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## **Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 1998**

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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 1998 is presented. The most significant change from 1997 was related to the appearance of cold, Labrador slope water along the outer edge of the Scotian Shelf. This subsequently penetrated onto the shelf through channels and gullies where it replaced the warm slope water remnants that were in the deep basins such as Emerald and Georges basins. The Labrador Slope water was located offshore of Emerald Bank in October of 1997, travelled southwestward during late 1997, entered Northeast Channel at the entrance to the Gulf of Maine by January of 1998, moved onto the southern flank of Georges Bank in February and by March was at the entrance to Great South Channel. Cold slope waters lay along the shelf edge for the remainder of the year although there was evidence of slight warming by the end of 1998. Temperatures in the deep region of Emerald Basin dropped by 2°C between December 1997 and February 1998 and a further 1°C by April and were well below their long-term means. On the northeastern Scotian Shelf, waters continued to experience below normal temperatures. This pattern was established in the mid-1980s with maximum cooling in the early 1990s. In recent years, including 1998, there has been a slow but steady increase in temperatures in these regions. 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, although the relative importance has not yet been established. Also of significance was the establishment of increased stratification in the upper water column (between surface and 50 m) throughout the Scotian Shelf since the 1990s with maximum values in recent years. This high stratification was not observed in the Gulf of Maine, however.

## Résumé

Les résultats de 1998 sont présentés relativement à l'examen des conditions océanographiques physiques sur le plateau néo-écossais ainsi que dans le golfe du Maine et les zones marines avoisinantes. Le plus important changement survenu depuis 1997 est lié à une avancée d'eau froide de talus du Labrador le long du plateau néo-écossais. Empruntant des chenaux et goulets, cette eau froide s'est par la suite introduite sur le plateau, venant y remplacer les restes d'eau chaude de talus reposant dans les bassins profonds, notamment dans les bassins Émeraude et Georges. La présence d'eau de talus du Labrador a été détectée au large du banc Émeraude en octobre 1997. Vers la fin de la même année, elle a progressé en direction sud-ouest, puis a pénétré dans le chenal Northeast à l'entrée du golfe du Maine en janvier 1998. En février, elle s'est déplacée sur le flanc sud du banc Georges pour gagner en mars l'entrée du chenal Great South. Les eaux froides de talus sont demeurées en bordure du plateau durant tout le reste de l'année, bien qu'on y ait noté des signes d'un léger réchauffement à la fin de 1998. Les températures dans la zone profonde du bassin Émeraude ont baissé de 2 °C entre décembre 1997 et février 1998, puis de 1 °C encore, entre février et avril. Elles étaient très inférieures aux moyennes à long terme. Sur la partie nord-est du plateau néo-écossais, les températures se sont maintenues sous la moyenne. Cette tendance au refroidissement a commencé vers le milieu des années 1980 et a atteint son apogée au début des années 1990. Ces dernières années, y compris en 1998, il y a eu une très lente, quoique régulière, remontée des températures dans ces régions. La présence de ces eaux froides est vraisemblablement due à une advection depuis le golfe du Saint-Laurent et le large du plateau de Terre-Neuve conjuguée au refroidissement hivernal *in situ*. Toutefois, l'importance relative de ce phénomène n'est pas clairement établie. Autre fait notable, on a observé depuis les années 1990 une stratification plus marquée de la couche superficielle de la colonne d'eau (de la surface à 50 m) sur l'ensemble du plateau néo-écossais, les valeurs maximales ayant été atteintes ces dernières années. Une telle tendance n'a toutefois pas été remarquée dans le golfe du Maine.

## Introduction

This paper describes temperature and salinity characteristics during 1998 of the waters on the Scotian Shelf and in the Gulf of Maine (Fig. 1). The results are derived from data obtained at coastal sea surface stations, long-term monitoring stations, 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 was updated several times in 1998 from the data archive at the Marine Environmental Data Service (MEDS) in Ottawa and most recently in early January 1999. Additional data were obtained directly from the DFO fisheries personnel. In order to detect temperature trends we have removed the large seasonal cycle by expressing oceanographic conditions as monthly deviations from their long-term means (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 1998 is described in Drinkwater et al. (1999).

### Coastal Sea Surface Temperatures

Monthly averages of sea surface temperature (SST) for 1998 were available at Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia. The Halifax averages have been estimated from data collected twice a day during weekdays off the DFO Halifax Laboratory wharf. With the closing of the Halifax Laboratory, no data were collected after August 1998. A continuous recording thermistor submerged just below low water on the wharf in Halifax Harbour by the Maritime Museum of the Atlantic will replace the Halifax Laboratory values in future. Note the 1998 August data from Halifax was based on only 11 days of data and so may not be truly representative of the entire month. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each site for 1997 and 1998 are shown in Fig. 2.

The dominant feature in 1998 at Boothbay Harbor and St. Andrews was the above normal temperatures throughout most of the year (9 and 10 out of the 12 months, respectively) which continues a trend of warm temperatures that began in June of 1994. The 1998 anomalies equalled or exceeded one standard deviation (based upon the years 1961-90) in 6 months at Boothbay Harbor (March-May, July, August and December) and in four months at St. Andrews (March-May and October). The maximum monthly anomaly was near 1.4°C in April at Boothbay while at St. Andrews it was 1.6°C in May. Having similar amplitude anomalies at St. Andrews as at Boothbay is unusual as increased vertical mixing by the tides in the Bay of Fundy typically results in lower amplitude anomalies at St. Andrews. At Halifax positive sea surface temperature anomalies also dominated 1998 with 6 of the available 8 months being warmer-than-normal (Fig. 2). These warm anomalies reverse the trend of colder-than-normal conditions observed at Halifax over the last several years. The temperature anomaly exceeds the long-term standard deviations from May through August, inclusive.

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). This minimum was as low as that of the

mid-1960s at St. Andrews but at Boothbay Harbor the minimum was only slightly below normal. Consistent with the recent trends, the 1998 annual mean temperature was above normal (mean of 7.6°C and 0.5°C above normal at St. Andrews and 9.1°C and 0.6°C above normal at Boothbay). At both sites the temperature rose relative to 1997 but remained below the recent peak of 1995 (Fig. 2). No annual mean in 1998 was estimated for Halifax because of the missing data for September to December.

### 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 have been obtained with a CTD (Conductivity, Temperature, Depth) profiler. Up to and including 1997, there was only one observation per month but in 1998 multiple occupations were taken in some months. In September and November there were three measurements, during April, June, July and December there were two, and for the remainder of the months there was only one. For months with multiple measurements, an arithmetic average was used to estimate the monthly mean temperature and salinity. A single, or even three observations per month, especially in the surface layers in the spring or summer, may not necessarily produce results that are representative of the true "average" conditions for the month 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 1998, monthly mean temperatures ranged from a minimum of over 2.5°C throughout the water column in February to a maximum of over 11°C near the surface in August and September (Fig. 3,4). Following mainly below normal temperatures in January, the monthly temperature anomalies were dominated by positive values through until July-August. In July, below normal temperatures were observed at 75 m and 90 m. These negative anomalies extended throughout most of the water column by September and continued for the remainder of the year. The highest negative anomalies (−1.6° to −1.7°C) were in September near bottom. The annual mean temperatures exhibit high year to year variability (Fig. 4). In 1998, the annual mean temperatures were above normal at the surface (anomaly of 0.4°C) and almost normal near bottom at 90 m (0.08°C above normal). This represents an increase relative to 1997 at the surface while near bottom the 1998 temperature decreased slightly. With the exception of the negative temperature anomalies in the early 1990s, temperatures at Prince 5 have been warmer than the long-term mean since the 1970s. The maximum annual temperatures at this site occurred in the early 1950s and the minimum in the mid-1960s.

Salinities at Prince 5 during 1998 were mostly fresher-than-normal (Fig. 3, 5). The lowest salinities (<30.5 psu) occurred in the upper half of the water column during April and May and the highest salinities (>32.5 psu) appeared near bottom in the autumn. The arrival of high salinity waters in autumn is typical. The largest negative anomalies (below 1 psu) were observed

throughout most of the water column in March and April and at mid-depth in May. Time series show that the annual salinity anomalies in 1998 fell by approximately 0.2 relative to 1997 values at both the surface and 90 m (Fig. 5). Although there has been large fluctuations in salinity anomalies throughout the water column, the longer-term trend shows that salinities have been freshening since the late 1970s with the lowest salinities on record at Prince 5 occurring in 1996. The recent low values parallel salinity events occurring 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).

### **Deep Emerald Basin Temperatures**

Petrie and Drinkwater (1993) assembled a time series of monthly temperature data from 1946 to 1988 at multiple depths in Emerald Basin in the centre of the Scotian Shelf. They showed that there was high temperature variance at low frequencies (decadal periods). This signal was more visible at depth (below 75 m) where the low-frequency variance was higher and there was less high-frequency (year-to-year) variability. High coherence at low frequencies was found throughout the water column as well as horizontally from the mid-Atlantic Bight to the Laurentian Channel, although year-to-year differences between locations were observed.

In 1998, deep temperature measurements in Emerald Basin were obtained in eight months with values at 250 m ranging from 6.4° to 8.0°C. This produced monthly anomalies of -0.4° to -0.6°C below normal (Fig. 6). The long-term (1961-90) annual average is 8.5°C and the long-term monthly means range from 7.9°C to 9.4°C. The strong negative anomalies in 1998 were generally representative of conditions in the Basin below approximately 50 m. These colder-than-normal temperatures in the Basin represent a significant cooling (2° to 3°C) relative to 1997 and most of the past decade or more. Cause of this cooling is due to the arrival along the outer Scotian Shelf of Labrador Slope water (Drinkwater et al., 1998). This cooler (typically 4°-8°C) slope water arrived in the autumn of 1997 off Banquereau and Emerald Banks replacing Warm Slope water (8°-12°C). The Labrador Slope water began to penetrate into Emerald Basin in December and by mid-February had replaced most of the warmer waters in the Basin. A similar pattern was observed in Georges Basin. The cold Labrador Slope water was observed entering Northeast Channel in January, 1998 (Drinkwater et al., 1998) and flooded Georges Basin by at least April, when the first measurements of 1998 were available in its deep waters. The long-term trend shows a maximum in the early 1950s, followed by a decline to a minimum in the early 1960s that has been described in detail by Petrie and Drinkwater (1993). The temperatures rose rapidly in the late 1960s, remained relatively high in the 1970s but dropped in the late 1970s and again in the early 1980s. With the exception of a short period in the early 1990s, the temperatures in the deep basin were well above the long-term mean and at the highest sustained levels on record in the mid-1990s.

### **Other Scotian Shelf and Gulf of Maine Temperatures**

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities 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). This has been updated by Petrie et al. (1996). We produced monthly mean conditions for 1998 at standard depths for selected

areas (averaging any data within the month anywhere within these areas) and compared 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, however. 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 and identified several important features. First, the temperatures in the upper 30 m tended to vary greatly from month to month, due to the greater influence of atmospheric heating and cooling. Second, 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 in 1994 and 1995 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. 1996). The third main feature was the presence of anomalously warm slope water off the shelf and in the deep basins such as Emerald on the Scotian Shelf and Georges in the Gulf of Maine. This warm deep water appeared to influence the intermediate depth waters above the basins, as their anomalies were generally warmer than elsewhere on the shelves.

The first two temperature patterns identified by Drinkwater and Pettipas (1994) have continued into 1998. Monthly mean temperature profiles reveal that cold conditions prevailed in the deeper waters on Sydney Bight, on Misaine Bank in the northeast Scotian Shelf, and on Lurcher Shoals. However, as revealed by the Emerald Basin temperatures at 250 m discussed above, the warmer-than-normal conditions that have prevailed over most of the last 20 to 30 years were replaced by below normal values in 1998 (Fig. 6). Below, we describe temperature conditions in representative areas of the Scotian Shelf.

On Sydney Bight (area 1 in Fig. 7) monthly mean profiles from 5 different months show highly variable temperature anomalies throughout the water column (Fig. 8). In the near surface (<10 m) waters, however, temperatures were primarily above the long-term mean (Fig. 8). The primary exception was in July when the 20 to 30 m layer was 1°-3°C below normal. 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

quickly to below normal values reaching a minimum anomaly around  $-1^{\circ}\text{C}$  in the early 1990s. Temperatures in recent years have generally remained below normal but have been slowly increasing with several monthly anomalies of above normal being observed since 1995. The 1998 anomalies at 100 m remained below normal.

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 7) are available for 6 months during 1998. They show primarily warmer-than-normal upper layer (0-30 m) temperatures (Fig. 9). From 75 m and deeper, however, the temperatures were principally below normal except in November. Between 30 and 75 m, the temperatures varied between above and below normal. The time series of the 100 m temperature anomalies show that these negative values have persisted since approximately the mid-1980s (Fig. 9). This pattern is generally indicative of the water column below 50 m. Recent years, although exhibiting generally below normal temperatures, have seen temperatures increasing slowly from the minimum in the early 1990s. 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  $-1^{\circ}\text{C}$  in the first half of the 1990s. Since then, as on Sydney Bight, temperatures have remained below normal but with evidence of a slow but steady increase that continued into 1998.

At Lurcher, data were available in 9 months during 1998 (Fig. 10). The dominant feature was below normal temperatures throughout most of the water column. Anomalies in January, August, October and November exceeded  $-1^{\circ}\text{C}$ , and in December exceeded  $-2^{\circ}\text{C}$ . The monthly 50 m temperature anomalies at Lurcher show mostly cooler-than-normal waters in 1998, the only exception being in July. This depth represents conditions over much of the bottom of the Shoals. The MCSST (Multi-Channel SST) satellite data for 1998 also shows a negative SST anomaly, particularly around the Lurcher area throughout the year, with the strongest anomaly in autumn. 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 elsewhere, temperatures declined by the mid-1980s to below normal reaching a long-term minimum in the early 1990s. Although there was a slight hint of warming since the early 1990s, and there have been some positive monthly temperature anomalies, annual mean temperatures and most monthly means continue to remain below normal.

