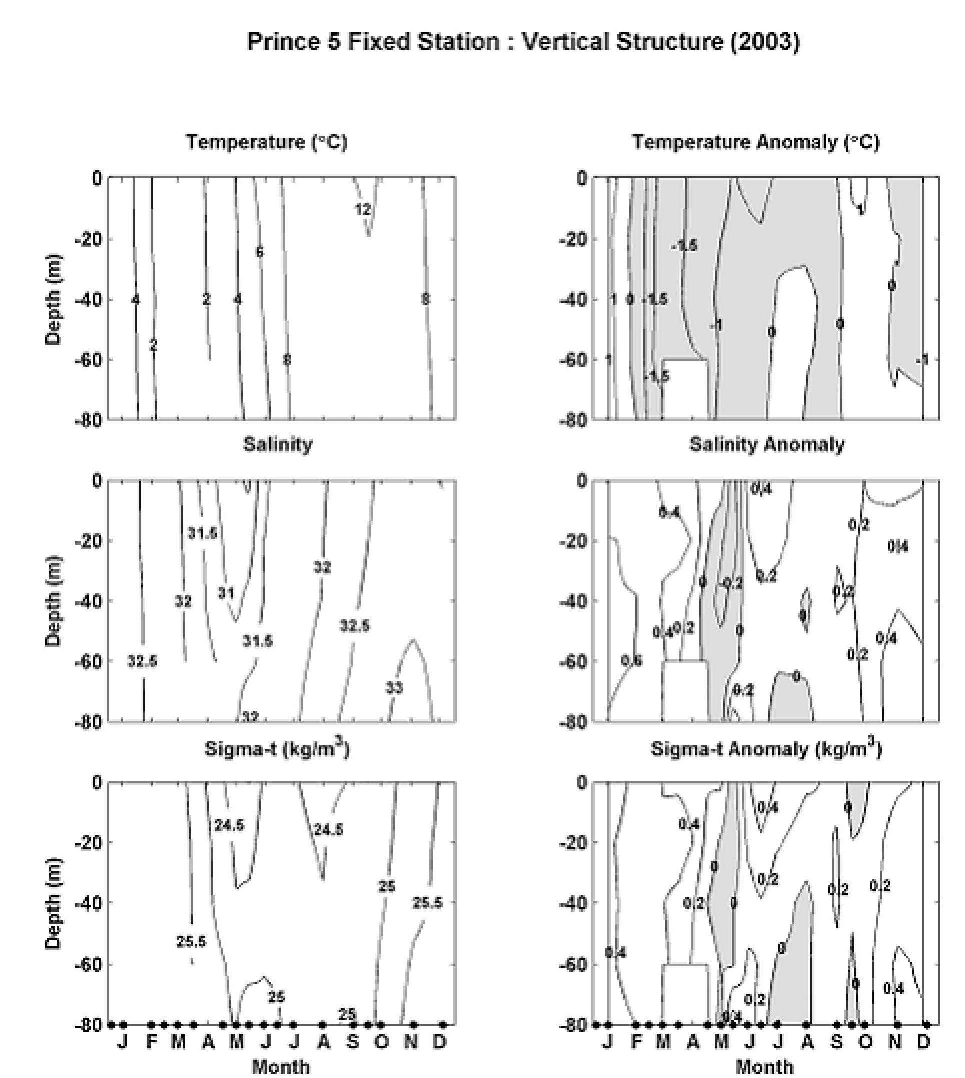


Fig. 3. Contours of temperature, salinity and sigma-t and their anomalies at Prince 5 as a function of depth during 2003 relative to the 1971-2000 means. Colder and fresher-than-normal conditions are shaded.

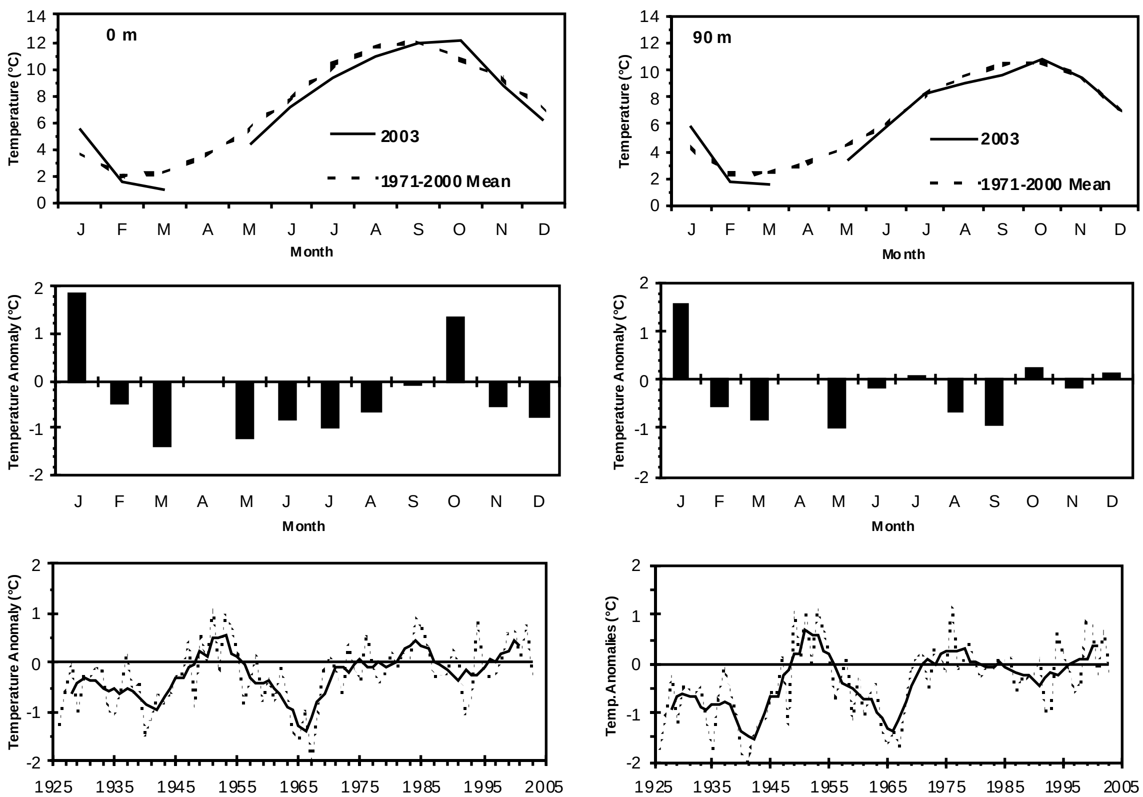


Fig. 4. The monthly mean temperatures for 2003 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

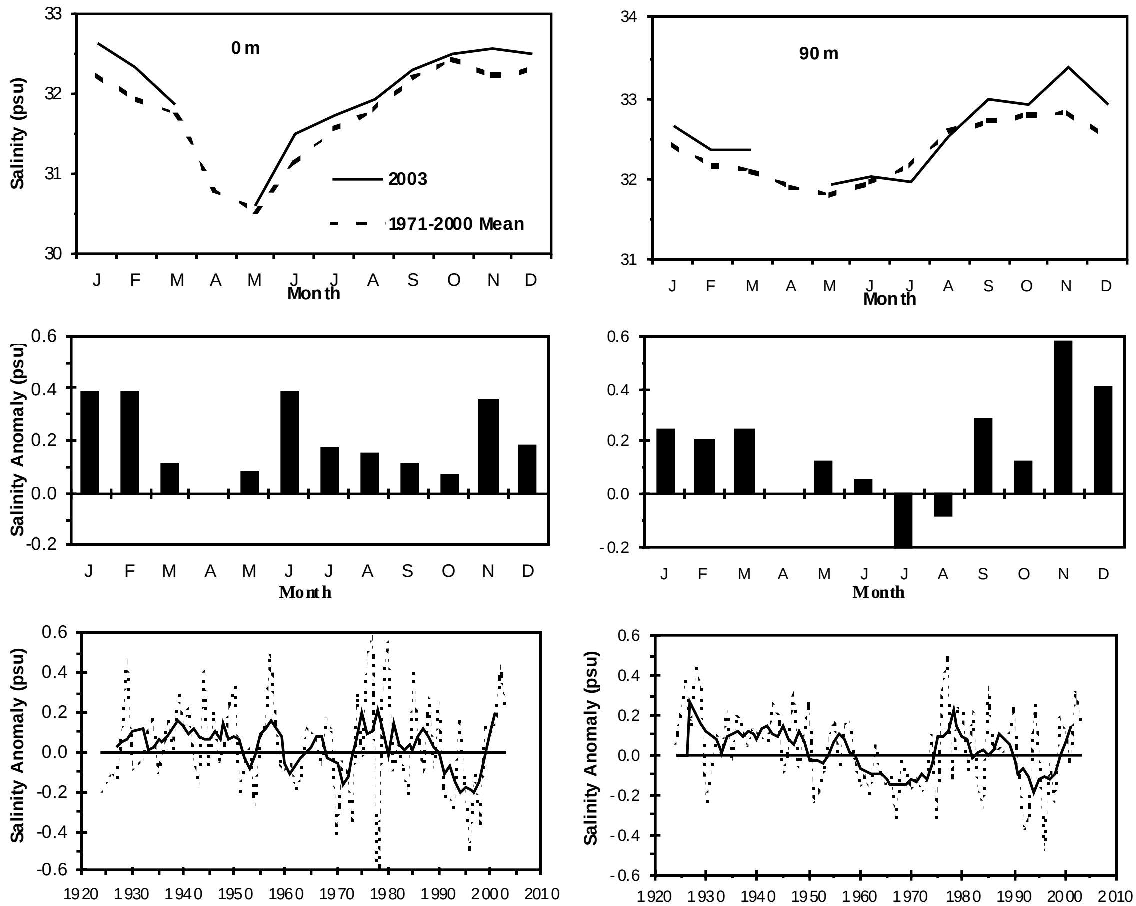


Fig. 5. The monthly mean salinities for 2003 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

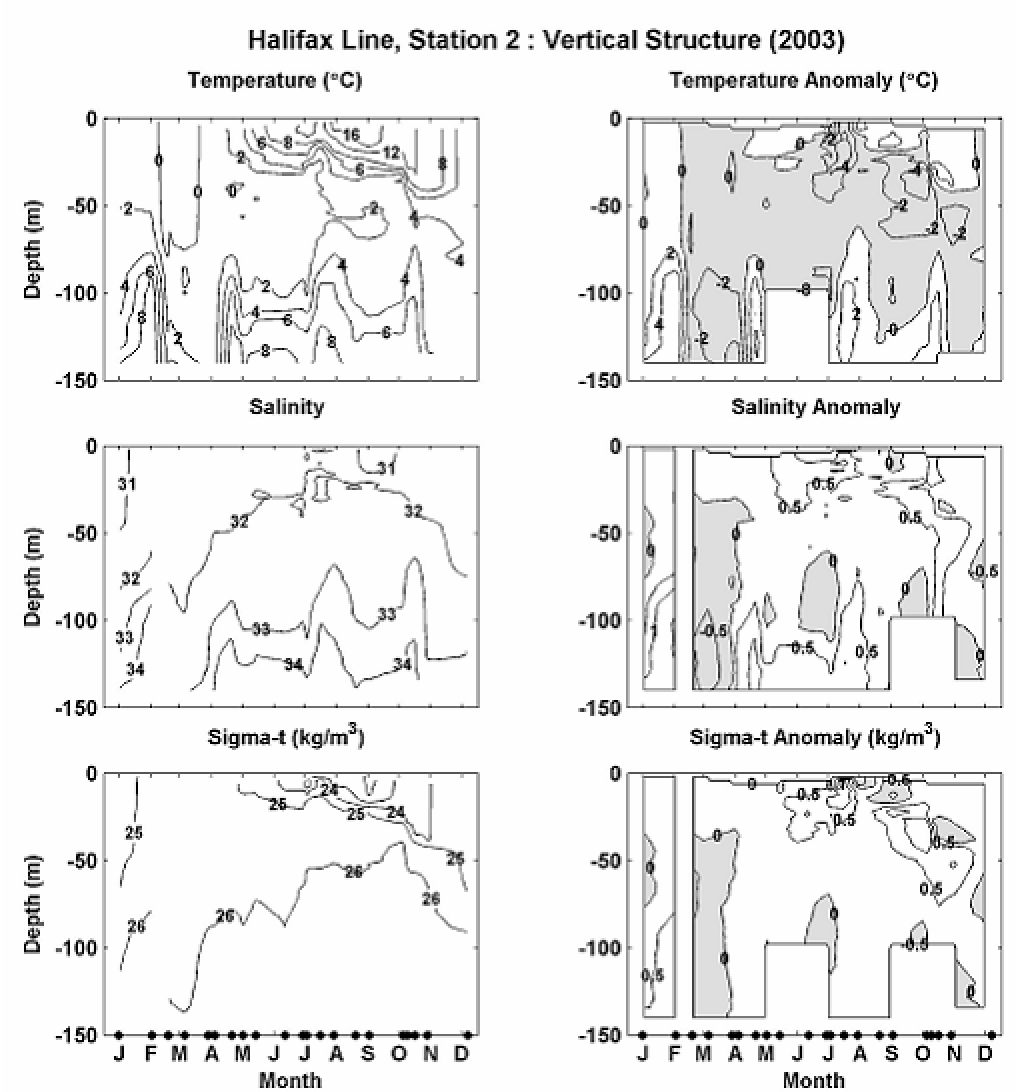


Fig. 6. Contours of the 2003 temperature, salinity and density (sigma-t) (left) and their anomalies (right) at the standard station H2. Negative anomalies are shaded.

