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Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 1999

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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 1999 is presented. Several significant changes have taken place. First, the cold, Labrador Slope Water observed along the outer edge of the Scotian Shelf in 1998 was replaced by Warm Slope Water. It subsequently penetrated onto the shelf through channels and gullies and displaced the cold slope water that occupied the deep basins, such as Emerald and Georges Basins, and covered much of the bottom of the southwestern Scotian Shelf. Temperatures in deep Emerald Basin increased by 2°-3°C in 1999 over 1998 values. Second, the waters below 50 m on the northeastern Scotian Shelf continued their gradually warming that began in the mid-1990s such that significant portions of the region's waters are now above normal for the first time in approximately 15 years. The presence of these cold waters is believed to be due to a combination of advection from the Gulf of St. Lawrence and off the Newfoundland Shelf and *in situ* cooling during the winter. Third was that very warm surface layer waters developed over the region. Anomalies of several degrees were observed in many months. This is related to the record air temperatures observed in 1999. Finally, there was continued high stratification in the upper water column (between surface and 50 m) throughout the Scotian Shelf. This high stratification was not observed in the Gulf of Maine.

Résumé

Les conditions océanographiques physiques en 1999 sur le plateau néo-écossais et dans le golfe du Maine et les zones marines adjacentes sont passées en revue. Plusieurs changements importants ont été observés. Premièrement, l'eau de talus froide du Labrador notée à la bordure extérieure du plateau néo-écossais en 1998 a été remplacée par une eau de talus chaude. En empruntant des chenaux et des goulets, celle-ci a ensuite progressé dans le plateau, déplaçant l'eau froide de talus qui occupait les bassins profonds, tels les bassins d'Emerald et de Georges, pour couvrir la majeure partie du fond dans le sud-ouest du plateau néo-écossais. Dans le bassin profond d'Emerald, les températures ont ainsi augmenté de 2-3 °C en 1999 par rapport aux valeurs de 1998. Deuxièmement, dans le nord-est du plateau néo-écossais, les eaux situées à plus de 50 m de profondeur ont continué de se réchauffer graduellement, poursuivant la tendance amorcée au milieu des années 1990; en conséquence, de vastes portions des eaux de la région sont maintenant plus chaudes que la normale, ce qui ne s'était pas produit depuis une quinzaine d'années. La présence de ces eaux froides est vraisemblablement due à une advection depuis le golfe du Saint-Laurent et le large de la plate-forme de Terre-Neuve conjuguée au refroidissement hivernal in situ. Troisièmement, les eaux de surface sont devenues très chaudes dans la région. Des anomalies de plusieurs degrés ont été observées pour de nombreux mois. Elles sont liées aux températures records de l'air enregistrées en 1999. Enfin, la forte stratification de la partie supérieure de la colonne d'eau (de la surface à 50 m) s'est poursuivie au-dessus de tout le plateau néo-écossais. Une telle stratification n'a pas eu lieu dans le golfe du Maine.

Introduction

This paper describes temperature and salinity characteristics of the waters on the Scotian Shelf and in the Gulf of Maine during 1999 (Fig. 1). The results are derived from data obtained at coastal sea surface stations, long-term monitoring stations, standard transects, annual groundfish surveys, ships-of-opportunity and research vessels. Most of the data are available in the BIO historical temperature and salinity (AFAP) database, which is updated monthly from the data archive at the Marine Environmental Data Service (MEDS) in Ottawa. The analyses in this paper use data up to and including the January 2000 update. Additional hydrographic data were obtained directly from the DFO fisheries personnel. This represents the first year that the environmental reviews for the FOC are being presented as part of the Atlantic Zonal Monitoring Program (AZMP). Included in the AZMP program for the Scotian Shelf are several standard sections and a new standard monitoring station (at Station 2 on the Halifax Line). Results from these are included in our report.

In order to detect long-term trends in the hydrographic properties, we have removed the potentially large seasonal cycle by expressing oceanographic conditions as monthly deviations from their long-term means (called anomalies). Where possible, these long-term means have been standardized to a 30-yr average using the base period 1961-1990 in accordance with the convention of the World Meteorological Organization and recommendations of the Northwest Atlantic Fisheries Organization (NAFO). Meteorological and sea ice information for the region during 1999 is described in Drinkwater et al. (2000a). Of particular relevance was that air temperatures during 1999 in the region from southern Labrador to the Gulf of Maine were the warmest on record, some of which were over 120 years in length.

Background

Last year's overview (Drinkwater et al., 1999) reported the southward extension of Labrador Slope water along the edge of the Scotian Shelf through to the Middle Atlantic Bight from the autumn of 1997 to the spring of 1998. Slope water occupies the region between the shelf water and the Gulf Stream. Two types of slope water were identified by Gatien (1976), one being Warm Slope Water with temperatures typically 8°-12°C and the other being Labrador Slope Water with temperatures 4°-8°C. During most of the past thirty years, the former has occupied the region seaward of the shelves north to the Laurentian Channel. The source of this water is from the south and tends to be of slightly higher salinity than Labrador Slope Water. The latter, as the name suggests, is derived from the deep (100-300 m) Labrador Current. It dominated along the shelf edge of the Scotian Shelf through to at least Georges Bank through most of the 1960s and is believed to appear in years of higher-than-normal transports of the Labrador Current (Petrie and Drinkwater, 1993). In turn, this is thought to be related to the strength of the large-scale atmospheric circulation patterns over the North Atlantic as reflected in the North Atlantic Oscillation (NAO) index. This index is defined as the atmospheric sea level pressure difference between the Azores and Iceland (Rogers, 1984). A high (low) index indicates strong (weak) westerly winds across the North Atlantic, an intense (weakened) Icelandic Low centered off southeastern Greenland and strong (weak) northwesterly winds over the Labrador Sea.

The colder, lower salinity slope water that appeared along the continental slope in the autumn of 1997 began to penetrate through the channels and gullies of the southwestern Scotian Shelf in December 1997 and by February 1998 had flushed all of Emerald Basin. It eventually replaced most of the lower-layer waters on the southwestern Shelf as evidenced by the data from the 1998 groundfish survey, which recorded the lowest temperatures in the 29 year time series for NAFO Subarea 4X. The effects were not restricted to the Scotian Shelf. In January of 1998, the cold Labrador Slope water had reached the entrance to the Gulf of Maine in the Northeast Channel. By spring it had replaced the deep waters of Georges and Crowell basins. Fishermen reported cold waters on Georges Bank at this time and felt that they were affecting the catchability of lobster. The Labrador Slope water did not penetrate further shoreward in the Gulf of Maine until the summer of 1998. Unlike the basins where the bottom waters were completely replaced, in the inner reaches of the Gulf, the Labrador Slope water appeared to mix with the resident waters. This event has been described in detail by Drinkwater et al. (2000b).

Coastal Sea Surface Temperatures

Monthly averages of sea surface temperature (SST) for 1999 were available at Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia. The Halifax averages are based on a continuous recording thermistor submerged just below low water on the wharf in Halifax Harbour by the Maritime Museum of the Atlantic. They replace the twice a day measurements taken during weekdays from the DFO Halifax Laboratory wharf, which ended in August 1998. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each site for 1998 and 1999 are shown in Fig. 2.

The dominant feature in 1999 at Boothbay Harbor and St. Andrews was the above normal temperatures throughout most of the year (12 months and 11 months, respectively). The 1999 anomalies equalled or exceeded one standard deviation (based upon the years 1961-90) in 7 months at Boothbay Harbor (February, April-September) and in 9 months at St. Andrews (April to December). The maximum monthly anomalies were in June, 3.3°C (over 4 standard deviations from the long-term mean) at Boothbay and 2.2°C at St. Andrews (over 2 standard deviations). At Halifax sea surface temperature anomalies showed high variability in 1999 with 6 of the available 12 months being warmer-than-normal, one normal (October) and 5 colder-than-normal (Fig. 2).

Time series of annual anomalies show that the surface temperature at both Boothbay Harbor and St. Andrews have been above their long-term means in recent years and generally on the increase since a minimum in the late 1980s (Fig. 2). That minimum was as low as one in the mid-1960s at St. Andrews but at Boothbay Harbor the minimum was only slightly below normal. Consistent with the recent trends, the 1999 annual mean temperature at these two sites was above normal (mean of 8.2°C and 1.1°C above normal at St. Andrews and 9.9°C and 1.4°C above normal at Boothbay). At both sites the temperature rose relative to 1998 and exceeded the recent peak observed in 1995 (Fig. 2). At St. Andrews, it was the 5th warmest year in the 79-year record while at Boothbay Harbor it was the 6th warmest year in the 94-year record. In contrast to these two stations, Halifax had an annual mean sea surface temperature that was normal.

Fixed Stations

Prince 5

Temperature and salinity measurements have been taken since 1924 at Prince 5, a station off St. Andrews, New Brunswick, near the entrance to the Bay of Fundy (Fig. 1). It is the longest continuously operating hydrographic monitoring site in eastern Canada. Prior to the 1990s, data were obtained using reversing thermometers and water bottles. During most of the 1990s, data had been obtained with a CTD (Conductivity, Temperature, Depth) profiler. Up to and including 1997, there was only one observation per month but in 1998 as part of the AZMP, multiple occupations were taken whenever possible. In 1999 there were 3 measurements during December, 2 in January and April-October and 1 in February, March and November. For months with multiple measurements, an arithmetic average was used to estimate the monthly mean temperature and salinity. A single observation, or even three per month, especially in the surface layers in the spring or summer, may not necessarily produce results that are representative of the true monthly "average" conditions and therefore the interpretation of the anomalies must be viewed with some caution. No significance should be placed on any individual monthly anomaly but persistent anomaly features are likely to be real. The general vertical similarity in temperatures over the 90 m water column is due to the strong tidal mixing within the Bay of Fundy.

In 1999, monthly mean temperatures ranged from a minimum of around 2.5°C throughout most of the water column in March to a maximum of over 13°C near the surface in September (Fig. 3,4). Following below normal temperatures in January, the monthly temperature anomalies for the remainder of the year were positive. The highest positive anomalies (>2°C) occurred in December below 10 m depth. In most months the anomalies exceeded or were near +1°C. The annual mean temperatures exhibit high year to year variability (Fig. 4). In 1999, they were above normal throughout the water column with the anomalies being approximately 1.2°C except at the surface where the anomaly was 0.9°C. This represents a large increase relative to 1998 at both the surface and near bottom. The surface values are the warmest since 1994 and at the bottom they are warmest in over 20 years (since 1976). With the exception of the negative temperature anomalies in the early 1990s, temperatures at Prince 5 have generally been warmer than the long-term mean since the mid-1970s at the surface and since the late 1960s near bottom. The maximum annual temperatures at this site occurred in the early 1950s and the minimum in the mid-1960s.

Salinities at Prince 5 during 1999 were fresher-than-normal during the first 4-5 months of the year and generally saltier-than-normal for the remainder of the year (Fig. 3, 5). The lowest salinities (<31 psu) occurred in the upper half of the water column during April and the highest salinities (>33 psu) appeared near bottom in the autumn. The arrival of higher salinity waters in autumn is typical. The largest negative anomalies (between 0.25

and 0.5 psu) were observed throughout most of the water column in January and February and in the upper half of the water column in April. Time series show that the annual salinity anomalies in 1999 rose by approximately 0.4-0.5 relative to 1998 values at both the surface and 90 m (Fig. 5). There have been large fluctuations in salinity but the longer-term trends show that salinities generally freshened from the late 1970s to at least the late-1990s with the lowest salinities on record at Prince 5 occurring in 1996. The salinity changes parallel events in the deep waters of Jordan and Georges Basin and appear to be related to advection from areas further to the north (P. Smith, BIO, personal communication). Whether the increase in salinity in 1999 is part of a high frequency fluctuation or if the high salinities will remain is unclear.

Halifax Line Station 2

As part of the AZMP, a standard monitoring site was established on the Scotian Shelf in 1998. Based on representativeness and logistic considerations, the selected site was Station 2 on the Halifax Line (H2, Fig. 1). It is situated approximately 30 km off the entrance to Halifax Harbour in about 150 m of water at the inner edge of Emerald Basin. It was felt that it was far enough offshore to avoid contamination by high frequency upwelling and downwelling but close enough to shore to be able to be monitored on a monthly basis using small vessels if necessary. Hydrographic measurements are taken using a CTD. In addition, nutrient and biological sampling are conducted. In this paper we only report on the hydrographic information.

The monthly mean temperature, salinity and density (sigma-t) for 1961-90 are shown in Fig. 6. The site is vertically mixed to 50 to 100 m during most of the winter. Minimum temperatures (<0°C) occur in the upper 40 m or so in March. The waters begin to stratify through the spring and reach maximum stratification in September. Surface layer temperatures warm to a maximum of around 16°C in September. Through the autumn, surface temperatures decline due to atmospheric cooling but also the surface layer heat is distributed down into the water column, probably by increased wind mixing. Surface layer salinities decline in the late spring reaching a minimum in late summer but remain low through into the winter. The later is related to the influence of the outflow of low salinity waters from the Gulf of St. Lawrence. In the waters below 100 m, there is evidence of higher density waters moving slowly upwards and reaching their shallowest levels in the late summer to early autumn. Accompanying this, lower layer temperatures and salinities both increase.

At the beginning of 1999, temperatures and salinities were warmer and saltier-than-normal at H2 (Fig. 7). In March there was a rapid deepening of the isotherms such that 2°C waters extended to about 125 m where previously it was shallower than 50 m. This was accompanied by deepening of the isohalines and the isopycnals as well. These relatively cool, fresh waters remained until early June when below 50 m they were replaced by warmer, saltier waters and returned to above normal conditions. No waters with temperatures less than 2°C were observed after early June. Through the summer, the temperature and salinities of the deep waters increased. Cooling of these waters began around September and continued throughout the remainder of the year. With the exception of the 50-75 m depth range, temperature and salinity anomalies were mostly positive during this period. In the surface layers, stratification began around May increasing in intensity through to August. During August, surface layer temperatures exceeded 18°C with salinities <31. Similar low salinities were first observed in late spring and continued into the summer through to the late autumn. During autumn, the surface layer heat and low salinity waters were gradually mixed down to 50 m and deeper resulting in a decrease in temperature and an increase in salinity at the surface. From mid-spring into the early autumn, the temperatures and salinities in the surface layer were generally warmer and fresher-than-normal. These conditions extended to depths of 50 m in the early autumn and occupied the top 50 m of H2 for most of the remainder of the year.

Deep Emerald Basin Temperatures

Emerald Basin is located in the central Scotian Shelf. As discussed in the Background Section above, the waters in the Basin were very cold in 1998. The temperature time series at standard depths from 100 m to 250 m from 1997 to late-1999 all show the large decline in the early months of 1998. There was a temperature minimum in the spring of 1998, a slow recovery and a return to the warm temperatures observed prior to the cold event between early to mid-1999 (Fig. 8). The largest temperature changes were at 100 to 150 m, which corresponds to the sill depth separating Emerald Basin from the offshore slope waters. This is consistent with the offshore slope waters being the source of the large temperature deviations in the Basin. In 1999, the cold Labrador Slope Water that had occupied the edge of the shelf from autumn of 1997 into 1998 retracted northward to be replaced by the Warm Slope Water. The latter then flowed onto the shelf and gradually flushed Emerald Basin. The time series of temperature anomalies at 250 m, which is reasonably representative of the lower layers from 100 m and deeper (Fig. 8), shows this cooling and subsequent warming (Fig. 9). Dominant in the time series are the cool period of the 1960s and the relatively warm periods of the 1970s to the 1990s.

Other Scotian Shelf and Gulf of Maine Temperatures

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities from available bottle data for irregularly shaped areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins (Fig. 10). Petrie et al. (1996) has published a more recent atlas containing all available hydrographic data. In this report we produce monthly mean conditions for 1999 at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compare them to the long-term averages (1961-90). Unfortunately, data are not available for each month at each area and in some areas the monthly means are based upon only one profile. As a result the series are characterized by short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1-2°C. The spikes represent noise and most often show little similarity between regions. Thus care again must be taken in interpreting these data and little weight given to any individual mean. The long period trends often show similarity over several areas. To better show such trends we have estimated the annual mean anomaly based on all available means within the year and then calculated the 5-year running mean of the annual values. This is similar to our treatment of the Emerald Basin data.

Drinkwater and Pettipas (1994) examined long-term temperature time series for most of the areas on the Scotian Shelf and in the Gulf of Maine. They showed that the temperatures in the upper 30 m tended to vary greatly from month to month, due to atmospheric heating and cooling. Also, at intermediate depths of 50 m to approximately 150 m, temperatures had declined steadily from approximately the mid-1980s into the 1990s. On Lurcher Shoals off Yarmouth, on the offshore banks and in the northeastern Scotian Shelf the temperature minimum in this period approached or matched the minimum observed during the very cold period of the 1960s. This cold water was traced through the Gulf of Maine from southern Nova Scotia, along the coast of Maine and into the western Gulf. Cooling occurred at approximately the same time at Station 27 off St. John's, Newfoundland, off southern Newfoundland on St. Pierre Bank (Colbourne 1995) and in the cold intermediate layer (CIL) waters in the Gulf of St. Lawrence (Gilbert and Pettigrew 1997). Data since 1994 had indicated warming of the intermediate layers in the Gulf of Maine but a continuation of colder-than-normal water on most of the Scotian Shelf (Drinkwater et al. 1999).

The warming referred to above has continued into 1999 and on the northeastern Scotian Shelf temperature anomalies have risen above normal for the first time in approximately 15 years. Below, we describe temperature conditions in several representative areas of the Scotian Shelf.

On Sydney Bight (area 1 in Fig. 10) off eastern Cape Breton, mean profiles from 3 months show near to or above normal temperatures throughout most of the water column (Fig. 11). In July surface temperatures were over 3°C warmer-than-usual. The time series of the 100 m temperature anomalies show high temperature anomalies in the 1950s that fell to a minimum around 1960 and then rose steadily through the 1960s. Temperatures remained relatively high during the 1970s. By the 1980s temperatures began to decline and by the mid-1980s dropped to below normal with a minimum anomaly around -1°C in the early 1990s. Temperatures in recent years have generally remained below normal but increased slowly with several monthly anomalies of above normal being observed since 1995. The 1999 anomalies at 100 m were on average above normal although two of the three available months show slightly below normal temperatures.

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 10) are available for 8 months during 1999. They show primarily warmer-than-normal temperatures in the upper 100 m (Fig. 12). The only exception is cold conditions in the top 30 m in October. Below 100 m the temperatures tend to be near or slightly below normal. Note that in July at 200 m there is a slight positive temperature anomaly. The time series of the 100 m temperature anomalies show consistent positive values in 1999, which contrast with the predominantly negative anomalies over the last 15 years (Fig. 12). As at Emerald Basin, temperatures were relatively high in the 1950s. Temperatures then declined and at Misaine Bank reached a minimum around 1960, several years earlier than areas further to the southwest.

Temperatures were near normal from the late-1960s to the mid-1970s before rising to a maximum in the late 1970s. By the late-1980s, temperatures fell to below normal and reached a record sustained minimum of around -1°C in the first half of the 1990s. Since then, as on Sydney Bight, temperatures have been slowly but steadily increasing.