The time series of temperature in the deep regions of Georges Basin (Fig. 11; area 26 in Fig. 7) shows a striking similarity to that observed in Emerald Basin including the very cold conditions in 1998 (Fig. 6). This includes 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. This is not surprising given that the source of the waters is primarily the offshore slope waters (Petrie and Drinkwater, 1993). On the Canadian portion of Georges Bank (area 28 in Fig. 7), the short-period variability is of much higher amplitude than in Georges Basin, for example (Fig. 11). This reflects not only the higher temporal fluctuations but also spatial differences within areas. The longer-term trend shows positive anomalies in the 1950s, low in the 1960s and a tendency towards positive anomalies since the 1970s. From the late 1980s on, the long-term temperature trend has not

been significantly different than normal. However, the cold that was present in the deep waters in 1998 appears to have also influenced the bank water.

### **Temperatures during the Summer Ground Fish Survey**

The most extensive temperature coverage over the entire Scotian Shelf is obtained during the annual groundfish survey, usually in July. In 1998, 175 conductivity-temperature-depth (CTD) stations were occupied. Off southwestern Nova Scotia, an ITQ (Individual Trip Quota) fleet survey was also conducted that collected CTD data at another 161 stations. Many of the latter were located in areas not traditionally occupied during the government run groundfish survey, e.g. over Lurcher Shoals and other inshore areas. Temperatures from both surveys were interpolated onto a 0.2 by 0.2 degree 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. Maximum depths for the interpolated temperature field were limited to 1000 m. The 1998 temperatures were also compared to the 1961-90 means for July.

Temperatures in 1998 at the surface varied from  $<9^{\circ}$  to  $>18^{\circ}\text{C}$  with the coldest temperatures on the Lurcher Shoals off Yarmouth and the warmest in the vicinity of Western Bank in the central Scotian Shelf region (Fig. 12a). Warmer temperatures and weaker temperature gradients prevailed on the Scotian Shelf relative to off southwest Nova Scotia and the Bay of Fundy. At 50 m the coldest temperatures ( $<2^{\circ}\text{C}$ ) cover much of the northeastern Shelf (Fig. 12a). Note the warm waters ( $4^{\circ}$ - $5^{\circ}\text{C}$ ) appear to be penetrating onto the central shelf regions from the offshore. The 100 m temperatures show a pattern of cold waters ( $<2^{\circ}\text{C}$ ) in the northeast and warm waters ( $>5^{\circ}\text{C}$ ) in the Gulf of Maine and along the outer Banks in the southwestern region of the Shelf (Fig. 12b). Bottom temperatures show similar features to 100 m and are typical (Fig. 12b). First is the large contrast between the northeast and central Scotian Shelf. In the northeast, bottom temperatures were generally cold with minima less than  $2^{\circ}\text{C}$  in the Misaine Bank region. Cool waters ( $<4^{\circ}\text{C}$ ) were also observed in Roseway Basin and over Browns Bank. Temperatures in Emerald Basin exceeded  $7^{\circ}\text{C}$ . Relatively high temperatures also were found in the upper reaches of the Bay of Fundy and in the deeper areas of the Gulf of Maine.

Temperature anomalies at the surface show generally positive anomalies over most of the Scotian Shelf by  $2^{\circ}$  to  $3^{\circ}\text{C}$  over Sable and Middle Banks and off the southeastern tip of Cape Breton (Fig. 13a). In contrast, in the Bay of Fundy and the rest of the Gulf of Maine, surface temperatures were below normal by around  $1^{\circ}\text{C}$ , consistent with the MCSST data. The dominant feature at 50 m is the below-normal temperatures over the shelf and throughout the Gulf of Maine and Bay of Fundy (Fig. 13a). The anomalies generally were between normal and  $-2^{\circ}\text{C}$ . At 100 m and near bottom the anomalies are below normal throughout almost all of the Scotian Shelf and Gulf of Maine (Fig. 13b). The greatest negative anomalies ( $-4^{\circ}\text{C}$  at 100 m and  $-3^{\circ}\text{C}$  near bottom) lay over Emerald Basin. The cause of these low anomalies was the influx of the cold Labrador Slope Water into the Basin as discussed above. The colder-than-normal temperatures over Emerald



Basin are different than 1997 when these were warmer-than-normal (Drinkwater et al., 1998). The cold water near bottom in Emerald Basin during the July survey is consistent with the 250 m temperature time series (Fig. 6) and the cold temperatures in the northeast with the temperature time series observed on Misaine Bank (Fig. 9).

Similar to last year, we also estimated the bottom area covered by each one degree temperature range (i.e. 1-2°C, 2-3°C, 3-4°C, etc.) within NAFO subareas 4Vn, 4Vs, 4W and 4X. These were obtained from the near bottom temperatures for the July groundfish and ITQ surveys optimally estimated onto the 0.2° x 0.2° grid and compared to previous years. Earlier years included not only data during the groundfish surveys but any data collected during the month. The area associated with each grid point in the optimal estimation was first determined, and then those areas that had a temperature within the designated range were summed. The time series of these areas for each NAFO subarea are shown in Fig. 14a,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°C and almost 50% <5°C (Fig. 14a). For 4Vs, 80-90% is <6°C and 75% <5°C (Fig. 14a). In 4W <50% and in 4X <20% is covered by temperatures <6°C (Fig. 14b). The time series for 4Vn and 4Vs show an increase in the 0°-1°C and especially <3°C waters during the late 1980s and early 1990s (Fig. 14a). Also in 4Vs there are waters <1°C during this colder period. In 4W there is also an increase in the area of the waters <3°C but it is of smaller amplitude than in 4V (Fig. 14b). In 4X there is an increase in waters <4°C but it is not as large an amplitude as in the other regions (Fig. 14b). While no significant changes occurred during 1998 in areas 4Vn or 4Vs, in 4W and 4X there was a significant increase in the area covered by the colder waters. In both 4W and 4X, there is a record amount of area covered by waters <5°, <6°, <7° and <8°C. This cooling was due to the influence of the Labrador Slope water.

These time series allow us to examine the changes in area of preferred temperature habitat for different stocks. We have examined the area of 2°-6°C bottom waters in 4Vs and 4W (Fig. 15). These correspond to temperatures at which most of the cod were caught during the July surveys (Page et al., 1994). In 4Vs there is high year-to-year variability with a general decrease in area of the 2°-6°C waters especially during the 1990s. During 1997 and 1998 the area has risen to levels comparable to 1993 and 1994 and above the extremely low values of the early 1990s and 1995. In 4W the area of the 2°-6°C water in 1998 was the second largest on record after 1970.

### **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 show that temperatures declined steadily between 1988 and 1991 to their lowest value since the late 1960s (near 4.5°C and an anomaly exceeding -0.9°C; Fig. 16). Then temperatures rose dramatically reaching 6.0°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 1998, temperatures were generally near the long-term mean and not that different from 1997 values. In April, however, the available data suggested cooler-than-normal deep temperatures in Cabot Strait (Fig. 16).

### **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. We examined the stratification by calculating the density ( $\sigma_t$ ) difference between 0 and 50 m. We first calculated the monthly mean density profile for each of the areas in Fig. 7. The density difference is then based upon these monthly profiles. The long-term monthly mean density stratification 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. The dominant feature is the higher stratification during recent years throughout the Scotian Shelf (Fig. 17a,b). The 5-year running mean began to increase steadily around 1990 and the most recent value represents the highest stratification in the approximate 50 year records in most areas. What is most surprising is the consistency from area to area, through most of the Scotian Shelf. This increased and high stratification does not seem to extend into the Gulf of Maine region and it was absent or weak in the Laurentian Channel and Sydney Bight areas. One expects the anomalies in density stratification in the Gulf to be lower than on the Scotian Shelf due to the more intense tidal mixing, however, if there were increased stratification in the Gulf of Maine, we should have detected it.

### **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

October to December of 1996 as well as 1997 and 1998 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 1998 annual mean position is shown in Fig. 18. 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 1998, the shelf/slope front was seaward of its long-term mean position from 75°W to 65°W, and also at 62°-61°W and 55°W. The largest deviations from the mean position occurred near the western end, the maximum value being at 72. 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 has been moving steadily seaward approximately 40 km, reaching its most southerly position since the early 1980s in 1997. In 1998, the frontal position was near that of 1997, although slightly more shoreward.

### ***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 1998 annual mean is shown in Fig. 19. 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 1998, the average position of the Stream was seaward at each degree of longitude except from 61° to 63°W. Similar to 1997, the largest deviations occurred west of 70°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. 19). 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 again in 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.

### **Summary**

In 1998, the most significant change was the arrival of cold, Labrador-type slope water along the shelf edge of the Scotian Shelf and the Gulf of Maine. This cold water penetrated onto the shelf through channels and gullies and replaced the warm slope water remnants that were in the deep basins such as Emerald Basin and Georges Basin. These cold waters remained for the rest of the year. Temperature changes in the deep region of Emerald Basin was of order 2°-3°C colder than last year and well below the long-term mean. In the northeastern Scotian Shelf, waters continued to experience below normal temperatures. This pattern was established in the mid-1980s

with maximum cooling in the early 1990s. In recent years, including 1998, there has been a slow but steady increase in temperatures in these regions. 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 although the relative importance has not yet been established. Also of significance was the establishment of increased stratification in the upper water column (between surface and 50 m) throughout the Scotian Shelf since the 1950s with maximum values in recent years. This high stratification was not observed in the Gulf of Maine, however.

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### References

- Bugden, G.L. 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. p. 139-147. In J.-C. Theriault [ed.] The Gulf of St. Lawrence: small ocean or big estuary? Can. Spec. Publ. Fish. Aquat. Sci. 113.
- Colbourne, E. 1995. Oceanographic conditions and climate change in the Newfoundland region during 1994. DFO Atlan. Fish. Res. Doc. 95/3, 36 p.
- Drinkwater, K.F. and R.G. Pettipas. 1994. On the physical oceanographic conditions in the Scotia-Fundy region in 1993. DFO Atlantic Fish. Res. Doc. 94/37, 31 p.
- Drinkwater, K.F. and R.W. Trites. 1987. Monthly means of temperature and salinity in the Scotian Shelf region. Can. Tech. Rep. Fish. Aquat. Sci. 1539: 101 p.
- Drinkwater, K.F., R.G. Pettipas and W.M. Petrie. 1997. Overview of physical oceanographic conditions in the Scotia-Fundy region in 1996. DFO Atlantic Fish. Res. Doc. 97/62, 27 p.
- Drinkwater, K.F., R.G. Pettipas and W.M. Petrie. 1999. Overview of meteorological and sea ice conditions off eastern Canada in 1998. DFO Atlantic Fish. Res. Doc. 99/51, 28 p.
- Gilbert, D. and B. Pettigrew. 1997. A study of the interannual variability of the CIL core temperature in the Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. Vol. 54 (Suppl. 1): 57-67.

- Page, F., R. Losier, S. Smith and K. Hatt. 1994. Associations between cod, and temperature, salinity and depth within the Canadian groundfish bottom trawl surveys (1970-93) conducted within NAFO divisions 4VWX and 5Z. Can. Tech. Rpt. Fish. Aquat. Sci. 1958: 160 p.
- Petrie, B. and K. Drinkwater. 1993. Temperature and salinity variability on the Scotian Shelf and in the Gulf of Maine, 1945-1990. J. Geophys. Res. 98: 20079-20089.
- Petrie, B., K. Drinkwater, A. Sandström, R. Pettipas, D. Gregory, D. Gilbert and P. Sekhon. 1996. Temperature, salinity and sigma-t atlas for the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 178: 256 p.

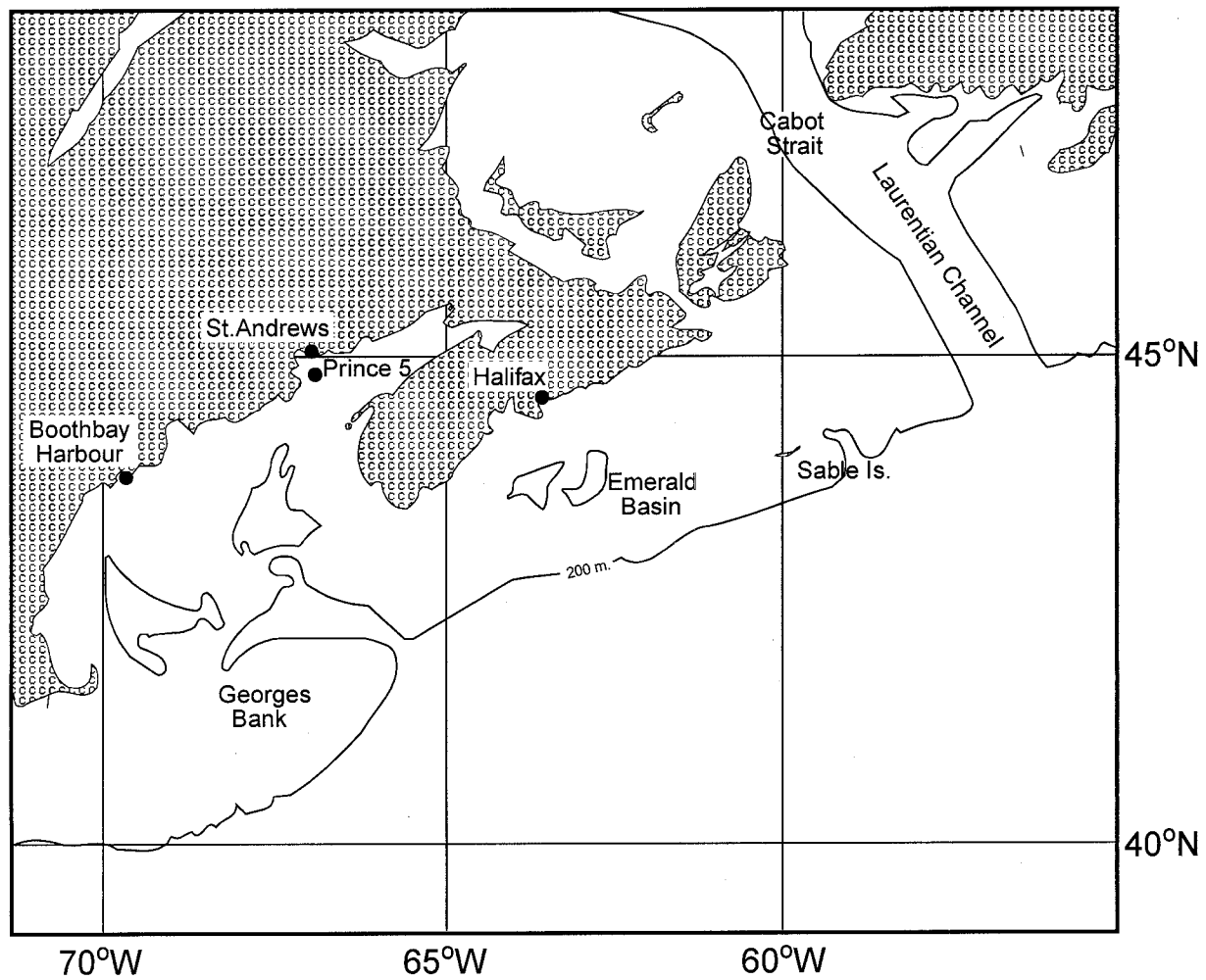


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations and topographic features.

