J. Northw. Atl. Fish. Sci., Vol. 34: 83–99

Publication (Upload) date: 24 September 2004

Hydrographic Variability in the Waters of the Gulf of St. Lawrence, the Scotian Shelf and the Eastern Gulf of Maine (NAFO Subarea 4) During 1991–2000

Kenneth F. Drinkwater[1]
Fisheries and Oceans Canada, Bedford Institute of Oceanography
P. O. Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2

Denis Gilbert
Fisheries and Oceans Canada, Institut Maurice Lamontagne
C.P. 1000, Mont Joli, Quebec, Canada G5H 3Z4

Drinkwater, K., and D. Gilbert. 2004. Hydrographic Variability in the Waters of the Gulf of St. Lawrence, the Scotian Shelf and the Eastern Gulf of Maine (NAFO Subarea 4) During 1991–2000. 2004. *J. Northw. Atl. Fish. Sci.*, **34**: 85-101. doi:10.2960/J.v34.m545

Abstract

This paper examines the hydrographic variability within the Gulf of St. Lawrence, the Scotian Shelf and the eastern Gulf of Maine, including the Bay of Fundy, during the decade 1991–2000. Comparisons are made with previous decadal means to place the 1990s into a longer-term perspective. The 1990s decadal means of the near-surface salinity were the lowest ever recorded for the northern Gulf of St. Lawrence, the Scotian Shelf and the Bay of Fundy. These low salinities were advected into these regions from the Labrador and Newfoundland Shelves and led to record or near record high vertical stratification in the upper layers of the water column. Also during the 1990s, the decadal means of the temperature of the intermediate layer waters (approximately 30–150 m) were well below normal throughout the Gulf of St. Lawrence and over much of the Scotian Shelf. Similar low temperatures were first observed in the late 1980s and were mainly caused by advection from the Labrador and Newfoundland Shelves, although local atmospheric cooling also contributed. In the deep channels and basins of NAFO Subarea 4, near-bottom decadal mean temperatures were high and linked to the persistence of Warm Slope Water along the shelf break. A notable exception occurred in 1998 when Labrador Slope Water moved southward along the continental slope as far as the Middle Atlantic Bight, pushing the Warm Slope Water offshore. This much colder water subsequently penetrated onto the Scotian Shelf and into the Gulf of Maine resulting in the coldest conditions in the deep basins since the 1960s.

Keywords: decadal variability, oceanography, salinity, stratification, temperature

Introduction

NAFO Subarea 4 encompasses the Gulf of St. Lawrence, the Scotian Shelf and the eastern Gulf of Maine, including the Bay of Fundy (Fig. 1). These regions are quite diverse with the primary forcing functions of oceanographic variability differing by region. The Gulf of St. Lawrence receives large quantities of freshwater from the St. Lawrence River system (Sutcliffe *et al.*, 1976; Koutitonsky and Bugden, 1991). The Gulf of St. Lawrence and the northeastern region of the Scotian Shelf are usually ice covered in winter, the latter region representing the southernmost limit of sea-ice in the Atlantic Ocean. Tides are a dominant force in the Gulf of Maine and Bay of Fundy causing intense vertical mixing through bottom generated turbulence by the strong tidal currents (Garrett *et al.*, 1978). Onshore flow of Slope Waters onto the shelf is a major cause of the observed variability in the deep basins of the Scotian Shelf and the Gulf of Maine (Petrie and Drinkwater, 1993). In addition, advection of waters from Labrador and the northeastern Newfoundland shelf is very important, both for the Gulf of St. Lawrence, through the Strait of Belle Isle and Cabot Strait (Banks, 1966; Petrie *et al.*, 1988; Koutitonsky and Bugden, 1991; Han *et al.*, 1999), and for the Scotian Shelf (Han *et al.*, 1999; Drinkwater *et al.*, 2003) through to the Gulf of Maine (Smith *et al.*, 2001). While local *in situ* heating and cooling also contribute to changes in the heat content of the upper layer of the water column, they do not control the long-term trends in temperature, at least not on the Scotian Shelf (Umoh and Thompson, 1994; Battisti *et al.*, 1995). Indeed, the only region of the North Atlantic

[1] *Present Address*: Institute of Marine Research, P. O. Box 1870 Nordnes, N-5817 Bergen, Norway.

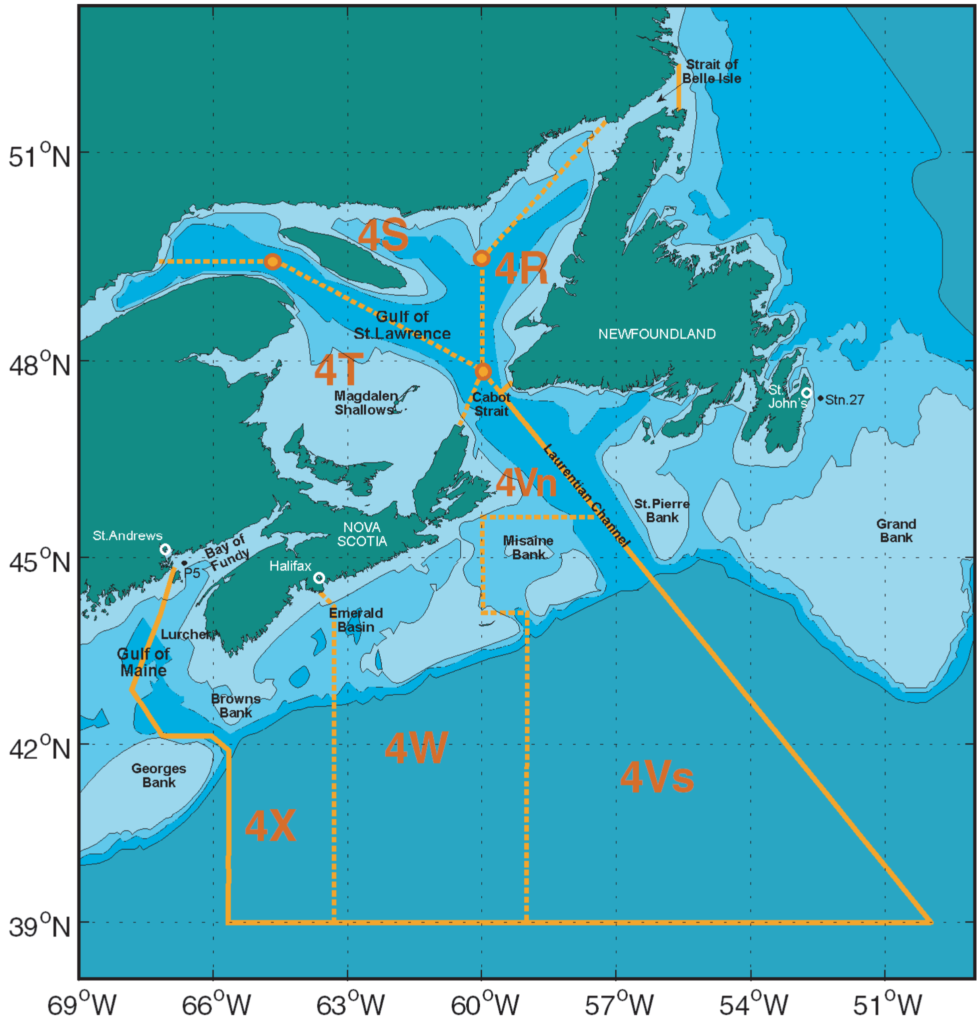

Fig. 1. NAFO Subarea 4 showing topographic features. The contours from lightest to darkest blue represent <100 m, 100–200 m, 200–1 000 m and >1 000 m, respectively.

where long-term sea surface temperature variability is not controlled by local atmospheric fluxes includes the Scotian Shelf, the Gulf of Maine and the Middle Atlantic Bight (Battisti *et al.*, 1995).

The mean circulation within NAFO Subarea 4 is principally southward with cyclonic flow through the Gulfs of St. Lawrence and Maine and the Bay of Fundy (Fig. 2). Generally, anticyclonic movement occurs over the banks with cyclonic flow around the basins of the Scotian Shelf (Sheng and Thompson, 1996; Han *et al.*, 1997).

The hydrographic properties within Subarea 4 vary spatially due to complex bottom topography, atmospheric fluxes, varying river runoff, transport from upstream sources, melting of sea-ice in spring, and exchange with the adjacent offshore slope waters. Water properties in the Gulf of St. Lawrence and northeastern Scotian Shelf are characterized by large seasonal cycles plus strong gradients in the vertical and horizontally (both along- and across-shelf). In contrast, the seasonal cycles and vertical gradients are weak in the Gulf of Maine and Bay of Fundy as a result of intense tidal mixing.

