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Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2004

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 2004 has shown the continuation of conditions similar to 2003. Cool conditions tended to dominate the Scotian Shelf and the eastern Gulf of Maine in 2004. The temperature data from Boothbay Harbor were suspicious; the Boothbay Harbor laboratory is investigating. St. Andrews sea surface temperature was 0.8°C below normal making 2004 the 14th coldest in 84 years. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by about 0.9°C. Salinities were within 0.1 of normal throughout the year. Halifax sea surface temperature was 1.0°C below normal, making 2004 the 9th coldest in 79 years. At Halifax Station 2, 0-140 m temperature anomalies were about -1°C; salinity was close to normal values. Misaine Bank, Emerald Basin, Georges Basin and eastern Georges Bank profiles featured anomalies of –1 to –2°C at most depths. Sydney Bight and Lurcher Shoals temperature profiles were quite variable. Standard sections in April, May and October on the Scotian Shelf support the overall conclusion of temperatures ~2°C below normal accompanied by an 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 at 50 m, 100 m and the bottom. Break-up of the strong stratification pattern established in the late 20th and early 21st century continued in 2004 with substantial variability of the stratification parameter throughout the region. The overall stratification was slightly below normal for the Scotian Shelf region. The Shelf/Slope front and the Gulf Stream were about 20 km south of their mean positions.

Introduction

This paper describes temperature and salinity characteristics during 2004 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 national archive at the Marine Environmental Data Service (MEDS) in Ottawa. Our analyses use data up to and including the 9 March 2005 update; only data up to and including 2004 are discussed. Additional hydrographic data were obtained directly from DFO fisheries cruises. We also provide information on the position of the Gulf Stream and the boundary between the shelf waters and the offshore slope waters.

In order to detect long-term trends, we have removed the potentially large seasonal cycle by determining the monthly differences, i.e. the anomalies, from the long-term means. Where possible, long-term monthly and annual means have been calculated for the base period 1971-2000. This follows the recommendations of the Northwest Atlantic Fisheries Organization (NAFO, 1983) and the Fisheries Oceanography Committee of DFO. Meteorological, sea ice and satellite-derived sea-surface temperature information for eastern Canada during 2004 are described in Petrie *et al.* (MS 2004). The air temperature anomalies for the Scotian Shelf and the Gulf of Maine were variable during 2004 with small annual values of -0.23^{o}C (Sable Island) and -0.51^{o}C (Boston); sea surface temperatures were below normal for the Scotian Shelf and the Gulf of Maine with annual values of 0.3-1.1^{o}C below normal. Ice cover for the Scotian Shelf was unexceptional in 2004.

Coastal Sea Surface Temperatures

Monthly averages of coastal sea surface temperature (SST) for 2004 were available at Boothbay Harbor (Maine), 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 2003 and 2004 are shown in Fig. 2.

At Boothbay Harbor in 2004, monthly temperatures were above normal throughout the year by 0.3-3.1^{o}C with an annual anomaly of about 1.5^{o}C. The monthly anomalies equalled or exceeded 2 standard deviations (SD, based upon the years 1971-2000) in 4 months (July-October) with the September value exceeding 4 SD. The annual anomaly was 1.55^{o}C, 3 SD above normal and the 4th highest in the 99 year record. The divergence of Boothbay Harbor temperatures from St. Andrews and indeed from other sites in the Gulf of Maine in 2004 is very suspicious; we have contacted the Boothbay Harbor Laboratory and they are presently checking into this matter. At St. Andrews, all months featured negative anomalies with May-July values exceeding 1 standard deviation. The 2004 annual anomaly was -0.8^{o}C, the 14th coldest in 84 years. The monthly anomalies at Halifax were generally negative but variable for the last half of 2004; the annual anomaly was –1.0^{o}C, making 2004 the 9th coldest in 79 years.

Time series of annual anomalies shows that the surface temperatures in 2004 at 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; 1998-2003 had multiple occupations per month; this past year sampling has been reduced to once per month because of financial and personnel restrictions. For months with multiple measurements, the arithmetic mean was used to estimate the monthly mean temperature and salinity. A single or even several observations per month (especially in the surface layers in the spring or summer when some stratification can develop) may not necessarily produce results that are representative of the true monthly "average" conditions. While this is less of a problem in such a well-mixed area as the Bay of Fundy, still the interpretation of the anomalies must be viewed with some caution. No significance should be placed on any individual monthly anomaly, but persistent anomaly features are likely to be real. The general vertical similarity in temperatures over the 90 m water depth is due to the strong tidal mixing within the Bay of Fundy.

In 2004, monthly mean temperatures ranged from a minimum in March of 1.74^{o}C at the surface to a maximum in September of 11.1^{o}C (Fig. 3, 4). Monthly temperature anomalies were negative throughout the year except for January. Negative anomalies were greatest from April to July by as much as -2.1^{o}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 2004, the annual temperature anomalies at 0 and 90 m were about –0.9. At 0 m, 2004 was the 13th coldest year in 80; at 90 m, it was the 22nd coldest year. The recent negative anomalies oppose the long-term warming trend that began in the early 1990s.

The salinity at Prince 5 had a broad minimum in the spring and summer at the surface (~31.5) and an atypical cycle at 90 m with low values in summer and fall (Fig. 3, 5). The salinity anomalies were positive in the first half of 2004 and negative in the second. The annual salinity anomalies were about 0.1 above normal at 0 m and 0.1 below normal at 90 m. 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).

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

Surface temperatures at H2 ranged from <0°C to >18°C in 2004 (Fig. 6). Near-bottom temperatures were generally between 4°C and 6°C throughout the year, cooler than those observed in 2003. Relative to the long-term means, 0-140 m temperatures were predominantly below normal for most of the year by about 1°C. A ~15 m deep near-surface layer had above normal temperatures from spring to fall; this warm anomaly appears to have been mixed downward in the fall. The temperature anomaly pattern suggests that there was a thicker Cold Intermediate Layer (CIL) than usual at H2 in 2004. The CIL off Halifax typically has a temperature range from about 1°C to 6°C depending on the time of the year.

Salinity anomalies were small in 2004 with slightly above normal values in the upper 50 m through most of the year and generally below normal values between 50 m and the bottom. Peak anomaly magnitude was about 0.5.

In the surface layers, stratification began to develop in early May increasing in intensity through to August-September. During autumn, the warmer and fresher surface layer was gradually mixed down to ~100 m. Density anomalies varied in the same manner as the salinity anomalies.

Scotian Shelf and Gulf of Maine Temperatures

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities from available bottle data for irregularly shaped areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins (Fig. 7). Petrie *et al.* (1996) updated the report using these same areas and all available hydrographic data. We present monthly mean conditions for 2004 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 2004 monthly means are based upon as few as 4 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 and then calculated the 5-year running mean of the annual values at selected depths.

Drinkwater and Pettipas (MS 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, MS 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.*, MS 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 2004 (Fig. 8) and as time series plots for a selected depth in each region (Fig. 9).

In Sydney Bight (area 1, Fig. 7) off eastern Cape Breton, the monthly profiles overall showed substantial variability of the temperature anomalies throughout the entire depth (Fig. 8). Misaine Bank profiles, on the other hand, had temperature anomalies that were 0.5-1.5°C below normal at all depths. With profiles in all months except December, Emerald Basin featured a mixture of above and below normal temperatures of ~2°C in the upper 30 m, predominantly below normal values from 50 to 175 m with a maximum annual anomaly of -2°C at 100 m. The annual anomaly crossed 0°C at 200 m and was slightly above normal at 250 m. Lurcher Shoals anomalies were highly variable in the upper 30 m and had a tendency to below normal temperatures from 50 to 100 m. Georges Basin generally had below normal temperatures from the surface to 175 m and then, as in Emerald Basin, crossed 0°C at 200 m and was slightly above normal deeper. Georges Bank anomalies were mostly negative, with a maximum value of about -2°C at 75 m.

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. Misaine Bank 100 m temperatures in 2004 were below normal. The Emerald Basin 250 m record reflects the influence of slope water on the Scotian Shelf. The intrusion of Labrador Slope Water onto the shelf in 1998 is very prominent. This event was followed by a period of slightly above normal temperatures which continued at depth in 2003 but reversed in 2004. Lurcher Shoals temperature anomalies (50 m) follow a similar pattern as the Misaine Bank series with 2004 having below normal temperatures. Since 1975 the filtered times series from Georges Basin has had quasi-periodic fluctuations of less than 1°C; the Labrador Slope Water intrusion of 1998 was observed but had a shorter duration than in Emerald Basin. The annual anomaly at 200 m in 2004 was near zero. On the other hand, the filtered temperature anomaly series from eastern Georges Bank has been almost flat for 30 years until 2003 when values were below normal, a tendency that continued in 2004.

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 195 CTD stations were taken during the 2004 survey and an additional 179 bottom temperature stations were obtained as part of the ITQ (Individual Transferable Quota) fleet survey. The groundfish survey takes 1 month to complete with the area west of Halifax sampled first and the area east of Halifax sampled second. The observations are plotted without taking the time of sampling into account. This means that the Sydney Bight area sampled at the end of the survey has had about a month longer solar heating than the area to the west of Halifax sampled at the start of the survey. This is not accounted for directly in the data displays. Thus the warmest area often ends up in Sydney Bight. On the other hand, the 1971-2000 temperature climatology is dominated by these surveys which are conducted in the same way every year. Thus we expect the anomalies to be largely unaffected by this temporal sampling bias. The ITQ survey fills in gaps in the DFO survey for the Bay of Fundy, off southwest Nova Scotia and on the southwestern Scotian Shelf. The temperature data from the ITQ survey were obtained using Vemco Minilogs© attached to the trawl. These data are quality controlled during processing at the Bedford Institute of Oceanography.

The temperatures from both surveys were combined and interpolated onto a 0.2° by 0.2° latitude-longitude grid using an objective analysis procedure known as optimal estimation. The interpolation method uses the 15 "nearest neighbours" with a horizontal length scale of 30 km and a vertical length scale of 15 m in the upper 30 m and 25 m at deeper depths. Data near the interpolation grid point are weighted proportionately more than those farther away. Temperatures were optimally estimated for 0, 50, 100 m and near bottom (Fig. 10). Maximum depths for the interpolated temperature field were limited to 1000 m off the shelf. The 2004 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 2004 was similar to past years with the warmest waters off eastern Cape Breton (>17°C) and near the shelf break south of Sable Island (>19°C), and the coldest (<9°C) in the Gulf of Maine/Bay of Fundy region (Fig. 10a). 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 2004 were warmer than normal over most of the eastern Shelf, but were as much as 2°C cooler than normal off western Nova Scotia in the Gulf of Maine (Fig. 11a). The anomaly pattern in 2003 was similar.