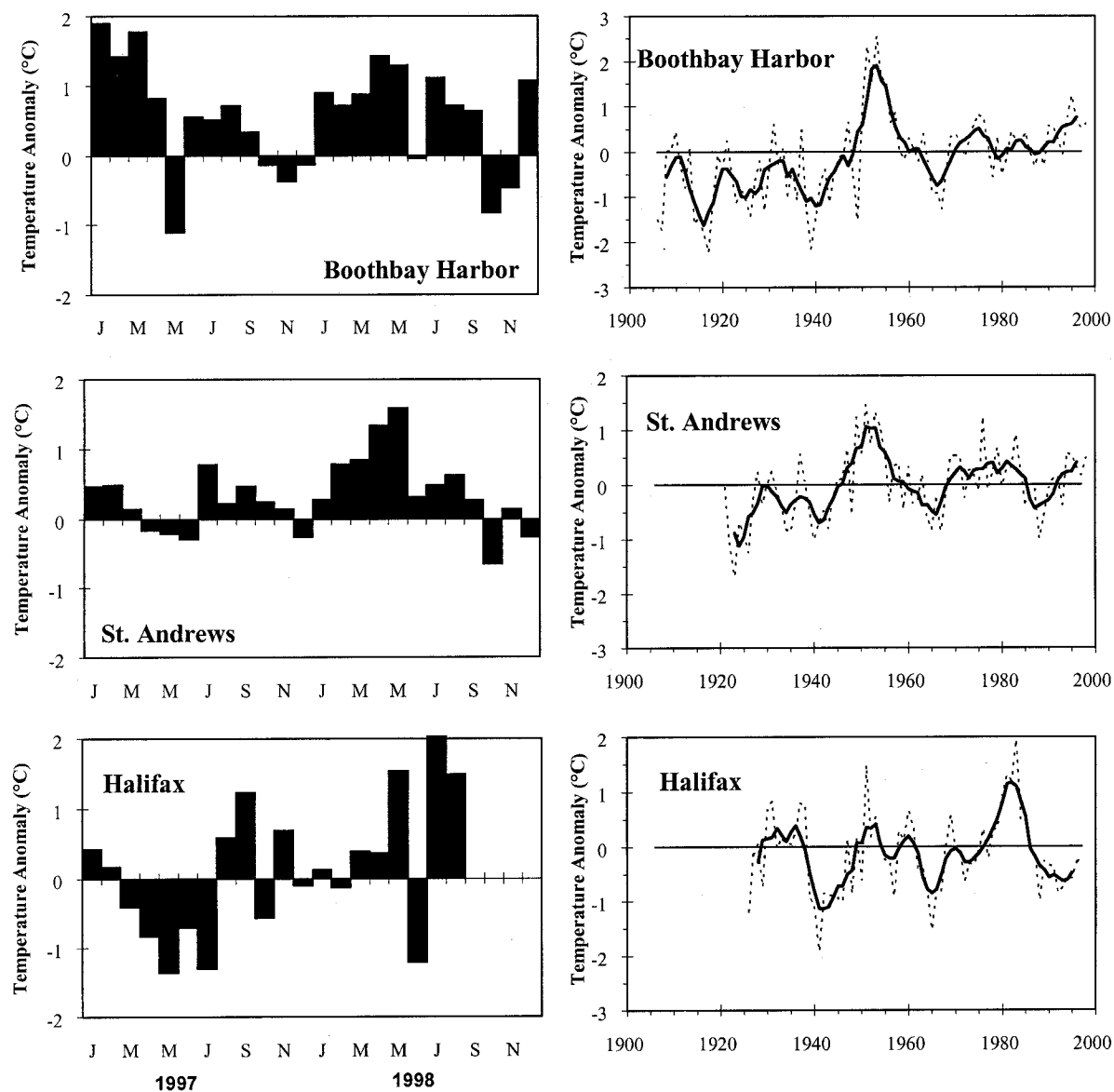


Fig. 2. The monthly sea surface temperature anomalies during 1997 and 1998 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax. Anomalies are relative to 1961-90 means.

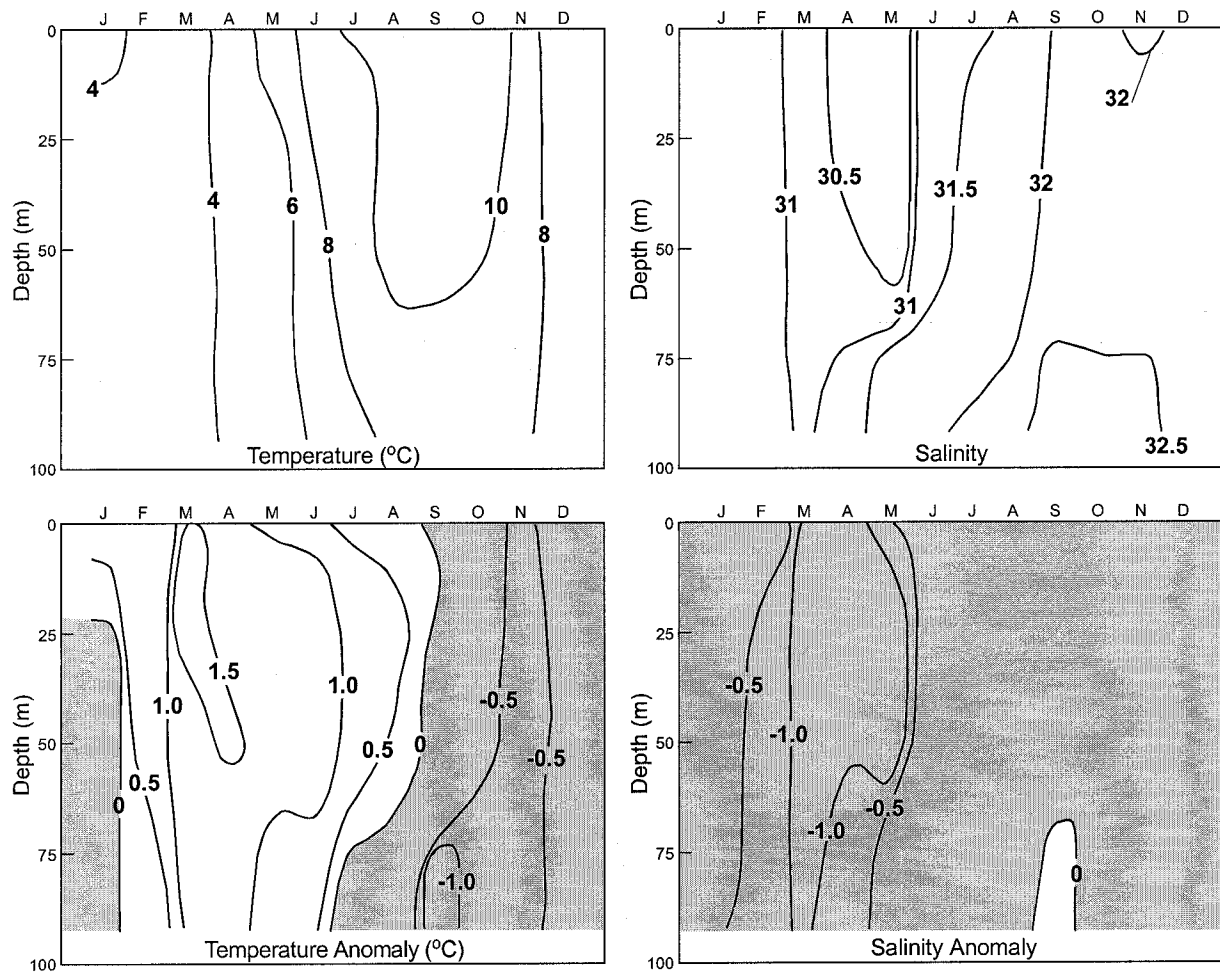


Fig. 3. Monthly temperatures and salinities and their anomalies at Prince 5 as a function of depth during 1998 relative to the 1961-90 means. Shaded areas are negative anomalies.



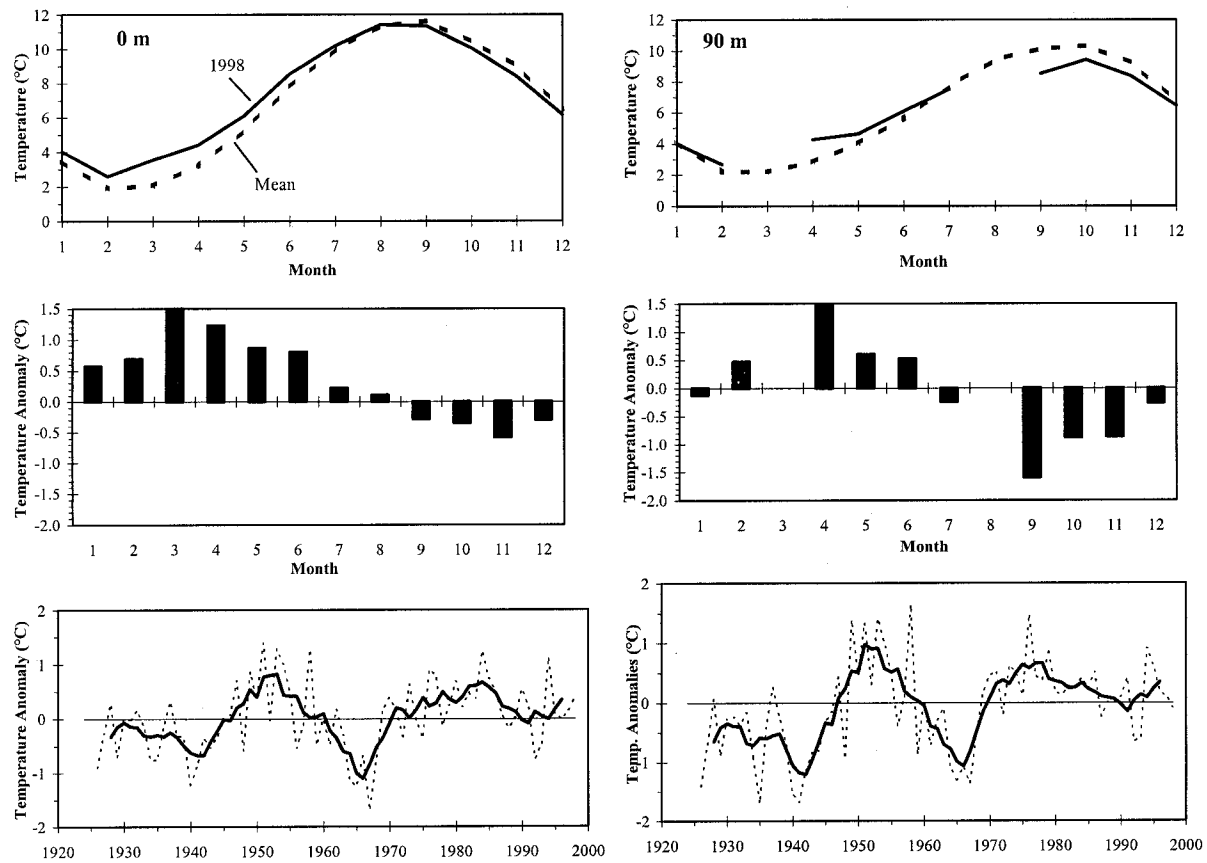


Fig. 4. The monthly mean temperatures for 1998 (solid line) and the long-term means (dashed line; top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels the time series of the annual means (dashed line) and 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

