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OVERVIEW OF ENVIRONMENTAL CONDITIONS IN THE NORTHWEST ATLANTIC IN 1996

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ABSTRACT

A review of environmental conditions in the Northwest Atlantic during 1996 is presented. Over the Labrador Sea, weak northwest winds in winter brought less cold Arctic air southward producing warmer-than-normal air temperatures. This reversed the cooling trend that had persisted through the 1990s. Air temperatures in the Gulf of St. Lawrence and over the Scotian Shelf were also relatively warm and contrasted with the colder-than-normal values from the southern Gulf of Maine to Cape Hatteras. These changes were associated with a reduction in the NAO index caused by a weakening of the Icelandic Low and Azores High. The decline in the NAO index was the largest annual decrease in over 100 years of record. The warmer air temperatures and weaker winds resulted in late ice formation, a smaller areal extent of ice and a shorter presence of ice, both on the Labrador/Newfoundland shelves and in the Gulf of St. Lawrence/Scotian Shelf area. Fewer icebergs reached the Grand Banks than in the early 1990s. Ocean temperatures off Labrador and northeastern Newfoundland also warmed during 1996. Monthly mean ocean temperatures at Station 27 were consistently warmer than normal for the first time in over a decade and well above the extreme cold period of the early 1990s. Also, from Hamilton Bank to the Grand Bank, the amount of water in the cold intermediate layer (CIL) was less then usual and bottom temperatures tended to be warmer-than-normal. In contrast, temperatures off southern Newfoundland remained relatively cold, continuing the below normal temperature trend that was established in the mid-1980s. A similar continuation of relatively cold conditions in the subsurface waters was observed within the Gulf of St. Lawrence and on the northeastern and southwestern Scotian Shelf although there was some slight warming over last year. In the central Scotian Shelf and in the Gulf of Maine, waters were relatively warm especially in the deeper basin, such as Emerald and Georges Basins. The source of these warm waters is thought to be the offshore slope waters.

Introduction

This paper examines the atmospheric, sea ice and hydrographic conditions in the Northwest Atlantic during 1996 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. Environmental conditions are compared with those of the preceding year as well as the long-term means. 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. Many annual indices presented in the paper are also expressed as 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 monthly mean temperature anomalies relative to the 1961-90 means for the North Atlantic Ocean in their publication *Die Grosswetterlagen Europas*. During January, colder-than-average temperatures (by <1°C) covered most of the Labrador Sea, Newfoundland, and the northeastern Scotian Shelf (Fig. 1). In contrast, over the Gulf of St. Lawrence, the remainder of the Scotian Shelf and the Gulf of Maine, temperatures were slightly above normal. Warm conditions generally prevailed from February to May over the Labrador Sea with a maximum in April as anomalies ranged from +1 to +6°C. The highest anomalies lay along the Labrador coast. The second highest monthly anomalies (+1 to +4°C) were in February. Warmer-than-normal air temperatures also dominated the southern regions of Atlantic Canada from February to April. From June to November, air temperatures throughout the entire northwest Atlantic fluctuated about their long-term average, with both the amplitude and sign of the anomalies varying spatially and month to month. In December, warm conditions once again covered most of the NW Atlantic with temperatures 2-6°C above normal. The warmest anomalies were found over northern Labrador and southern Baffin Island.

Monthly air temperature anomalies for 1995 and 1996 relative to their 1961-90 mean at 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 western Gulf of Maine, and Cape Hatteras at the southern boundary of the NAFO region (see Fig. 2 for locations) are shown in Fig. 3. The predominance of warmer-than-normal air temperatures in the first half of 1996 is clearly evident at most sites. At Godthaab, June to November anomalies were negative but rose to 2°C above normal in December. Cartwright and St. John's show a somewhat similar pattern to Godthaab except for the very warm temperatures in mid-summer. The Magdalen Islands in the Gulf of St. Lawrence were warmer-than-normal throughout the year. From Sable Island south, the late autumn was cold. Note that for all sites, December generally shows extremely warm conditions. The highest December anomalies were recorded at Iqaluit (6°C) and the lowest at Cape Hatteras (<1°C).