The temperatures at 50 m ranged from 2°C to over 7°C with the coldest waters in the northeast and the warmest waters in the Gulf of Maine and Bay of Fundy (Fig. 10a). The lower temperatures over the inner half of the shelf indicate a cold, broad intermediate layer similar to the one seen in 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. 11a) were below normal nearly everywhere by as much as 5°C, but anomalies of -1 to -2°C were more typical. Conditions in 2004 were very similar to those in 2003.

The temperatures at 100 m ranged from <1-2°C in the northeastern Scotian Shelf to over 6°C in Northeast Channel (Fig. 10b). Anomalies were predominantly negative, ranging from 0°C to 4°C below normal over the region (Fig. 11b). The largest anomalies (about -6°C) occurred along the outer shelf off Emerald Bank suggesting the presence of colder-than-normal slope waters. Again conditions were similar to those in 2003.

Near-bottom temperatures over the Scotian Shelf ranged from ~1°C in the northeastern Scotian Shelf to nearly 9°C in Emerald Basin and the upper Bay of Fundy (Fig. 10b). 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 the1971-2000 means, the near-bottom temperatures were predominantly colder than normal in the region; -1°C was a representative anomaly (Fig. 11b).

We also estimated the area of the bottom covered by each one degree temperature range (e.g. 1-2°C, 2-3°C, 3-4°C, etc.) within NAFO Subareas 4Vn, 4Vs, 4W and 4X (Fig. 1). The areas were obtained from the optimally estimated temperature distributions from the July groundfish and ITQ surveys. The time series for each NAFO Subarea are shown in Fig. 12a, b. There were generally higher temperature towards the southwest, from 4Vs/4Vn to 4W and 4X. In 4Vn, most of the bottom is covered by waters <6°C and about 70% is <5°C. For 4Vs, ~100% is <6°C and 93% is <5°C (Fig. 12a). In 4W, 70% and in 4X, 47% of the bottom is covered by temperatures <6°C (Fig. 12b). Except for 4Vn, bottom waters were colder in 2004 than in 2003.

The interannual variability can be summarized by determining the average bottom temperatures in each region (Fig. 13). All areas in 2004 featured average bottom temperatures below the 1971-2000 norms. Area 4Vn was 0.46°C (0.9 standard deviations) below normal and the 7th coldest in 35 years. Areas 4Vs and 4W were 0.96 (1.3 standard deviations) and 1.85°C (2.9 standard deviations) below normal, the 7th and 1st coldest years in 35 years. NAFO area 4X was 1.32°C below normal (1.9 standard deviations), making it the 2nd coldest in 35 years.

Standard Sections

Hydrographic data for the Cabot Strait (April, October), Louisbourg (April, October), Halifax (April-May, October, December) and Browns Bank (April, October) sections 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, 0-50 m temperatures were 0-2°C across the Cabot Strait and Louisbourg, and most of the Browns Bank sections, and 2-4°C across the Halifax section to the shelf break (Fig. 14a). Temperature anomalies intensified from Cabot Strait where they were a mixture of positive and negative values, to between 0°C and -1°C on the Louisbourg Section, -1°C to -2°C on the Halifax Section and finally to ~2°C below normal at Browns Bank. Salinity was 31-33 over the shelf, approximately equal to the long-term mean (Fig. 14b).

The May Halifax section had 50-75 m thick cold intermediate layer extending about 200 km offshore, with temperatures 0-3°C below normal and salinities 0-0.5 above normal (Fig. 14c). Over the slope, subsurface temperatures and salinities were normal.

In October there was an extensive subsurface cold layer with temperatures 0-2°C below normal at Cabot Strait and 1-6°C below normal along the Louisbourg line (Fig. 14d, e). A remnant cold intermediate layer 50 m thick at the coast and extending 250 km offshore was observed at the Halifax section. Temperatures were up to 2°C below normal. Browns Bank temperatures were 1-4°C above normal in the upper 50 m and 0-4°C below normal deeper than 50 m. Salinity anomalies varied over the shelf with large values on the Louisbourg and Halifax Sections.

Cabot Strait Deep Temperatures

Bugden (1991) investigated the long-term temperature variability in the deep waters of the Laurentian Channel in the Gulf of St. Lawrence from data collected from the late 1940s to 1988. The variability in the average temperatures within the 200-300 m layer in Cabot Strait was dominated by low-frequency fluctuations, with no discernible seasonal cycle. A phase lag was observed along the major axis of the channel such that events propagated from the mouth towards the St. Lawrence Estuary on time scales of several years. The updated time series shows that temperatures declined steadily between 1988 and late 1991 to their lowest value since the late 1960s (about 4.5°C, giving an anomaly exceeding -0.9°C; Fig. 15). The temperature increased reaching 6°C (anomaly of 0.6°C) by late 1993. During the remainder of the 1990s, temperatures oscillated about the long-term mean with a slight tendency towards positive values. In 2004, the temperature was 0.16°C above the long-term mean, the same as in 2003.

Density Stratification

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. Stratification can affect the extent of vertical mixing, the ocean's response to wind forcing, the timing of the spring bloom, vertical nutrient fluxes and plankton speciation. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper, lower layers. We examined the variability in stratification by calculating the density (sigma-t) difference between 0 and 50 m. The density difference was based on a monthly mean density profile calculated for each area in Fig. 7. The long-term monthly mean density gradients for 1971-2000 were estimated; these were subtracted from the monthly values to obtain monthly anomalies. Annual anomalies were estimated by averaging all available monthly anomalies within a calendar year. This could be misleading if, in a particular year, most data were collected in months when stratification was weak, while in another year, sampling was in months when stratification was strong. However, initial results, whereby the observations were normalized by dividing the anomalies by the monthly standard deviation, were qualitatively similar to the plots presented here. The 5-yr running means of the annual anomalies were then calculated for subareas 4-23 on the Scotian Shelf (Fig. 16, 17). These anomalies were weighted by the surface areas of the subareas. The monthly and annual means show high variability but the 5-yr running means feature some distinctive trends. The density anomalies are presented in g/ml/m. A value of 0.01 represents a difference of 0.5 of a sigma-t unit over the 50 m.

The dominant feature of the 5-year means is the higher stratification during the 1990s throughout the Scotian Shelf (Fig. 16a, b). In 2004, there was considerable spatial variability of the stratification index throughout the region. For example, in the Sydney Bight to Misaine Bank area (top panel, Fig. 16a), the tendency is for above normal values of the parameter. On the other hand, in the central shelf region (Emerald Bank to LaHave Basin, Fig. 16a, bottom panel), the opposite situation prevails. The average stratification parameter for areas 4-23 showed decreased stratification (Fig. 17).

Sea Level

Sea level is a primary variable in the Global Ocean Observing System. On Canada's east coast, two gauges, one at Halifax and the other on the Labrador coast, are part of Canada's proposed contribution to this global effort. Relative sea level at Halifax (1990-2004) 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 (1990-2004) has a positive slope of 25.2 (±9.9) 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 1990-2004 by only 2.2 cm/century; 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 2004 relative sea level reversed its downward trend at Halifax.

Frontal Analysis

Shelf/Slope Front

The waters on the Scotian Shelf and in the Gulf of Maine have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters offshore. The relatively narrow boundary between the shelf and slope waters is regularly detected in satellite thermal imagery. Positions of this front and of the northern boundary of the Gulf Stream between 50°W and 75°W for the years 1973 to 1992 were assembled through digitization of satellite derived SST charts (Drinkwater *et al*., 1994). From January 1973 until May 1978, the charts covered the region north to Georges Bank, but in June 1978 the coverage was extended to include east to 55°W and eventually 50°W. Monthly mean positions of the shelf/slope front in degrees latitude at each degree of longitude were estimated. NOAA updated this data set until the termination of the satellite data product in October 1995. A commercial company has continued the analysis but did not begin until April 1996. These initial charts did not contain data east of 60°W but within a year were extended east to 55°W. Data for 2004 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 and the 2004 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 2004, the shelf/slope front was slightly southward of its long-term mean position. The time series of the annual mean position (averaged over 56°W-75°W) shows the front was at a maximum shoreward location in 1985 with another maximum in 1993. Since 1993, the front moved steadily seaward approximately 40 km, reaching its most southerly position in 1996. 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. In 2004, the front again moved about 19 km offshore of its mean position to its farthest southern point since 1981.

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 2004 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. 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. 20). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed by a rapid southward movement in 1996. By 2000 the position of the Gulf Stream was again shoreward of its long-term mean and has remained so through to 2002. In 2003, the Gulf Stream front moved about 32 km seaward of its 2002 position, i.e. about 17 km south of its mean position. In 2004, it remained in roughly the same location, about 19 km south of its mean position.

Summary

A review of physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine and adjacent offshore areas during 2004 has shown the continuation of conditions similar to 2003. Cool conditions tended to dominate the Scotian Shelf and the eastern Gulf of Maine in 2004. The temperature data from Boothbay Harbor were suspicious; the laboratory running this gauge is investigating. St. Andrews sea surface temperature was 0.8^{o}C below normal making 2004 the 14th coldest in 84 years. At Prince 5, 0-90 m, monthly mean temperatures were generally below normal by about 0.9^{o}C. Salinities were within 0.1 of normal throughout the year. Halifax sea surface temperature was 1.0^{o}C below normal, making 2004 the 9th coldest in 79 years. At Halifax Station 2, 0-140 m temperature anomalies were about -1^{o}C; salinity was close to normal values. Misaine Bank, Emerald Basin, Georges Basin and eastern Georges Bank profiles featured anomalies of –1 to -2^{o}C at most depths. Sydney Bight and Lurcher Shoals temperature profiles were quite variable. Standard sections in April, May and October on the Scotian Shelf support the overall conclusion of temperatures ~2^{o}C below normal accompanied by an 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 at 50 m, 100 m and the bottom. Break-up of the strong stratification pattern established in the late 20th and early 21st century continued in 2004 with substantial variability of the stratification parameter throughout the region. The overall stratification was slightly below normal for the Scotian Shelf region. The Shelf/Slope front and the Gulf Stream were about 20 km south of their mean positions.

