NAFO Sci. Coun. Studies, 32: 75–121

Overview of Environment Conditions in the Northwest Atlantic in 1997

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Abstract

A review of environmental conditions on the continental shelves and adjacent offshore areas off northeastern North America during 1997 is presented. Annual air temperatures were warmer-than-normal over much of the Labrador Sea and colder-than-normal along the Atlantic coast from Newfoundland to Cape Hatteras although it generally cooled relative to 1996 in both regions. The NAO index in 1997 was below normal for the second consecutive year but above that recorded in 1996. Although the sea ice on the southern Labrador and Newfoundland shelves generally appeared late and left early resulting in a shorter duration than usual, the areal extent in 1997 exceeded that of 1996. The number of icebergs reaching the Grand Banks increased over 1996 by 60% but still remained well below the large numbers reported in the early 1990s. In the Gulf of St. Lawrence, ice generally appeared late but remained longer than expected. Temperatures continued their moderating trend over much of Labrador and northern Newfoundland shelves and the Grand Banks. This was evident both near bottom and within the water column throughout much of the year from Hamilton Bank in the north to the Grand Banks. An exception was over the shallow portions of the Grand Bank, where temperatures were colder than normal during late spring and early summer. The CIL volume was near the lowest recorded in the almost 20 years of data. In contrast to these generally warm conditions, cold waters continue to occupy St. Pierre Bank area and were also observed in the deep waters on Flemish Cap. In both locations these cold conditions have persisted since the mid-1980s. Colder-than-normal conditions since the mid-1980s have also been observed in the CIL in the Gulf of St. Lawrence and in the near bottom waters on the Magdalen Shallows. These waters continued to remain at below normal temperatures in 1997 but have been moderating. In the deep waters of Cabot Strait (200–300 m), temperatures remained slightly above the long-term mean. On the Scotian Shelf and Gulf of Maine, colder-than-normal temperatures continued to occupy the northeastern Scotian Shelf and the intermediate depths on the southwestern Scotian Shelf. These cold waters have persisted since the mid-1980s. In contrast, the water in the deep basins, such as Emerald and Georges, displayed above-normal temperatures. A significant change in the offshore slope waters occurred in late 1997 as cold waters believed to be of Labrador origin flooded the outer edge of the Scotian Shelf. Both the slope/shelf front and the Gulf Stream were further southward than normal in 1997.

Key words: climate, environment, Grand Bank, Gulf of Maine, Gulf of St. Lawrence, oceanography, Scotian Shelf, temperature

Introduction

This paper examines the atmospheric, sea ice and hydrographic conditions in the Northwest Atlantic during 1997 and continues the series of annual reviews presented to NAFO that began in 1982. It is based upon selected sets of oceanographic and meteorological data. In order to detect climate trends we have removed the seasonal cycle by expressing conditions as monthly deviations from their long-term means, called anomalies. Where possible, the long-term means have been averaged over a standardized 30-yr base period (1961–90) in accordance with the convention of the World Meteorological Organization and recommendation of the NAFO Scientific Council.

Meteorological Observations

Air Temperatures

The German Weather Service publishes annual and monthly mean temperature anomaly (relative to the 1961–90 means) charts for the North Atlantic Ocean in their publication *Die Grosswetterlagen Europas*. During 1997, the annual means tended to be warmer-than-normal over most of the Labrador Sea area, the southern Gulf of St. Lawrence, the Gulf of Maine and parts of the Middle Atlantic Bight. None of these areas had annual anomalies exceeding 1°C, however. Colder-than-normal annual air temperatures occurred over southern Labrador, around Newfoundland, in the northern Gulf of St. Lawrence, on the Scotian Shelf, on parts of the Middle Atlantic Bight and offshore of the Gulf of Maine and the Middle Atlantic Bight (Fig. 1).

Monthly data from *Die Grosswetterlagen Europas* show that during January, positive anomalies covered most of the NAFO area with

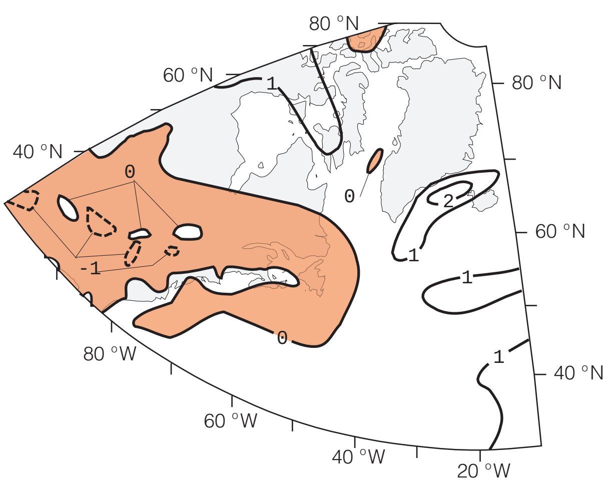

Fig. 1. Annual air temperature anomalies (in °C) over the northwest Atlantic in 1997 relative to the 1961–90 means (taken from *Grosswetterlagen Europas*). The shaded anomalies indicate areas of colder-than-normal temperatures.

values reaching 4°C in Baffin Bay off West Greenland (Fig. 2). Air temperature anomalies on the northern Labrador Shelf exceeded 1°C. Rapid cooling during February resulted in very cold air temperatures with anomalies over the Labrador Sea exceeding -3°C. Air temperatures in the Gulf of St. Lawrence and the Newfoundland area were also below normal but of lower magnitude than over the Labrador Sea. South of Nova Scotia, anomalies were above normal by as much as 3°–4°C in the Cape Cod to New York region. Colder-than-normal conditions continued to cover most of the region during the late winter and spring. In March, temperatures over the Gulf of St. Lawrence were 2–4°C below normal. In June, the Labrador Sea was covered by air whose temperatures were above normal while from the Gulf of St. Lawrence south, air temperatures were below normal by up to 2°C. During the summer months, the anomalies varied about normal both spatially and from month to month. In September, warm air pervaded the region. Over the Labrador Sea, temperatures generally remained above their long-term means through to the end of the year. From Newfoundland south, however, air temperatures were colder-than-normal during October and November but warmed to near normal and above by December.

Monthly air temperature anomalies for 1996 and 1997 were calculated for Godthaab in Greenland, Iqaluit on Baffin Island, Cartwright on the Labrador coast, St. John's in Newfoundland, Magdalen Islands in the Gulf of St. Lawrence, Sable Island on the Scotian Shelf, Boston in the Gulf of Maine and Cape Hatteras on the eastern coast of the United States (see Fig. 3 for locations). Canadian air temperatures were available from the *Canadian Climate Summaries* published by the Canadian Atmospheric Environment Service and for non-Canadian locations from the NOAA publication *Monthly Climatic Data for the World*. The warm air temperatures in the northern sites during January noted above were a continuation of conditions established in December 1996 (Fig. 4). This was followed by a rapid decline in temperature anomalies in February. Temperatures remained colder-than-normal at most of the northern sites for another month or two before returning to above normal values by the spring. From then until autumn, air temperature anomalies from Cartwright north were predominately above normal, while those from Sable Island south were below normal. The cold conditions at the latter stations followed a winter, which in contrast to the northern regions

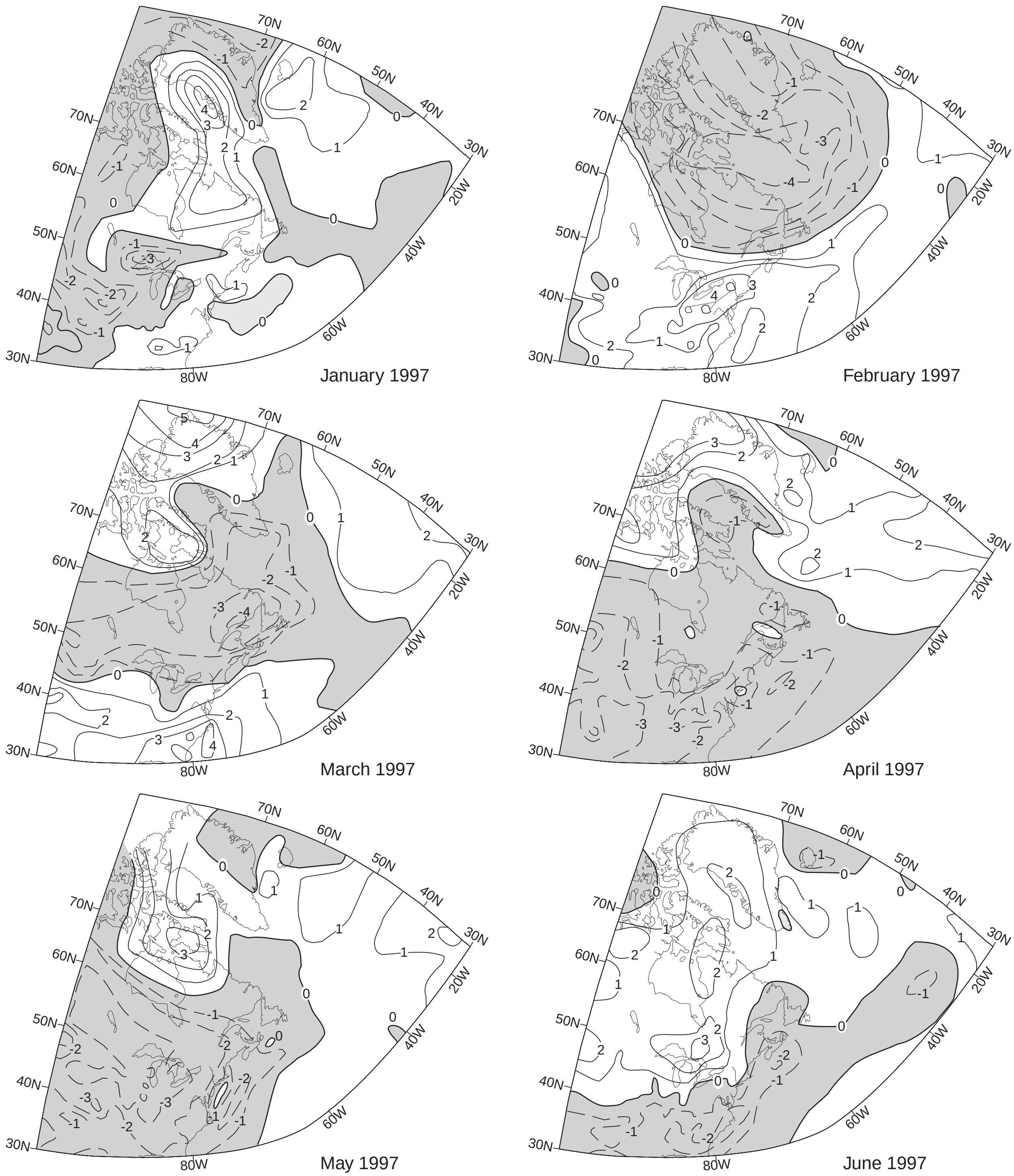

Fig. 2. Monthly air temperature anomalies (in °C) over the northwest Atlantic in 1997 relative to the 1961–90 means (from *Grosswetterlagen Europas*). The shaded anomalies indicate areas of colder-than-normal temperatures.

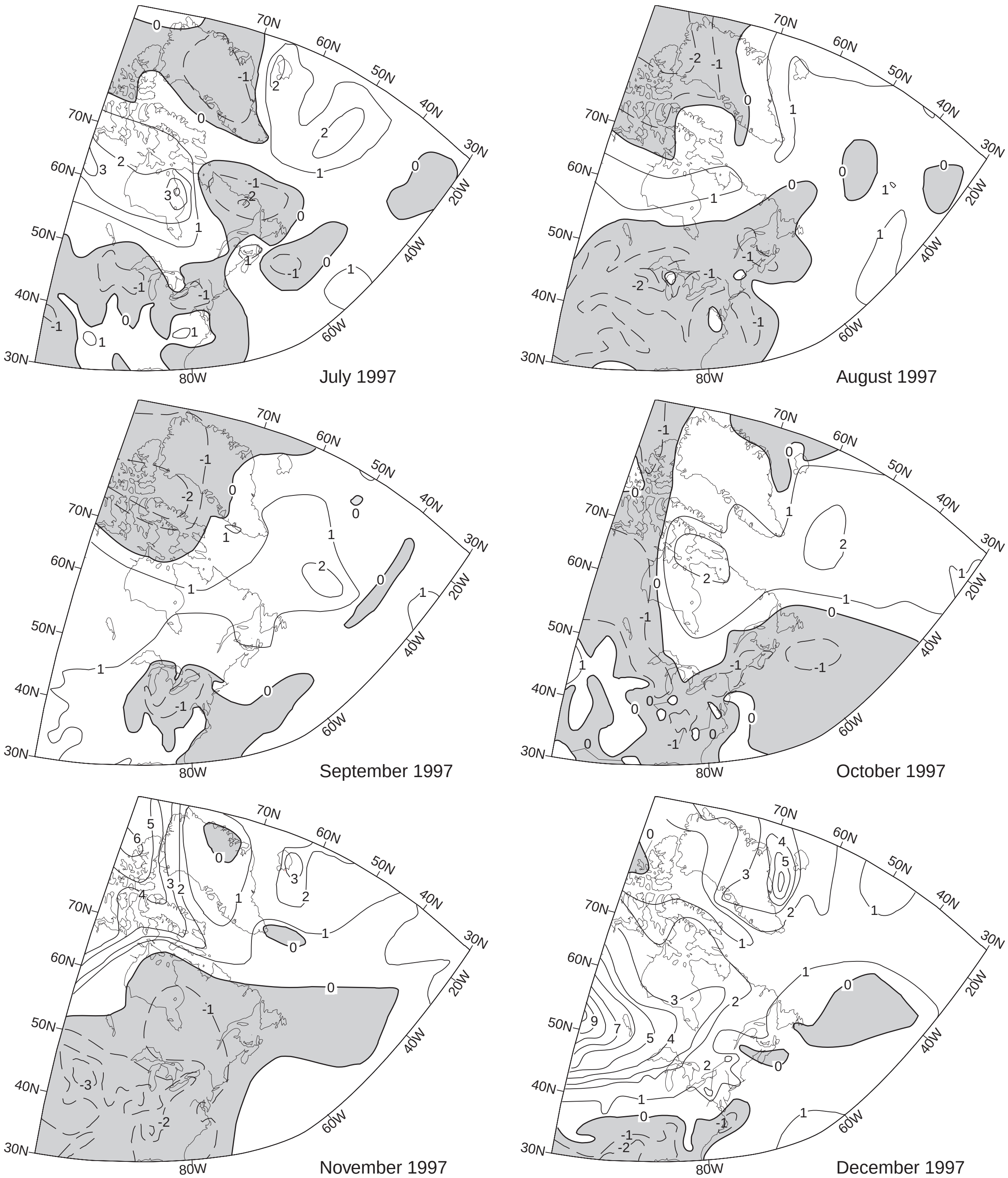

Fig. 2. (Continued). Monthly air temperature anomalies (in °C) over the NW Atlantic in 1997 relative to the 1961–90 means (from *Grosswetterlagen Europas*). The shaded anomalies indicate areas of colder-than-normal temperatures.

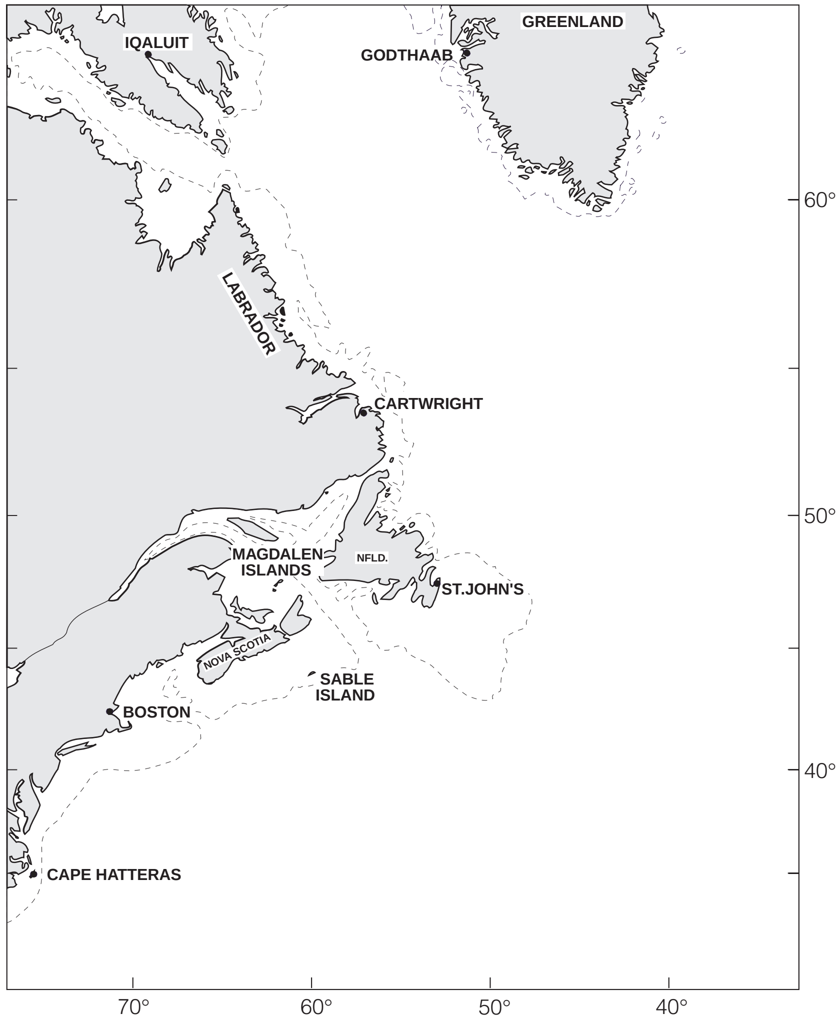

Fig. 3. Northwest Atlantic showing coastal air temperature stations.

was warmer-than-normal. At St. John's and the Magdalen Islands, air temperatures from the spring to the end of the year showed no strong trend, fluctuating about the long-term normal.

The annual mean air temperatures for 1997 were above normal at the northern most sites of Iqaluit (anomaly of 1.0°C) and Godthaab (0.2°C). At Cartwright and the Magdalen Islands they were normal while at St. John's and the remaining stations the annual anomalies were negative. The maximum negative anomaly was at St. John's (-0.6°C), followed by Sable Island (-0.4°C) and then Boston and Cape Hatteras (-0.3°C). These are generally consistent with the anomaly pattern in Fig. 1.

The time series of annual temperature anomalies for the eight sites are shown in Fig. 5. The 1997 anomalies generally declined from 1996 values except at Boston and Cape Hatteras where they were similar to last year's value. Note that the interannual variability since 1960 at Godthaab, Iqaluit, Cartwright, and, to a lesser extent, St. John's have been dominated by the large amplitude fluctuations with minima in the early 1970s, early to mid-1980s and the early 1990s, suggesting a quasi-decadal period. Indeed, the recent rise in temperature at these sites is consistent with a continuation of this near decadal pattern. These oscillations coupled with a general downward trend have resulted in temperature anomalies since 1970 being predominantly below normal. Temperature anomalies at the Magdalen Islands and Sable Island have been of much lower amplitude than those to the north and show no signs of the general downward trend. They do, however, contain minima

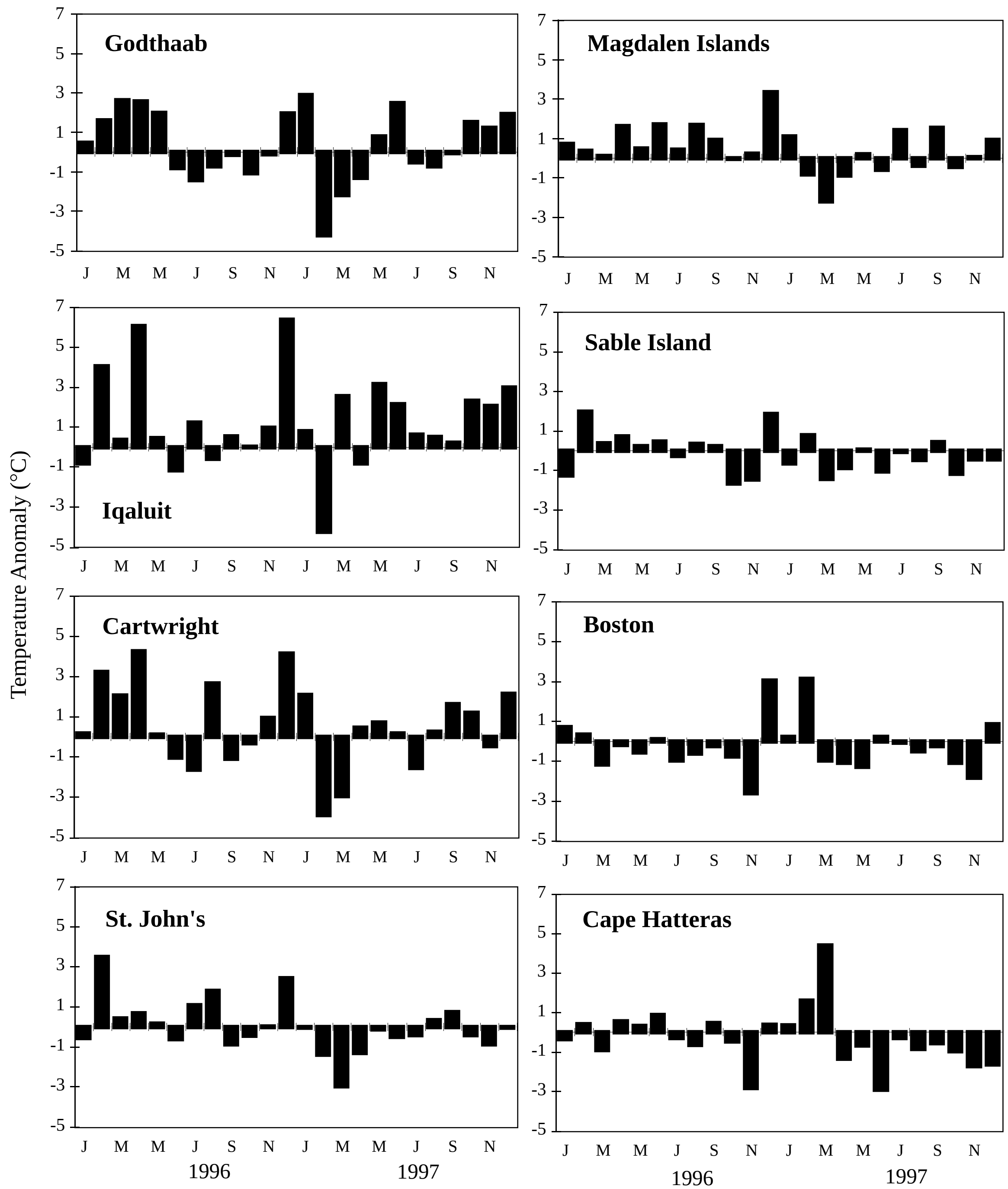

Fig. 4. Monthly air temperature anomalies in 1996 and 1997 at selected coastal sites (see Fig. 3 for locations).

in the early 1970s (both sites), the mid-1980s (Sable Island only) and in the 1990s (Magdalen Islands only). At Boston and Cape Hatteras, there has also been decadal variability in air temperatures but they have generally been out of phase with the temperature fluctuations in the Labrador Sea area. Thus, for example, when the temperatures were very cold in Labrador during the early 1990s, they were relatively warm along the US seaboard (Fig. 5).