The seasonal changes in water temperature decrease with depth throughout Subarea 4. At the surface in the southern Gulf of St. Lawrence and the northeastern Scotian Shelf, the range is near 16°C, one of the widest in the Atlantic Ocean (Weare, 1977; Yashayaev and Zveryaev, 2001). The temperature range rapidly declines with depth with little or no seasonal change at depths greater than approximately 100 to 150 m. Towards the Gulf of Maine, the

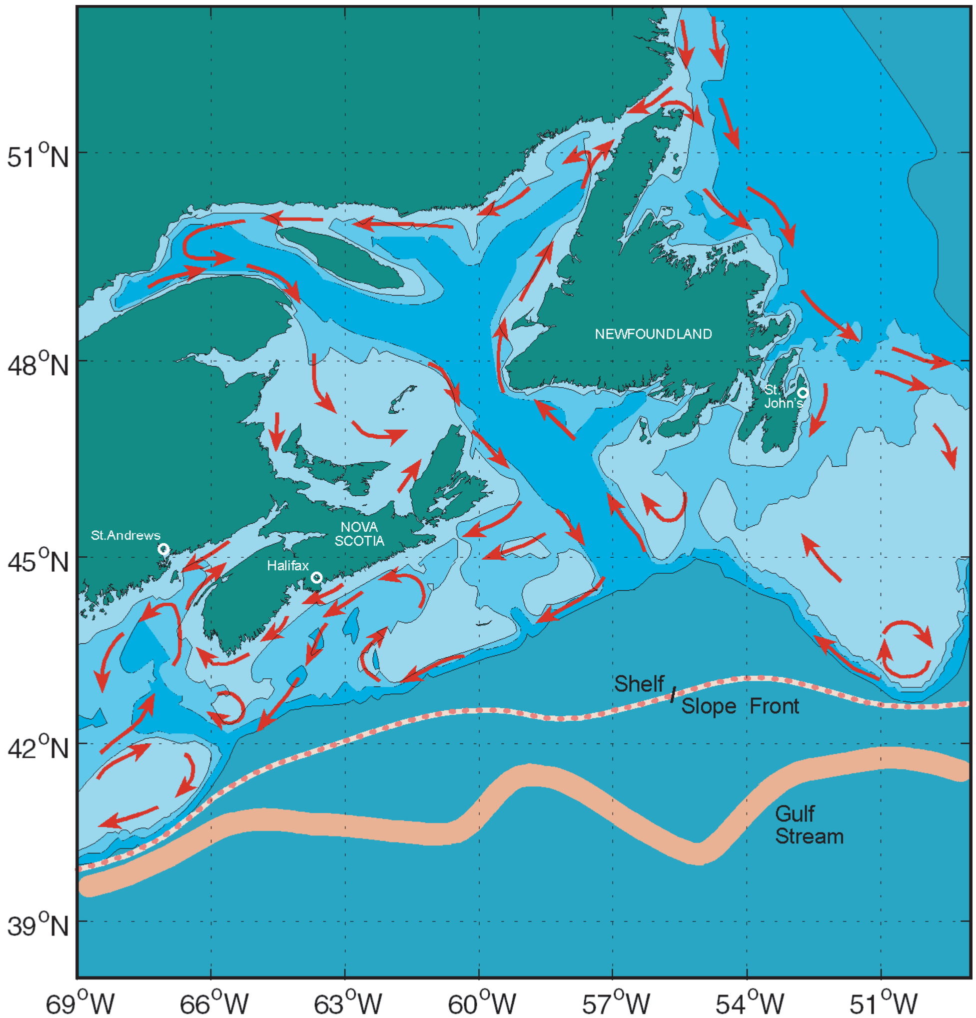

Fig. 2. Schematics of the surface circulation and the positions of the Shelf/Slope Front and the Gulf Stream.

seasonal cycle shows a more uniform temperature range with depth because of tidally generated vertical mixing. This mixing results in a reduced seasonal temperature range near the surface but a larger range at depth, relative to the rest of NAFO Subarea 4. In the winter, the water column in the deeper regions of the Scotian Shelf and the Gulf of St. Lawrence consists of two layers separated by a transition zone. The upper layer is mixed by the winter winds and contains cold, relatively 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) in the 40–150 m depth range and the warm bottom layer remains unchanged. On the northeast Scotian Shelf, topography prevents the warm offshore waters from penetrating into the region and hence waters typical of the CIL (temperatures less than 5°C) extend to the bottom. In areas of strong tidal currents, such as off southwest Nova Scotia, the waters are relatively well mixed even in summer.

Temperatures and salinities in the waters on the Scotian Shelf generally increase from northeast to southwest, because of the influence of the colder, less saline waters emanating from the Gulf of St. Lawrence. In addition, warmer, more saline offshore waters results in an inshore to offshore gradient of both water properties. 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 of increasing temperatures to the southwest is in the surface layer in summer, when temperatures are warmest in the northeast due to the transport of very warm (16–18°C) surface waters flowing out of the Gulf of St. Lawrence. 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.

On a year-to-year basis, 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.

Drinkwater *et al.* (2003) discussed changes in the hydrography of the Scotian Shelf during the 1990s. They highlighted three main events: (1) an extended period of cooling that began in the mid-1980s that occurred in the northeast, nearshore along the coast of Nova Scotia and off southwestern Nova Scotia; (2) a rapid but short-term cooling below about 100 m in 1998 in the central basins due to the influx of cold Slope Water from offshore; and (3) an increase in stratification due to a general lowering of surface salinities. In this paper we examine the decadal means of the 1990s for a large number of climate indices covering the entire Subarea 4 and compare these to conditions during previous decades. In addition, we also discuss the within decade variability of these ocean climate indices.

Data and Methods

Most of the climate indices that are presented in this paper have been used in annual environmental overviews presented to the NAFO Standing Committee on Fisheries Environment or STACFEN (see e.g. Drinkwater *et al.*, 2000).

Temperature and salinity data are derived from the historical hydrographic database held at the Bedford Institute of Oceanography (Petrie *et al.*, 1996a, b). Because there are no monitoring sites in the Gulf of St. Lawrence and on the Scotian Shelf for which there is continuous 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.* (1996a, b) and are shown in Fig. 3. 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 1971–2000 to obtain long-term monthly climatologies. These monthly climatological averages were then subtracted from the monthly means from each year to obtain monthly anomalies. Data were not available in all months of each year, however. The available monthly anomalies within a calendar year were then averaged to obtain an estimated annual anomaly. Note that this method means that the average of the annual mean anomalies for the period 1971–2000 will not necessary add up to be zero, although they are usually close. Areal averages for the northern (areas 2–6, 9 in Fig. 3a) and southern (areas 11–13, 15–16 in Fig. 3a) Gulf of St. Lawrence and for the Scotian Shelf (areas 4–23 in Fig. 3b) were also estimated for the near-surface temperatures and salinities. These were based on arithmetic averages of the area anomalies.

Within each month of each calendar year, for which there were data, a monthly mean density profile was also estimated for each of the areas in Fig. 3a, b. The density difference (in kg m^{-3}) was calculated for each profile between the closest depths to 0 and to 50 m, then normalized to a density difference over 50 m. Acceptable depth ranges for the density estimates were 0–10 m for the surface and 50 m ±10 m. A value of 0.01 represents a difference of 0.5 of a sigma-*t* unit over the 50 m. Monthly and annual estimates of this stratification index and their anomalies were calculated in a manner similar to that described above for temperature and salinity.

The groundfish surveys conducted by the Department of Fisheries and Oceans Canada form a special subset of the hydrographic data. Hydrographic measurements have been taken during such surveys, in the northern Gulf during August since 1984, in the southern Gulf of St. Lawrence during September since 1971, and on the Scotian Shelf during July since 1970. The random stratified station data from the surveys were interpolated using optimal estimation onto a grid (0.1° latitude by 0.1°longitude in the Gulf of St. Lawrence and 0.2° by 0.2º on the Scotian Shelf). 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. Bottom temperatures were estimated and contoured. Areal

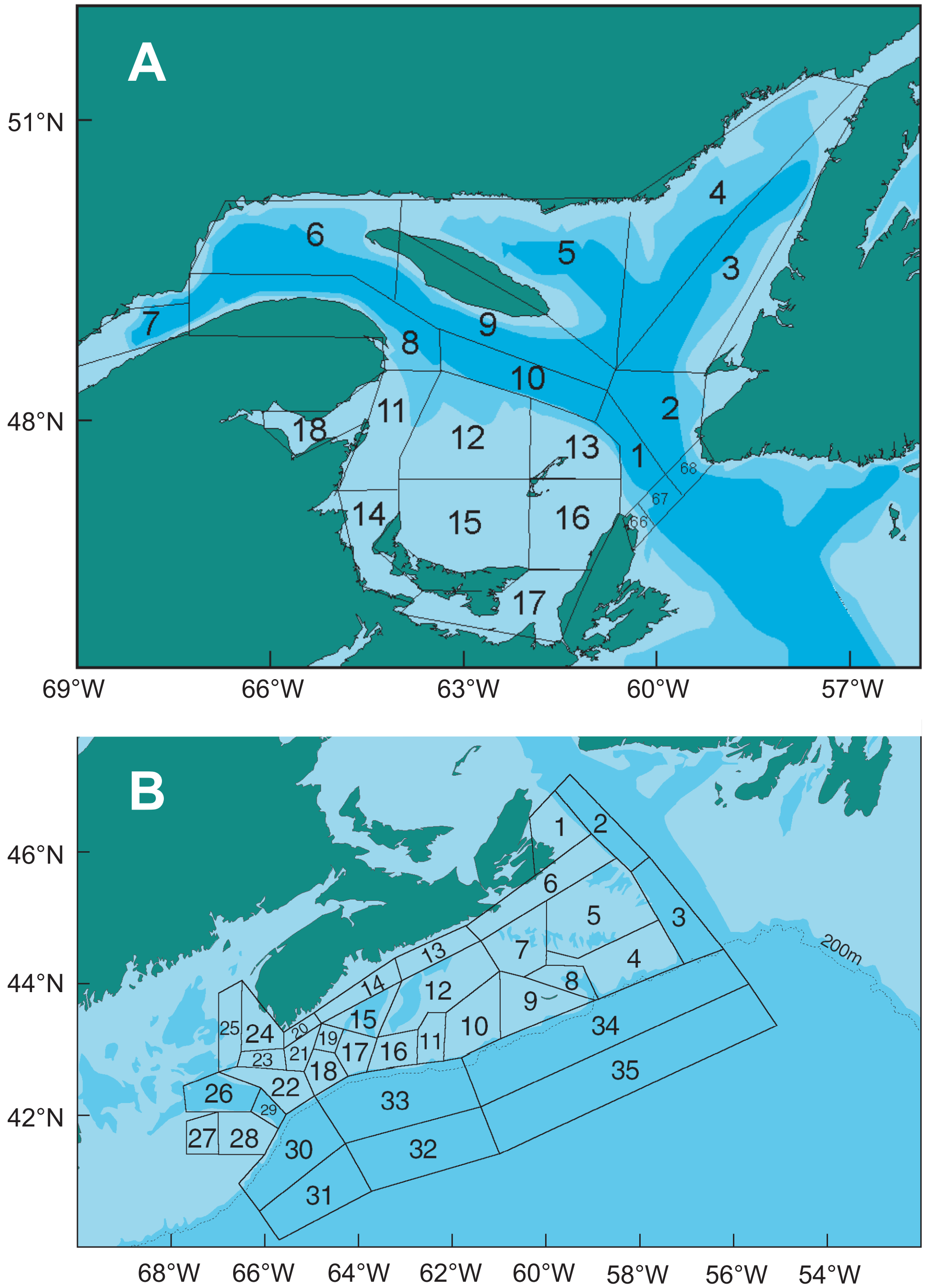

Fig. 3. (**A**) The Gulf of St. Lawrence showing the Subareas used in this paper for which areal means of hydrographic data were derived (taken from Petrie *et al*., 1996b), and (**B**) the Scotian Shelf and eastern Gulf of Maine showing the Subareas used in this paper for which areal means of hydrographic data were derived (taken from Petrie *et al*., 1996a).

indices are determined by multiplying the grid temperature by the area the grid point represents.