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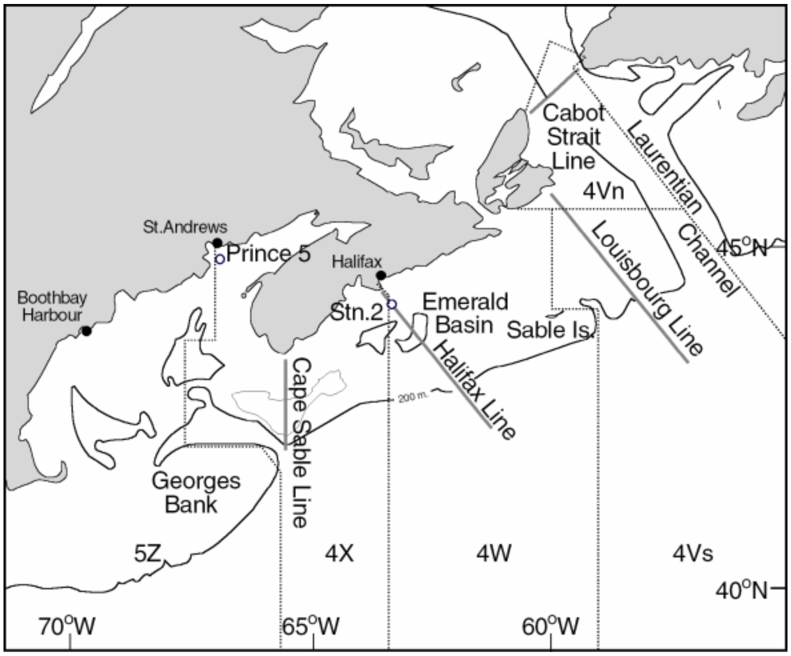


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

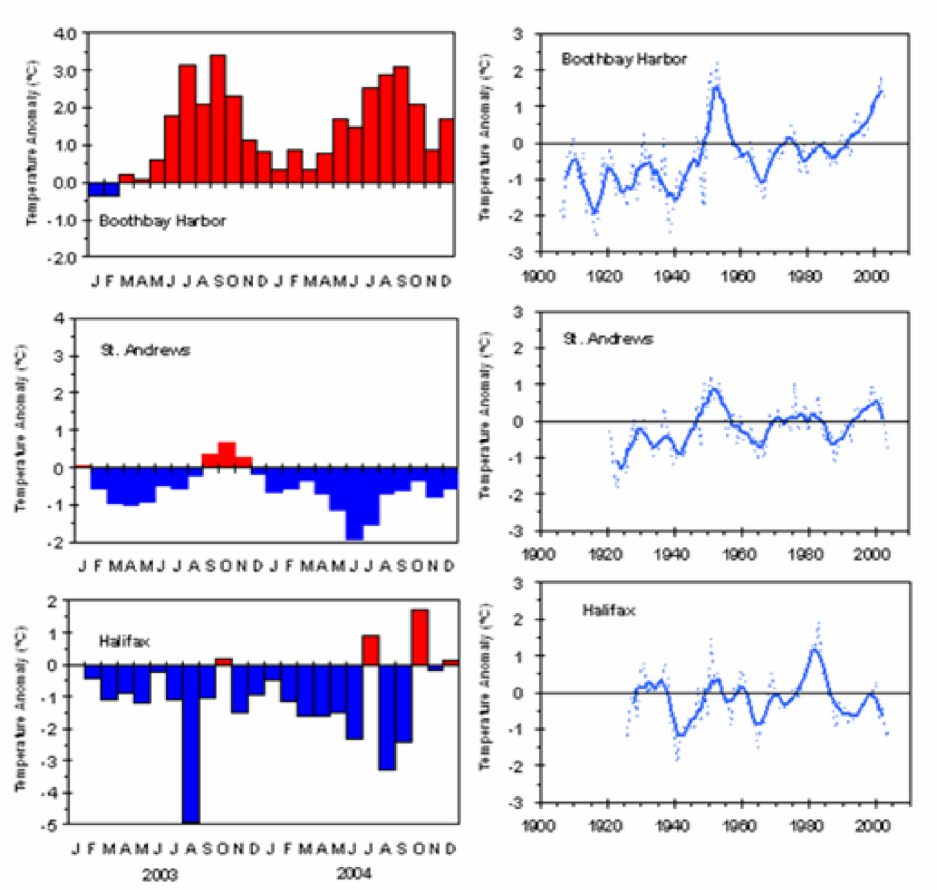


Fig. 2. The monthly sea surface temperature anomalies during 2003 and 2004 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Anomalies are relative to the 1971-2000 means.

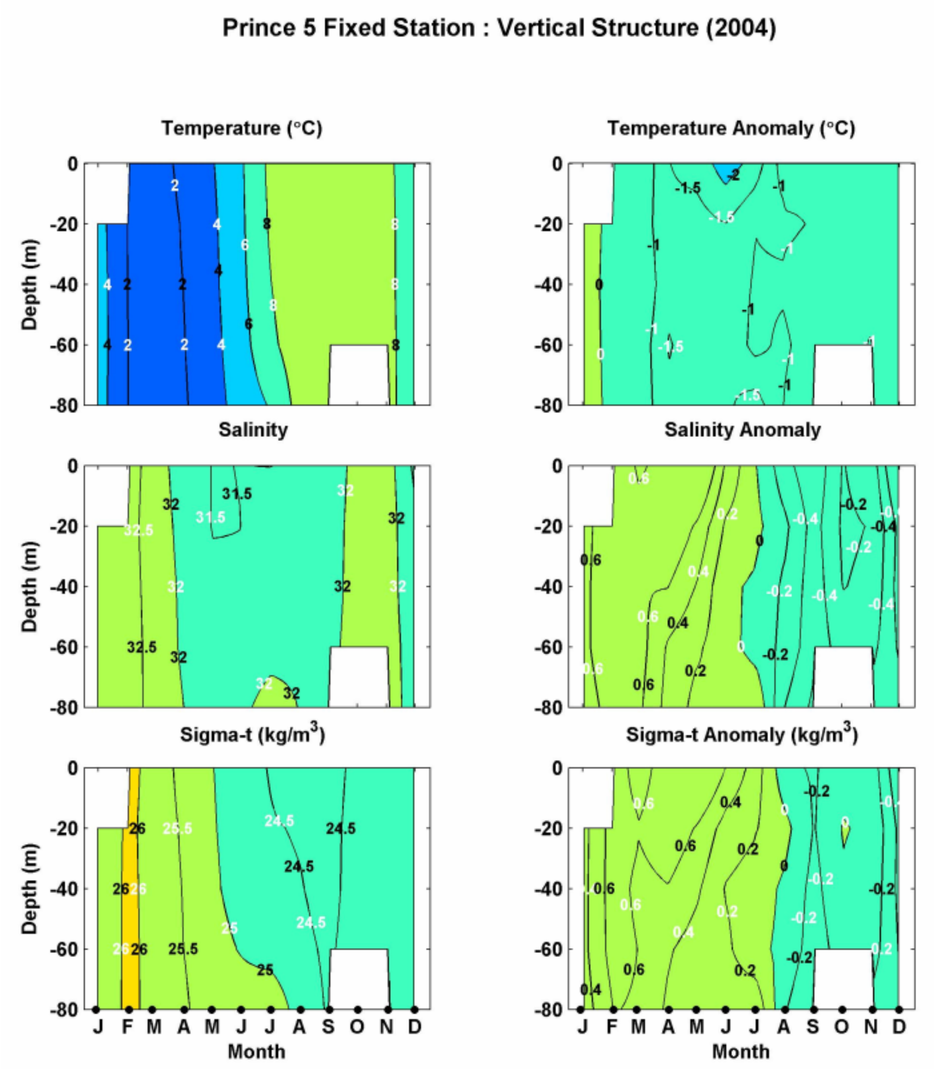


Fig. 3. Contours of temperature, salinity and sigma-t and their anomalies at Prince 5 as a function of depth during 2004 relative to the 1971-2000 means.

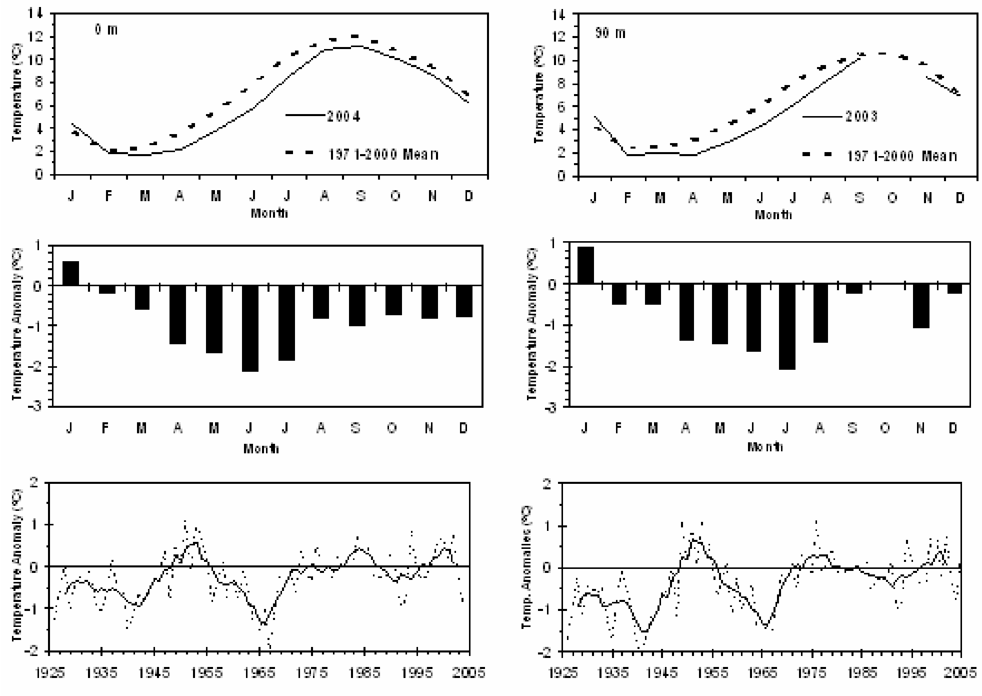


Fig. 4. The monthly mean temperatures for 2004 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