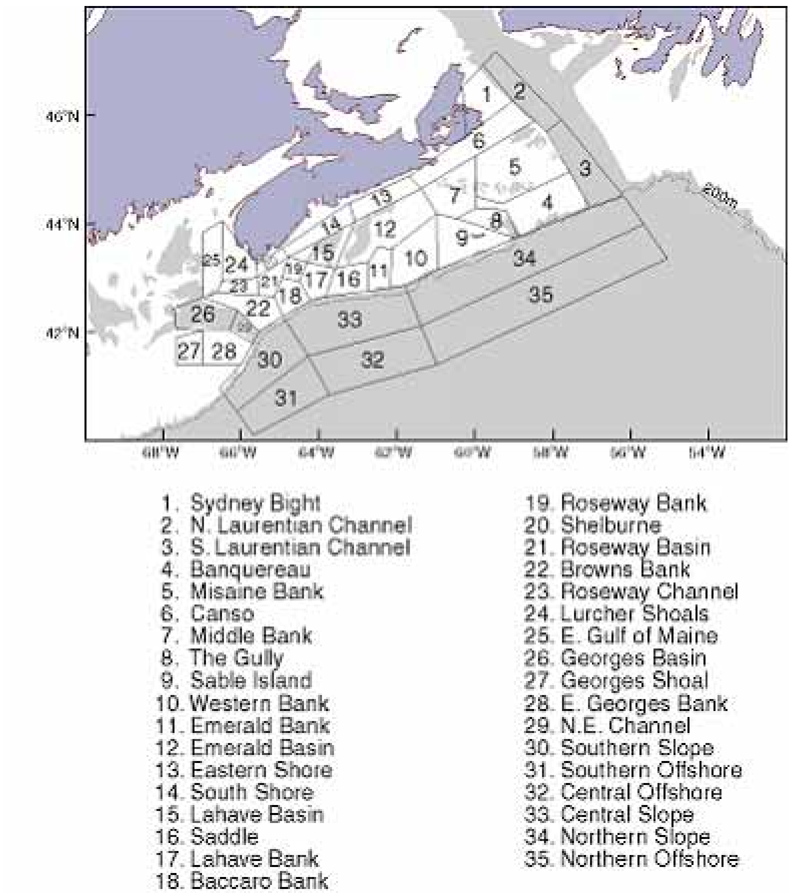


Fig. 7. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

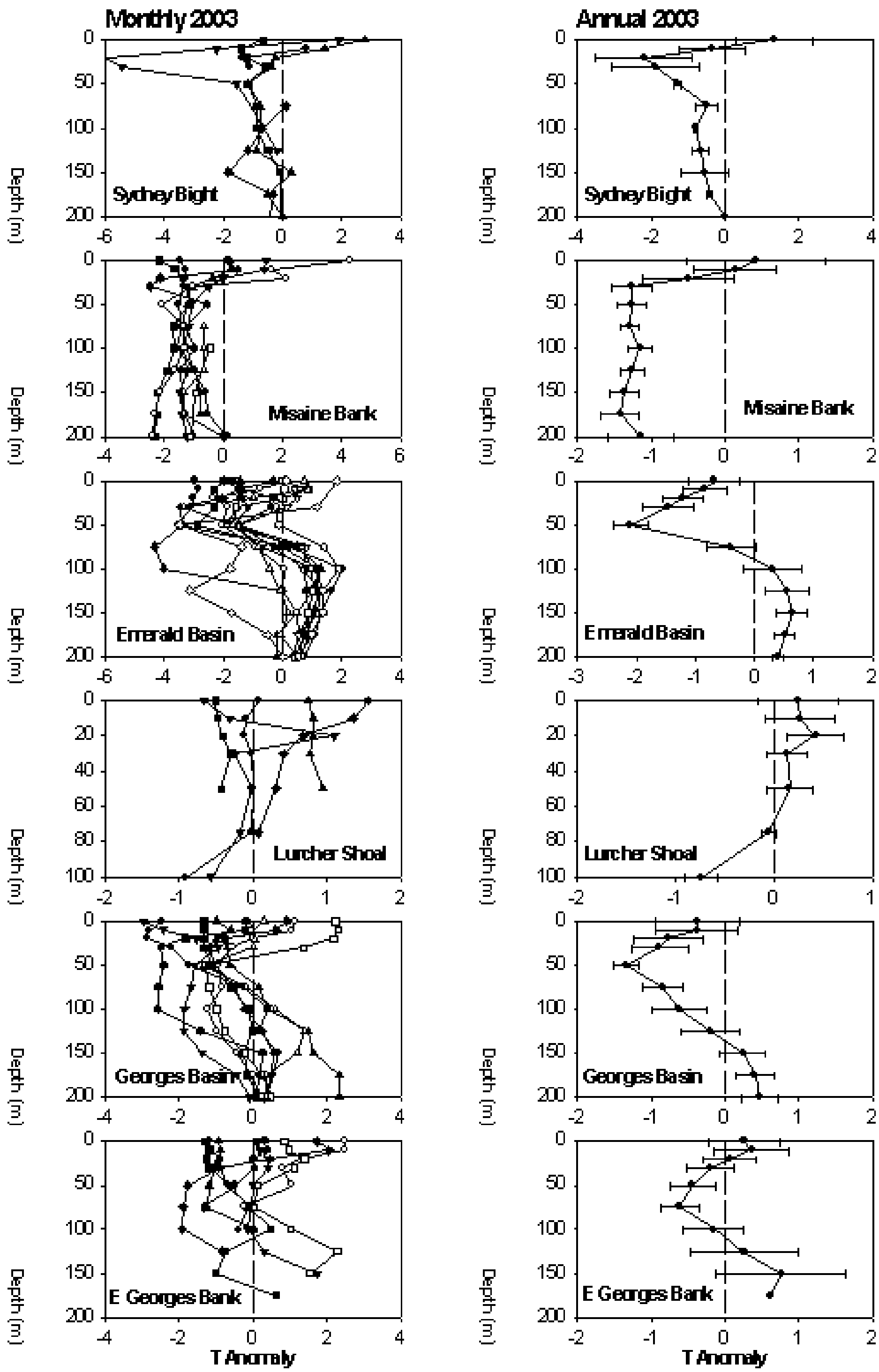


Fig. 8. Monthly (left) and annual (±std. error, right) temperature anomaly profiles for selected locations. Symbol order is filled dot, square, up triangle, down triangle, diamond, hexagon, then open symbols in the same order.

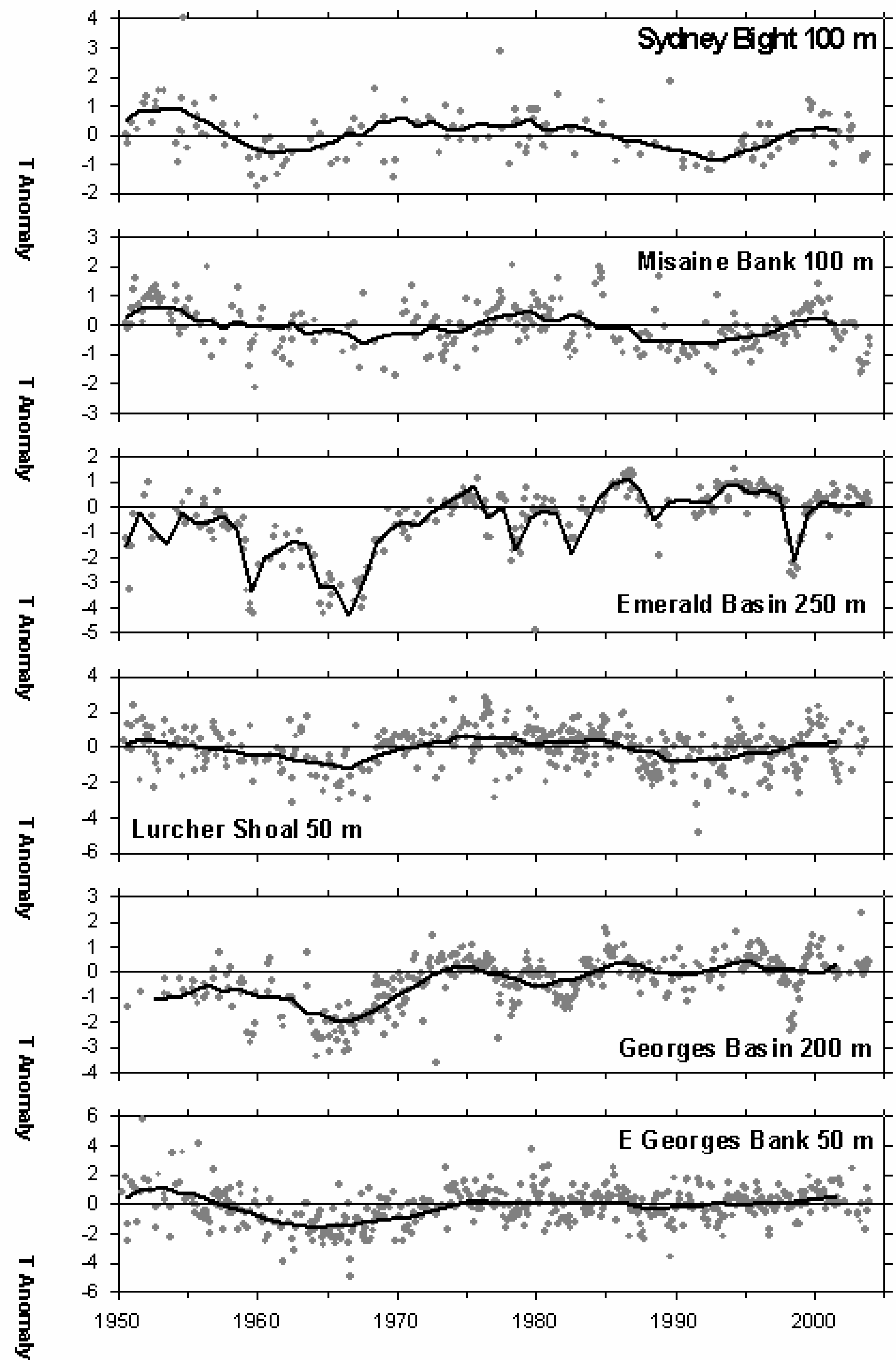


Fig. 9. The monthly mean temperature anomaly time series (grey dots) and the 5-yr running mean of the estimated annual anomalies (solid line) at 6 sites on the Scotian Shelf and in the Gulf of Maine (see Fig. 7).