Long-term monthly mean coastal sea surface temperature data are available from St. Andrews, New Brunswick, since 1921 and from Halifax since 1926. These are based upon continuous measurements by thermistor recorders from which daily values are computed. Prior to the use of thermistors, daily means were calculated from two measurements per day taken by attendants.

Temperature and salinity measurements have been taken since 1924 at Prince 5, 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. Since then, data have been collected with a CTD (Conductivity, Temperature, Depth) profiler. Up to and including 1997, there was only one observation per month, but since 1998 there have been 2–3 occupations per month.

The waters on the Scotian Shelf have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters offshore. The relatively narrow boundaries between the shelf and slope waters, as well as between the slope waters and the Gulf Stream are regularly detected in satellite thermal imagery. Positions of these fronts at each degree of longitude 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). NOAA updated this data set until the termination of the satellite data product in October 1995. A commercial company (Jennifer Clarke's Gulf Stream®) continued the analysis, beginning in April 1996. Initially, these charts only contained data east of 60°W but within a year were extended consistently east to 56°W. Within this study, we have calculated averages between 75°W and 56°W.

River discharge data for the St. Lawrence River system were obtained from Environment Canada.

For the present investigation, the available monthly means of the various indices were averaged to obtain annual means and these were then combined to produce decadal means. Estimates of uncertainty in the decadal means were determined using the error of the means based upon the annual values. We consider decadal means statistically different if their means ± the error of the means do not overlap.

Results

Gulf of St. Lawrence

River Discharge. Large quantities of freshwater flow into the Gulf of St. Lawrence leading to relatively low salinities, especially on the Magdalen Shallows in the southern Gulf. Peak runoff occurs in the spring with the melting of the snow pack. The largest runoff comes from the St. Lawrence River system. Sutcliffe *et al.* (1976) combined the discharges from the St. Lawrence, Ottawa and Saguenay rivers into an index they labeled as RIVSUM. The decadal mean runoff from the combination of these three rivers during the 1990s was 10.9×10^3 m^3s^{-1}, and the third highest in the past 9 decades (Fig. 4). Only the previous two decades had slightly higher runoff although only the 1970s are considered statistically different from the 1990s. Seasonally, the 1990s had the highest winter (January–March) runoff of any decade but the third lowest spring (April–June), which coincides with the time of peak runoff. Interannual variability within the decade of the 1990s was high but typical of most decades (Fig. 4).

Near-Surface Temperatures and Salinities. Decadal mean near-surface (5 m ± 5 m) temperature anomalies in the southern Gulf have increased gradually since the 1970s (Fig. 5A). The 1990s mean is statistically higher than for the 1970s but not considered statistically different from any other decade. The within-decade variability in the 1990s is similar to other decades, again with the exception of the 1970s when there was greatly reduced variability. Temperature anomalies generally increased throughout the 1990s reaching the highest value since the 1950s in 1999. The high ocean temperature anomalies are consistent with the record air temperatures in the region in 1999 (Drinkwater, 2004). In the northern Gulf, a slightly different decadal pattern emerges with the 1990s having surface temperature anomalies not significantly different than zero and slightly lower, but not significantly so, than the 1980s (Fig. 5B). As in the southern Gulf, within the 1990s temperature anomalies fluctuated but generally rose, with the peak in 1999. The highest surface temperature in the northern Gulf was observed in 1982.

The decadal mean near-surface salinity anomaly in the southern Gulf during the 1990s was near zero and not significantly different than the decadal means over the previous 50 years, with the exception of the 1960s when the salinity was much higher (Fig. 6A). The 1960s correspond to a time of relatively low runoff from the St.

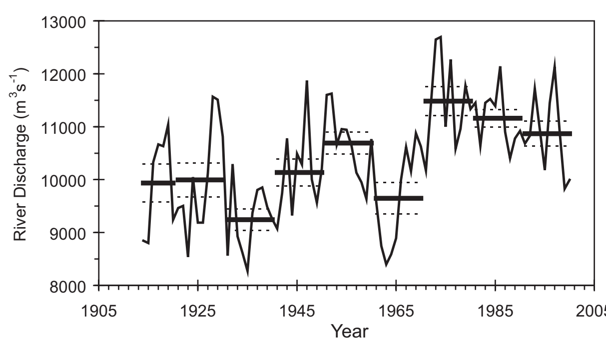

Fig. 4. The time series of the annual discharge from the combined St. Lawrence River system. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

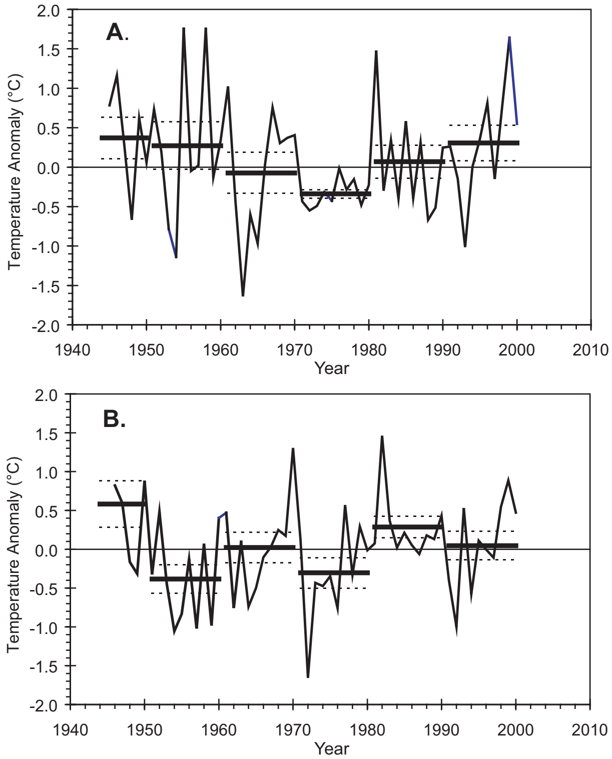

Fig. 5. The time series of the near surface annual temperature anomalies for (**A**) the southern and (**B**) northern Gulf of St. Lawrence. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

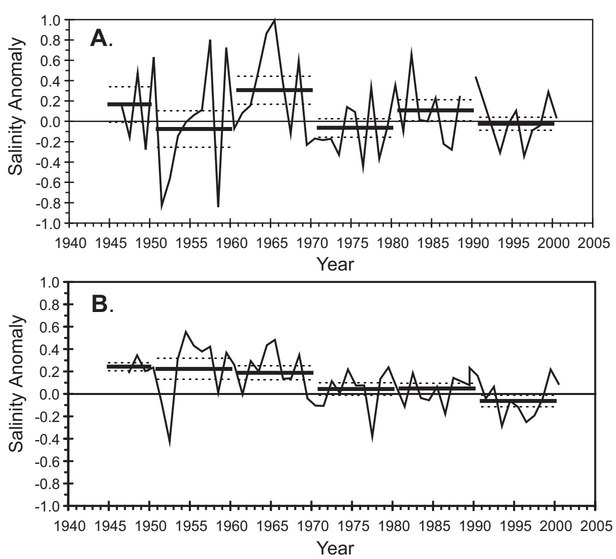

Fig. 6. The time series of the near surface annual salinity anomalies for (**A**) the southern and (**B**) northern Gulf of St. Lawrence. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

Lawrence River system (Fig. 4). In the northern Gulf, the annual salinity variability is much smaller than in the southern Gulf due to reduced influence of freshwater runoff. The decadal means of salinity anomalies for the northern Gulf generally decline from the 1940s with the 1990s being the lowest on record (Fig. 6B). However, by the end of the 1990s, salinity anomalies had risen well above the low values observed earlier in the decade.

Near-Surface Stratification. The mean density difference between 50 m and the surface was estimated for the southern and northern Gulf regions. The density gradient anomalies in both regions generally have been increasing since the 1960s (Fig. 7). For the southern Gulf, the 1990s represented the maximum of the past 6 decades whereas in the northern Gulf the decadal mean for the 1990s was not statistically different than the 1970s and 1980s but was higher than during the 1940s to the 1960s. The more variable annual stratification index in the south relative to the north is believed to be due to the highly variable freshwater runoff. The stratification during the 1990s in the southern Gulf showed a general increasing trend in contrast to the northern Gulf that experienced no overall trend. Peak stratification of the 1990s occurred in 1998 in the south and 1997 in the north.