Lurcher Shoals is located off Yarmouth, Nova Scotia (area 24 in Fig. 10). This area exhibited warmer-than-normal temperatures in 1999 in the 7 months of 1999 when data were available (Fig. 13). This contrasts with the very cold temperatures observed during 1998. Anomalies in July, August, September and November exceeded +1°C. The time series at 50 m clearly shows high temperature anomalies in 1999 relative to the cold conditions over most of the past 15 years. Temperatures over Lurcher Shoals tended to be high in the late 1940s and early 1950s, declined to a mid-1960s minimum, rose rapidly into the 1970s and remained above normal into the mid-1980s. As in the northeastern Scotian Shelf, temperatures declined by the mid-1980s to below normal reaching a long-term minimum in the early 1990s. Although there had been some positive monthly temperature anomalies, annual mean temperatures and most monthly means remain below normal through the 1990s until 1999.

Georges Basin is located near the southeastern entrance to the Gulf of Maine (area 26 in Fig. 10) and is connected to the offshore slope water through the Northeast Channel. The time series of temperature in the deep regions (200 m) of Georges Basin (Fig. 14) shows a striking similarity to that of Emerald Basin including the very cold conditions in 1998 and warm in 1999 (Fig. 9). Also, the low values in the mid-1960s, rising sharply to a peak in the early 1970s and varying slightly but generally remaining above the long-term (1961-90) mean until 1998 are similar in the two basins. This is not surprising given that the source of the waters for both is primarily the offshore slope waters (Petrie and Drinkwater, 1993).

Temperature conditions were also examined on eastern Georges Bank (area 28 in Fig. 10). The Georges Bank 50 m temperatures exhibit higher variability than many of the other sites, in large part because of its shallowness. In spite of this, the long-term trend as revealed by the 5-year running mean at 50 m, shows many similarities to those in Georges Basin and in areas on the Scotian Shelf (Fig. 15). These again include the low temperatures in the 1960s, the higher-than-average conditions in the 1970s into the 1990s. In 1999, temperatures were generally above normal while in 1998 they were below normal.

Temperatures during the Summer Groundfish Surveys

The most extensive temperature coverage over the entire Scotian Shelf is obtained during the annual DFO groundfish survey, usually undertaken in July. A total of 200 CTD stations were taken during the 1999 survey and an additional 186 temperature stations were obtained as part of the ITQ (Individual Transferable Quota) fleet survey. The ITQ survey fills in gaps in the DFO survey for the Bay of Fundy, off southwest Nova Scotia and in the southwestern Scotian Shelf. Temperatures from both surveys were combined and interpolated onto a 0.2° by 0.2° latitude-longitude grid using an objective analysis procedure known as optimal estimation. The interpolation method uses the 15 "nearest neighbours" and a horizontal length scale of 30 km and vertical length scale of 15 m in the upper 30 m and 25 m below that. Data near the interpolation grid point are weighted proportionately more than those further away. Temperatures were optimally estimated onto the grid for depths of 0, 50, 100 m and near bottom (Fig. 16). Maximum depths for the interpolated temperature field were limited to 1000 m off the shelf. The 1999 temperature anomalies relative to the July 1961-90 means were also computed at the same four depth levels (Fig. 17).

The pattern of near-surface temperatures in July 1999 was similar to past years. They ranged from 19°C off the northeastern coast of Nova Scotia to 10°C off the southwestern shore (Fig. 16). The latter may be related to wind-induced upwelling by the predominantly southwesterly winds in summer. The cooler temperatures in the Gulf of Maine are due to the intense bottom-generated vertical mixing caused by the high tidal currents. The 1999 surface temperatures were generally much warmer than the long-term averages with a maximum anomaly of over 6°C off southern Cape Breton and >3°C over the entire northeastern Scotian Shelf (Fig. 16). This is consistent with the satellite imagery which has shown high sea surface temperature anomalies throughout the Scotian Shelf during much of 1999 (Petrie and Mason, 2000). These warm conditions contrast with the colder-than-normal temperatures off southwestern Nova Scotia, which again are believed to be due to wind-induced upwelling. As such, it may have been a short-lived phenomenon and not represented of the average surface conditions for the month. Relative to 1998, the surface temperatures generally increased. The maximum increase was off southern Cape Breton, by upwards of 4ºC. The very warm surface waters over most of the Scotian Shelf in 1999 are most likely related to atmospheric heating, which is consistent with the above normal-air temperatures in the region (Drinkwater et al., 2000a).

The temperatures at 50 m ranged from <2°C to over 10°C with the coldest waters in the northeast and the warmest waters in the deep Gulf of Maine (Fig. 16). There appears to be penetration of warmer waters (>6°C) towards Emerald Basin from offshore. Temperature anomalies at 50 m (Fig. 17) were predominantly positive in the northeastern region of the Shelf (mostly <1°C) and from Browns Bank to the Bay of Fundy including the eastern Gulf of Maine (1°-3°C). To the east of Browns the survey encountered slightly colder-than-normal temperatures (mostly between 0 and -1°C).

The temperature pattern at 100 m resembles that at 50 m although the actual temperatures are higher (Fig. 16). The temperatures at 100 m ranged from <3°C to over 10°C in the central Gulf of Maine and offshore between 63°-64°W. Most of the Scotian Shelf had anomalies between -1°C and 1°C and were not considered to be significantly different from normal (Fig. 17). As observed at 50 m, the central Gulf of Maine appeared very warm being upwards of 3°C warmer-than-normal.

The near-bottom temperatures over the Scotian Shelf had a similar range to that at 100 m, from 3°C in the northeast to over 10°C in the Gulf of Maine/Bay of Fundy and in the Scotian Gulf seaward of Emerald Basin (Fig. 16). The pattern of colder temperatures in the northeastern Shelf and warmest in the Gulf of Maine with relatively warm waters in the deep basins of the central Shelf is typical. The former is derived largely from the Gulf of St. Lawrence while in the deep basins of the Scotian Shelf the waters mainly originate from the offshore slope waters. The warm waters around Sable Island are in large part due to the shallowness, with the bottom depths being near to or within the surface mixed layer. Elsewhere on the shelf the bottom depths lay below the mixed surface layer. Relative to the long-term mean, the near bottom temperatures are predominantly near to or warmer-than-normal (Fig. 17). The largest deviation from the mean (warmer by over 2°C) is off southwestern Nova Scotia and in the Browns Bank region. Another region of above normal temperatures is in the Scotian Gulf seaward of Emerald Basin. These temperatures represent much warmer conditions than the previous year, upwards of 4°C in the Browns Bank region and 2°-3°C over most of the southwestern Scotian Shelf. This is related to the replacement of cold Labrador Slope Water by the Warm Slope Water. In the northwest, near-bottom temperatures also warmed producing above normal temperatures in the region for the first time in almost 15 years. The mechanism here is thought to be a combination of atmospheric forcing and advection from the Gulf of St. Lawrence or off southern Newfoundland.

We also estimated the area of the bottom covered by each one degree temperature range (i.e. 1-2^{o}C, 2-3^{o}C, 3-4^{o}C, etc.) within NAFO Subareas 4Vn, 4Vs, 4W and 4X (see Fig. 1 for Subarea boundaries). These were obtained from optimally estimated temperatures from the July groundfish and ITQ surveys. The time series of these areas for each NAFO Subarea are shown in Fig. 18a,b. Several points are noteworthy. First is the increase in temperature from 4Vs/4Vn to 4W and 4X. In 4Vn most of the bottom is covered by waters <6^{o}C and almost 50% <5^{o}C (Fig. 18a). For 4Vs, 80-90% is <6^{o}C and 75% <5^{o}C (Fig. 18a). In 4W <50% and in 4X<20% is covered by temperatures <6^{o}C (Fig. 18b). The time series for 4Vn and 4Vs show an increase in the 0^o-1^{o}C and especially <3°C waters during the late 1980s and early 1990s (Fig. 18a). Also in 4Vs there are waters <1^{o}C during this colder period. In 4W there is also an increase in the area of the waters <3^{o}C but it is of smaller amplitude than in 4V (Fig. 18b). In 4X there is an increase in waters <4^{o}C but it is not as large an amplitude as in the other regions (Fig. 18b). During 1999 in all areas there was a significant decrease in the area covered by temperatures in the colder ranges. This is consistent with the flooding of the warm slope water back into the deep basins and onto the southwestern Scotian Shelf and with the warming observed in the northeastern Shelf.

Cabot Strait Deep Temperatures

Bugden (1991) investigated the long-term temperature variability in the deep waters of the Laurentian Channel in the Gulf of St. Lawrence from data collected between the late 1940s to 1988. The variability in the average temperatures within the 200-300 m layer in Cabot Strait was dominated by low-frequency (decadal) fluctuations with no discernible seasonal cycle. A phase lag was observed along the major axis of the channel such that events propagated from the mouth towards the St. Lawrence Estuary on time scales of several years. The updated time series shows that temperatures declined steadily between 1988 and 1991 to their lowest value since the late 1960s (near 4.5^{o}C and an anomaly exceeding -0.9^{o}C; Fig. 19). Then temperatures rose dramatically reaching 6^{o}C (anomaly of

0.6°C) in 1993. By 1994 temperatures had begun to decline although anomalies remained positive. Temperatures continued to fall in 1995 and 1996 towards near normal. In 1999, temperatures rose significantly reaching near record highs during the middle of the year but declined thereafter. Temperatures at the end of 1999 were still over 6°C, however, and up over those observed in 1998.

Standard Sections

As part of the AZMP, seasonal sampling along the historical standard sections was re-established by the Canadian Department of Fisheries and Oceans in 1998. On the Scotian Shelf this included transects off Cape Sable, Halifax, Louisbourg and across Cabot Strait (Fig. 1). While four occupations per section has been the goal, this has not been achieved for all sections due primarily to budgetary constraints. Dedicated monitoring cruises have provided some of the section data while others have been obtained from fisheries surveys. Similar to the standard stations, the data collected usually include CTDs, nutrient and chemical sampling and plankton. Only the hydrographic data are discussed in the present paper. Anomalies relative to the 1961-90 means were only estimated for the Halifax Line. At the other sections, the historical data were considered of insufficient quantity to determine reliable means for this time period.

Cape Sable

Extending south from Cape Sable off the southwestern tip of Nova Scotia across Browns Bank to the entrance of the Northwest Channel into the Gulf of Maine, this section was occupied three times in 1998 (April, October and November) and twice in 1999 (April and November). In 1998, the main feature was the presence of the cold Labrador Slope Water (temperatures 4°-8°C) offshore (Fig. 20). Shelf waters were also relatively cold. By April 1999 the offshore was occupied by Warm Slope Water (temperatures >8°C) and was still there in October of 1999 (Fig. 21). The Shelf waters remained cold, however, until October 1999. For example, in 1998, below 50 m there are few temperatures >6°C whereas in 1999 there are no waters colder than 6°C (Fig. 20, 21). Salinities too differed, being mostly >32 in 1998 and mostly >33 in 1999. Density on the other hand changed only slightly as the temperature and salinity changes compensated in terms of their effect on density.

Halifax Line

The Halifax Line was occupied 5 times in 1998 and in 1999 (April, June, July, October, and November in both years). Contours of temperature, salinity and sigma-t across the section and their anomalies for June 1998 and 1999 are shown in Fig. 22 and 23, respectively. In 1998, we again see the cold Labrador Slope Water characteristics off the Shelf and in the deeper reaches of Emerald Basin, which lead to the negative anomalies (cold and fresh) below 100 m. Temperature anomalies were upwards of 2°-3°C below normal and salinities >0.5 fresher-than-normal. This contrasts with 1999, when temperatures were much warmer and the temperature anomalies in the deep waters (>100 m) were positive. Salinity anomalies offshore also had switched from negative to positive from 1998 to 1999 although in the inner Emerald Basin the salinities remained negative. Sigma-t anomalies in both years were predominantly negative indicating lighter-than-normal water.

From the other occupations of the Halifax Line, the gradual warming of the Basin through 1998 (see Fig. 8) can be detected. The largest change offshore occurs between November 1998 and April 1999 when the Labrador Slope Water is replaced by Warm Slope Water. Temperature anomalies reach over 6°C and salinities over 2 in the outer reaches of the Halifax Line in the upper 50 m by April 1999.

Louisbourg Line

This line runs southeast off Louisbourg, across Banquereau Bank and out into the Slope Water region. It was occupied twice in 1998 (April and October) and four times in 1999 (March, April, July and October). The temperature, salinity and sigma-t contours for July (Fig. 24) show strong upper layer stratification with high temperatures (>18°C) and low salinities (< 31) in the near surface waters. Below approximately 50 m, the waters are between 2-4°C and salinities mainly between 32-33. The surface temperatures are higher-than-normal and consistent with the satellite imagery, which show positive anomalies of about 1°C.

Cabot Strait Line

This line extends from northern Cape Breton to southwestern Newfoundland and was occupied twice in 1998 (April and October) and three times in 1999 (April, August and October). The August transect of 1999 is representative (Fig. 25). The coldest waters generally are found between about 50 m and 150 m on the Cape Breton side. These are the cold intermediate (CIL) waters exiting the Gulf of St. Lawrence. The lowest salinities are also usually on the Cape Breton side near the surface. The >6°C waters in the 200 to 300 m layer are consistent with the Cabot Strait temperature index (Fig. 19). Also of note are the very warm waters in the near surface layer, with temperatures exceeding 20°C. These are warmer-than-normal and consistent with the very warm surface waters on the Scotian Shelf.

Density Stratification

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. The extent of the 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. Last year we examined the variability in stratification for the first time 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. 10. The long-term monthly mean density gradients for the years 1961-90 were estimated and these then subtracted from the monthly values to obtain monthly anomalies. Annual anomalies were estimated by averaging all available monthly means within a calendar year. A 5-yr running mean of the annual anomalies was then calculated. The monthly and annual means show high variability but the 5-yr running means show some distinctive trends. The density anomalies are presented in g/ml/m. A value of 0.1 represents a difference of 0.5 a sigma-t unit over the 50 m. As reported last year (Drinkwater et al., 1999), the dominant feature is the higher stratification during recent years throughout the Scotian Shelf (Fig. 26a,b). The 5-year running mean began to increase steadily around 1990 and the most recent values are at or near the highest values in the approximate 50-year records in most areas. The 1999 values confirm a continuation of high stratification. There is surprising consistency from area to area, through most of the Scotian Shelf. This higher-than-average stratification does not extend into the Gulf of Maine region and it was absence or weak in the Laurentian Channel and Sydney Bight areas. One expects the anomalies in density stratification in the Gulf of Maine to be lower than on the Scotian Shelf due to the more intense tidal mixing in the former. Examination of the temperature and salinity characteristics reveals that the primary cause of the increased stratification was due to changes in surface salinity, although in 1999 the high surface temperatures also contributed.

Frontal Analysis

Shelf/Slope Front

The waters on the Scotian Shelf and in the Gulf of Maine have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters offshore. The relatively narrow boundary between the shelf and slope waters is regularly detected in satellite thermal imagery. Positions of this front and of the northern boundary of the Gulf Stream between 50°W and 75°W for the years 1973 to 1992 were assembled through digitization of satellite derived SST charts (Drinkwater et al., 1994). From January 1973 until May 1978, the charts covered the region north to Georges Bank, but in June 1978 the areal coverage was extended to include east to 55°W and eventually 50°W. Monthly mean positions of the shelf/slope front in degrees latitude at each degree of longitude were estimated. NOAA updated this data set until the termination of the satellite data product in October 1995. A commercial company has continued the analysis but did not begin until April 1996. Even then, the initial charts did not contain data east of 60°W. Data for 1999 have been digitized, estimates of monthly means positions determined and anomalies relative to the 20 year period, 1978 to 1997, were calculated.

The overall mean position of the Shelf/Slope front together with the 1999 annual mean position is shown in Fig. 27. The average position is close to the 200 m isobath along the Middle Atlantic Bight, separates slightly from the shelf edge off Georges Bank and then runs between 100-300 km from the shelf edge off the Scotian Shelf and the southern Grand Bank. It is generally furthest offshore in winter and onshore in late summer and early autumn. During 1999, the shelf/slope front was shoreward of its long-term mean position from 74°W to 60°W and east of 60°W it was seaward of the mean. The largest deviations from the mean position occurred near Georges Bank and the entrance to the Northeast Channel around 65°W. The time series of the annual mean position (averaged over 55°W-75°W) shows the front was at a maximum seaward location in 1985 and again in 1993.

Since 1993, the front moved steadily seaward approximately 40 km, reaching its most southerly position in 1997. During the 1998 and 1999, the frontal position has been moving northward again with the largest change occurring in 1999.

Gulf Stream

The position of the northern boundary or "wall" of the Gulf Stream was also determined from satellite imagery by Drinkwater et al. (1994) up to 1992 and has been updated in a manner similar to that for the shelf/slope front. Thus, the time series consists of the monthly position at each degree of longitude from 55°W to 75°W. The average position of the north wall of the Stream and the 1999 annual mean is shown in Fig. 28. The Stream leaves the shelf break near Cape Hatteras (75°W) running towards the northeast. East of approximately 62°W the average position lies approximately east-west. During 1999, the average position of the Stream was near the long-term mean position at most degrees of longitude. The stream was slightly seaward of the mean between 63° to 66°W and farthest shoreward at 56°W. The Stream was located south of its mean position during the late-1970s and 1980, near the long term mean through most of the 1980s and north of it during the late-1980s and into the first half of the 1990s (Fig. 28). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed a rapid decline in 1996 and remained low through 1997 and 1998. The 1996 position is not well defined, however, since it is based upon only three months of the data (October to December). The decline does match the large decline in the NAO index in 1996 and is consistent with the finding of a significant positive correlation between the Gulf Stream position and the NAO. In 1999, the average position of the front moved shoreward but remained south of the mean.

Summary

In 1999, three significant features or events dominated the climate changes on the Scotian Shelf and in the Gulf of Maine. The first was the disappearance of the cold, Labrador-type slope water along the shelf edge of the Scotian Shelf and the Gulf of Maine. This cold water had extended southward to the outer reaches of the Middle Atlantic Bight in early 1998 and had penetrated onto the central and southwestern Scotian Shelf and central Gulf through channels and gullies. It resulted in the coldest near-bottom temperatures in these areas since the 1960s. In 1999, this Labrador Slope Water retracted northward to be replaced by Warm Slope Water. This warm water eventually flowed onto the shelf and replaced the colder waters that had occupied the shelf during 1998. Temperatures in deep Emerald Basin were of order 2°-3°C warmer than last year and above the long-term mean. Similar warming occurred in the deep waters from Emerald Basin south into the Gulf of Maine. The second major event occurred in the northeastern Scotian Shelf where temperatures below about 50 m have been below normal since the mid-1980s. These waters have been gradually warming since a minimum in the early 1990s and in 1999 rose above normal for an extended period for the first time in approximately 15 years. Cause of the changes on the Scotian Shelf is believed to be a combination of atmospheric forcing and advection from the Gulf of St. Lawrence and the southern Newfoundland shelf. The third feature was the very warm surface layer temperatures throughout much of the Scotian Shelf and the Gulf of Maine. This is also considered to be of atmospheric origin and is consistent with the extreme warm air temperatures over the region. Also worthy of mention is the continued strong stratification in the upper water column (between surface and 50 m) throughout the Scotian Shelf. This high stratification has been present during most of the 1990s but has not extent into the Gulf of Maine.