Sea Surface Air Pressures

Climatic conditions in the Labrador Sea area are closely linked to the large-scale pressure patterns and associated atmospheric circulation. Monthly mean

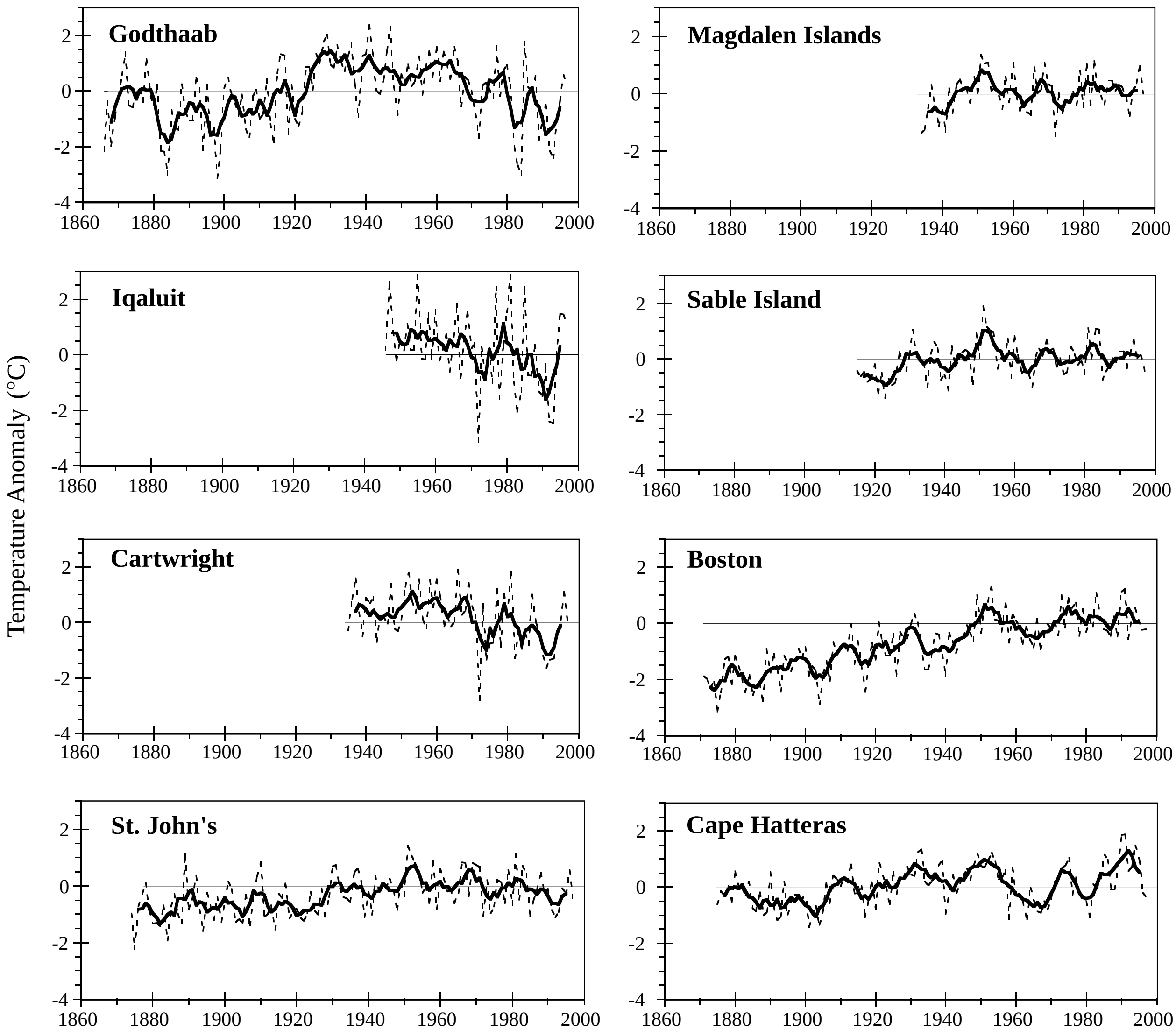

Fig. 5. Annual (dashed) and 5-year running (solid) means of the air temperature anomalies at selected sites.

sea-surface pressures over the North Atlantic are published in *Die Grosswetterlagen Europas*. The long-term seasonal means are dominated by the Icelandic Low centred between Greenland and Iceland and the Bermuda-Azores High centred between Florida and northern Africa (Fig. 6). Winds rotate counterclockwise around the Low and clockwise around the High. The strength of the wind is larger where the pressure contours are closer together (pressure gradients are steeper). The strengths of the Low and High vary seasonally from a winter maximum to a summer minimum. Seasonal anomalies of the sea-surface pressure for 1997, relative to the 1961–90 means, are shown in Fig. 7. Winter includes December 1996 to February 1997, spring is March to May, summer is June to August and autumn is September to November.

In the winter of 1996/97, a positive air pressure anomaly developed over the western North Atlantic with a maximum (exceeding 3 mb) centred south of Newfoundland. A ridge of high pressure anomalies extended from there to the northeast covering eastern Greenland. This ridge separated two negative anomaly areas, one centred over Foxe Basin in eastern Canada (-2.6 mb) and the other near the Azores (near -3 mb). This pressure pattern suggests stronger than normal offshore winds off Labrador and northern Newfoundland but anomalous southerly winds along the Middle Atlantic Bight to the Scotian

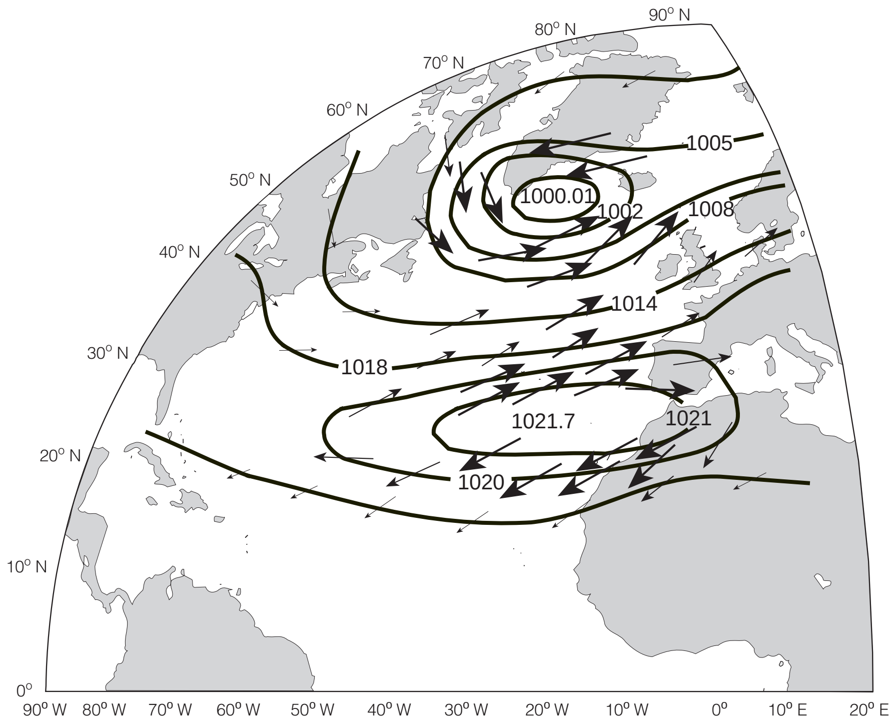

Fig. 6. The long-term (1961–90) mean sea surface pressure during the winter (average of December, January and February). A schematic of the wind field associated with the mean pressures is also shown.

Shelf. Western Greenland would have experienced greater amounts of southwesterly winds. In the spring of 1997, a negative anomaly covered most of the northern North Atlantic with the centre (-4.9 mb) east of Newfoundland. Further to the east, positive anomalies developed with two separate centres, one over France (5.6 mb) and the other over northern Greenland (3.1 mb). A second negative anomaly pressure system formed (minimum -3.3 mb) off northern Norway. In contrast to the winter, the winds off Labrador and northern Newfoundland would have been principally onshore, from the northwest in the Gulf of St. Lawrence and offshore over the Scotian Shelf to the Middle Atlantic Bight. Both the winter and spring pressure patterns show more meridional flow than usual. In the summer, the negative pressure anomalies over the North Atlantic were weaker than in the spring but extended further eastward to cover the entire ocean from North America to Europe. The largest negative anomaly (near -3 mb) was recorded over southwestern Ireland. To the north and south of this band of below-normal pressures were positive anomalies, with the maximum values being located on the eastern side of the Atlantic. Two centres of positive anomalies were observed in the north, one near Norway and the other over northern Greenland. In the south the centre of positive pressure anomaly was situated just off West Africa. This pressure pattern resulted in a predominance of easterly to northeasterly winds over eastern North America. The autumn air pressure pattern is similar to that of summer but of higher magnitude. The negative pressures extended latitudinally both north and south with the centre located to the southeast of Newfoundland (-5.3 mb). The centre of the positive anomaly remained over northern Greenland (7.7 mb). This would cause principally anomalous westerly winds on the Labrador coast and over the Labrador Sea and southwesterly between Newfoundland and the Middle Atlantic Bight.

NAO Index

The North Atlantic Oscillation (NAO) Index is the difference in winter (December, January and February) sea level pressures between the Azores and Iceland and is a measure of the strength of the winter westerly winds over the northern North Atlantic (Rogers, 1984). A high NAO index corresponds to an intensification of the Icelandic Low and Azores High. Strong northwest winds, cold air and sea temperatures and heavy ice in the Labrador Sea area

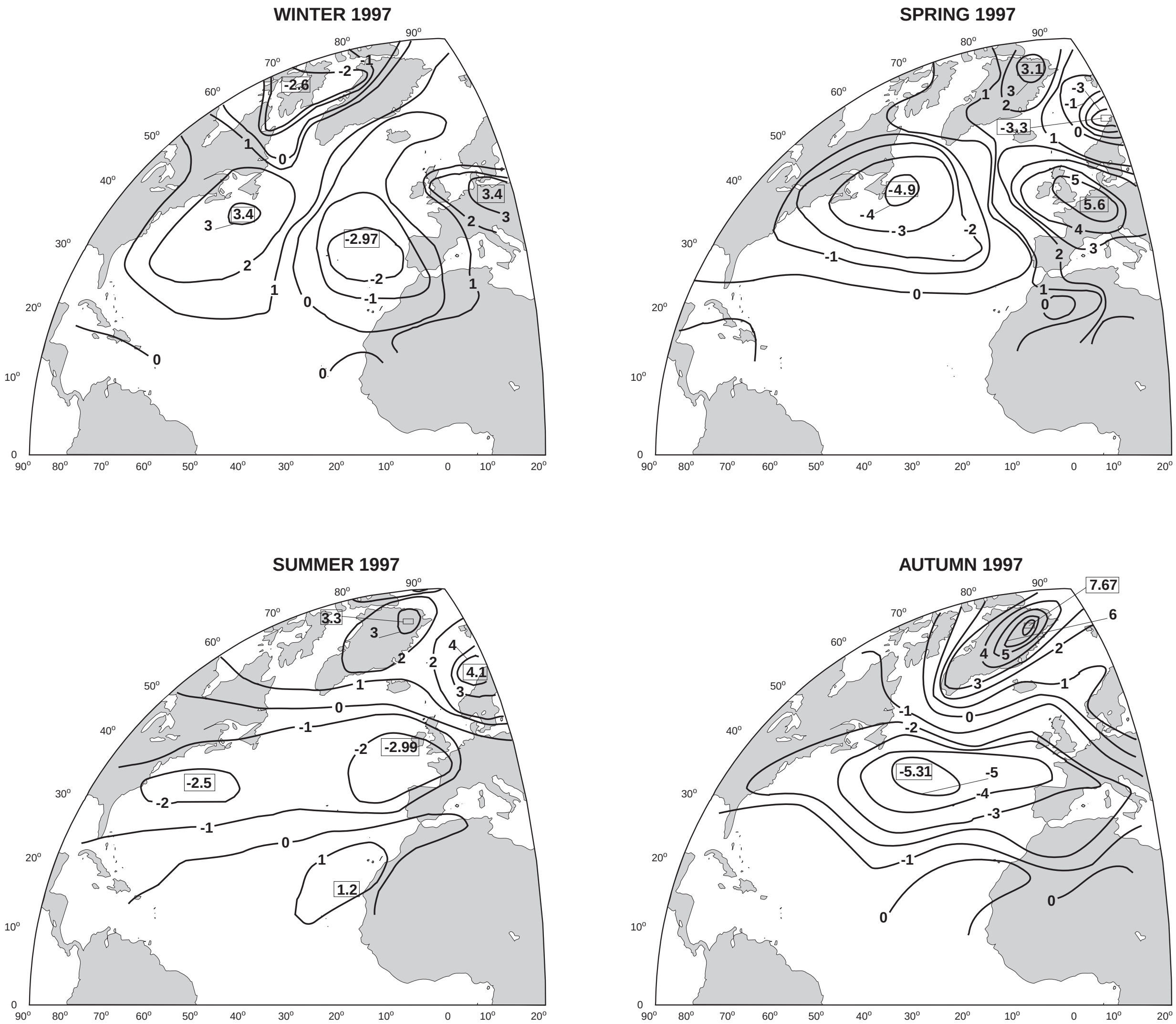

Fig. 7. Seasonal sea-surface air pressure anomalies (mb) over the North Atlantic in 1997 relative to the 1961–90 means.

are also associated with a high positive NAO index (Colbourne *et al.*, 1994; Drinkwater, 1996). The annual NAO index is derived from the measured mean sea level pressures at Ponta Delgada in the Azores minus those at Akureyri in Iceland. The small number of missing data early in the time series was filled using pressures from nearby stations. The NAO anomalies were calculated by subtracting the 1961–90 mean.

In 1997, the NAO anomaly was below normal for the second consecutive year but up from the minima observed in 1996 (Fig. 8). These two years contrast with the very high NAO anomalies that had persisted since the late 1980s and indicate the possibility of a significant shift in the large-scale atmospheric circulation. However, this decline also fits the pattern of near decadal variability that has persisted since the 1960s, and as such was expected, although its amplitude was greater than anticipated.

Sea Ice Observations

Information on the location and concentration of sea ice is available from the daily ice charts published by Canadian Ice Service of Environment Canada in Ottawa. The long-term medians, maximum and minimum positions of the ice edge (concentrations above 10%) based on the composite for the years 1962 to 1987 are taken from Coté (MS

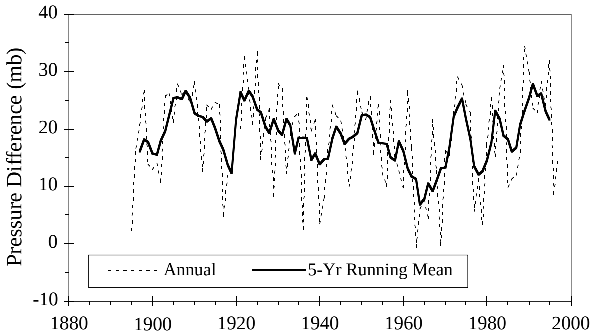

Fig. 8. Annual and 5-year running means of the anomalies of the North Atlantic Oscillation Index.

1989). It must be remembered that the location of the ice edges are constantly in motion due to the action of the winds and ocean currents and hence rapid changes can occur from one day to the next.

Newfoundland and Labrador

At the end of 1996, sea ice lay off the southern Labrador coast in the vicinity of Hamilton Inlet resulting in an areal coverage that was slightly less than the long-term median for that time of the year (Fig. 9a). This was in part due to above normal air temperatures during the second half of December that slowed ice formation. By the beginning of January, the ice extent along the south Labrador coast was approximately two weeks later than normal. By mid-January, the ice had extended south to Belle Isle Strait but remained much closer inshore than normal. This resulted in much less ice covered than usual, due to the continuing relatively warm air temperatures, especially off southern Labrador. By the first of February, ice coverage was near its median value, a response to the presence of very cold temperatures during the second half of January. Continuing cold air temperatures and moderate to strong northwesterly winds during February pushed the ice pack southward and offshore, increasing the areal coverage to between median and maximum values by the beginning of March. Cold, windy conditions prevailed throughout March. These left the sea ice again intermediate between median and maximum extent by 1 April (Fig. 9b). The northern Newfoundland communities and harbours were clear of ice, as the ice edge lay offshore. By 1 May, strong northeasterly winds over southern Labrador and northern Newfoundland packed the ice inshore from St. John's north. Retreat of the ice proceeded during May resulting in ice coverage near the long-term median by 1 June. There was, however, an isolated patch of ice off northern Newfoundland between Notre Dame and White bays at this time. Ice remained off the mouth of Hamilton Inlet through June and was still there on 1 July. By 10 July all traces of ice had disappeared from southern Labrador.

The time series of the areal extent of ice on the Newfoundland and southern Labrador shelves (between 45–55°N; I. Peterson, pers. comm., Bedford Institute, Nova Scotia, Canada) show the peak extent during 1997 was greater than in 1996 and was near, but slightly below, that of the early 1990s (Fig. 10). The average area during the period of general advancement (January to March) and retreat (April to June) also increased slightly compared to 1996. These values indicate that the areal coverage on average was less than the early 1990s and was extremely low during the time of retreat. The monthly means similarly show ice coverage in 1997 was typically higher than in 1996 but less than the early 1990s (Fig. 11). In summary, 1997 was an average to lighter-than-average ice year on the Labrador and Newfoundland shelves. Note that during January through April there has been a general increase in the area of ice over the past 30 years but no such trend exists during May through July. Variations in ice volume tend to mirror the trends in ice area, based upon correlative studies we have carried out in the Gulf of St. Lawrence.

Past reviews included an analysis of the time of onset, duration and last presence of sea ice based upon data from 24 sites located off southern Labrador, the east and north coasts of Newfoundland and in the Gulf of St. Lawrence. Up to and including 1994, the Ice Service of Environment Canada in Ottawa provided this analysis. In 1995, we took over the analysis. During this year, similar analyses were undertaken using more comprehensive sea-ice databases that are maintained at the Bedford Institute of Oceanography. The weekly concentration and types of ice within 0.5° latitude by 1° longitude areas were recorded through the ice season. The dates of the first and last appearance of ice within these areas as well as the duration of ice were determined. The databases begin in the early 1960s and persist to the present. Long-term means (30-years, 1964–93) of each variable were determined (using only data during the years ice was present) and subtracted from the 1997 values to obtain anomalies. Optimal estimation of the gridded data was used to smooth the data for plotting purposes. In 1997, ice first appeared north of Hamilton Bank off southern Labrador in late December, and gradually spread southward with ice first appearing on the northeastern Grand Bank in mid-March (near day 70, Fig. 12). Relative to the long-term mean, ice on the Newfoundland and Labrador shelves generally appeared slightly later-than-normal with the exception of some offshore locations where it arrived on schedule or slightly earlier (Fig. 12, note positive anomalies indicate ice formed late which is generally associated with warmer conditions). Ice began to disappear from some of the offshore and southern sites in March (Fig. 13). It started to retreat from northern Newfoundland waters during April, from southern Labrador in May but lasted in the region south of Hamilton Inlet until 8 June. Over most of the Newfoundland and Labrador region ice disappeared earlier-than-normal (positive anomaly), greater than 30 days early off southern Labrador and northern Newfoundland. The only exceptions were small areas along the coast of Newfoundland and in the extreme offshore areas where ice was observed later-than-normal. The duration of the ice season ranged from less than a month off the northern Grand Banks and offshore to over 170 days north of Hamilton Inlet on the southern Labrador (Fig. 14). Note that the duration is not simply the date of the first presence minus the last presence because the

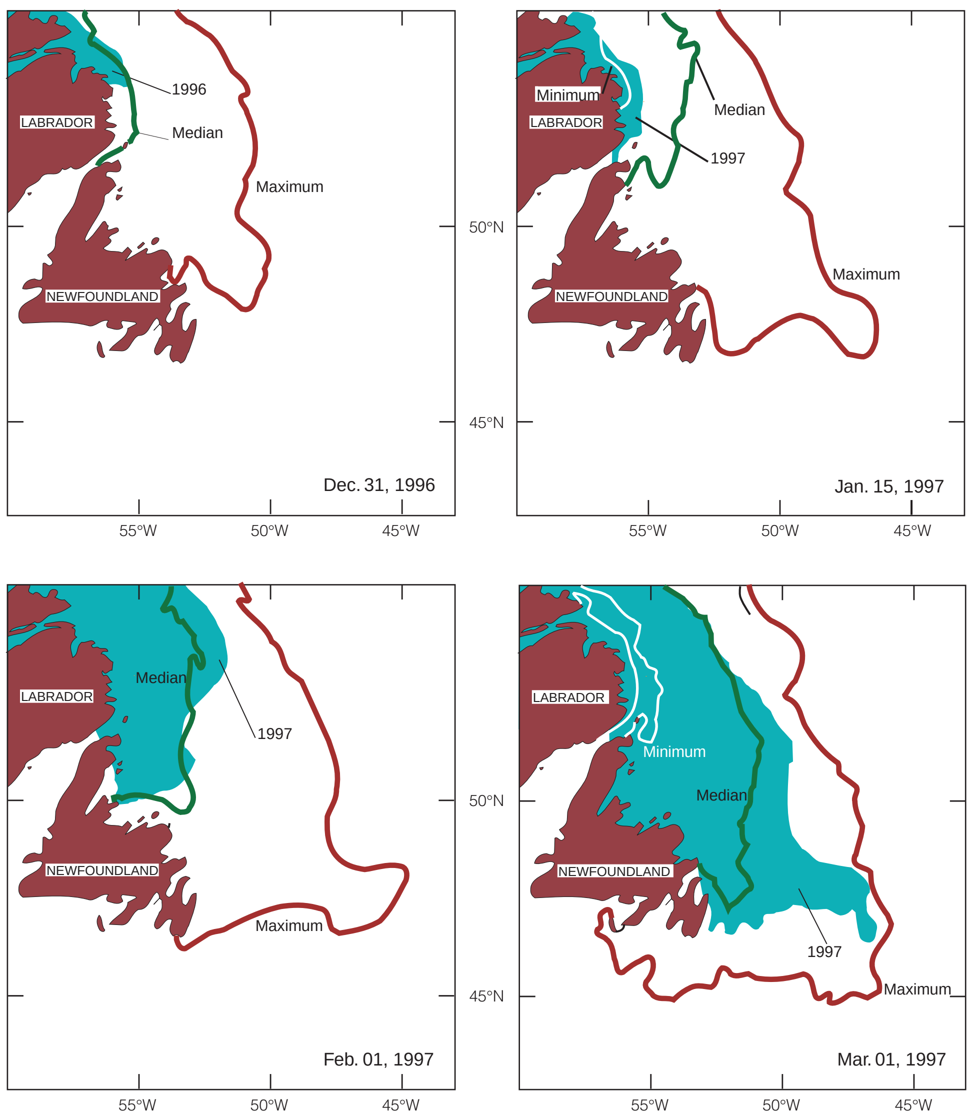

Fig. 9a. The area of sea ice (>10% concentration) together with the historical (1962–87) minimum, median and maximum positions of the ice edge off Newfoundland and Labrador between December 1996 and March 1997.

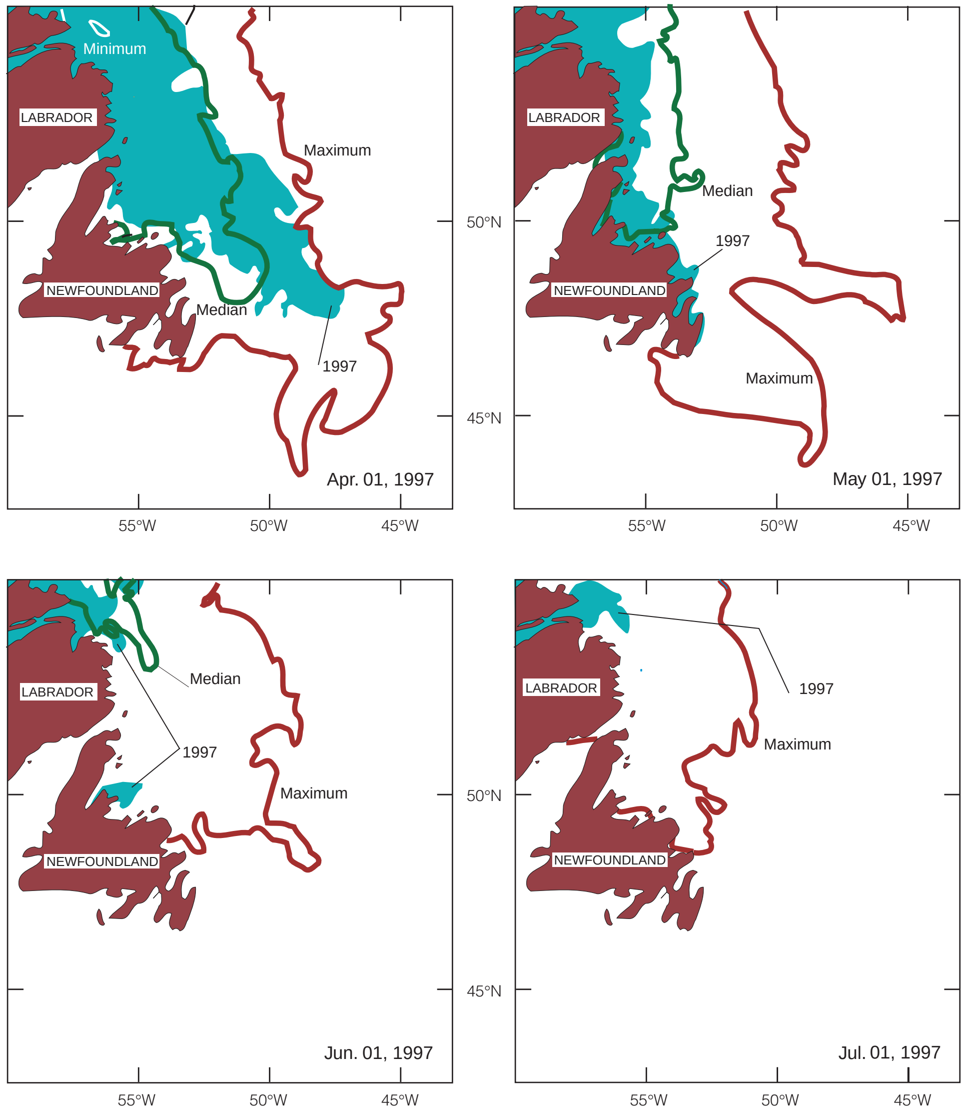

Fig. 9b. The area of sea ice (>10% concentration) together with the historical (1962–87) minimum, median and maximum positions of the ic edge off Newfoundland and Labrador between April and July 1997.

ice may disappear for a time and then reappear. The ice duration was shorter-than-normal (negative anomaly) over most of the Labrador and Newfoundland waters, over 1 month in some areas. Exceptions included the White Bay area of northern Newfoundland and the far offshore regions, especially off southern Labrador where the duration was slightly longer-than-normal by upwards of 10 days or more in some locations.