Cold Intermediate Layer. Gilbert and Pettigrew (1997) produced an index of the core temperature of the

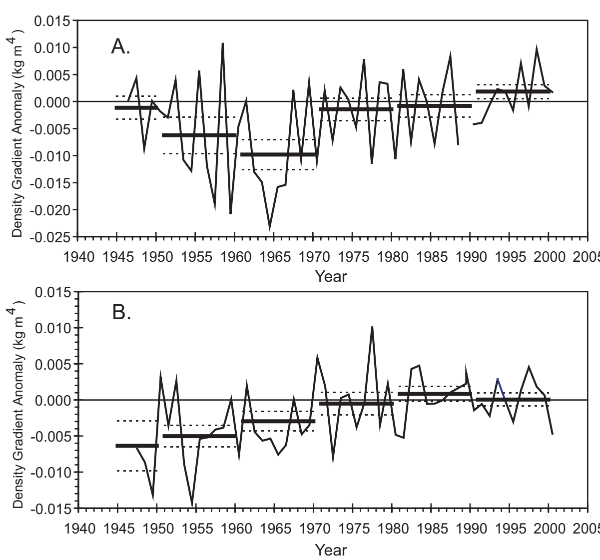

Fig. 7. The time series of the anomalies in the annual near surface density gradient (between 50 m and the surface) for (**A**) the southern and (**B**) northern Gulf of St. Lawrence. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

Cold Intermediate Layer in the Gulf of St. Lawrence as of July 15 of each year. This index was estimated from the observed data coupled with the long-term mean measured warming rate in summer and continues to be updated annually. On average, the core temperature in the CIL during the 1990s was the coldest of the last 5 decades (Fig. 8). The mean core temperature was -0.3°C in the 1990s and almost 1°C below the highest decadal mean in the 1950s. The 1990s also had the lowest within decade variability, approximately half that recorded during the 1960s when it was maximum. The recent cold period within the CIL began in the mid-1980s. From 1991 to 1998, the index remained low (~-0.5°C) with little variability, but in the last two years of the 1990s it increased above 0°C.

Subsurface Layer Temperatures. The hydrographic data collected from May to September in the Gulf of St. Lawrence were combined to estimate mean temperatures over the entire Gulf within specified layers (30–100 m, 100–200 m and 200–300 m; Fig. 9). The decadal means for the 1990s were below normal in all three layers and there is evidence of declining temperatures during the past 3 decades although these declines are not significant. The temperature pattern in the 30–100 m layer resembles that of the CIL index, with the 1990s being the lowest decade on record. For the 200–300 m layer, the 1990s decadal mean is below that of the previous 2 decades but not significantly so. It was also higher than the 1960s but again not significantly different than the 1950s and 1940s. Temperatures appeared to exhibit less variability than usual during the 1990s in the 200–300 m layer. The 100–200 m layer decadal mean temperature in the 1990s is lower than the previous 2 decades but not statistically different than any other decade. All three layers exhibited a general temperature increase within the 1990s, the largest change (>1.5°C) being in the 100–200 m layer.

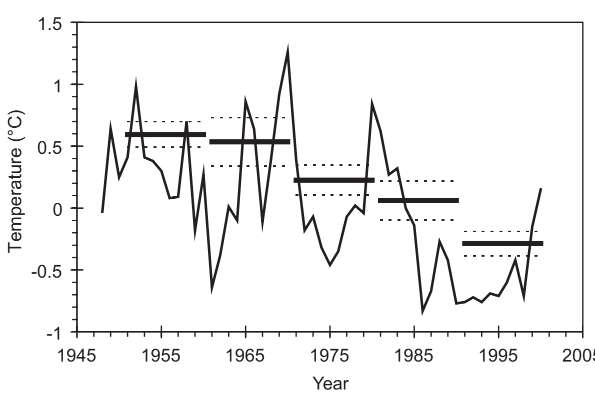

Fig. 8. The annual mid-summer CIL core temperature time series. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

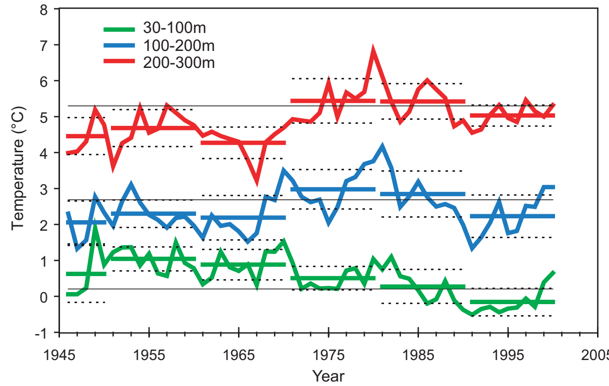

Fig. 9. The annual values of the mean temperature time series for three subsurface depth layers. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

Bottom Temperatures. In the 1990s, most of the southern Gulf was covered by bottom temperatures <3°C and substantial portions were <1°C and <0°C (Fig. 10). Temperatures increase towards the deeper Laurentian Channel and inshore towards the coast since the bottom depths of 50–100 m lie within the CIL. Relative to the 1970s and 1980s, the bottom temperatures in the 1990s over most of the Shallows were colder by between 0°–1°C. In the shallower nearshore regions, the 1990s appeared to be warmer than previous decades, however, extrapolation of temperatures into the nearshore regions where temperature gradients can be large and the regions sparsely sampled must be viewed with caution.

Using these groundfish survey data, a thermal index was developed by Swain (MS 1993) based upon the area of the bottom of the southern Gulf covered by temperatures <1°C and <0°C. The 1990s had the greatest area of cold water during the past three decades, both for temperatures <1°C and <0°C (Fig. 11). The area covered by temperatures <0°C was twice as much as in the 1980s and more than twice that of the 1970s. For temperatures <1°C, the area in the 1990s was approximately 20% higher than in either of the previous two decades.

Cabot Strait. 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 and 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 decadal means for the deep temperatures in Cabot

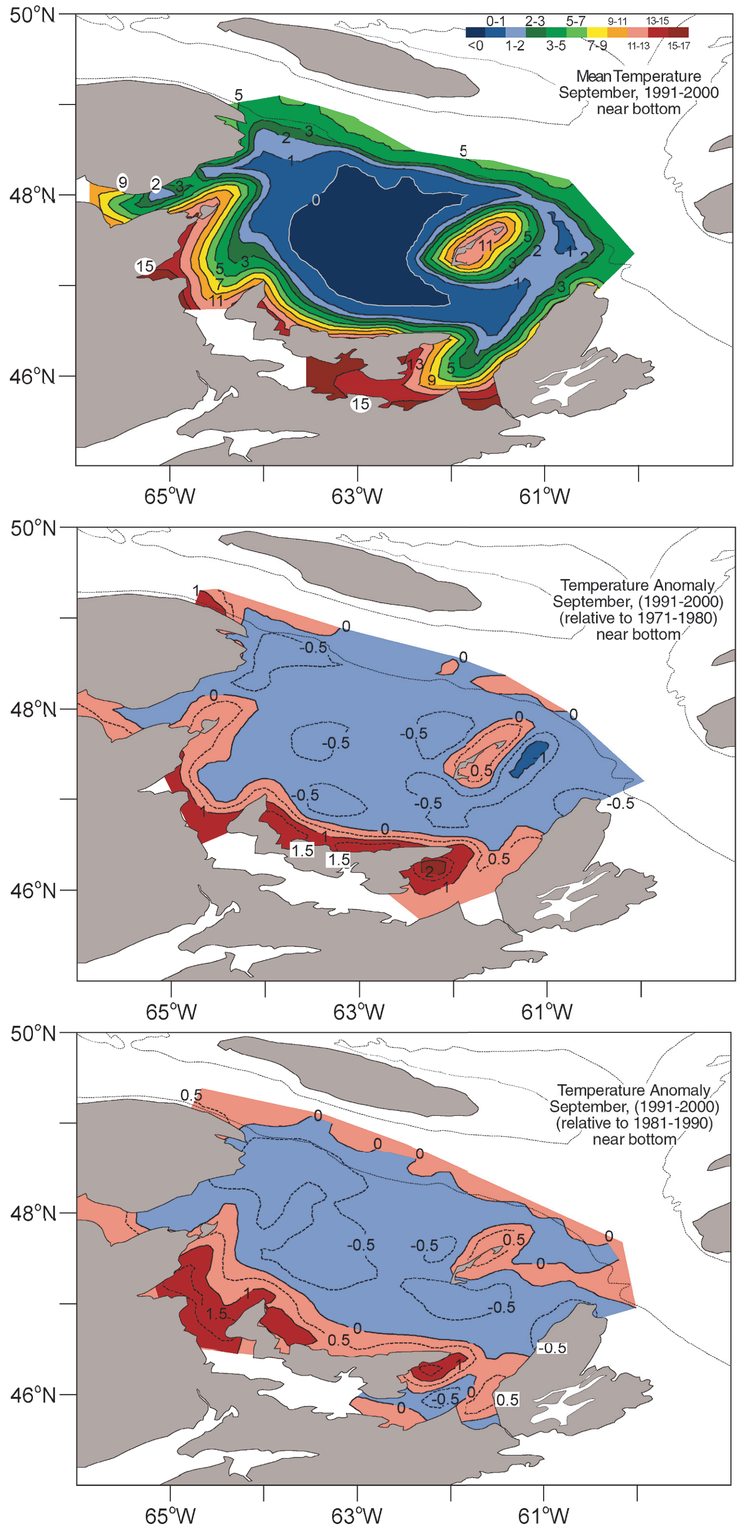

Fig. 10. The decadal mean bottom temperatures taken during the September groundfish surveys (top panel) and the difference between the 1990s and those of the 1970s (middle panel) and 1980s (bottom panel). Blues in the bottom two panels designate where it was colder in the 1990s and reds where it was warmer.