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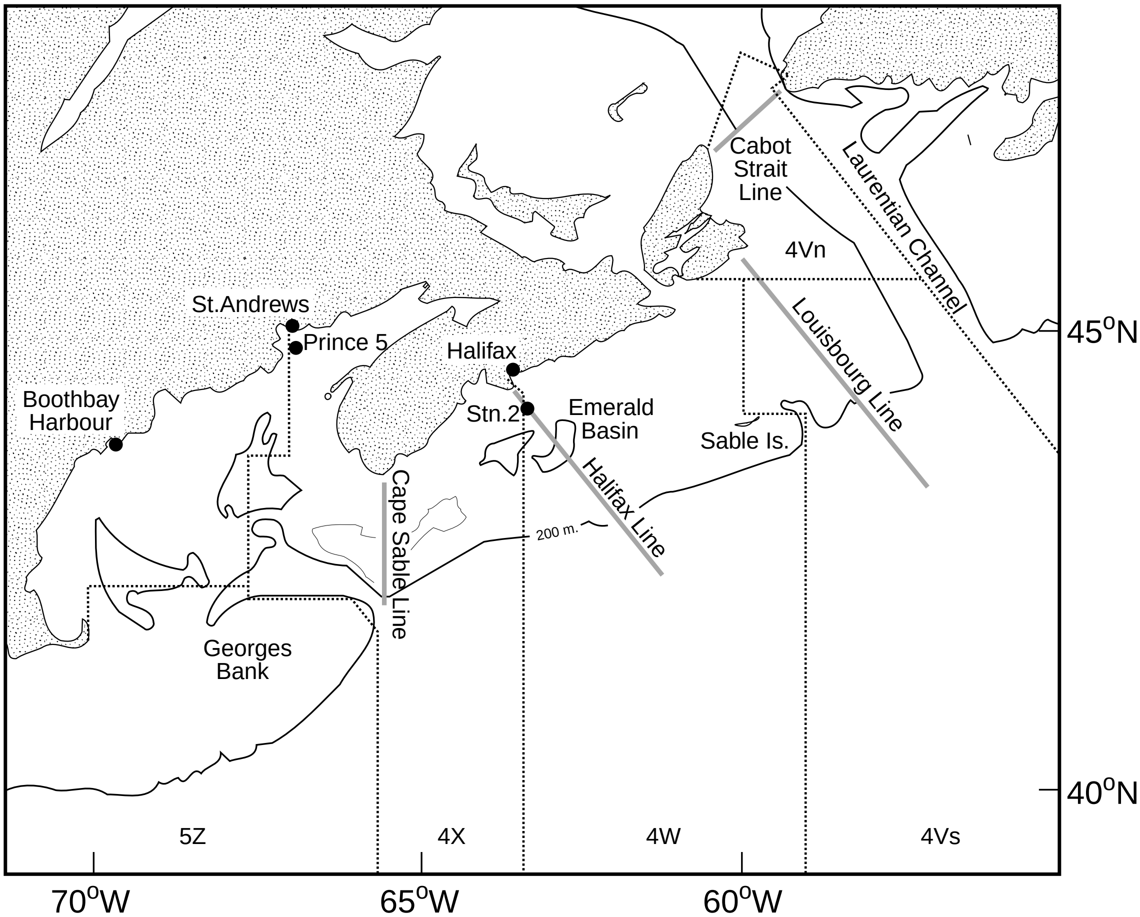


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas.

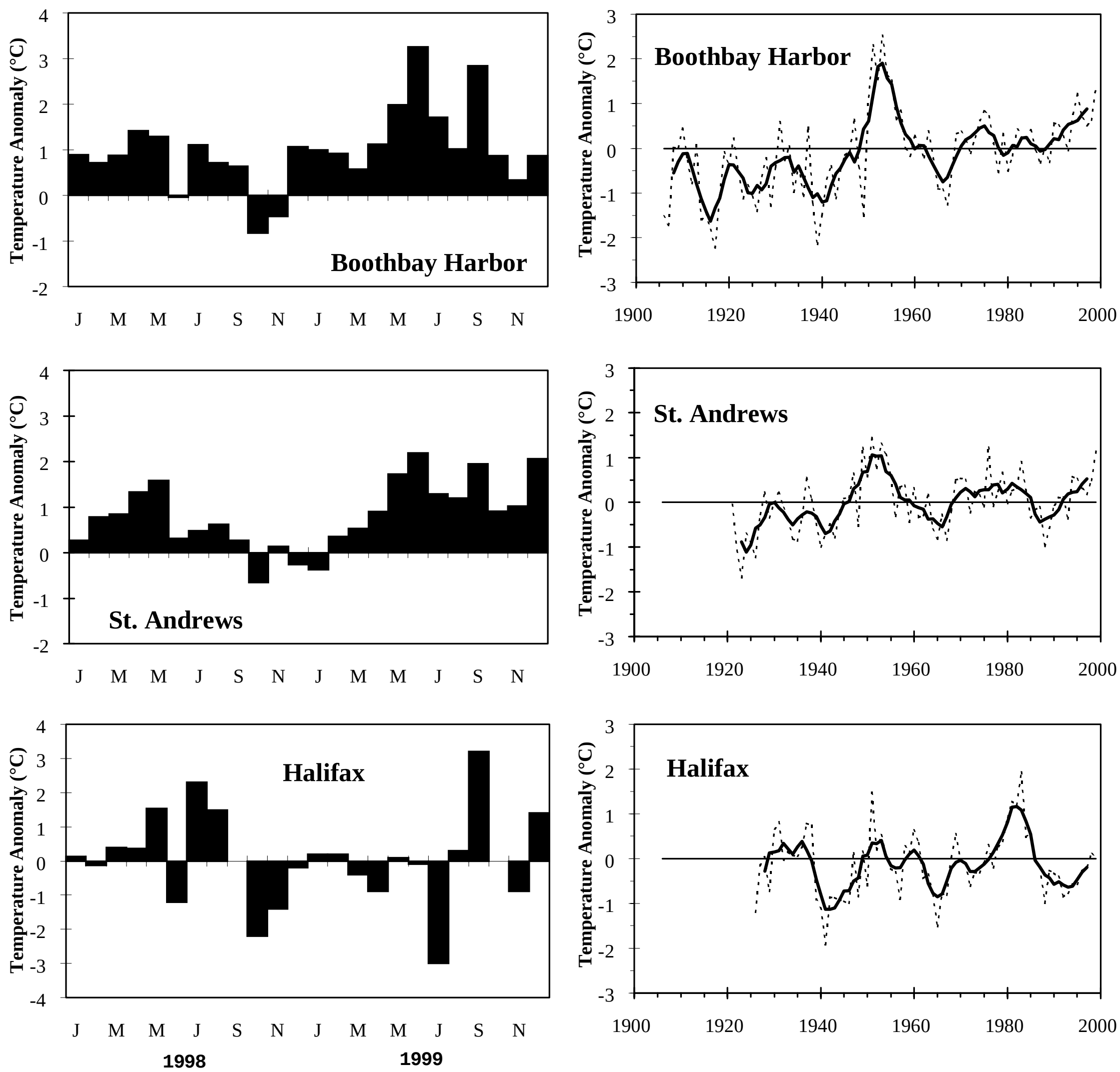


Fig. 2. The monthly sea surface temperature anomalies during 1998 and 1999 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax Harbour. Anomalies are relative to the 1961-90 means.

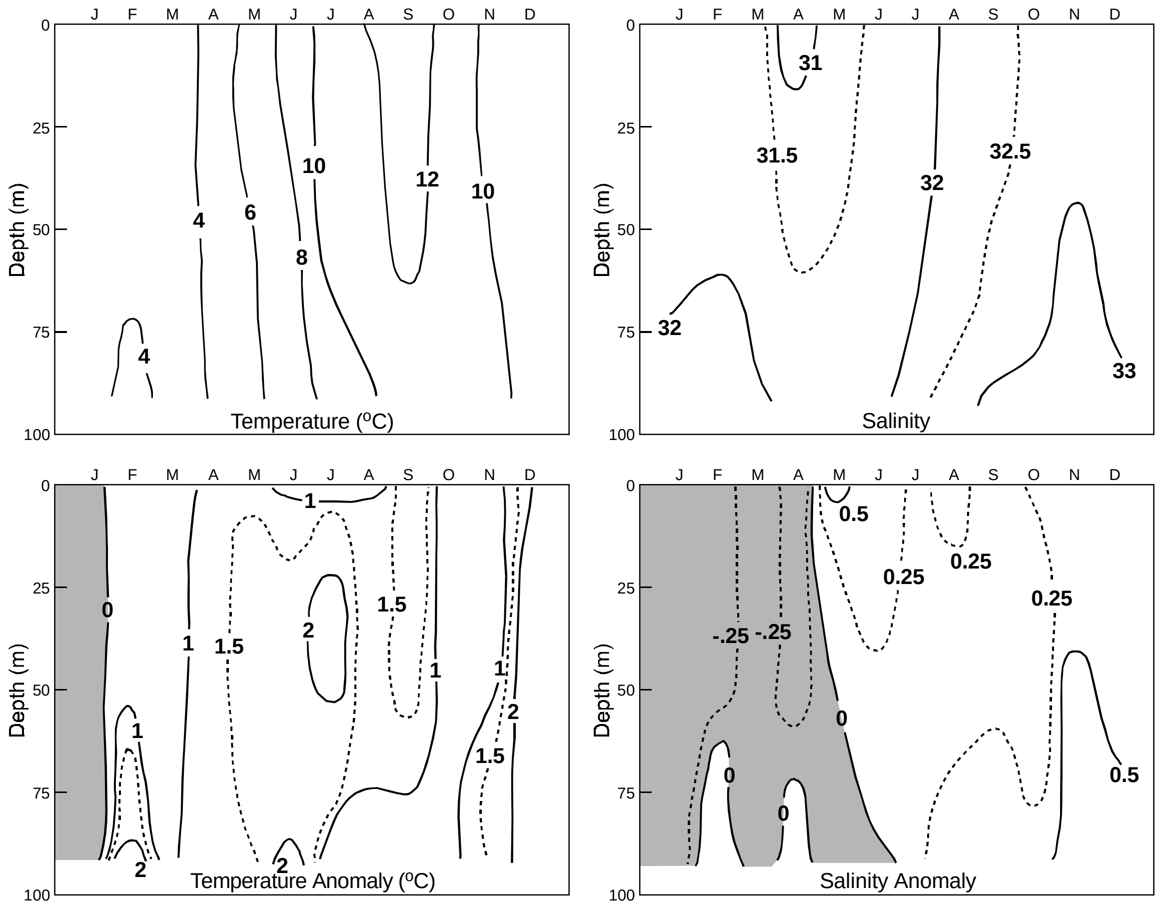


Fig. 3. Contours of monthly mean temperature (left) and salinity (right) and their anomalies (bottom panels) at Prince 5 as a function of depth during 1999 relative to the 1961-90 means. Colder and fresher-than-normal conditions are shaded.

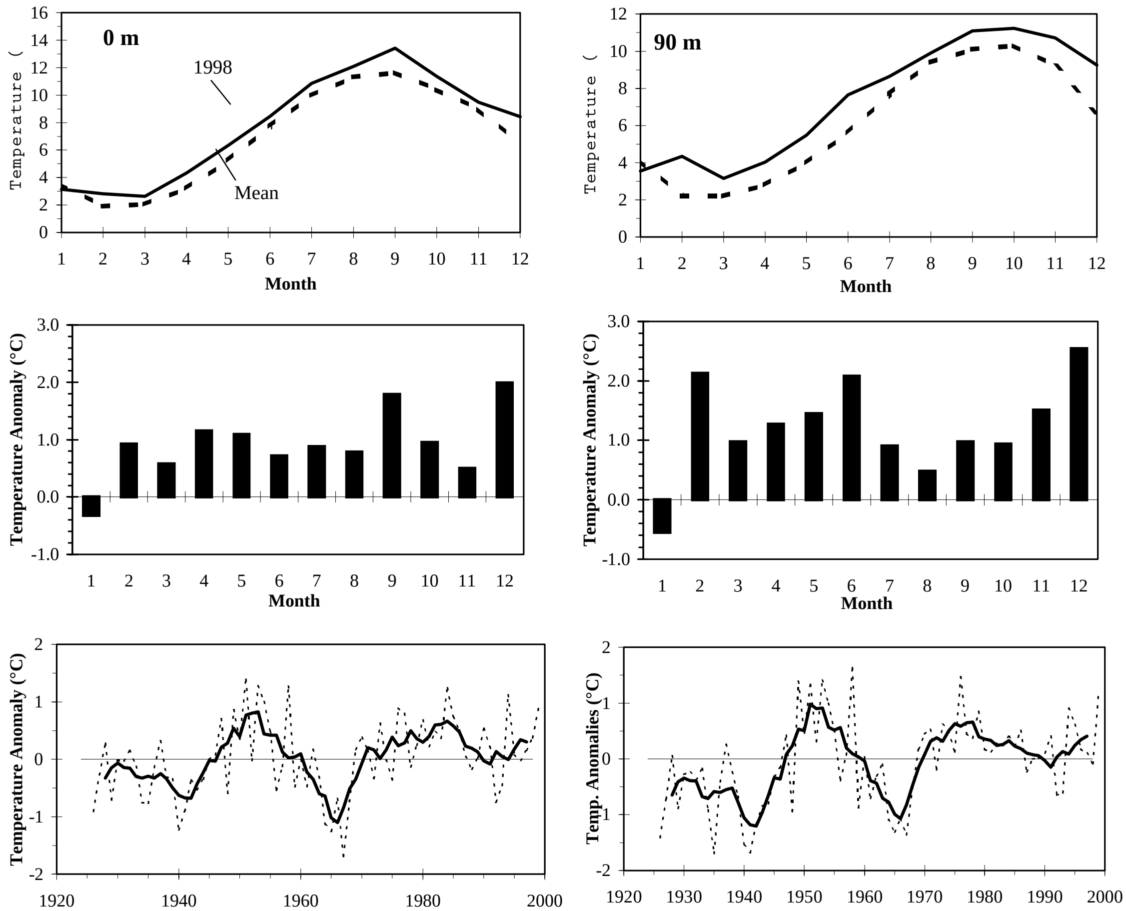


Fig. 4. The monthly mean temperatures for 1999 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

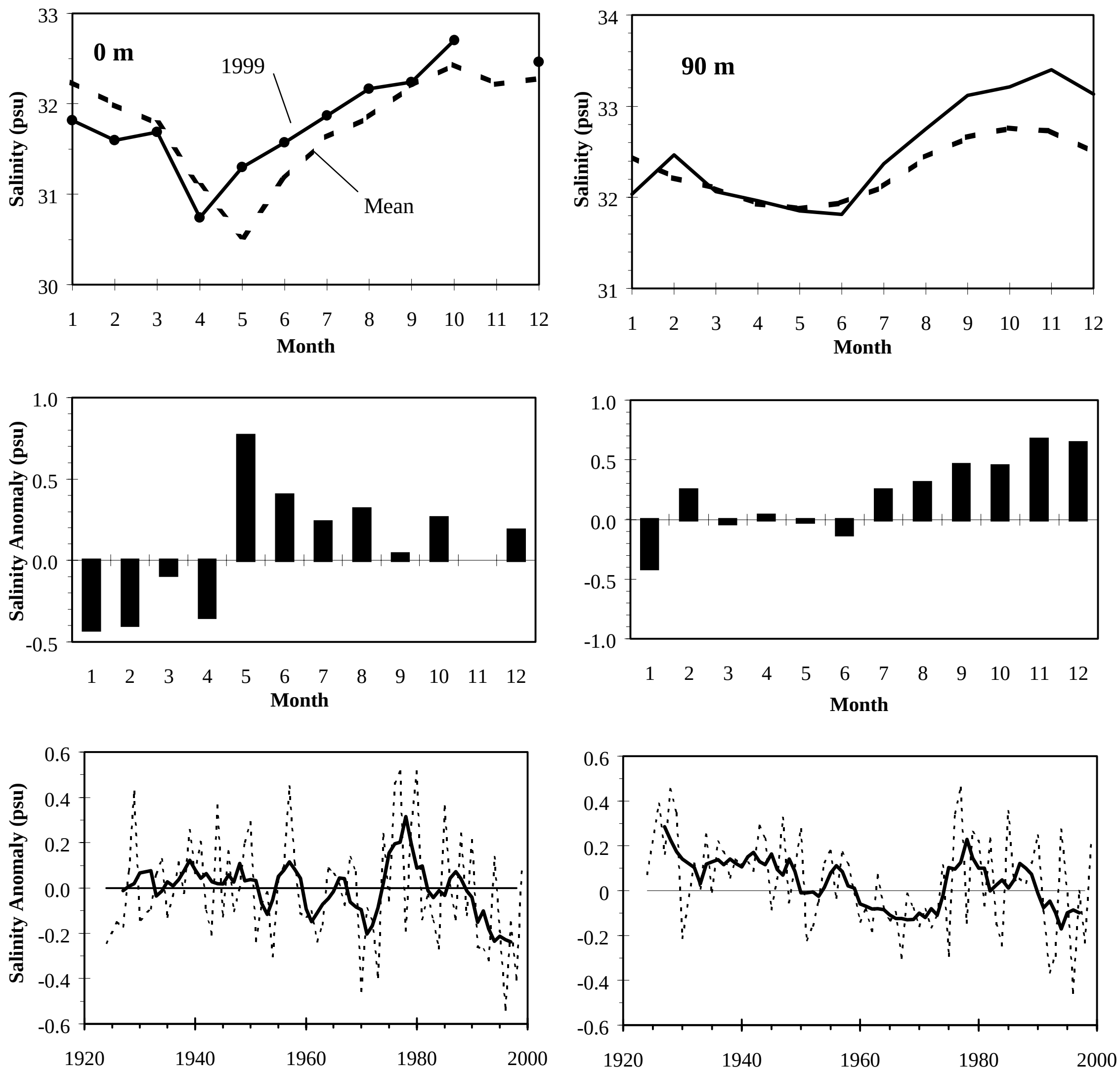


Fig. 5. The monthly mean salinities for 1999 (solid line; top panels) and their long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels are the time series of the annual means (dashed lines) and their 5-year running averages (solid line) for Prince 5, 0 m (left) and 90 m (right).