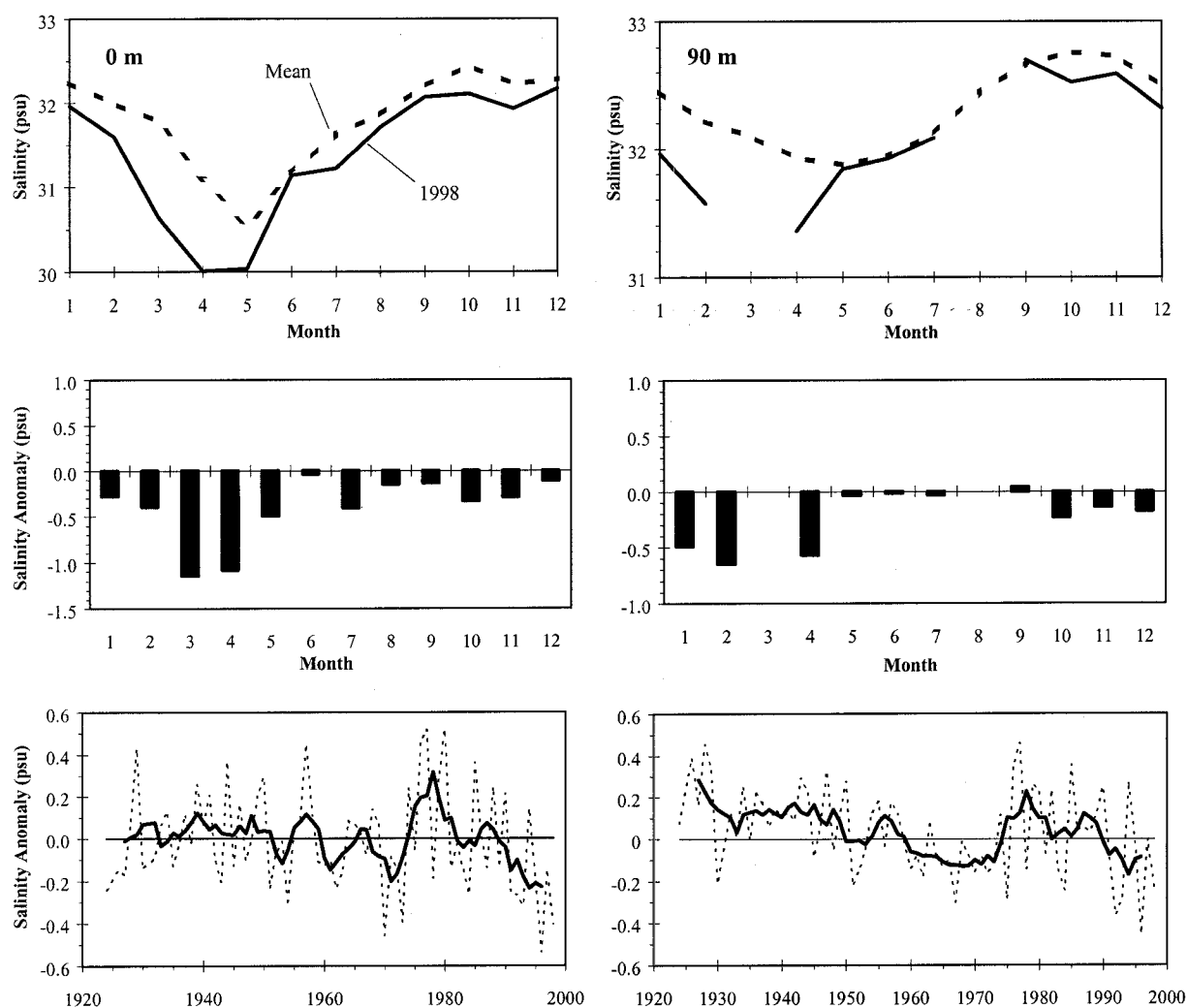


Fig. 5. The monthly mean salinities for 1998 (solid line) and the long-term means (top panels), the monthly anomalies relative to the long-term means for 1961-90 (middle panels) and in the bottom panels the time series of the annual means (dashed line) and 5-year running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

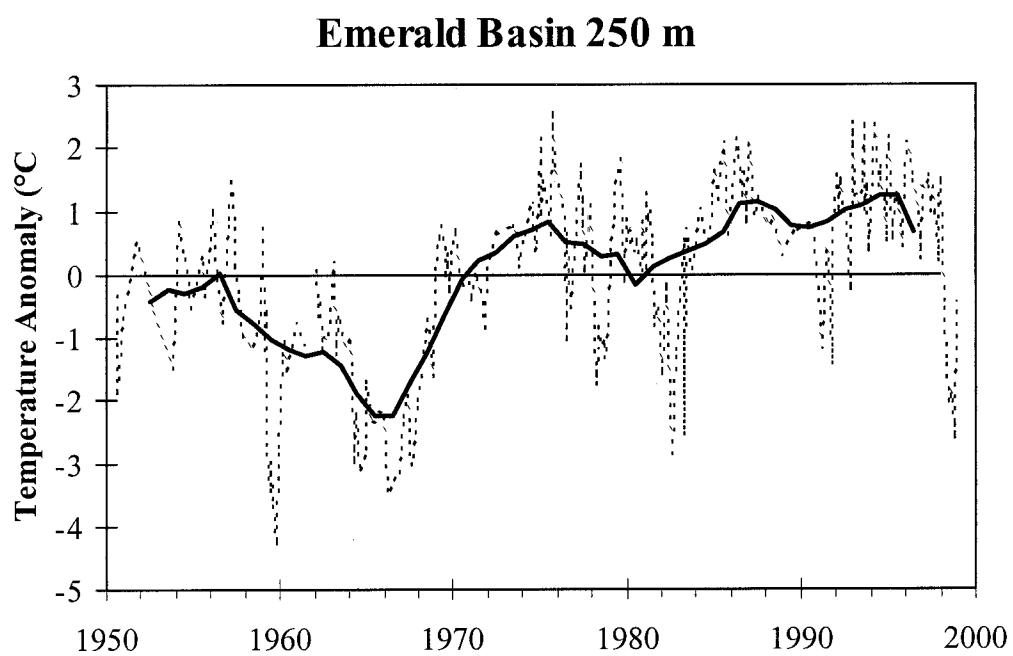


Fig. 6. Temperature anomalies (relative to 1961-90) at 250 m in Emerald Basin.

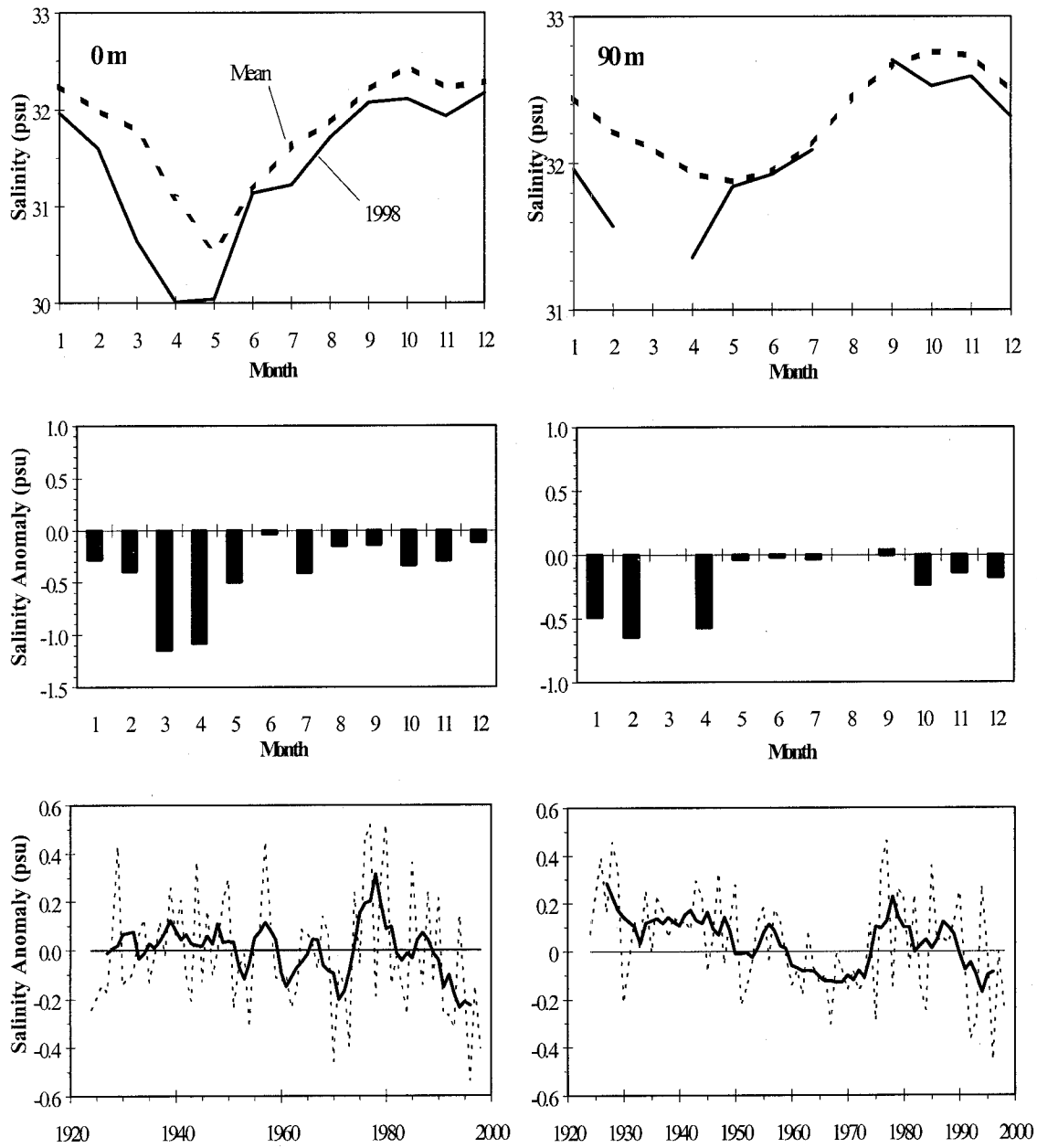
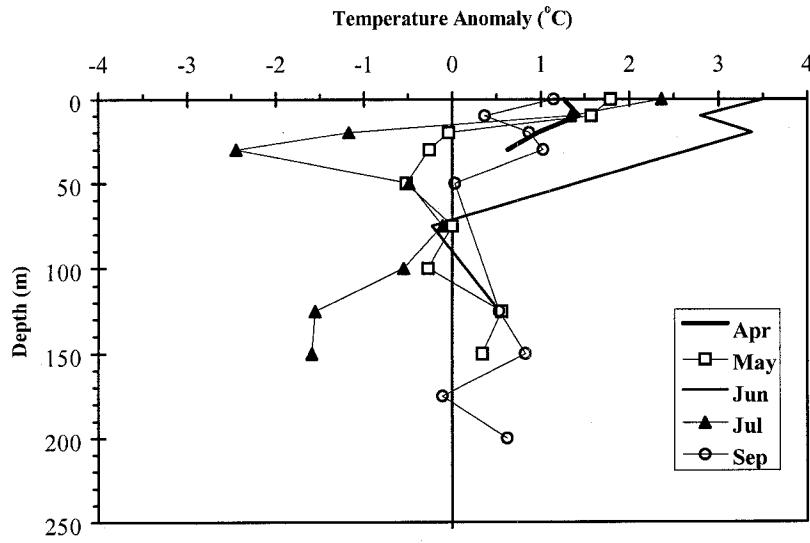


Fig. 7. The areas in which monthly means of temperature were estimated by Drinkwater and Trites (1987).

### 1998 Monthly Temperature Anomaly - Sydney Bight



### Sydney Bight - 100 m.

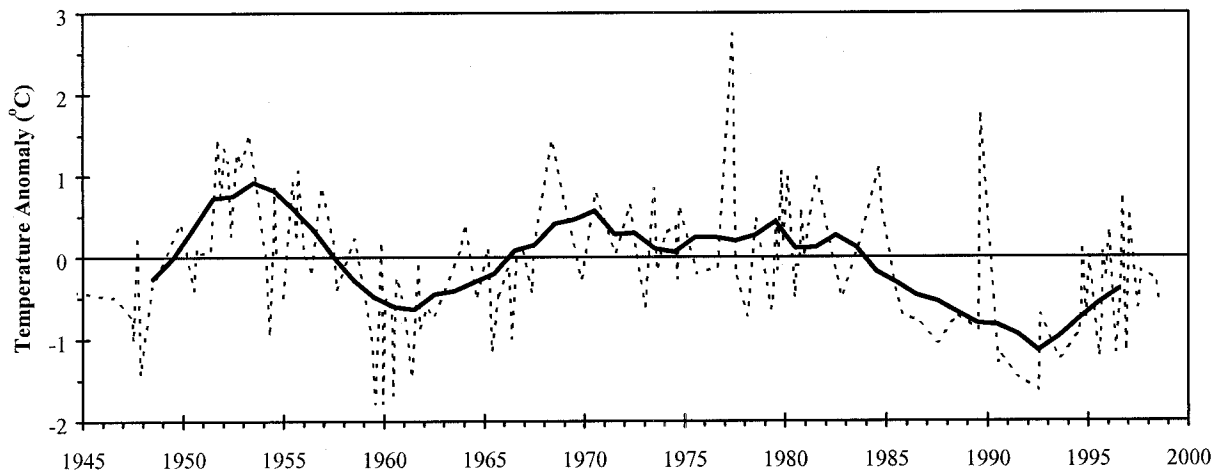
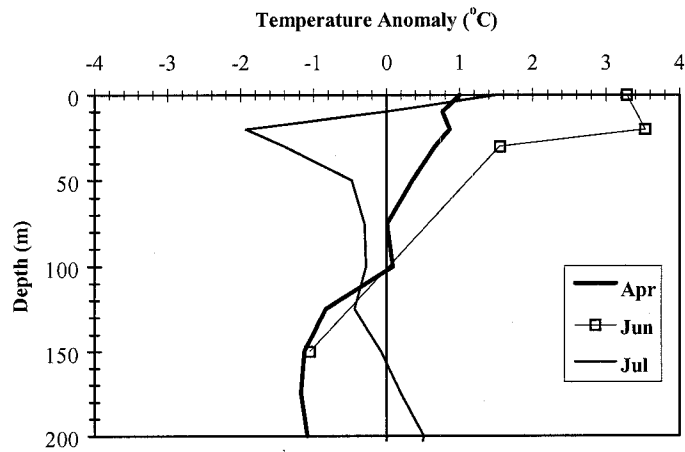
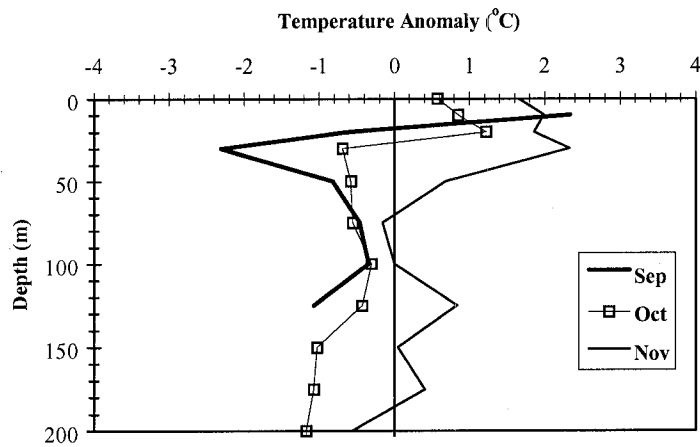


Fig. 8. 1998 monthly temperature anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1-Fig. 7).