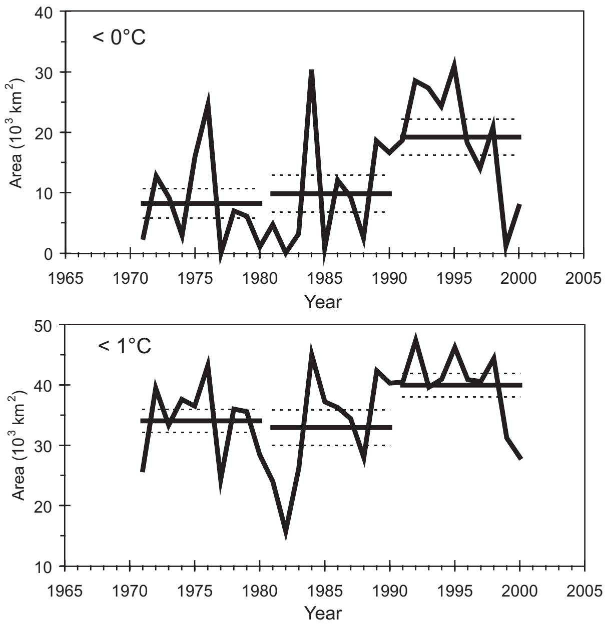

Fig. 11. The area of the bottom of the Magdalen Shallows in the southern Gulf of St. Lawrence covered by temperatures <0ºC (top panel) and <1ºC (bottom panel). The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

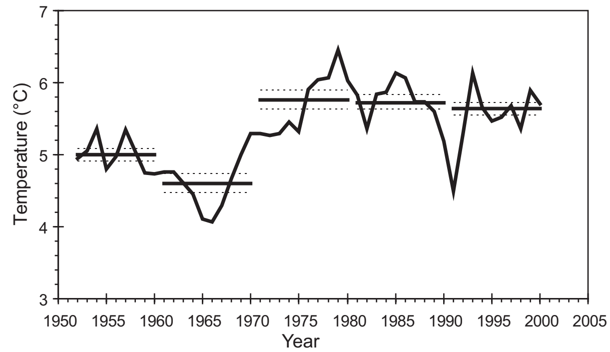

Fig. 12. The annual temperature time series in the deep layer (200–300 m) of Cabot Strait. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

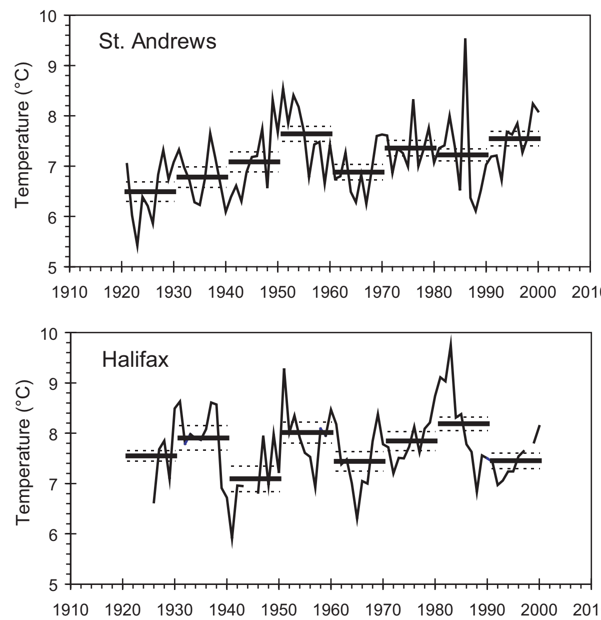

Fig. 13. The annual mean sea-surface temperature at coastal sites in St. Andrews and Halifax. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

Strait show slightly lower values in the 1990s compared to the 1970s and 1980s but not significantly so (Fig. 12). These three decades were much higher than those of the 1950s and 1960s, however. Within the decade, 1991 had a significantly lower annual mean temperature (4.5°C) compared to the rest of the 1990s when annual means were about 1°C warmer.

Scotian Shelf and Bay of Fundy

Coastal Sea Surface Temperatures. At St. Andrews in New Brunswick, decadal mean surface temperatures during the 1990s were the second highest in the past 8 decades with only the 1950s being warmer (Fig. 13). This is in contrast to Halifax where the mean temperature in the 1990s was similar to the 1960s and only the 1940s were colder (Fig. 13). The differences between the two areas are further highlighted by the time series of annual mean temperatures, although both sites exhibit large variability at low frequencies (periods of a decade and greater). At St. Andrews, following a period of low temperatures in the 1930s and 1940s, conditions warmed and reached a peak in the late–1940s and early–1950s. After that, there was a major cooling reaching minima in the mid-1960s and in the late–1980s. Through the 1990s, temperatures generally increased. At Halifax, the warmest period in the record occurred during the 1980s. Like St. Andrews, temperatures rose through the 1990s.

Prince 5. At Prince 5 in the Bay of Fundy (Fig. 1) during the 1990s, surface temperature anomalies were near the 1971–2000 mean and not significantly different to the previous two decades (Fig. 14). These years were much warmer than the 1960s, which was the coldest decade on record. The warmest decade appears to be the 1950s but it is not considered statistically different to the most recent three decades. Within the 1990s, there was high variability in the temperatures with suggestion of a slight warming trend. Surface salinity anomalies at Prince 5 during the 1990s were well below the 1971–2000 mean and the lowest in 8 decades. Salinities had been declining since the

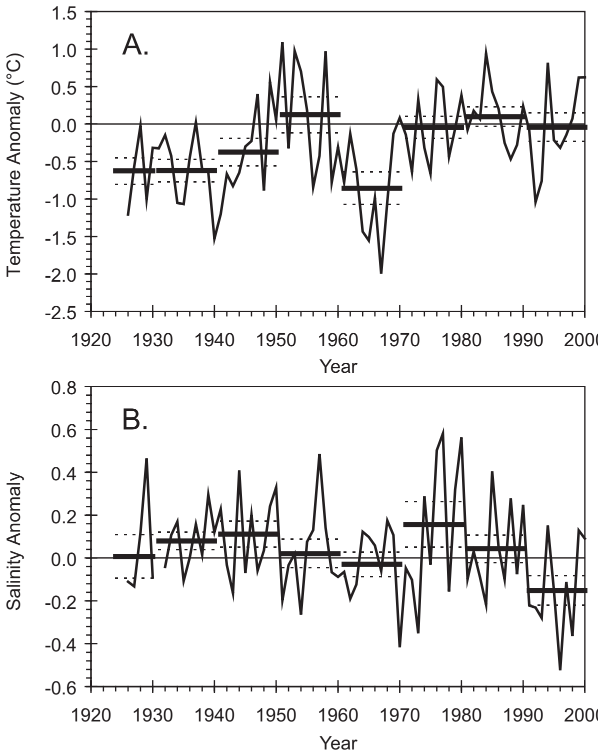

Fig. 14. The annual mean sea-surface (**A**) temperature anomalies and (**B**) salinity anomalies at station P5 in the Bay of Fundy (see Fig. 1). The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

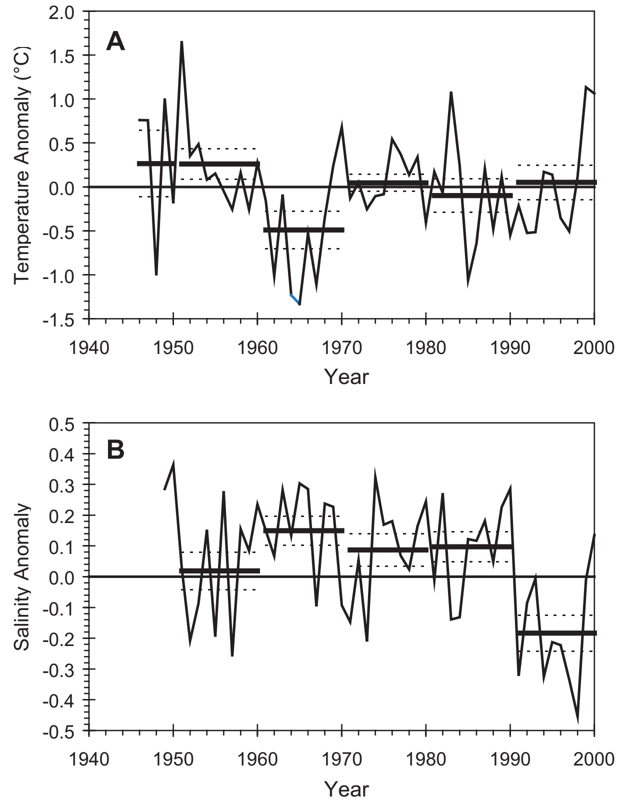

Fig. 15. The time series of the annual (**A**) temperature and (**B**) salinity anomalies at the surface for the Scotian Shelf. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

highest decadal mean in the 1970s. Again, the interannual variability was large in the 1990s. For example, the lowest annual anomaly in the 77-year record occurred in 1996 but by the end of the decade the salinity anomalies had risen above the long-term mean.

Near-Surface Temperature and Salinity. The 1990s decadal mean of the near-surface temperature anomalies averaged over the Scotian Shelf was not significantly different to the previous 5 decades, with the exception of the 1960s, which was much colder. Within the decade, following a decrease in the early–1990s, surface temperature anomalies rose, generally fell again to a minimum in 1997 then rose rapidly to reach a peak of 1.3°C in 1999, the second highest value in the 55-year record (Fig. 15A). The high amplitude anomaly in 1999 was similar to those obtained from satellite-derived sea surface temperatures and was linked to a broad area of warming that extended from southern Labrador to the Gulf of Maine (Drinkwater *et al.*, 2003). The ocean temperatures mirror air temperatures in the Scotian Shelf region (the correlation between the annual sea-surface temperatures and the air temperatures as measured on Sable Island is 0.74). However, as stated earlier, a heat budget analysis indicates that *in situ* heating and cooling do not control the long-term trends in the heat content of the upper waters of the Scotian Shelf (Umoh and Thompson, 1994; Battisti *et al.*, 1995).

The 1990s decadal salinity anomaly averaged over the Scotian Shelf was significantly different than the previous 4 decades and the lowest on record. This is consistent with the observations at Prince 5. Within the decade, there was high variability about this low level, with a minimum annual value in 1998 (Fig. 15B). This minimum (approximately 0.5 fresher than the 1971–2000 mean) represents the lowest annual salinity anomaly recorded on the Scotian Shelf in the 52-year time series. Salinities then rose rapidly to return to above 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).

