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Climate variability on the Scotian Shelf during the 1990s

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The temperature and salinity conditions of the waters on the Scotian Shelf during the 1990s are described. Three major features are highlighted. First is the presence of cold subsurface waters throughout much of the 1990s in the northeast and nearshore regions of the Shelf. The principal cause of these cold conditions, initially established in the mid-1980s, is thought to be along-shelf advection from the Gulf of St Lawrence and off southern Newfoundland with the possibility of some contribution from local *in situ* cooling. The second major feature was caused by the arrival in 1997–1998 of cold Labrador Slope water along the shelf break, which subsequently flooded the lower layers of the central and southwestern regions of the Scotian Shelf. While this event produced the coldest near-bottom conditions in these Shelf regions since the 1960s it was of short duration, lasting only for approximately one year. Finally, the changes in the near-surface waters of the Scotian Shelf are described. Of particular relevance were the extremely warm surface temperatures in the late 1990s and the strong vertical stratification throughout the decade. The latter was a result of record low salinities in the near-surface waters that appear to be advected onto the Shelf from off the Grand Banks. The impact of these changes in ocean climate on some of the Shelf fish stocks is briefly discussed.

Keywords: advection, cooling, impacts, Labrador Slope Water, stratification.

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Introduction

The Scotian Shelf is located in the Northwest Atlantic off Nova Scotia, Canada (Figure 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 mean surface circulation is dominated by southwestward flow, much of which originates from the Gulf of St. Lawrence (Hachey *et al.*, 1954; Loder *et al.*, 1998). Anticyclonic circulation tends to occur over the banks and cyclonic circulation 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 in the Atlantic Ocean. In the southwest, high tidal currents associated with the Gulf of Maine–Bay of Fundy tidal system result in strong bottom-generated mixing and tidally modulated mean flows (Tee *et al.*, 1988).

In this article we highlight the three most significant hydrographic changes in the waters on the Scotian Shelf during the 1990s. These include: (1) the presence throughout the decade of colder-than-usual waters in the northeast and nearshore regions of the Atlantic coast, (2) the arrival of cold Labrador Slope Water at the shelf edge in 1997–1998 and its subsequent movement onto the Shelf, and (3) the variability in the surface water properties included increased vertical stratification throughout the decade. Before discussing these three features we provide some background information on the hydrographic properties and their seasonal and interannual variability in order to place the changes observed in the 1990s into perspective.

Temperature and salinity of the Scotian Shelf waters vary spatially due to complex bottom topography, advection from upstream sources such as the Gulf of St Lawrence and the Grand Bank of Newfoundland, melting of sea ice in spring, local ocean-atmosphere fluxes and exchange with the adjacent offshore slope waters. The seasonal temperature range at the surface in northeastern and central shelf regions is upwards of 16°C, one of the highest in the Atlantic Ocean (Weare, 1977;

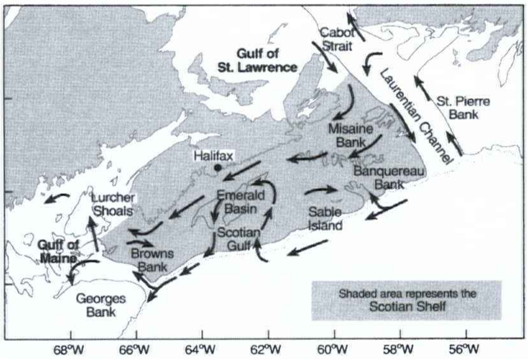


Figure 1. Scotian Shelf showing near-surface circulation and topographic features mentioned in the text. The solid line indicates the 200-m isobath and the dashed line 1000 m.

Yashayaev and Zveryaev, 2001). The range decreases almost exponentially with depth with near negligible changes at depths greater than ~150 m. Towards the southwest, the annual temperature range is more uniform with depth due to increased vertical mixing by the tidal currents. This results in a smaller temperature range at the surface and larger at depth, relative to elsewhere on the Shelf.