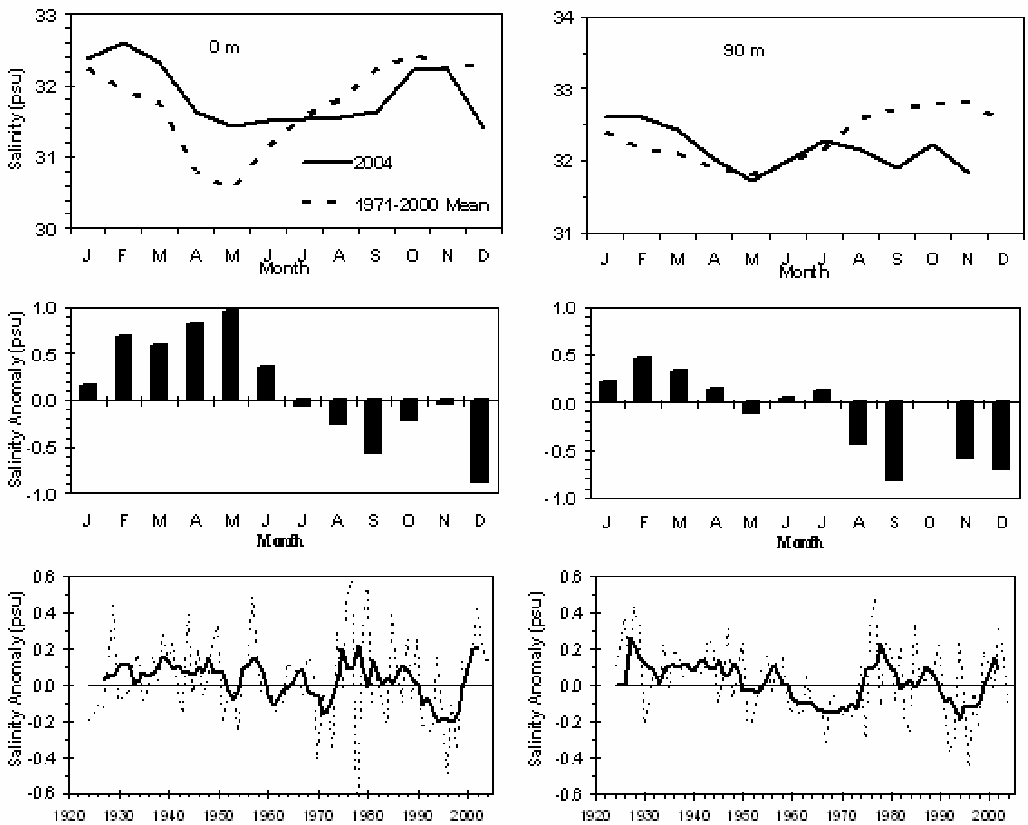


Fig. 5. The monthly mean salinities for 2004 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1971-2000 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

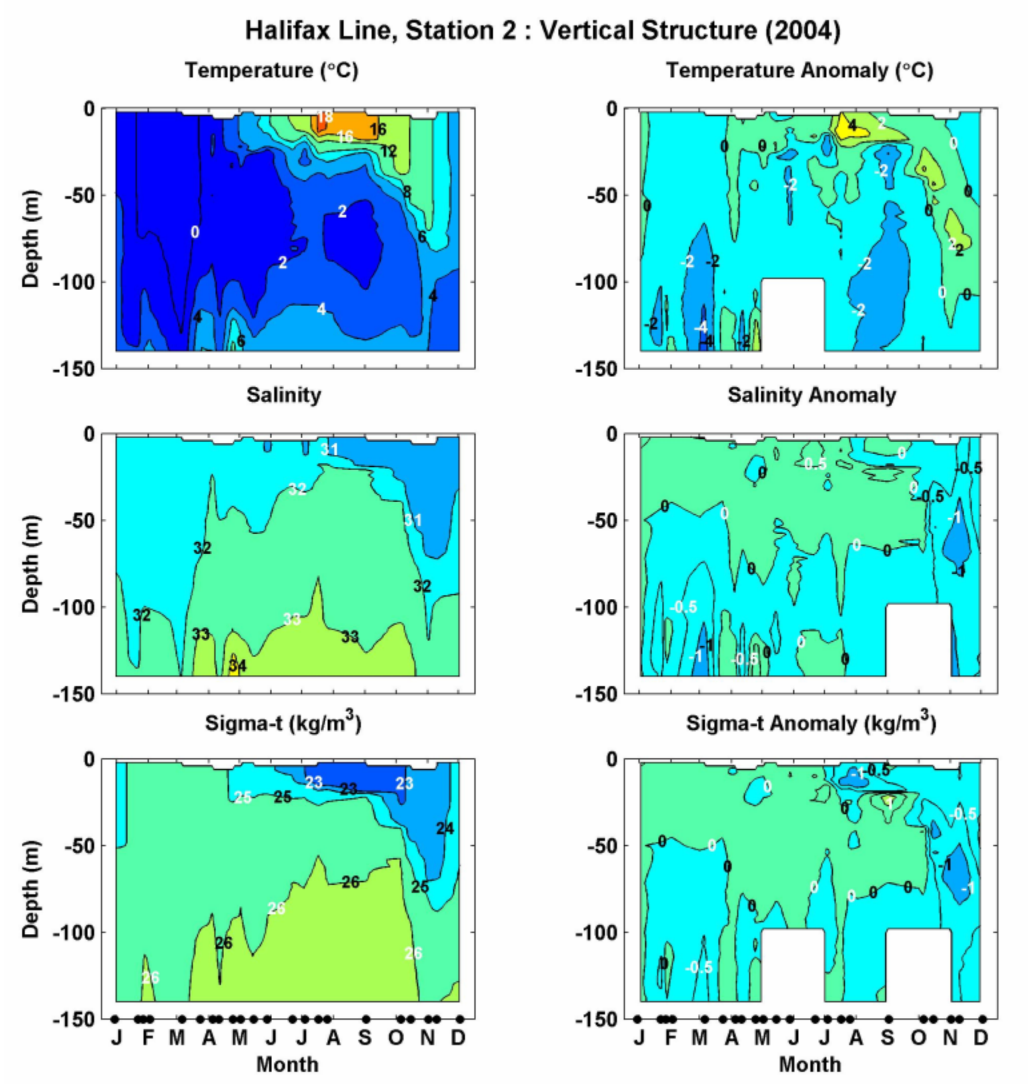


Fig. 6. Contours of the 2004 temperature, salinity and density (sigma-t) (left) and their anomalies (right) at the fixed station Halifax Section Station 2.

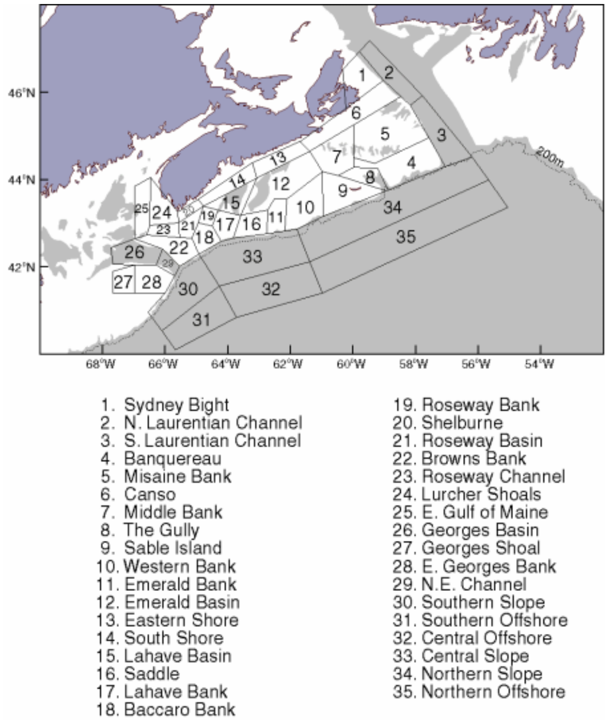


Fig. 7. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

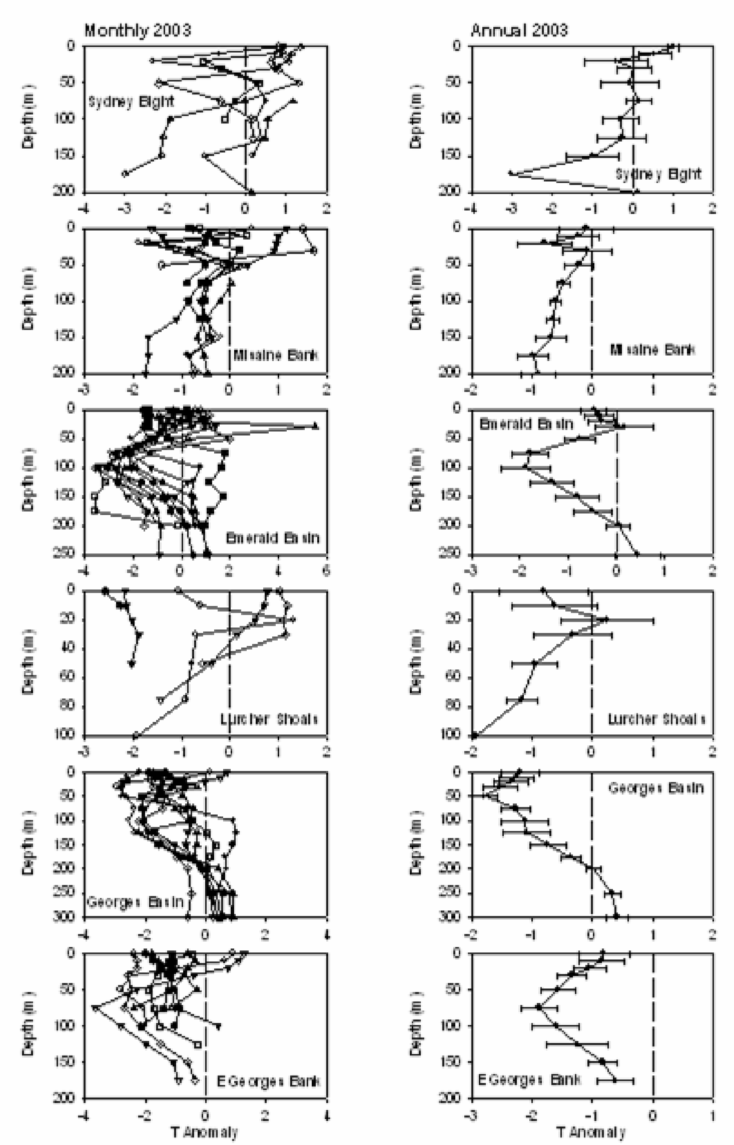


Fig. 8. Monthly (left) and annual (±std. error, right) temperature anomaly profiles for selected locations. Symbol order for monthly profiles is filled dot, square, up triangle, down triangle, diamond, hexagon for January-June,, then open symbols in the same order for July-December.

