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Hydrographic Variability on the Scotian Shelf During the 1990s[1]

by

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Abstract

The temperature, salinity and nutrient conditions of the waters on the Scotian Shelf during the 1990s are described and compared to the long-term variability. Three major features are highlighted. First is the presence of cold subsurface waters throughout much of the decade in the northwest and nearshore regions of the Shelf. These cold conditions, initially established in the mid-1980s, were also observed off southern Newfoundland and in the Gulf of St. Lawrence. The temperature trends on the Scotian Shelf are believed to have resulted from downstream advection with some contribution from *in situ* cooling. Second was the arrival in 1997-98 of cold Labrador Slope water along the shelf break, which subsequently flooded onto the Scotian Shelf. This produced the coldest near-bottom conditions on the central and southwestern shelf in the past 30 years but was of short duration, lasting only for approximately a year. Major changes in the dissolved oxygen and nutrient concentrations accompanied the Labrador Slope water intrusion; oxygen levels increased while nutrients decreased. These changes were consistent with a longer-term event in the mid-1960s. Finally, the changes in the near surface waters are described. Of particular importance was the increase in near-surface vertical stratification due primarily to the presence of low salinity waters at the surface. The impact of these ocean climate changes on the Shelf fisheries is also briefly discussed.

Introduction

The Scotian Shelf is located in the Northwest Atlantic off Nova Scotia, Canada (Fig. 1). It consists of a series of outer shallow banks and inner basins separated by gullies and channels. The mean depth is approximately 116 m with a maximum depth in Emerald Basin of around 270 m. The Shelf is bounded on the northeast by the Laurentian Channel, to the southeast by the offshore slope water region, to the southwest by the Gulf of Maine and to the northwest by the coast of Nova Scotia. The mean circulation is dominated by southwestward flow, which carries waters from the Gulf of St. Lawrence along the Shelf (Fig. 1; Hachey *et al*., 1954; Loder *et al*., 1998). Anticyclonic movement tends to occur over the banks and cyclonic around the basins (Sheng and Thompson, 1996; Han *et al*., 1997). The northeastern region of the Shelf is the southernmost limit of winter sea-ice off the east coast of North America. In the southwestern region of the Shelf, high tidal currents result in strong bottom-generated mixing.

Temperature and salinity on the Scotian Shelf vary spatially due to complex bottom topography, transport from upstream sources, melting of sea-ice in spring, atmospheric fluxes and exchange with the adjacent offshore slope waters. Water properties are also characterized by large seasonal cycles, depth differences and horizontal gradients both along- and across-shelf.

The seasonal temperature range of the waters over the Scotian Shelf decreases with depth. At the surface, the range is about 16°C, one of the highest in the Atlantic Ocean (Weare, 1977; Yashayaev and Zveryaev, 2001). The range rapidly declines with depth with little or no seasonal change at depths greater than approximately 100 to 150 m. In the

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southwest, the seasonal cycle shows a more uniform temperature range with depth because of vertical mixing by the strong tidal currents. This mixing results in a reduced seasonal temperature range at the surface but a larger range at depth relative to elsewhere on the Shelf. In the winter, the water column in deep regions of the Scotian Shelf consists of two layers separated by a transition zone. The upper layer is mixed by the winter winds and contains cold, low salinity water. The relatively warm and salty bottom layer originates from the offshore slope region and enters the Shelf through deep channels or gullies. In summer, a 3-layer vertical structure develops. Seasonal heating forms a thin (30-40 m) warm upper layer. The winter-cooled waters produce a cold intermediate layer (CIL) of 40-150 m thick and the warm bottom layer remains unchanged. This vertical structure varies over the shelf. Topography prevents the warm offshore waters from penetrating onto the northeastern Scotian Shelf and hence waters typical of the CIL (temperatures less than 5°C) extend to the bottom. Elsewhere on the Scotian Shelf, where depths are shallower than approximately 150 m, the warm bottom layer is very thin or is not present. In areas of strong tidal currents, such as off southwest Nova Scotia, the waters are relatively well mixed even in summer.

Temperatures and salinities generally increase from northeast to southwest because of the influence of the Gulf of St. Lawrence and from inshore to offshore because of the influences of the warmer, more saline offshore waters. For example, in the summer within the CIL, the 50-m temperatures typically range from 0°-3°C over the eastern Scotian Shelf, 3°-8°C over much of the central shelf and 6°-9°C over the western Scotian Shelf, eastern Gulf of Maine and Bay of Fundy. The exception to the general trend is the surface temperatures in summer, which decrease from northeast to southwest due to the transport of very warm surface outflow from the Gulf of St. Lawrence onto the northeastern Shelf. The near-bottom temperatures display similar ranges to those at 50 m, except over the central shelf where the range increases to 3-9°C, the slightly higher range being caused by the intrusion of the offshore waters.

Year-to-year, water temperatures on the Scotian Shelf and in the Gulf of Maine are also among the most variable in the North Atlantic Ocean (Weare, 1977). Petrie and Drinkwater (1993) examined temperature and salinity variability from the late-1940s to 1990. They found that the long-period trends in Emerald Basin in the central Scotian Shelf were reasonably representative of the Scotian Shelf and the Gulf of Maine. Temperatures were near or above average in the 1950s and declined to below average in the 1960s. The extended period with the lowest temperatures occurred during the mid-1960s. Temperatures rose rapidly in the late-1960s and from the 1970s to 1990 generally remained warmer-than-average.

In the remainder of the paper, we highlight the three most significant hydrographic changes on the Scotian Shelf during the 1990s. These include (1) the continual presence throughout the decade of cold subsurface waters, especially in the northeastern region of the Shelf, (2) the arrival of cold Labrador Slope Water at the shelf edge in 1997-98 and its subsequent movement onto the central and southwestern Shelf, and (3) the hydrographic variability in the surface waters including record high stratification. The temperature and salinity data used within our study are derived from the historical hydrographic database held at the Bedford Institute of Oceanography (Petrie *et al*., 1996). Because there are no monitoring sites on the Scotian Shelf for which there are long-term time series of the water column properties, we have assembled area-averages of the hydrographic data. The areas we choose are similar to those in Petrie *et al*. (1996) and are shown in our Fig. 4. Data within an area were assembled and averaged by month for each year, regardless of the number of stations per month. These monthly means were then averaged for the 30-year period 1961-1990 to obtain long-term monthly normals. These normals were then subtracted from the monthly means from each year to obtain monthly anomalies. Note that there were not data in all months of each year. The available monthly anomalies within a calendar year were then averaged to obtain an estimated annual anomaly.