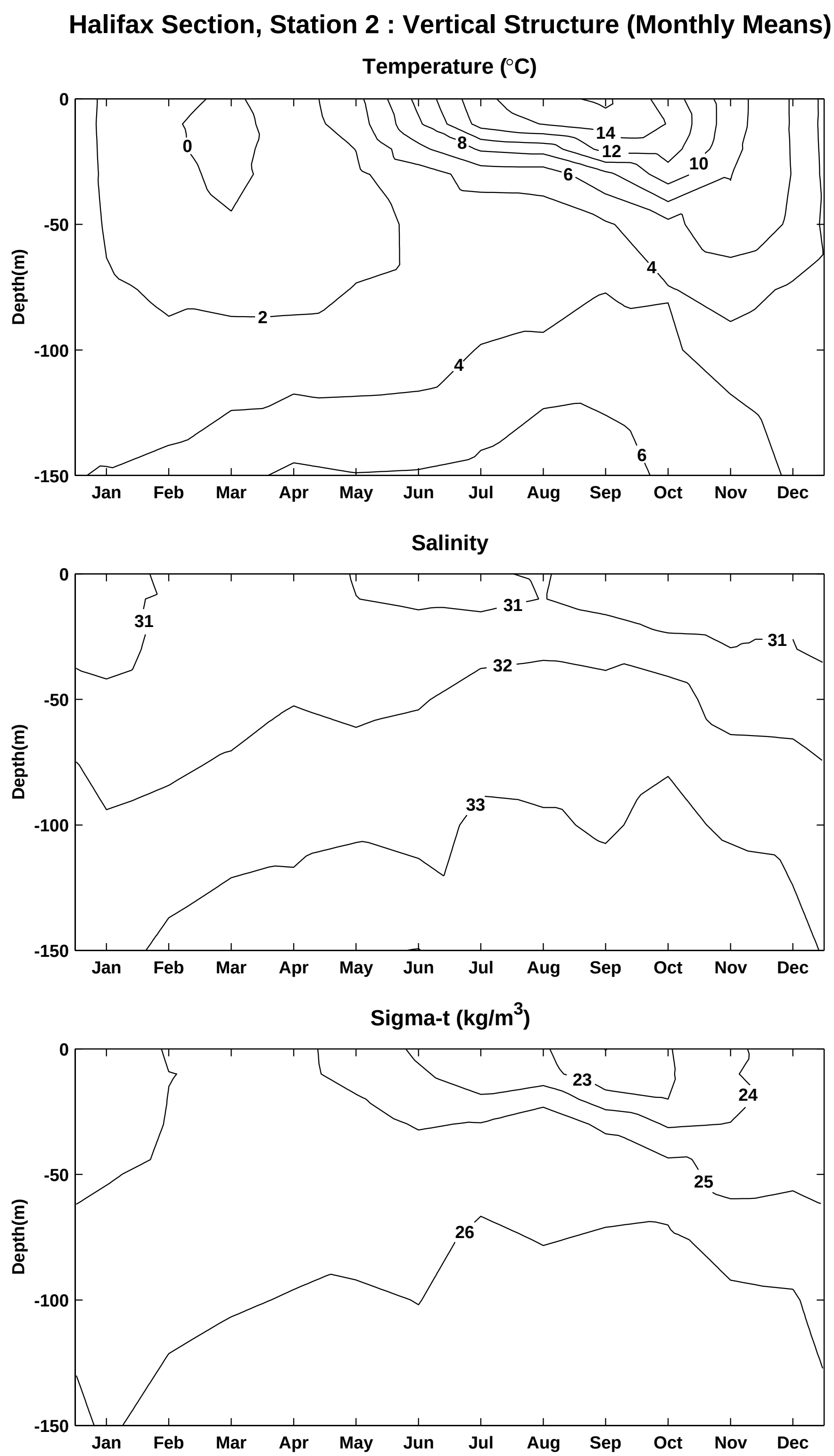


Fig. 6. Contours of the long-term monthly means of temperature, salinity and density (sigma-t) at the standard station H2 (Halifax Line 2).

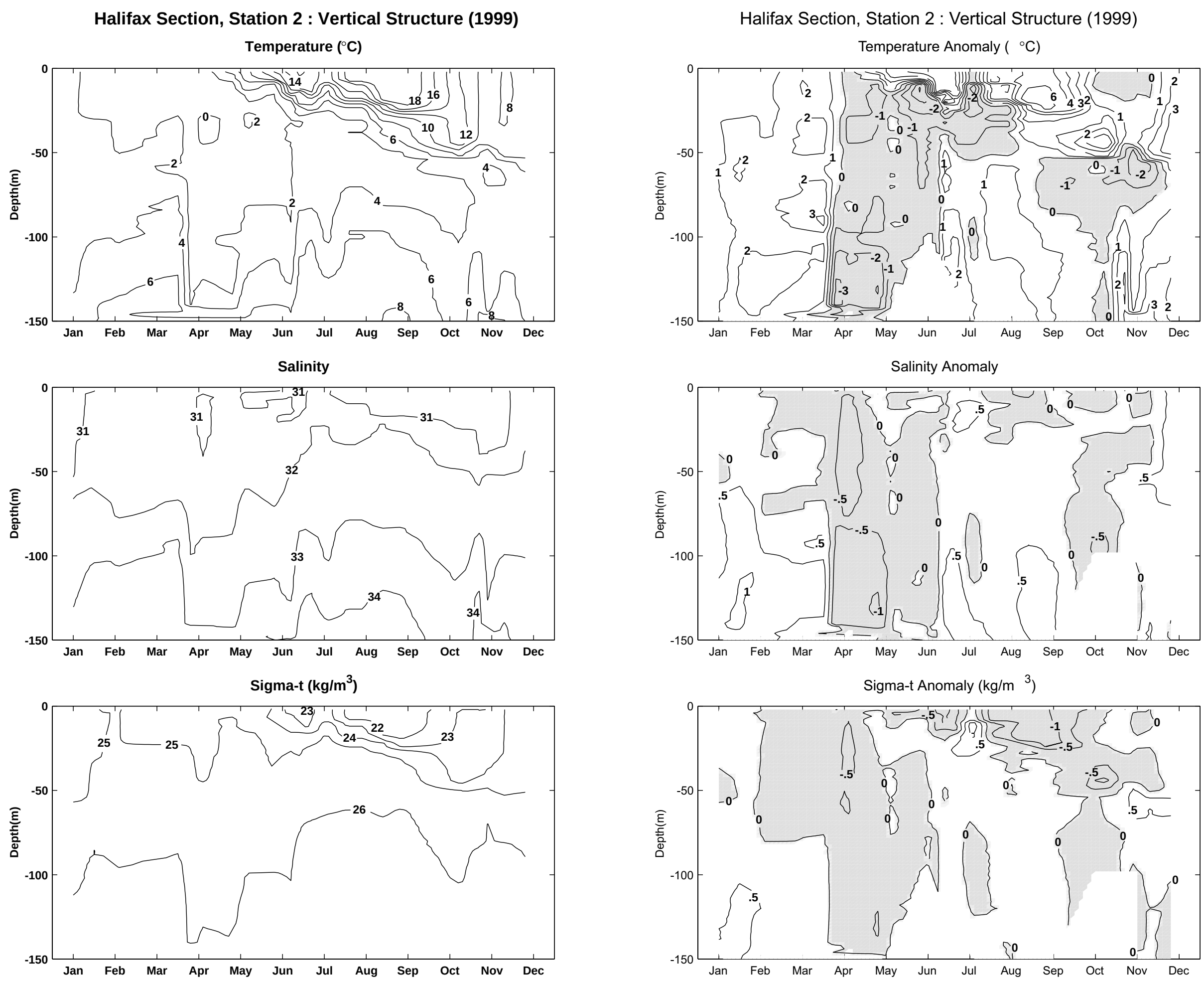


Fig. 7. Contours of temperature, salinity and density (sigma-t) for 1999 (left) and their anomalies (right) at the standard station H2.

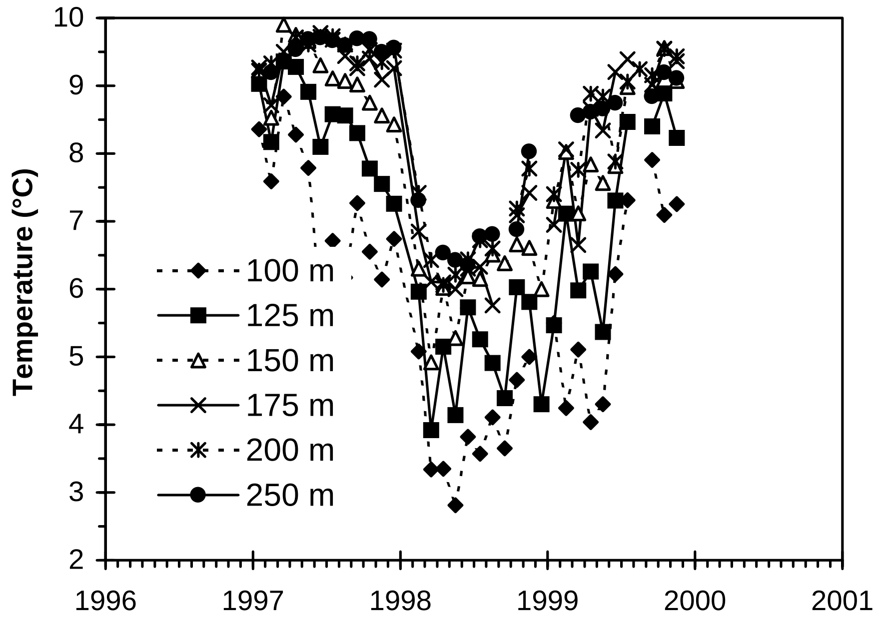


Fig. 8. Time series of temperature by depth in Emerald Basin from available data for 1997 to 1999.

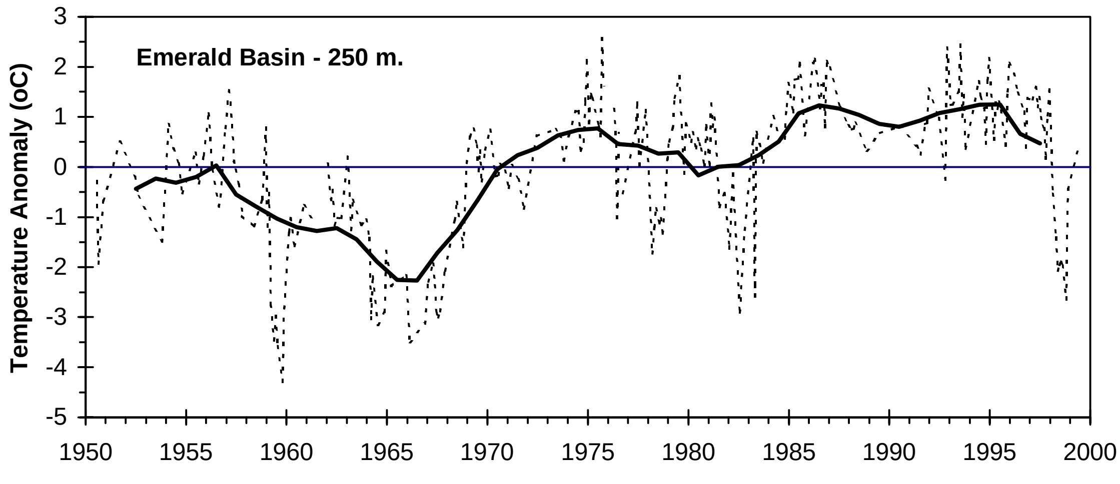
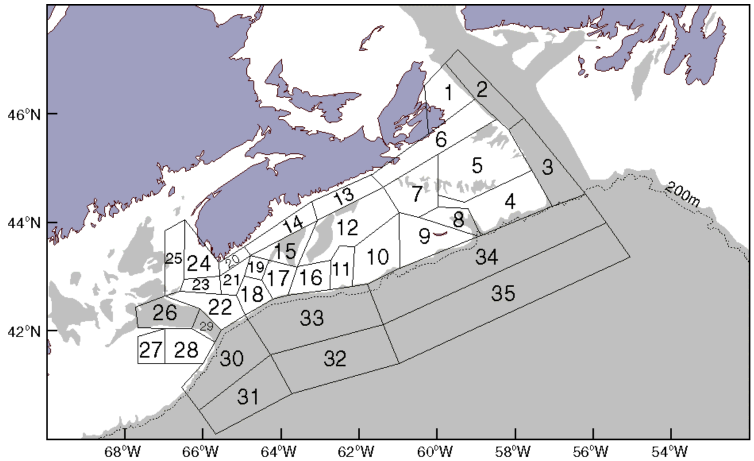


Fig. 9. Time series of available monthly mean temperature anomalies at 250 m in Emerald Basin Bank (dashed line) and their 5-year running means (solid line).



1. Sydney Bight
2. N. Laurentian Channel
3. S. Laurentian Channel
4. Banquereau
5. Misaine Bank
6. Canso
7. Middle Bank
8. The Gully
9. Sable Island
10. Western Bank
11. Emerald Bank
12. Emerald Basin
13. Eastern Shore
14. South Shore
15. Lahave Basin
16. Saddle
17. Lahave Bank
18. Baccaro Bank
19. Roseway Bank
20. Shelburne
21. Roseway Basin
22. Browns Bank
23. Roseway Channel
24. Lurcher Shoals
25. E. Gulf of Maine
26. Georges Basin
27. Georges Shoal
28. E. Georges Bank
29. N.E. Channel
30. Southern Slope
31. Southern Offshore
32. Central Offshore
33. Central Slope
34. Northern Slope
35. Northern Offshore

Fig. 10. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

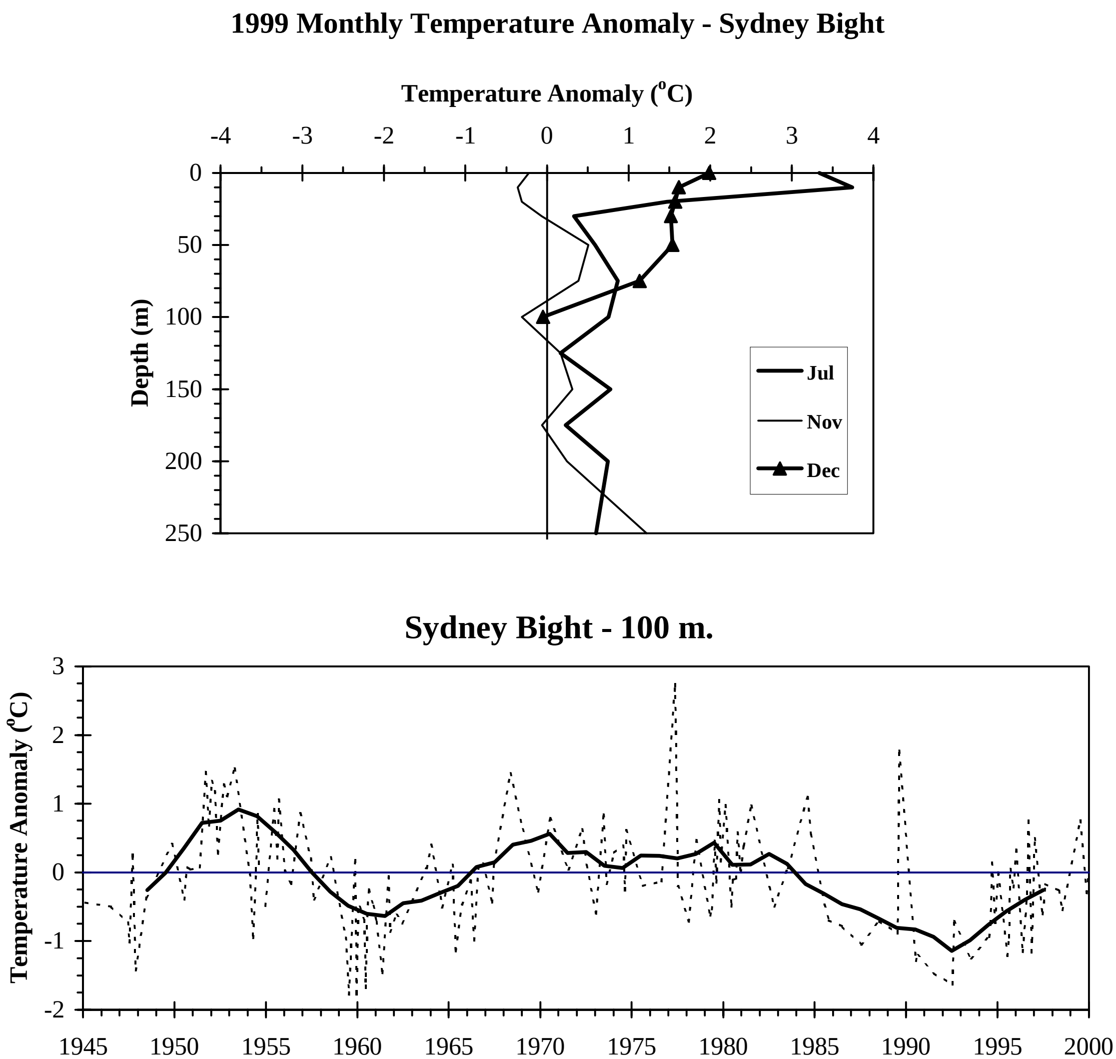


Fig. 11. 1999 monthly temperature anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1-Fig. 10).

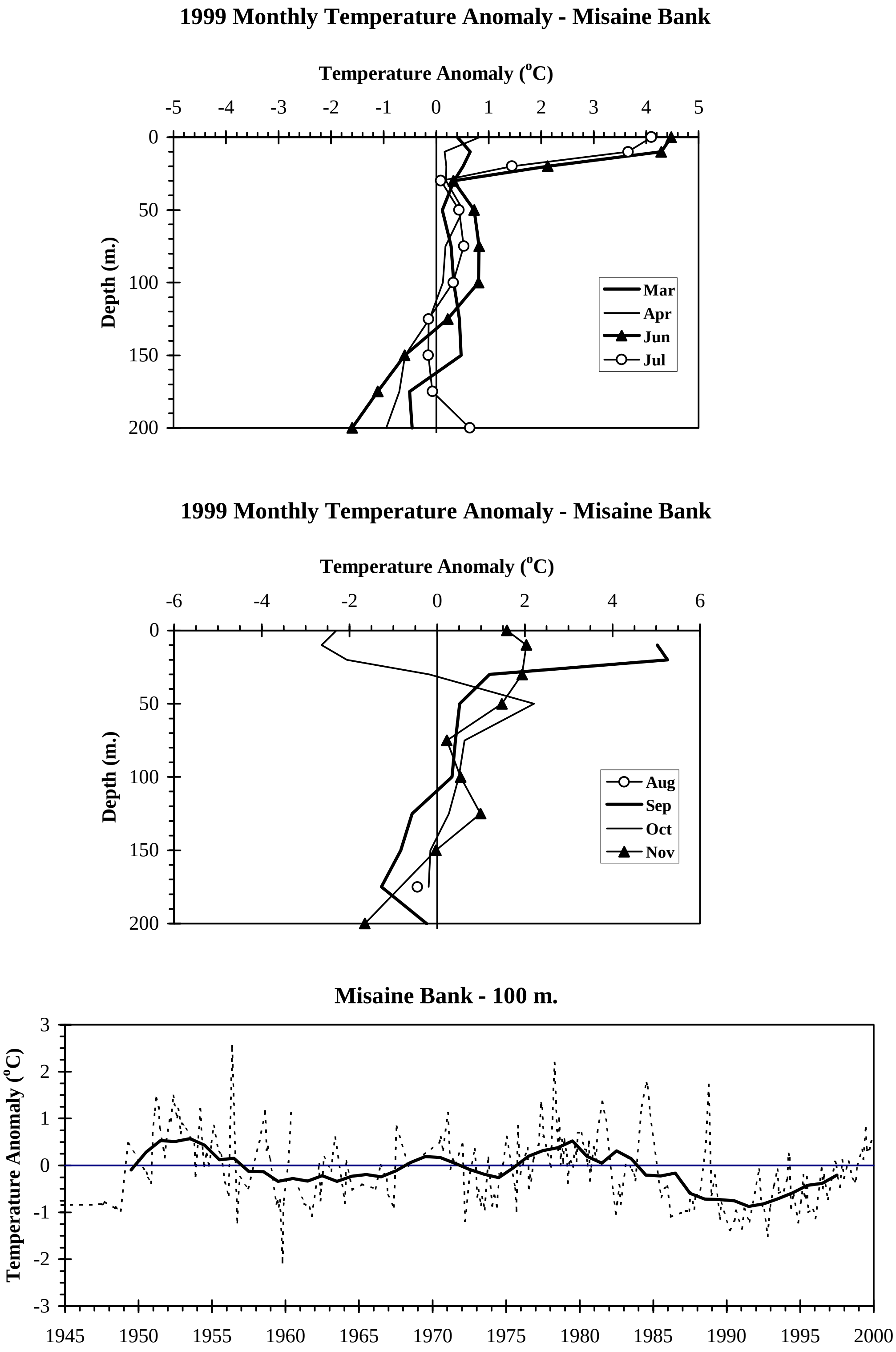


Fig. 12. 1999 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5-Fig. 10).