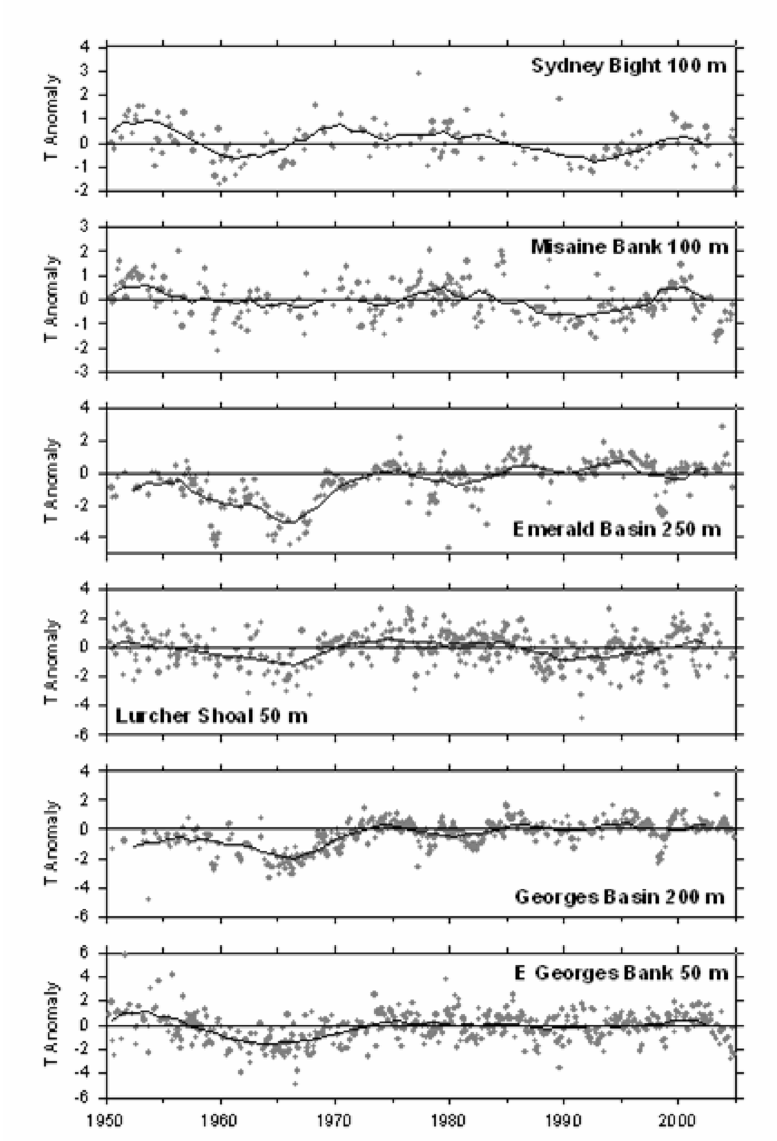


Fig. 9. The monthly mean temperature anomaly time series (grey dots) and the 5-yr running mean of the estimated annual anomalies (solid line) at 6 sites on the Scotian Shelf and in the Gulf of Maine (see Fig. 7).

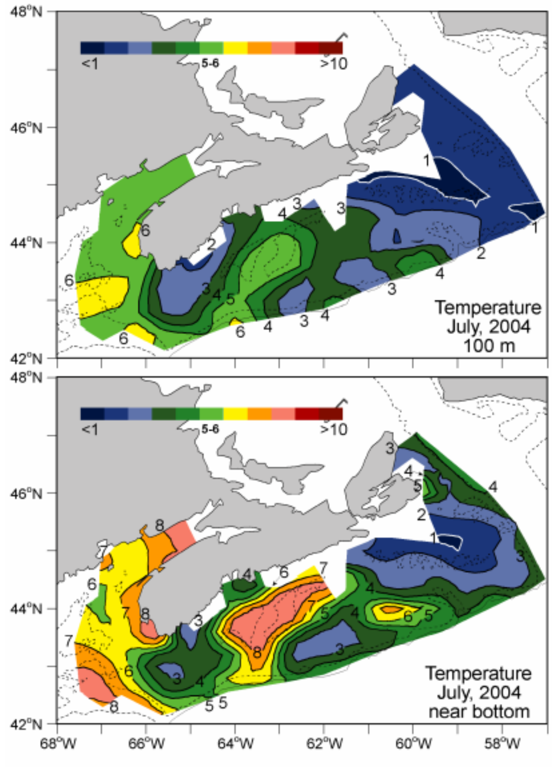


Fig.10a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 2004 July groundfish and ITQ surveys.

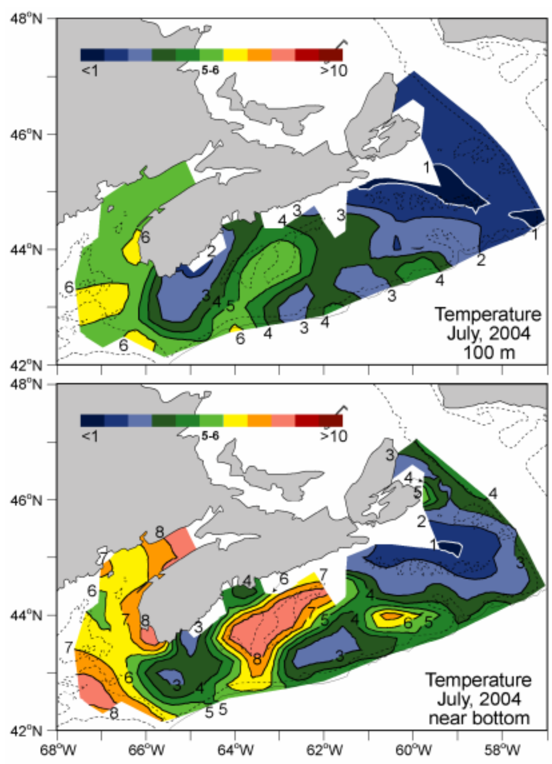


Fig. 10b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 2004 July groundfish and ITQ surveys.

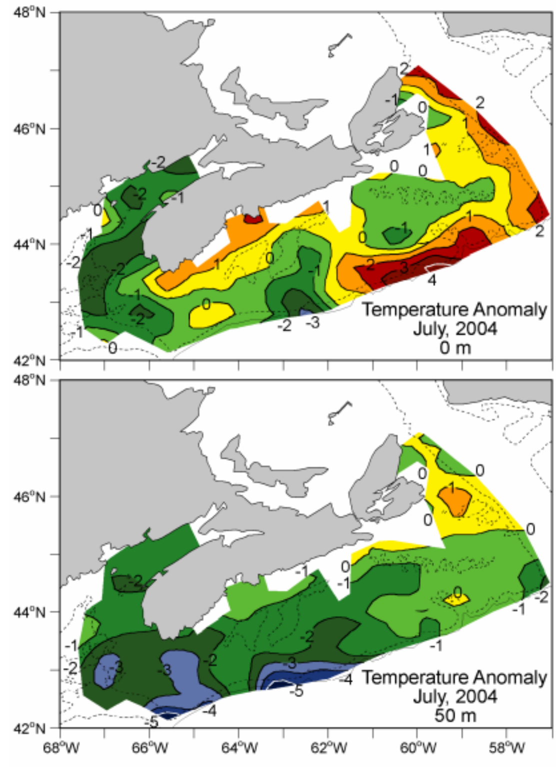


Fig. 11a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 2004 July groundfish and ITQ surveys.

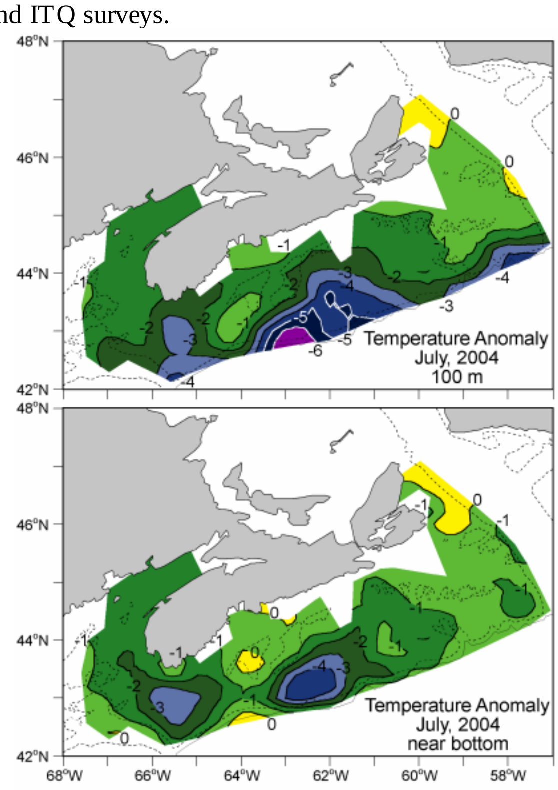


Fig. 11b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 2004 July groundfish and ITQ surveys.