Presence of Cold Subsurface Waters

One of the primary features of the ocean conditions in the 1990s was the persistence of colder-than-normal temperatures, most noticeably in the subsurface waters of northeastern area of the Shelf. The 100-m temperature anomalies from Misaine Bank (Fig. 2a) are representative of the temperature trends below 50 m in this region. Note that the high month-to-month variability evident reflects both real temporal changes and possible aliasing. The latter can arise when the measurements do not reflect the true mean because of limited sampling, either temporally (e.g. a single measurement in a month) or spatially (e.g. at a single site in the presence of horizontal temperature gradients within the area). While individual estimates for a month or even a year may not represent true average conditions for that time period, the longer-term persistent trends are considered real. The cold waters in the northeastern Shelf first appeared in the mid- to late-1980s, reached a minimum temperature in the early-1990s and gradually warmed to above normal temperatures by the end of the decade. The decreasing temperatures resulted in an expansion of the amount of cold water as evidenced by increase in the area of the bottom covered by waters with temperatures <3ºC (Fig. 3). Throughout the 1990s the subsurface temperatures generally remained colder-than-normal. The colder temperatures were accompanied by lower salinities.

The presence of the cold water on the northeastern Scotian Shelf is believed to have led to an expansion of the distribution of cold-water species such capelin, turbot, shrimp and snow crab (Frank *et al*., 1996; Tremblay, 1997; Drinkwater, 1999; Zwanenburg *et al*., 2001) and contributed to lower growth rates of Atlantic haddock and other demersal fish species (Zwanenburg *et al*., 2000). It also coincided with low abundance of Atlantic cod although it is not clear to what extent the decline in cod in the northeastern Scotian Shelf was due to over-fishing (Zwanenburg *et al*., 2001).

The presence of cold water from the mid-1980s through most of the 1990s was not restricted to the northeastern Shelf, but also occurred along the Atlantic coast of Nova Scotia and off its southwestern tip over Lurcher Shoals (Fig. 2b, 4). The cold water is believed to have been advected into the coastal regions. This is consistent with numerical models of the circulation that show water from the northeast Shelf tends to be confined inshore as it flows southwestward as the Nova Scotia Current (Fig. 1; Han *et al*., 1997). Its presence in the surface waters at Halifax (Fig. 2b) is due in part to the consistent upwelling in summer along the coast (Petrie *et al*., 1987) and the deep mixed layer in the winter. Much of this water eventually makes it into the Gulf of Maine (Smith, 1983; Smith *et al*., 2001), which accounts for the observed cold water on Lurcher Shoals. The cold water during the late-1980s and into the 1990s was traced with decreasing amplitude through to the Maine coast before losing its signature entirely. It was not observed in the central Scotian Shelf or on the outer banks from Sable to Browns. This is consistent with the central shelf region being dominated more by the flow-through of the shelf break current (Sheng and Thompson, 1996; Han *et al*., 1997) and the penetration of offshore slope water through the Scotia Gulf (Petrie and Drinkwater, 1993).

The cause of the cold water on the northeastern Scotian Shelf during the late-1980s and through most of the 1990s is believed to be a combination of advection from more northern areas and *in situ* cooling. Advection is supported on the strength of the residual circulation patterns (Sheng and Thompson, 1996; Han *et al*., 1997) and the similarity of the temperature changes in the upstream regions. Temperature trends in the Gulf of St. Lawrence (Gilbert and Pettigrew 1997) and off southern Newfoundland (Colbourne, 2000) mirror those on the northeastern Scotian Shelf including a shift from relatively high temperatures in the early 1980s to low temperatures in the late 1980s and into the 1990s (Fig. 2c). The amplitudes of the negative temperature anomalies in the 1990s were similar in all three regions. However, in the late 1990s the waters on the shelf appear to warm up earlier than in the upstream regions. This suggests the possibility that the downstream flows might have gradually diminished in strength through the late-1990s. The other possible cause of the persistent cold water was *in situ* cooling. To explore this we examined the monthly and annual mean heat fluxes estimated from the COADS dataset between 1960 and 1993 for the 2º x 2º latitude-longitude area centered over the northeastern Scotian Shelf. These show negative heat flux anomalies from 1986 through to the end of available record, suggestive of colder-than-normal temperatures. To determine if they could produce temperature anomalies of the correct order, we assume that the annual heat flux anomalies are distributed over the top 100 m (approximate depth limit to which the seasonal temperature cycle is observed) and do not accumulate (i.e. the water leaves the area within a year). The temperature change then can be estimated from

$$\Delta T = \frac{Q\Delta t}{rC_p z}$$

where ΔT is the temperature change produced by a heat flux anomaly Q during the time Δt over a water column of depth z, r is the density of the water and C_p is its specific heat. Δt was taken to be 1 year, r was assumed to be 1025 kg m^{-3} and C_p to be 4200 joules kg^{-1}. The estimated temperature changes due to annual heat flux anomalies are of the right order and do show a somewhat similar pattern to that of the observed temperature anomalies at Misaine Bank (Fig. 2d). The heat flux model accounts for approximately just under 50% of the variance in the observed anomalies in the overlapping years. However, there are several reasons to question the importance of local heat fluxes in determining the presence of the cold waters on the Scotian Shelf in the late-1980s and 1990s. First, the heat flux model estimates lag the observed temperature anomalies by around two years. Second, the thermal conditions from year-to-year are not independent, i.e. there is thermal inertia. Third, the temperature changes were accompanied by salinity fluctuations, which suggests changes in the component water masses. Finally, temperatures in the upper 50 m show a somewhat different trend to the subsurface waters. If the heat fluxes were dominating the temperature changes one would expect that the temperature trends in the surface and subsurface layers would be similar but they are not (see later section on the surface layer). Based upon the available information, we believe that the primary source of the cold, fresh conditions on the northeastern Scotian Shelf was likely advection from the Gulf of St. Lawrence and/or the southern Newfoundland shelf. However, local *in situ* atmospheric cooling had the potential to cause significant temperature variability and may have contributed in part to the presence and persistence of these cold waters.

Slope Water Intrusion 1997-98

Arguably the most dramatic ocean climate event during the 1990s was the penetration of cold Labrador Slope water from offshore onto the central and southwestern Scotian Shelf during 1998. Slope waters occupy the region between the continental shelf and the Gulf Stream from the Tail of the Banks to Cape Hatteras. They are a combination of colder, fresher deep Labrador Current water and warmer, saltier North Atlantic Central Water. Gatien (1976) identified two types of slope waters, Labrador Slope Water with temperatures generally 4º-8ºC and salinities 34.3-35 and Warm Slope Water with temperatures typically 8º-12ºC and salinities 34.7-35.5. The slope water properties at a particular location depend upon whether the North Atlantic Central or Labrador Current water mass component is dominant. The temperature and salinity characteristics of the Slope Water adjacent to the Scotian Shelf vary depending upon the volume flow of the deep (100-300 m) Labrador Current around the Tail of the Grand Banks (Petrie and Drinkwater, 1993). In years of high baroclinic transport, such as occurred in the 1960s, Labrador Slope Water was found along the shelf edge as far south as the Middle Atlantic Bight (Gatien, 1976). In years of low transport, such as in the 1950s and again in the 1970s through to the 1990s, the Labrador Slope Water seldom penetrated much farther south than the Laurentian Channel. During these times, Warm Slope Water dominated the shelf edge off the Scotian Shelf. The Slope Water penetrates onto the Shelf through gullies and channels forced by a combination of horizontal density gradients, warm-core Gulf Stream rings, and meteorological events. It occupies the deep basins and the deep layers of the central and southwestern Scotian Shelf. Through the 1990s temperatures along the shelf break and in the deep basins of the Scotian Shelf and the Gulf of Maine remained relatively warm, indicative of Warm Slope Water. Indeed, the warmest extended period in the last 50 years within these deep basins was during the mid-1990s (Fig. 5a).