The 1996 annual mean air temperatures at the six northernmost sites were warmer than normal and, with the exception of Iqaluit, exceeded their 1995 values. On the other hand, Iqaluit recorded the maximum anomaly observed at all eight sites (1.5°C) but it was similar to that observed in 1995. All sites surrounding the Labrador Sea had annual air temperature anomalies equal to or exceeding 0.6°C. On the Magdalen Islands in the Gulf of St. Lawrence, the annual anomaly was 1°C while at Sable Island it was <0.2°C. At Boston and Cape Hatteras, annual air temperatures in 1996 were cooler than average by 0.24 and 0.2°C, respectively, and decreased for the second year in succession.

The time series of annual temperature anomalies show the positive values in 1996 and the general increase at the six most northern sites and the negative values and decrease at the two most southern sites (Fig. 4). 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 is consistent with a continuation of this near decadal pattern. A general downward trend at these sites, in addition to the near decadal oscillations, has 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 and show no signs of a general downward trend since 1970. They do, however, contain minima in the early 1970s (both sites), the mid-1980s (Sable Island only) and in the 1990s (Magdalen Islands only). At Boston, there was a gradual increase from the 1800s to the mid-1900s, followed by temperature oscillations without any overall trend. The latter is also observed on the Magdalen Islands and Sable Island. At Cape Hatteras, temperatures in the early 1990s were near their long-term maximum but have declined rapidly during the last two years. Since the 1960s temperatures have generally been opposite those in the northern regions, i.e. when it was cold in the north, it tended to be warm at Cape Hatteras.

Sea Surface Air Pressures

Climatic conditions in the Labrador Sea area are closely linked to the large-scale pressure patterns and atmospheric circulation. Monthly mean sea-surface pressures over the North Atlantic are published in *Die Grosswetterlagen Europas*. The long-term seasonal mean pressure patterns are dominated by the Icelandic Low centred between Greenland and Iceland and the Bermuda-Azores High centred between Florida and northern Africa (Fig. 5). Winds rotate counterclockwise around lows and clockwise around highs. 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 1996, relative to the 1961-90 means, are shown in Fig. 6. Winter includes December 1995 to February 1996, spring is March to May, summer is June to August and autumn is September to November.

In winter, positive air pressure anomalies covered the northern North Atlantic with a maximum (exceeding 10 mb) centred over eastern Norway. In contrast, a centre of negative anomalies (maximum exceeding -8 mb) was observed over the southeastern North Atlantic. This pattern represents a weakening of both the Icelandic Low and the Bermuda-Azores High and a significant shift in 1996 from the rest of the 1990s when these pressure systems were more intense-than-normal. The anomalous pressure pattern would tend to reduce the mean westerly winds over the northern North Atlantic, especially over eastern sections and Great Britain where the anomalous pressure gradients were steepest. Note that the anomalous winds are from the east and would oppose the mean westerly winds, thereby resulting in weaker westerly winds. Anomalous southerly winds over East Greenland would oppose the southward flowing East Greenland Current, perhaps contributing to a decrease in its transport. Anomalous southerly winds in winter would have caused weaker-than-usual northwesterly winds over Baffin Bay and the Labrador Sea while over Newfoundland, the Gulf of St. Lawrence and the Scotian Shelf/Gulf of Maine winds would have been more northeasterly than normal for the second year in a row. The anomaly pressure pattern established in the winter extended into spring although the peak values decreased slightly and shifted westward (anomalies of 7.9 mb near Iceland and -6 mb near the Azores). This would have contributed to a continuation of weaker westerly winds than normal across the North Atlantic and northwesterly over the Labrador Sea. In summer, an anomalous low developed east of Newfoundland with a maximum pressure anomaly of -2.3 mb. This would produce weaker southerly and southwesterly winds than usual over Newfoundland, the Gulf of St. Lawrence and the Gulf of Maine. The autumn saw a return to the winter and spring anomaly pattern with positive values in the north and negative to the south. However, this pattern shifted northward such that the centre of the positive anomaly was over Greenland and the low lay between Newfoundland and Great Britain. An anomalous high also developed off northwest Africa. This pattern would have resulted in anomalous northeasterly winds over south Labrador and the Atlantic provinces of Canada.