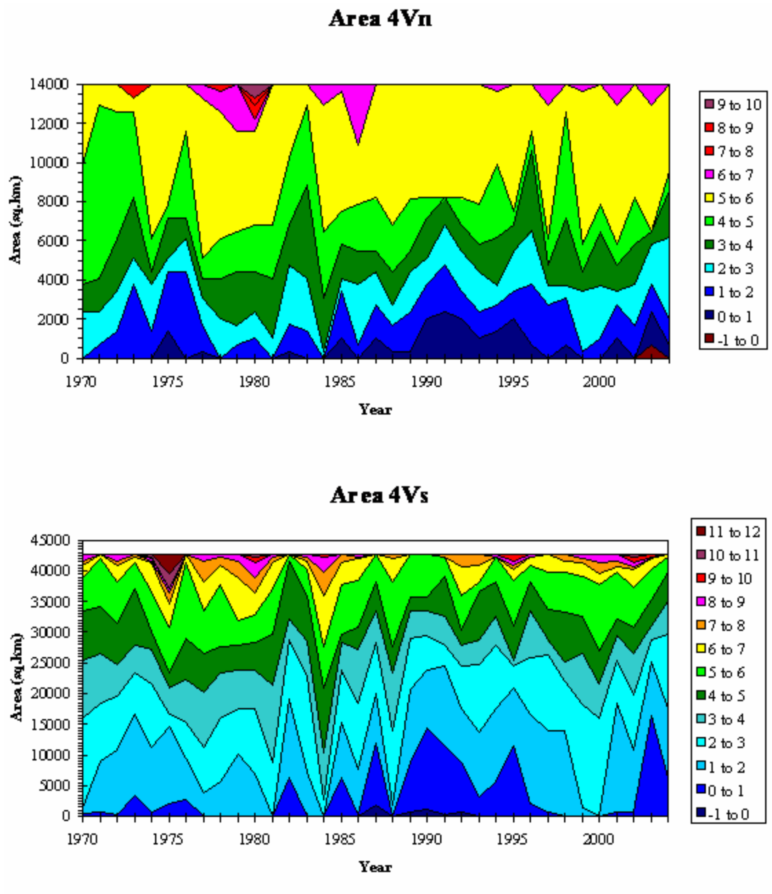


Fig. 12a. The time series of the area of the bottom for each 1^{o}C temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).

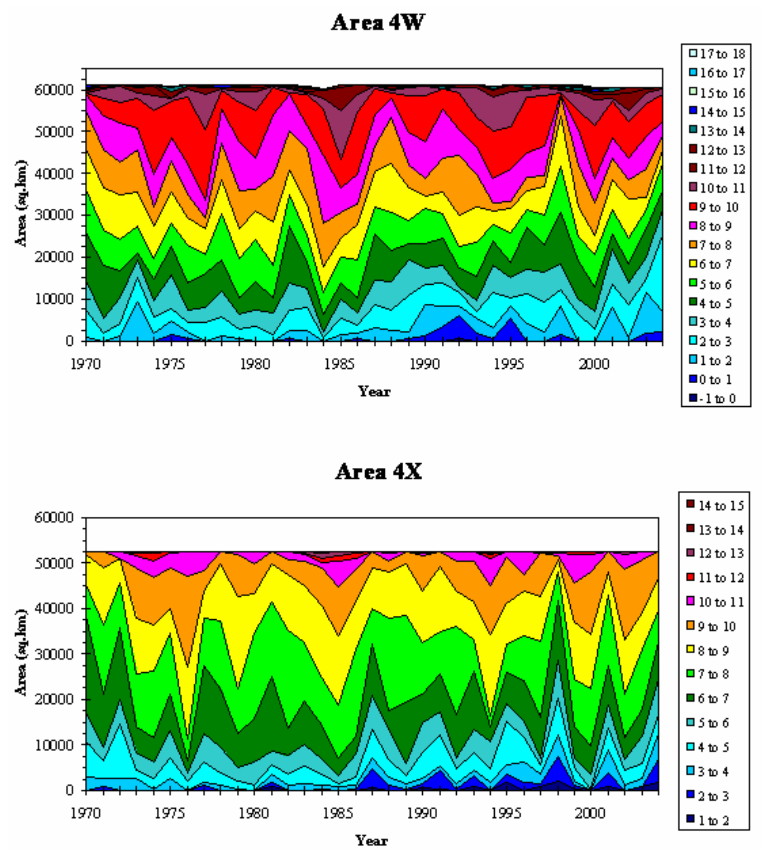


Fig. 12b. The time series of the area of the bottom for each 1°C temperature range for NAFO Subareas 4W (top panel) and 4X (bottom panel).

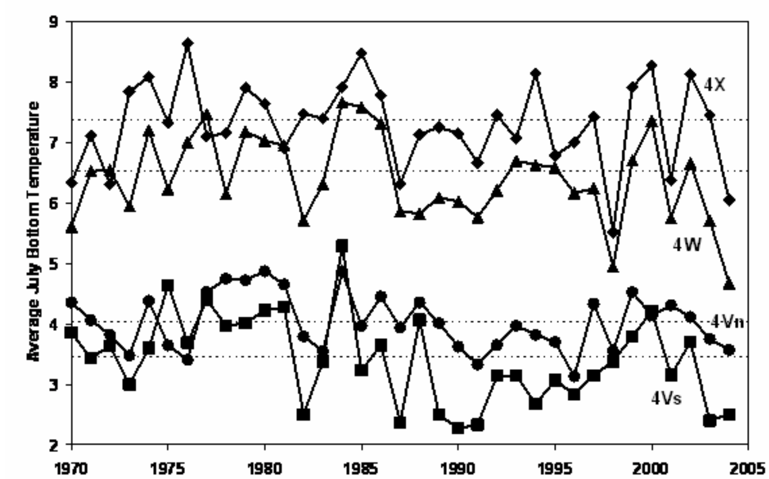


Fig. 13. Time series of annual mean bottom temperatures from areas 4Vn, 4Vs, 4W and 4X. The horizontal lines are the 1971-2000 means.

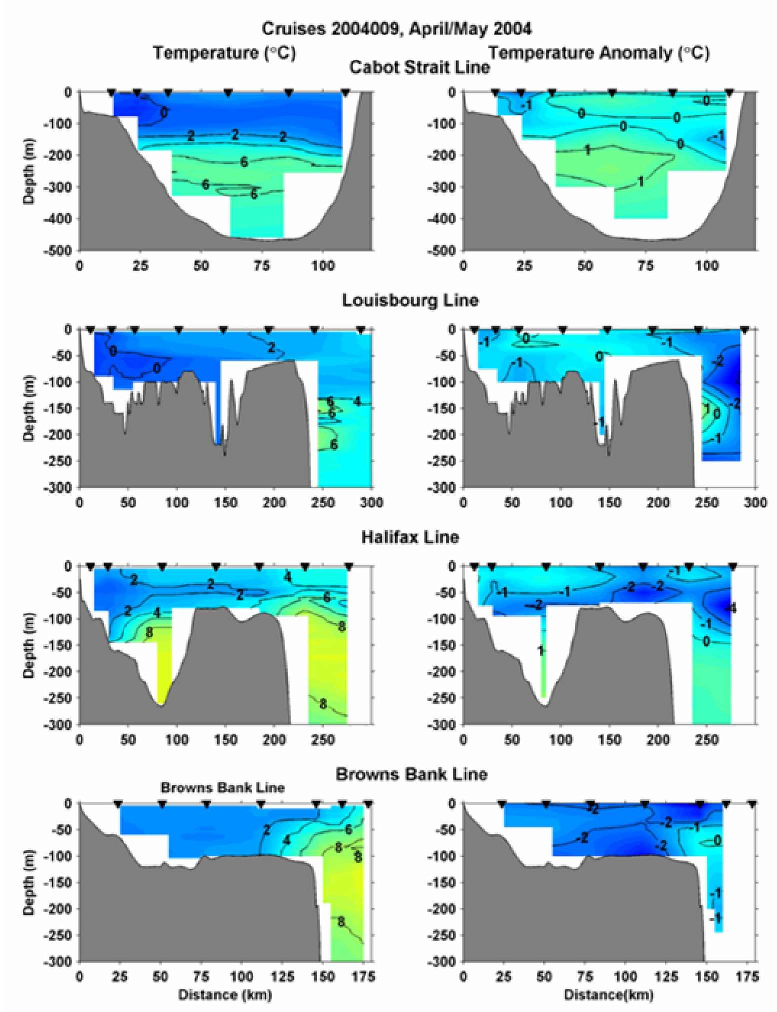


Fig. 14a. Temperature and temperature anomalies for standard Scotian Shelf sections, April/May 2004.

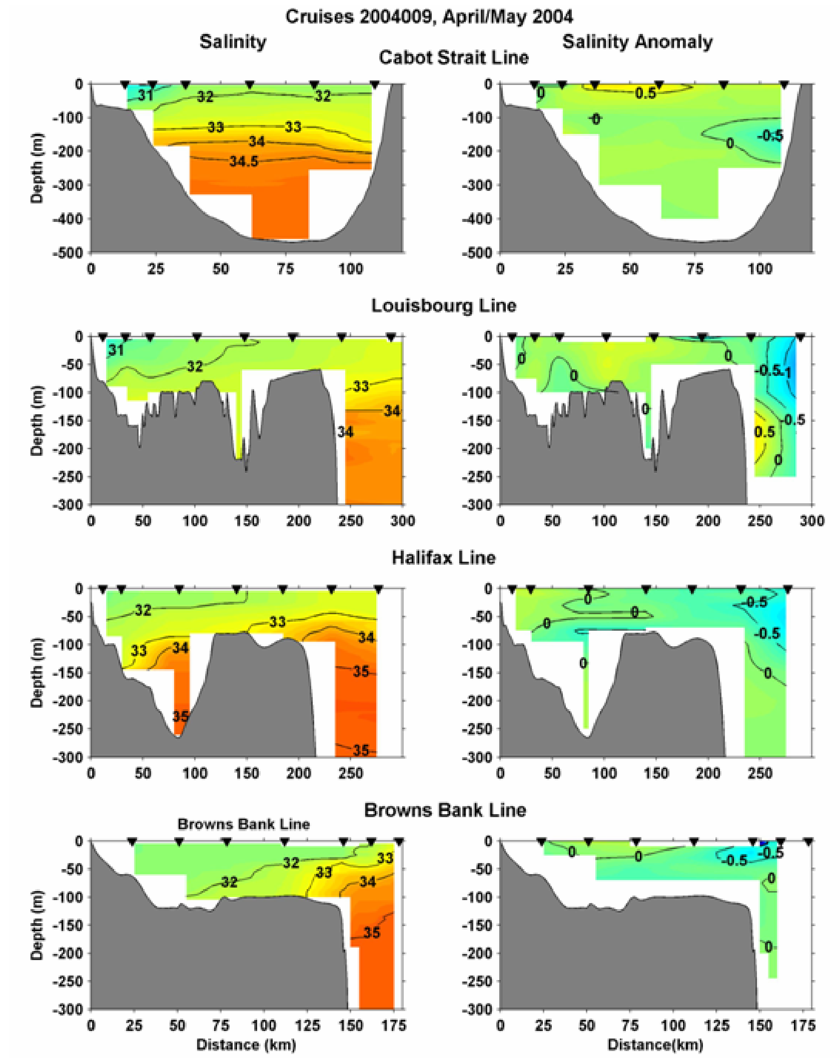


Fig. 14b. Salinity and salinity anomalies for standard Scotian Shelf sections, April/May 2004.