In the autumn of 1997, the Labrador Slope water extended southward along the edge of the Scotian Shelf reaching the Gulf of Maine in January of 1998 and eventually the Middle Atlantic Bight by the spring of 1998 (Fig. 6). Drinkwater *et al*. (2001) provided details of the timing of this water mass as it flowed southward as well as its subsequent movement onto the Scotian Shelf and into the Gulf of Maine. The Labrador Slope Water arrived off the central Scotian Shelf in October, and began to penetrate Emerald Basin via the Scotia Gulf in December 1997. By February of 1998 the lower layers of Emerald Basin were completely flushed. Temperatures dropped by over 4ºC (Fig. 5b) and salinities by approximately 1 during this event. The Labrador Slope Waters continued to spread onto the Shelf eventually replacing most of the near-bottom waters on the southwestern Shelf by the time of the comprehensive shelf groundfish survey in July 1998. This survey recorded the lowest temperatures for southwestern shelf in its 30-year time series. Its effects were not restricted to the Scotian Shelf but also were felt in the Gulf of Maine (Drinkwater *et al*., 2001a). The Labrador Slope Water at the shelf edge began to retreat northeastward early in 1998 and by late that year was located around the mouth of the Laurentian Channel. Along the Scotian Shelf it was replaced by Warm Slope Water. The Labrador Slope Water on the shelf gradually disappeared through 1998 (Fig. 5b).

The intrusion of the Labrador Slope Water also led to variability in the oxygen and nutrient levels. Oxygen in the deeper waters of Emerald Basin rose substantially in 1998 as the Labrador Slope Water flooded in (Fig. 7). A similar rise in oxygen levels occurred during the 1960s cold period that was dominated by Labrador Slope Water. In contrast to the oxygen, the nutrient concentrations within Emerald Basin were relatively low in 1998 although not as low as in the 1960s (Fig. 7). Nitrates actually declined a year earlier while silicates and phosphates declined even earlier than the nitrates.

The increased volume transport of the Labrador is believed to be related to the strength of the large-scale atmospheric circulation patterns over the North Atlantic as reflected in the intensity of the Icelandic Low (Worthington, 1964) or its related North Atlantic Oscillation (NAO) index (Marsh *et al*., 1999; Drinkwater *et al*., 2001a). Increased transport coincides with a weakened Icelandic Low (low NAO index). The high transports of Labrador Current water around the Tail of the Banks found during the 1960s by Petrie and Drinkwater (1993) are consistent with this relationship. In 1996, the NAO index experienced the largest decline in its 100-year record as the Icelandic Low and the Azores High both weakened substantially. Drinkwater *et al*. (2001a) suggest that this decline eventually lead to the increased transport and the subsequent southward extension of the Labrador Slope Water. The time delay between the NAO decline and the arrival of the Labrador Slope Water off the Gulf of Maine and Middle Atlantic Bight was about 20 months much longer than the 8 months for the 1958 event (Worthington, 1964). The cause of such long delay in 1997-1998 is unexplained. The cold water was observed off St. Pierre Bank in January 1997 (unpublished current meter data, P.C. Smith), 10 months after the low wintertime NAO index of 1996. It took another 7 months to cross the Laurentian Channel being observed off Banquereau Bank on the Scotian Shelf in September and then 3 more months to the Middle Atlantic Bight.

Although relatively short-lived, this event is known to have affected at least the catchability of certain fisheries on the Scotian Shelf and on Georges Bank (Drinkwater *et al*., 2001a). They noted, for example, that shark catches declined drastically in the Emerald Basin region in early 1998 after the cold Labrador Slope Water replaced the Warm Slope Water. Also, lobster fisherman on Georges Bank noted declines in their catches that they attributed to the presence of cold water. Cold water is known to limit the activity of the lobsters and hence their likelihood of encountering fishing traps (McLeese and Wilder 1953).

Variability in the Near-surface layer

Petrie and Drinkwater (1993) noted the similarity in temperature trends throughout the water column, which were generally dominated by the warm 1950s, the cold 1960s and the above normal temperatures in the 1970s and 1980s. In contrast, the 1990s exhibited greater differences in the vertical, especially between the near-surface (0-30 m) and deeper layers. Consequently, we examined the trends in surface temperature and salinity as well as the density differences between the surface and 50 m. Annual means of these variables were estimated for each area in Fig. 4 then areas 4 through 23 were combined to produce a Shelf-wide average. For all three variables, there was strong similarity over the entire Shelf as revealed by their relatively small error of the means (Fig. 8).

Following a decrease in the early-1990s, *in situ* measurements indicated surface temperature anomalies rose, generally fell again to a minimum in 1997 then rose rapidly to reach a near record positive value in the over 50-year period (Fig. 8a). The annual anomaly in 1999 reached a peak of 1.3ºC. This amplitude as well as the temporal pattern of the anomalies was similar to those obtained from satellite-derived sea surface temperatures, as described by Drinkwater *et al*. (2001b). They also showed that this temperature pattern extended from southern Labrador to the Gulf of Maine, including over the Grand Banks. The ocean temperatures mirror air temperatures in the Scotian Shelf region (approximately 55% of the variance in annual sea surface temperature can be accounted for by the air temperatures as measured on Sable Island). Indeed when ocean temperatures peaked in 1999, record high air temperatures were set from southern Labrador to the Gulf of Maine, including over the Scotian Shelf (Drinkwater *et al*., 2001b).

Near-surface salinity anomalies averaged over the Shelf showed a general decline through most of the 1990s reaching a minimum around 1998 (Fig. 8b). This minimum (approximately 0.5 fresher-than-normal) represented the lowest salinity recorded on the Scotian Shelf in the over 50-year time series. In following years salinities increased rapidly to return to near normal values by 2000. Similar low salinities in the 1990s were observed in the eastern Gulf of Maine (areas 24-28), consistent with the findings of Smith *et al*. (2001). The primary source of the low surface salinities on the Scotian Shelf is the outflow from the Gulf of St. Lawrence through Cabot Strait (McLellan, 1954). These in turn reflects the runoff from the St. Lawrence River system (Lauzier, 1957). Examination of the freshwater discharge from the St. Lawrence showed that the during the 1990s, the runoff was higher than the long-term (1961-90) mean but had decreased relative to the 1970s and 1980s, and thus cannot by itself explain the low salinities on the Scotian Shelf. Sea ice was above normal on the Scotian Shelf in the early-1990s but since 1995 has been at or near the lowest on record (Drinkwater *et al*., 2000). Smith *et al*. (2001) suggested that the salinity variability on the inner Shelf for the years 1994 to 1996 was due to advection of anomalies from upstream off Newfoundland. We examined the sea-surface salinity changes at Station 27, the long-term monitoring site off St. John's, Newfoundland, in the inner branch of the Labrador Current. It shows below normal salinities through most of the 1990s and reasonable correspondence with salinity fluctuations on the Scotian Shelf throughout the last half of the 1900s (Fig. 9). Approximately 42% of the variance in the annual salinity over the Shelf can be accounted for by changes in the upstream salinities off Newfoundland. Thus, it appears that the most likely source of the Scotian Shelf low salinity surface water in the 1990s was from off the Newfoundland Shelf.