NAO Index

The North Atlantic Oscillation (NAO) Index is a measure of the large-scale circulation. Rogers (1984) defined the index as the difference in winter (December, January and February) sea level pressures between the Azores and Iceland and hence it is a measure of the strength of the winter westerly winds over the northern North Atlantic. Recently, Hurrell (1995) has used the pressure difference (December through March) between Iceland and Lisbon, Portugal. Although there are differences between the two indices, the overall patterns are similar. In this paper we use the index as defined by 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 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 1996, the NAO index fell dramatically relative to last year producing an anomaly that was strongly negative (Fig. 7). This reverses the trend of very high NAO anomalies that had persisted since the late 1980s. Indeed, the decrease from 1995 to 1996 was the single largest annual decline in the NAO index in over 100 year's of record. While this change may indicate a significant shift in the large-scale atmosphere circulation, it also fits the pattern of near decadal variability that has persisted since the 1960s. Based upon this approximate decadal oscillation, a decrease in the NAO index was not surprising, although its observed amplitude was much greater than expected.

Sea Ice Observations

Information on the location and concentration of sea ice is available from the daily ice charts published by Ice Central 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 (1989).

Newfoundland and Labrador

At the end of 1995, 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 mean for that time of the year (Fig. 8a). This was in large part due to above normal air temperatures during the second half of December that slowed ice formation, coupled with strong northeasterly winds over south Labrador that pushed ice inshore. During the first half of January 1996, ice spread rapidly south to St. Anthony on Newfoundland's northern Peninsula and offshore, such that the ice edge was near its long-term median position by the middle of the month. Moderating air temperatures and southwesterly winds slowed the ice advancement during the second half of the month and by the end of January the ice coverage off northern Newfoundland was again less than the long-term normal. Continuing positive temperature anomalies and strong southwesterly winds caused the southern ice edge to retreat northward during February, which is very unusual for this time of the year. Several strong wind storms also broke up and loosen the ice. By 1 March the ice edge was well north of its long-term median position but lay close to its maximum location offshore. Variable temperatures and wind through March left the southern ice edge far north of the long-term median location by April and between the median and maximum locations offshore. During April the ice retreated quickly northward. By 1 May, ice was limited to southern Labrador and was patchy. Ice remained off the mouth of Hamilton Inlet through June but by 1 July it had disappeared.

An analysis of the time of onset, duration and last presence of sea ice at 24 sites (Fig. 9) off the east coast of Newfoundland and southern Labrador and in the Gulf of St. Lawrence was carried out by Ice Central of Environment Canada until 1994. For each site, the extracted data include ice duration in weeks, as well as minimum, maximum and mean duration for years when ice was present (Table 1). For the last two years, we have continued the analysis. In 1996, ice first appeared off southern Labrador in early January, approximately 1 week later-than-normal (Fig. 10, positive anomaly). On the Newfoundland and Labrador shelves, the ice generally appeared later-than-normal by <1 week except in a region offshore where it arrived up to two weeks early. Ice was not observed during the season at the far offshore sites N27 and N70, and at the southern sites N108 through to N114 and at N228. However, ice has never been observed at sites N27 and N70, in 36 years of observations has only reached N114 five times, and has only been observed in 15 of the 37 years of record at N112. By contrast, at N110, N112 and N228 the total absence of ice is relative rare, having occurred only 17, 20 and 30% of the time respectively, at the 3 sites. At sites N25 and N68 ice has appeared in so few years that a long-term mean and annual anomalies have little meaning. Ice began to disappear in March from the furthest offshore sites (Fig. 11). Ice retreated from northern Newfoundland waters during April, from southern Labrador in May but lasted in the region south of Hamilton Inlet until 20 June. At most sites this resulted in ice disappearing early-than-normal, including up to 4 weeks early off the northern tip of Newfoundland. Exceptions to this are sites N19 off Hamilton Inlet where the ice remained slightly later-than-normal and at N23 where the last ice was observed 1 week later-than-normal. The duration of the ice season ranged from less than 5 weeks far offshore to just over 15 weeks off Hamilton Inlet on the southern Labrador (Fig. 12). Note that the duration is not simply the date of the first presence minus the last presence because the 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 but were longer-than-normal by up to 6 weeks at site N23 offshore of Labrador.