### 1998 Monthly Temp. Anomaly - Misaine Bank



### 1998 Monthly Temp. Anomaly - Misaine Bank



### Misaine Bank - 100 m.

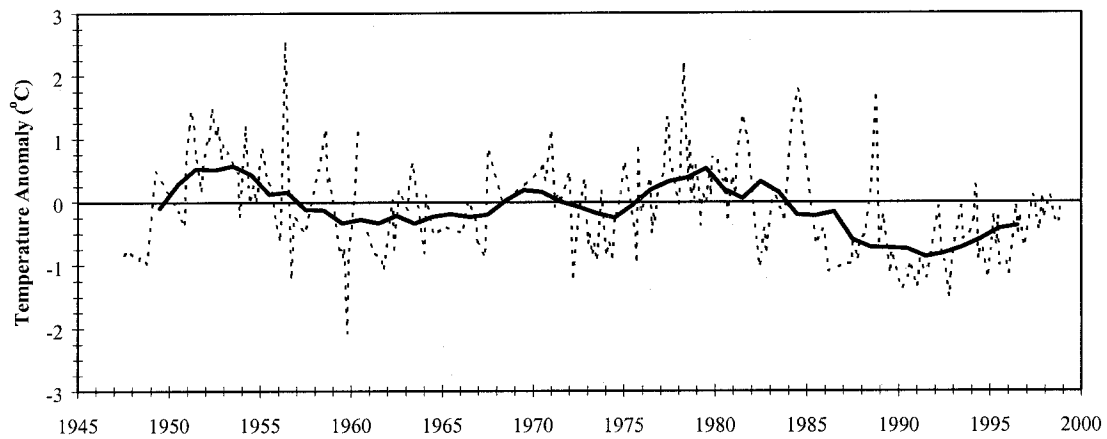


Fig. 9. 1998 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5-Fig. 7).

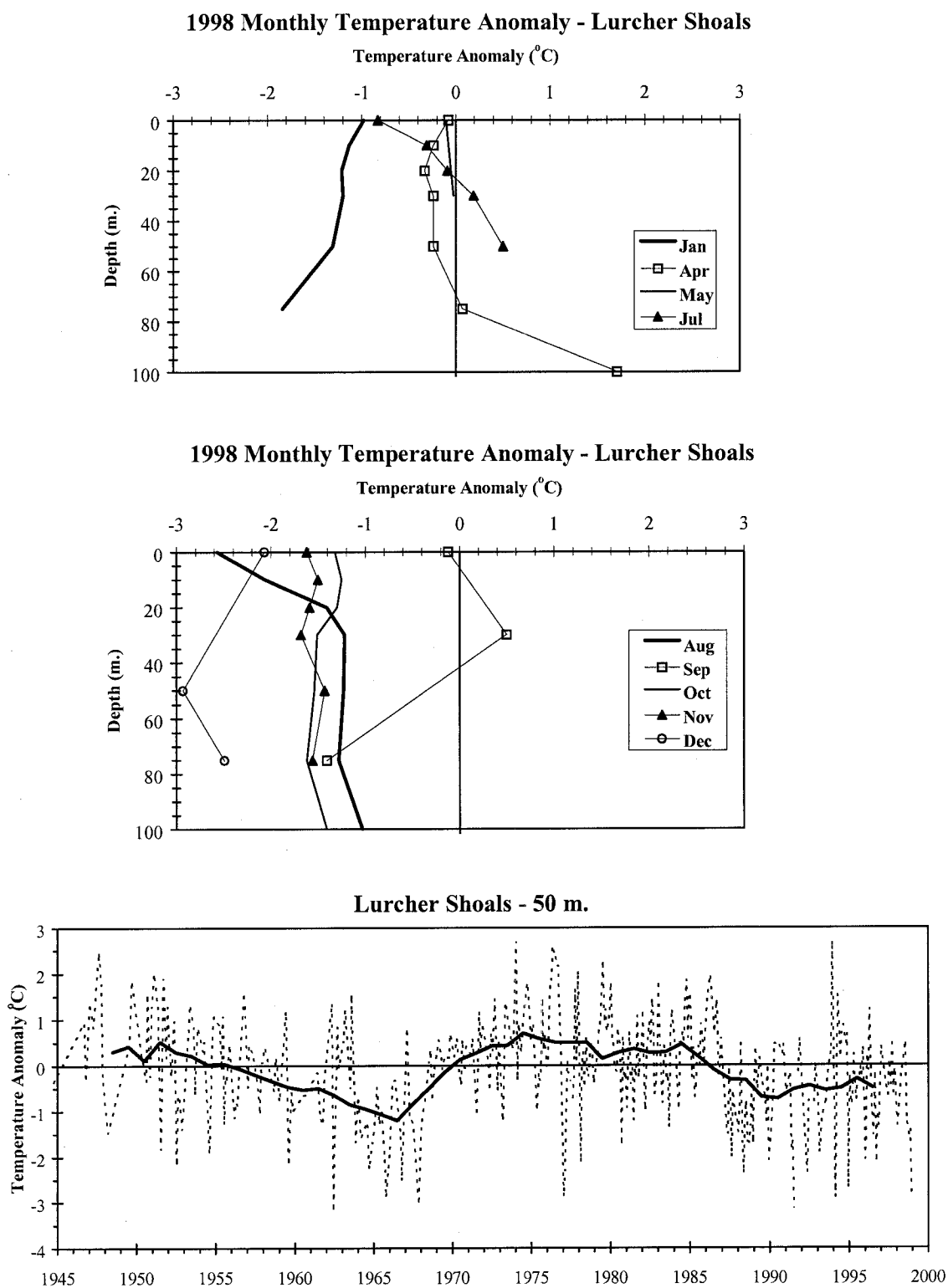


Fig.10. 1998 monthly temperature anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 50 m (bottom panel) for Lurcher (area 24-Fig. 7).

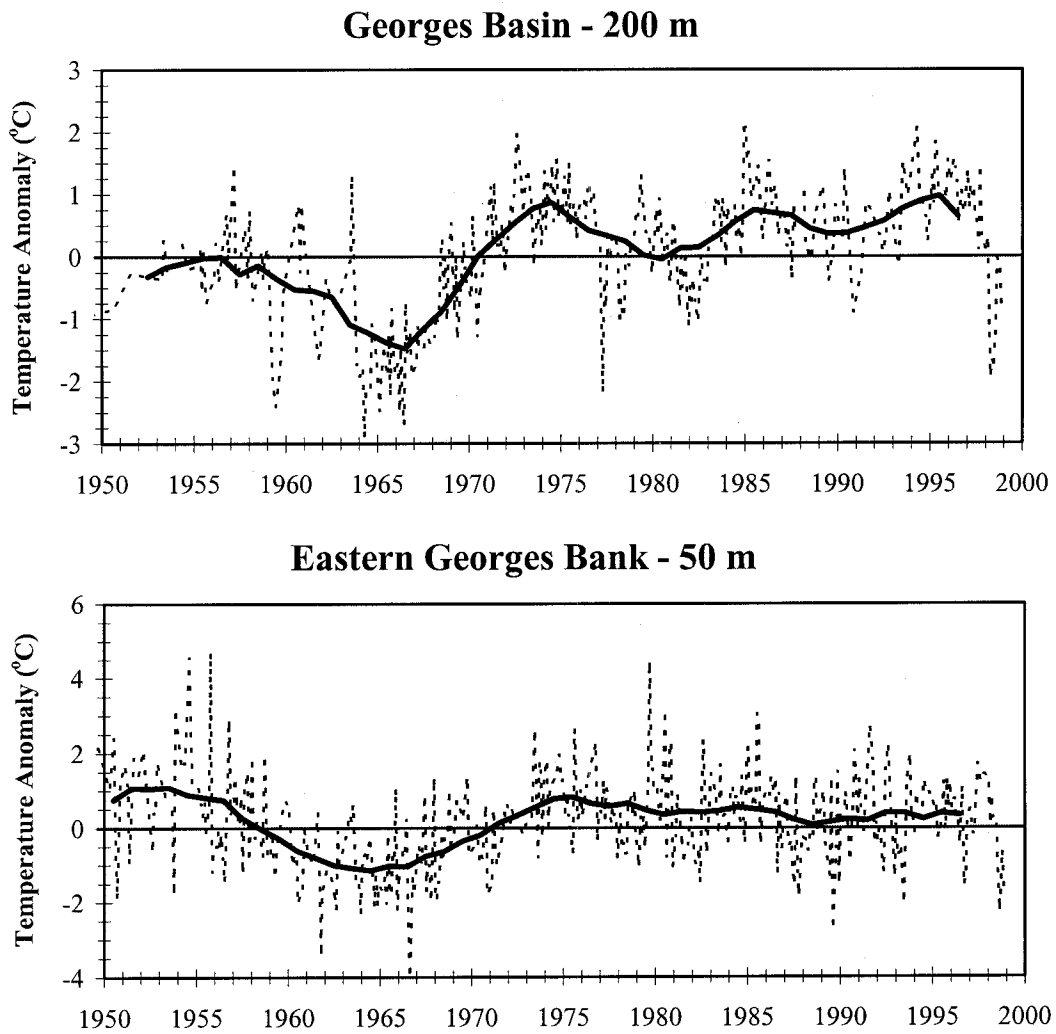


Fig.11. Time series of the monthly means (dashed lines) and the 5-year running means of the annual anomalies at 200 m in Georges Basin (top panel; area 26 in Fig. 7) and eastern Georges Bank (bottom panel; area 28 in Fig. 7).



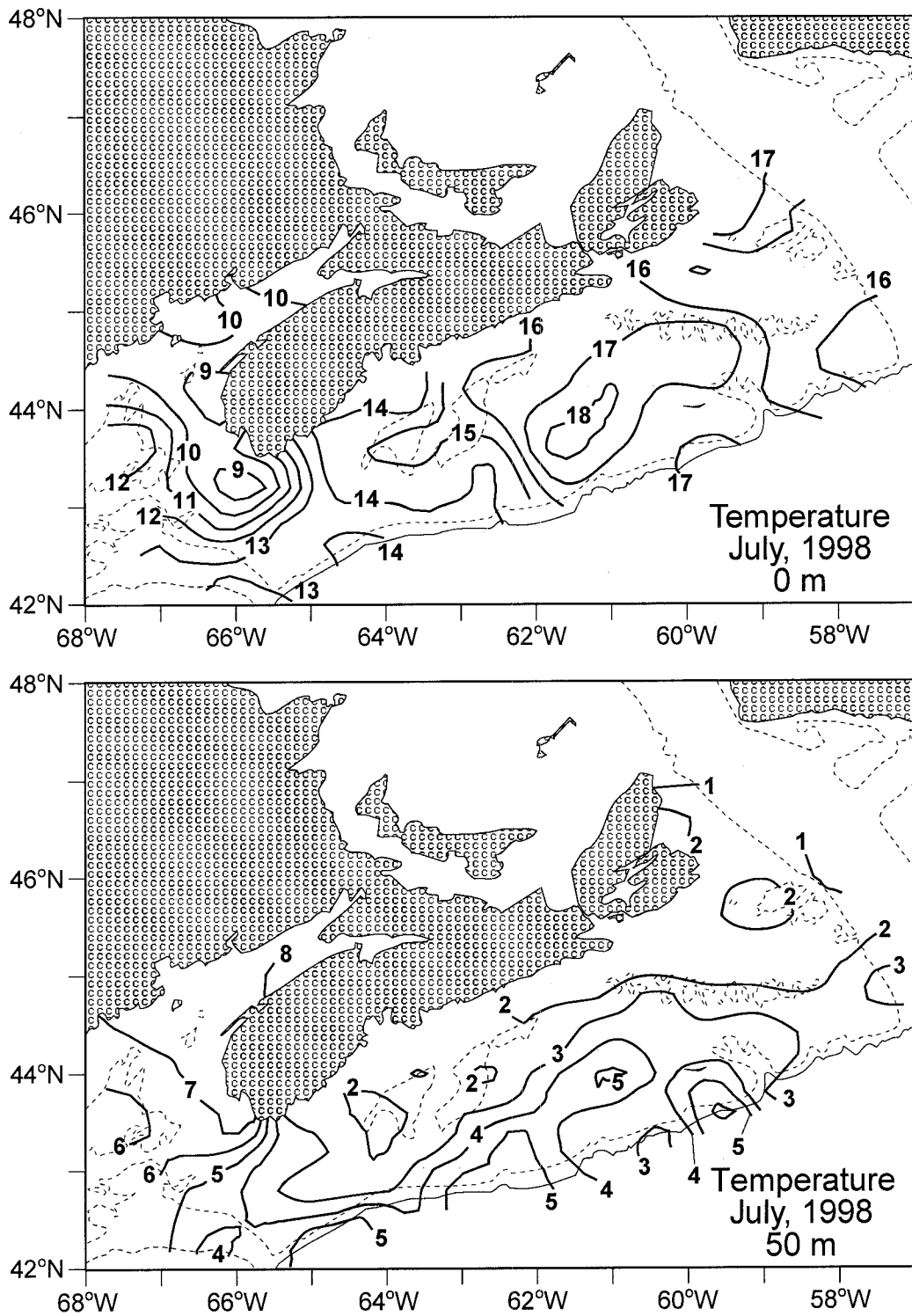


Fig. 12a. Contours of optimally estimated temperatures at the surface (top panel) and 50 m (bottom panel) during the 1998 July groundfish and ITQ surveys.