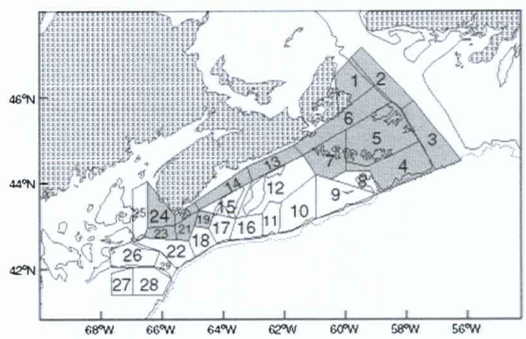
In the winter, the water column in the deep regions of the Scotian Shelf consists of two layers. The upper layer, which extents to 100 m and deeper, is mixed by the winter winds and contains cold, low salinity water. The bottom layer is relatively warm and salty, originating from the offshore "slope waters", and enters the Shelf through deep channels and gullies. In summer, the remnant winter-cooled waters are sandwiched between the solar-heated warm upper layer (30–40 m deep) and the warmer bottom waters. The former, referred to as the cold intermediate layer (CIL), occupies depths from approximately 40 to 150 m. Spatial variation in this vertical structure occurs over the shelf, however. The warm offshore waters cannot penetrate far onto the northeastern Scotian Shelf due to topographic restrictions; therefore the CIL (temperatures <5°C) generally extends to the bottom throughout the year in this area. In areas of strong tidal currents, such as off southwest Nova Scotia, the waters even in summer are relatively well-mixed and no CIL is present.

Horizontally over the Shelf, temperatures and salinities generally increase from northeast to southwest due to the decreasing influence of the Gulf of St Lawrence waters and from inshore to offshore due to mixing with the warmer, more saline offshore waters. For example, in the summer the 50-m temperatures typically range from 0°C to 3°C over the eastern Scotian Shelf, 3°C to 8°C over much of the central shelf and 6°C to 9°C over the western Scotian Shelf, eastern Gulf of Maine, and Bay of Fundy. The near-bottom temperatures display similar ranges to those at 50 m, except over the central shelf where the range increases to 4°C to >10°C, the slightly higher range being caused by the intrusion of the offshore slope waters. The one exception to the general trend in horizontal distributions is the surface temperature in summer, which decreases from northeast to southwest, due to the very warm (typically >16°C) surface outflow from the Gulf of St Lawrence.

Year-to-year, water temperatures on the Scotian Shelf and in the Gulf of Maine are among the most variable in the North Atlantic Ocean (Weare, 1977). Petrie and Drinkwater (1993), in an examination of hydrographic variability, found similar long-period temperature trends over much of the Scotian Shelf. Temperatures were near or above average in the 1950s, declined to below average in the 1960s, rose rapidly in the late 1960s and from the 1970s to 1990 generally were warmer-than-average. Periods of warm temperatures were generally associated with high salinities and cool temperatures with lower salinities.

Data and methods

Much of the temperature, salinity, and density data in this study were derived from an historical hydrographic database held at the Bedford Institute of Oceanography (Petrie *et al.*, 1996). Monthly and annual means of temperature, salinity, and density (sigma-t) and their anomalies were calculated by spatially averaging within areas selected on the basis of topography or oceanography (Figure 2). These



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;

Figure 2. 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.

areas are those used by Petrie *et al.* (1996). The data were averaged within the areas by month for each year, regardless of the number of stations per month. These monthly means were averaged for the years 1961–1990 to obtain monthly normals. The normals were then subtracted from the monthly means to obtain monthly anomalies, although we note that there are not data in all months. The available monthly anomalies within a calendar year were then averaged to obtain an annual anomaly. High month-to-month variability is evident, which might reflect real temporal changes but also might be due to bias. This can arise due to either poor temporal coverage (e.g. a single measurement in a month) or poor spatial coverage (e.g. a single location within an area that contains horizontal temperature gradients). While individual values for a month or even a year may not represent true average conditions, the longer-term trends are considered real based on observed similarities between areas.

An index of vertical stratification was formed from the density (sigma-t) difference between the closest depths to 0 and 50 m and normalized to a density difference over 50 m. Monthly mean density profiles were estimated by averaging the available normalized density differences within each area in Figure 2 for each calendar year for which there were data. The long-term monthly mean density gradients for the years 1961–1990 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.

Annual anomalies of sea surface temperature, salinity, and density stratification over the entire Scotian Shelf were derived by averaging the annual anomalies for areas 4–23 in Figure 2.

Persistent presence of cold subsurface waters

One of the primary features of the water properties on the Scotian Shelf in the 1990s was the persistence of very cold conditions in the subsurface waters (deeper than 30–50 m) in the northeast. This is reflected in the 100-m temperature anomalies from Misaine Bank (Figure 3A). The cold waters 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 period of decreasing temperatures coincided with an expansion of the area of the bottom covered by waters with temperatures <2°C (Figure 4). Throughout the 1990s, the subsurface temperatures in this region generally remained colder-than-normal. These cold temperatures were typically accompanied by lower-than-normal salinities.