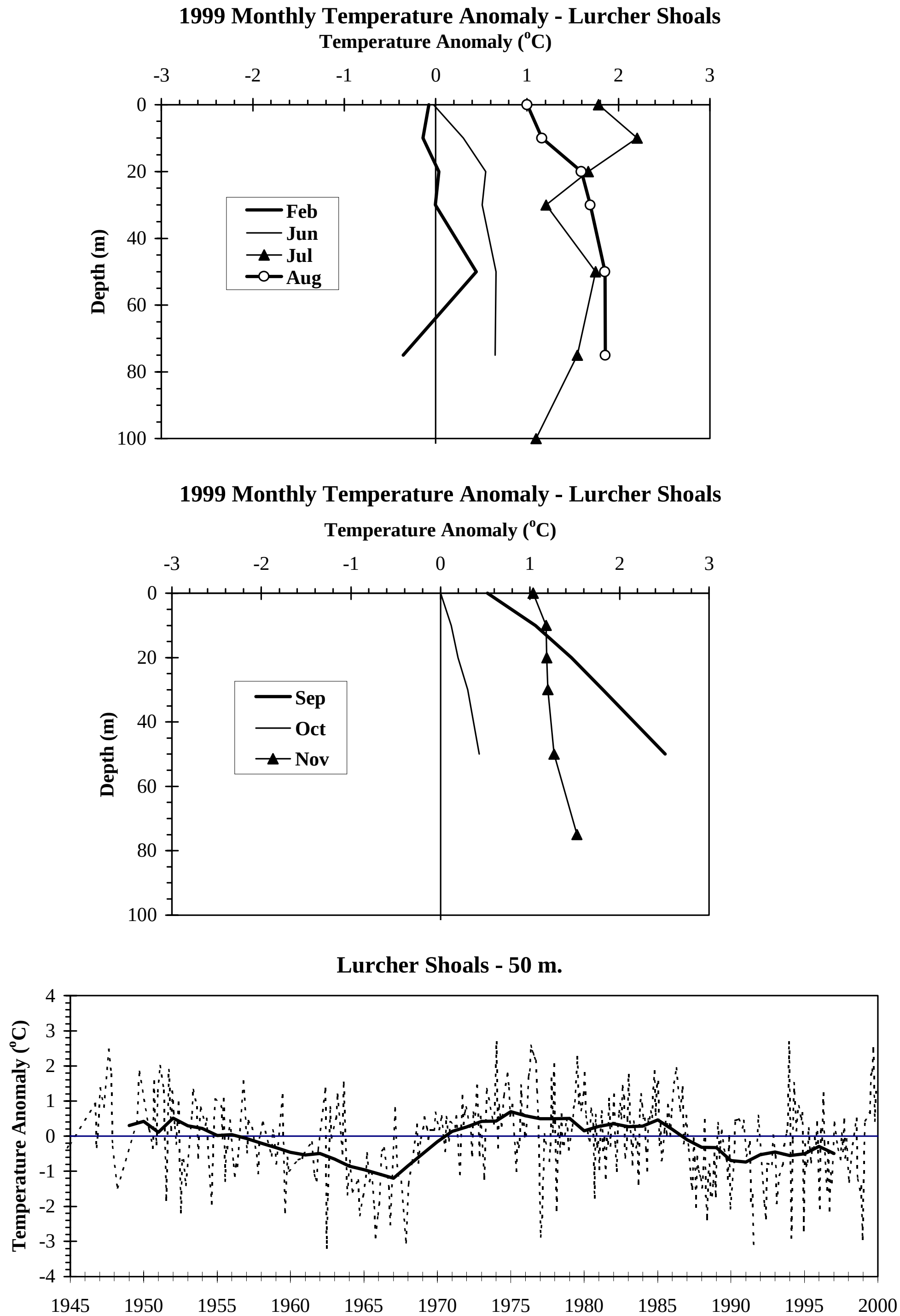


Fig. 13. 1999 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Lurcher (area 24-Fig. 10).

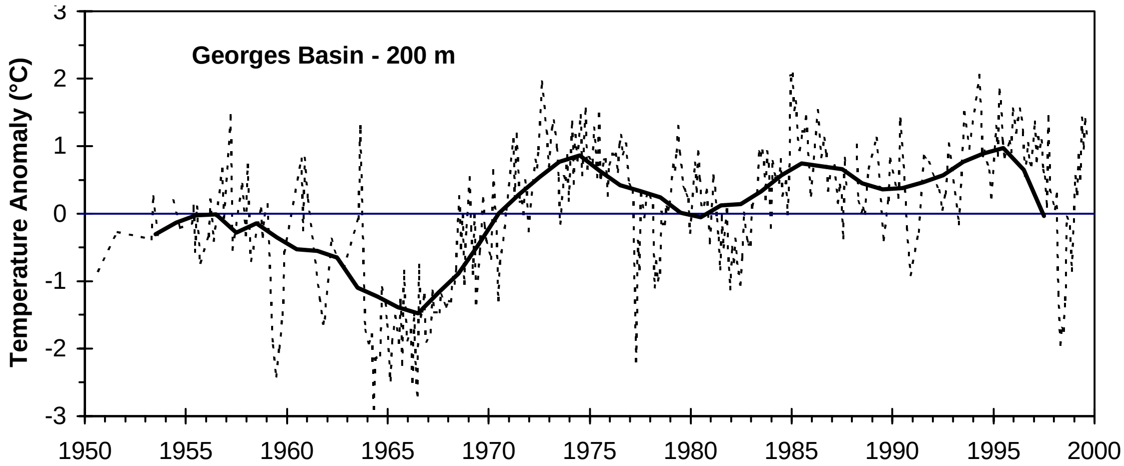


Fig. 14. Time series of monthly mean temperature anomalies at 200 m in Georges Basin (dashed lines) and their 5-year running means (solid line).

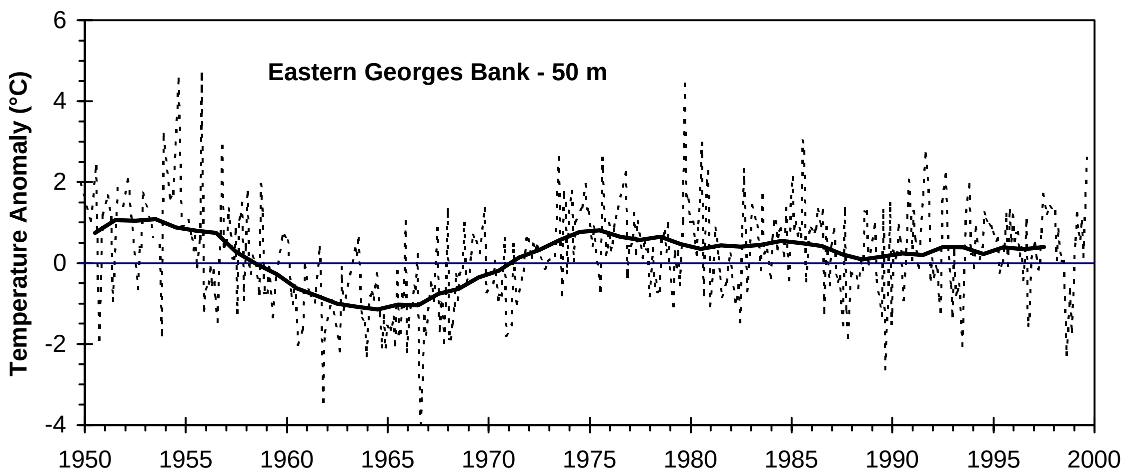


Fig. 15. Time series of monthly mean temperature anomalies at 50 m on eastern Georges Bank (dashed lines) and their 5-year running means (solid line).

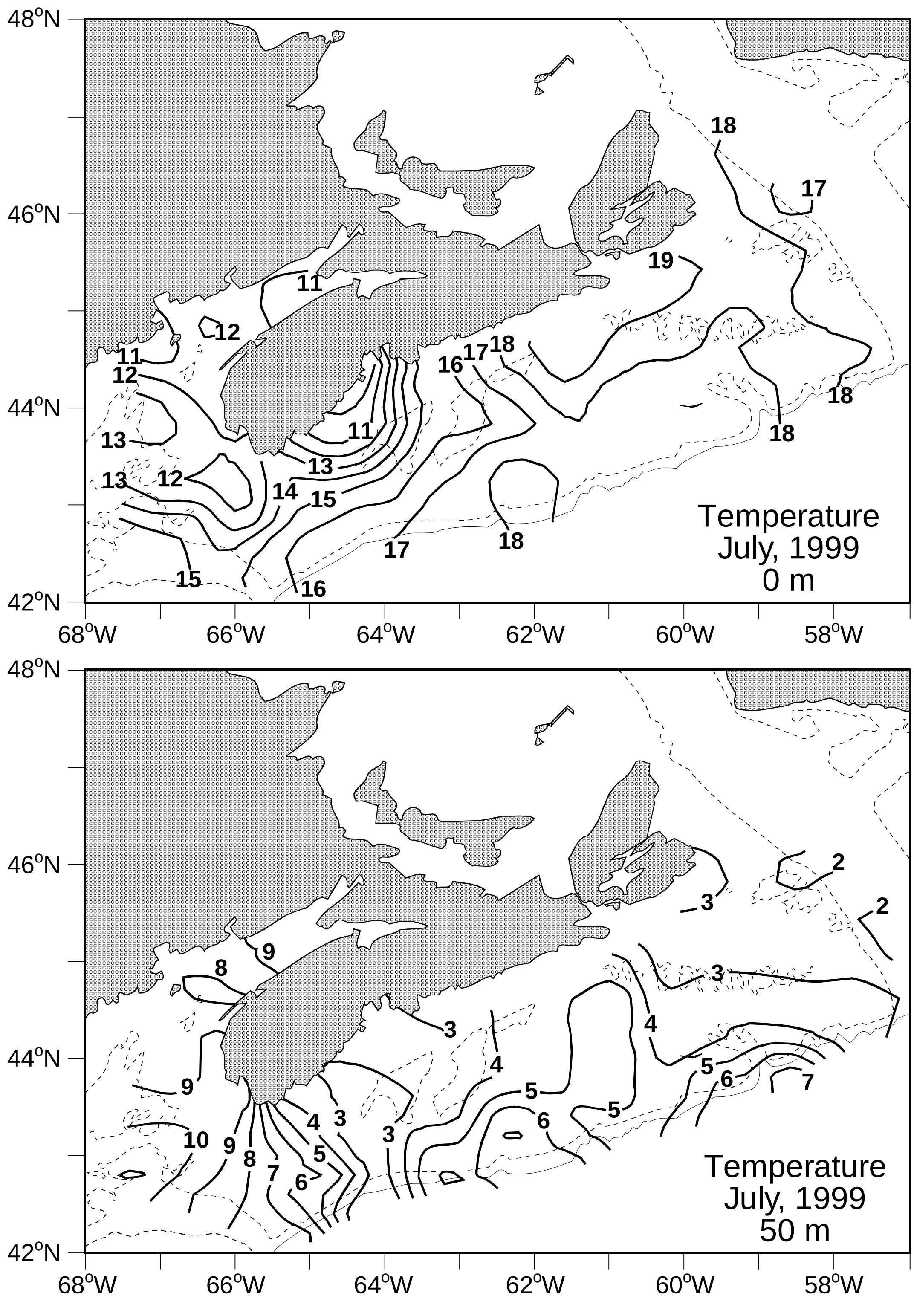


Fig. 16a. Contours of temperatures at the surface (top panel) and 50 m (bottom panel) during the 1999 July groundfish and ITQ surveys.

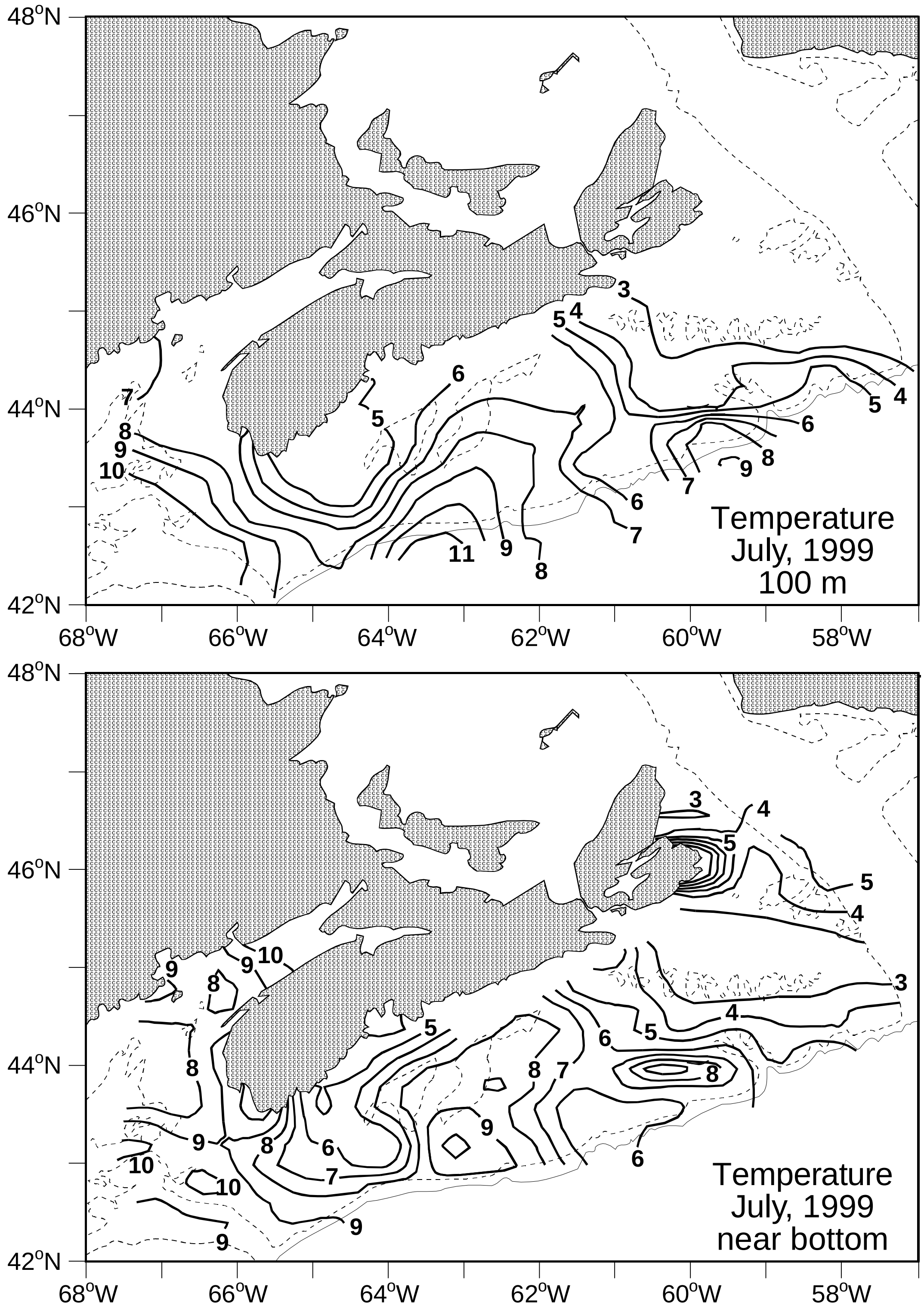


Fig. 16b. Contours of temperatures at 100 m (top panel) and near bottom (bottom panel) during the 1999 July groundfish and ITQ surveys.

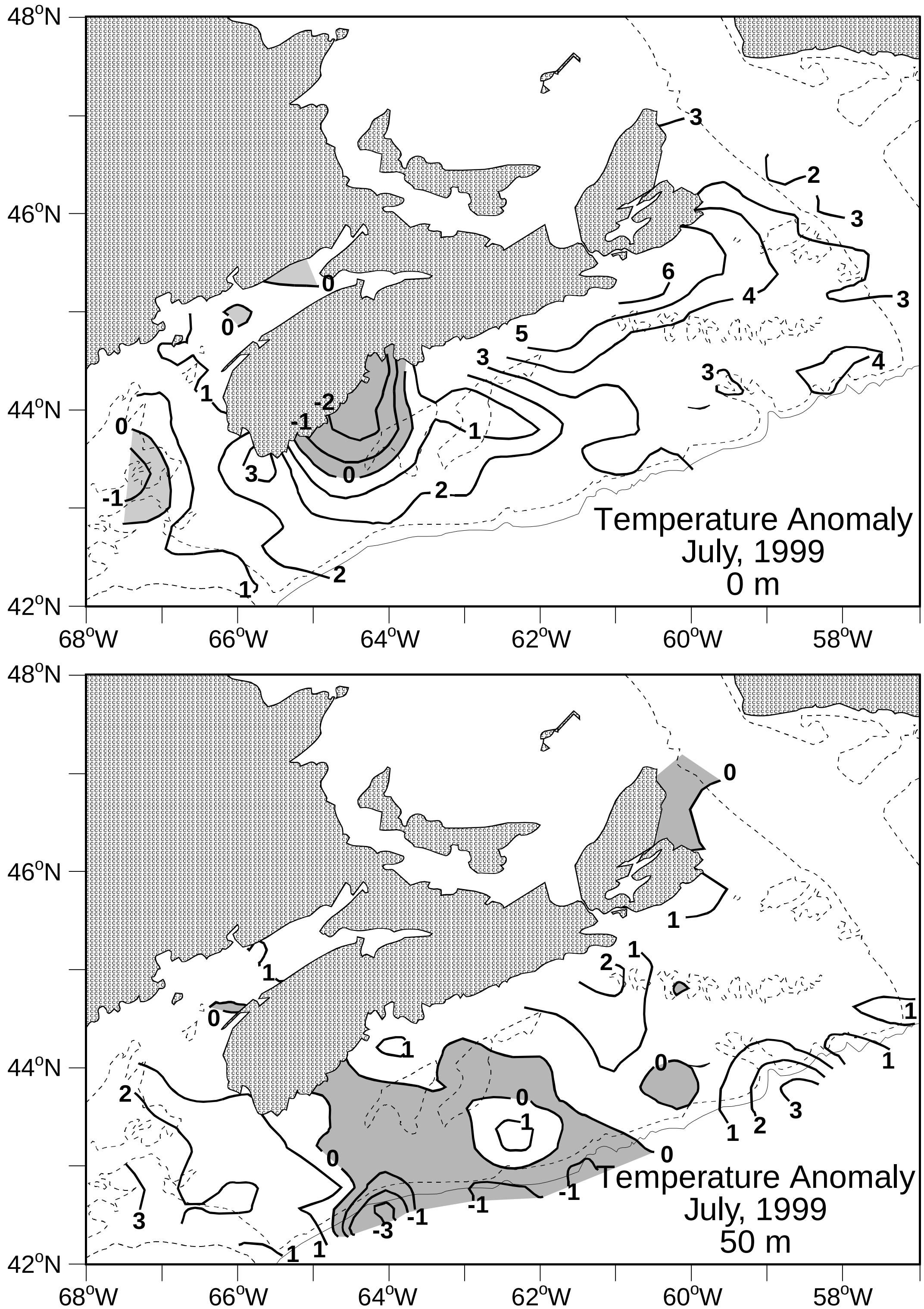


Fig. 17a. Contours of temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 1999 July groundfish and ITQ surveys.