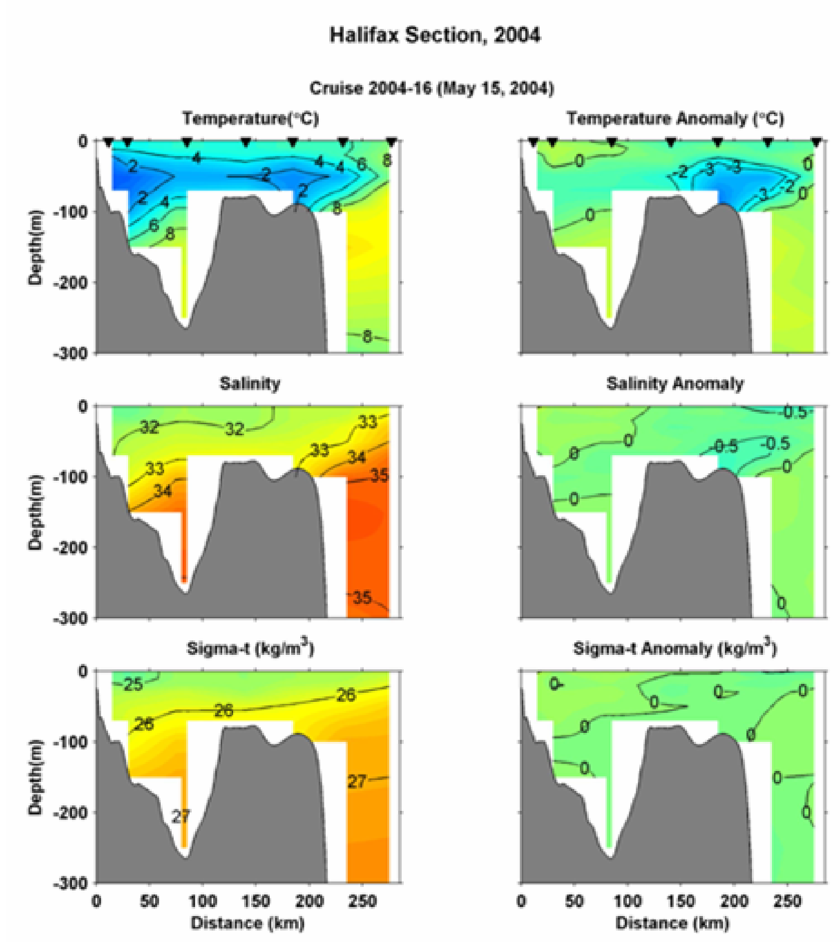


Fig. 14c. Temperature, salinity, density and their anomalies for the Halifax section, May 2004.

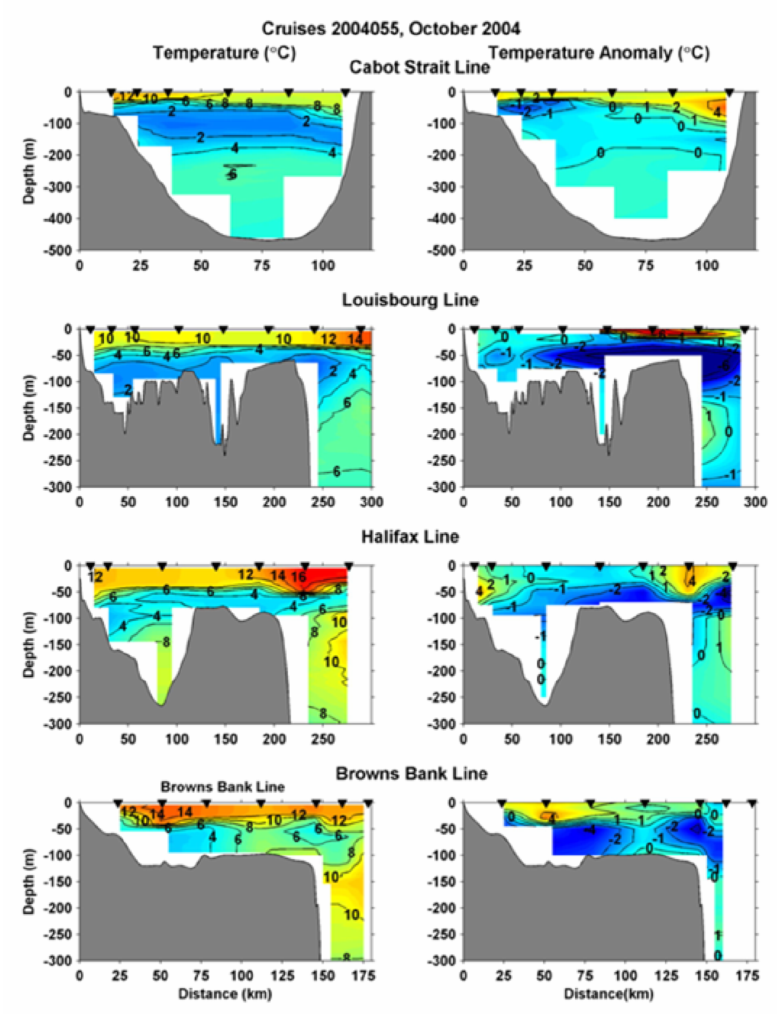


Fig. 14d. Temperature and temperature anomalies for standard Scotian Shelf sections, October 2004.

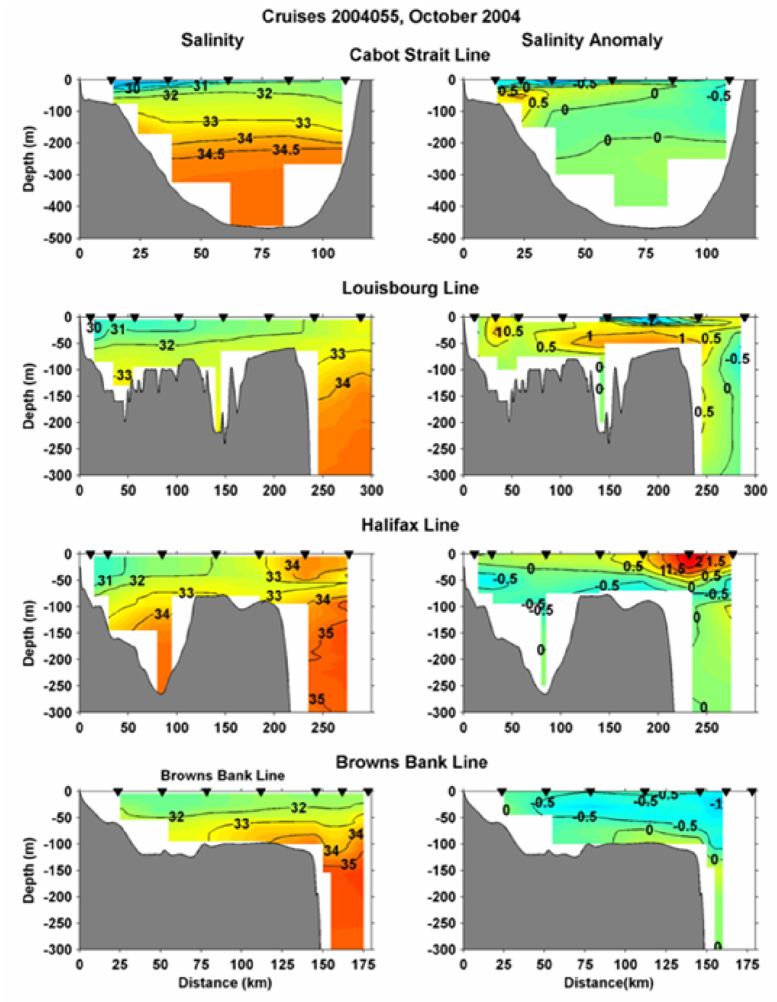


Fig. 14e. Salinity and salinity anomalies for standard Scotian Shelf sections, October 2004.

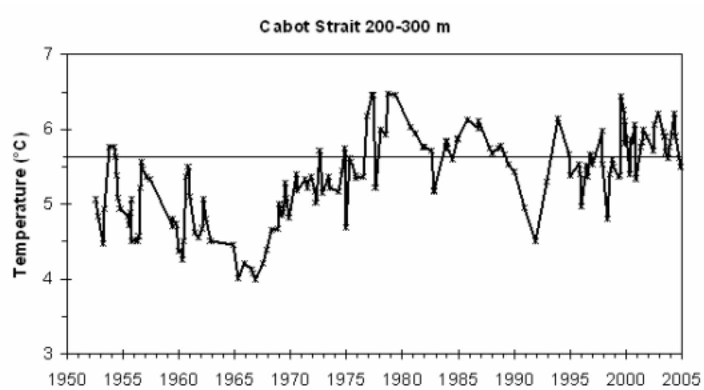


Fig. 15. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the 1971-2000 mean.