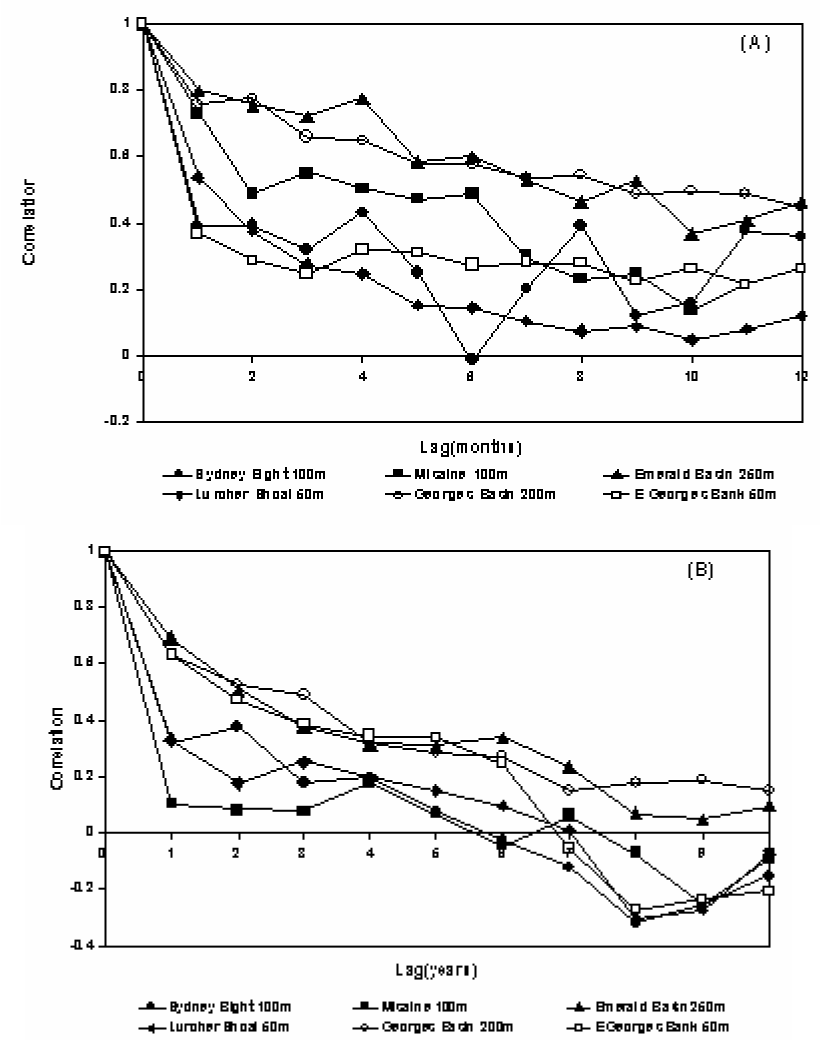


Fig. 10. Autocorrelations of the temperature series of Fig. 9 for the (A) monthly and (B) annual anomalies.

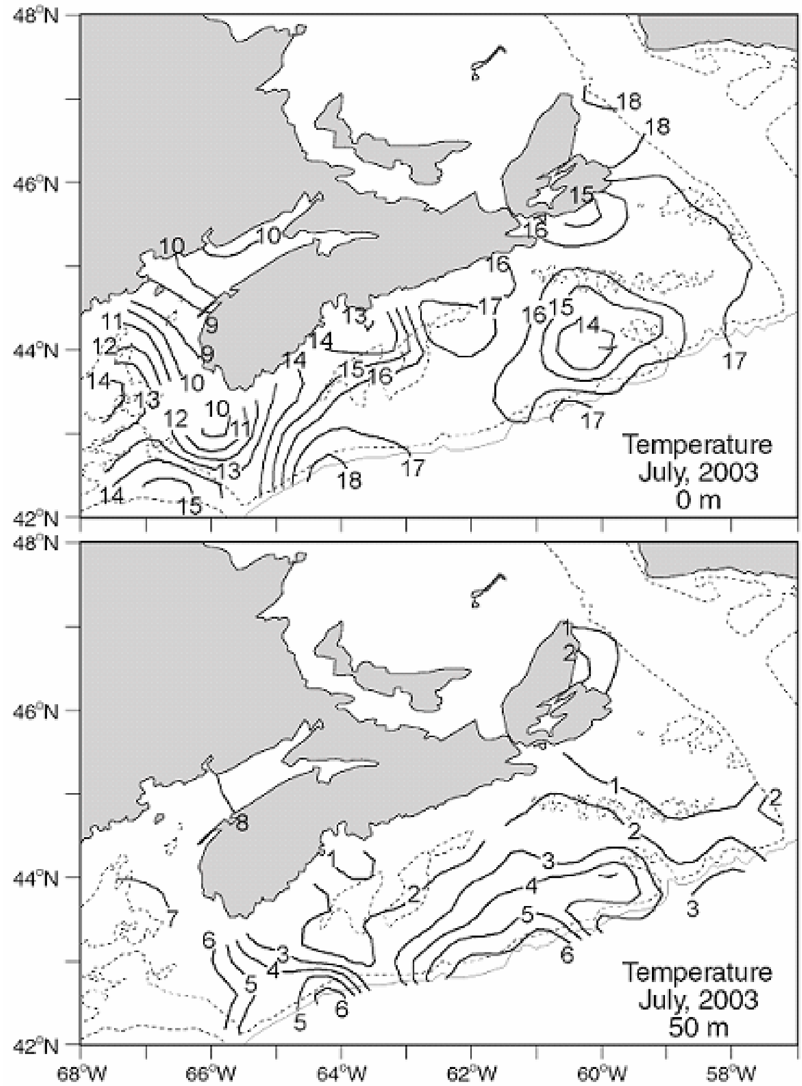


Fig.11a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2003 July groundfish and ITQ surveys.

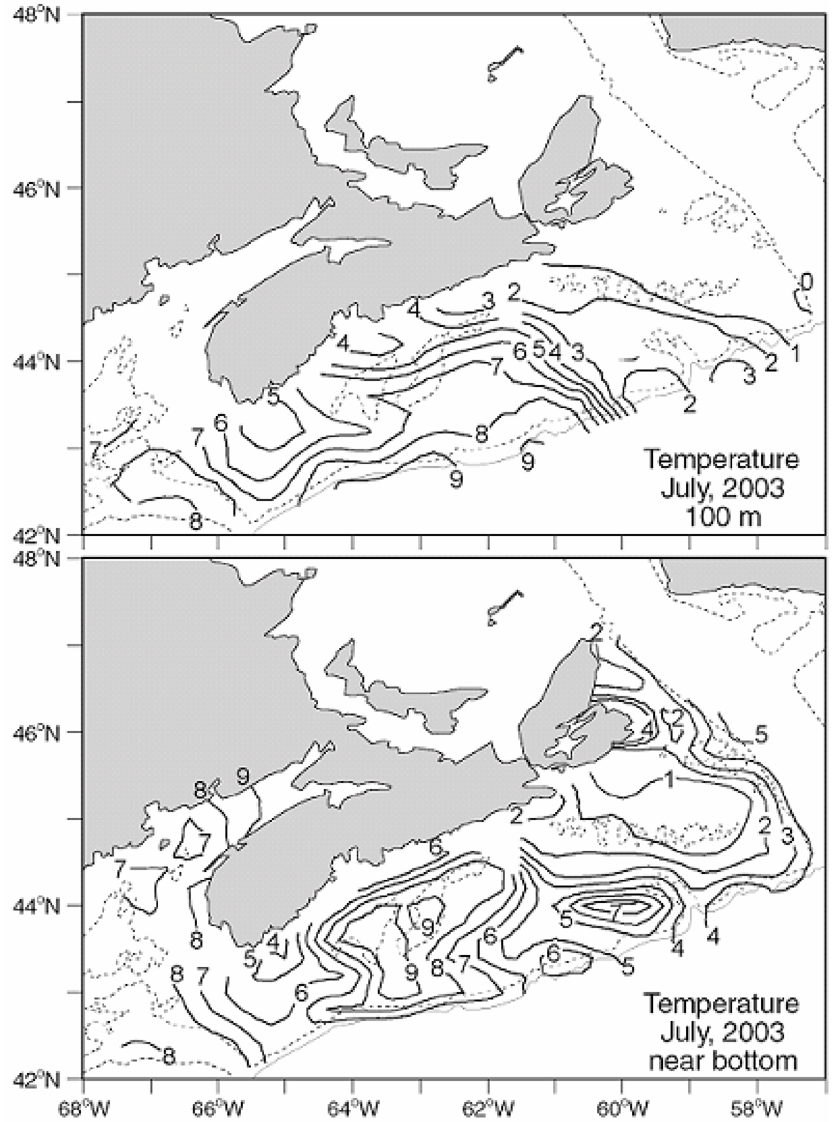


Fig. 11b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2003 July groundfish and ITQ surveys.

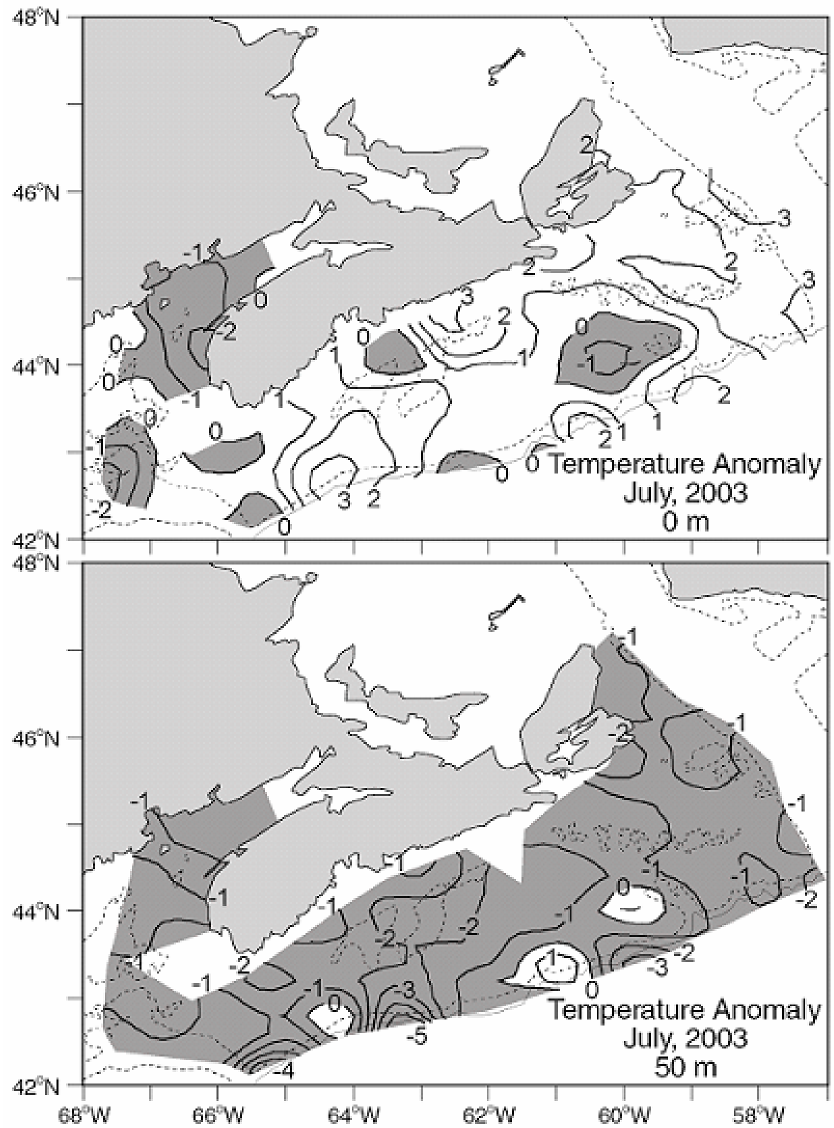


Fig.12a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2003 July groundfish and ITQ surveys.