Icebergs

The International Ice Patrol Division of the United States Coast Guard monitors the number of icebergs that pass south of 48°N latitude each year. Since 1983, data have been collected with SLAR (Side-Looking Airborne Radar). During the 1996/97 iceberg season (October to September), a total of 1 011 icebergs were spotted south of 48°N. The monthly totals for February to August were 10, 475, 162, 238, 80, 43, and 3 (Fig. 15). No icebergs were spotted between October 1996, and January 1997, inclusive, or in September 1997. In 1997, 98.7% of the icebergs were observed during the primary iceberg season of March to July, higher than the mean in 1983–97 of 91%. Almost 50% of the total number of icebergs during 1997 penetrated south of 48°N in

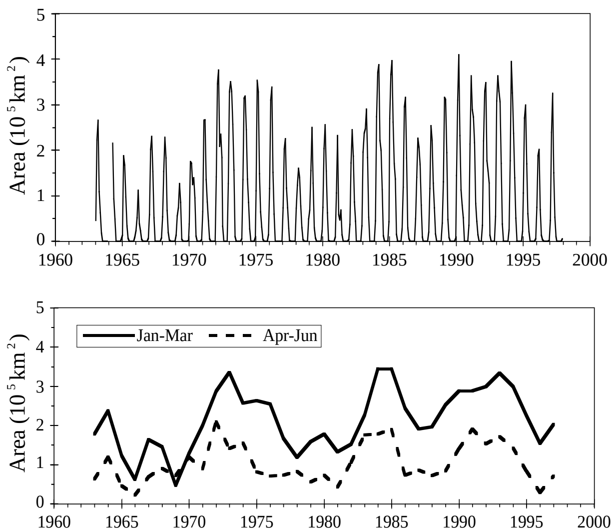

Fig. 10. Time series of the mean ice area by month (top panel) and the during ice advance (Jan–Mar) and ice retreat (Apr–Jun) (bottom panel) on the southern Labrador and Newfoundland shelves.

March, proportionally more then on average during the years icebergs have been detected using SLAR. The total number of icebergs in 1997 was above the long-term mean and up from 1996 but was lower than the earlier years of the 1990s (Fig. 15). Note that periods of large number of icebergs reaching south of 48°N occurred in the early 1970s, the mid-1980s and the early to mid-1990s, all periods of cold air temperatures, strong NW winds and extensive ice cover.

Gulf of St. Lawrence

At the end of December 1996, no ice was present in the Gulf of St. Lawrence and the upper St. Lawrence Estuary due to warmer-than-normal air temperatures (Fig. 16). By mid-January, ice had formed in the western Gulf along the coast from the Gaspe Peninsula to Nova Scotia including throughout most of Northumberland Strait. Ice had also appeared along most sections of the north shore of Quebec from Anticosti Island to the Strait of Belle Isle. The ice was approximately two weeks behind schedule and the areal coverage was much less than the long-term median. This again was primarily due to the relatively warm air temperatures during the first half of January. In the second half of January, northwesterly winds and below normal temperatures over the northwestern portion of the Gulf resulted in rapid spreading of the ice, such that ice coverage was only slightly less than the long-term median by the beginning of February. The ice was thinner than normal, however. Cold air and strong northwest winds continued during February resulting in the Gulf being ice covered by 1 March, except for St. Georges Bay, Newfoundland. The ice edge was very near its median position at this time. Ice retreated during March and by 1 April it had left the Estuary and many of the coastal areas of the southwestern Gulf. There was, however, more ice than normal in the Gulf at this time. By 1 May, ice was limited to the southern Magdalen Shallows and the Strait of Belle Isle but still was more extensive than normal. The ice disappeared from the southern Gulf by the 17 May but remained in the northern Gulf until 3 June. The last ice in the Gulf was located north of Anticosti Island.

During 1997, an ice database for the Gulf of St. Lawrence and Scotian Shelf was completed (Drinkwater *et al.*, 1999) and a comprehensive analysis of the first and last appearance of ice and the ice duration was carried out similar to that for the Newfoundland area. The Gulf and Scotian Shelf was divided into 130 areas of dimensions 0.5° latitude by 1° longitude. During 1997, ice formation within the Gulf (landward of Cabot Strait) ranged from near the beginning of the year (prior to day 15) along the north shore of Quebec, the St. Lawrence Estuary and the western Magdalen Shallows to after mid-February (day 45) off southwestern Newfoundland (Fig. 12). Except around the eastern end of Anticosti Island, this represented a later-than-normal appearance of ice, typically by 10 days to over 20 days with the later occurring off western Newfoundland. The day of last appearance shows the typical pattern with ice lasting longest in the southern Magdalen Shallows and along the north shore of Quebec through to the Strait of Belle Isle (Fig. 13). Over most of the region this represented later-than-normal disappearance, although in the outer St. Lawrence Estuary and part of the Magdalen Shallows, the ice left early. Note that north of Anticosti Island, ice remained over 60 days later-than-usual. The duration of ice ranged from less than 60 days off southwestern Newfoundland to over 130 days along the Quebec north shore (Fig. 14). Relative to the long-term mean during years when ice was present, ice lasted longer than normal throughout the eastern Gulf, around Anticosti Island and the southern Magdalen Shallows. In contrast, there were fewer days of ice

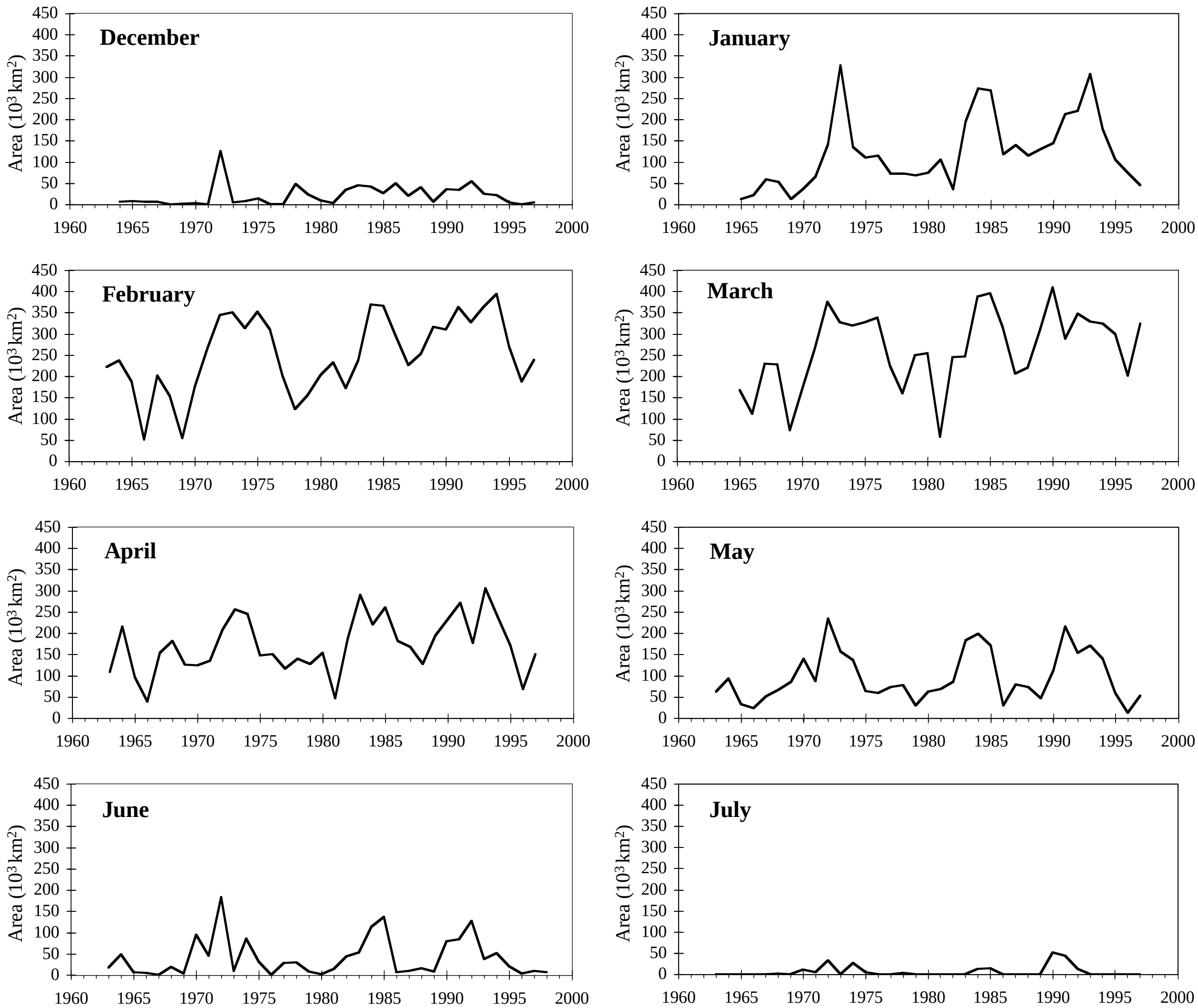

Fig. 11. Ice area on the southern Labrador and northern Newfoundland shelves between 45°N–55°N by month.

over the rest of the Magdalen Shallows and in most of the St. Lawrence Estuary. The maximum anomaly in duration of ice was around 20 days, off eastern Prince Edward Island and small areas near southwestern Newfoundland and the Quebec north shore.

Scotian Shelf

Sea ice normally flows out of the Gulf of St. Lawrence through Cabot Strait pushed by northwest winds and the mean ocean currents. Seaward of Cabot Strait, ice first appeared during the first half of February (Fig. 12), continued to spread over the northeastern Scotian Shelf through March, and appeared off the Atlantic coast of Nova Scotia south of Chedabucto Bay in mid-April. This was later-than-normal by 10 to over 50 days. Most of this ice had disappeared during the latter half of April, which is 10 to 30 days later than normal (Fig. 13). The duration of ice south of Cabot Strait ranged from 90 days off Cape North on Cape Breton Island to 10 and less on the northeastern Scotian Shelf and off southern Newfoundland (Fig. 14). Note that a duration of less than 10 days is not plotted. The duration of ice in 1997 was close to the long-term mean in these areas (Fig. 14).

The maximum area of ice seaward of Cabot Strait was near normal in 1997 and up from the very low value of 1996 (Fig. 17). While there were more

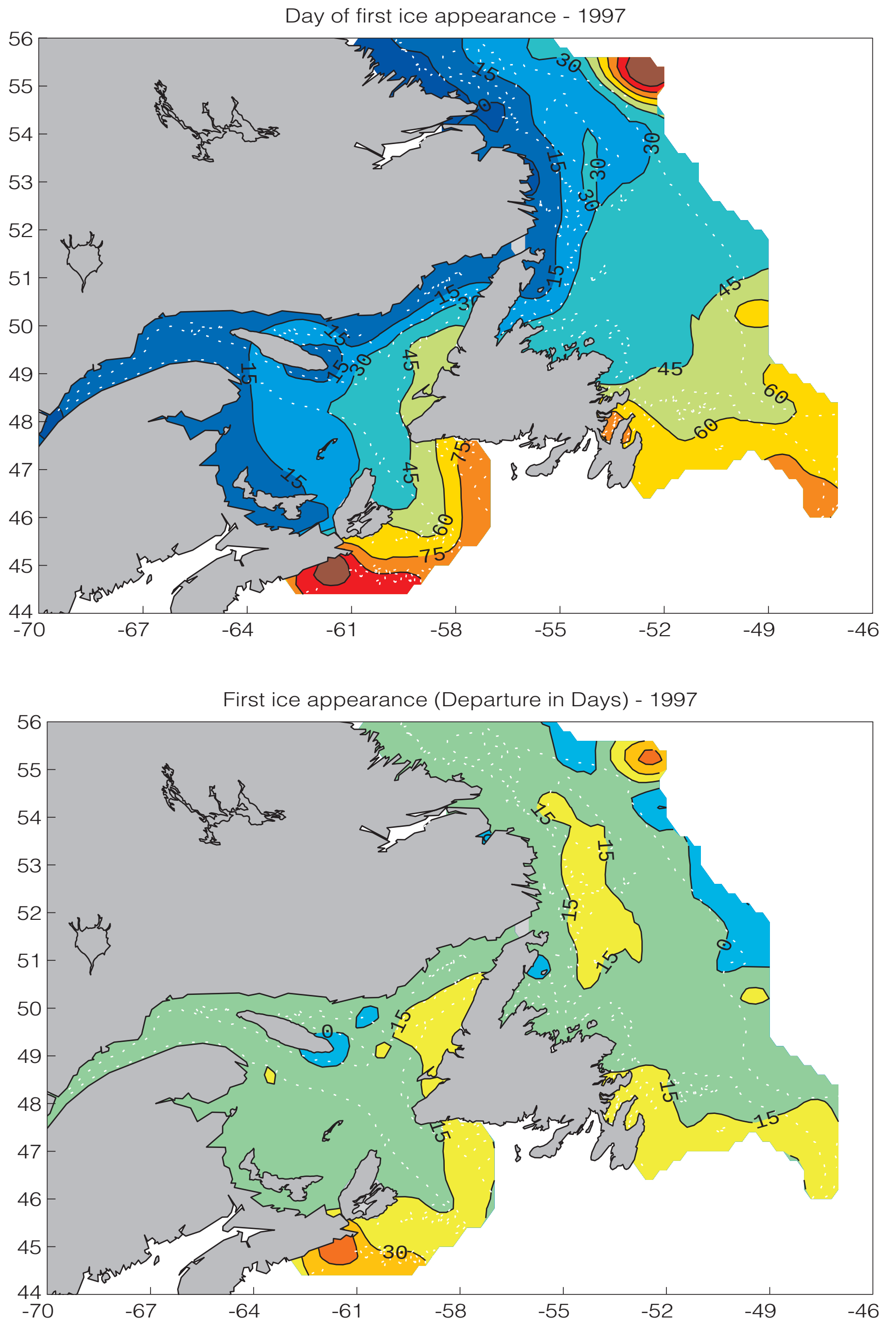

Fig. 12. The time of first presence of ice during 1997 measured in days from the end of 1996 (top panel) and their anomalies relative to the long-term mean in days (bottom panel).

ice days than usual, the integrated ice area (sum of the ice area times the number of days) was less than normal. This suggests that although ice remained for a long time, ice conditions on the Scotian Shelf were less severe than usual. This can also be seen from the monthly time series of ice area (Fig. 18). Based upon data collected since the 1960s, the furthest south that the ice penetrates is just past Halifax along the Atlantic coast of Nova Scotia. However, historical records, albeit incomplete, suggest that in the past ice penetrated much further south, for example in the late 1800s sea ice was observed in the Gulf of Maine (A. Ruffman, pers. comm., Halifax, Canada).

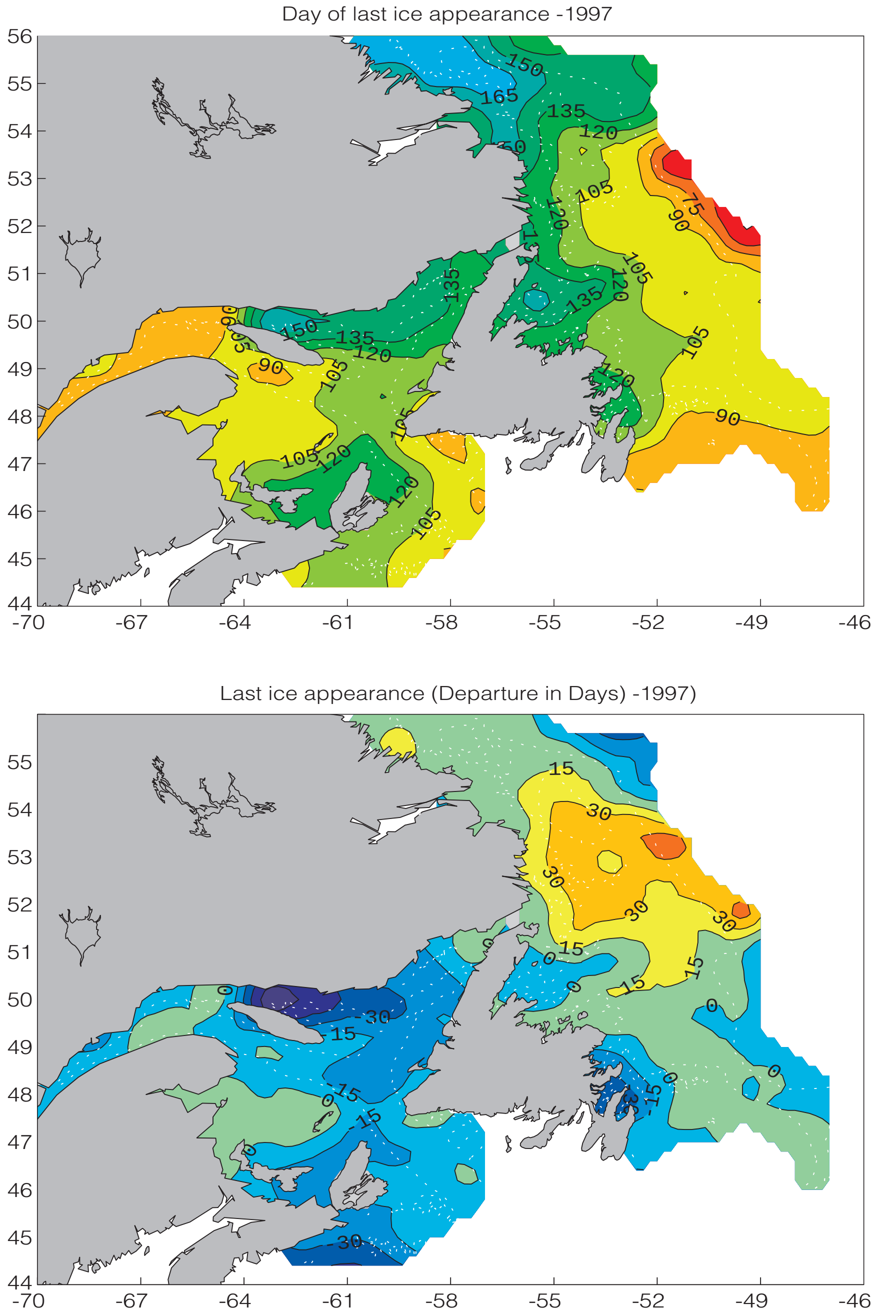

Fig. 13. The time of last presence of ice in 1997 measured in days from the end of 1996 (top panel) and their anomalies relative to the long-term mean in days (bottom panel).

Oceanographic Observations

Newfoundland and Labrador

Station 27

Temperature and salinity have been monitored since 1946 at Station 27, a site located approximately 10 km off St. John's, Newfoundland. This site lies within the inshore branch of the Labrador Current but is considered to be representative of hydrographic conditions at long periods (inter-annual to decadal) over the continental shelf from southern Labrador to the Grand Banks (Petrie *et al.*, 1992). The station was visited 47 times in 1997, with a monthly maximum of 8 in May and again in July. No measurements were taken in February or

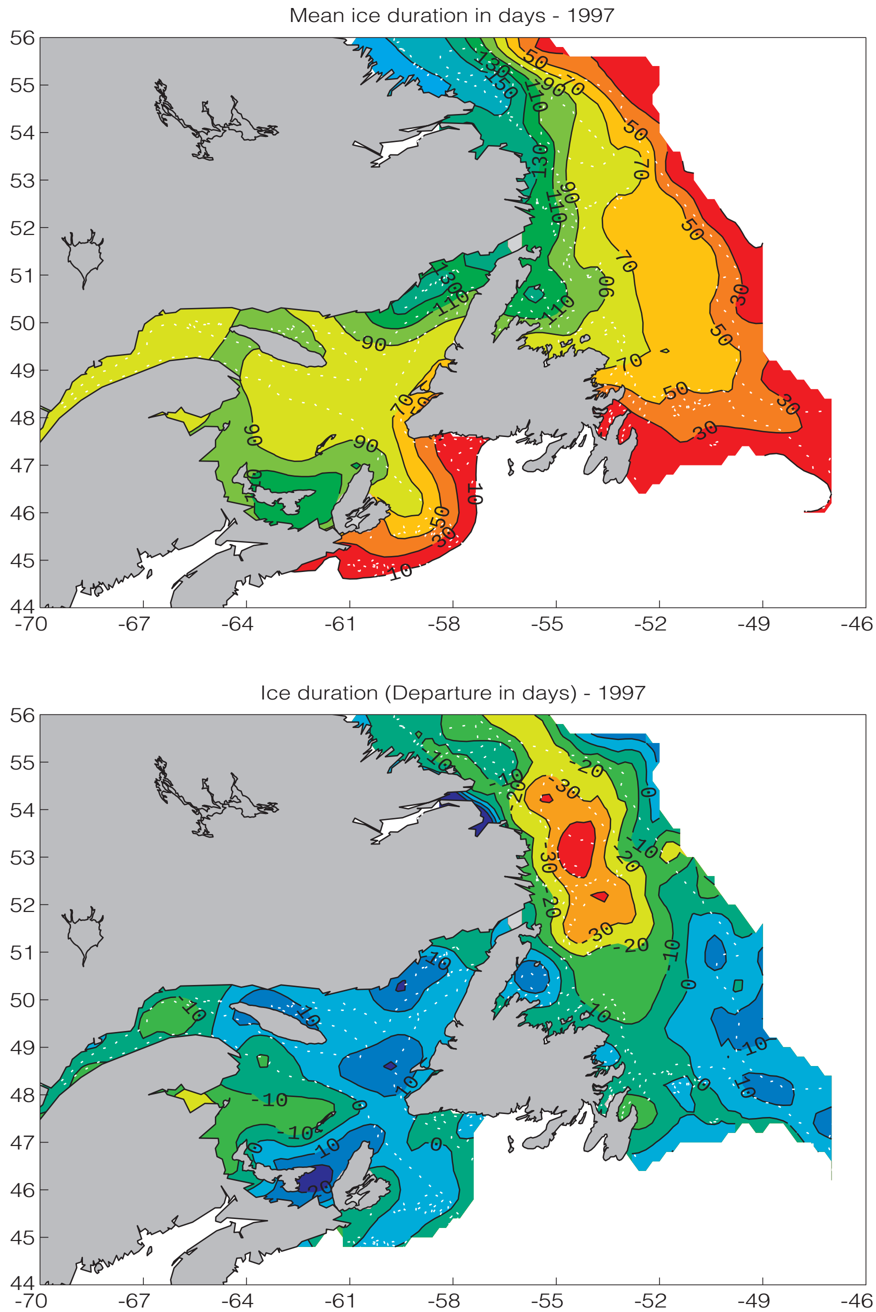

Fig. 14. The duration of sea ice in days during 1997 (top panel) and their anomalies relative to the long-term mean (bottom panel).

March. The data were collected at, or linearly interpolated to, standard depths (0, 10, 20, 30, 50 75, 100, 125, 150 and 175 m) and monthly means were calculated for each depth. The monthly averaged temperatures and salinities in 1997 together with their anomalies relative to 1961–90 are shown in Fig. 19.

The water column is usually isothermal during the winter with mean temperatures falling below -1°C in March. Although no data were available for March 1997, it is believed that temperatures were in this range given the appearance of subsurface temperatures colder than -1°C in April. Below 0°C waters were observed through until the autumn (Fig.

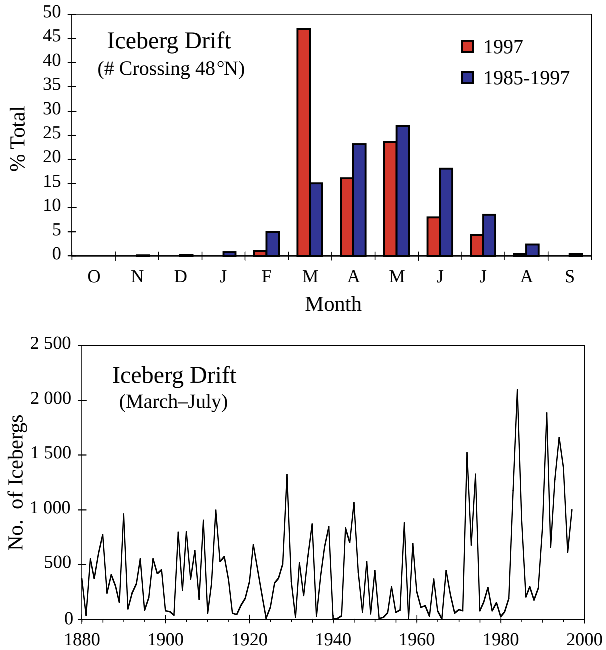

Fig. 15. The percentage of the total number of icebergs crossing south of 48°N by month during the iceberg season 1996/97 and the mean for 1983–97 (top panel) and the number of icebergs during March to July from 1880 to 1997 (bottom panel).

19). Upper layer (generally <50 m) temperatures were below 0°C until April, after which they began to rise and reached a peak of over 12°C at the surface in August before autumn cooling set in. The August mean temperature was approximately 2°C below that recorded in 1996. Note the propagation of surface layer heat down into the lower layers in the late autumn. Below normal temperatures dominated the anomaly pattern with the maximum amplitudes in the surface layer in spring and early summer and just below the surface layer in October (Fig. 19, 20). Positive temperature anomalies were observed throughout the water column in January, in the surface layer in the autumn, and near bottom during most of the year.

In 1997, near surface salinites at station 27 were slightly less than 32 in winter, rose above 32 in the spring and then declined to a minimum of <31 in September and October (Fig. 19). Based on the studies of Myers *et al*. (1990) and Petrie *et al*. (1991), the low salinities in late summer and early autumn are related to the arrival of ice melt from the Labrador Shelf. The maximum salinities (>33) appeared near bottom. Salinities in 1997 were relatively fresh causing negative anomalies throughout most of the year (Fig. 19, 20). This is the third consecutive year of such conditions. The largest negative salinity anomaly was in the surface waters in May (below -0.25). Positive salinity anomalies appeared at mid-depth during the second half of the year and extended to the bottom in October.

The time series of monthly temperature anomalies at Station 27 at 0, 50, 100, 150 and 175 m for 1970–97 are shown in Fig. 21. Note that the temperature scales on the plots for 100 m and above are larger than those for depths deeper than 100 m. At the surface and 50 m there is large, short-term variability reflecting atmospheric heating and cooling. Cooling was observed between 1996 and 1997, most evident from 50 to 150 m. This cooling resulted in below normal temperatures at 50 and 100 m and near normal temperatures by year's end elsewhere. At 150 and 175 m, negative anomalies had persisted almost continuously from 1982 or so until 1996. The coldest periods at Station 27 roughly correspond to those identified from the air temperature anomalies, i.e. the early 1970s, the mid-1980s and the 1990s.