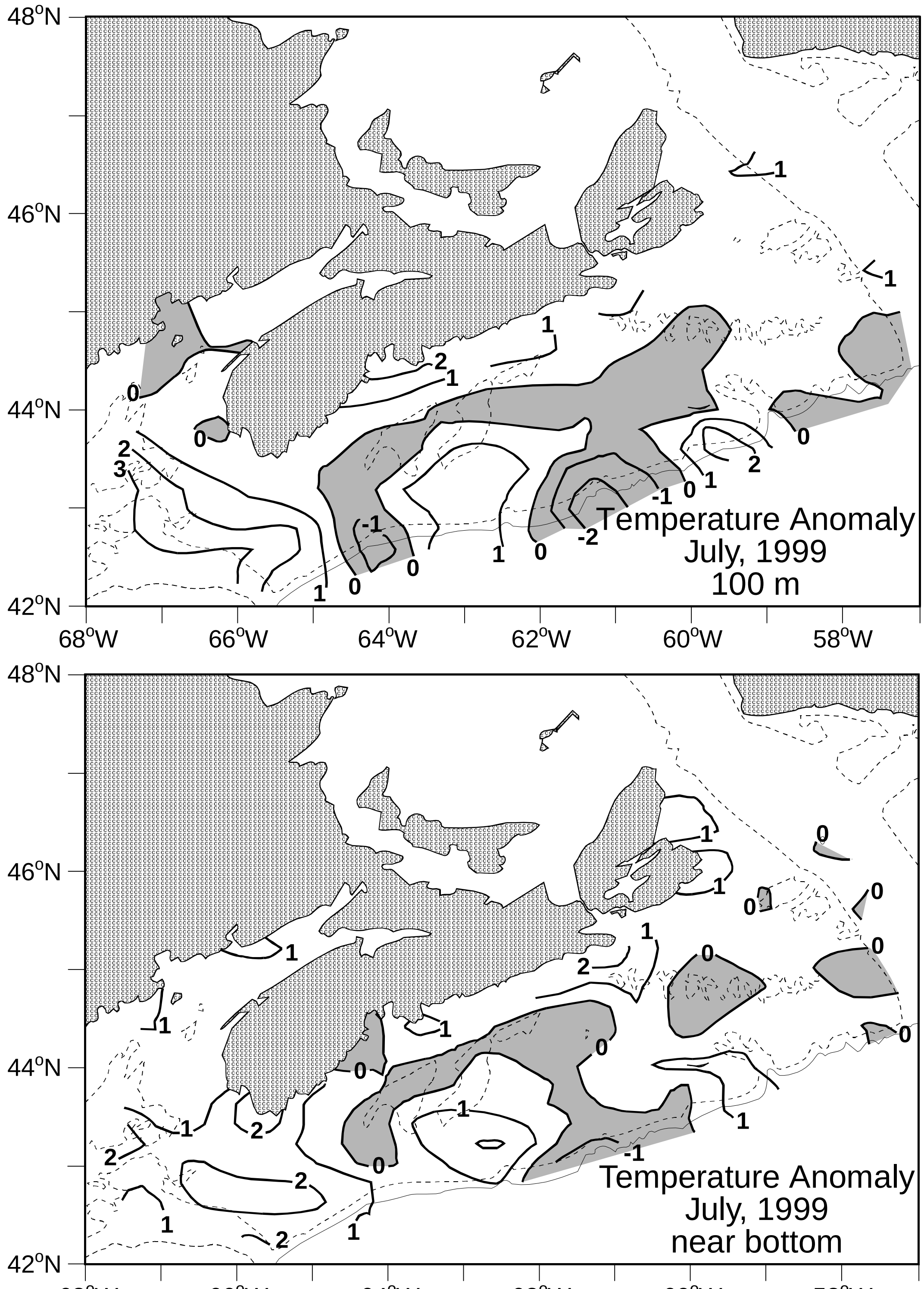


Fig. 17b. Contours of temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 1999 July groundfish and ITQ surveys.

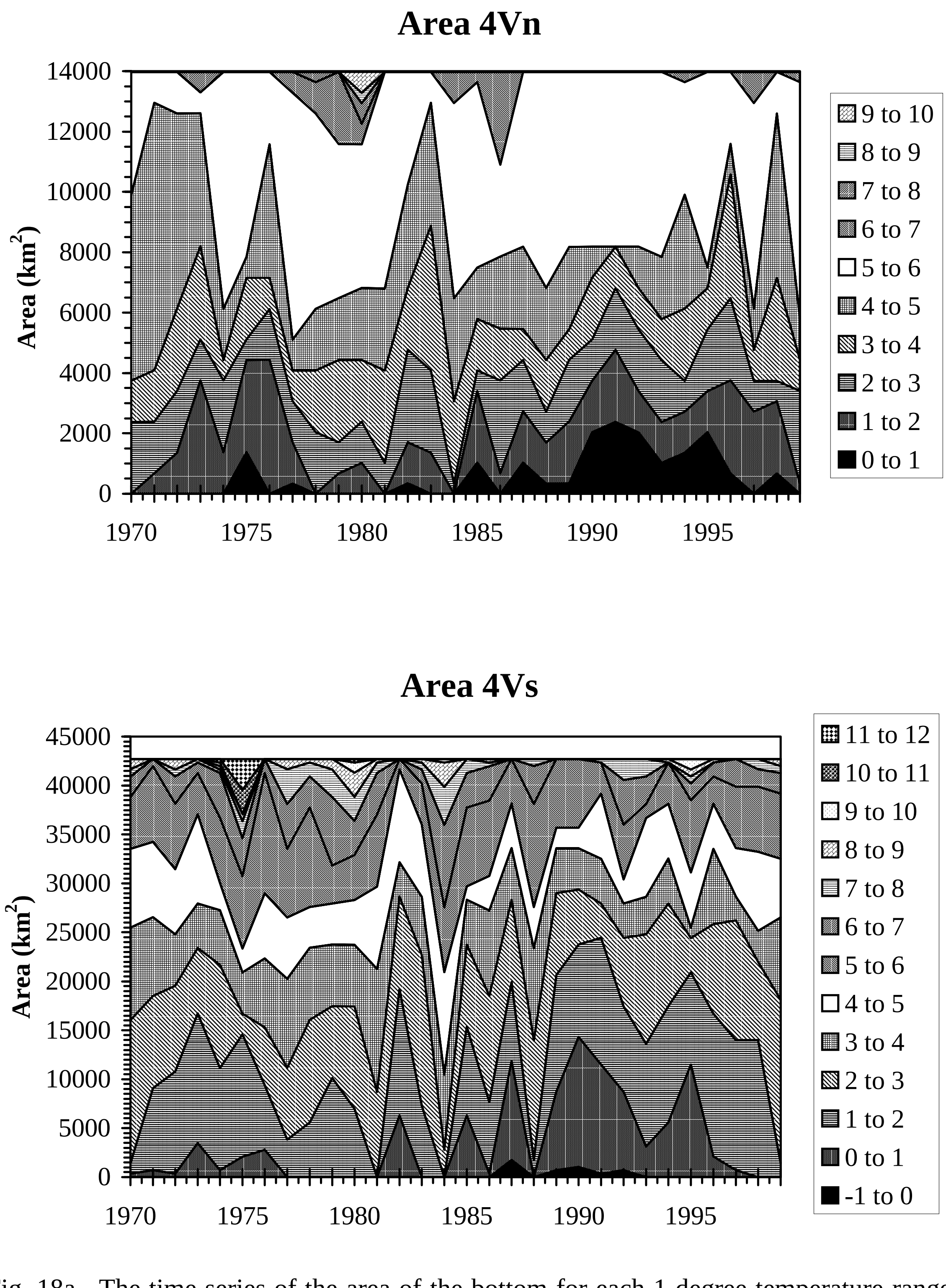
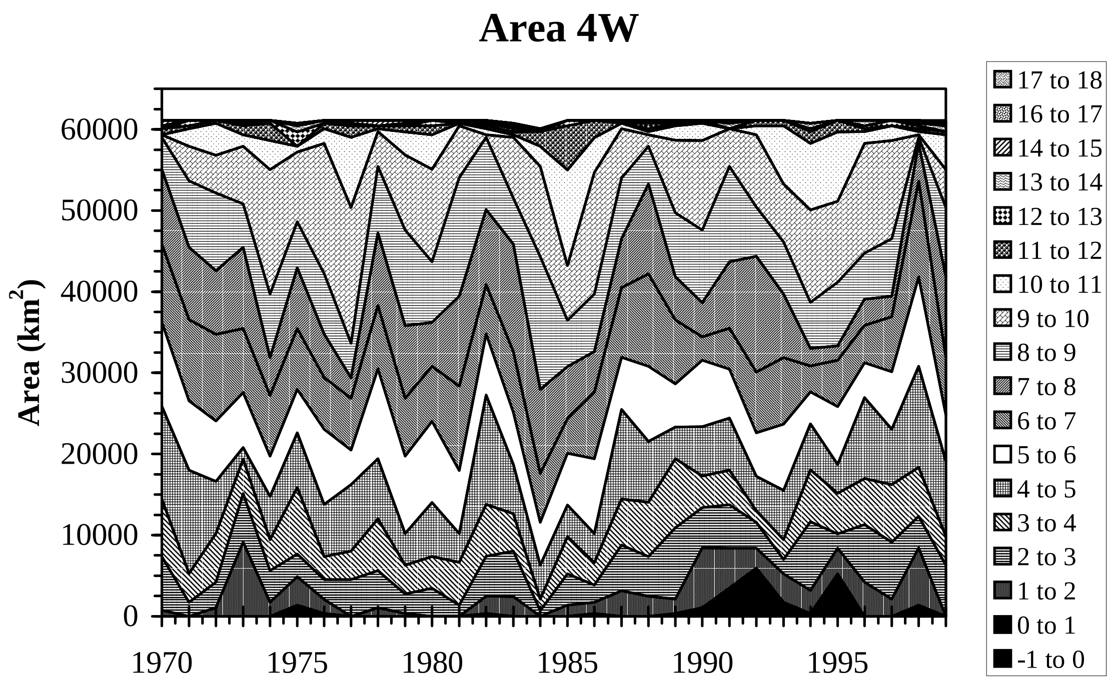


Fig. 18a. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4Vn (top panel) and 4Vs(bottom panel).



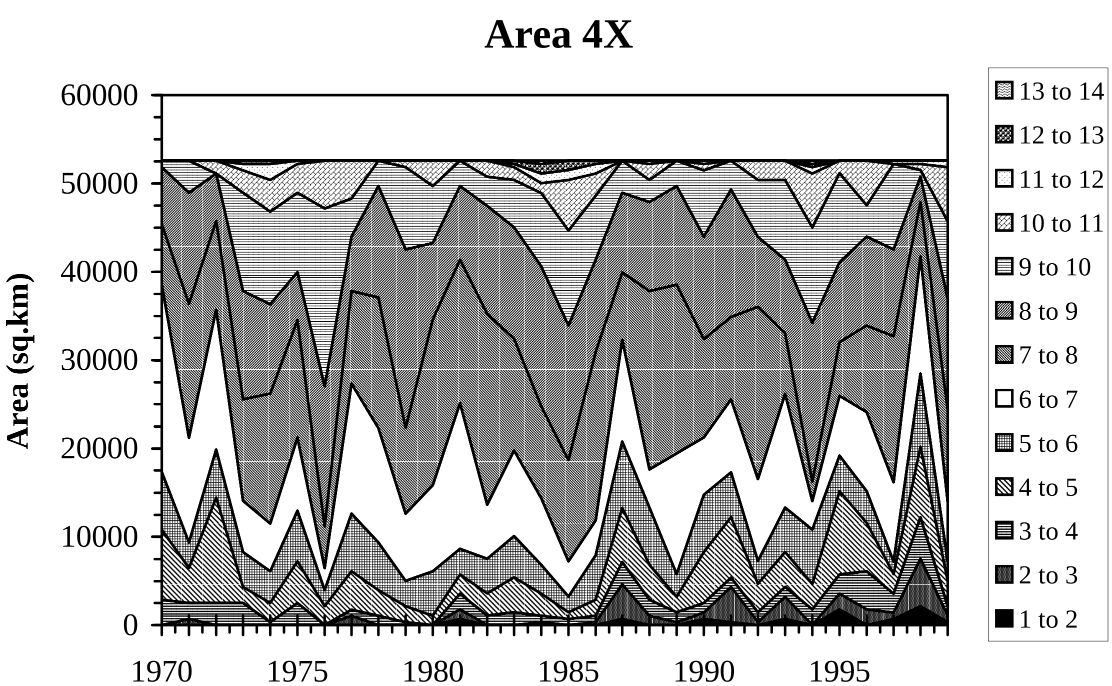


Fig. 18b. The time series of the area of the bottom for each 1 degree temperature range for NAFO Subareas 4W (top panel) and 4X(bottom panel).

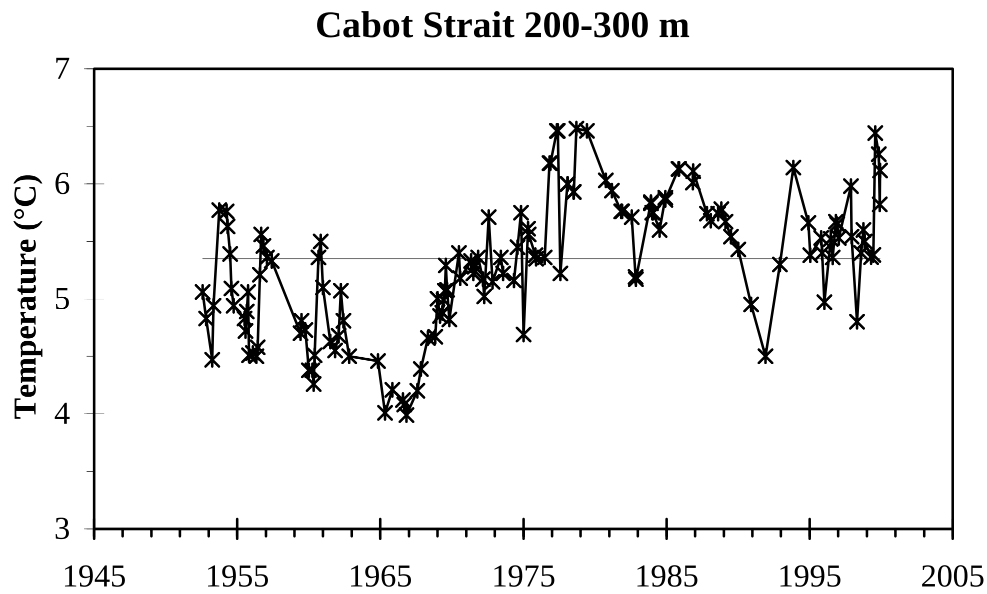


Fig. 19. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the long-term mean during 1961-90.

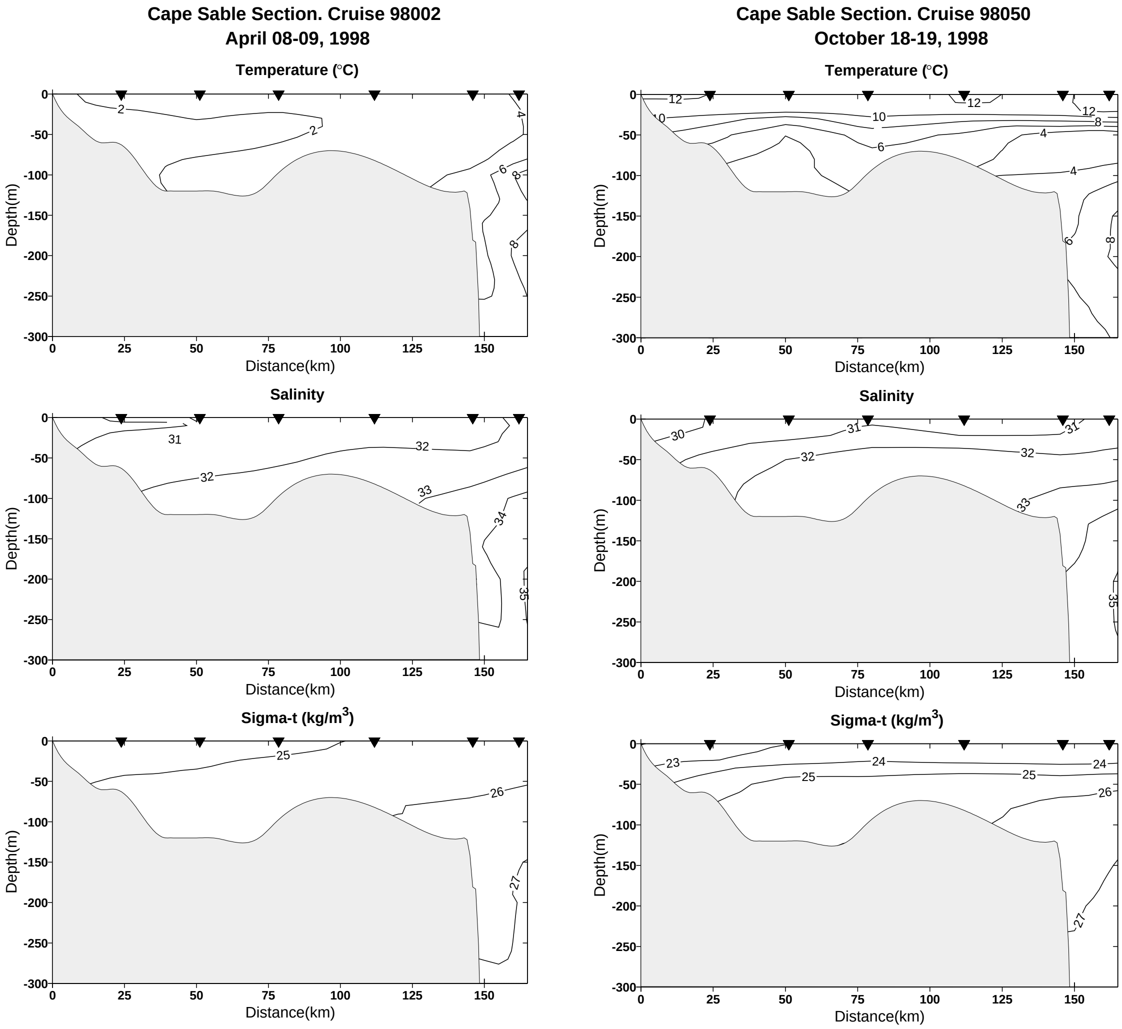


Fig. 20. The temperature, salinity and sigma-t contours along the Cape Sable Section during April (left panels) and October (right panels) of 1998. The triangles denote the location of the CTD profiles.