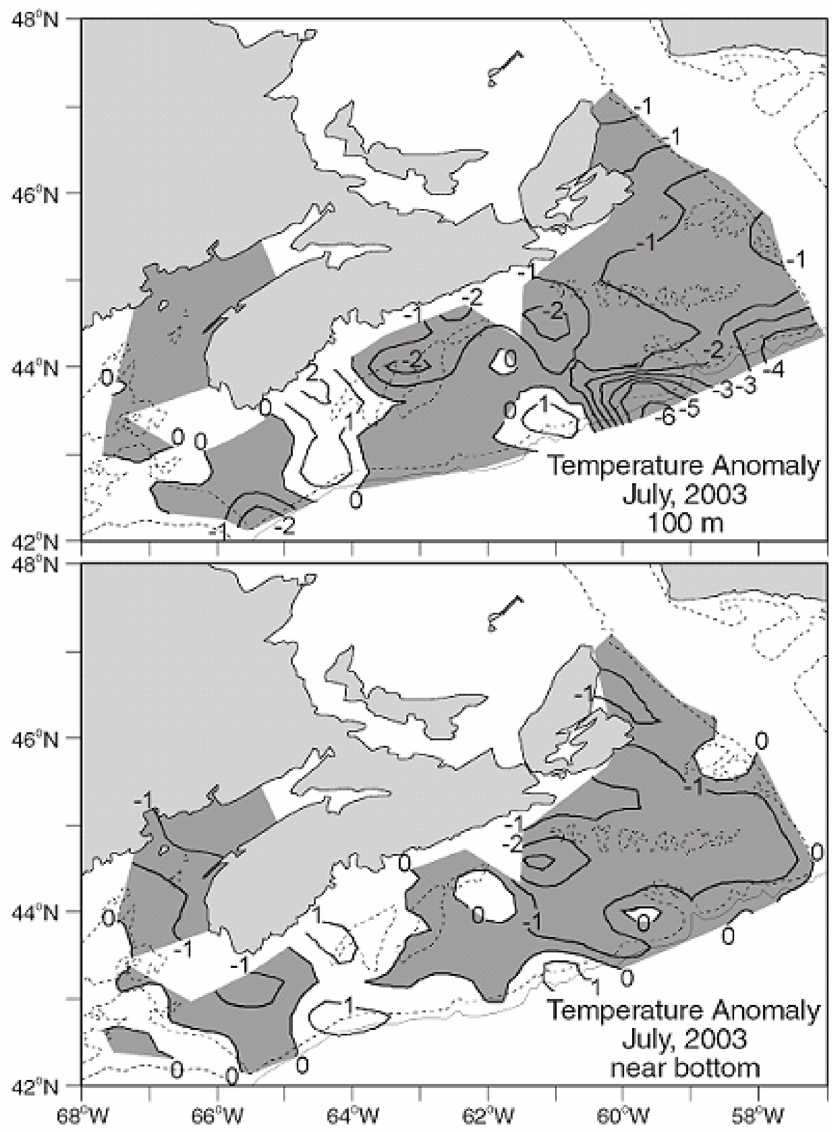


Fig.12b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2003 July groundfish and ITQ surveys.

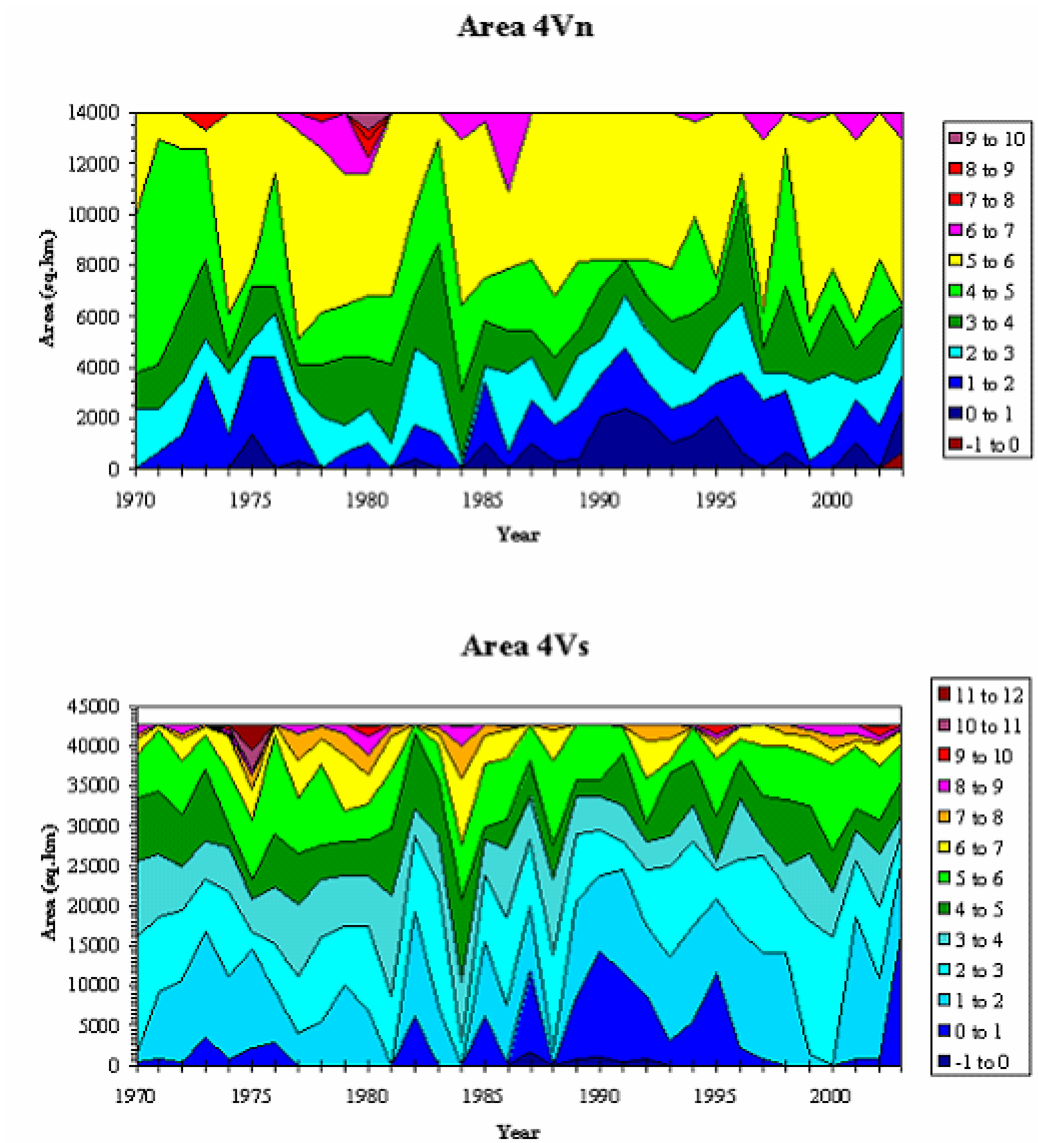


Fig.13a. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).

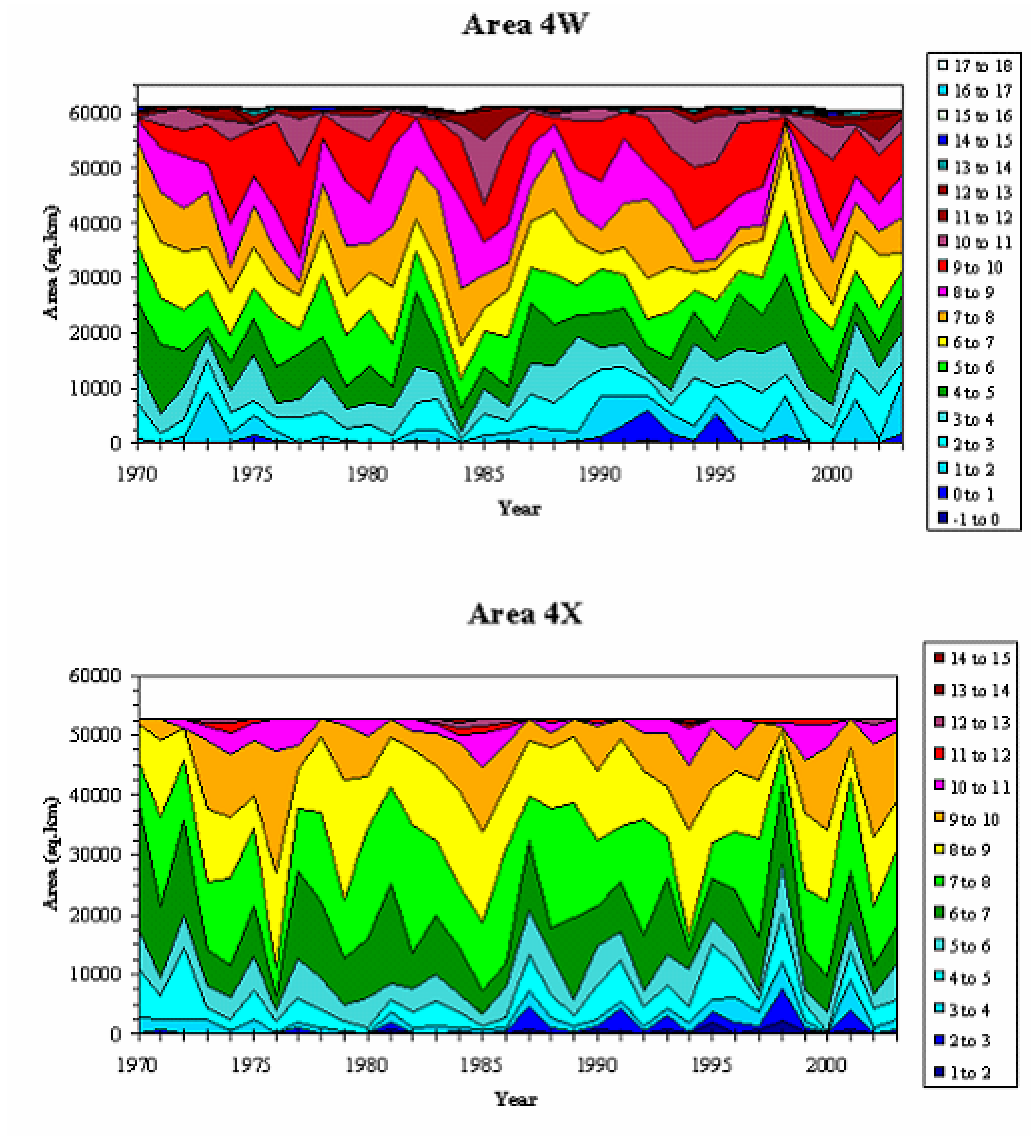


Fig. 13b. The time series of the area of the bottom for each $1^{o}C$ temperature range for NAFO Subareas 4W (top panel) and 4X(bottom panel).