The depth-averaged temperature, which is proportional to the total heat content within the water column, also shows large amplitude fluctuations at near decadal time scales with cold periods during the early 1970s, mid-1980s and early 1990s (Fig. 22). The total heat content of the water column, which was at a record low in 1991, increased sharply in 1996 and reached a level that matched those observed during the warm 1950s and 1960s. The heat content in 1997 decreased relative to 1996 and was near the long-term mean. The 0 to 50 m depth-averaged summer salinity is also plotted in Fig. 22. The low salinity values of the early 1990s are comparable to values experienced during the Great Salinity Anomaly of the early 1970s (Dickson *et al*., 1988). In 1997, salinities rose to near-normal values, up from the very low salinities of 1995. The 50 m depth-averaged summer salinities had been shown to be positively related to cod recruitment by Sutcliffe *et al*. (1983) and Myers *et al*. (1993) but the validity of this relationship has been seriously questioned (Hutchings and Myers, 1994).

Cold Intermediate Layer

On the continental shelves off eastern Canada from Labrador to the Scotian Shelf, intense

Fig. 16. The area of sea ice (>10% concentrations) together with the historical (1962–87) minimum, median and maximum positions of the ice edge in the Gulf of St. Lawrence at selected dates between December 1996 and May 1997.

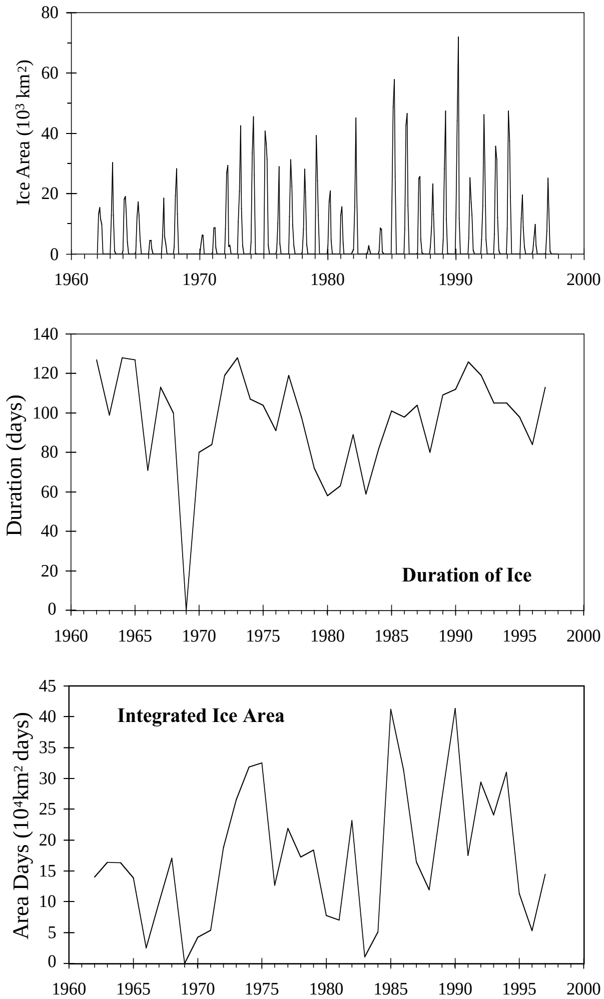

Fig. 17. Time series of the monthly mean area of sea ice (top panel), the duration of ice (middle panel) and the annual integrated ice area (summation of the area times the number of days, bottom panel) seaward of Cabot Strait.

vertically mixing and convection during winter produce a homogeneous cold upper layer that overlays a warmer deeper layer, or occasionally may extend to the bottom in shallow areas. With spring heating, ice melt and increased river runoff, a warm low-saline shallow surface layer develops. The strong stratification in this upper layer inhibits downward transfer of heat, and the waters below remain cold throughout the spring and summer. The latter are called the cold intermediate layer (CIL) waters.

Three standard hydrographic transects (Hamilton Bank, off Bonavista Bay and along 47°N to Flemish Cap) have been occupied during the summer and autumn by the Northwest Atlantic Fisheries Centre in St. John's, Newfoundland in most years since 1950. The areal extent of the CIL in summer along each transect (as defined by waters <0°C) is plotted in Fig. 23. The annual variability in the cross-sectional areas of the CIL are highly correlated between transects (Petrie *et al*., 1992). In 1997, the summertime CIL areas were below the long-term means and declined relative to 1996 at Seal Island and Bonavista but were slightly above normal and increased from 1996 values on the Flemish Cap section. The total cross-sectional area of <0°C water on the Newfoundland Shelf, except on the Grand Bank, is continuing a below normal trend established in 1995. In general, periods of warmer-than-normal core temperatures are correlated with smaller-than-normal CIL areas. The minimum temperature observed in the core of the CIL along the Seal Island transect during the summer of 1997 was -1.62°C compared to a normal of –1.57°C. Core temperatures along the Bonavista transect were -1.66°C compared to a normal of -1.63°C and about normal along the Flemish Cap transect at -1.51°C. These minimum temperatures were somewhat colder than values during the same time period in 1996.

The total volume of CIL water (<0°C) over the 2J3KL area since 1980 (Fig. 24) has been estimated following the method of Colbourne and Mertz (MS 1995). The mean volume in summer for the period 1980–94 is just over 4×10^4 km^3, roughly one-quarter the total volume of water on the shelf. Maximum volumes tend to occur during the cold periods of the mid-1980s and early 1990s. Since 1990, the summertime volume has been declining and by 1995 was similar to that recorded in the early 1980s and from 1986 to 1989. The 1997 volume was well below normal, and close to the volume recorded in 1996. The autumn CIL volume is about half that in summer but the pattern of their interannual variability is similar. In the autumn of 1997, the CIL volume was near its lowest value on record. Unfortunately, limited data prevent extending the volume estimates farther back in time than 1980.

Horizontal Temperature Distributions Near Bottom in 2J3KL

The mean (1961–90) and 1997 autumn temperatures over the shelf from southern Labrador

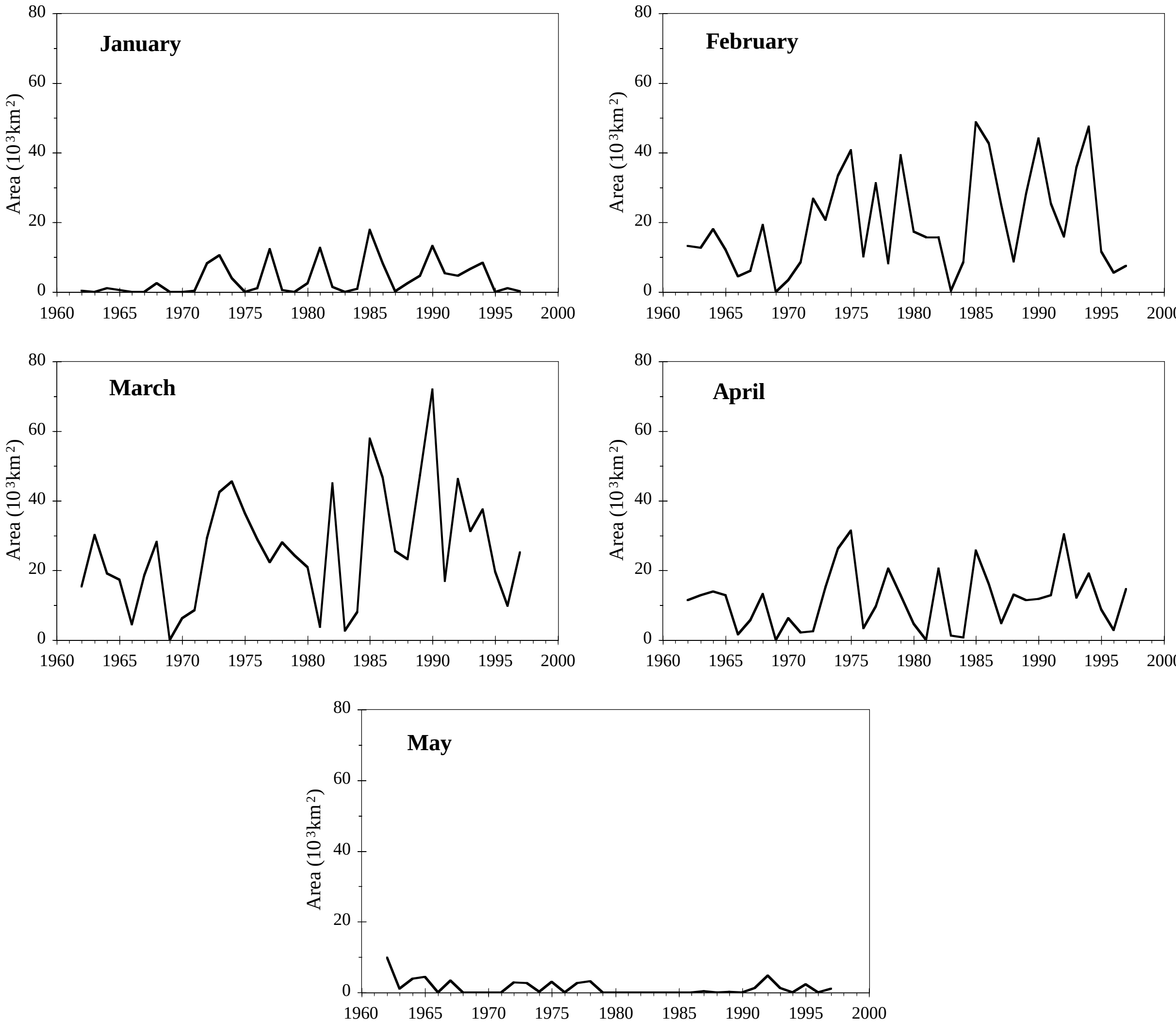

Fig. 18. The time series of ice area seaward of Cabot Strait by month.

to the Grand Banks from groundfish surveys are shown in Fig. 25 (dotted lines indicate bathymetry). The average bottom temperature over most of the northeast Newfoundland Shelf (2J3K) in autumn ranges from < 0°C inshore, to >3°C offshore at the shelf break whereas over most of the Grand Bank it varies from -0.5°C to 3°C. In general, bottom isotherms follow the bathymetry producing cross-shelf temperature gradients. From 1990 to 1994, the area of bottom of the Grand Bank and northeast shelf covered by waters with temperatures <-0.5°C was significantly larger than the 1961–90 average. During 1995, conditions warmed such that the area of water less than -0.5°C on the continental shelf declined significantly to below average values. Since then, bottom temperatures have continued to be warmer than average in most areas of the Newfoundland Shelf with anomalies of around +0.5°C.

Hydrographic Conditions on Hamilton Bank

The time series of temperature and salinity anomalies from 1950 to 1997 on Hamilton Bank at standard depths of 0, 50, 75 and 150 m are shown in Fig. 26 and 27, respectively. A low frequency trend was calculated by smoothing the time series using a five-point running mean. This suppresses the high frequency variations at seasonal scales, which gives an indication of the long-term variations. It should be noted that the monthly averages consist of a variable number of observations.

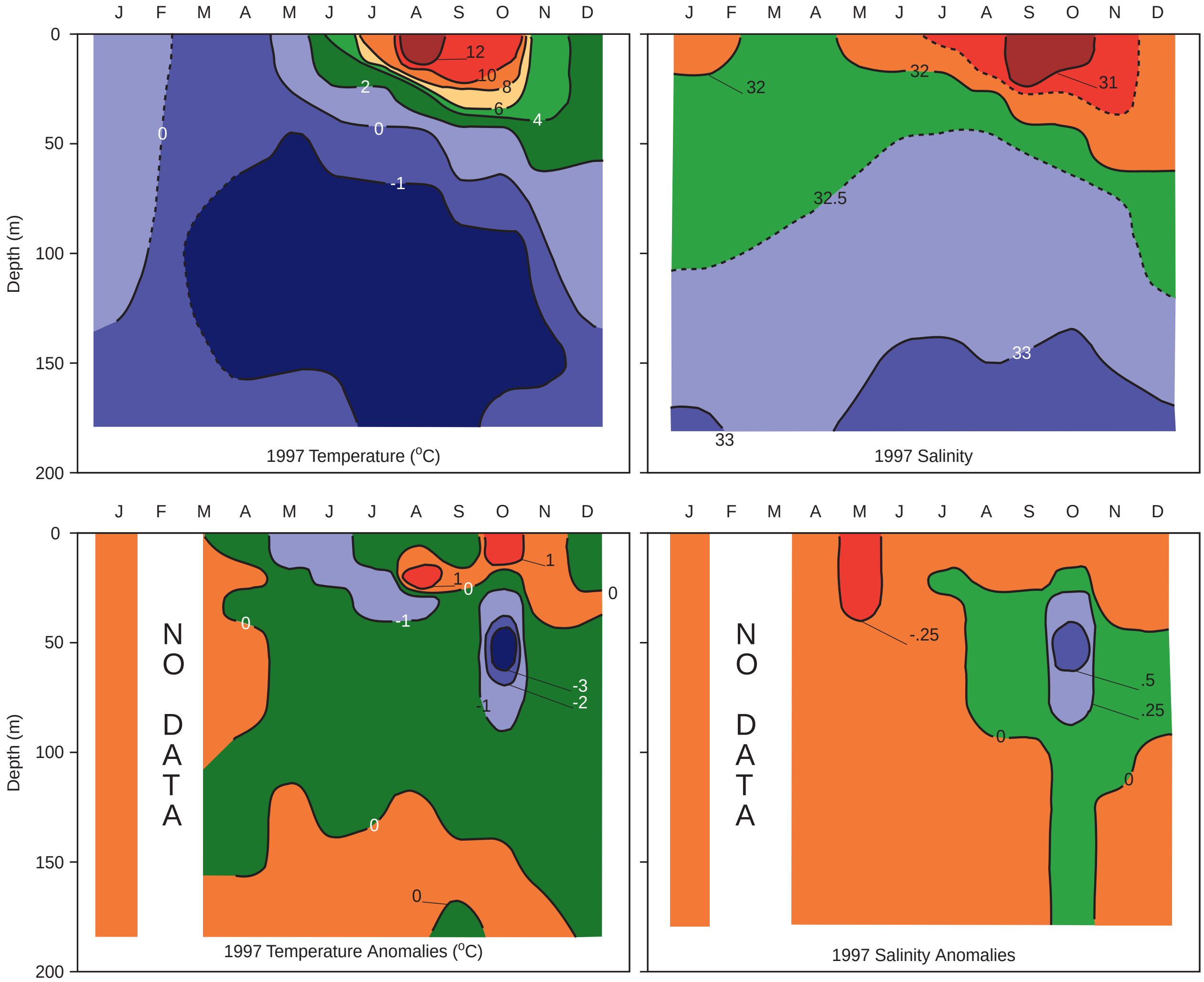

Fig. 19. Monthly mean (top panel) and anomalies relative to the 1961–90 long-term average (bottom panel) of temperature (in °C) and salinity at Station 27 as a function of depth during 1997.

The time series is characterized by large fluctuations with amplitudes ranging from ±1°C and with periods ranging from 2 to 10 years. The cold periods of the early 1970s, the mid-1980s and to a lesser extent the early 1990s are present, however, the amplitude of these anomalies vary considerably with depth. Temperatures on Hamilton Bank have been warming since 1994, particularly in the deeper layers. During 1997, temperatures appear to be near normal at the surface and above normal near bottom (150 m). The smoothed salinity time series shows a very similar pattern as elsewhere on the shelf with fresher-than-normal conditions in the early 1970s, mid-1980s and early 1990s. With the exception of the surface layer, the below average salinities established in the early 1990s continued into 1996, however, measurements made during 1997 indicate a return towards average conditions.

Hydrographic Conditions on Flemish Cap

Three major cold periods are evident from the temperature anomalies over the top 100 m on Flemish Cap; most of the 1970s, the mid-1980s and the late 1980s to early 1990s (Fig. 28). The cold conditions beginning around 1971 continued until 1977 in the upper layers. From 1978 to 1984, temperature anomalies showed a high degree of variability in the upper water column with a tendency towards positive anomalies. By 1985, negative temperature anomalies had returned in the top 100 m of the water column. This cold period moderated briefly in 1987 but returned again by

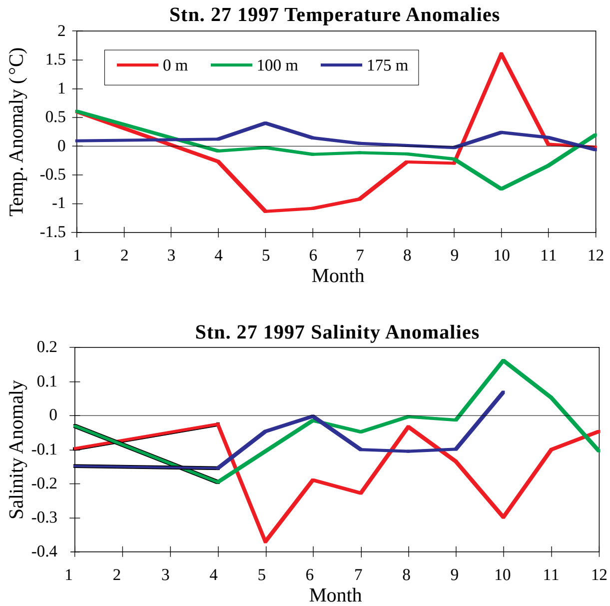

Fig. 20. Monthly temperature (top panel) and salinity (bottom panel) anomalies at 0, 100, and 175 m at Station 27 during 1997.

1988 and continued into the early 1990s. Since 1995 upper layer temperatures have moderated slightly but colder-than-normal conditions still exist below 100 m depth. Note the decline to very cold waters at 200 m beginning around 1985.

Fresher-than-normal salinities persisted on Flemish Cap from 1971 to 1976 and from 1983 to 1986 in the upper 100 m of the water column with the largest anomalies reaching 0.6 below normal (Fig. 29). Salinity during the early 1990s ranged from slightly above normal at the surface to below normal at 50 and 100 m depth, and near normal at 200 m. Anomalies were similar to those at Station 27 and elsewhere on the Newfoundland shelf at comparable depths (Colbourne, MS 1994).

Hydrographic Conditions on St. Pierre Bank

Monthly temperature anomalies from 1950 to 1997 on St. Pierre Bank bounded by the 100 m isobath were computed at standard depths of 0, 20, 50 and 75 m (Fig. 30). These temperature time series are characterized by large variations in the monthly averages with amplitudes ranging from ±3°C. The long-term trend shows amplitudes generally less than ±1°C with periods between 5 to 10 years. The cold periods of the mid-1970s and the mid-1980s in the upper water column are coincident with severe meteorological and ice conditions in the Northwest Atlantic and colder and fresher oceanographic anomalies over most of the Canadian continental shelf. During the cold period of the 1980s, temperatures decreased by up to 2°C in the upper water column and by 1°C in the lower water column. The below normal temperatures in the upper layers continued until 1994. Since then, temperatures have moderated over the top 50 m but remained below average at 75 m depth. During 1996 and 1997, temperature anomalies fluctuated above and below normal, respectively. Note the similarity in the smoothed temperatures at the deepest depths on St. Pierre Bank and Flemish Cap.

The mean (1961–90) and the 1997 bottom temperature maps for April within NAFO Subdiv. 3Ps and 3Pn are shown in Fig. 31. In general, the bottom isotherms follow the bathymetry around the Laurentian Channel and the southwest Grand Bank increasing from 2°C at 200 m depth to 5°C in the deeper water. The mean April bottom temperatures ranged from 5ºC in the Laurentian, Burgeo and Hermitage Channels to about 3°C to 4°C on Rose Blanche and Burgeo banks, and from 0°C on the eastern side of St. Pierre Bank to 2°C on the western side. During April 1997, temperatures were above average over Burgeo Bank, in Hermitage Channel and along the western side of St. Pierre Bank. On the central and eastern side of St. Pierre Bank temperatures ranged from 0.5–1°C below average, similar to conditions through most of the 1990s.

Gulf of St. Lawrence

Cabot Strait Deep Temperatures

Bugden (1991) investigated the long-term temperature changes in the deep waters of the Gulf of St. Lawrence from data collected in Laurentian Channel between the late 1940s to 1988. Temperature variability within the 200–300 m layer in Cabot Strait is dominated by long period (>10 year) fluctuations. This pattern is believed to reflect changes in the slope water characteristics near the mouth of the Laurentian Channel (Bugden, 1991; Petrie and Drinkwater, 1993). These temperature disturbances were found to take several years to propagate the length of the Laurentian Channel from the mouth to the St. Lawrence Estuary.

We have updated the Cabot Strait temperature time series. Temperatures declined steadily after 1988, and in 1991 reached their lowest value since

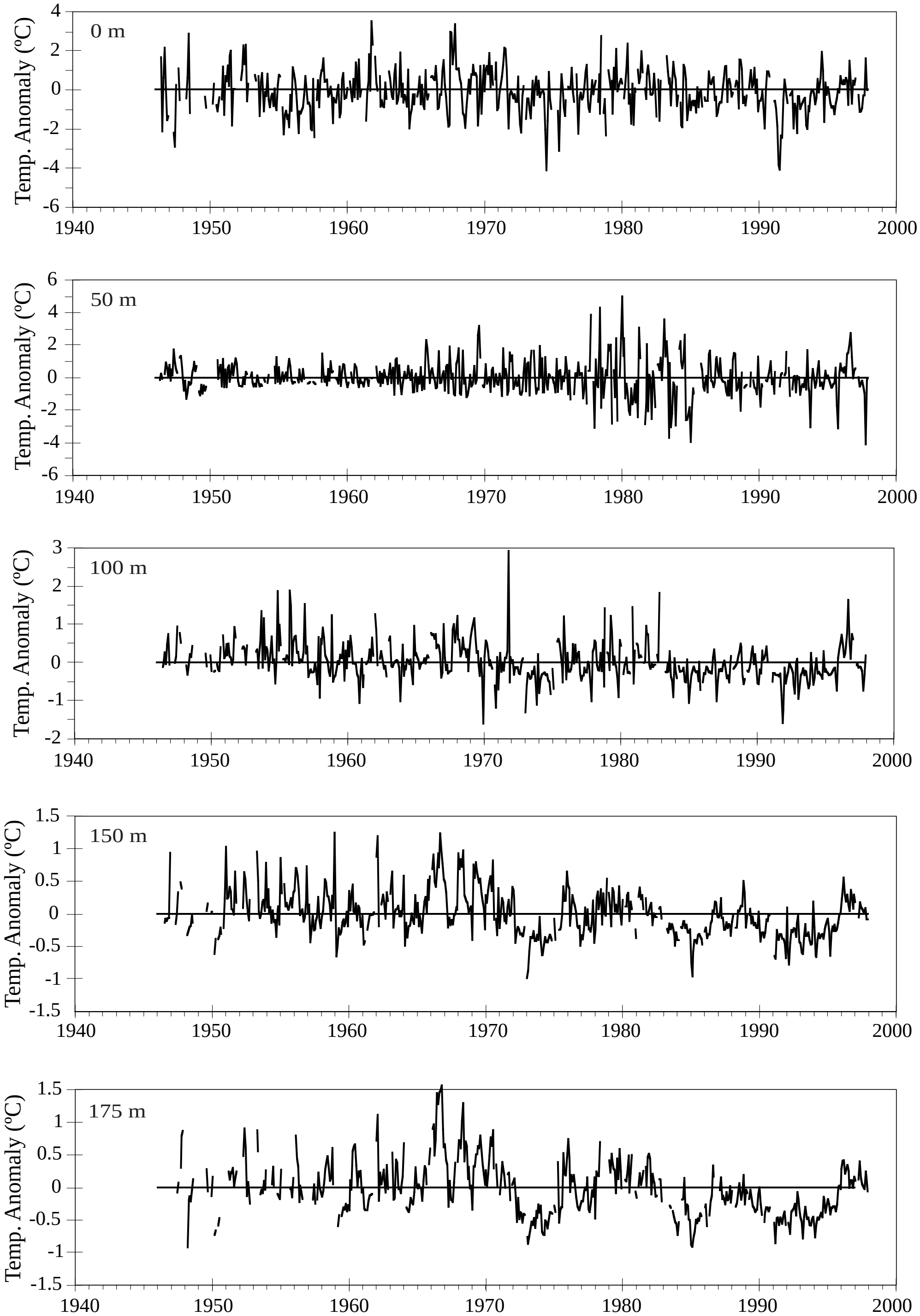

Fig. 21. Monthly mean temperature anomalies at selected depths from Station 27.

the late 1960s (near 4.5°C representing an anomaly of -0.9°C; Fig. 32). They then rose dramatically, reaching 6.0°C (anomaly of 0.6°C) in 1993. By 1994, temperatures were again declining, although anomalies remained positive. Temperatures continued to fall towards normal through 1995 and 1996. In 1997, temperatures were between 5.5° and 6°C, slightly above the long-term mean.

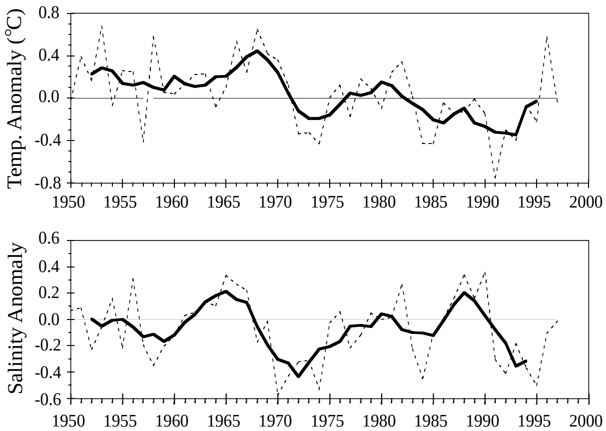

Fig. 22. Vertically averaged (0–176 m) temperature and (0–50 m) salinity from Station 27. The annual values are designated by the lighter dashed line and the 5-yr running means by the heavy sold line.