These conditions were not limited to the northeastern Shelf, but also appeared along the Atlantic coast of Nova Scotia through to Lurcher Shoals (Figure 3B). The latter are believed to be due to advection and are consistent with direct current observations and numerical models of the circulation that show water from the northeast Shelf tends to be squeezed inshore as it flows southwestward along the Atlantic coast of Nova Scotia (Han *et al.*, 1997) and eventually into the Gulf of Maine (Smith, 1983; Smith *et al.*, 2001). The presence of the cold anomalies in the surface waters at Halifax (Figure 3B) is due in part to the consistent upwelling in summer along the coast (Petrie *et al.*, 1987) and deep mixing in the winter. Both of these processes would act to bring the cold subsurface waters into the surface mixed layer. The cold anomalies during the late 1980s and into the 1990s were traced "downstream" past Lurcher Shoals through to the Maine coast but disappeared further south in the Gulf of Maine. On the Scotian Shelf, these colder waters were not observed in the outer half of the Shelf from Sable Island to Browns Bank. This is consistent with the central shelf region being dominated more by offshore waters. In the upper layers, part of the current along the shelf break flows onto the shelf at the southern end of Western Bank and contributes to the cyclonic flow around Emerald Basin (Figure 1; see also Sheng and Thompson, 1996; Han *et al.*, 1997) and, in the deep waters, the offshore slope waters penetrate onto the Shelf through the Scotian 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 could be due to advection from more northern areas or *in situ* cooling or a combination of both processes. 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, 1999) mirror those on the northeastern Scotian Shelf including a shift from relatively high temperatures in the early to mid-1980s to low temperatures in the late 1980s and into the 1990s (Figure 3C). The amplitude of the temperature anomalies was similar in all three regions. The waters on the Scotian Shelf appear to warm up earlier and more quickly than in the more northerly regions, perhaps suggesting that the along-shelf advection might have gradually diminished in strength through the late-1990s.

The other possible cause was *in situ* cooling. To explore this possibility, we examined the monthly and annual mean heat fluxes estimated from the COADS (Comprehensive Ocean and Atmospheric