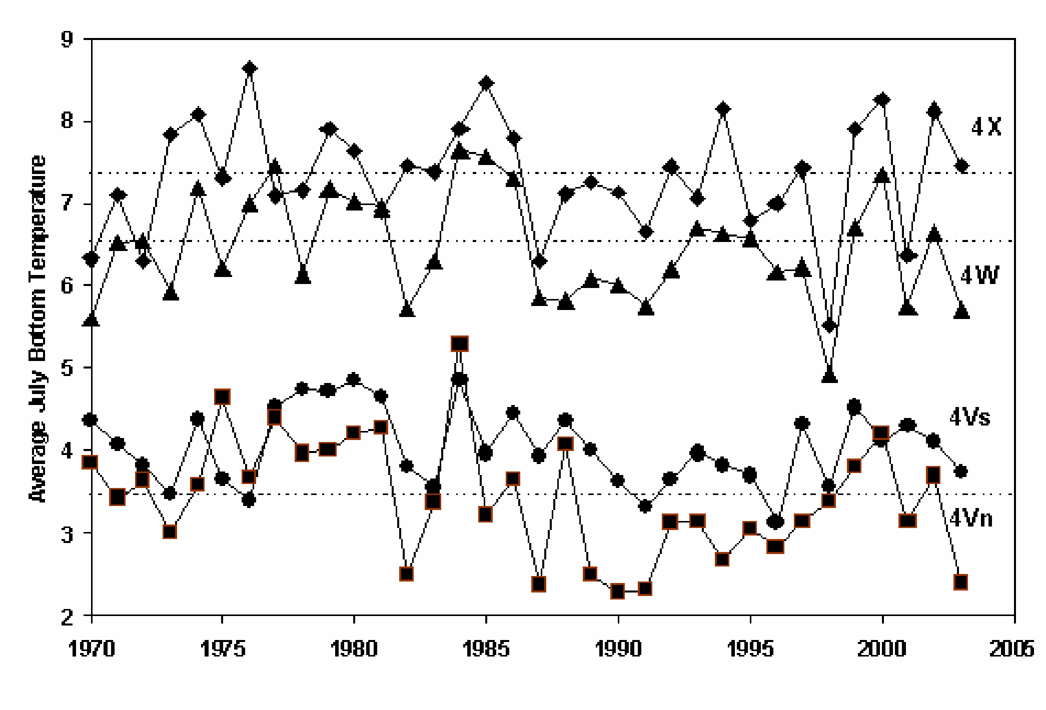


Fig. 14. Time series of annual mean bottom temperatures from areas 4Vn, 4Vs, 4W and 4X. The horizontal lines are the 1971-2000 means.

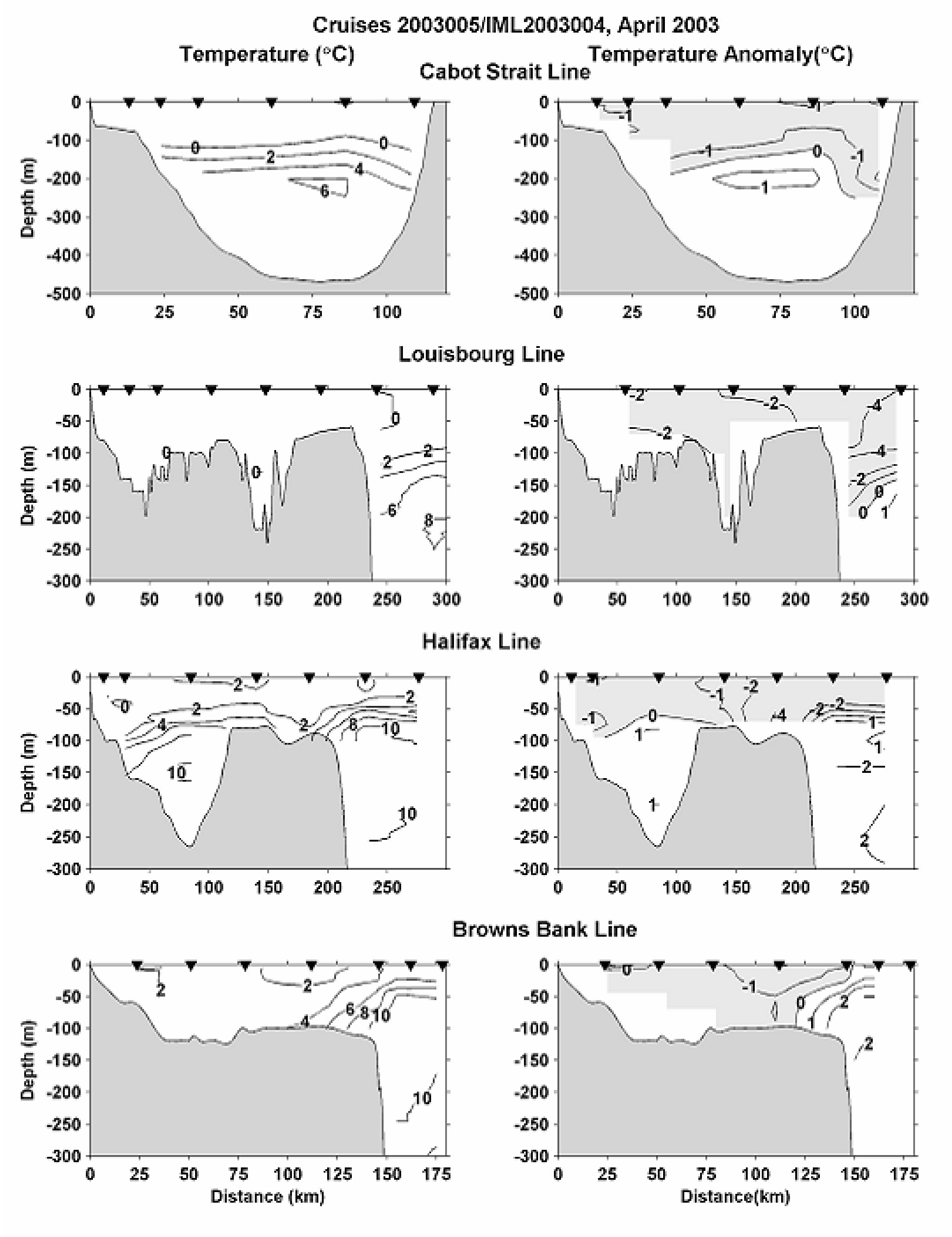


Fig.15a. Temperature and temperature anomalies for standard Scotian Shelf sections, April 2003.

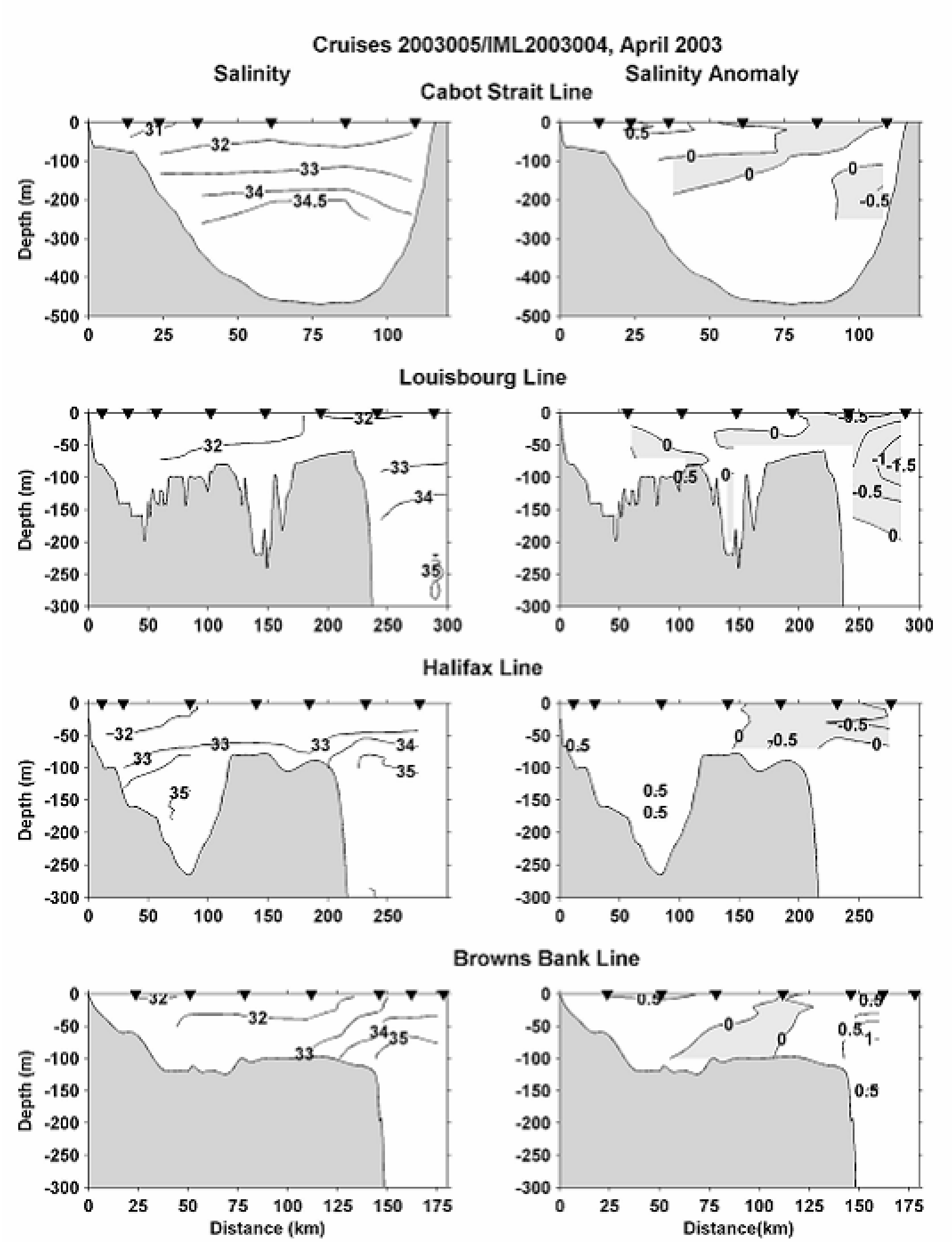


Fig.15b. Salinity and salinity anomalies for standard Scotian Shelf sections, April 2003.

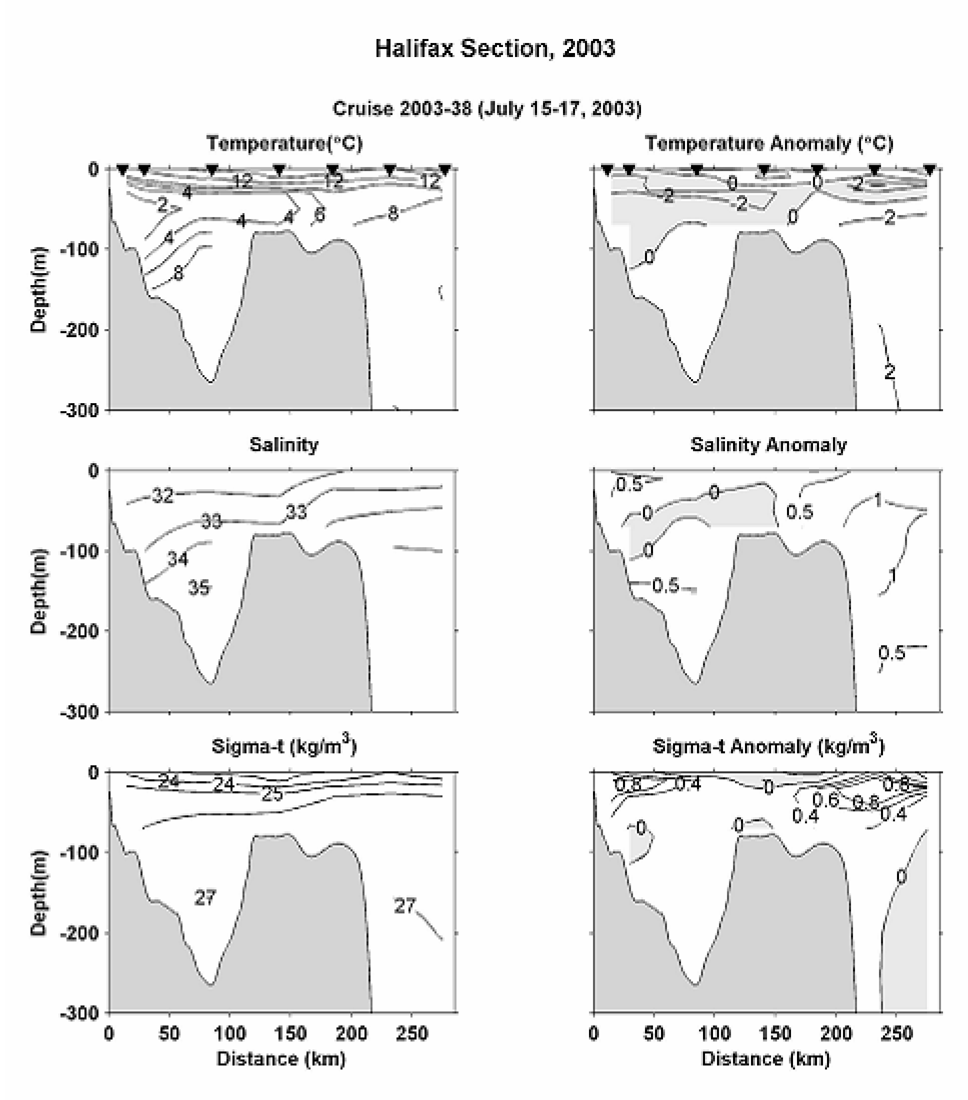


Fig.15c. Temperature, salinity, density and their anomalies for the Halifax section, July 2003.