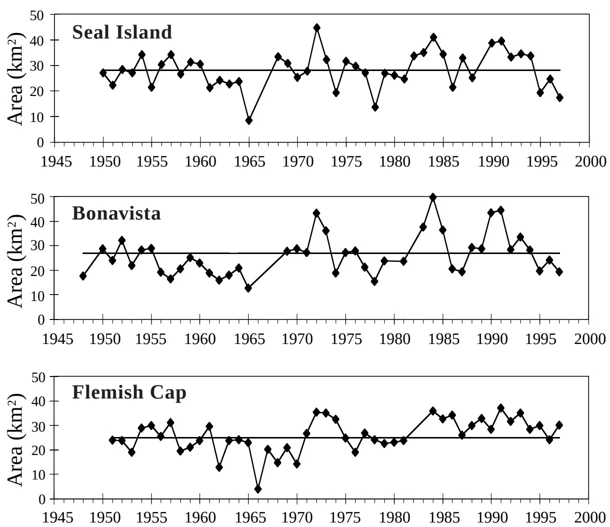

Fig. 23. The CIL area (in km^2) during the summer along standard sections off Seal Island (southern Labrador), Bonavista Bay (northern Newfoundland) and Flemish Cap (Grand Banks).

Cold Intermediate Layer

The CIL in the Gulf of St. Lawrence has a maximum thickness in the northeast and a minimum (where depths exceed 100 m) in Cabot Strait and the St. Lawrence Estuary. During 1997, the CIL thickness (defined by waters <0°C) decreased by approximately 5% relative to 1996, much less than the 40% decrease observed between 1996 and 1995. The largest decrease in 1997 was observed in the northwestern Gulf. Gilbert and Pettigrew (1997), in a study of the CIL layer, produced a Gulf-wide index of core temperatures for mid-July based upon available observed data and the mean measured warming rate. Their index shows temperature anomalies having an approximate 5–8 year periodicity prior to 1985 (Fig. 33). Temperatures in the CIL have been below normal since 1985 with minima in the late 1980s and early 1990s. Since 1994, the CIL waters have been slowly warming. The mid-summer core CIL temperature in 1997 was -0.25°C (anomaly of approximately -0.35°C), and was warmer than 1996 by 0.2°C. High correlations between the CIL core temperatures and air temperatures along the west coast of Newfoundland, suggest the importance of atmospheric forcing in determining the interannual changes in the extent and severity of the CIL (Gilbert and Pettigrew, 1997). Advection may also contribute to the low CIL temperatures of recent years as is suggested by the similar cold pattern observed in the deep waters on St. Pierre Bank (Fig. 30) and Flemish Cap (Fig. 28).

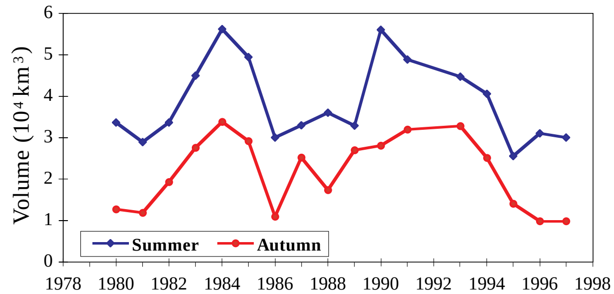

Fig. 24. The CIL volume in the summer and autumn within Divisions 2J and 3KL.

Bottom Temperatures on the Magdalen Shallows

Annual groundfish surveys in the southern Gulf of St. Lawrence during September have been carried out since 1971. Bottom temperatures tend to be lowest in the central region of the Magdalen Shallows and increase towards both the shore and the Laurentian Channel (Fig. 34). Near-bottom temperatures in 1997 were predominantly colder-than-normal with the largest negative anomalies off the northwest point of Prince Edward Island (PEI). However, the total area of the Magdalen Shallows covered by below normal bottom temperatures decreased. This decrease was most noticeably north of PEI, around the Magdalen Islands and along the slope of the Laurentian Channel. Relative to 1996,

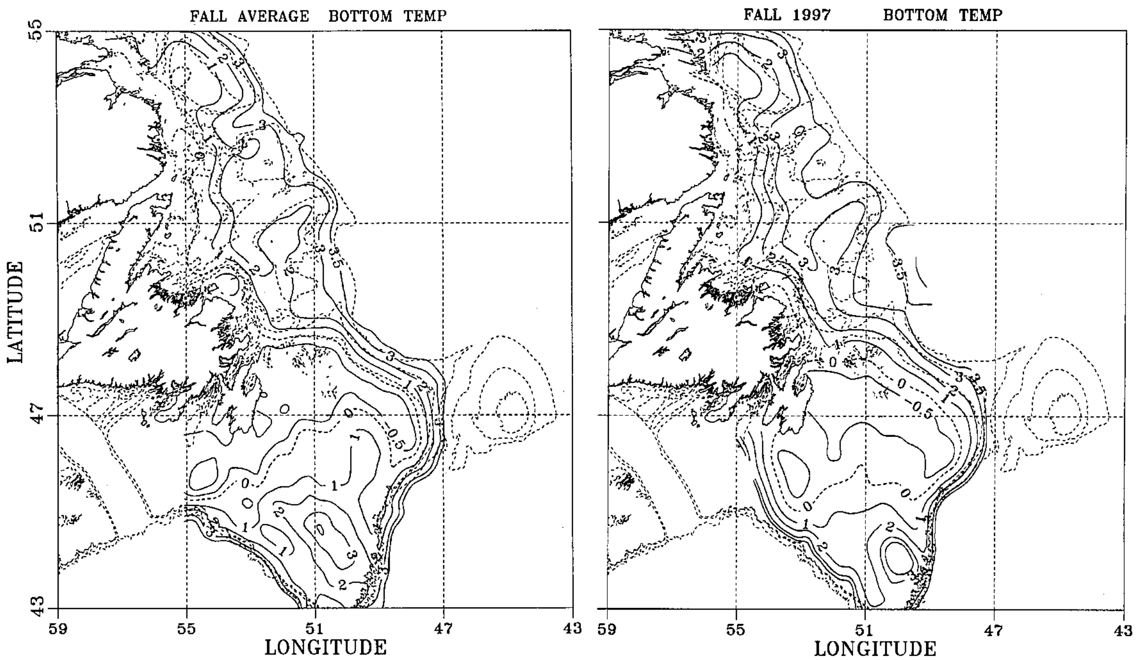

Fig. 25. The 1961–90 average (left side panel) and the 1997 (right side panel) bottom temperatures during the autumn for the Newfoundland Shelf region.

bottom temperatures increased slightly over most of the Shallows but cooled around the Magdalen Islands, northwest of PEI and in St. Georges Bay east of PEI. Swain (MS 1993) developed an index of near bottom temperature defined as the area of the Magdalen Shallows covered by waters <0°C and <1°C. These two indices show strong similarity and have been above normal since 1990 (Fig. 35). This is consistent with the colder-than-normal CIL since the CIL is in direct contact with the bottom over much of the shallows. The areal indices decreased for the second consecutive year, however, with the area <0°C falling to almost normal. The shrinking of the area covered by these cold waters is consistent with the gradually warming and decreasing thickness of the CIL throughout the Gulf noted above.

Summer Temperature and Salinity Fields

The hydrographic data collected during the September groundfish surveys on the Magdalen Shallows were combined with data from fisheries surveys conducted throughout the remainder of the Gulf during August–September. Average temperatures and salinities were then calculated within layers (0–30, 30–100, 100–200 and 200–300 m) for each of the 21 areas defined by Petrie *et al*. (1996). In the surface layer, the average temperature during 1997 ranged from over 6°C in the St. Lawrence Estuary to 14°C off eastern Prince Edward Island. There was slight warming compared to 1996 along the north shore of Quebec but a decrease over most of the southern Gulf, including off the west coast of Newfoundland. The amplitude and sign of the temperature anomalies in this layer varied spatially with no distinct trend. In the 30–100 m layer, which encompasses the CIL, temperatures varied from -0.1°C off western Newfoundland to 1.3°C in the St. Lawrence Estuary and near Cabot Strait. These temperatures were colder-than-normal for this time of the year with the largest negative anomaly (1.7°C) off the west coast of Newfoundland. Throughout most of the Gulf, temperatures warmed relative to 1996 but only slightly (<0.5°C). In the 100–200 m layer, they ranged from 1.7°C in the northeastern Gulf to 4.4°C in Cabot Strait while in the deep layer (200–300 m) temperatures varied from 4.5°C to over 6°C in Cabot Strait. Temperature anomalies in both layers were above normal except in the 100–200 m layer in the northeast Gulf where they were 0.5°C below normal. Compared to 1996,

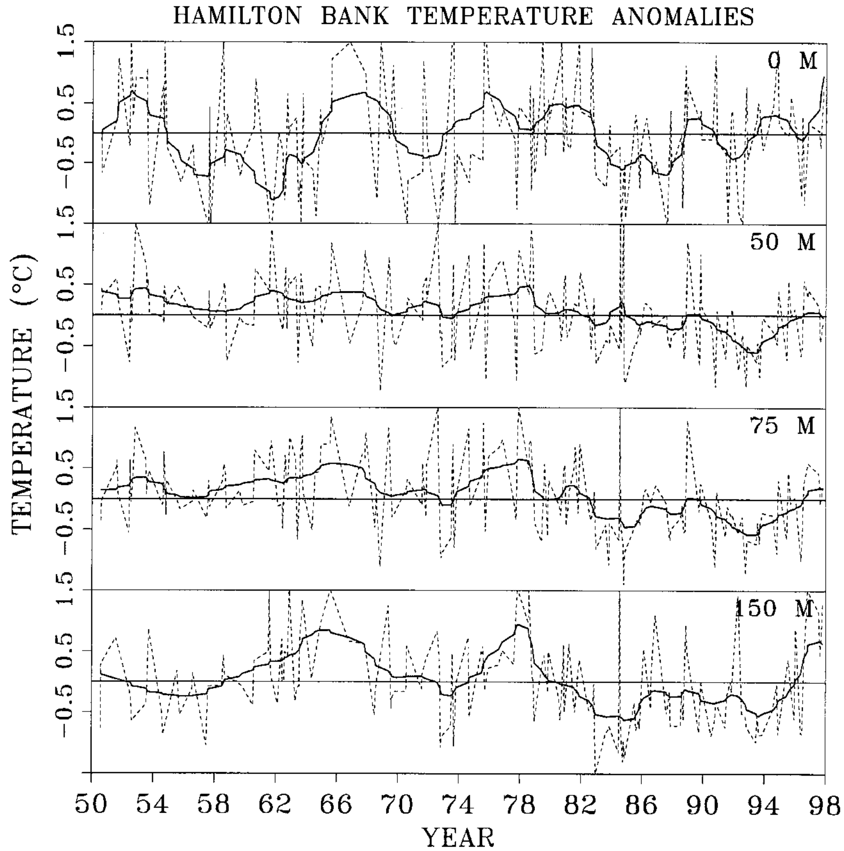

Fig. 26. Monthly mean temperature anomalies at selected depths on Hamilton Bank in Division 2J. The solid line represents the smoothed temperature anomalies.

the temperatures in both layers increased with the largest rise in Cabot Strait (>2°C in the 100–200 m) and immediately to the north (>1°C in the 200–300 m). The time series of the average temperature in the lower three layers indicates warming in 1997 with above normal conditions in the deepest layer but still below normal in the 30–100 m layer (Fig. 36).

Scotian Shelf and Gulf of Maine

Coastal Sea Surface Temperatures

Monthly averages of sea surface temperature (SST) for 1997 were available at Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each site for 1996 and 1997 are shown in Fig. 37. At Boothbay Harbor and St. Andrews, 1997 temperatures were above normal throughout most of the year (8 out of the 12 months at both sites), which continued the warm trend that began in June 1994. Anomalies equalled or exceeded one standard deviation (based upon the years 1961–90) in 6 months at Boothbay Harbor (January–May and August) but in only one month at St. Andrews (July). The maximum anomaly was in January at Boothbay (1.9°C) and in October at St. Andrews (0.8°C). The lower amplitude anomalies at St. Andrews are typical and are due to the increased vertical mixing by the tides in the Bay of Fundy. In contrast to the Gulf of Maine sites, Halifax was dominated by negative sea surface temperature anomalies with 7 of the 12 months being colder-than-normal (Fig. 37). This continues the cold trend observed at Halifax over the last several years. Temperatures are increasing at Halifax, however, as indicated by more months with positive temperature anomalies. Only in 2 months at Halifax (May and July) did the anomaly exceed its long-term standard deviation.

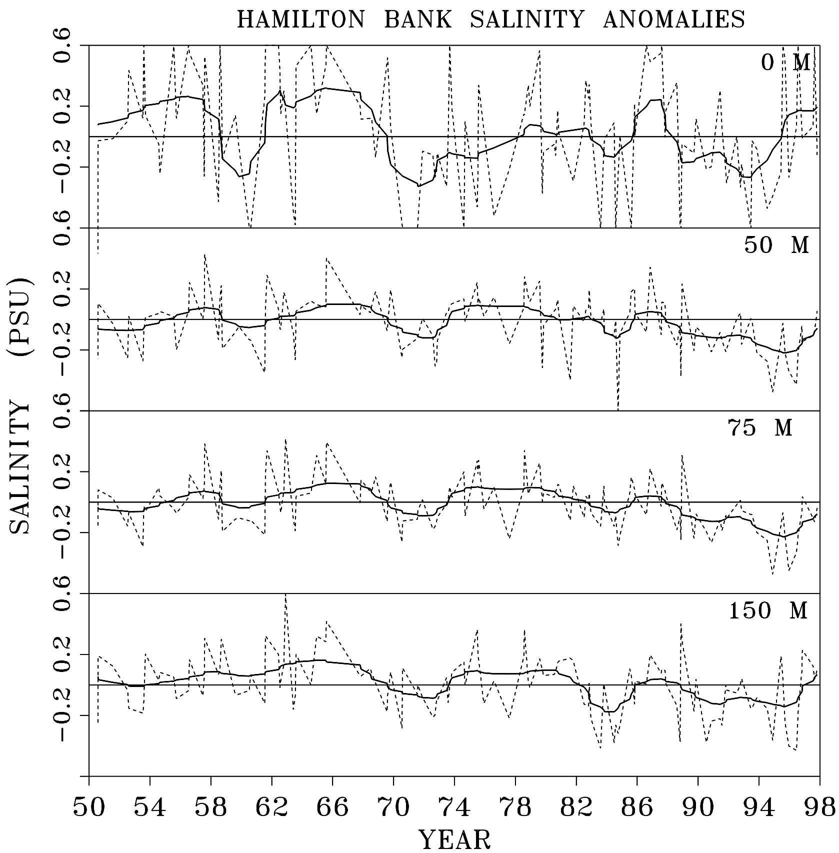

Fig. 27. Monthly mean salinity anomalies at selected depths on Hamilton Bank in Division 2J. The solid line represents the smoothed salinity anomalies.

Annual surface temperature anomalies at Boothbay Harbor and St. Andrews have been above their long-term means in recent years and generally increasing since the late 1980s minima (Fig. 37). This minimum was as low as that of the mid-1960s at St. Andrews but at Boothbay Harbor the minima was only slightly below normal. Consistent with recent trends, the 1997 annual mean temperature was above normal (mean of 7.3°C and 0.2°C above normal at St. Andrews and 9.0°C and 0.5°C above normal at Boothbay). However, at both sites temperatures fell relative to 1996 and 1995. In contrast, Halifax temperatures have been below normal since the mid-1980s with a slow but steady warming since the early 1990s. The 1997 annual sea-surface temperature at Halifax was 7.8°C, producing an anomaly of -0.2°C.

Prince 5

Since 1924, monthly temperature and salinity measurements have been taken near the entrance to the Bay of Fundy at Prince 5, a station off St. Andrews, New Brunswick. It is the longest continuously operating hydrographic monitoring site in eastern Canada. Single observations per month, especially in the surface layers in the spring or summer, may not be representative of the "average" conditions for the month and therefore the interpretation of the anomalies must be viewed with some caution. No significance should be placed on any individual anomaly but persistent features are likely to be real. The general vertical similarity in temperatures over the 90 m water column is due to the strong tidal mixing within the Bay of Fundy.

In 1997, no data were collected in March. Monthly mean temperatures ranged from a minimum of over 2.5°C throughout the water column in February to a maximum of over 12°C near the surface in September (Fig. 38, 39). Monthly anomalies were predominately positive, the exception being the late spring and at the surface and near-bottom during the

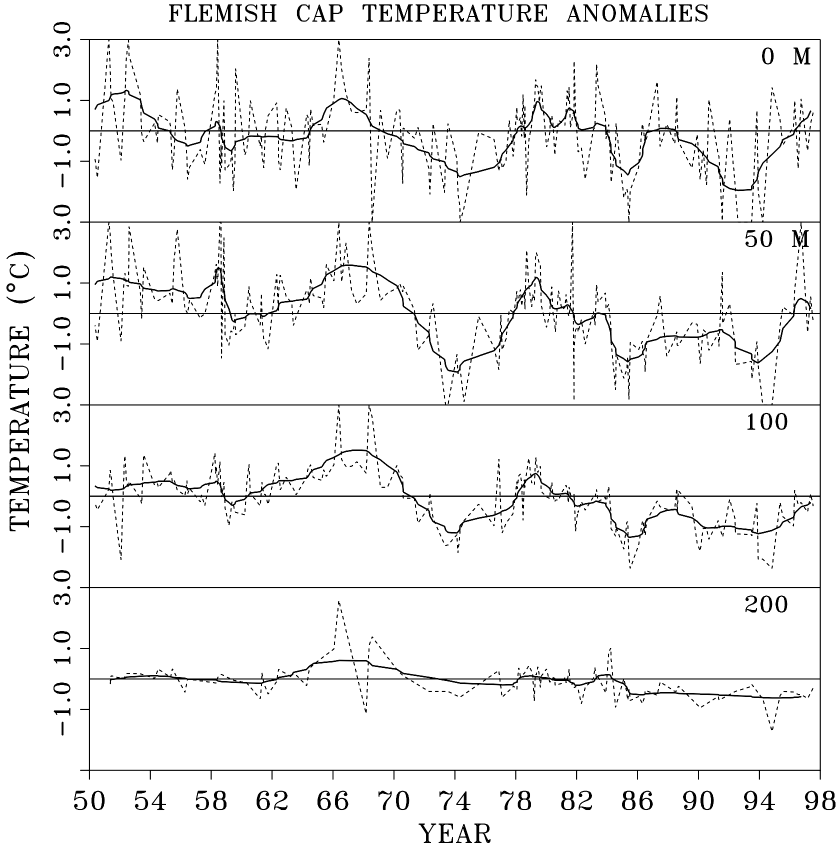

Fig. 28. Monthly mean temperature anomalies at selected depths over Flemish Cap in Division 3M. The solid line represents the smoothed temperature anomalies.

summer (Fig. 38). The maximum negative anomaly was during June in the surface waters (-1°C). The annual mean temperatures at Prince 5 exhibit high year-to-year variability (Fig. 39). In 1997, they were just above normal at both the surface (anomaly of 0.16°C) and near bottom at 90 m (0.10°C). Relative to 1996, this is a slight increase at the surface and similar near bottom. They are also down from the mid-1990s peak but above the low levels of the early 1990s. At both depths, the maximum annual temperature occurred in the early 1950s and the minimum in the mid-1960s.

Salinities at Prince 5 during 1997 were predominantly fresher-than-normal (Fig. 38). As occurs in most years, the lowest salinities (<31 psu) appeared during May and June and the highest (>32.5 psu) near bottom in the autumn. The largest negative anomalies (greater than -0.5) were observed in January and February. The 1997 annual salinity anomaly rose by approximately 0.4–0.5 relative to 1996 at both the surface and 90 m (Fig. 40). The 1996 salinities were the lowest on record at Prince 5 and continued the generally freshening that began in the late 1970s. The recent low salinities parallel events in the deep waters of Jordan and Georges Basin and appear to be related to advection of fresher waters from areas further to the north (P. Smith, BIO, pers. comm, Bedford Institute, Dartmouth, Canada).

Gulf of Maine Temperature Transect

The Northeast Fisheries Science Centre in Narragansett, Rhode Island, has collected expendable bathythermograph (XBT) data approximately monthly from ships-of-opportunity since the late 1970s. The XBTs are dropped along a transect in the Gulf of Maine from Massachusetts Bay to the western Scotian Shelf as part of their continuous plankton recorder program. We grouped the available data into 10 equally spaced boxes along the transect, then averaged by month any data within these boxes at standard depths. Data for 1997 were only available for 8 months of the year.

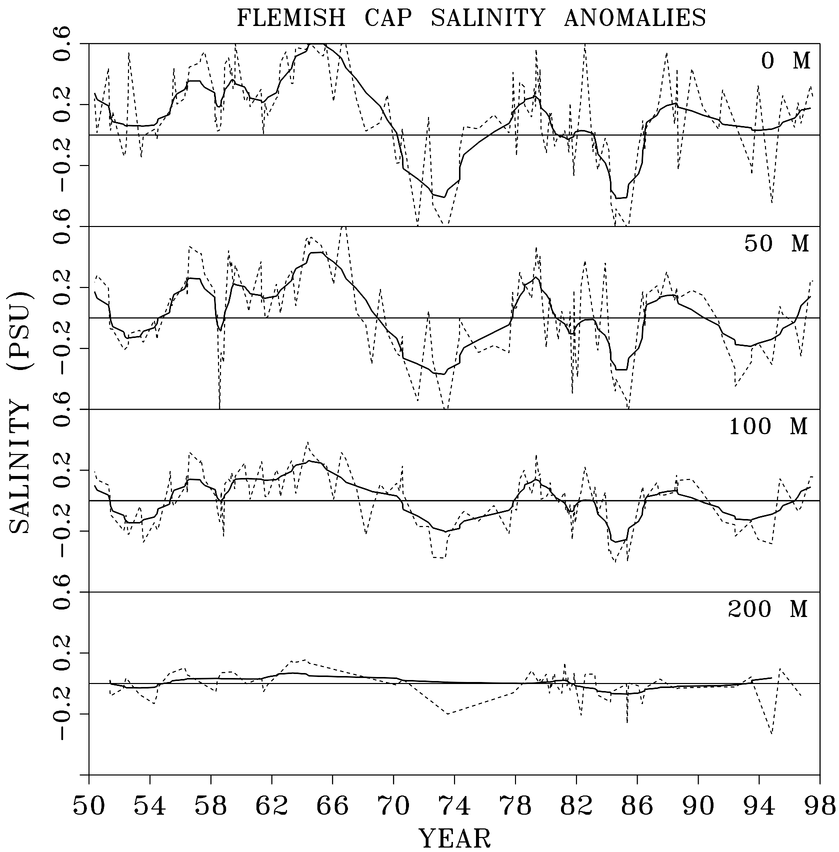

Fig. 29. Monthly mean salinity anomalies at selected depths over Flemish Cap in Division 3M. The solid line represents the smoothed salinity anomalies.

Data from May and July 1997 are shown together with the site locations (centre of the boxes) in Fig. 41. The temperature patterns in the two months are similar with high near surface thermal stratification, the "cool pool" at intermediate depths in the central and western Gulf, well-mixed near surface waters in the eastern Gulf, and near-bottom waters of approximately 7° to over 9°C. Depths below 50 m are predominantly warmer-than-normal while the upper 50 m varied about normal during the 2 months. Anomalies from other months (not shown) indicate similar conditions.

Deep Emerald Basin Temperatures

Petrie and Drinkwater (1993) assembled a time series of monthly temperature data from 1946 to 1988 at multiple depths in Emerald Basin in the centre of the Scotian Shelf. They showed that there was high temperature variance at long periods (decadal and longer). This was more visible at depth (below 75 m) where the amplitude of the signal was higher and there was less short period (year-to-year) variability. For the long-period oscillations, the coherence was high both vertically throughout the water column and horizontally from the mid-Atlantic Bight to the Laurentian Channel, although some year-to-year differences between locations were observed. Temperature anomalies at 250 m in Emerald Basin have thus been used as one index of thermal variability on the Scotian Shelf.