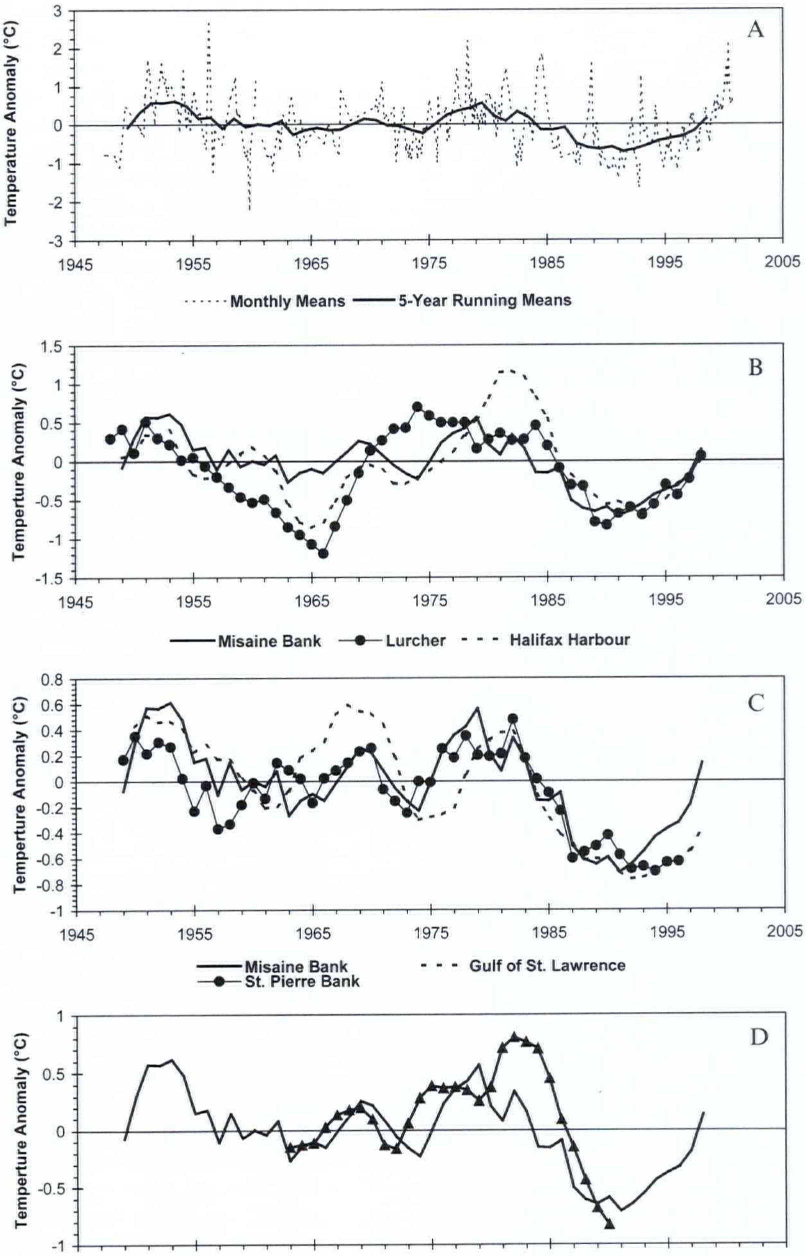


Figure 3. The 5-year-running means of the annual temperature anomalies at 100 m on Misaine Bank together with: (A) the monthly means of Misaine Bank temperature anomalies, (B) the 5-year running means of temperature anomalies at 75 m on Lurcher Shoals off southwest Nova Scotia and at 0 m in Halifax Harbour, (C) the 5-year running means of temperature anomalies 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 anomalies based on an annual heat flux model for the northeastern Scotian Shelf.

Data Sets) between 1960 and 1993 for the 2° × 2° latitude–longitude area centred over the northeastern Scotian Shelf. These show negative heat flux anomalies from 1986 through to the end of the available record, suggestive of colder-than-normal temperatures. Assuming that these annual heat flux anomalies are distributed over the top 200 m and do not accumulate (i.e. the water leaves the area within a year), the temperature change can be estimated from

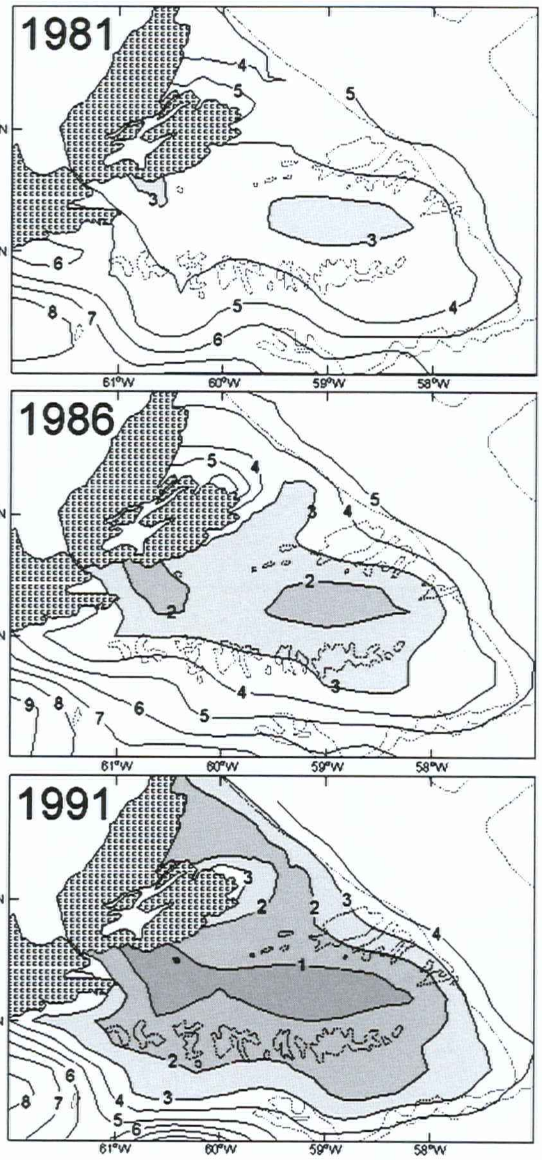


Figure 4. The near-bottom temperatures during July in 1981, 1986, and 1991. The 200-m contour on the shelf and the 1000 m off the shelf are denoted by dashed lines. Temperatures <3°C are shaded.