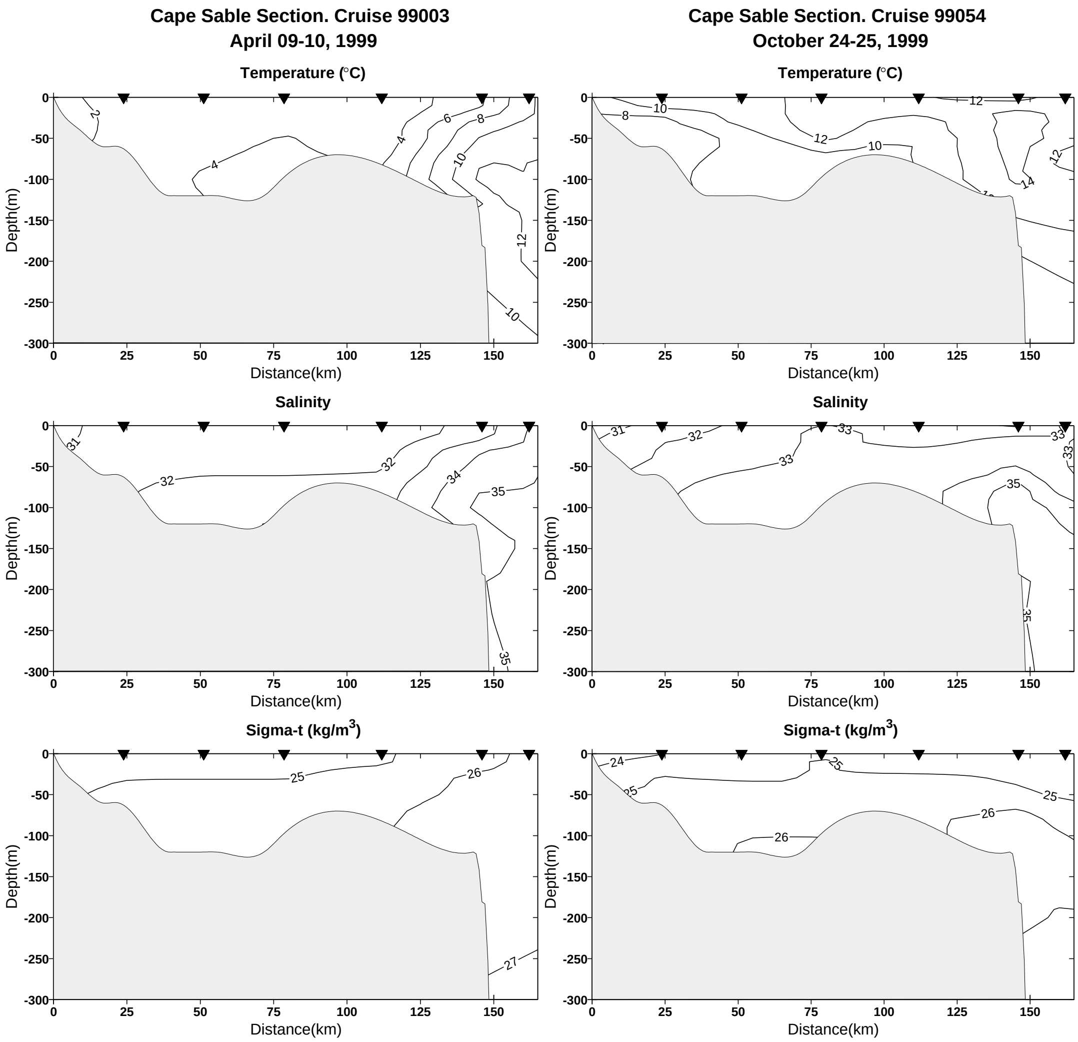


Fig. 21. The temperature, salinity and sigma-t contours along the Cape Sable Section during April (left panels) and October (right panels) of 1999. The triangles denote the location of the CTD profiles.

Halifax Section, 1998

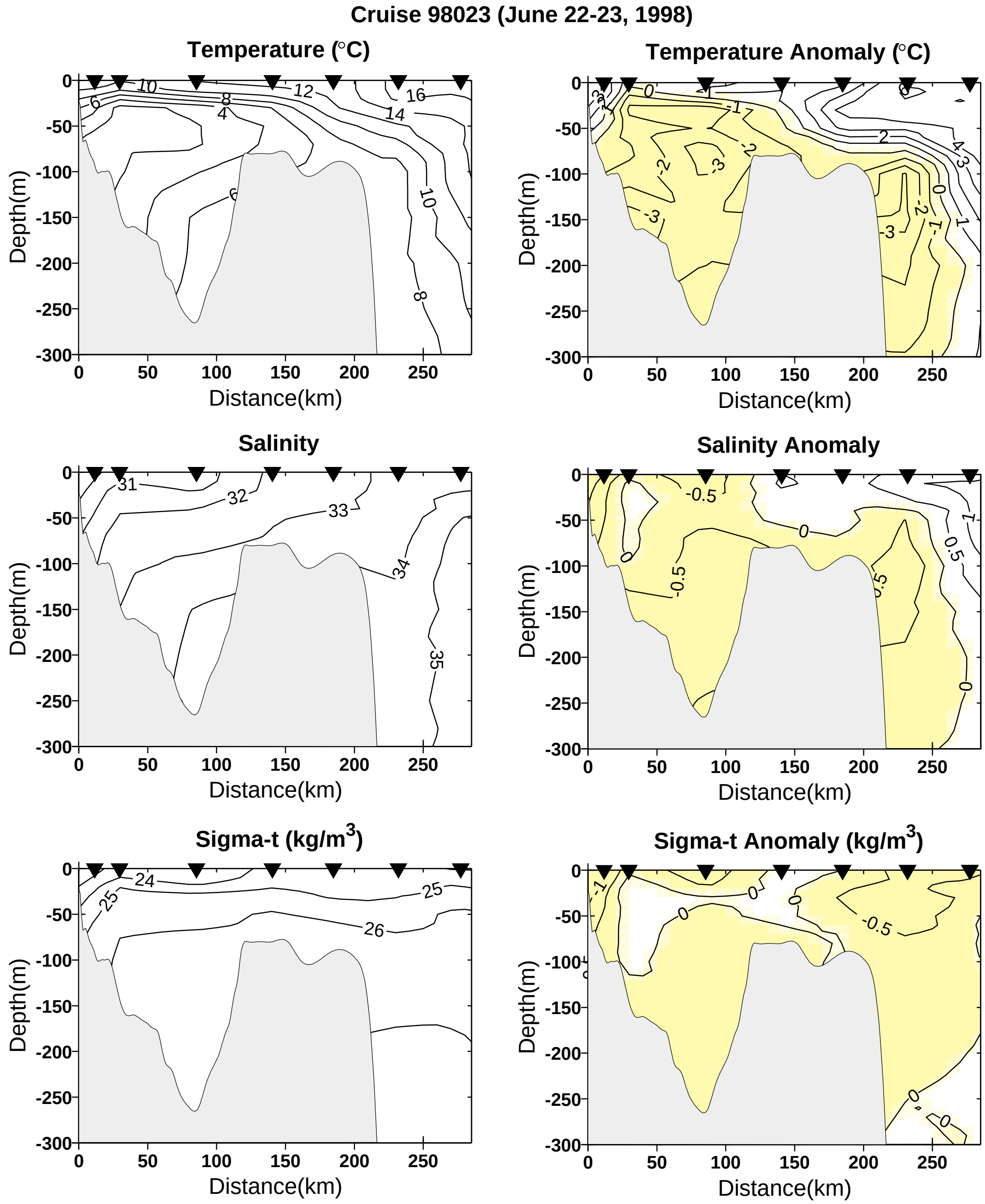


Fig. 22. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during June 1998 (left panels). The triangles denote the location of the standard stations.

Halifax Section, 1999

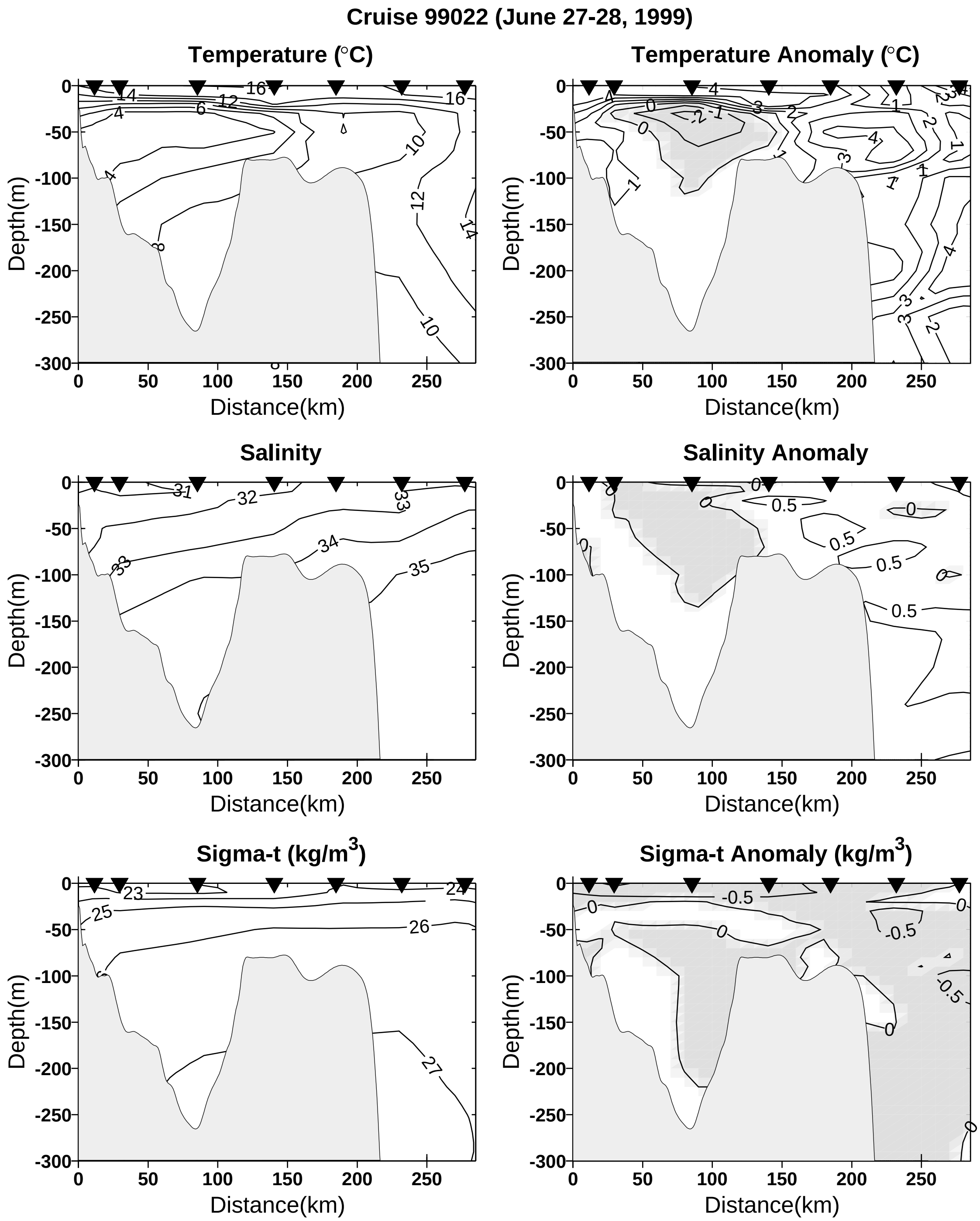


Fig. 23. Contours of the temperature, salinity and sigma-t (left panels) and their anomalies (right panels) along the Halifax Line during June 1999 (left panels). The triangles denote the location of the standard stations.

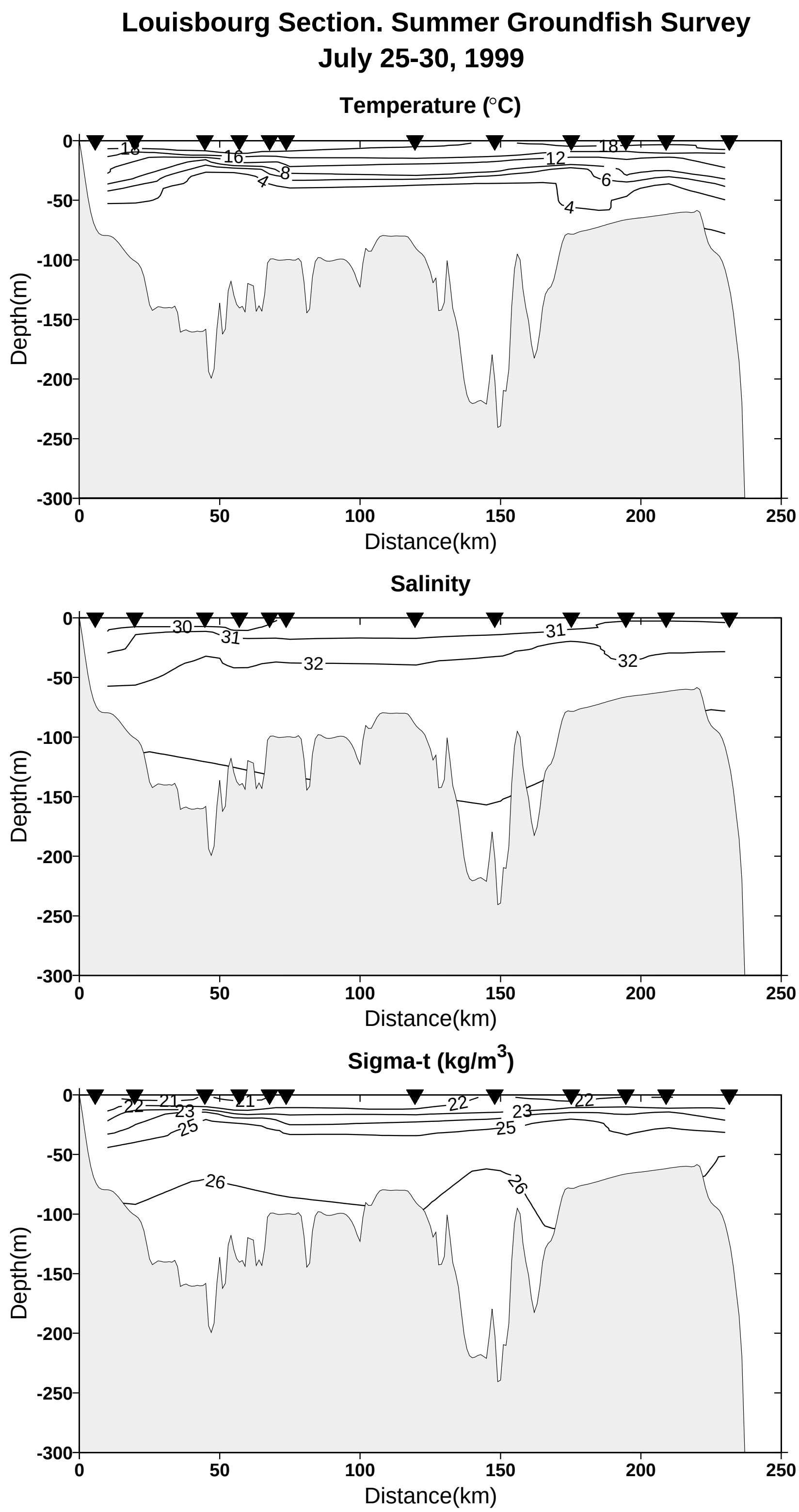


Fig. 24. Contours of the temperature, salinity and sigma-t along the Louisbourg Line during July 1999. The triangles denote the location of the standard stations.

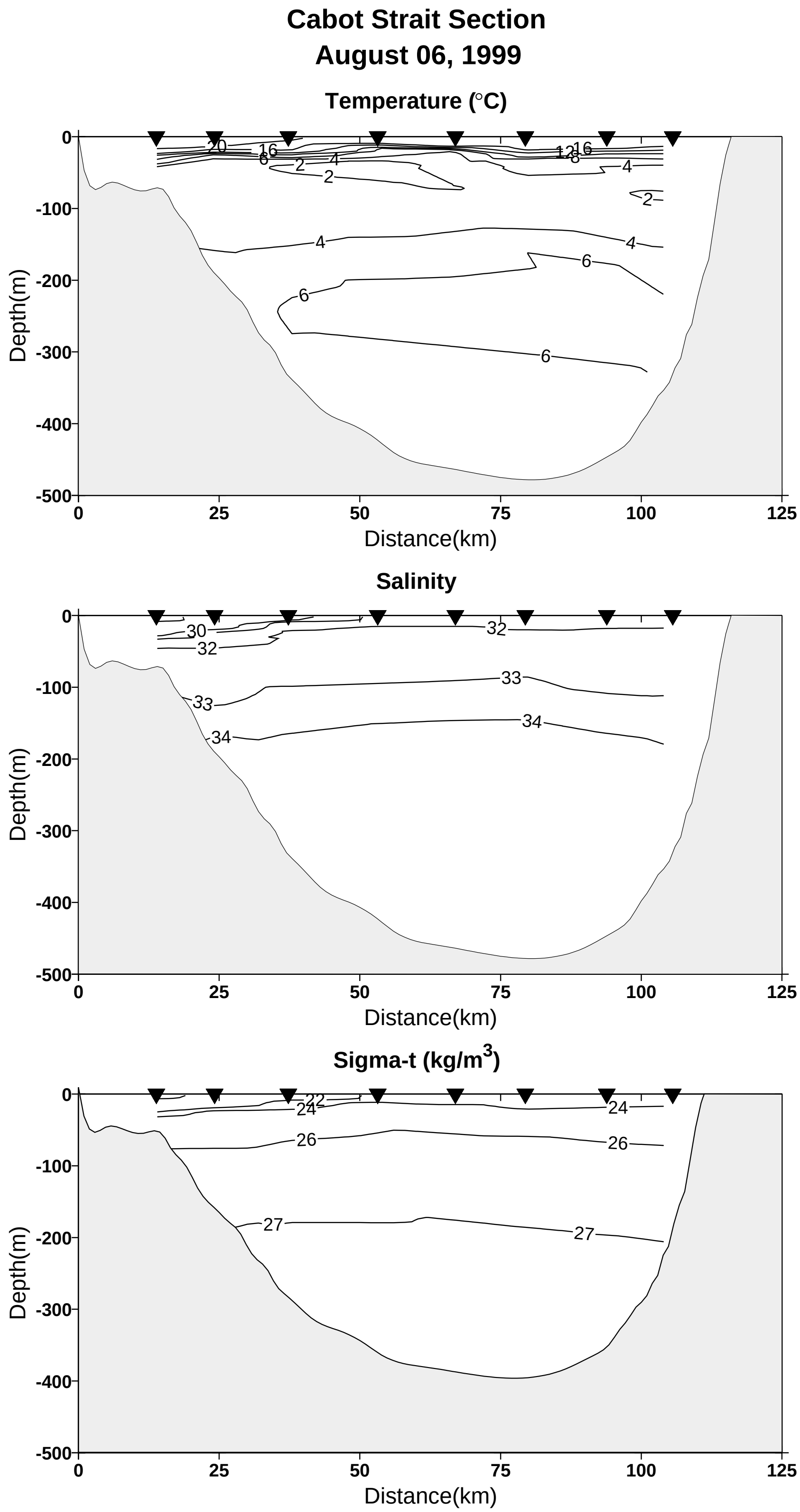
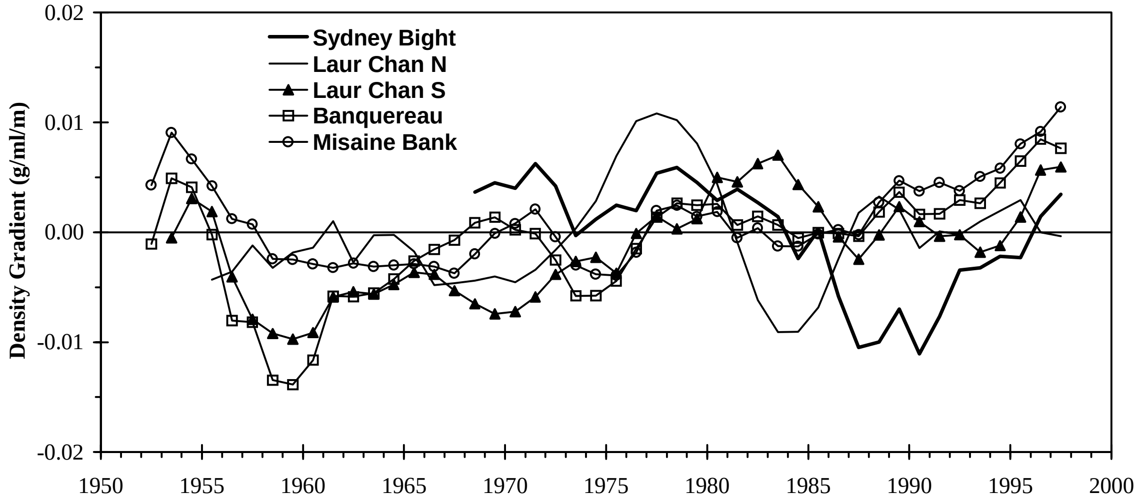
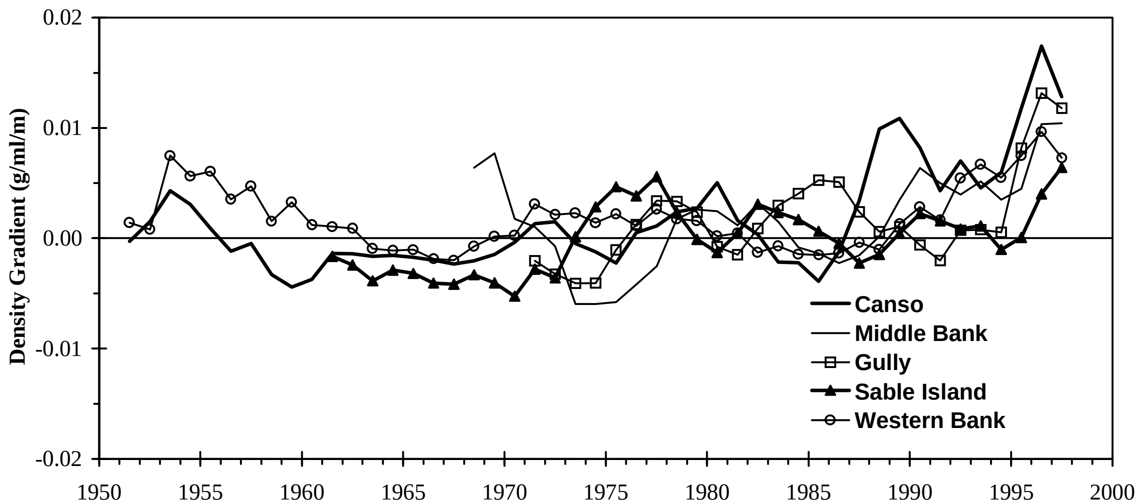