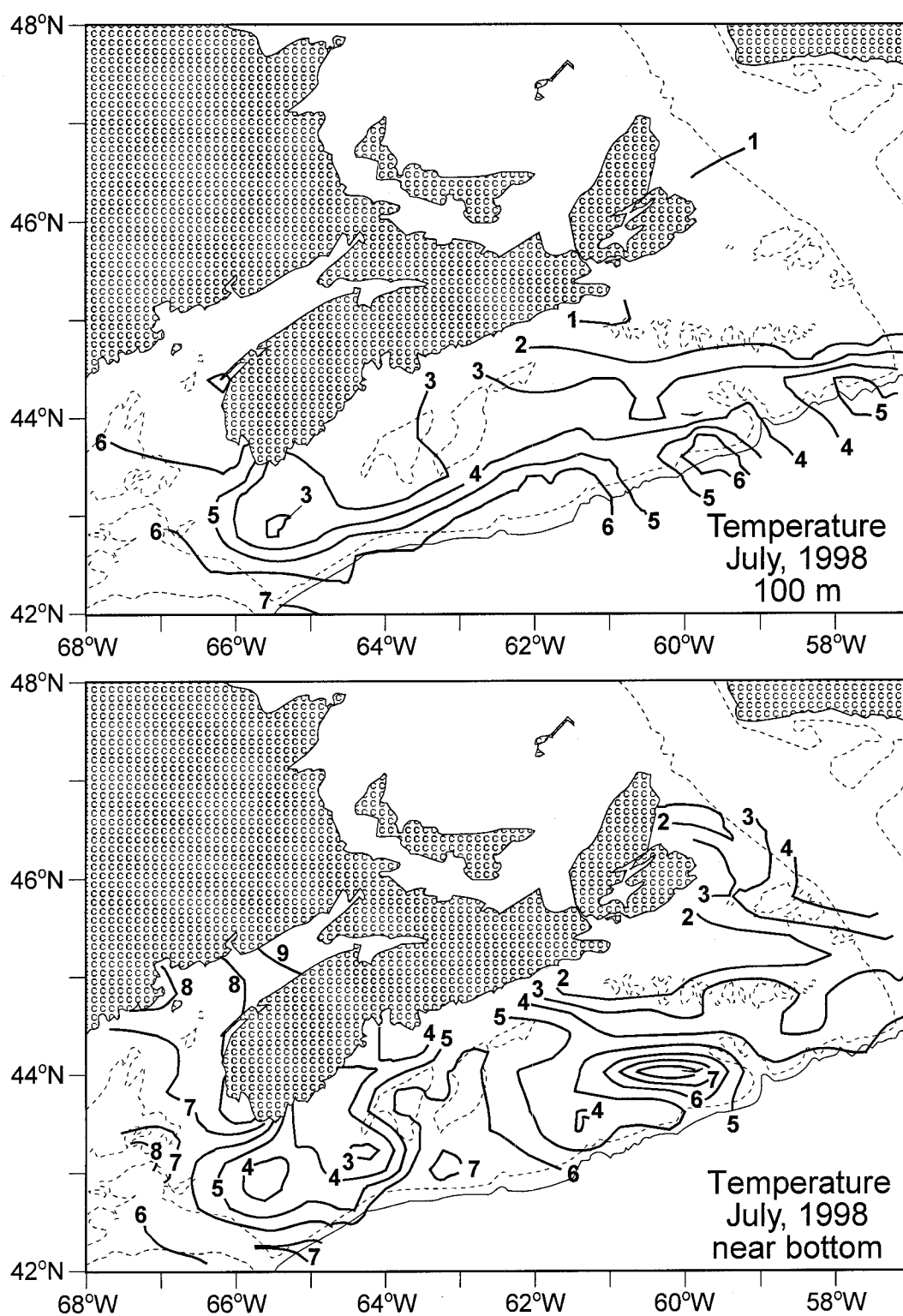


Fig. 12b. Contours of optimally estimated temperatures at 100 m (top panel) and near bottom (bottom panel) during the 1998 July groundfish and ITZ surveys.

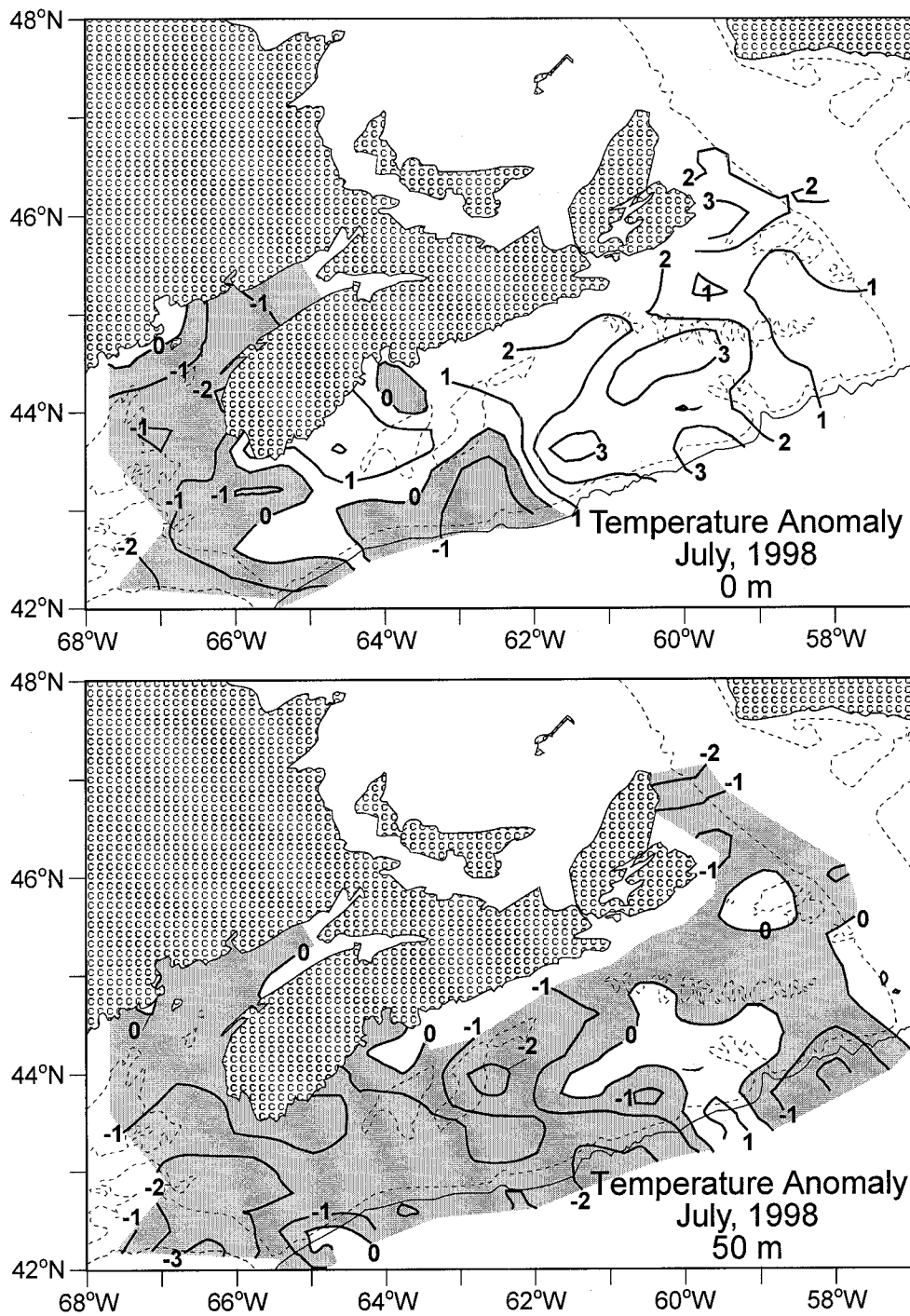


Fig. 13a. Contours of optimally estimated temperature anomalies at the surface (top panel) and 50 m (bottom panel) during the 1998 July groundfish and ITQ surveys. Shading indicates colder-than-normal temperatures.

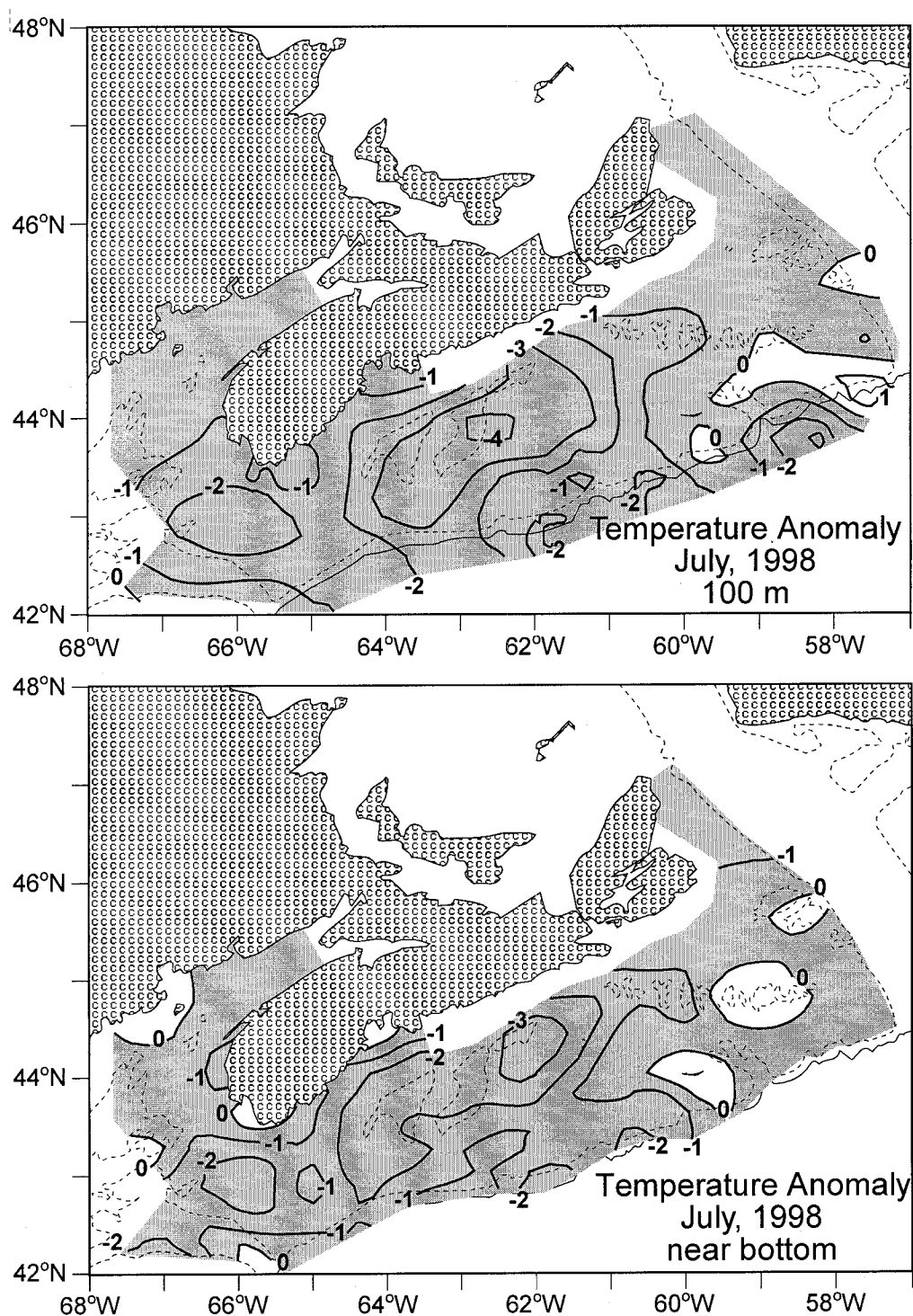


Fig. 13b. Contours of optimally estimated temperature anomalies at 100 m (top panel) and near bottom (bottom panel) during the 1998 July groundfish and ITQ surveys. Shading indicates colder-than-normal temperatures.

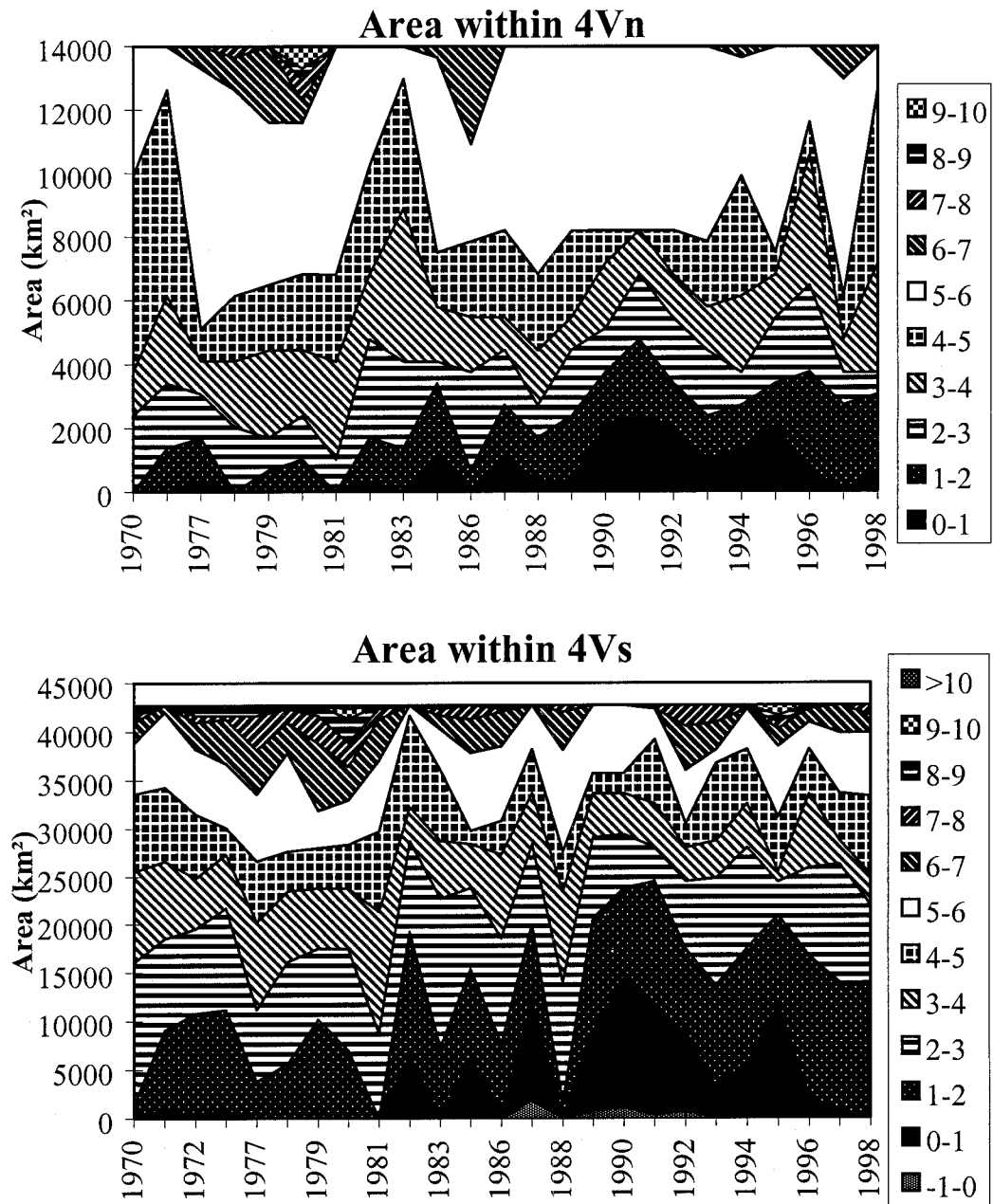


Fig. 14a. The time series of the area of the bottom for each one degree temperature range for NAFO subareas 4Vn (top panel) and 4Vs (bottom panel).