The time series of the areal extent of ice on the Newfoundland and southern Labrador shelves (between 45-55°N; I. Peterson, personal communication, Bedford Institute) show that the peak extent during 1996 declined for the second consecutive year, was well below the high values in the early 1990s and was the lowest in almost 20 years (Fig. 13). The average area during the typical months of ice advancement (January-March) and retreat (April to June) also show ice coverage was less than that observed during the last few years and the lowest since the late 1970s (Fig. 13). Indeed, in all months of 1996 ice coverage was less than that observed during the last few years. In summary, 1996 was an average to lighter-than-average ice year on the Labrador and Newfoundland shelves. Note that during the months of ice advance there has been a general increase in the area of ice over the past 30 years but no such trend exists during the period of ice retreat. Variations of ice area reflect similar changes in ice volume as the two are highly correlated based on studies we have carried out in the Gulf of St. Lawrence.

Icebergs

The number of icebergs that pass south of 48°N latitude each year is monitored by the International Ice Patrol Division of the United States Coast Guard. Since 1983, data have been collected with SLAR (Side-Looking Airborne Radar). During the 1995/96 iceberg season (October to September), a total of 611 icebergs were spotted south of 48°N. The monthly totals for March to August were 4, 297, 187, 108, 14, and 1 (Fig. 14). No icebergs were spotted between October, 1995, and February, 1996, inclusive, or in September, 1996. All icebergs in 1996 were observed during the primary iceberg season of March to July, higher than the mean during 1983-96 of 89%. The percentage of the total number of icebergs by month for the 1995/96 season shows that proportionally more penetrated south of 48°N in April and May then on average during the years icebergs have been detected using SLAR (1983-96). Indeed, almost 50% of the icebergs in 1996 arrived in April. The total number of icebergs in 1996 was above the long-term mean but was well down from the high numbers during the earlier years of the 1990s (Fig. 14). The decline in iceberg numbers matches the decline in sea ice extent and follows from the warmer air temperatures and reduced northwest winds. 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

Near normal air temperatures over the Gulf of St. Lawrence during December 1995 resulted in the ice edge being close to its long-term mean position at the end of that year (Fig. 15). Ice had formed in the St. Lawrence Estuary and along the coast from Baie des Chaleur to Pictou, Nova Scotia. Ice advanced at its normal rate through January and the ice edge lay near the long-term median location by 1 February. However, the ice was looser than normal, in large part, because of several strong wind storms that caused considerable ice destruction. Uncharacteristically warm temperatures during February slowed the ice advance and left the ice edge north of the long term median by 1 March. Winds also pushed ice away from the shores of northern Prince Edward Island, off Cape Breton, western Newfoundland and out of the St. Lawrence Estuary. Wind storms continued to keep the ice loose. Ice coverage remained near the long-term median by 1 April but continued to be thinner and looser than normal. Above normal temperatures during April resulted in rapid melting so that by mid-month most of the ice had disappeared from the Gulf. By 1 May the only significant amount of ice left in the Gulf was located in the Strait of Belle Isle and this disappeared by the 5 May. In summary, the ice coverage in the Gulf was near normal during 1996 but it was thinner and looser than normal.

Ice in the Gulf of St. Lawrence generally appeared within a week of its usual arrival date although it tended to be later-than-normal (Fig. 10). Exceptions were north of Anticosti Island where the ice was 3 weeks late and off Baie des Chaleurs which was near normal but slightly early. No ice was observed at grid point G35 off southern Newfoundland. On the eastern side of the Gulf, ice lasted longer than normal by upwards of 2 weeks in the Estuary but on the western side it left early (Fig. 11). In the Strait of Belle Isle the ice disappeared 2-4 weeks early. The ice duration (Fig. 12) was shorter-than-normal (by 1-4 weeks) throughout the Gulf with the shortest duration relative to the mean being in the Strait of Belle Isle and in the Cabot Strait region. No records for maximum or minimum ice duration or first or last presence were set anywhere in the Gulf in 1996.