Stratification. The low salinities during the 1990s led to strong vertical stratification, as the decadal mean of the anomaly of the density gradient was significantly higher than the previous five decades (Fig. 16). Annual values of this stratification index reached a peak in 1998 and declined through to 2000 when it was near its long-term mean. The 1998 value is the highest in the 54-year record. Approximately 65% of the variance in the stratification index can be accounted for by fluctuations in surface salinity (Drinkwater *et al.*, 2003). Sable Island wind stresses were on average 15% below normal during the 1990s, which also might have contributed to increased stratification through reduced vertical mixing. The higher-than-average stratification found on the Shelf did not appear to extend into the Gulf of Maine region.

Subsurface Temperature Conditions. Time series of annual subsurface temperature anomalies at 100 m on Misaine Bank (4Vs), at 250 m in Emerald Basin (4W) and 50 m on Lurcher Shoal (4X) are shown in Fig. 17. These are representative of temperature trends in the deep waters (>50 m) in the northeastern Scotian Shelf, in the deep basins (>100 m) of the central Shelf and the well-mixed waters off southwest Nova Scotia, respectively.

The 1990s decadal mean temperature anomaly at 100 m on Misaine Bank was below the 1971–2000 mean and the second consecutive decade of cold temperatures. Although the mean temperature of the 1960s was colder than either of the 1980s or 1990s, it is not considered significantly different. The warmest decade was the 1950s. Within the 1990s, there was a general increase in temperature from the 3rd lowest annual mean in 1991 to the 4th warmest in the 54-year record in 2000.

In Emerald Basin, the 1990s decadal mean near bottom temperature anomaly at 250 m was above the 1971–2000 average and the highest in the past 5 decades, although not considered significantly different than the past two decades. The last three decades have been significantly warmer than the 1950s and the 1960s, the latter being the coldest decade. The year-to-year changes in the temperature anomalies during the 1990s were relatively small except for a large negative anomaly in 1998. At this time, temperatures were at their lowest levels since the 1960s. They were caused by an increase in the transport of cold Labrador Slope Water south along the continental shelf from the Grand Bank of Newfoundland through to the Middle Atlantic Bight off the United States (Drinkwater *et al.*, MS 1998).

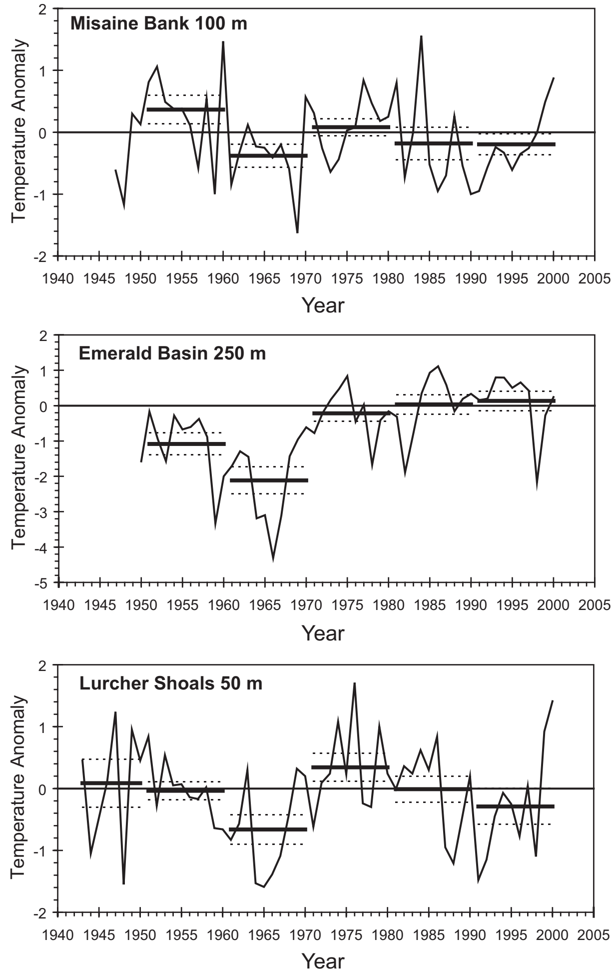

Fig. 17. The annual mean temperature anomalies on Misaine Bank (100 m), in Emerald Basin (250 m) and on Lurcher Shoals (50 m). The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

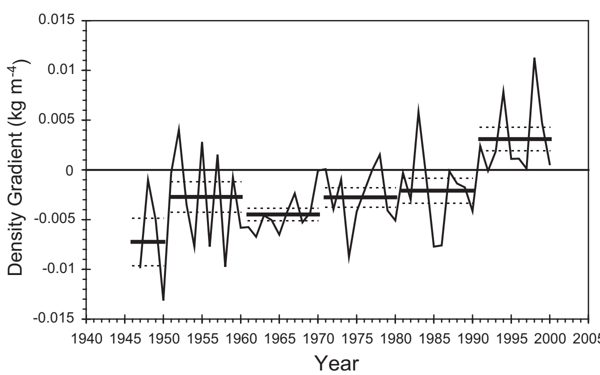

Fig. 16. The time series of the anomalies of the annual near-surface density gradient (between 50 m and the surface) for the Scotian Shelf. The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

Lurcher Shoals is in an area of strong tidal mixing due to its shallowness and strong tidal currents. The 50 m temperatures are reasonably representative of events throughout the water column, which has a typical bottom depth of between 60 and 75 m over the Shoals. The decadal temperature trend at Lurcher is closer to that of Misaine Bank than Emerald Basin, being below normal in the 1990s. The decadal means have been declining from the 1970s, which was the warmest decade at this site. The coldest decade was the 1960s. The within decade variability was high in the 1990s and showed an increase from the 4th coldest year on record (1991) to the 2nd warmest (2000).

Bottom Temperatures. The mean decadal bottom temperatures on the Scotian Shelf during July for the 1990s show the typical spatial pattern of cold (2º–4ºC) temperatures in the northeast, warm temperatures (>8ºC) in the central region, including Emerald Basin, and intermediate temperatures (5º–7ºC) in the southwest (Fig. 18). In the Bay of Fundy and Gulf of Maine, the 1990s mean bottom temperatures ranged between 7º–9ºC. Relative to the 1970s and 1980s, the 1990s tended to be slightly colder over most of the shelf (Fig. 18).

Offshore Thermal Boundaries. The decadal anomalies of the mean positions of the Shelf/Slope front and the north wall of the Gulf Stream (Fig. 2) both show increasing northward movement (positive and shoreward) with the most northward position in the relatively short time series during the 1990s (Fig. 19). The mean positions of these fronts in the 1990s were approximately 20 km further north than their positions during the 1970s. Interannual variability of the position of the two fronts shows similar trends, including during the 1990s. The fronts were well northward of their mean positions during the first half of the 1990s. Indeed, the most northerly position ever recorded for the Gulf Stream occurred in 1995 and in 1993 the Shelf/Slope front was the 3rd most northerly in its 28-year record. In 1996, the Gulf Stream moved rapidly southward followed by the Shelf/Slope front in 1997. However, these southward positions were short-lived and both fronts were situated well northward of their long-term means by the end of the decade.

Discussion

The decadal means of the hydrographic properties of the waters in NAFO Subarea 4 exhibited several noteworthy features during the 1990s. These included record low near-surface salinities; an extended period of cold subsurface (50–150 m) waters throughout much of the Gulf of St. Lawrence, the northeastern Scotian Shelf and the eastern Gulf of Maine; and relatively warm waters in the deep basins and channels.

The decadal mean near-surface temperatures throughout NAFO Subarea 4 showed no dominant pattern in the 1990s. This contrasted with the salinities. During the 1990s, the lowest decadal mean for the near-surface salinity anomaly was recorded for the northern Gulf of St. Lawrence (Fig. 6), the Scotian Shelf (Fig. 15) and the Bay of Fundy at the Prince 5 monitoring station (Fig. 14). These salinity anomalies were significantly lower than those recorded previously. In the case of the Scotian Shelf and the Bay of Fundy, they were the lowest over 6 and 8 decades, respectively. While the southern Gulf of St. Lawrence also experienced a below-normal decadal mean salinity anomaly in the 1990s, it is not considered statistically different from the 1971–1990 mean (Fig. 6). The 1960s, which had the highest salinities, was the only decade that was significantly different from the 1990s. The St. Lawrence River discharges were relatively high in the 1990s (Fig. 4) and might at first glance be thought to have contributed to the low salinities throughout Subarea 4. However, the river discharges were even higher during the previous 2 decades when salinities in the region were not as low or the same as the salinities in the 1990s. Therefore, the St. Lawrence River discharge is not believed to be the source of the salinity variability in most of Subarea 4. Indeed, the changes in the salinities on the Scotian Shelf are closely related to those observed on the Newfoundland Shelf and therefore arise through advection of waters from the north (Smith *et al.*, 2001; Drinkwater *et al.*, 2003). Low salinities have been recorded during the 1990s on the Newfoundland shelf (Colbourne, 2004) and in the surface waters in the Gulf of Maine and Middle Atlantic Bight (Mountain, 2004). The low salinities in the Northern Gulf are believed to have arisen through the flow of water from the Labrador Shelf through the Strait of Belle Isle. Since the low salinities during the 1990s were not recorded off West Greenland (Stein, 2004), this suggests their origin may have been in Baffin Bay or Hudson Strait.

The impact of this decreased near-surface salinity led to increased vertical stratification, most notably, on the Scotian Shelf. There, the decadal mean of the upper layer vertical density gradient was at its highest level in 6 decades and significantly above previous decadal values (Fig. 16; see also Drinkwater *et al.*, 2003). In the northern Gulf, the vertical stratification was higher than normal but not significantly different to the 1980s, which exhibited the highest mean value (Fig. 7). The southern Gulf of St. Lawrence also recorded its highest stratification during the 1990s but is believed due to higher-than-normal surface temperatures in combination with low salinities derived from high St. Lawrence River runoff.