The lower salinities and higher temperatures in the late 1990s have important implications on the vertical stratification. A stratification index was formed from the density (sigma-t) difference between 0 and 50 m. The density difference was calculated for each profile between the closest depths to 0 and 50 m, then normalized to a density difference over 50 m. Within each month of each calendar year for which there were data, a monthly mean density profile was estimated for each of the areas in Fig. 4. 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 anomalies within a calendar year. The annual means were then averaged spatially over the shelf using areas 4 through 23, inclusive (Fig. 4). The dominant feature is high stratification through the 1990s (Fig. 8c). 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 stratification began to increase steadily around 1990, reached a peak around 1997-1998 and declined slightly since then. The late-1990s values are the highest in the approximate 50-year records. There was strong similarity in the density gradients from area to area over the Scotian Shelf as evidenced by the relatively small error of the means (Fig. 8c). This consistency is surprising given the generally poor temporal resolution of the data upon which the annual area averages are based. This consistency gives further weight to the significance of the result. The higher-than-average stratification found on the Shelf did not extend into the Gulf of Maine region (not shown). Due to the more intense tidal mixing in the Gulf of Maine, one might expect the anomalies in density stratification to be much reduced compared to those on the Scotian Shelf. The trend in the density stratification matches closely the trend in surface salinity. Indeed, 65% of the variance in the stratification index was accounted by fluctuations in surface salinity. The dominance of the surface salinity in controlling the 0-50 m stratification index was further confirmed through comparing the changes in the hydrographic properties at the surface and 50 m separately. We also found that the local wind stress as measured on Sable Island was on average 15% below normal during from 1990 to 1995. This would contribute to increased stratification through reduced vertical mixing by the winds during these years.

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. Stratification can affect the extent of vertical mixing, the vertical structure of the wind forced ocean currents, 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. This led Frank *et al*. (1994) to speculate that increased stratification should lead to higher percentage of pelagic fish relative to demersal species. Indeed, during the 1990s, the ratio of pelagic to demersal fish biomass did increase and by the mid-1990s the ratio was the highest in over 25 years (Zwanenburg, *et al*., 2001).

Concluding Remarks

We have described several important ocean climate changes that occurred over the Scotian Shelf during the1990s. These have included record setting or near record setting cold conditions with different durations and forcing mechanisms in the northeast and coastal Nova Scotia compared to those in Emerald Basin and the southwestern shelf. Surface layer conditions also set near long-term record warm temperatures, low salinities and high stratification during the late-1990s. The cause of most of these changes was advection either along the shelf from the Gulf of St. Lawrence and off the Newfoundland Shelf or from offshore as in the case of the Labrador Slope Water intrusion. Local *in situ* forcing seems to play a minor role in controlling the major climate changes on the Scotian Shelf. Also the extent of the changes were often not limited to the Shelf but were part of ocean climate variability that encompassed other parts of the Northwest Atlantic continental shelves. Finally, at the beginning of the decade it appeared that the horizontal and vertical differences in the hydrographic trends over the Scotian Shelf were relatively small (Petrie and Drinkwater, 1993). This had suggested that a single station or area could be used as an index to capture much of the long-term hydrographic variability occurring over the Shelf. The past decade has seen much larger hydrographic differences vertically as well as horizontally in the deeper layers than in the past and emphasizes the importance of establishing several hydrographic indices in order to adequately capture the long-term trends in the hydrographic properties over the Shelf.

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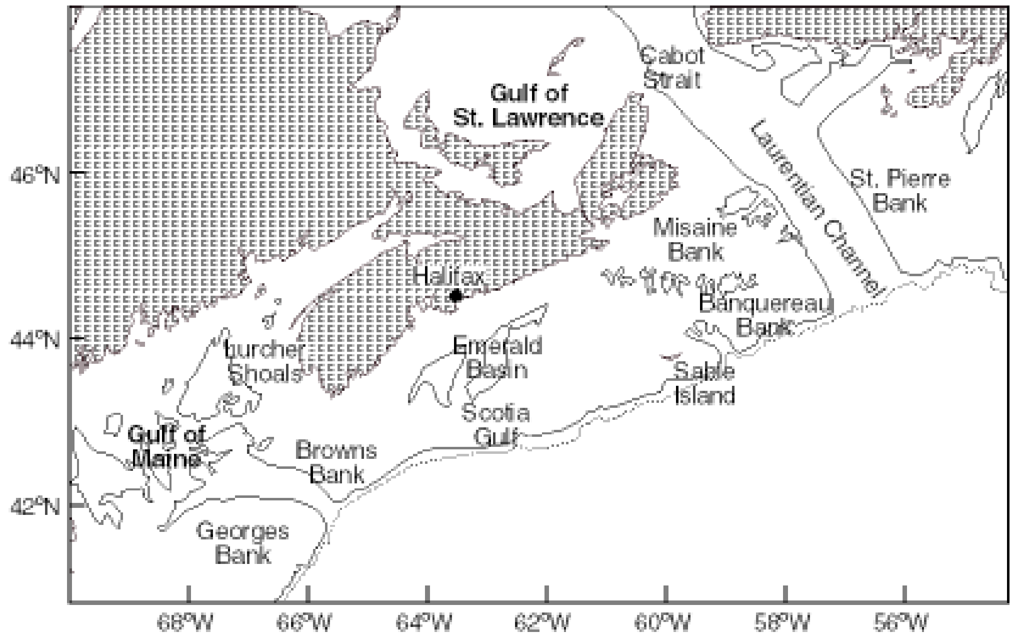

Fig. 1. Scotian Shelf showing locations and topographic features. The solid contour line is the 200 m isobath and the dashed line the 1000 m.