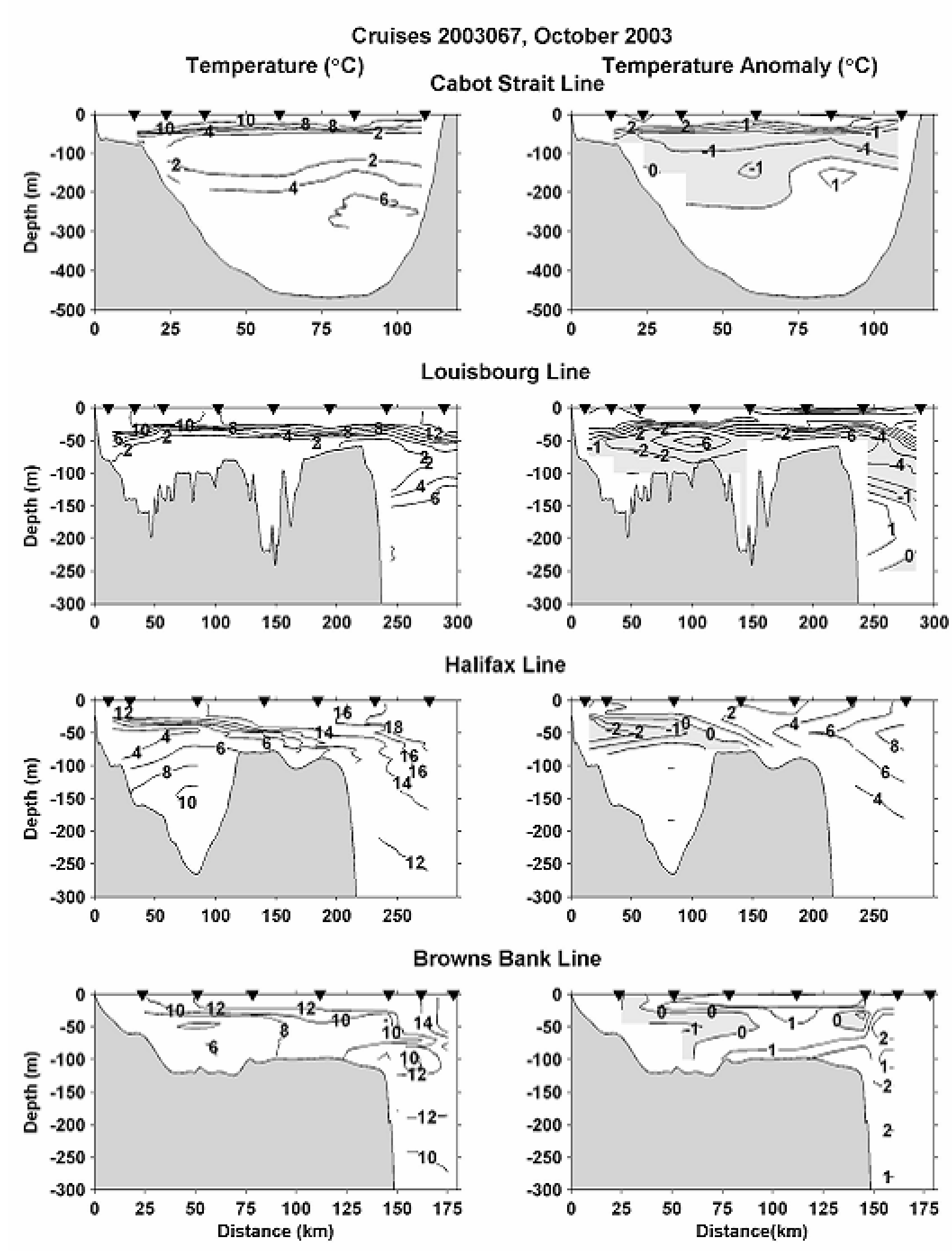


Fig.15d. Temperature and temperature anomalies for standard Scotian Shelf sections, October 2003.

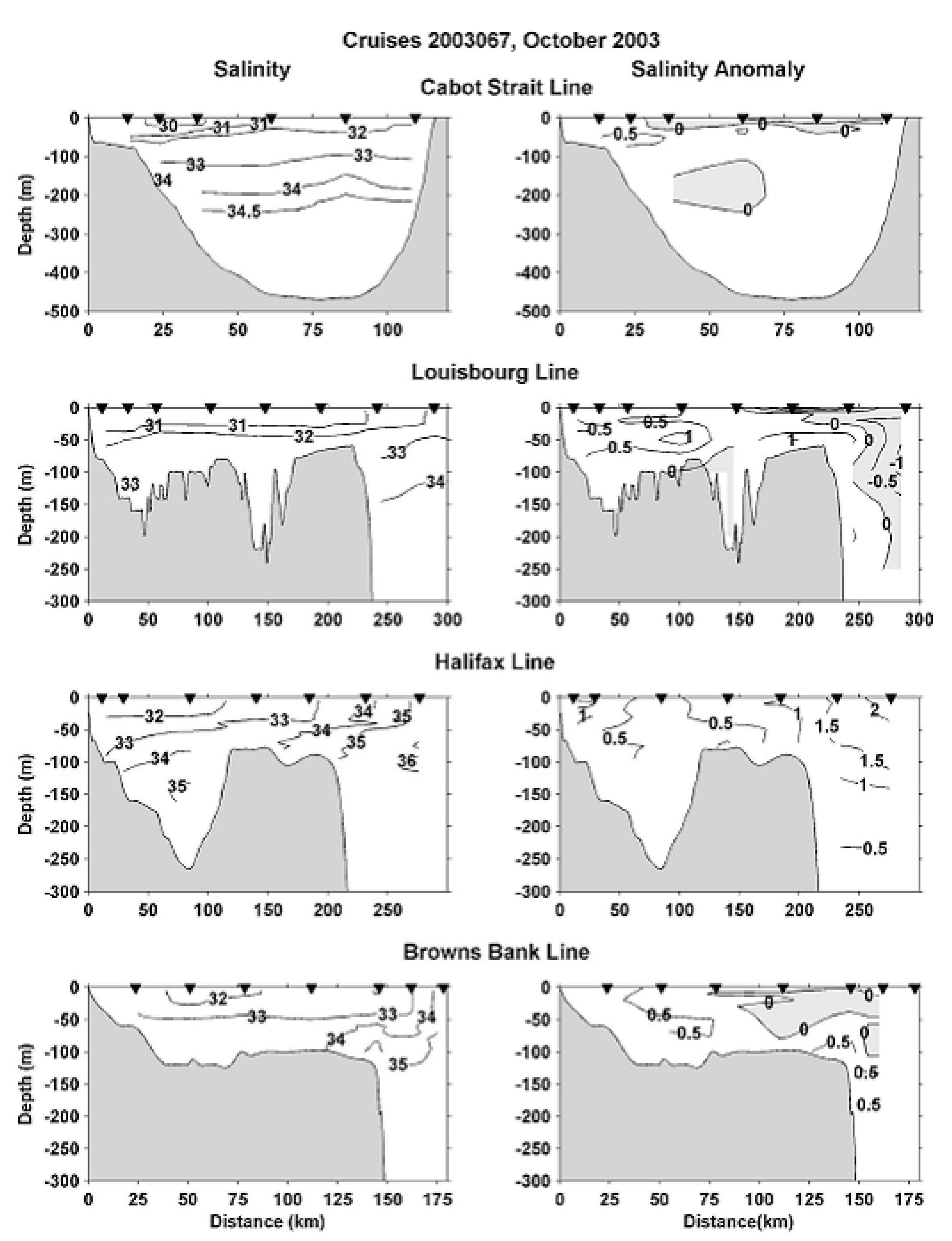


Fig.15e. Salinity and salinity anomalies for standard Scotian Shelf sections, October 2003.

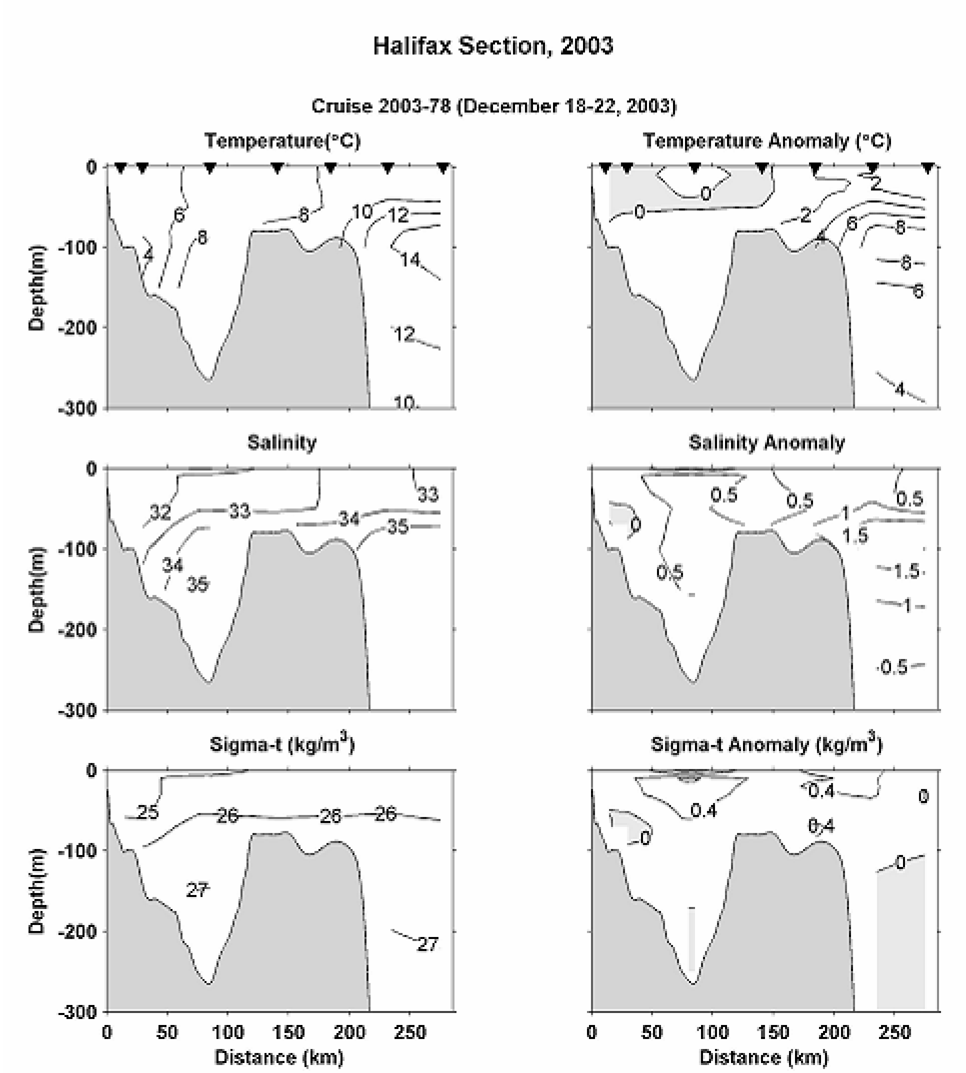


Fig.15g. Temperature, salinity, density and their anomalies for the Halifax section, December 2003.