$$\Delta T = \frac{Q\Delta t}{\rho C_p z}$$

where ΔT is the temperature change produced by a heat flux anomaly Q during the time Δt over a water column of depth z. ρ is the density of the water and C_p is its heat capacity. Δt was taken to be 1 year, ρ 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 show a similar pattern to that of the observed temperature anomalies at Misaine Bank (Figure 3D). This simple heat flux model accounts for just under 50% of the variance in the observed anomalies in the overlapping years. However, there are several reasons for questioning this result. First, the heat flux model estimates lag the observed temperature anomalies by around 2 years. Second, the assumptions upon which the model estimates were made, such as constant mixing to 200 m and treating each year independently, are incorrect. Third, the temperature changes were accompanied by observed salinity fluctuations, which suggests changes in the component water masses, not just the heat content. Finally, temperatures in the upper 50 m show a different trend to that of 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. Based on all the available information, we conclude that the primary source of the cold, fresh conditions in the subsurface waters on the northeastern Scotian Shelf was most likely advection from the Gulf of St Lawrence and/or the southern Newfoundland Shelf, but that local *in situ* atmospheric cooling may have contributed to the persistent cold waters on the northeastern Scotian Shelf.

Slope water intrusion 1997–1998

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 Grand Bank 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 4°C to 8°C and salinities 34.3 to 35 and Warm Slope Water with temperatures typically 8°C to 12°C and salinities 34.7 to 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 Bank (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 penetrates much farther south than the Laurentian Channel. During these times, Warm

Slope Water dominates the shelf edge off the Scotian Shelf. The slope waters are important to the Shelf since they penetrate onto the Shelf through gullies and channels to occupy the deep basins and the deep layers of the central and southwestern areas of the Scotian Shelf. The exchange between the offshore and shelf waters is forced by a combination of horizontal density gradients, warm-core Gulf Stream rings, and meteorological events. During the 1990s, at least until 1997, 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 (Figure 5A).

In the autumn of 1997, the Labrador Slope water moved southward along the edge of the Scotian Shelf reaching the Gulf of Maine in January of 1998 and off the Middle Atlantic Bight by the spring of 1998 (Figure 6). Drinkwater *et al.* (2002) provided details of the timing of this water mass as it flowed south, as well as its subsequent movement onto the Scotian Shelf and into the Gulf of Maine. Although the Labrador Slope Water was first detected in the offshore waters adjacent to the central Scotian Shelf in October, it did not begin to penetrate into the deep reaches of Emerald Basin until December 1997. By February 1998 the lower layers of Emerald Basin were completely flushed. Temperatures dropped by over 4°C (Figure 5B) and salinities by approximately 1 during this event. By July 1998, waters with Labrador Slope Water characteristics covered most of the ocean bottom on the southwestern Shelf and temperatures were the lowest recorded in over 30 years. These waters were not restricted to the Scotian Shelf but also penetrated into the Gulf of Maine (Drinkwater *et al.*, 2002). The Labrador Slope Water along the edge of the Scotian Shelf began to retract during the summer of 1998 and late that year was confined to the Laurentian Channel area and north, having been replaced by the Warm Slope Water all along the Scotian Shelf. The Labrador Slope Water on the shelf also gradually disappeared through 1998 (Figure 5B).

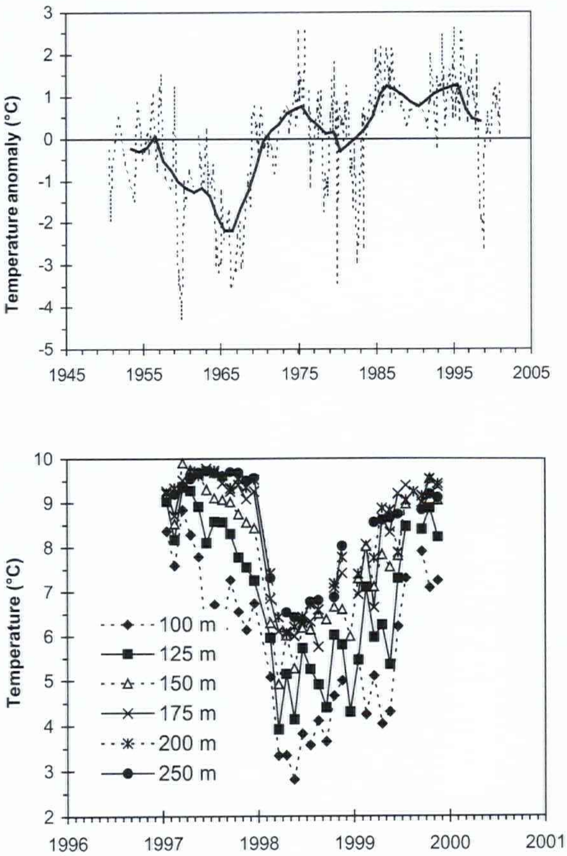


Figure 5. Monthly (dashed line) and 5-year running means (solid line) of the temperature anomalies near-bottom (250 m) in Emerald Basin (top panel). The monthly temperatures from 100 to 250 m in Emerald Basin during 1997–1999 (lower panel).