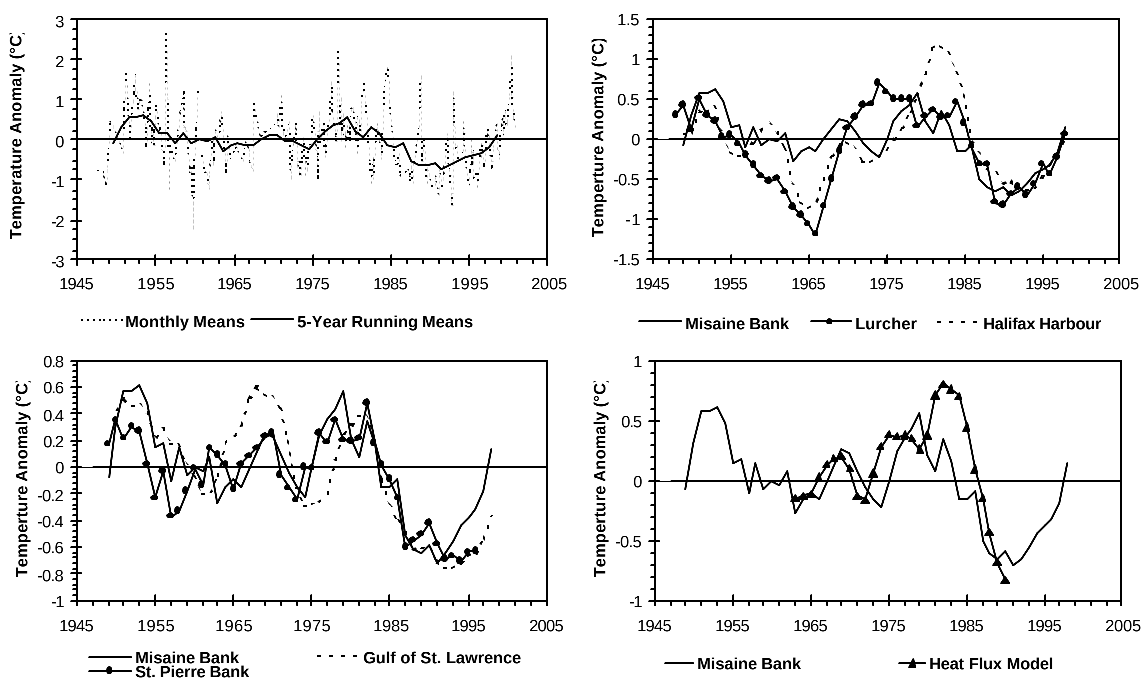

Fig. 2. The 5-year-running means of the temperatures at 100 m on Misaine Bank are plotted together with (a.) the monthly means on Misaine Bank, (b.) the 5-year running means of temperature at 75 m on Lurcher Shoals off southwest Nova Scotia and at the sea-surface in Halifax Harbour, (c.) the 5-year running means at 75 m on St. Pierre Bank off southern Newfoundland and of the CIL core temperature in the Gulf of St. Lawrence, and (d.) the 5-year running means at estimated temperature change based upon the annual heat flux anomalies for the northeastern Scotian Shelf.

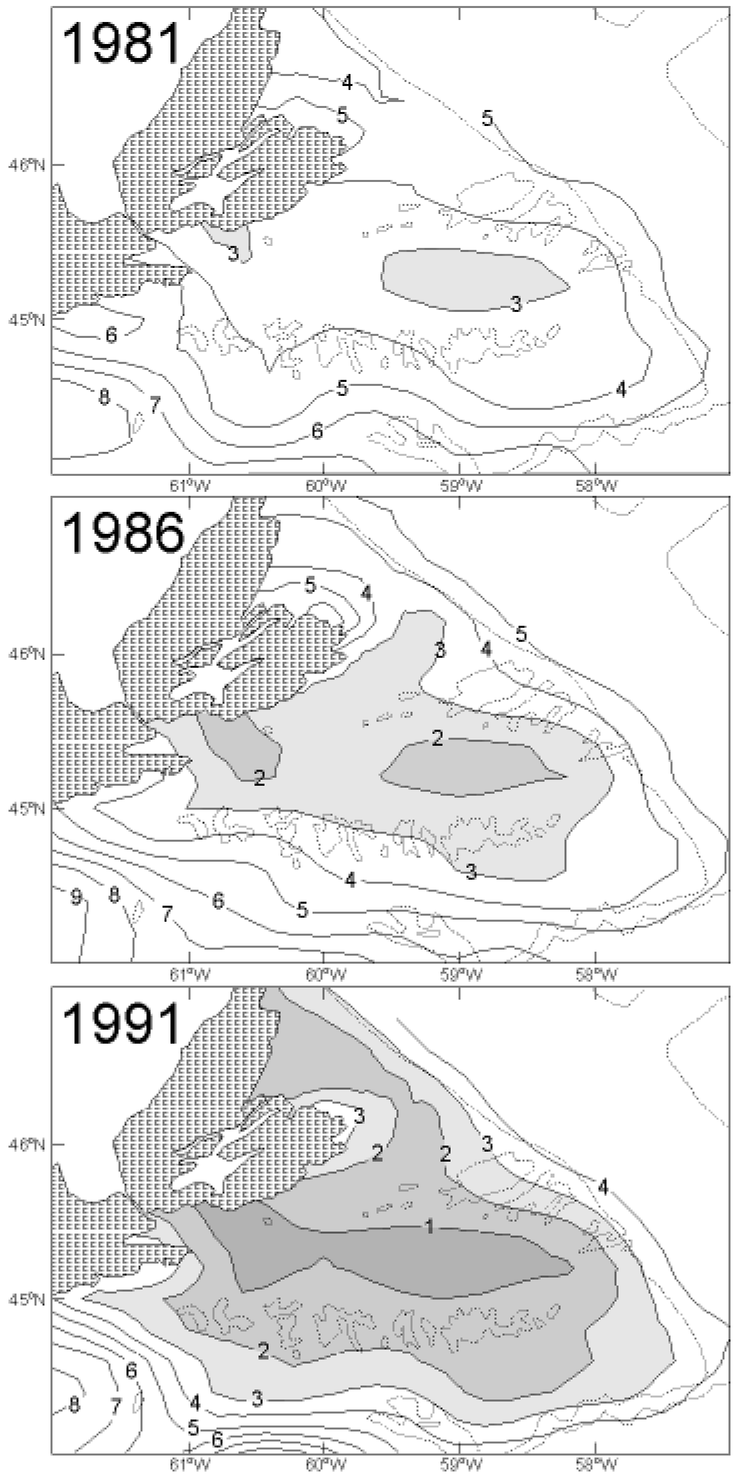

Fig. 3. The near-bottom temperatures during July in 1981, 1986 and 1991. The 200-m contour on the shelf and the 1000 m off the shelf are denoted by dashed lines. Temperatures <3ºC are shaded.