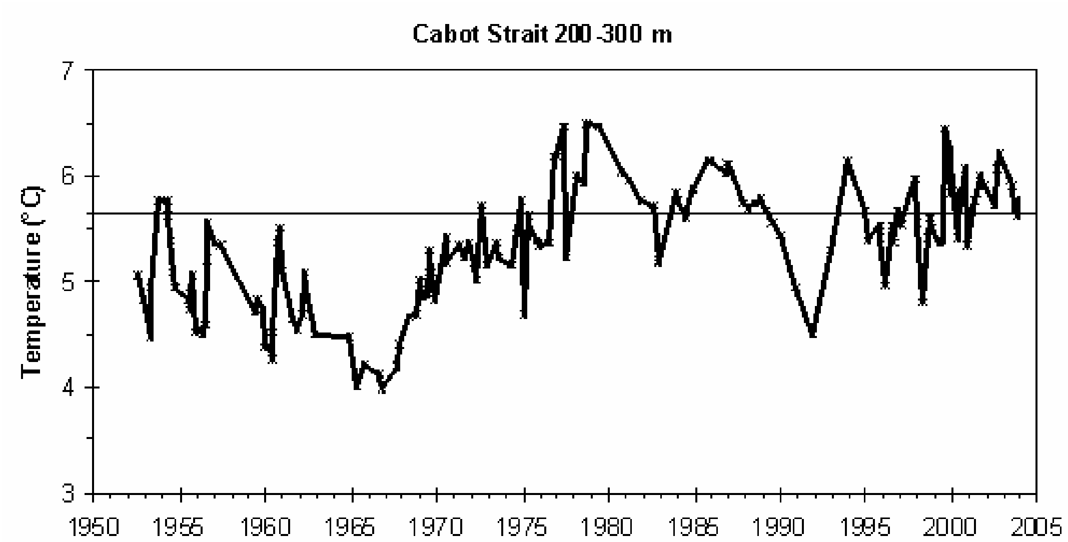


Fig. 16. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the 1971-2000 mean.

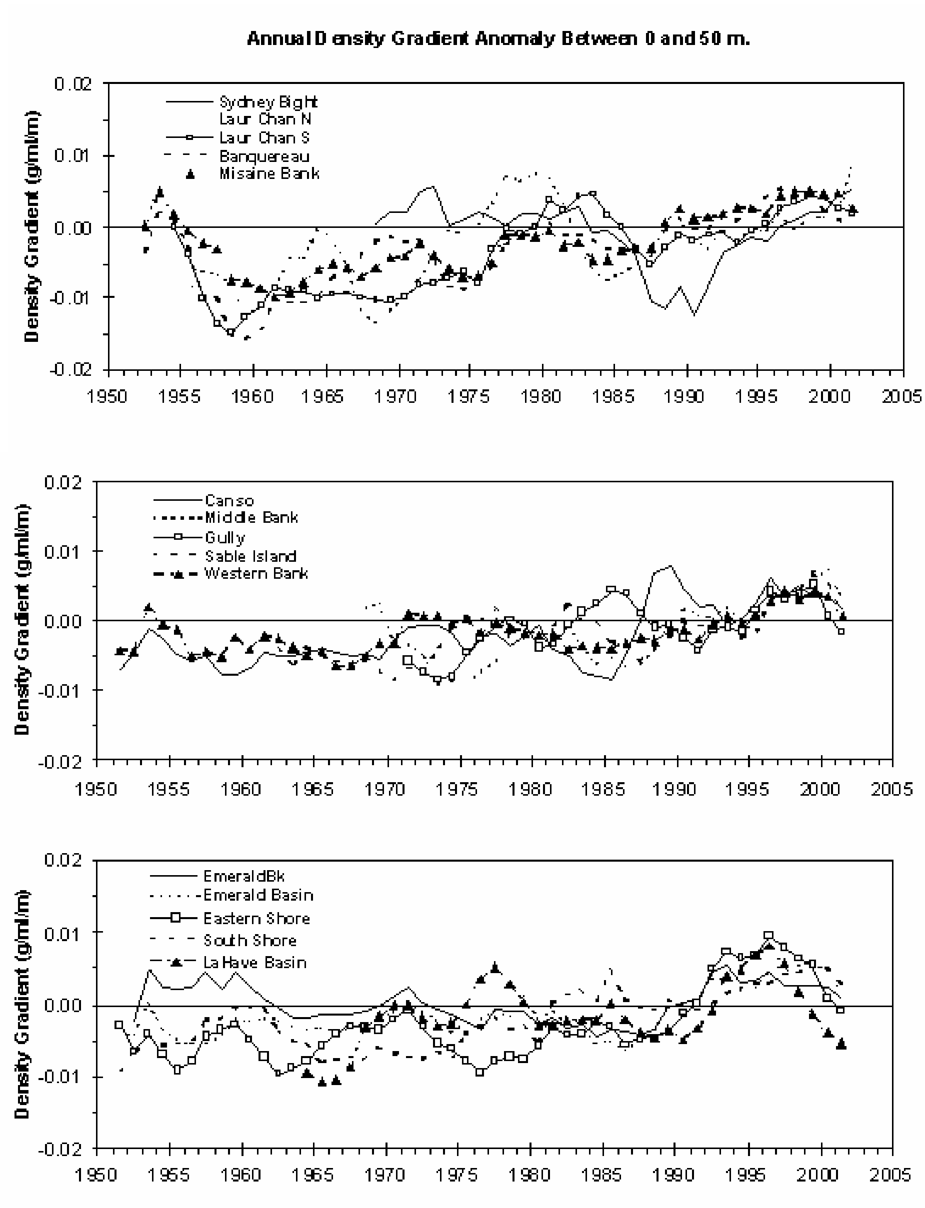


Fig.17a. Five-year running means of the annual density gradient anomalies between the surface and 50 m calculated for the areas 1-15 in Fig. 7.

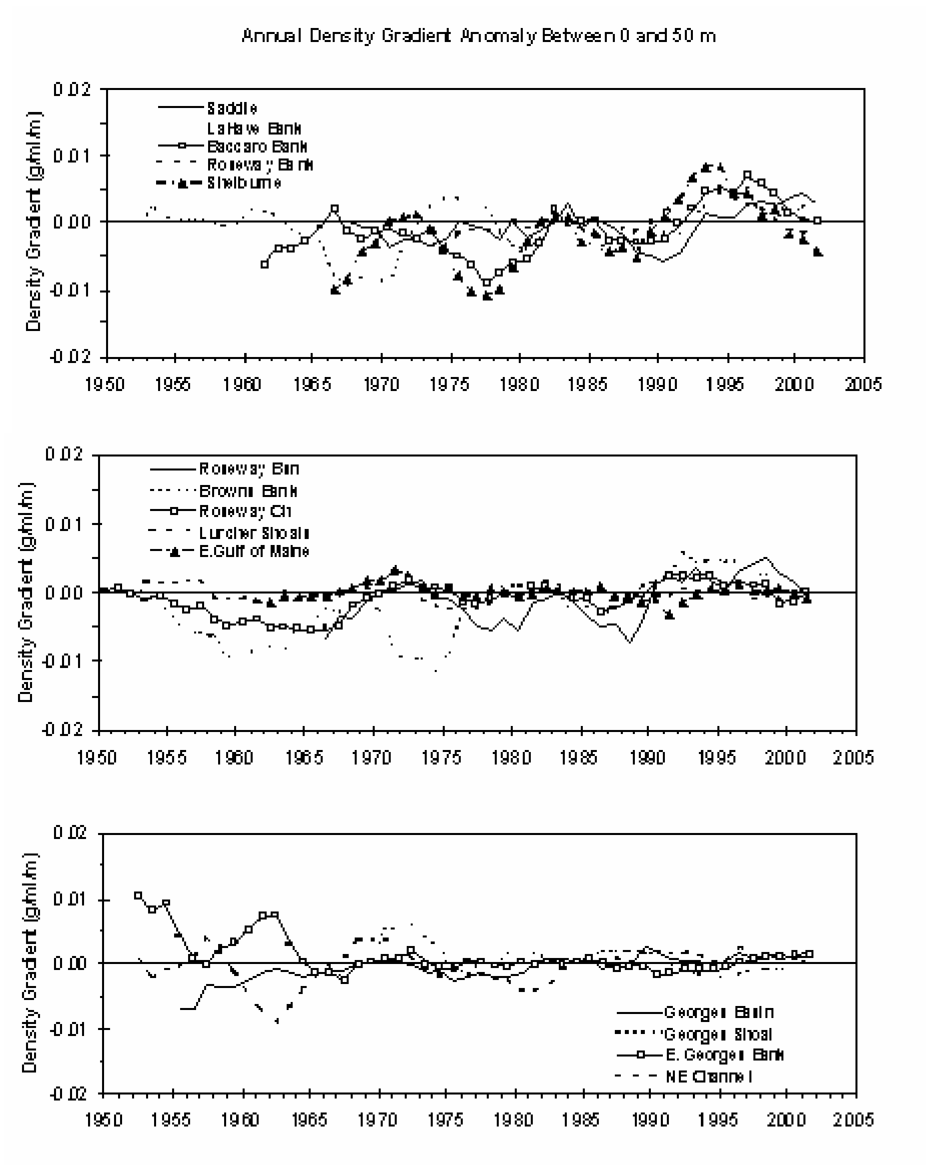


Fig.17b. Five-year running means annual density gradient anomalies between the surface and 50 m calculated for the areas 16-29 in Fig. 7.

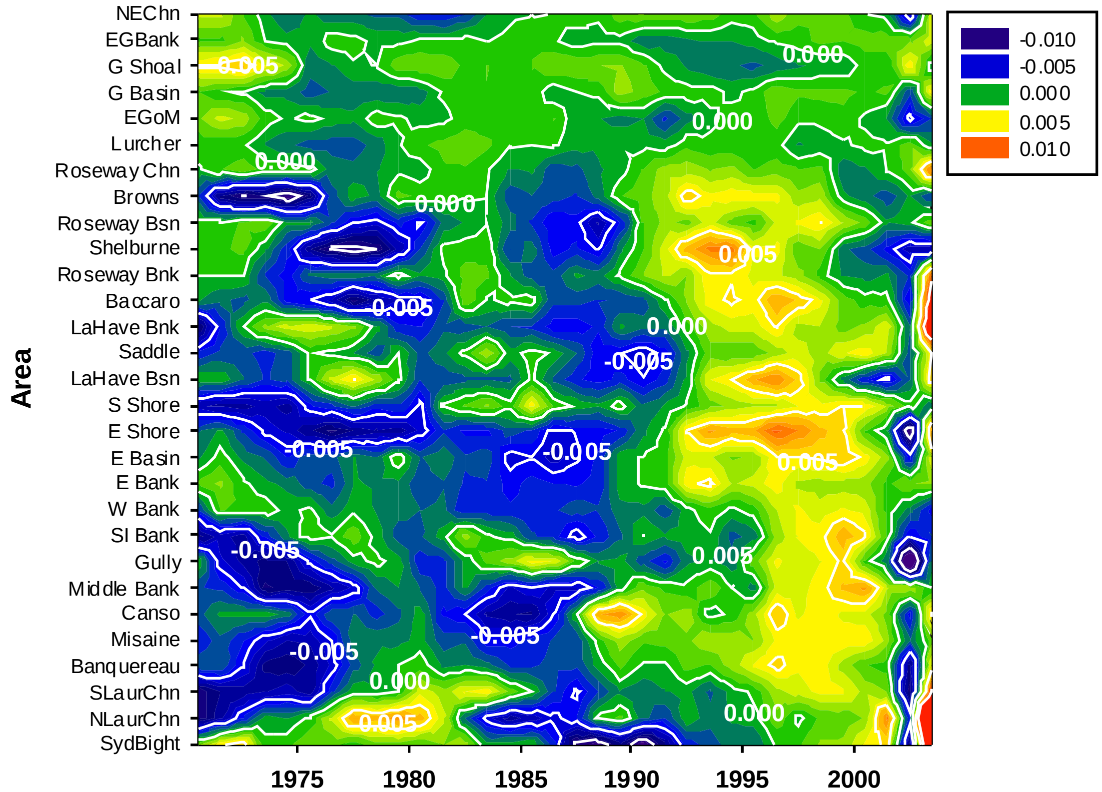


Fig. 18. The contoured density anomaly for 1970-2003. The anomalies for 1970-2001 are the 5 y running mean values; the annual values are shown for 2002-03.