Record or near-record decadal mean temperatures were recorded in the subsurface waters (50 m to 150 m)

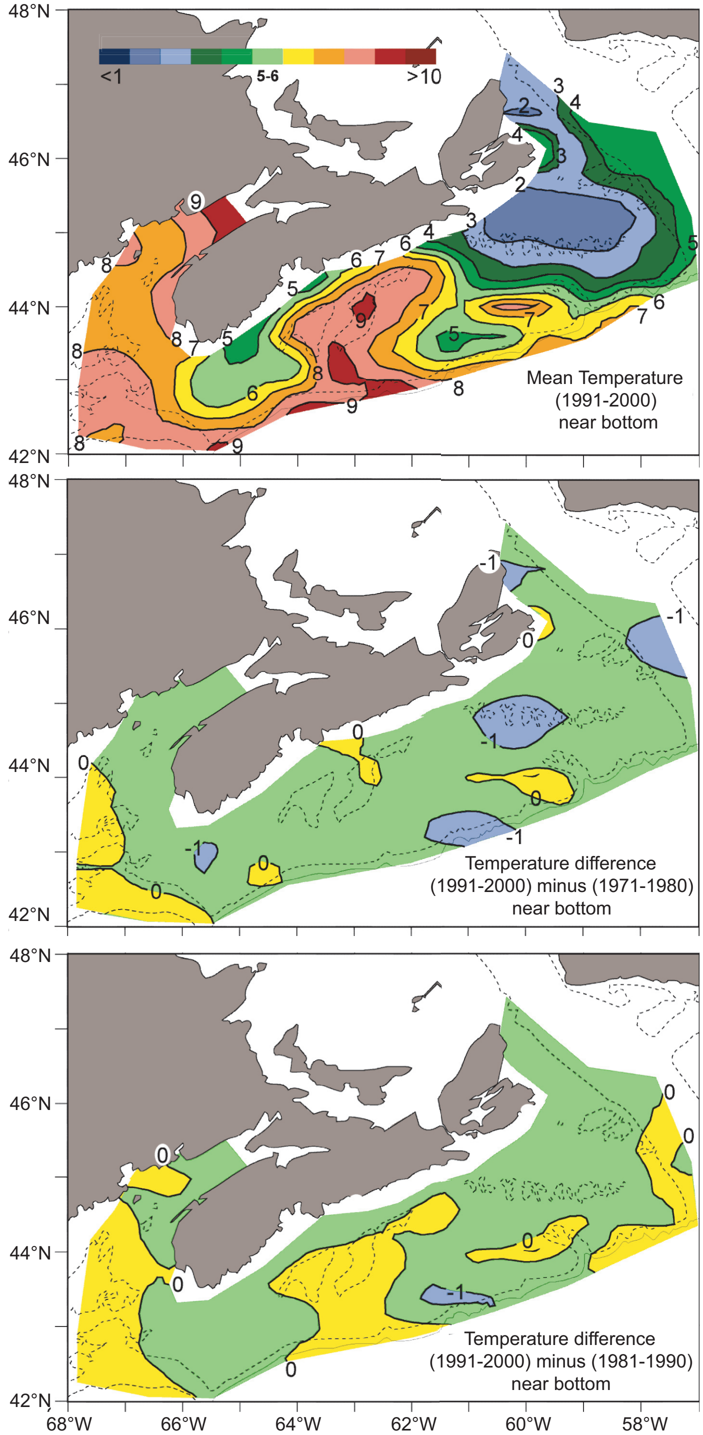

Fig. 18. The 1991–2000 decadal mean bottom temperatures taken during the July groundfish surveys (top panel) and the difference between the 1990s and those of the 1970s (middle panel) and 1980s (bottom panel). Greens and blues in the bottom two panels designate where it was colder in the 1990s and yellow where it was warmer.

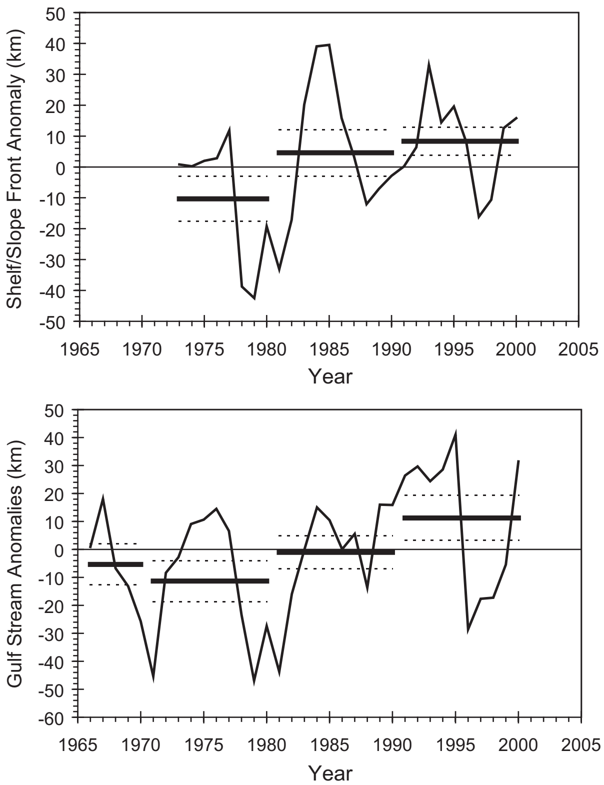

Fig. 19 The anomalies in the position of the Shelf/Slope front (top panel) and the Gulf Stream (bottom panel). The horizontal lines represent the decadal means (solid) ± the error of the mean (dashed).

of the Gulf of St. Lawrence and much of the Scotian Shelf during the 1990s. This was evident by the coldest decadal mean temperature in both the minimum temperature of the Cold Intermediate Layer (Fig. 8) and in the 30 to 100 m layer for the Gulf of St. Lawrence (Fig. 9). Also, the area of the bottom of the southern Gulf covered by temperatures <0°C and <1°C also was the highest recorded, although the time series only covers 3 decades. On the Scotian Shelf, the decadal mean temperatures on Misaine Bank and over Lurcher Shoals in the eastern Gulf of Maine were the 2nd coldest on record with only the 1960s being colder. In both the Gulf of St. Lawrence and the Scotian Shelf, cold temperatures persisted from the mid-1980s to the late-1990s, almost without exception.

Drinkwater *et al.* (2003) discussed the cause of the cold water on the Scotian Shelf. Based upon atmospheric heat fluxes and upstream hydrographic conditions, they concluded that the primary source of the cold conditions on the northeastern Scotian Shelf was advection from further north. However, local *in situ* atmospheric cooling was thought to have contributed in part to the presence and persistence of these cold waters. Saucier *et al.* (2003) suggests that local atmosphere-ice-ocean heat and salt fluxes play a major role in the CIL formation in the Gulf of St. Lawrence, with Belle Isle Strait inflow also playing a significant role. The decline in temperatures on the Newfoundland Shelf during the 1980s and 1990s has been shown to be part of large-scale cooling induced by increased northwest winds and cooler air temperatures over the Labrador Sea region that, in turn, have been linked to changes in the North Atlantic Oscillation (NAO) index (Colbourne *et al.*, 1994; Drinkwater, 1996; Colbourne, 2004). The biological consequences of the cooler water included an expansion of cold-water species into the region, lower growth rates of several groundfish and perhaps a role in the decline of the cod stocks in the area (Zwanenburg *et al.*, 2002; Drinkwater *et al.*, 2003).

The mean decadal temperature patterns for the deep channels and basins show similarities throughout Subarea 4 (e.g. Cabot Strait, Fig. 12; Emerald Basin, Fig. 17; Georges Basin in the Gulf of Maine, not shown). Temperatures were generally warm during the 1990s, as well as in the 1970s and 1980s, and well above the temperatures observed in the 1950s and 1960s (the coldest decade). These trends reflect the presence of the type of slope water that occupies the area adjacent to the shelf (Petrie and Drinkwater, 1993). Warm Slope Water dominated from the 1970s through the 1990s in contrast to the 1960s when Labrador Slope Water penetrated farther south than usual, displacing the Warm Slope Water (Petrie and Drinkwater, 1993; Drinkwater *et al.*, MS 1998).

High interannual variability in ocean temperatures was observed during the 1990s, although such variability is common. Some particular events are notable. The near-surface temperatures in most regions of Subarea 4 experienced a general warming trend through the 1990s, although the decadal averages were near the long-term (1971–2000) means. In the late-1990s, these temperatures rose rapidly and were near or at record highs in the Gulf of St. Lawrence (Fig. 5), on the Scotian Shelf (Fig. 15) and in the Bay of Fundy (Fig. 14). This is consistent with the record warm air temperatures in the area from the southern Labrador Shelf to the Gulf of Maine in 1999 (Drinkwater, 2004). The subsurface temperatures in those areas that experienced cold conditions through most of the late-1980s and into the mid- to late-1990s, also rose at the end of the decade to above normal values in the late-1990s. This includes the CIL minimum temperature (Fig. 8) and all depth layers in the Gulf of St. Lawrence (Fig. 9), as well as on Misaine Bank on the Scotian Shelf and Lurcher Shoals (Fig. 17) in the eastern Gulf of Maine. The warming of these subsurface waters is believed to be due to a combination of advection of warmer waters from the north and *in situ* warming through atmospheric heat fluxes (Drinkwater *et al.*, 2003).