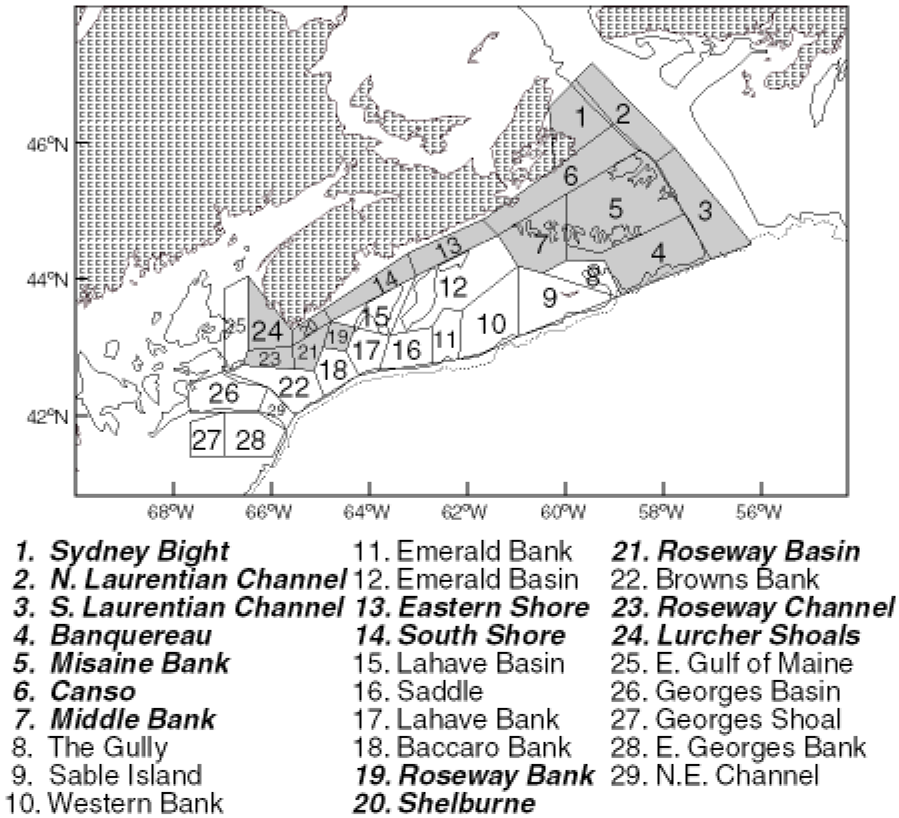

Fig. 4. Areas on the Scotian Shelf in which the monthly and annual mean temperatures were estimated. Shading (and bold italic notation) denotes areas that experienced the cold conditions during the mid- to late-1980s and through most of the 1990s.

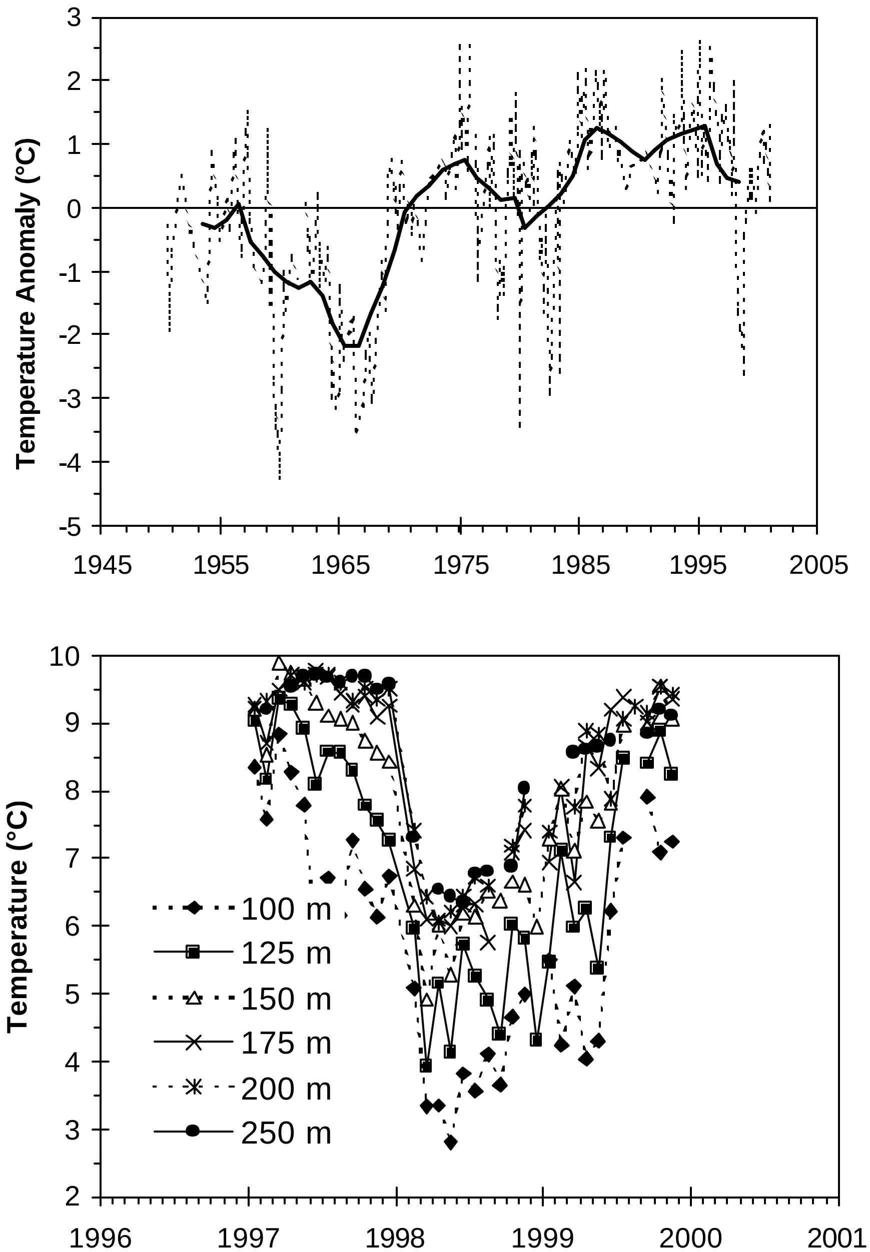

Fig. 5. Monthly (dashed line) and 5-year running means (solid line) of the temperature anomalies near-bottom (250 m) in Emerald Basin (top panel). The monthly temperatures from 100 to 250 m in Emerald Basin during 1997-2000.