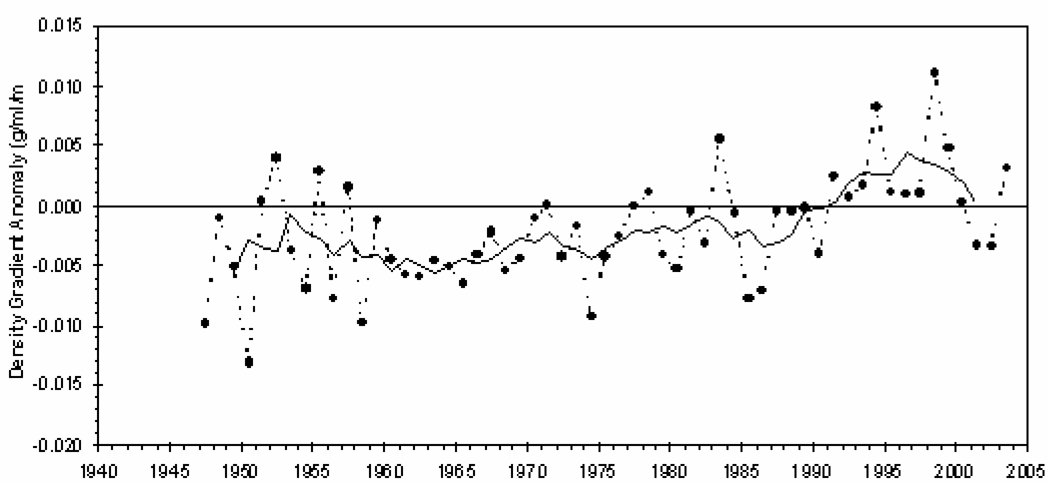


Fig. 19. The mean annual (dashed line) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive). The short horizontal lines for each year represent the standard errors of the different areas.

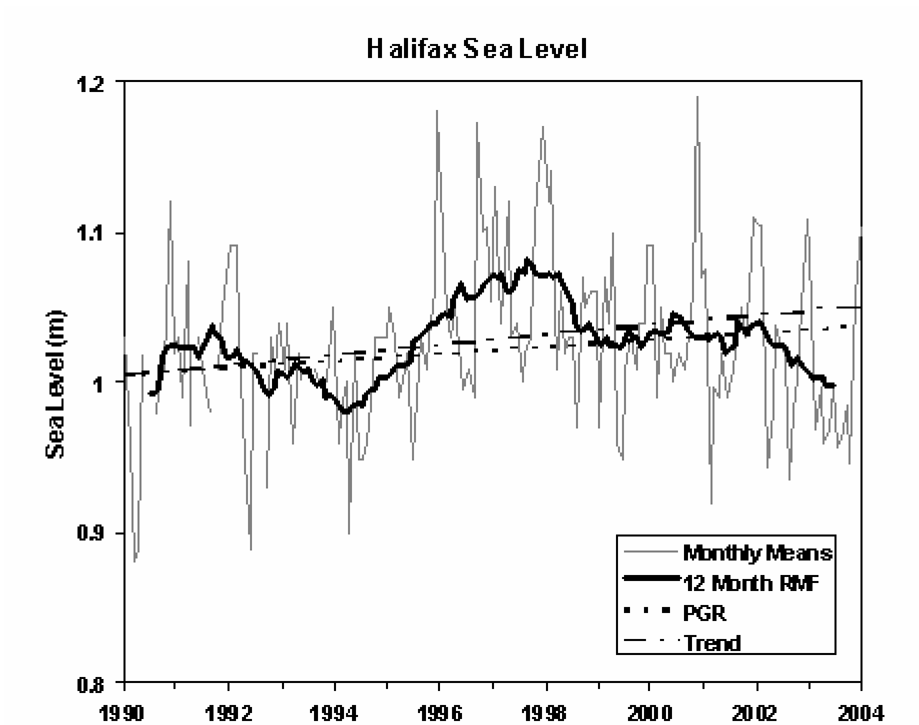


Fig. 20. The time series of the monthly means and a 12 month running mean of the sea level elevations at Halifax, along with the observed linear trend and that predicted by a model from post-glacial rebound.

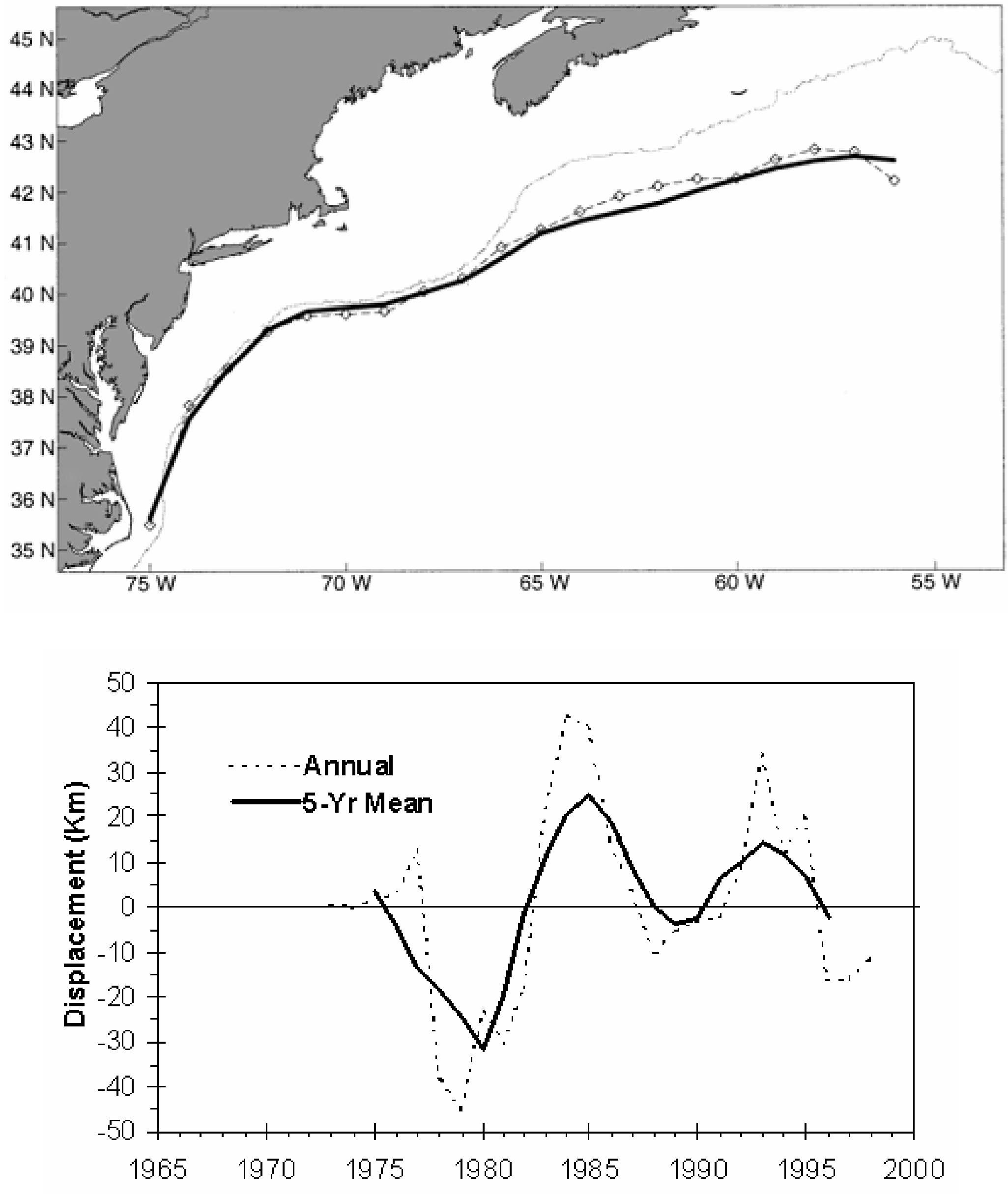


Fig. 21. The 2003 (dashed line) and long-term mean (1973-2000; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).

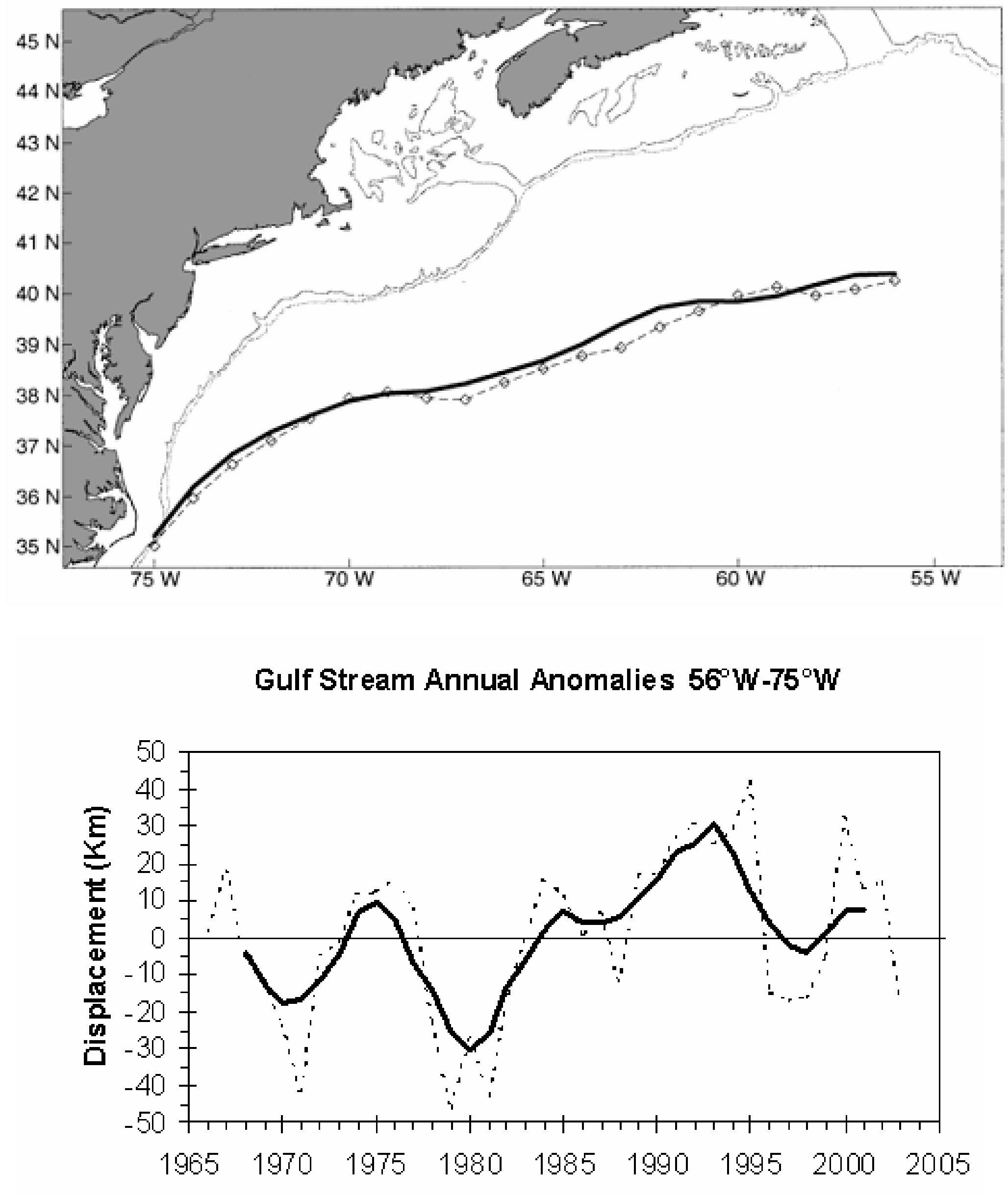


Fig. 22. The 2003 (dashed line) and long-term mean (1973-2000; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).