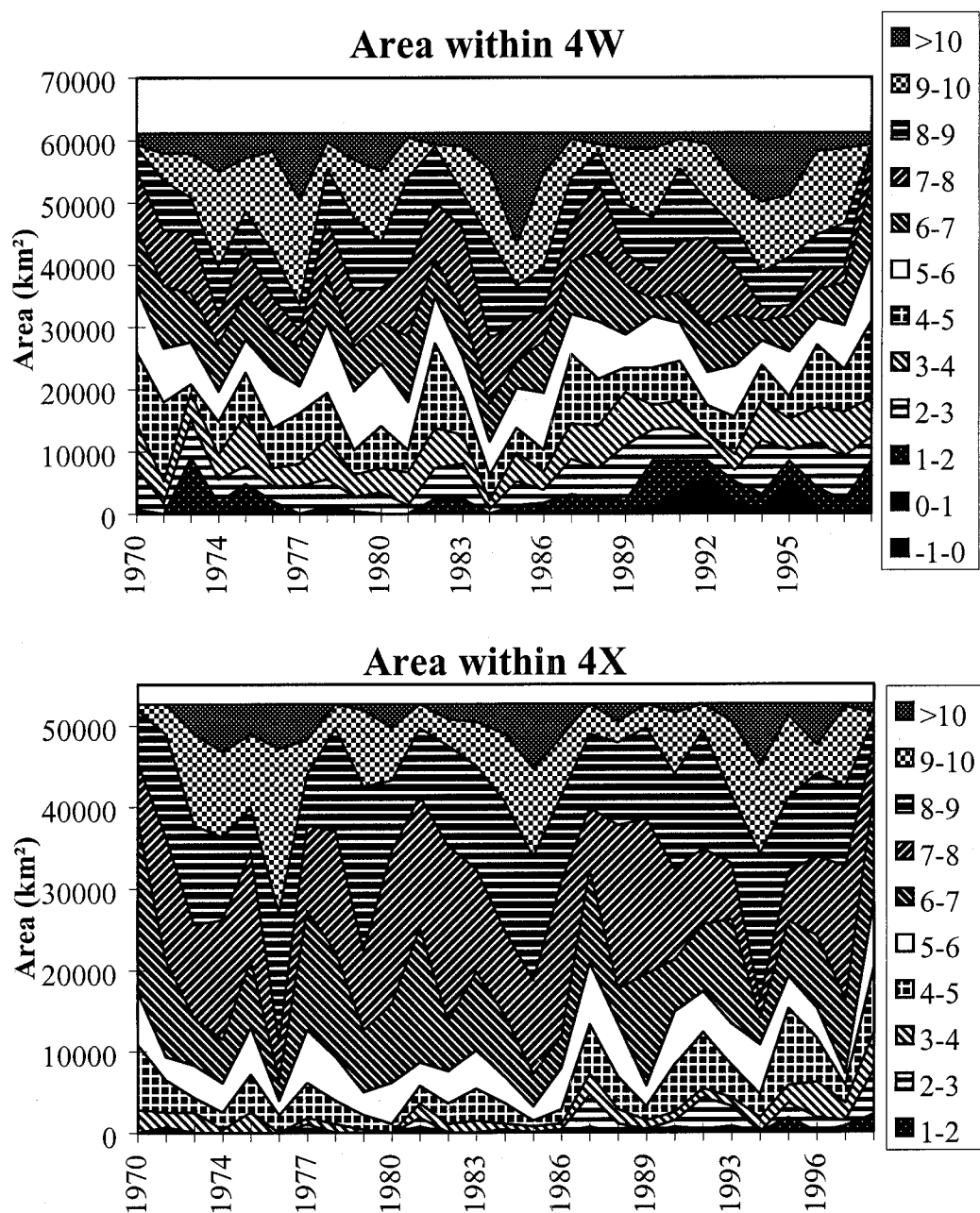


Fig. 14b. The time series of the area of the bottom for each one degree temperature range for NAFO subareas 4W (top panel) and 4X (bottom panel).

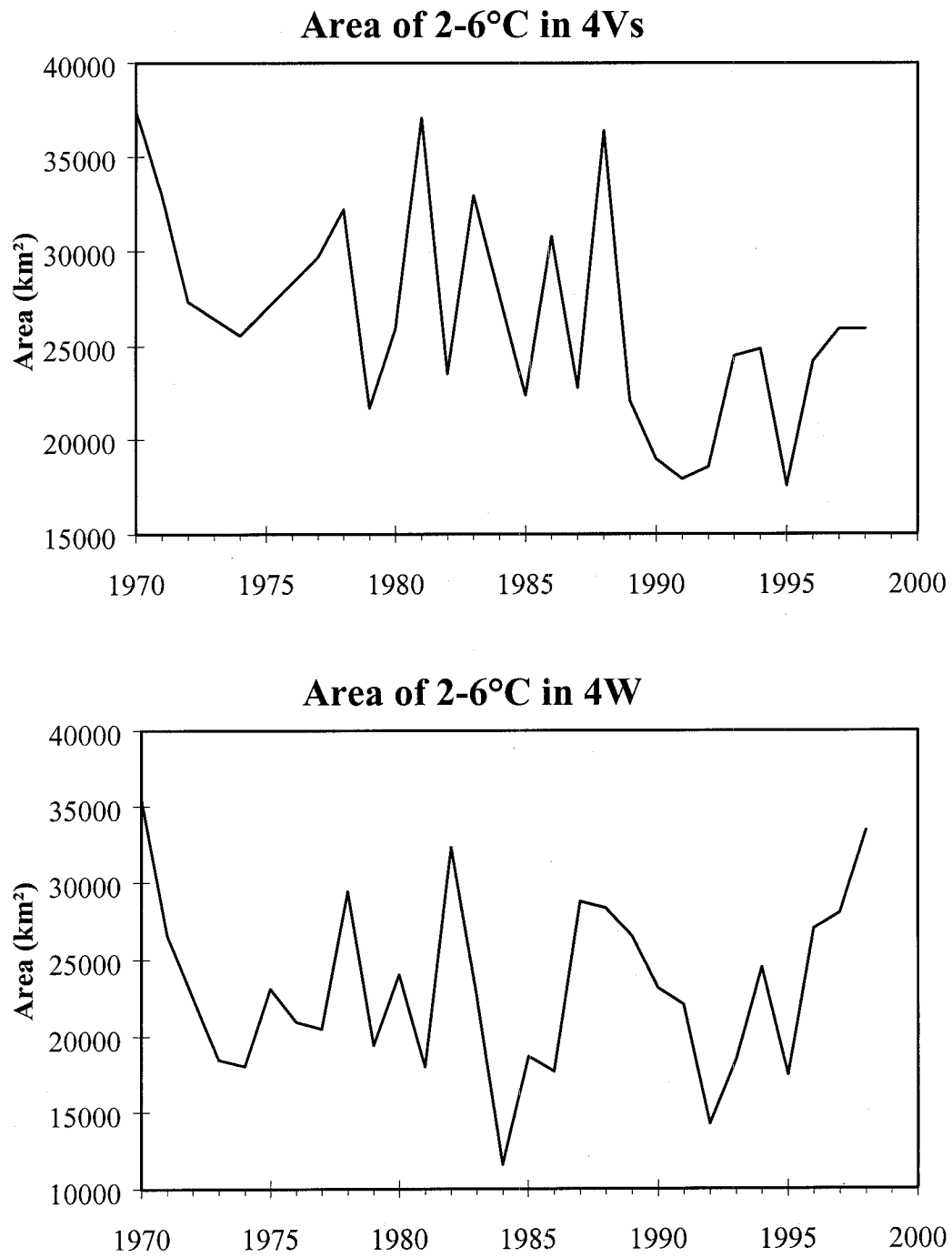


Fig. 15. The area of bottom covered by water of temperatures 2-6°C in NAFO subareas 4Vn (top panel) and 4Vs (bottom panel).

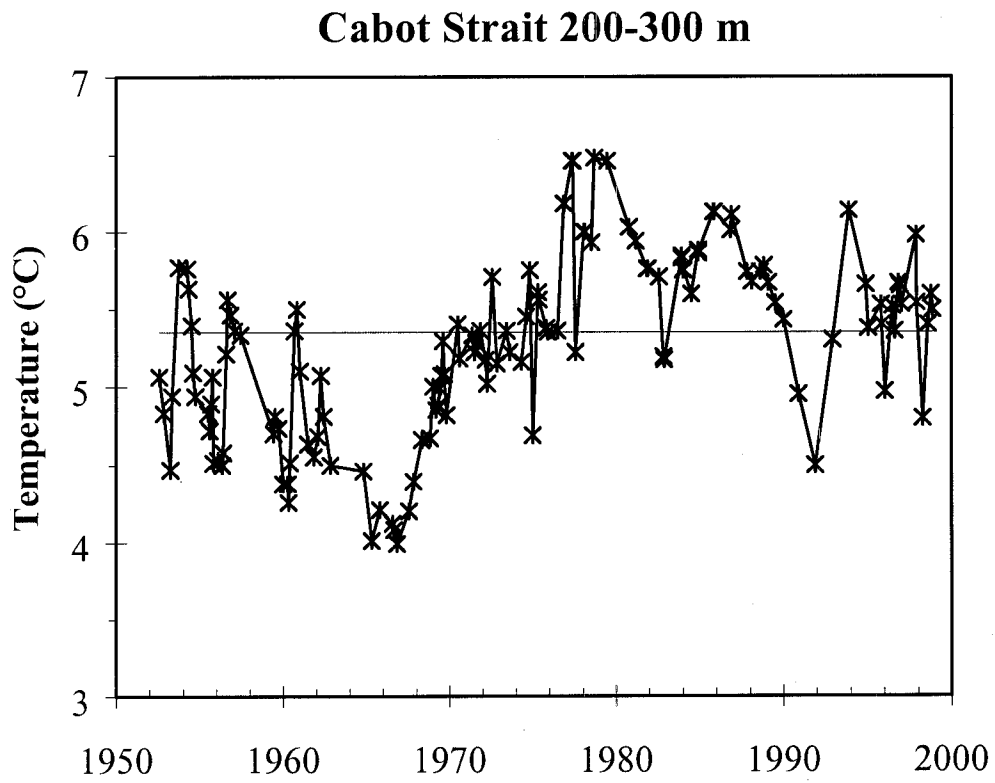


Fig. 16. Average temperature over the 200-300 m layer in Cabot Strait. The horizontal line indicates the long-term mean during 1961-90.



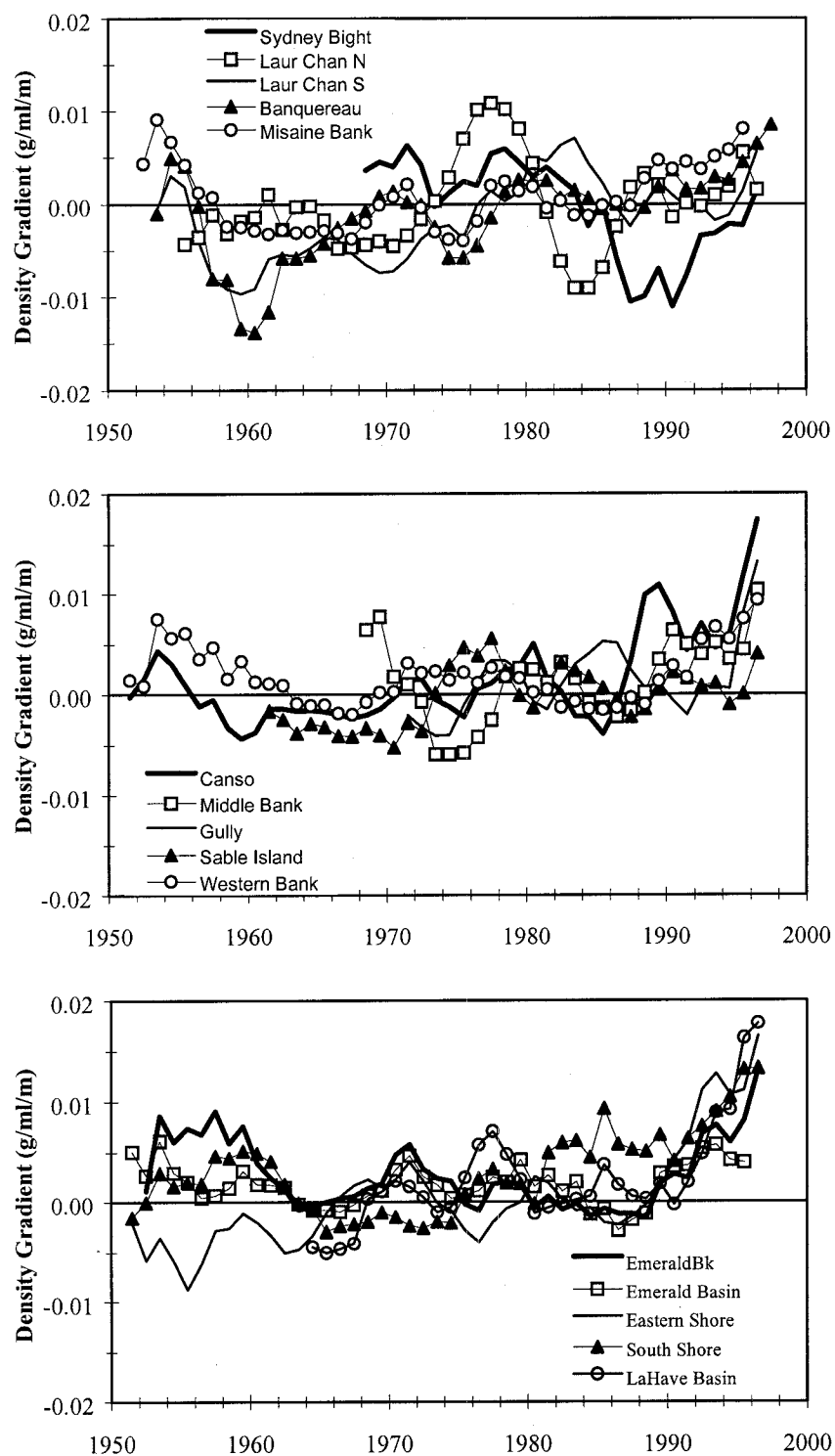


Fig. 17a. Five-year running means of the annual anomalies of the density gradient between the surface and 50 m calculated for the areas 1-15 in Fig. 7.