The other very notable event was the cooling observed in 1998 in Emerald Basin. This was due to the penetration of cold Labrador Slope water from offshore onto the Scotian Shelf. This was mentioned by Drinkwater *et al.* (2003) and described in more detail by Drinkwater *et al.* (MS 1998). Only a brief review is provided here. 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. It subsequently moved onto the central and southwestern Scotian Shelf and into the Gulf of Maine. Temperatures dropped by over 4ºC and salinities by approximately 1 in Emerald Basin and at the mouth of the Gulf of Maine during this event. The Labrador Slope Waters also spread onto the Shelf eventually replacing most of the near-bottom waters on the southwestern Shelf by July 1998. This survey recorded the lowest temperatures for the southwestern shelf in its 30-year time series. The Labrador Slope Water at the shelf edge began to retreat northeastward in mid-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 Scotian Shelf gradually lessened through late-1998 and early-1999. The presence of the Labrador Slope Water is believed to be related to an increase in the volume transport of the deep (100–300 m) Labrador Current (Petrie and Drinkwater, 1993). Han (2002) presented interannual sea level changes from the Laurentian Channel to the Middle Atlantic Bight in the 1990s from satellite altimetry and tide-gauge data. The sea level fell rapidly in early 1997–98 progressively from the eastern Scotian Shelf to the Middle Atlantic Bight. The sea level changes were attributed to an increase in the Labrador Current transport and its offshore movement. Such increased transport has been related to the large-scale atmospheric circulation patterns over the North Atlantic as reflected in the intensity of the Icelandic Low (Worthington, 1964) or the related NAO index (Marsh *et al.*, 1999). The increased transport in 1998 is thought to be a response to the low NAO index in 1996 (Drinkwater *et al.*, 2003), although this has not been firmly established. The low temperatures were observed to affect the catchability of sharks in Emerald Basin and offshore lobsters in the Gulf of Maine (Drinkwater *et al.*, 2003).

Finally, it is worth noting that during the 1990s, much more attention has been paid to hydrographic variability in the region with several publications not only documenting this variability but more importantly providing insights into the mechanisms causing these changes. They include the dominant role of advection of waters from both the offshore slope water region and off the Newfoundland shelf. Two other significant achievements have occurred during the 1990s. First is the great strides in modeling the circulation in the region and second, the establishment of the Atlantic Zonal Monitoring Program (AZMP) by Fisheries and Oceans Canada in the late- 1990s. This dedicated long-term monitoring includes nutrients and plankton, as well as hydrography. We therefore look forward to future decadal reviews that will hopefully go beyond hydrography to provide a more comprehensive view of the marine ecosystem and its variability.

Acknowledgements

We acknowledge Roger Pettipas for data analysis support and Liam Petrie for drafting the bottom temperature plots.

References

BANKS, R. E. 1966. The cold layer in the Gulf of St. Lawrence. *J. Geophys. Res*., **71**: 1603–1610.

BATTISTI, D. S., U. S. BHATT, and M. A. ALEXANDER. 1995. A modeling study of the interannual variability in the wintertime North Atlantic Ocean. *J. Climate*, **8**: 3067–3083.

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. *In*: The Gulf of St. Lawrence: small ocean or large estuary? J.-C. Therriault (ed.). *Can. Spec. Publ. Fish. Aquat. Sci*, **113**: 139–147.

COLBOURNE, E. 2004. Decadal changes in the ocean climate in Newfoundland and Labrador waters from the 1950s to the 1990s. *J. Northw. Atlan. Fish. Sci*., **34**: 41–59 (this volume).

COLBOURNE, E., S. NARAYANAN, and S. PRINSENBERG. 1994. Climatic changes and environmental conditions in the Northwest Atlantic, 1970–1993. *ICES Mar. Sci. Symp*., **198**, 311–322.

DRINKWATER, K. F. 1996. Climate and oceanographic variability in the Northwest Atlantic during the 1980s and early-1990s. *J. Northw. Atl. Fish. Sci.*, **18**: 77–97.

2004. Atmospheric and sea-ice conditions in the Northwest Atlantic during the decade, 1991–2000. *J. Northw. Atl. Fish. Sci*., **34**: 1–11 (this volume).

DRINKWATER, K. F., E. COLBOURNE, and D. GILBERT. 2000. Overview of environmental conditions in the Northwest Atlantic in 1998. *NAFO Sci. Coun. Studies*, **33**: 39–87.

DRINKWATER, K. F., D. B. MOUNTAIN, and A. HERMAN. MS 1998. Recent changes in the hydrography of the Scotian Shelf and Gulf of Maine – a return to conditions of the 1960s? *NAFO SCR Doc*., No. 37, Serial No. N3024,16 p.

DRINKWATER, K. F., R. A. MYERS, R. G. PETTIPAS, and T. L. WRIGHT. 1994. Climatic data for the Northwest Atlantic: The position of the shelf/slope front and the northern boundary of the Gulf Stream between 50°W and 75°W, 1973–1992. *Can. Data Rept. Fish. Ocean. Sci*., **125**, 103 p.

DRINKWATER, K. F., B. PETRIE, and P. C. SMITH. 2003. Climate variability on the Scotian Shelf during the 1990s. *ICES Mar. Sci. Symp*., **219**: 40–49.

GARRETT, C. J. R., J. R. KEELEY, and D. A. GREENBERG. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. *Atmosph.-Ocean*, **16**: 403–423.

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*., **54** (Suppl. 1): 57–67.

HAN, G. 2002. Interannual sea-level variations in the Scotia-Maine region in the 1990s**.** *Can. J. Remote Sensing***, 28**: 581–587.

HAN, G., C. G. HANNAH, J. W. LODER, and P. C. SMITH. 1997. Seasonal variation of the three-dimensional mean circulation over the Scotian Shelf. *J. Geophys. Res*., **102**: 1011–1025.

HAN, G., J. W. LODER, and P. C. SMITH. 1999. Seasonal-mean hydrography and baroclinic circulation in the Gulf of St. Lawrence and on the eastern Scotian and southern Newfoundland Shelves. *J. Phys. Oceanogr*., **29**: 1279–1301.

KOUTITONSKY, V. G., and G. L. BUGDEN. 1991. The physical oceanography of the Gulf of St. Lawrence: a review with emphasis on the synoptic variability of the motion. *In*: The Gulf of St. Lawrence: small ocean or large estuary? J.-C. Therriault (ed.). *Can. Spec. Publ. Fish. Aquat. Sci*., **113**: 57–90.

MARSH, R., B. PETRIE, C. R. WEIDMAN, R. R. DICKSON, J. W. LODER, C. G. HANNAH, K. FRANK, and K. DRINKWATER. 1999. The Middle Atlantic Bight tilefish fill of 1882. *Fish. Oceanogr*., **8**: 39–49.

MOUNTAIN, D. G. 2004. Variability of the water properties in NAFO Subareas 5 and 6 during the 1990s. *J. Northw. Atlan. Fish. Sci*., **34**: 101–110 (this volume).

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, D. GREGORY, R. PETTIPAS, and A. SANDSTRÖM. 1996a. Temperature and salinity atlas for the Scotian Shelf and the Gulf of Maine. *Can. Tech. Rep. Hydrogr. Ocean Sci*., **171**: 398 p.

PETRIE, B., K. DRINKWATER, A. SANDSTRÖM, R. PETTIPAS, D. GREGORY, D. GILBERT, and P. SEKHON. 1996b. Temperature, salinity and sigma-*t* atlas for the Gulf of St. Lawrence. *Can. Tech. Rep. Hydrogr. Ocean Sci*., **178**: 256 p.

PETRIE, B., B. TOULANY, and C. J. R. GARRETT. 1988. The transport of water, heat and salt through the Strait of Belle Isle. *Atmos.-Ocean*, **26**: 234–251.

SAUCIER, F. J., F. ROY, D. GILBERT, P. PELLERIN, and H. RITCHIE. 2003. Modeling the formation and circulation processes of water masses and sea ice in the Gulf of St. Lawrence, Canada. *J. Geophys. Res*., **108**(C8): 3269, 10.1029/2000JC000686.

SHENG, J., and K. R. THOMPSON. 1996. A robust method for diagnosing regional shelf circulation from scattered density profiles. *J. Geophys. Res*., **101**: 25647–25659.

SMITH, P. C., R. W. HOUGHTON, R. G. FAIRBANKS, and D. G. MOUNTAIN. 2001. Interannual variability of boundary fluxes and water mass properties in the Gulf of Maine and on Georges Bank: 1993–1997. *Deep-Sea Res. II*, **48**: 37–70.

STEIN, M. 2004. Climatic overview of NAFO Subarea 1, 1991–2000. *J. Northw. Atlan. Fish. Sci*., **34**: 29–40 (this volume).

SUTCLIFFE, W. H. Jr., R. H. LOUCKS, and K. F. DRINKWATER. 1976. Coastal circulation and physical oceanography of the Scotian Shelf and the Gulf of Maine. *J. Fish. Res. Board Can*., **33**: 98–115.

SWAIN, D. P. MS 1993. Variation in September near-bottom temperatures in the southern Gulf of St. Lawrence, 1971–1992. *DFO Atl. Fish. Res. Doc*., No. 93/48, 17 p.

UMOH, J. U., and K. R. THOMPSON. 1994. Surface heat flux, horizontal advection, and the seasonal evolution of water temperature on the Scotian Shelf. *J. Geophys. Res*., **99**: 20403–20416.

WEARE, B. C. 1977. Empirical orthogonal function analysis of Atlantic Ocean surface temperatures. *Quart. J. Roy. Meteorol. Soc*., **103**: 467–478.

WORTHINGTON, L. V. 1964. Anomalous conditions in the Slope Water area in 1959. *J. Fish. Res. Board Can*., **21**: 327–333.

YASHAYAEV, I. M., and I. I. ZVERYAEV. 2001. Climate of the seasonal cycle in the North Pacific and North Atlantic Oceans. *Internat. J. Climatology*, **21**: 401–417.

ZWANENBURG, K. C. T., D. BOWEN, A. BUNDY, K. DRINKWATER, K. FRANK, R. N. O'BOYLE, D. SAMEOTO, and M. SINCLAIR. 2002. Decadal changes in the Scotian Shelf large marine ecosystem. *In*: Large Marine Ecosystems of the North Atlantic: Changing States and Sustainability. K. Sherman and H.-R. Skjoldal (eds.), Elsevier, Amsterdam, the Netherlands, p. 105–150.