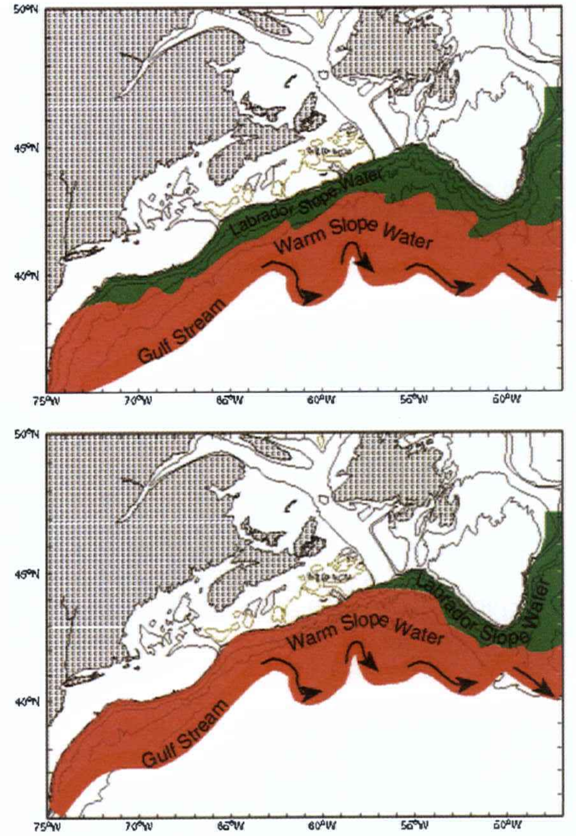


Figure 6. A schematic diagram of the distribution of the offshore Labrador Slope Water at approximately 200 m during the maximum southward extension in 1998 (top panel) and its more typical distribution during the past 30 years (bottom panel).

The southward extension of the Labrador Slope Water is believed to be due to an increased volume transport of the deep Labrador Current (Petrie and Drinkwater, 1993). This in turn is 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.*, 2002). Increased transport coincides with a weakened Icelandic Low (low NAO index). 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. There was also increased geostrophic transport on the Newfoundland Shelf during several years of the mid-1990s (Colbourne, 2000). Drinkwater *et al.* (2002) suggest that this decline in the NAO and the increased geostrophic transport in the Labrador Current eventually led to the southward movement of the Labrador Slope Water through to the Middle Atlantic Bight in 1997–1998. However, 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 of the order of 20 months, whereas during the 1958 event Worthington (1964) found a delay of only 8 months. The cause of the longer delay in 1997–1998 is unclear, although only 10 months after the low wintertime NAO index of 1996 cold water was observed upstream off St Pierre Bank at 50 m in January 1997 and 2–3 months later at 150 m (unpublished current meter data, P. C. Smith). The 5–7 month delay from St Pierre Bank to Banquereau Bank is unexplained.

Variability in the near-surface layer

During the 1950s to the 1990s, the temperature trends throughout the water column on the Scotian Shelf were generally similar and dominated by the warm 1950s, the cold 1960s, and the above normal temperatures in the 1970s and 1980s (Petrie and Drinkwater, 1993). In the 1990s, there were greater differences between the near-surface trends in the hydrographic properties and those elsewhere in the water column. There were three significant features of the surface layers in the 1990s.

The first relates to the surface layer temperatures. Following a decrease through the 1980s, temperature anomalies averaged over the Scotian Shelf were below normal in the early-1990s, rose slightly in the mid-1990s, then fell again before rising rapidly to near maximum values (approximately 1.3°C) over the 50-year record in the last years of the decade (Figure 7A). The ocean temperatures mirror air temperatures in the region with approximately 50%