Fig. 25. Contours of the temperature, salinity and sigma-t along the Cabot Strait Line during August 1999. The triangles denote the location of the standard stations.


Sydney Bight
Laur Chan N
Laur Chan S
Banquereau
Misaine Bank
Density Gradient (g/ml/m)
0.02
0.01
0.00
-0.01
-0.02
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000


Canso
Middle Bank
Gully
Sable Island
Western Bank
Density Gradient (g/ml/m)
0.02
0.01
0.00
-0.01
-0.02
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000

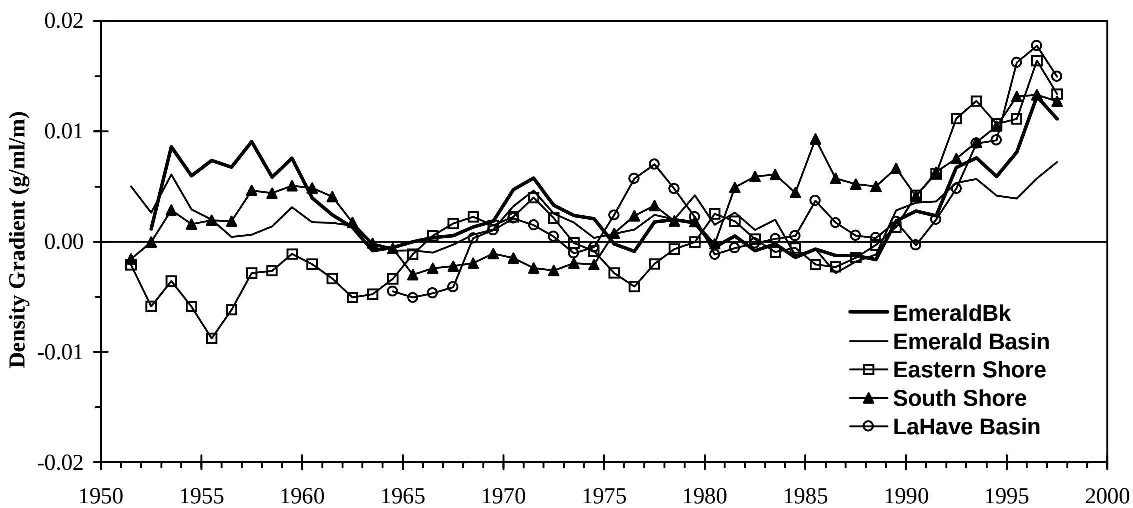
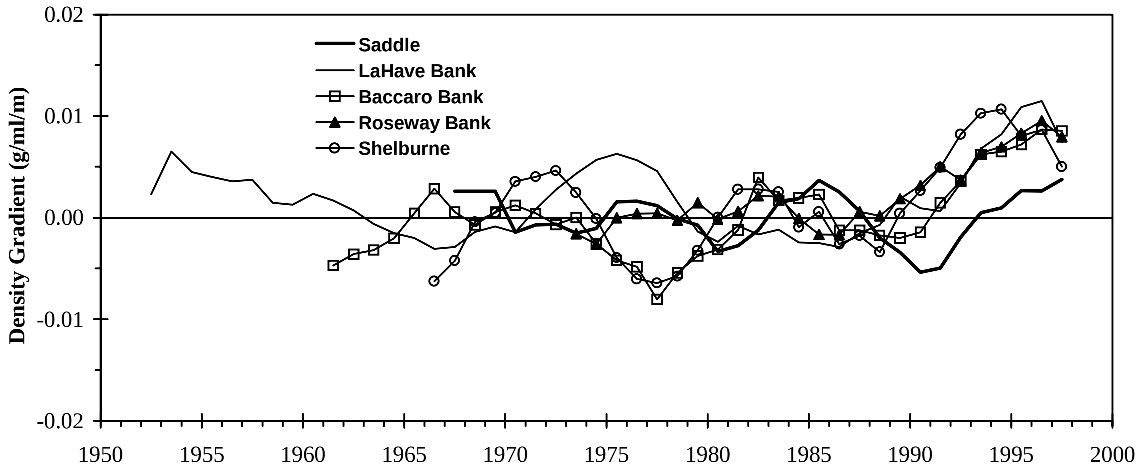
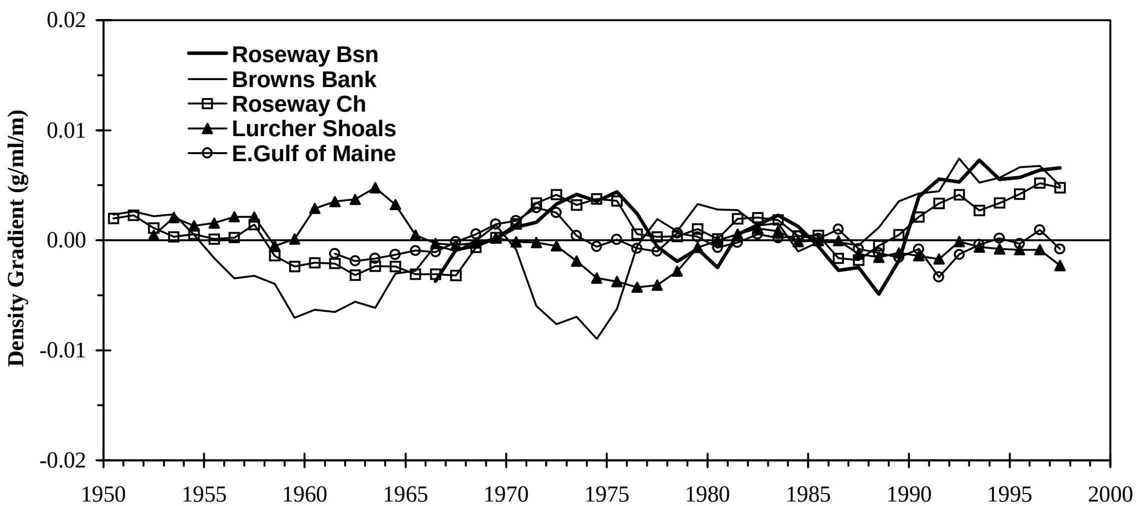

EmeraldBk
Emerald Basin
Eastern Shore
South Shore
LaHave Basin
Density Gradient (g/ml/m)
0.02
0.01
0.00
-0.01
-0.02
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000

Fig. 26a. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 1-15 in Fig. 10.





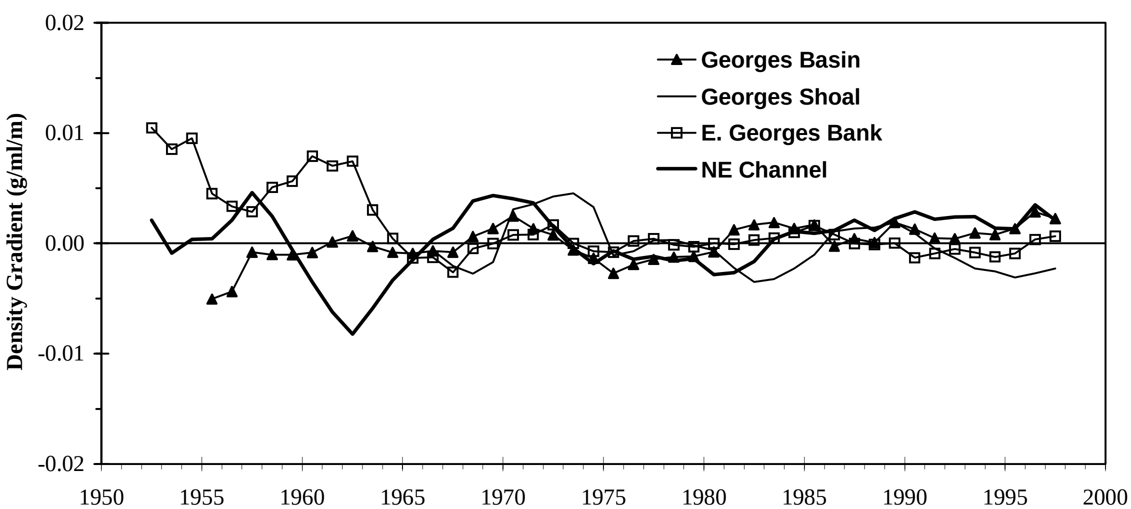
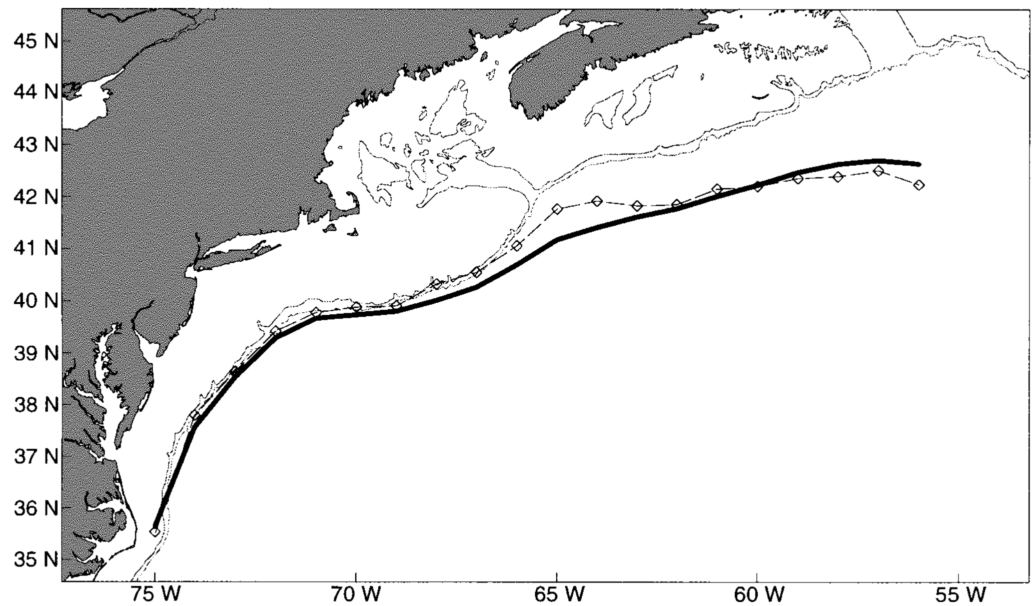


Fig. 26b. Five-yr running means of the annual anomalies of the density gradient between the surface and 50 calculated for the areas 16-29 in Fig. 10.



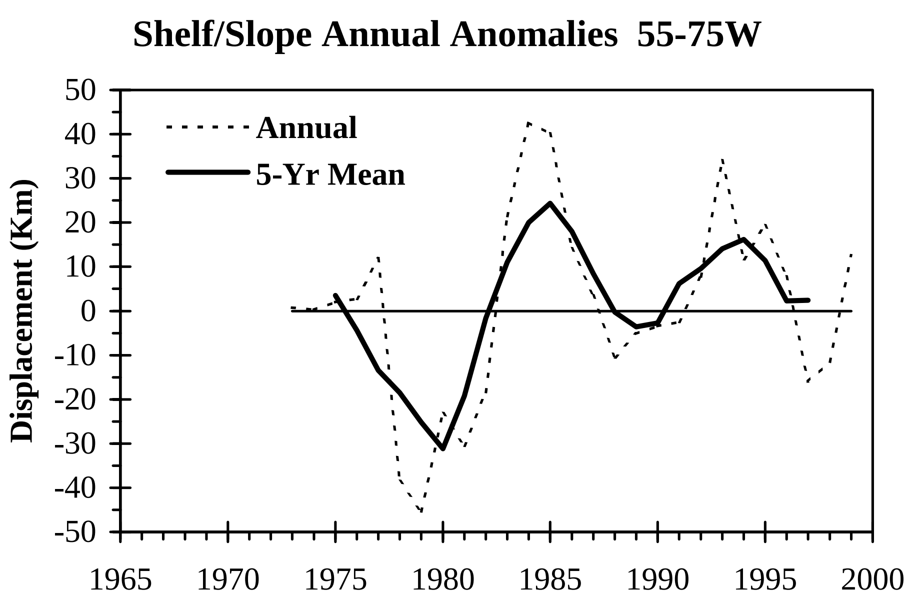
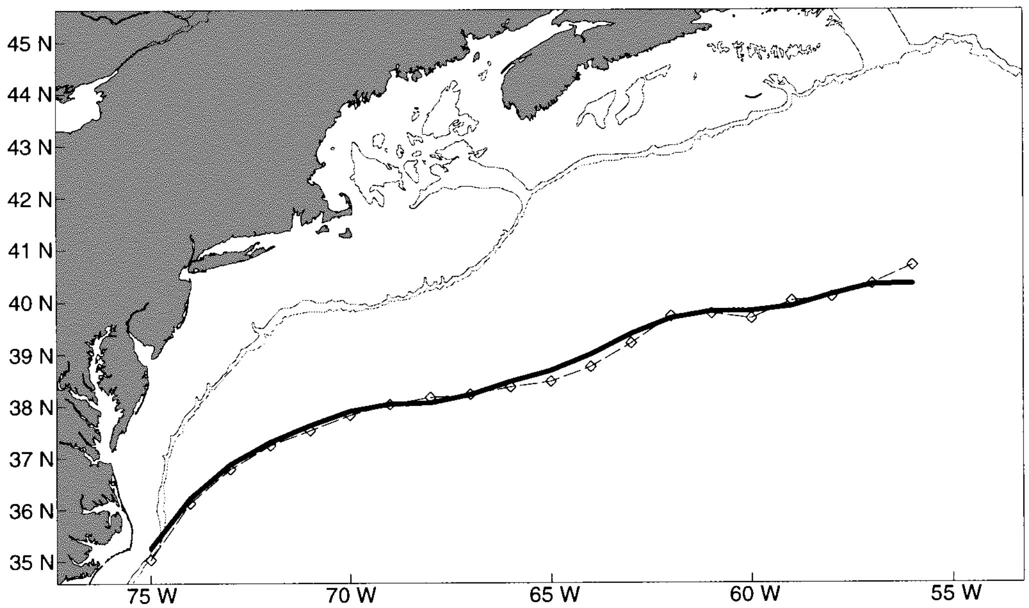


Fig. 27. The 1999 (dashed line) and long-term mean (1973-97; solid line) positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the shelf/slope front (bottom panel).



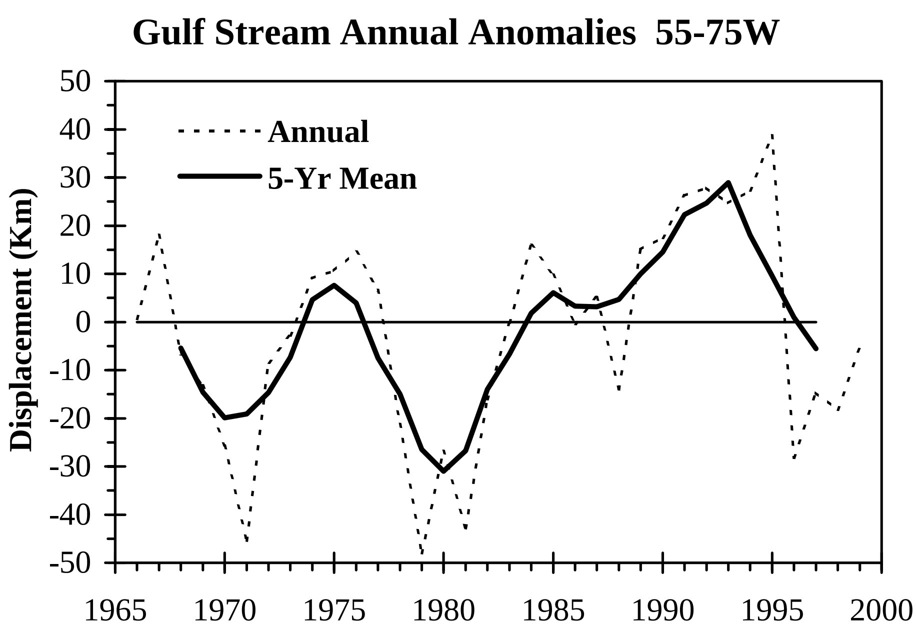


Fig. 28. The 1999 (dashed line) and long-term mean (1973-97; solid line) positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the Gulf Stream front (bottom panel).