In 1997, temperature measurements in Emerald Basin were obtained to depths of 250 m in nine separate months with values ranging from 9.2° to 9.7°C. This produced monthly anomalies of 0.9°–1.6°C above normal (Fig. 42). The long-term (1961–90) annual average is 8.5°C. The high positive anomalies in 1997 were generally representative of conditions in the Basin below approximately 50 to 100 m. The most recent period of warm waters in the deeper regions of Emerald Basin began with an

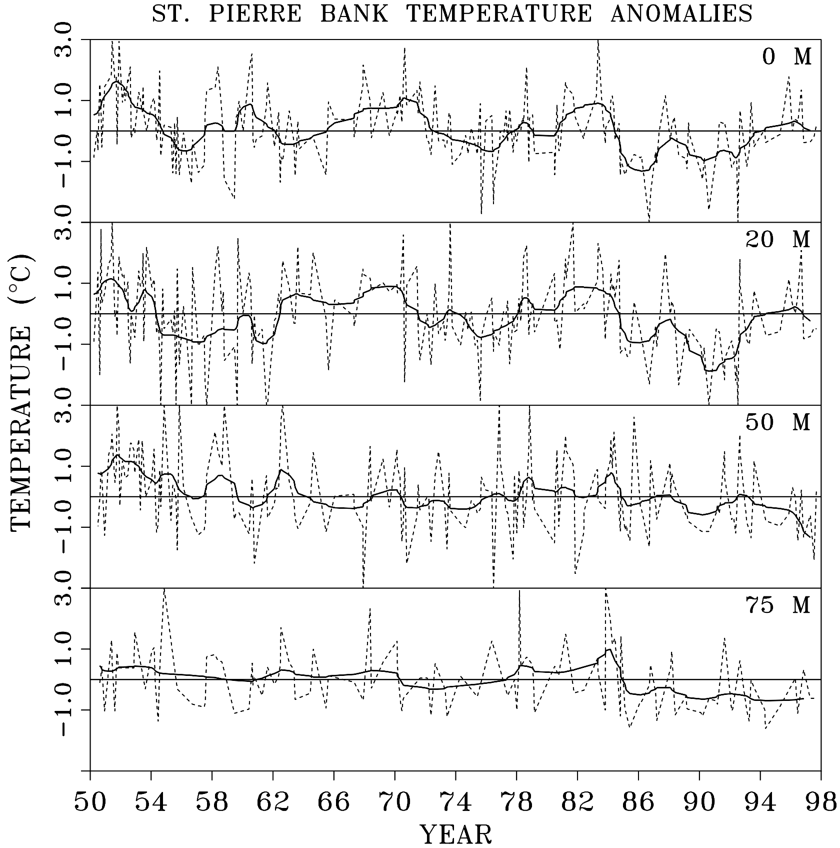

Fig. 30. Monthly mean temperature anomalies at selected depths over St. Pierre Bank. The solid line represents the smoothed temperature anomalies.

intrusion of warm slope water late in 1991 or early 1992. The solid line in Fig. 42 is the 5-year running mean of the annual anomalies. These are the averages of all available monthly anomalies within the calendar year. In some years 10–12 months of data were available and in others only 1 or 2 months. The long-term trend shows a peak in the early 1950s declining to a minimum in the early 1960s (described in detail by Petrie and Drinkwater, 1993). Temperatures rose rapidly in the late 1960s and have remained high except for brief cooling periods in the late 1970s, the early 1980s and the early 1990s. Most recently, temperatures in deep Emerald Basin have been at the highest sustained levels in the approximate 50 year record.

Other Scotian Shelf and Gulf of Maine Temperatures

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities for irregularly shaped areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins (Fig. 43). Their analysis has been updated and extended to include all of the Gulf of Maine by Petrie *et al*. (1996). We produced 1997 monthly mean conditions at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compared them to their long-term averages (1961–90). Unfortunately, data are not available for each month at each area and in some areas the monthly means are based upon only one profile. As a result the series are characterized by short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1–2°C. The spikes represent noise and most often show little similarity between regions. Thus care must be taken in interpreting these data and little weight given to any individual mean. The long period trends often show similarity over several areas, however. To better show such trends we have estimated the annual mean anomaly based on all available means within the year and then calculated the 5-year running mean of the

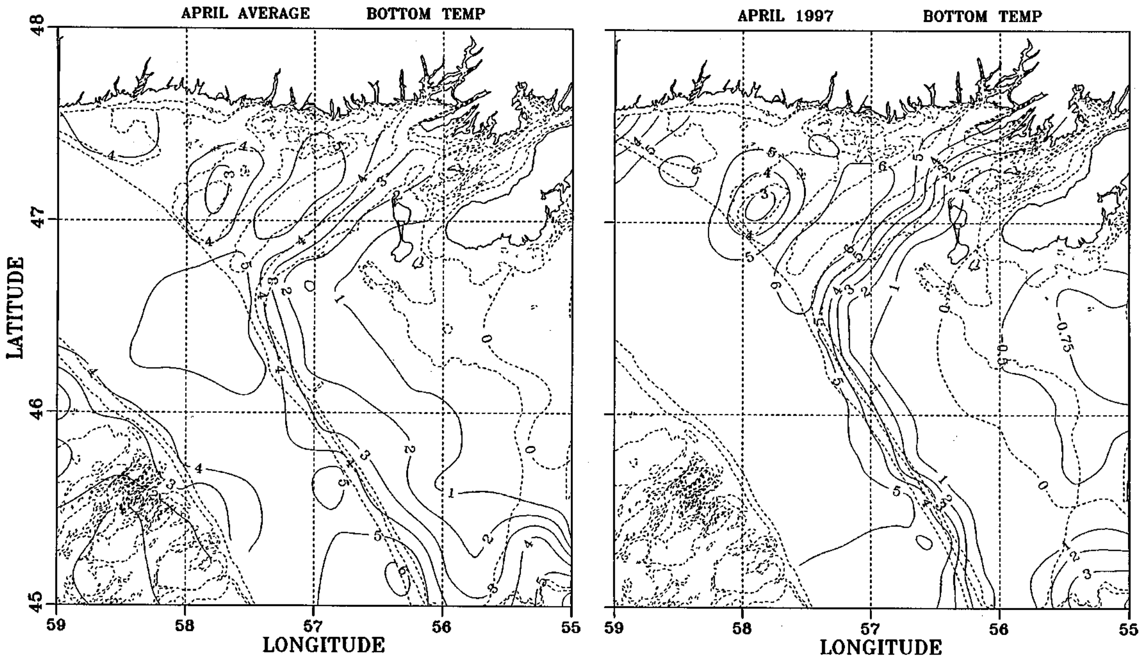

Fig. 31. The 1961–90 average (left panel) and the 1997 (right panel) bottom temperatures during April off southern Newfoundland.

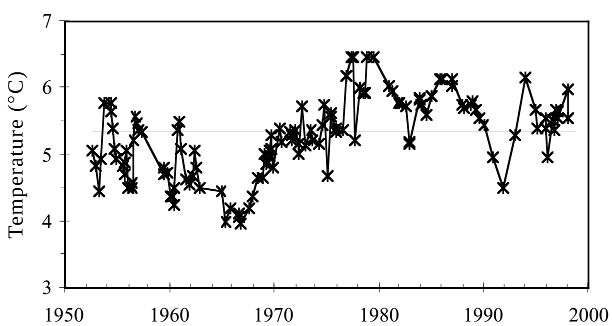

Fig. 32. Anomalies in the average temperature for the 200–300 m deep layer in Cabot Strait.

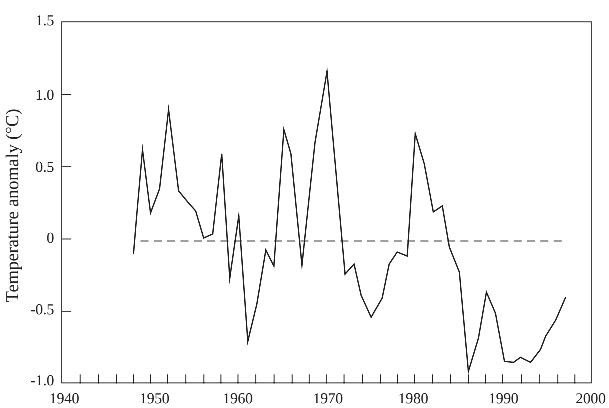

Fig. 33. Anomalies of the CIL core temperatures (extrapolated to July 15) for the Gulf of St. Lawrence from the 1948–94 mean (of 0.08°C).

annual values. This is similar to our treatment of the Emerald Basin data.

Drinkwater (1995) examined long-term temperature time series for most of the areas on the Scotian Shelf and in the Gulf of Maine and identified several important features. First, the temperatures in the upper 30 m tended to vary greatly from month to month, due to the greater influence of atmospheric heating and cooling. Second, at intermediate depths of 50 m to approximately 150 m, temperatures had declined steadily from approximately the mid-1980s into the 1990s. On Lurcher Shoals off Yarmouth, on the offshore banks and in the northeastern Scotian Shelf the temperature minimum in this period approached or matched the minimum observed during the very cold period of the 1960s. This cold water was traced through the Gulf of Maine from southern Nova Scotia, along the coast of Maine and into the western Gulf. Cooling occurred at approximately the same time at Station 27 off St. John's, Newfoundland, off southern Newfoundland on St. Pierre Bank (Colbourne, MS 1995) and in the cold intermediate layer (CIL) waters in the Gulf of St. Lawrence (Gilbert and Pettigrew, 1997). Data in 1994 and 1995 indicated warming of the intermediate layers in the Gulf of Maine but a continuation of colder-than-normal water on most of the Scotian Shelf (Drinkwater *et al*., 1996). The third main feature was the presence of anomalous warm slope

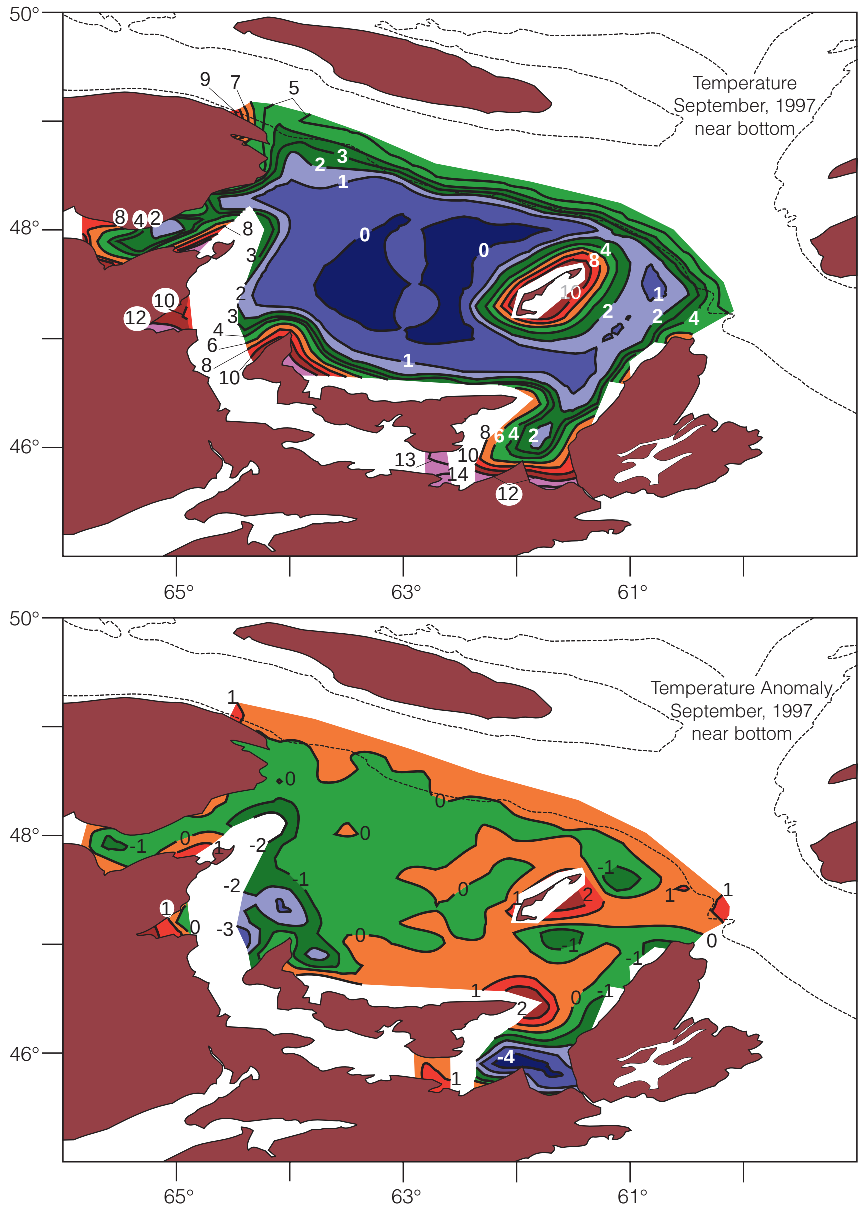

Fig. 34. Temperature (top panel) and temperature anomalies (bottom panel) in the southern Gulf of St. Lawrence in September 1997. The dotted line represents the 200 m isobath.

water off the shelf and in the deep basins such as Emerald on the Scotian Shelf and Georges in the Gulf of Maine. This warm deep water appeared to influence the intermediate depth waters above the basins, as their anomalies were generally warmer than elsewhere on the shelves.

The general patterns first identified by Drinkwater (1995) have continued into 1997. Monthly mean temperature profiles reveal that cold conditions prevailed in the deeper waters on Sydney Bight, on Misaine Bank in the northeast Scotian Shelf, and on Lurcher Shoals.

On Sydney Bight (area 1 in Fig. 43) monthly mean profiles from 7 different months show highly variable temperature anomalies throughout the water column (Fig. 44). In the near surface (<10 m) waters, temperatures were primarily above the long-term mean with the exception of August. August showed

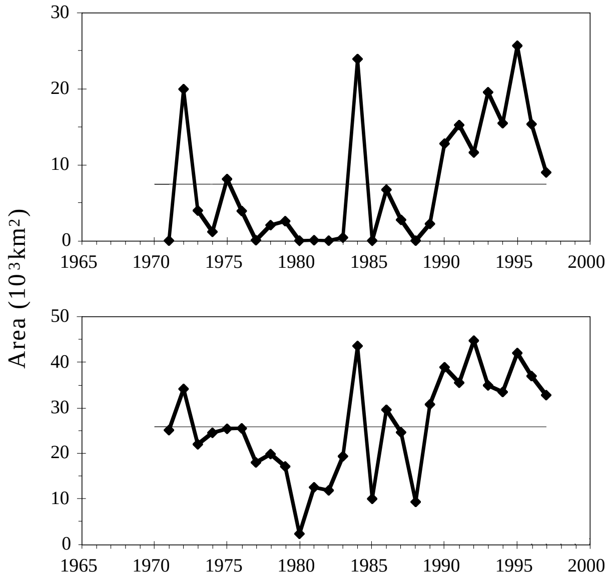

Fig. 35. Area of the Magdalen Shallows with bottom temperatures <0°C and <1°C during September.

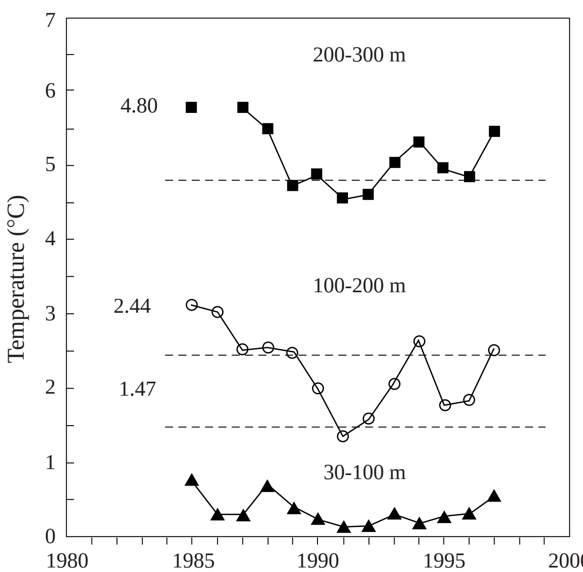

Fig. 36. The temperature of the 30–100 m, the 100–200 m and the 200–300 m layers in the Gulf of St. Lawrence during August–September. The dashed lines indicate the long-term averages based upon Petrie (1990).

the coldest anomalies, but this was limited to the top 100 m. The 100 m temperature anomalies were high in the 1950s, fell to a minima around 1960 and then rose steadily through the 1960s (Fig. 44). Temperatures remained high during the 1970s. By the 1980s, temperatures began to decline and by the mid-1980s dropped quickly to below normal values reaching a minimum anomaly of around -1°C in the early 1990s. Temperatures in recent years have generally remained below normal but have been slowly increasing. Indeed, since 1995 several monthly anomalies each year have been above normal.

Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 43) are available for 6 months during 1997. They show variable upper layer (0–30 m) temperatures (Fig. 45). However, below approximately 30 m temperatures were predominantly colder-than-normal throughout the year with anomalies of 0° to -1.5°C. The 100 m temperature anomalies on the bank have been negative since the mid-1980s (Fig. 45). This pattern is indicative of the water column below 50 m. As on Sydney Bight, temperatures were high in the 1950s, then declined to a minimum around 1960. This was several years earlier than when the minimum appeared in areas further to the southwest on the Scotian Shelf. Temperatures were near normal from the mid-1960s to the mid-1970s before rising to a maximum in the late 1970s. By the mid-1980s, temperatures fell below normal and reached a record sustained minimum of around -1°C in the first half of the 1990s. Since then, and similar to Sydney Bight, temperatures have remained below normal but with evidence of a slow but steady increase that continued into 1997.

At Lurcher Shoals off southwest Nova Scotia (area 24 in Fig. 43), data were available in 8 months during 1997 (Fig. 46). There was high temperature variability about the long-term mean in the top 40 m. At depths between 40 and 80 m which covers most of the bottom of Lurcher Shoals, 1997 shows more months with below normal temperatures than above normal. At 100 m, which lays at the edge of the Shoals, there was an equal number of months of above and below normal temperatures. The monthly 50 m temperature anomalies at Lurcher show a predominance of cooler-than-normal waters in 1997 (Fig. 46). This depth represents conditions over much of the bottom of the Shoals. The late 1940s and early 1950s were warm, then temperatures declined to a mid-1960s minimum, rose rapidly into the 1970s and remained above normal into the mid-1980s. As on the northeastern Scotian Shelf (Misaine Bank and Sydney Bight), temperatures declined by the mid-1980s to below normal reaching the long-term

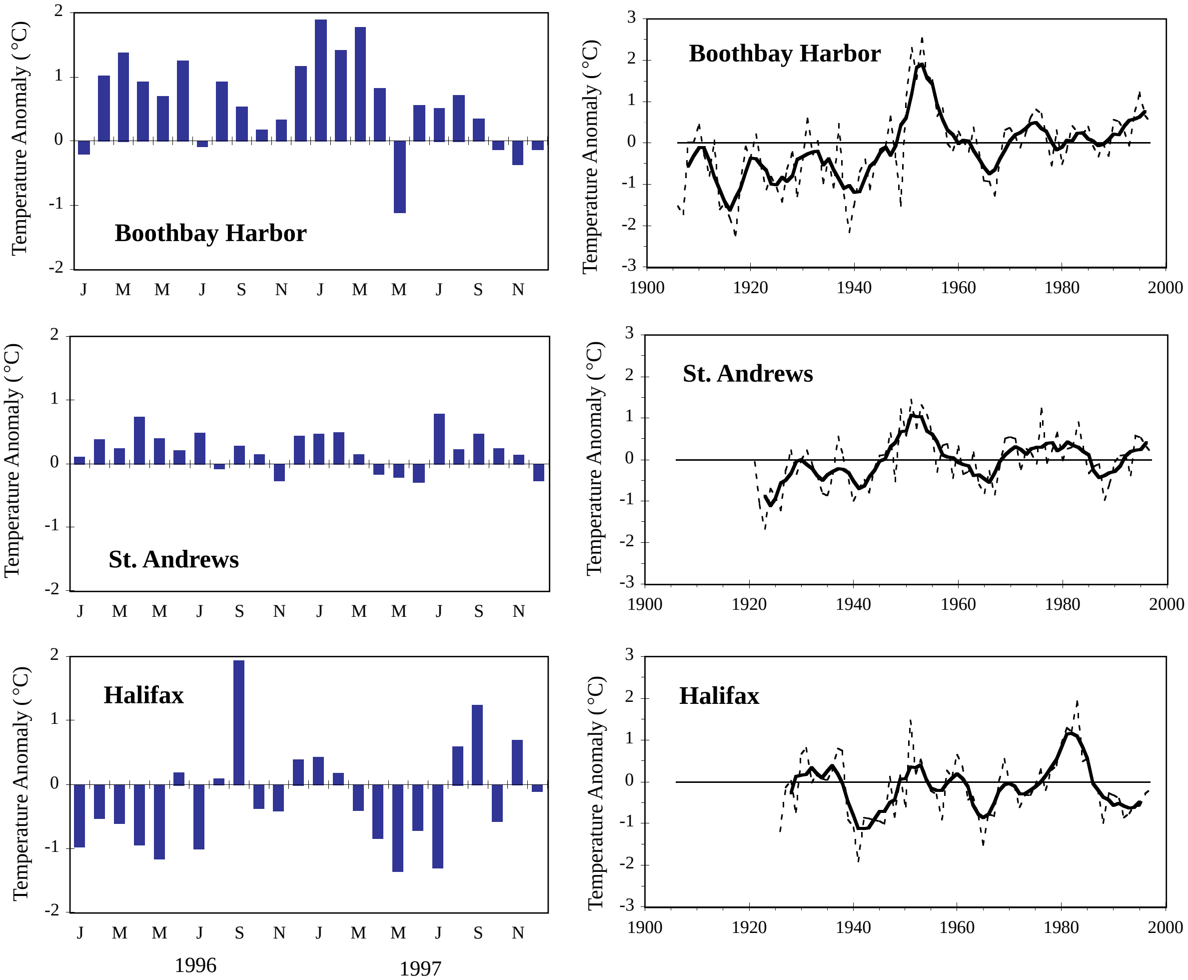

Fig. 37. The monthly sea surface temperature anomalies during 1996 and 1997 (left) and the annual temperature anomalies and their 5-year running mean (right) for Boothbay Harbor, St. Andrews and Halifax. Anomalies are relative to 1961–90 means.

minimum in the early 1990s. Since then temperatures have been warming and from 1994 on, some months have experienced positive anomalies, although the annual means have remained below normal

Temperatures in the deep regions of Georges Basin (Fig. 47; area 26 in Fig. 43) show a striking similarity to that observed in Emerald Basin (Fig. 42). This includes the low values in the mid-1960s, rising sharply to a peak in the early 1970s and varying slightly but generally remaining above the long-term (1961–90) mean ever since. This is not surprising given that the source for both areas is the offshore slope waters (Petrie and Drinkwater, 1993). On the Canadian portion of Georges Bank (area 28 in Fig. 43), the short period variability is of much higher amplitude than in Georges Basin (Fig. 47). This reflects not only higher temporal fluctuations but also larger spatial differences within the designate area. The longer-term trend shows positive anomalies in the 1950s, the low 1960s and a tendency towards positive anomalies since the 1970s. However, from the late 1980s on, the long-term temperature trend has not been significantly different than normal.

Offshore Conditions

Temperature conditions were obtained in the deep (200 m) waters off the northeastern and southwestern Scotian Shelf (areas 34 and 33, respectively in Fig. 44). Temperatures in these areas (Fig. 48) are similar to those in Emerald (Fig. 42)

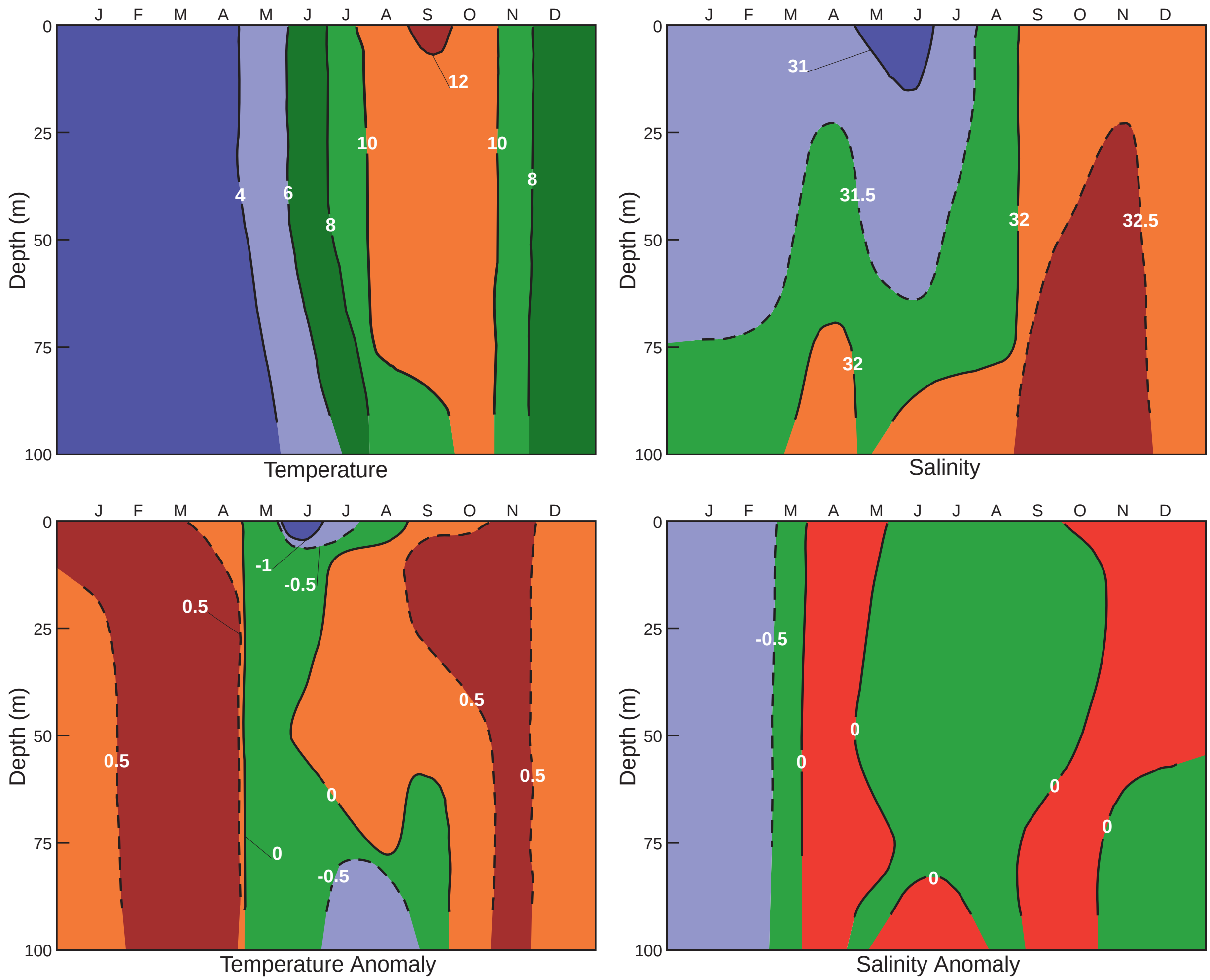

Fig. 38. Monthly temperatures and salinities (top panels) and their anomalies (bottom panels) at Prince 5 as a function of depth during 1997 relative to the 1961–90 means.

and Georges (Fig. 47) basins, consistent with the findings of Petrie and Drinkwater (1993). Of particular note is the presence of very cold water offshore in late 1997. This water is as cold as that observed in the 1960s and is of Labrador Slope origin (Drinkwater *et al*., MS 1998). While such waters are often observed at the mouth of the Laurentian Channel, they are relatively rare off the central Scotian Shelf, e.g. Emerald Bank. This cold water began to penetrate into the southern side of Emerald Basin in December but did not reach the deepest sections of the basin (Drinkwater *et al*., MS 1998).