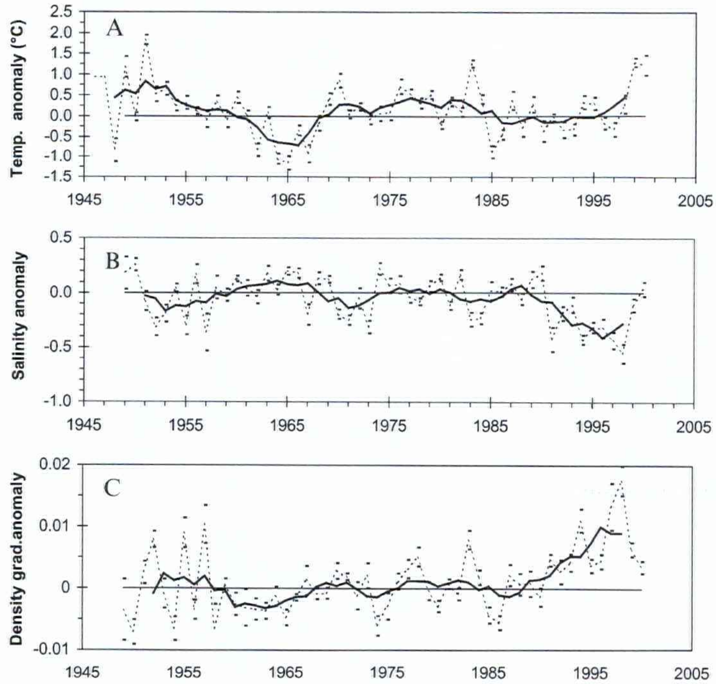


Figure 7. The estimated annual (dashed line) and 5-year running averages (solid line) of the anomalies (relative to their 1971–2000 means) of (A) surface temperature, (B) surface salinity, and (C) 0–50 m density gradient. All plots represent averages over the Scotian Shelf (areas 4–23 in Figure 2). The horizontal tick marks on the annual values denote the error of the mean.

of the variance in sea surface temperatures accounted for by air temperatures. Consistent with this, the high sea surface temperatures in the late 1990s coincided with high air temperatures. Indeed, historic highs of the annual air temperature in over 100 years of records were set in 1999 throughout the region from southern Labrador to the Gulf of Maine, including over the Scotian Shelf (Drinkwater *et al.*, 2000).

The second significant change was in the near-surface salinity anomalies averaged over the Shelf. They showed a general decline through most of the 1990s reaching a minimum in 1998 (Figure 7B). 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 1999, salinities increased rapidly and returned to near normal values by 2000. Similar lower-than-normal salinities in the 1990s were observed in the eastern Gulf of Maine (areas 24–28; Figure 2), consistent with the findings of Smith *et al.* (2001). The primary source of the low surface salinities on the Scotian Shelf has generally been considered to be the outflow from the Gulf of St Lawrence through Cabot Strait (McLellan, 1954; Sutcliffe *et al.*, 1976). The Gulf of St Lawrence salinities in turn reflect the run-off from the St Lawrence River system (Lauzier, 1957). The freshwater discharge from the St Lawrence during the 1990s was higher than the long-term (1961–1990) mean but decreased relative to the 1970s and 1980s, and thus it cannot 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 (consistent with the results of Colbourne, 2001) and reasonable correspondence with salinity fluctuations on the Scotian Shelf throughout the last half of the 1900s (Figure 8). Approximately 42% of the variance in the annual salinity over the Scotian Shelf can be accounted for by changes in the upstream salinities off Newfoundland. Thus, the most likely source of the Scotian Shelf low salinity surface water in the 1990s is from off the Newfoundland Shelf.

The third significant feature of the near-surface layer in the 1990s was a change in stratification. Monthly and annual means of the stratification index show high variability but the 5-year running means show distinctive trends. The dominant feature over the Scotian Shelf is higher stratification during the 1990s (Figure 7C). The stratification

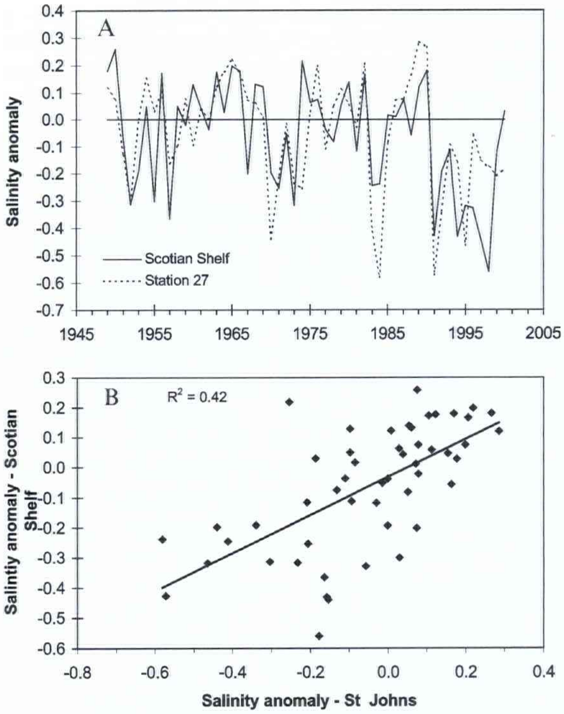


Figure 8. The annual sea-surface salinity anomalies averaged over the Scotian Shelf (areas 4–23 in Figure 2) and at Station 27 off St John's, Newfoundland, plotted as (A) time series and (B) an XY plot. The linear regression line is also plotted in (B) along with the R^2 value.