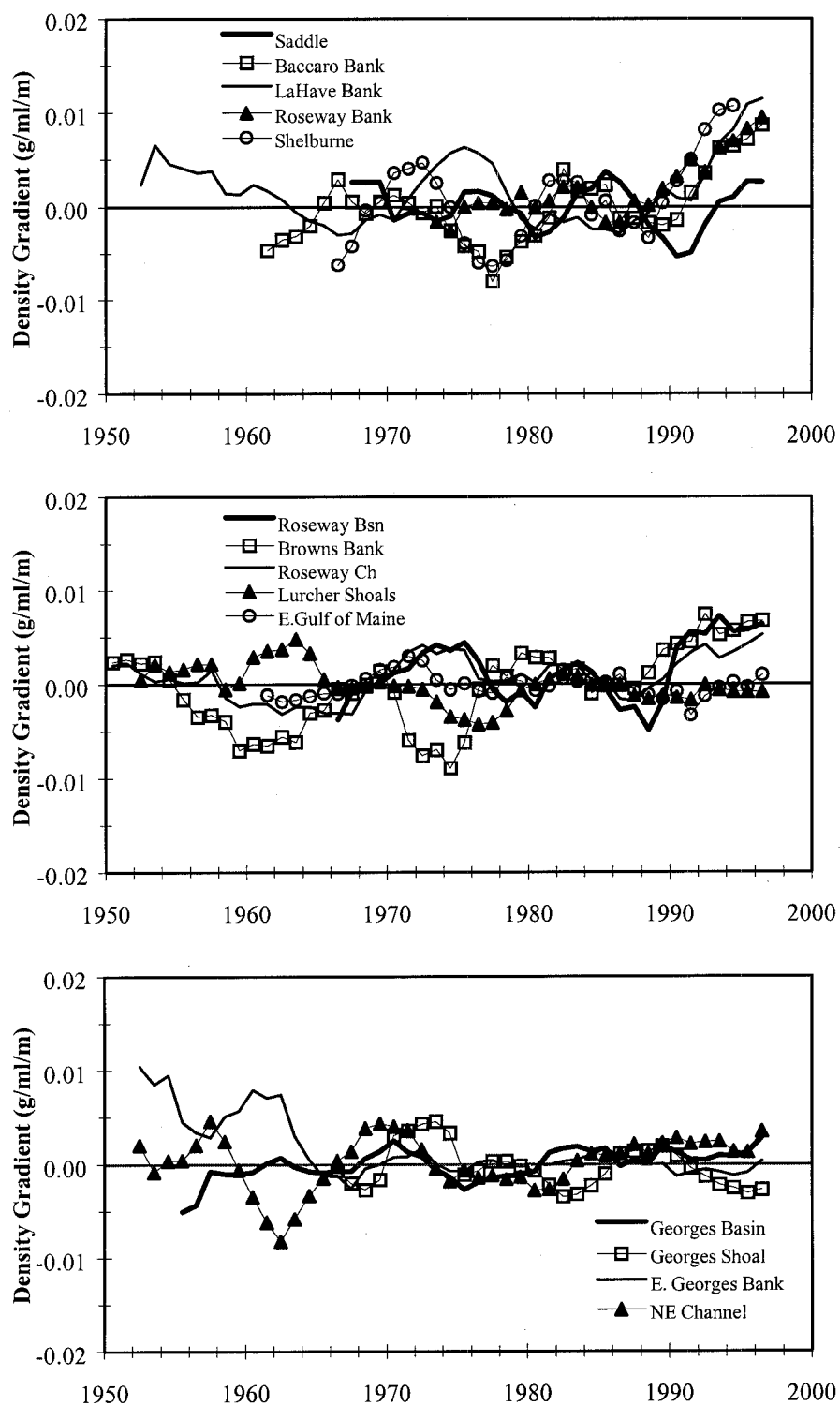


Fig. 17b. Five-year running means of the annual anomalies of the density gradient between the surface and 50 m calculated for the areas 16-29 in Fig. 7.

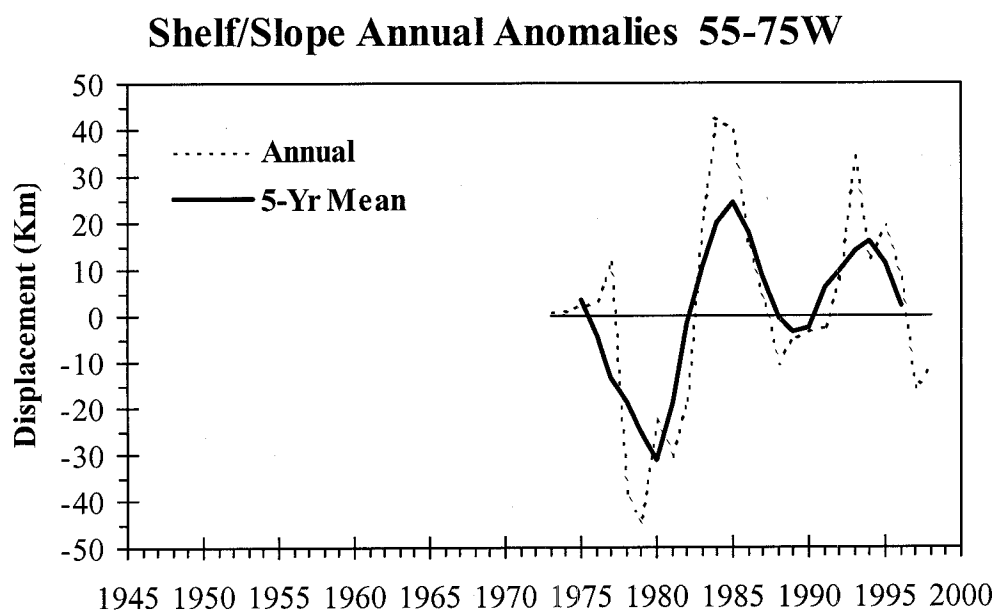
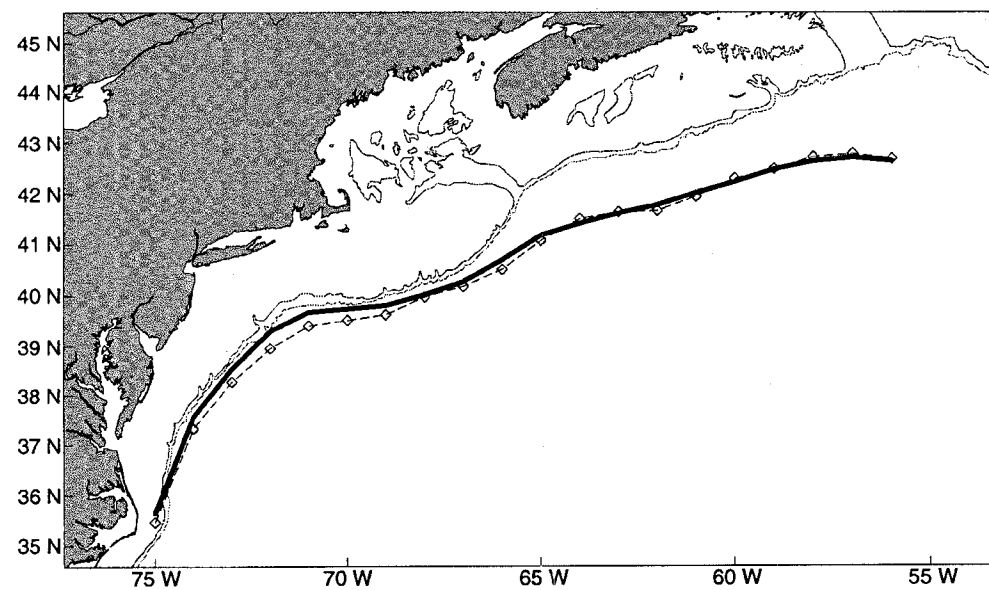


Fig.18. The 1998 (dashed line) and long-term (1973-97; solid line) mean positions of the shelf/slope front (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the shelf/slope front (bottom panel).

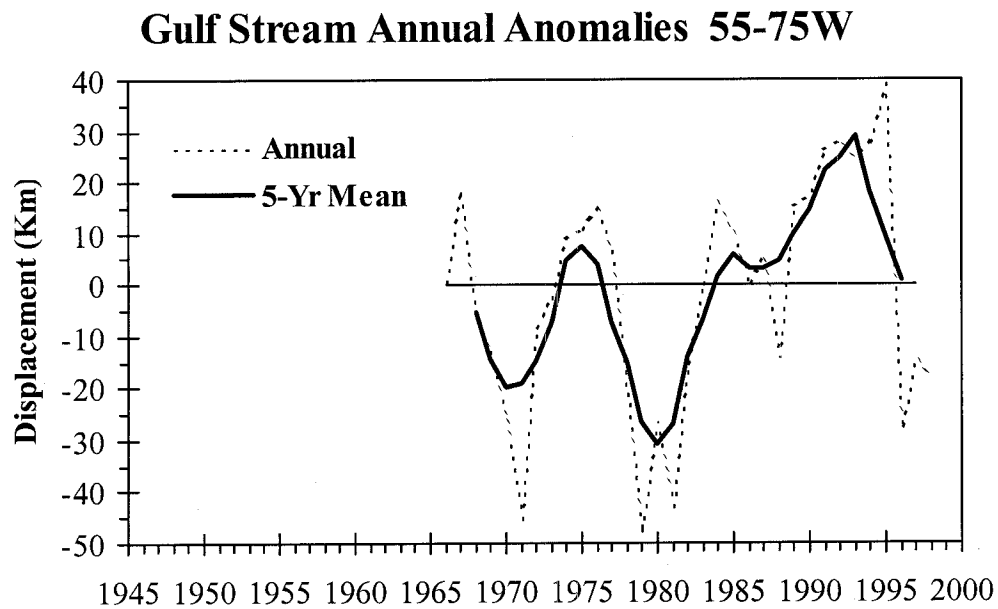
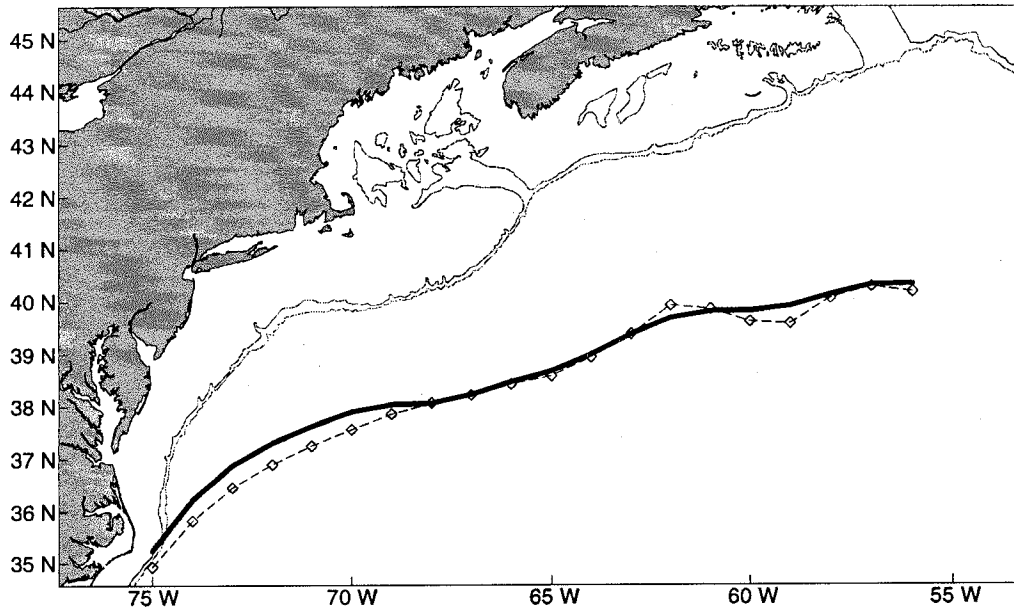


Fig. 19. The 1998 (dashed line) and long-term (1973-97; solid line) mean positions of the northern edge of the Gulf Stream (top panel) and the time series of the annual anomaly of the mean (55°-75°W) position of the Gulf Stream front (bottom panel).