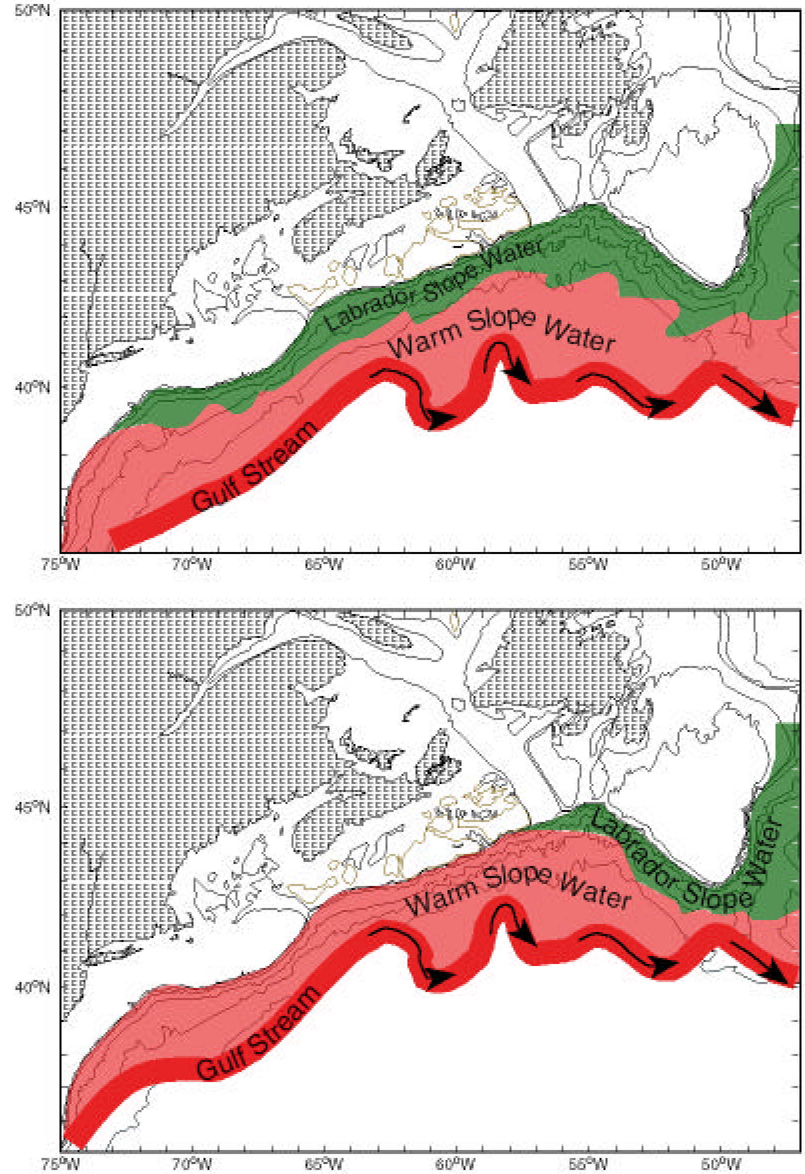

Fig. 6. The distribution of the offshore Labrador Slope Water at approximately 200 m during the maximum southward extension in 1998 (top panel) and its more typical distribution during most of the 1970s through the 1990s (bottom panel).

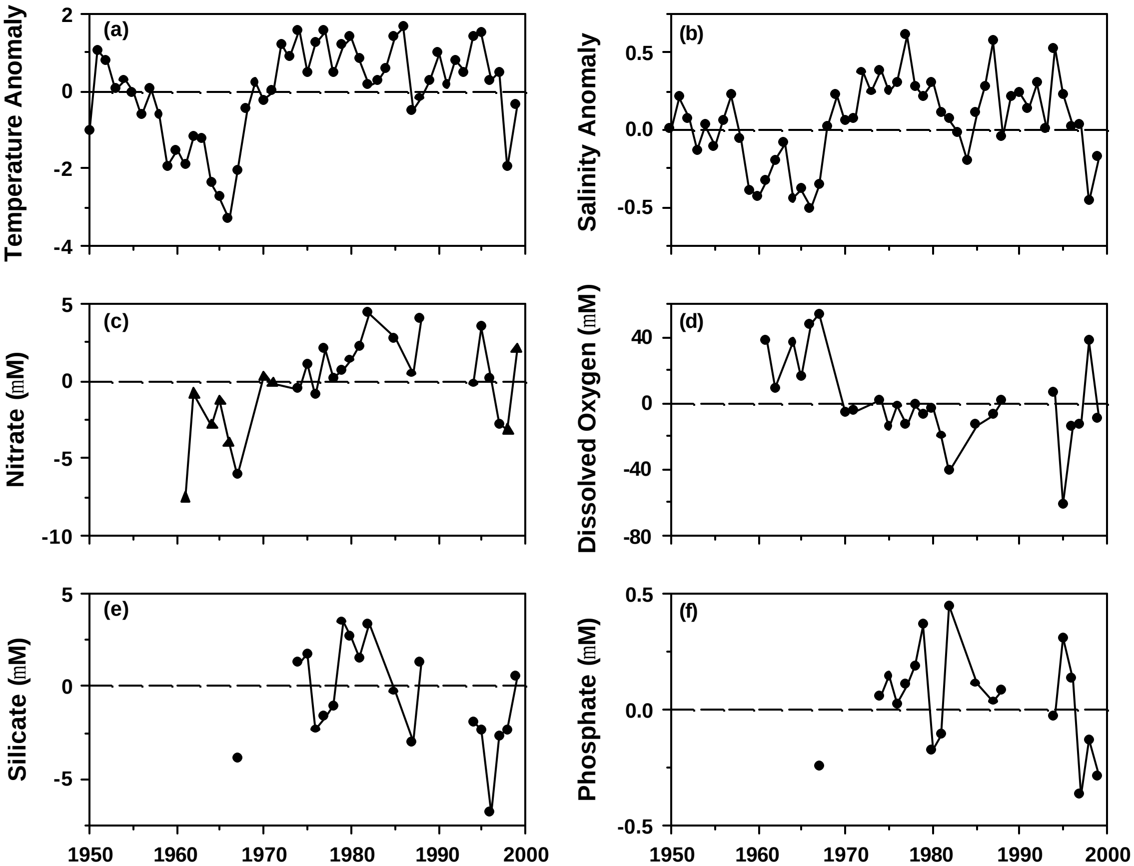

Fig. 7. Time series of the annual (a) temperature and (b) salinity anomalies (100-200 m), (c) nitrate, (d) dissolved oxygen, (e) silicate and (f) phosphate anomalies (depth ≥150 m) for the central Scotian Shelf. Nitrate values represented by a triangle in (c) have been computed from a regression with dissolved oxygen. Representative standard deviations of the monthly anomalies are 0.9°C (temperature), 0.2 (salinity), 1.9 µM (nitrate), 24 µM (oxygen), 2.4 µM (silicate) and 0.13 µM (phosphate).