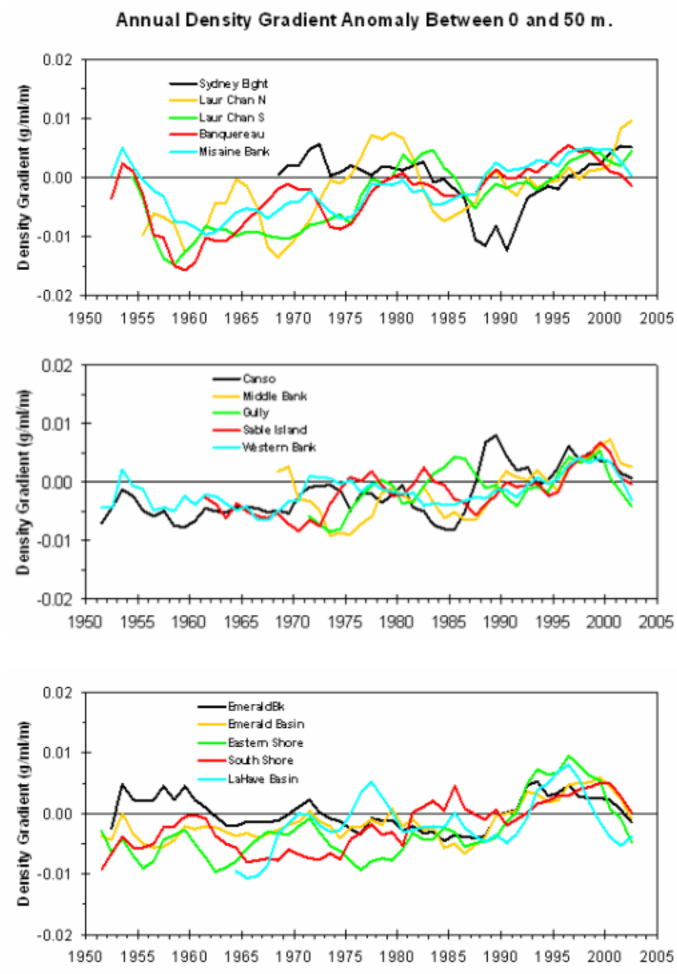


Fig. 16a. Five-year running means of the annual density gradient anomalies between the surface and 50 m calculated for the areas 1-15 in Fig. 7.

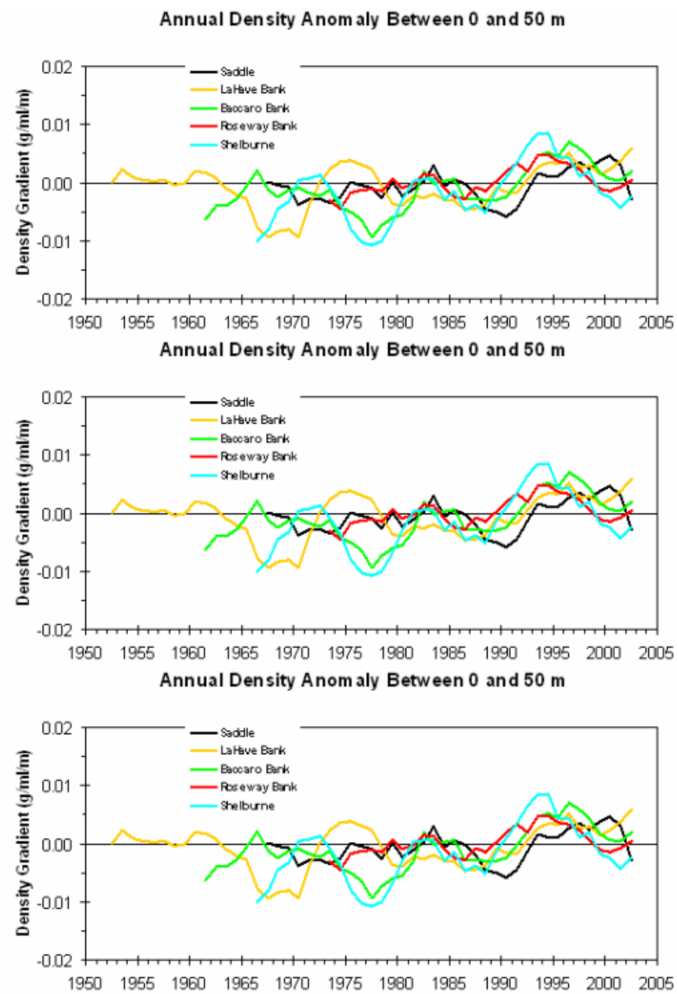


Fig. 16b. Five-year running means annual density gradient anomalies between the surface and 50 m calculated for the areas 16-29 in Fig. 7.

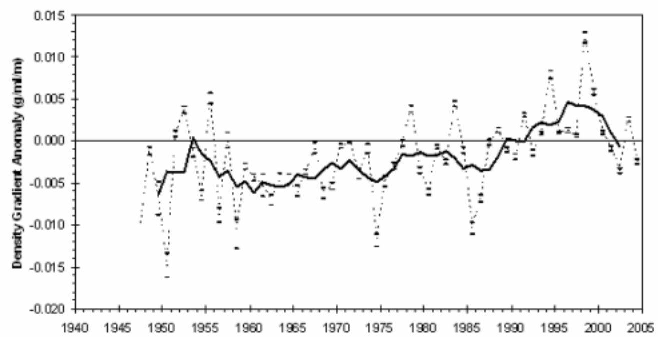


Fig. 17. The mean annual (dashed line) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive). The short horizontal lines for each year represent the standard errors of the different areas.

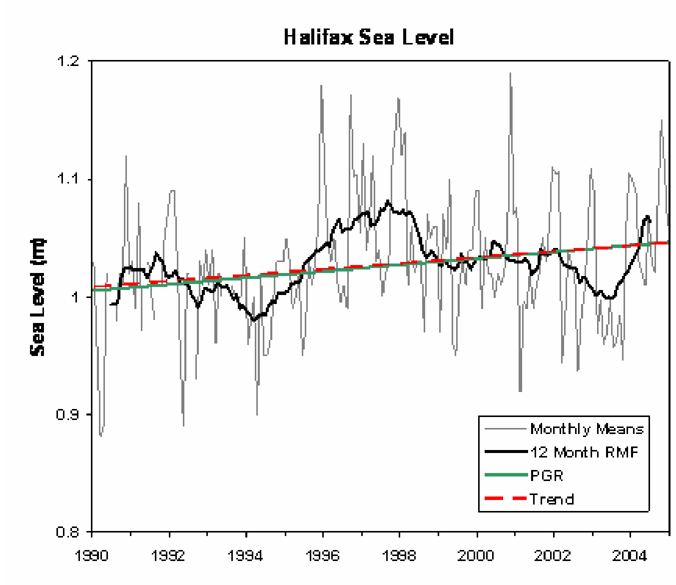


Fig. 18. The time series of the monthly means and a 12 month running mean of the sea level elevations at Halifax, along with the observed linear trend and that predicted by a model from post-glacial rebound.

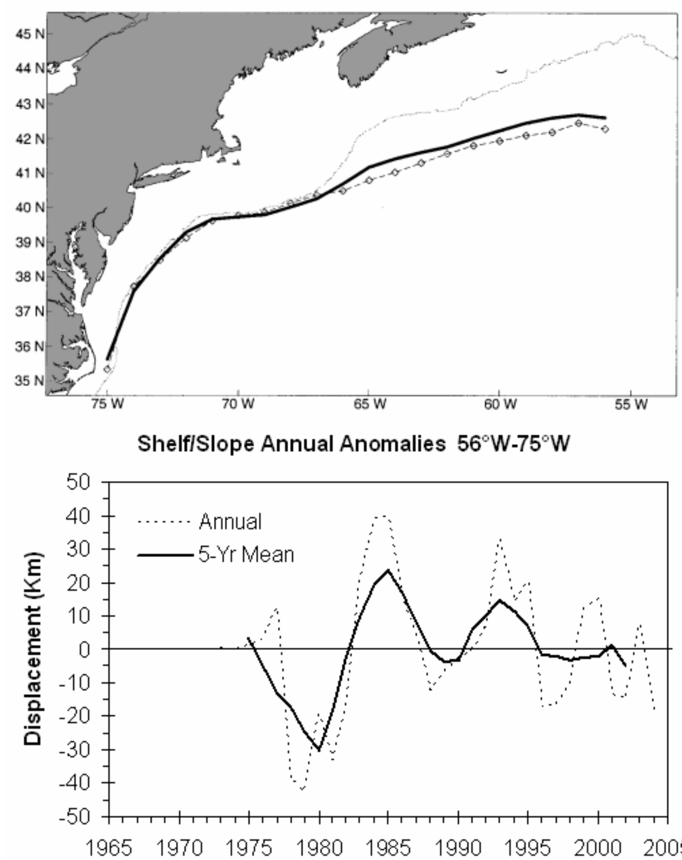
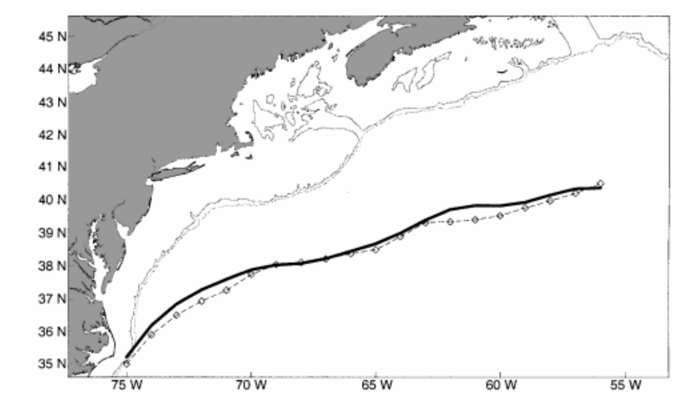


Fig. 19. The 2004 (dashed line) and long-term mean (1973-2000; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the shelf/slope front (bottom panel).



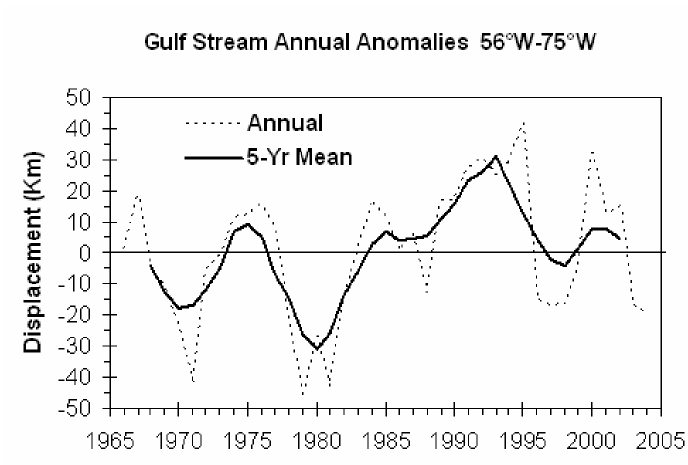


Fig. 20. The 2004 (dashed line) and long-term mean (1973-2000; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (56°-75°W) position of the Gulf Stream front (bottom panel).