index began to increase steadily after 1990, reaching a peak around 1997–1998 and declining slightly after that. The late-1990 anomalies are, or are near to, the highest values in the approximate 50-year record. The principal cause of this increased stratification was the decrease in surface salinities (Figure 7B). The increased stratification was observed in all regions of the Scotian Shelf but did not extend into the Gulf of Maine region. This lack of signal might be due to the more intense tidal mixing in the Gulf of Maine.

Biological consequences

All three of the major ocean climate features that occurred in the 1990s on the Scotian Shelf and that were discussed above had measurable influences on the local biology. The presence of the cold water on the northeastern Scotian Shelf in the late 1980s and 1990s is believed to have led to an expansion of the distribution of cold-water species such as capelin (*Mallotus villosus*), Greenland halibut (*Reinhardtius hippoglossoides*), shrimp (*Pandalus borealis*), and snow crab (*Chionoecetes opilio*) (Frank *et al.*, 1996; Tremblay, 1997; Drinkwater, 1999; Zwanenburg *et al.*, 2002), and contributed to lower growth rates of Atlantic haddock (*Melanogrammus aeglefinus*) (Drinkwater *et al.*, 2000) and most demersals (Zwanenburg *et al.*, 2002). It also coincided with low abundance of Atlantic cod (*Gadus morhua*), but it is not clear to what extent the decline in cod in the northeastern Scotian Shelf was due to over-fishing or other possible factors (Zwanenburg *et al.*, 2002).

Although relatively short-lived, the penetration of the cold Labrador Slope Water onto the shelf in 1998 is known to have affected the catchability of certain fisheries on the Scotian Shelf and on Georges Bank (Drinkwater *et al.*, 2002). They noted, for example, that catches of porbeagle shark (*Lamna nasus*) and silver hake (*Merluccius bilinearis*) declined dramatically in the Emerald Basin in early 1998, shortly after the cold Labrador Slope Water replaced the Warm Slope Water. Also, fishermen on Georges Bank noted declines in their catches of lobster (*Homarus americanus*) that they attributed to the presence of cold water. Cold water has been shown to limit the activity of the lobsters and hence their likelihood of encountering a lobster trap (McLeese and Wilder, 1958).

Stratification of the upper water column is an important characteristic that influences both physical and biological processes. Stratification can affect the extent of vertical mixing, the vertical structure of the wind forcing, the timing of the spring bloom, vertical nutrient fluxes, and plankton speciation to mention just a few. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper, lower layers. This general tendency led Frank *et al.* (1990) to speculate that increased stratification should lead to a 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.*, 2002; Frank and Drinkwater, 2002).

Conclusions

We have described three important ocean climate changes that occurred on the Scotian Shelf during the1990s, mainly associated with advective processes. These have included record setting or near record-setting conditions over the past 30 to 50 years. The first was an extended period of cold temperatures in the northeast region of the Shelf and along the Atlantic coast of Nova Scotia. This is believed to be due to along-shelf advection of cold waters from the Gulf of St Lawrence and southern Newfoundland, with the possibility of some contribution by local *in situ* atmospheric cooling. The second event, in 1998, occurred in the deep, near-bottom waters in Emerald Basin and the southwestern shelf. These waters, which originate offshore and then penetrate onto the Shelf, cooled dramatically due to the unusual appearance of cold, low saline Labrador Slope Water along the shelf edge, which replaced the high saline, Warm Slope Water. Finally, long-term records for warm temperatures, low salinities, and high stratification were set in the near-surface waters during the late 1990s. While the high sea surface temperatures most likely resulted from local atmospheric heat exchanges, the primary mechanism of the salinity changes and subsequent stratification appears to be through advection from off Newfoundland.

It is worth noting that 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 spatial variability in the anomalies of the hydrographic properties than in the past, both vertically and horizontally, and indicates that several hydrographic indices will be required in order to capture the long-term trends over the Scotian Shelf.

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