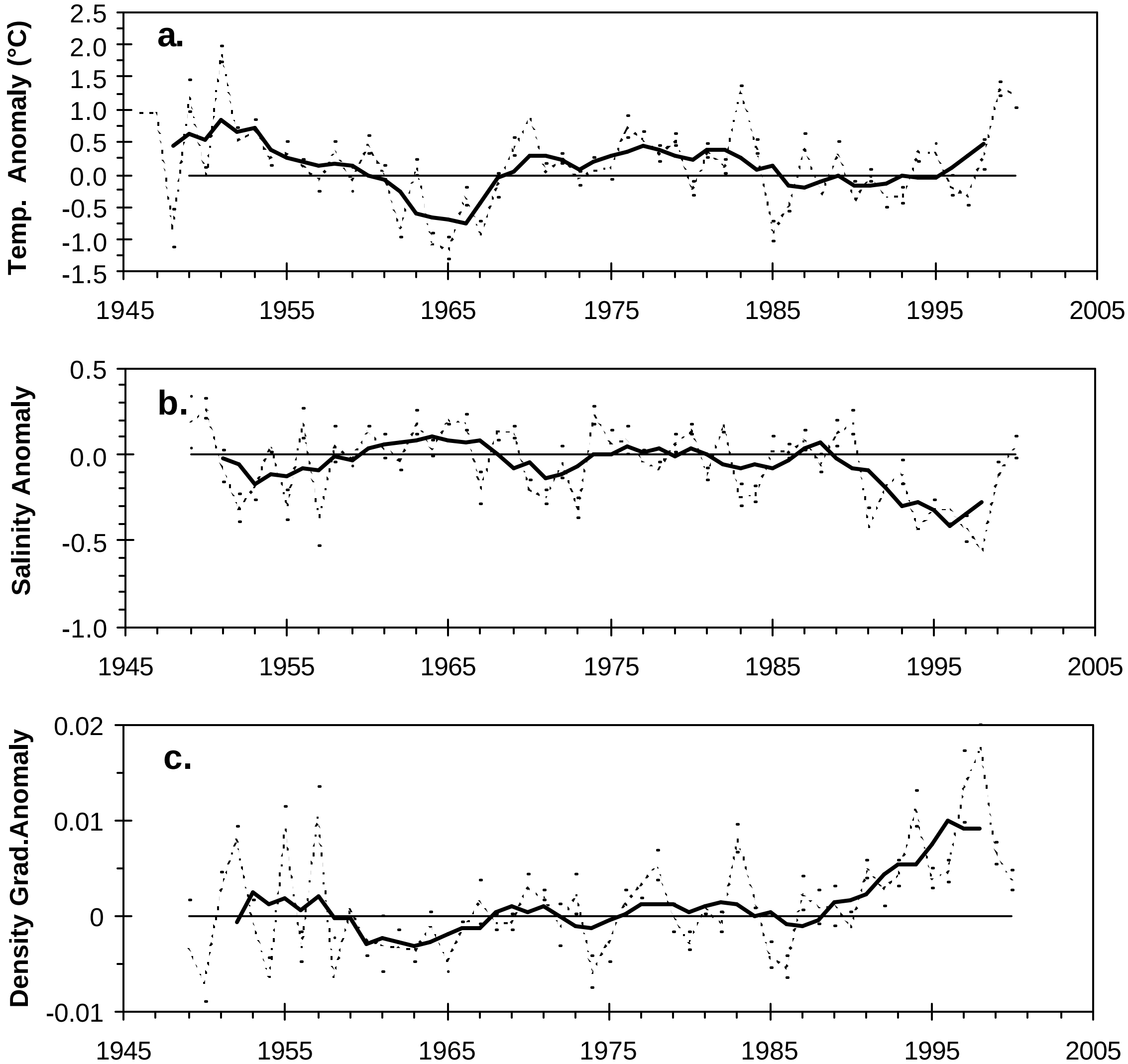

Fig. 8. The estimated annual (dashed line) and 5-year running means (solid line) of the (a) surface temperature, (b) surface salinity and (c) 0-50 m density gradient. All represent averages over the Scotian Shelf (areas 4 through 23 in Fig. 4). The horizontal tick marks denote the error of the means.

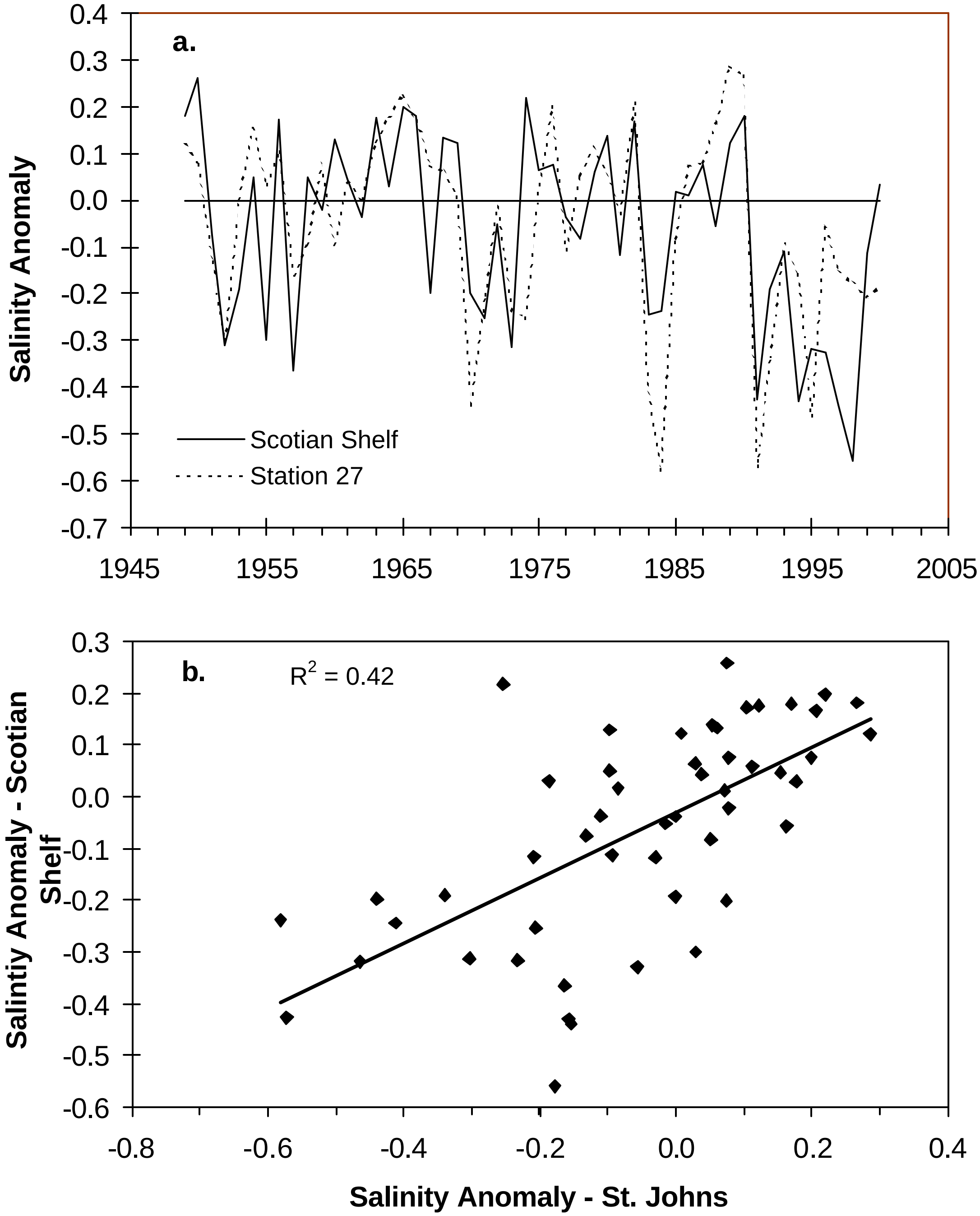

Fig. 9. The annual sea-surface salinity anomalies averaged over the Scotian Shelf and at Station 27 off St. John's, Newfoundland plotted as (a) time series and as (b) an XY plot. The linear regression line is also plotted in (b) along with the R^2 value.