Temperatures during the Summer Groundfish Survey

The most extensive temperature coverage over the Scotian Shelf occurs during the annual groundfish survey, usually in July. In 1997, around 200 conductivity-temperature-depth (CTD) stations were occupied. Temperatures were interpolated onto a 0.2 × 0.2 degree latitude-longitude grid using an objective analysis procedure known as optimal estimation. The interpolation method uses the 15 "nearest neighbours" and a horizontal scale length of 30 km and vertical scale lengths of 15 m in the upper 30 m and 25 m below that. Data near the interpolation grid point are weighted proportionately more than those further away. Temperatures were optimally estimated onto the grid for depths of 0, 50, 100 m and near bottom. Maximum depths for the interpolated temperature field were limited to 500 m as we were primarily interested in the temperatures over the shelf. The 1997 temperatures were also compared to the 1961–90 means for July.

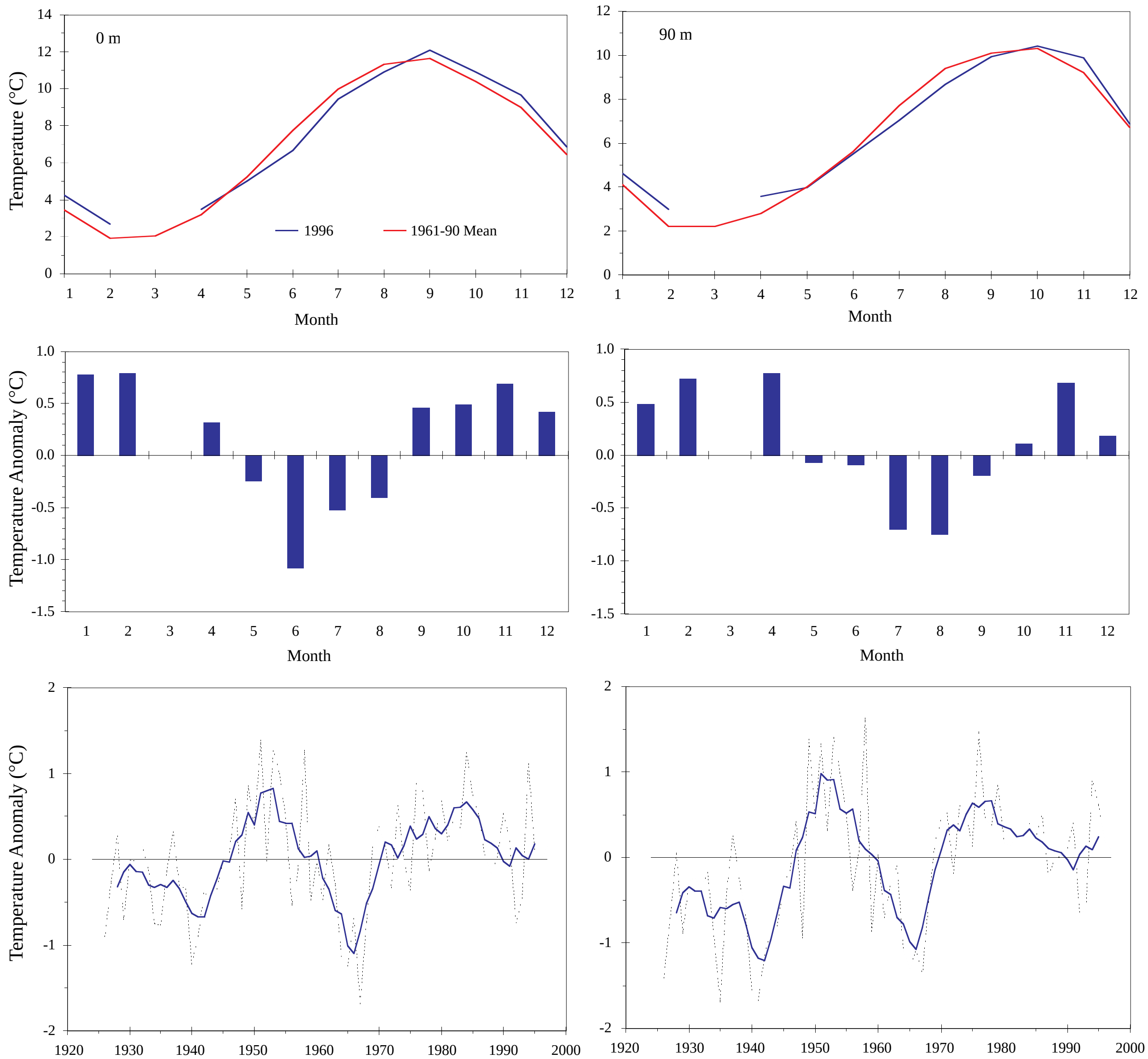

Fig. 39. Monthly mean temperatures for solid 1997 (blue line) and the long-term means (red line; top panels), the monthly anomalies relative to the long-term means for 1961–90 (middle panels) and in the bottom panels the time series of the annual means (dashed line) and 5-yr running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

Temperatures in 1997 at the surface varied from <9° to >16°C, the mouth of the Bay of Fundy being coldest and Sydney Bight and the central Scotian Shelf being warmest (Fig. 49). No data were collected on the Lurcher Shoals during this survey. At 50 m the coldest temperatures (<1°C) are in the extreme northeast and off Mahone Bay on the Atlantic coast of Nova (Fig. 49). Note that warm waters (4°–5°C) appear to penetrate onto the central shelf regions from the offshore. The 100 m and near bottom temperatures show a pattern of colder waters in the northeast and warmer waters to the southwest (Fig. 49).

Surface temperature anomalies are generally weak and spatially varying. An exception was the Bay of Fundy, where the anomaly was lower than -1°C (Fig. 50). At 50 m, temperatures were below normal over most of the shelf with anomalies colder than -2°C in the vicinity of Emerald Basin (Fig. 50). At 100 m and near bottom the anomalies were below normal in the northeastern Scotian Shelf and on Sable

Fig. 40. Monthly mean salinities for 1997 (solid line) and the long-term means (top panels), the monthly anomalies relative to the long-term means for 1961–90 (middle panels) and in the bottom panels the time series of the annual means (dashed line) and 5-yr running means (solid line) for Prince 5, 0 m (left) and 90 m (right).

and Western banks on the outer shelf (Fig. 50b). At 100 m, temperatures over Emerald Basin and in the Bay of Fundy were also colder-than-normal. This differs from 1996 when the 100 m temperatures over the basin were warmer-than-normal (Drinkwater *et al*., 1998). The warm water near bottom in Emerald Basin during the July survey is consistent with the 250 m temperature time series (Fig. 42) while the cold temperatures in the northeast are consistent with the Misaine Bank data (Fig. 45).

Frontal Analysis

Shelf/Slope Front

The waters on the continental shelves of the Northwest Atlantic have distinct temperature and salinity characteristics from those found in the adjacent deeper slope waters. The narrow boundary between the shelf and slope waters is regularly detected in satellite thermal imagery. Positions of this front and of the northern boundary of the Gulf Stream

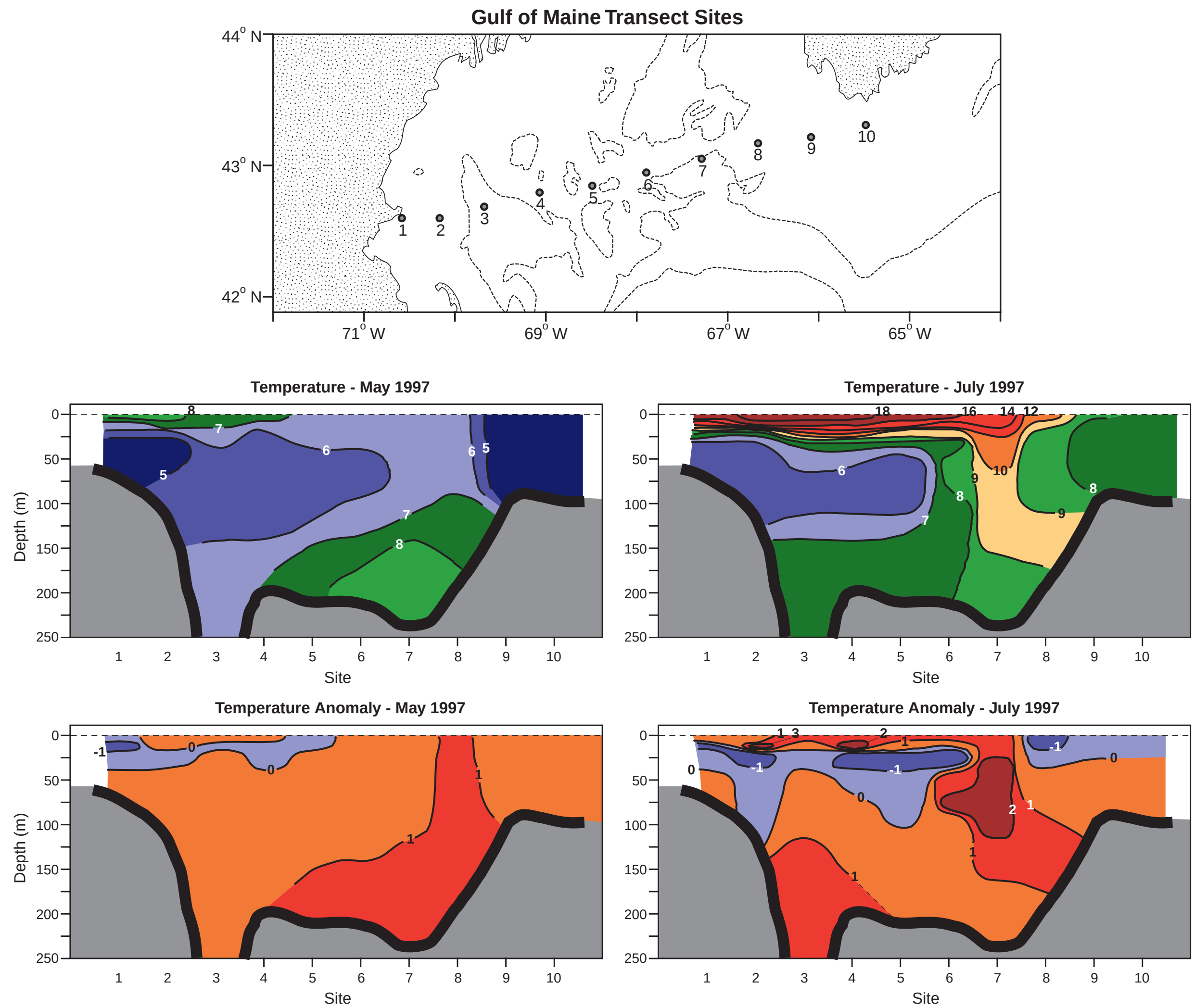

Fig. 41. The temperature (middle panels) and temperature anomalies (bottom panels) in °C along a XBT transect (top panel) across the Gulf of Maine during May and July 1997.

between 50°W and 75°W for the years 1973 to 1992 were assembled through digitization of satellite derived SST charts (Drinkwater *et al.*, 1994). From January 1973 until May 1978, the charts covered the region north to Georges Bank, but in June 1978 the areal coverage was extended to include east to 55°W and eventually 50°W. Monthly mean positions of the shelf/slope front at each degree of longitude were estimated. This data set was updated from the NOAA images until the termination of the satellite data product in October 1995. A commercial company has continued the analysis but did not begin until April

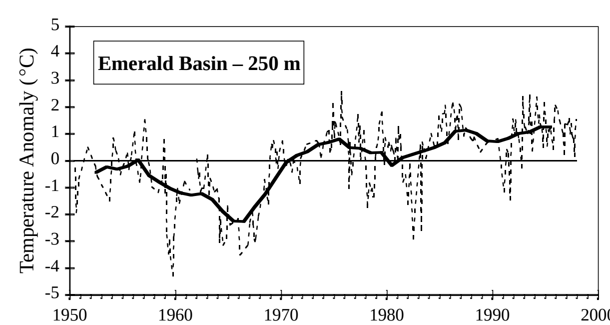

Fig. 42. Temperature anomalies (relative to 1961–90) in Emerald Basin at 250 m.

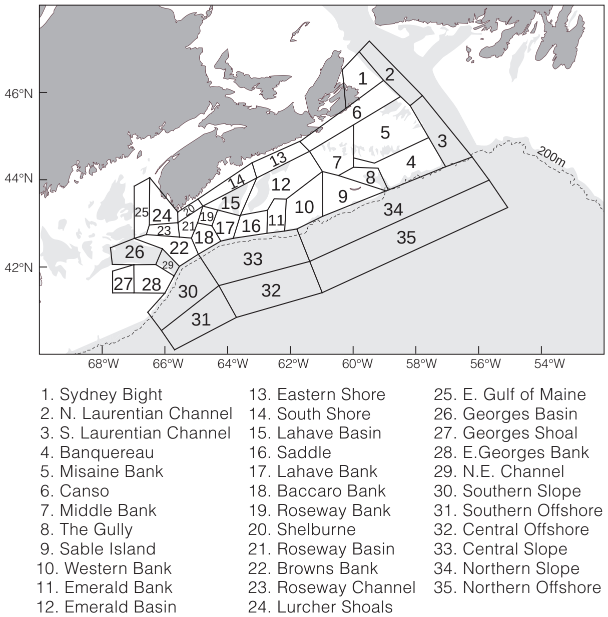

Fig. 43. The areas in which monthly mean temperature and temperature anomalies were estimated (from Drinkwater and Trites, 1987).

1996. Even then, the initial charts did not contain data east of 60°W. Data for 1997 and October to December of 1996 have been digitized; estimates of monthly means positions determined and anomalies relative to 1978 to 1997 were calculated.

The long-term mean position of the Shelf/Slope front together with the 1997 position is shown in Fig. 51. The mean position is close to the 200 m isobath along the Middle Atlantic Bight, separates slightly from the shelf edge off Georges Bank and then runs between 100–300 km from the shelf edge off the Scotian Shelf and the southern Grand Bank. It is generally furthest offshore in winter and onshore in late summer and early autumn. During 1997, the shelf/slope front was seaward of its long-term mean position along the entire pathway from 75°W to 56°W, the furthest east that reliable statistics could be determined using the commercial product. The largest deviations occurred at the eastern end. The time series of the annual mean position (averaged over 55°W–75°W) shows the front was at a maximum northward location in 1985 and again in

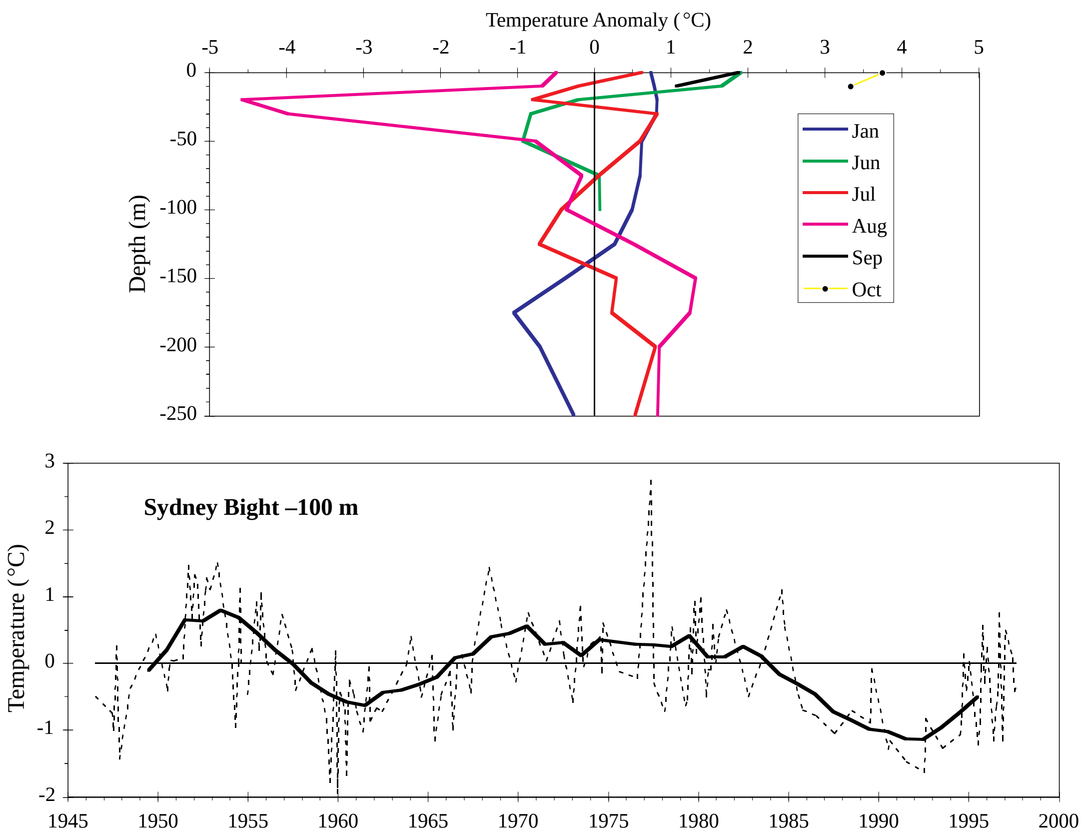

Fig. 44. The 1997 monthly anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Sydney Bight (area 1 in Fig. 43).

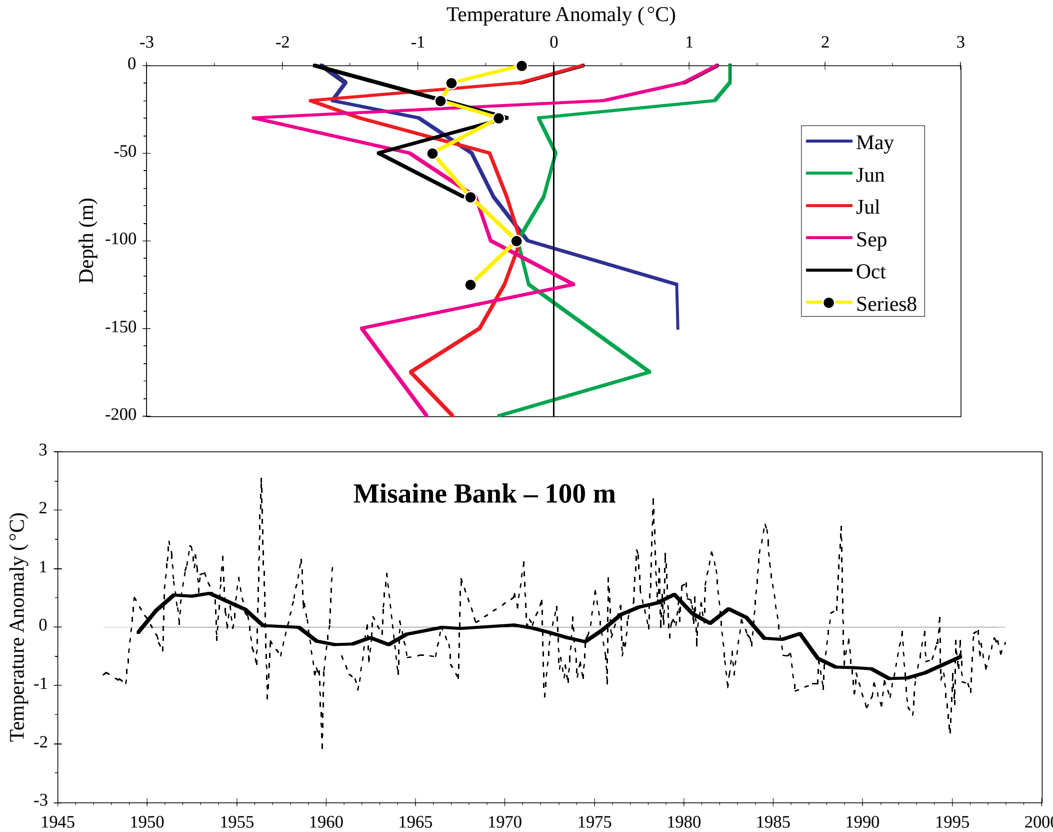

Fig. 45. The 1997 monthly anomaly profiles (top panel) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 100 m (bottom panel) for Misaine Bank (area 5 in Fig. 43).

1993. Since 1993, the front has been moving steadily southward (approximately 40 km) and is presently at its most southerly position since the early 1980s.

Gulf Stream

The position of the northern boundary or "wall" of the Gulf Stream was also determined from satellite imagery by Drinkwater *et al*. (1994) up to 1992 and has been updated in a manner similar to that for the shelf/slope front. Time series consists of the monthly position at each degree of longitude from 55°W to 75°W. The long-term mean and 1997 positions of the north wall of the Stream are shown in Fig. 52. The Stream normally leaves the shelf break near Cape Hatteras (75°W) and runs towards the northeast. East of approximately 62°W, the average position lies approximately east-west. During 1997, the Stream was south of its long-term mean position at each degree of longitude except at 56°W. The largest deviations occurred west of 70°W. The Stream was located south of its mean position during 1970, and again in the late-1970s and 1980, near the long term mean through most of the 1980s, and north of it during the late-1980s and into the first half of the 1990s (Fig. 52). The annual anomaly of the Gulf Stream was at its most northerly position in 1995. This was followed a rapid decline in 1996 and remained south through 1997. The 1996 position is not well defined, however, since it is based upon only three months of the data (October to December). The time of southward shift in the Stream matches the large decline in the NAO index and is consistent with the finding of a significant positive correlation between the Gulf Stream position and the NAO.

Summary

During 1997, the NAO index was below normal for the second consecutive year, but higher than in 1996. The relatively weaker Icelandic Low resulted in weak northwest winds in winter over the Labrador Sea. This in turn contributed to generally warmer

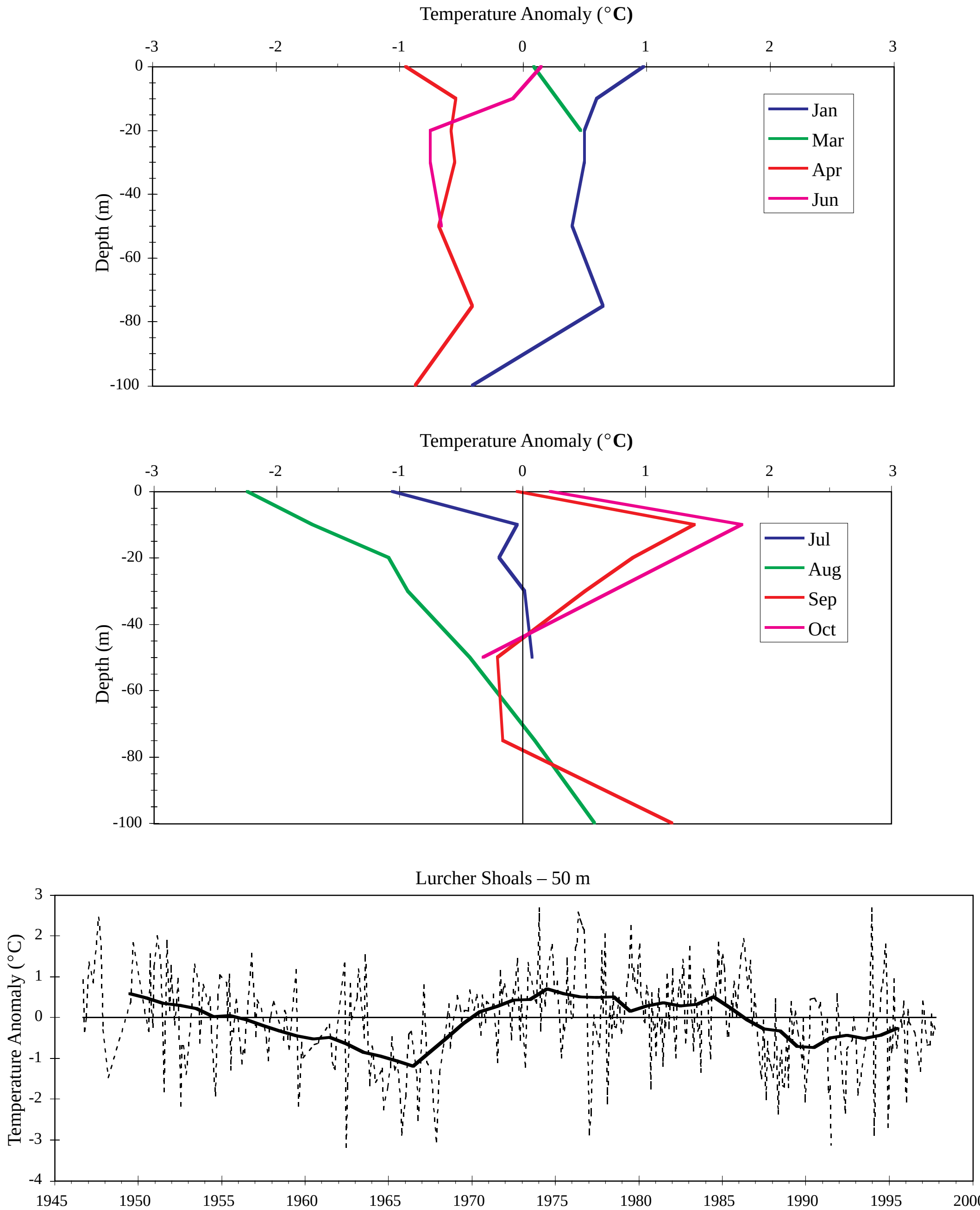

Fig. 46. The 1997 monthly anomaly profiles (top 2 panels) plus the monthly mean temperature anomaly time series (dashed line) and the 5-yr running mean of the estimated annual anomalies (solid line) at 50 m (bottom panel) for Lurcher Shoals (area 24 in Fig. 43).

winter air temperatures over the region. Notable, however, was a significant shift from very warm in the first half of the winter to cold in the second half. The warm temperatures and weak winds early in the winter resulted in later-than-normal ice formation, but as the cold conditions and stronger northwest winds developed during the latter half of the winter, the sea ice spread quickly. Ice lasted longer than normal throughout most of the Gulf and on the Scotian Shelf but not on the Newfoundland and Labrador shelves. In spite of the long ice duration, the areal extent of ice on the Scotian Shelf was below normal. The number of icebergs reaching the Grand Banks in 1997 was higher than 1996 but below the

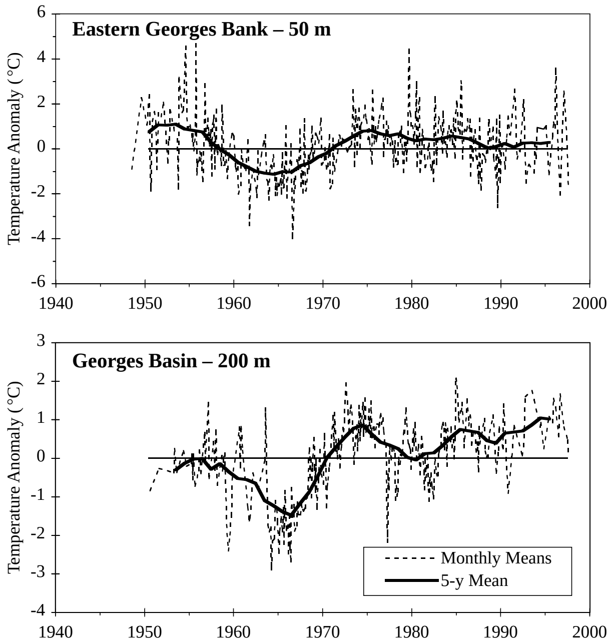

Fig. 47. Monthly means (dashed lines) and the 5-yr running means of the annual anomalies at 200 m in Georges Basin (top panel, area 26 in Fig. 43) and eastern Georges Bank (bottom panel; area 28 in Fig. 43).

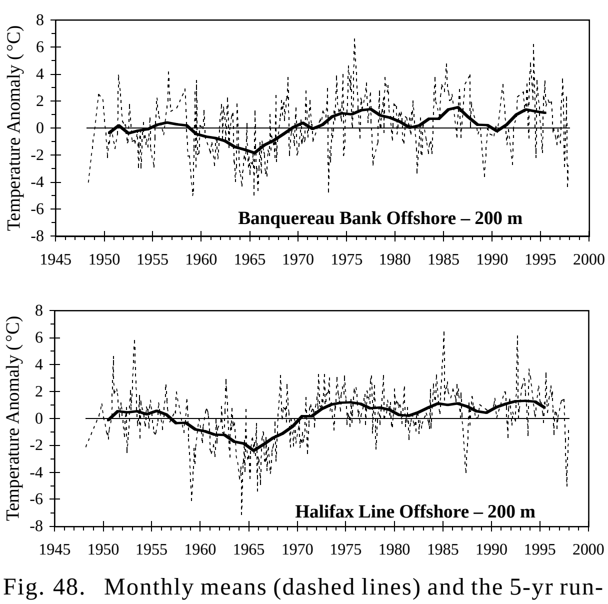

Fig. 48. Monthly means (dashed lines) and the 5-yr running means of the annual anomalies at 200 m in the offshore slope regions off Banquereau and the Halifax Line (areas 34 and 33, respectively, in Fig. 41).

large numbers recorded in the earlier 1990s. During spring 1997, air temperature anomalies were generally below normal, consistent with the air pressure pattern and weaker northwest winds over the Labrador Sea. In summer, air temperatures anomalies tended to relatively small, fluctuated about their long-term means, and varied spatially.

Off northern Newfoundland and Labrador, the relatively warm ocean conditions that were first observed in 1996 generally continued. Station 27 temperatures ranged from 0° to 0.5°C above normal in the winter, although by mid-April a strong negative surface temperature anomaly developed. By May surface anomalies were near -1°C. They later appeared to propagate downward, reaching a depth of 100 m by October. Autumn temperatures in the upper layer were about normal, as where bottom temperatures throughout the year. Salinities at Station 27 tended to be slightly below normal throughout the year except in the autumn at mid-depth when they were up to 0.5 above normal. The volume of <0°C water (CIL) on the Newfoundland Shelf was well below normal and continued the trend established in 1995. Bottom temperatures on Hamilton Bank and the Grand Bank in the autumn of 1996 increased significantly over previous years and were up to 0.5°C above normal over many areas. During the 1997 autumn survey, bottom temperatures were still above normal over many areas, particularly in the far offshore portion of the southern Labrador Shelf and northeast Newfoundland Shelf.

Temperature anomalies on St. Pierre Bank show the cold period that started around 1984, continued through to the spring of 1995 but moderated slightly during 1996, particularly in the upper 20 m. During 1997, however, temperatures decreased again to below normal values. During the spring in Subdiv. 3Ps, bottom temperatures in the Laurentian Channel were above normal but they were below normal on St. Pierre Bank, by more than 1°C on the southeast portion of the bank.

In the Gulf of St. Lawrence, moderating conditions are suggested by increasing temperatures, a reduction in the thickness of the CIL layer and a decline in the area of near bottom on the Magdalen Shallows covered by waters <1°C.

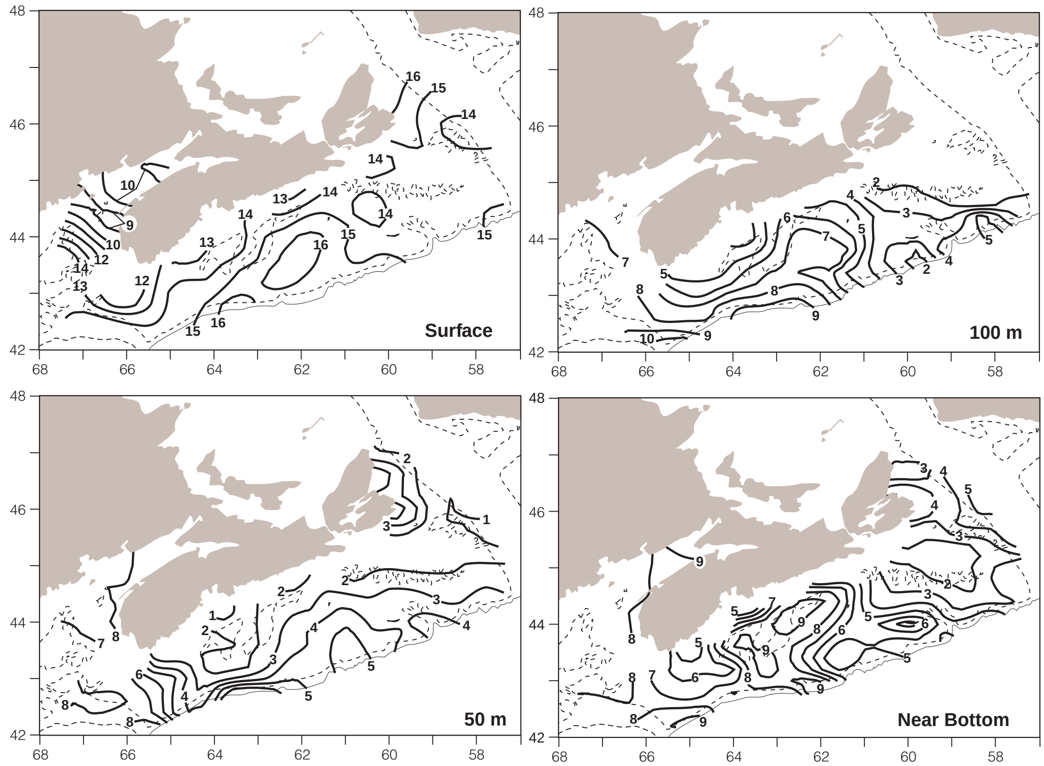

Fig. 49. Contours of optimally estimated temperatures at the surface, 50 m, 100 m and near bottom during the 1997 July groundfish survey.

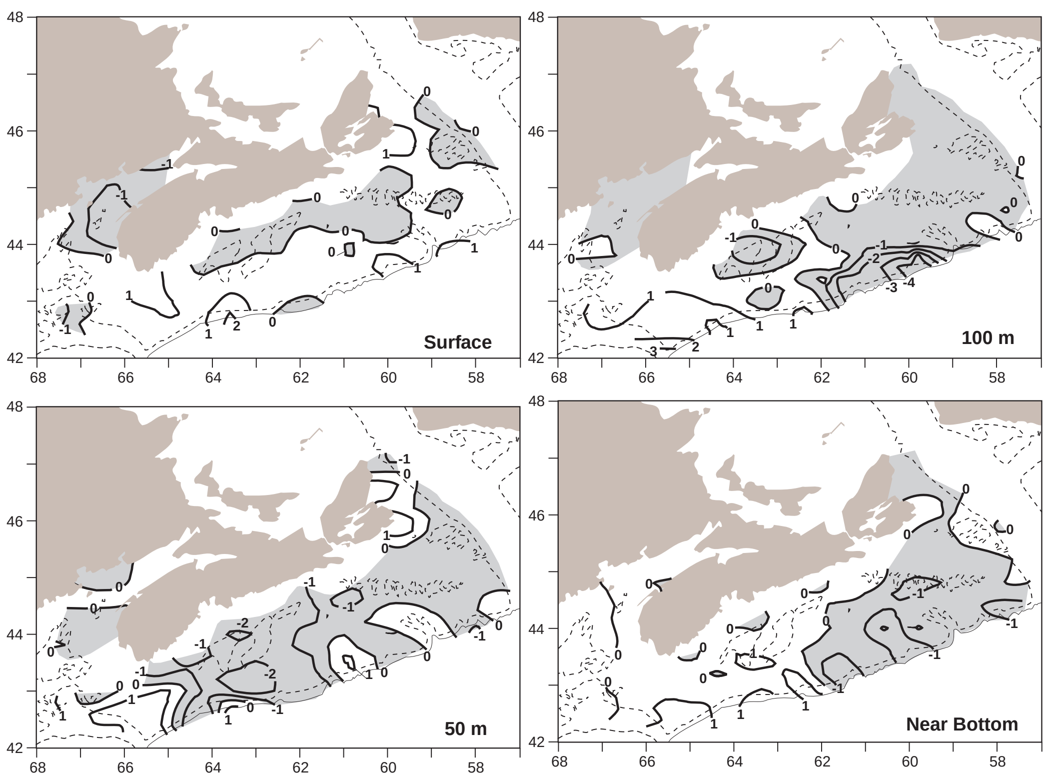

Fig. 50. Contours of optimally estimated temperature anomalies at the surface, 50 m, 100 m and near bottom during the 1997 July groundfish survey. Shaded areas indicate colder than normal temperatures.

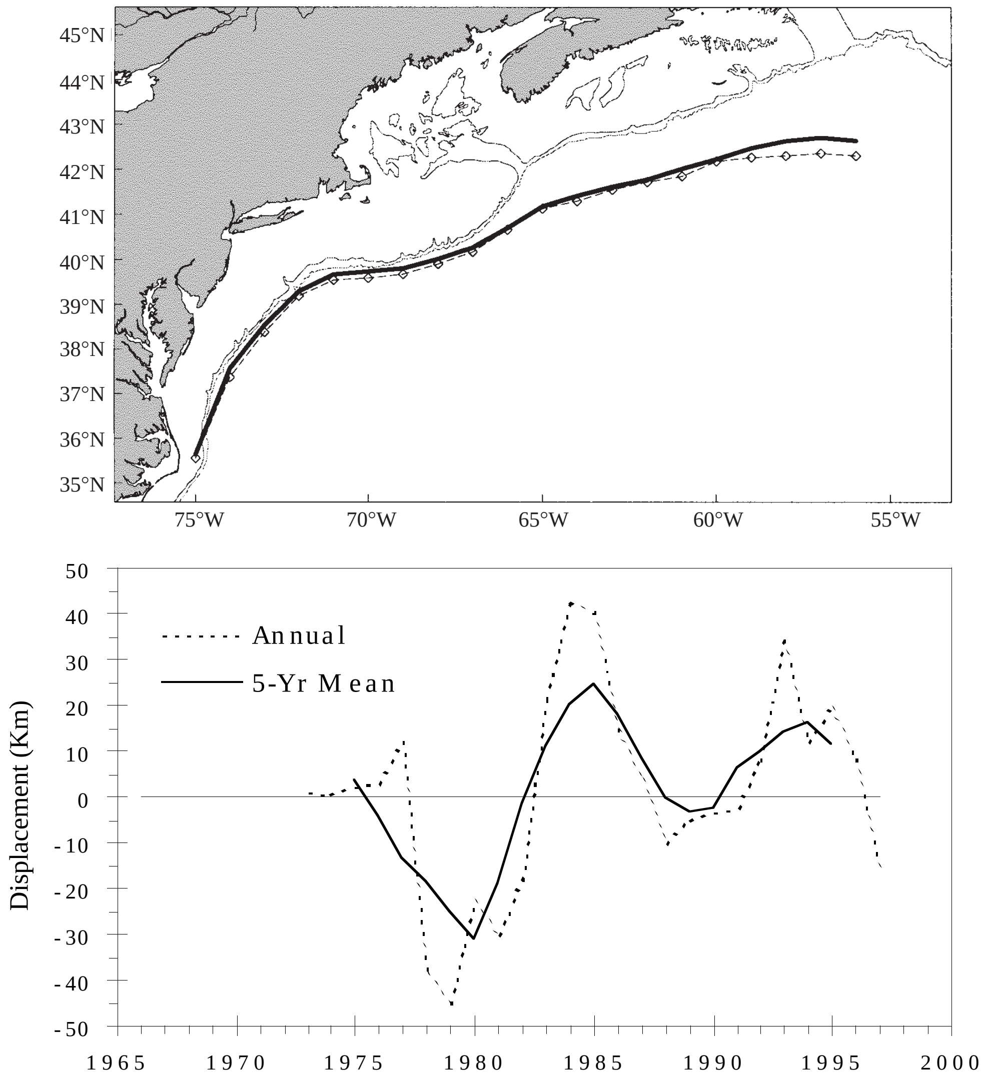

Fig. 51. The 1997 (dashed line) and long-term (1973–97; solid line) mean positions of the shelf/slope front (top panel) and the annual mean anomaly of the average (55°–75°W) position of the shelf/slope front (bottom panel).

Indeed, a larger proportion of the bottom of the Shallows had near normal and even above normal temperatures for the first time in several years.

On the northeastern Scotian Shelf, along the Atlantic coast of Nova Scotia and off southwestern Nova Scotia, colder-than-normal conditions persisted through 1997. This pattern was established in the mid-1980s with minimum temperatures in the early 1990s. In recent years there has been a slow but steady increase in temperatures in these regions. The presence of these cold waters are believed to be due to advection from the Gulf of St. Lawrence and off the Newfoundland Shelf and to a lesser extent *in situ* cooling during the winter, although the relative importance has not yet been established. In contrast to these cool conditions, the waters in the central Scotian Shelf over Emerald Basin and in the deep basins of the Gulf of Maine were warmer-than-normal and near the highest on record. These very warm conditions generally reflect the presence of warm slope water offshore. However, for the first time in almost a decade, cold offshore waters were observed along the outer edge of the Scotian Shelf with temperatures dropping to values last observed in the 1960s. By the spring of 1998, these cold waters had moved south to the Gulf of Maine and were penetrating onto the Shelf (Drinkwater *et al.*, MS 1998).

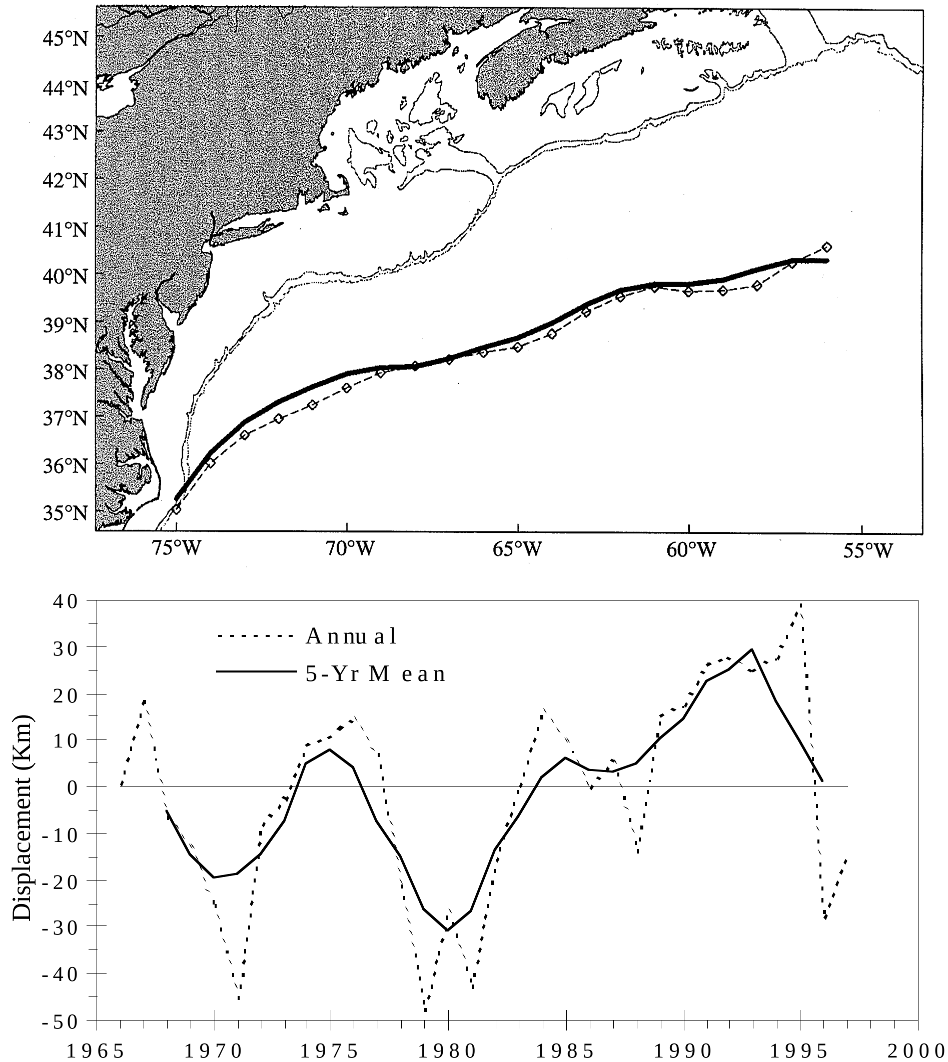

Fig. 52. The 1997 (dashed line) and long-term (1973–97; solid line) mean positions of the northern edge of the Gulf Stream (top panel) and the annual mean anomaly of the average (55°–75°W) position of the Gulf Stream front (bottom panel).

Both the shelf/slope and Gulf Stream fronts were southward of their long-term mean positions during 1997. This appears associated with the low NAO index, although the mechanisms are as yet unresolved.

Acknowledgements

We wish to thank those who provided data, especially I. Peterson of the Bedford Institute for the monthly areal ice extent data for the Newfoundland region; the U.S. Coast Guard for the iceberg data; the Marine Environmental Data Service in Ottawa for updating the BIO hydrographic database; the Bigelow Laboratory for providing Boothbay Harbor temperature data; F. Page and R. Losier of the Biological Station in St. Andrews, for providing St. Andrews and Prince 5 data, J. McRuer of BIO for the Scotian Shelf July groundfish survey data; P. Fraser of the Halifax Laboratory and B. Petrie of the BIO for the Halifax sea surface temperature data, G. Bugden of the BIO for his Cabot Strait temperature data, D. Swain of the Gulf Fisheries Centre in Moncton for data from the Gulf of St. Lawrence. We also thank R. Pettipas, L. Petrie, C. Fitzpatrick, P. Dubé, B. Pettigrew, M. Couture and D. Foote for their technical support in preparation of this paper.

References

BUGDEN, G.L. 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. *In*: The Gulf of St. Lawrence: small ocean or big estuary? J.-C. Therriault [ed.] *Can. Spec. Publ. Fish. Aquat. Sci.*, **113**: 139–147.

COLBOURNE, E. MS 1994. Environmental conditions during the fall of 1993 in NAFO Divisions 2J3KL. *NAFO SCR Doc.*, No. 28, Serial No. N2394, 26 p.

MS 1995. Oceanographic conditions and climate change in the Newfoundland region during 1994. *DFO Atl. Fish. Res. Doc.*, No. 3, 36 p.

COLBOURNE, E. and G. MERTZ. MS 1995. Spatial and temporial variability in the CIL on the Newfoundland shelves. *NAFO SCR Doc.,* No. 33, Serial No. N2542, 14 p.

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.

COTÉ, P. W. MS 1989. Ice limits eastern Canadian seaboard. Environment Canada, Ottawa. 39 p. (Unpubl. Manuscript).

DICKSON, R. R., J. MEINCKE, S.-A. MALMBERG, and A. J. LEE. 1988. The "great salinity anomaly" in the northern North Atlantic 1968–1982. *Prog. Oceanogr.*, **20**: 103–151.

DRINKWATER, K.F. 1995. Overview of environmental conditions in the Northwest Atlantic in 1993. *NAFO Sci. Coun. Studies,* **23**: 9–42.

1996. Atmospheric and oceanic variability in the Northwest Atlantic during the 1980s and early-1990s. *J. Northw. Atl. Fish. Sci.*, **18**: 77–97.

DRINKWATER, K.F. and R.W. TRITES. 1987. Monthly means of temperature and salinity in the Scotian Shelf region. *Can. Tech. Rep. Fish. Aquat. Sci.*, **1539**: 101 p.

DRINKWATER, K.F., E. COLBOURNE and D. GILBERT. 1996. Overview of environmental conditions in the Northwest Atlantic in 1995. *NAFO Sci. Coun. Studies,* **27**: 1–37.

1998. Overview of environmental conditions in the Northwest Atlantic in 1996. *NAFO Sci. Coun. Studies,* **31**: 111–146.

DRINKWATER, K., D. 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 pp.

DRINKWATER, K. F., R. G. PETTIPAS, G. L. BUGDEN, and P. LANGILLE. 1999. Climatic data for the Northwest Atlantic: A sea ice database for the Gulf of St. Lawrence and the Scotian Shelf. *Can. Tech. Rep. Hydrogr. Ocean Sci.*, **199**: 134 p.

GILBERT, D. and B. PETTIGREW. 1997. A study of the interannual variability of the CIL core temperature in the Gulf of St. Lawrence. *Can. J. Fish. Aquat. Sci.*, **54**(Suppl. 1): 57–67.

HUTCHINGS, J. A. and R. A. MYERS. 1994. What can be learned from the collapse of a renewable resource? Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. *Can. J. Fish. Aquat. Sci.*, **51**: 2126–2146.

MYERS, R. A., S. A. AKENHEAD, and K. F. DRINKWATER. 1990. The influence of Hudson Bay runoff and ice-melt on the salinity of the inner Newfoundland Shelf. *Atmosphere-Ocean*, **28**: 241–256.

MYERS, R. A., K. F. DRINKWATER, N. J. BARROWMAN, and J. BAIRD. 1993. The influence of salinity on cod recruitment in the Newfoundland region. *Can. J. Fish. Aquat. Sci.*, **50**: 1599–1609.

PETRIE, B. and K. DRINKWATER. 1993. Temperature and salinity variability on the Scotian Shelf and in the Gulf of Maine, 1945–1990. *J. Geophys. Res.*, **98**: 20079–20089.

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

PETRIE, B., J.W. LODER, S. AKENHEAD, and J. LAZIER. 1991. Temperature and salinity variability on the eastern Newfoundland Shelf: The annual harmonic. *Atmosphere-Ocean*, **29**: 14–36.

1992. Temperature and salinity variability on the eastern Newfoundland Shelf: The residual field. *Atmosphere-Ocean*, **30**: 120–139.

ROGERS, J. C. 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon. Wea. Rev.*, **112**: 1999–2015.

SUTCLIFFE, W. H. Jr., R.H. LOUCKS, K. F. DRINKWATER, and A. R. COOTE. 1983. Nutrient flux onto the Labrador Shelf from Hudson Strait and its biological consequences. *Can. J. Fish. Aquat. Sci.*, **40**: 1692–1701.

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