Scotian Shelf

Sea ice normally flows out of the Gulf of St. Lawrence, pushed by northwest winds and the mean ocean currents. Seaward of Cabot Strait, ice can appear as early as January and remain as late as May. Based on ice records since the 1960s, ice often extends onto the Scotian Shelf covering a large area of the northeastern region and will reach south along the Atlantic coast of Nova Scotia to Halifax. Historical records suggest that back in the late 1800s ice extended as far south as the Gulf of Maine on rare occasions (A. Ruffman, Halifax, personal communication). The monthly estimates of the ice area seaward of Cabot Strait since the 1960s shows that less ice than normal was transported onto the Scotian Shelf during 1996 (Fig. 16) and it was significantly less than 1995 in all months. The loose and thin ice observed in the Gulf likely contributed to its rapid break-up and melting once it reached the Scotian Shelf. The data indicate that 1996 was a light ice year on the Scotian Shelf.

Oceanographic Observations

Newfoundland and Labrador

Station 27

Temperature and salinity have been monitored since 1946 at Station 27, situated 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 over the continental shelf from southern Labrador to the Grand Banks at interannual to decadal time scales (Petrie et al., 1992). The station was visited 57 times in 1996, with a monthly maximum of 8 in May and a minimum of 2 in August. 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 1996 together with their anomalies relative to 1961-90 are shown in Fig. 17.

The water column was nearly isothermal during the winter with mean temperatures falling to near -1°C in March. Temperatures below -1°C were observed at subsurface depths until August. Upper layer temperatures (generally < 50 m) were below 0°C until April afterwhich they began to rise steadily and reached a peak of over 14°C at the surface in August before autumn cooling set in. The August mean temperature was approximately 2°C above that recorded in 1995. Note the propagation of surface layer heat down into the lower layers in the late autumn. The entire water column generally experienced positive temperature anomalies throughout the year (Fig. 17, 18). The maximum anomalies were centred around 50 m during the summer. Colder-than-normal temperatures were observed only in the very near surface layer in July and October.

In 1996 near surface salinites were slightly less than 32 in January and February, rose above 32 in the spring and then declined to a minimum of < 31 in September and October (Fig. 17). 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. Relative to the long-term mean, salinities in 1996 were fresher resulting in negative anomalies (Fig. 17, 18). This represented the second consecutive year of such conditions. The largest negative salinity anomalies exceeded -0.25 in April, September and in the near bottom waters in November and December. Positive salinity anomalies appeared only in the near surface during the summer and in the bottom waters in February.

The time series of monthly temperature anomalies at Station 27 at 0, 50, 100, 150 and 175 m for 1940-1996 are shown in Fig. 19. Note that the temperature scale is different for each depth. At the surface and 50 m there is larger short-term variability reflecting atmospheric heating and cooling. The warming during 1996 predominates throughout the water column but is least evident at 0 m. The largest positive anomalies were found at 100 m. At 150 and 175 m, negative anomalies had persisted almost continuously since 1982 and at 100 m since 1983. In 1996, temperature anomalies at these depths reached above normal for the first time in well over a decade. The coldest periods 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. 20). The total heat content of the water column which reached a record low in 1991 increased sharply in 1996 reaching a level that matches those observed during the warm 1950s and 1960s. The heat content in 1996 was well above that observed in 1995. The 0 to 50 m depth-averaged summer salinity is also plotted in Fig. 20. 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). During 1993 and 1994 summer salinities returned to more normal values but in 1995, salinities again decreased to near the 1992 value. In 1996, salinities rose slightly but were well below the long-term mean. The 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 more recently by Hutchings and Myers (1994).

CIL

On the continental shelves off eastern Canada from Labrador to the Scotian Shelf, intense 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. With spring heating, ice melt and increased river runoff, a warm low-saline surface layer develops. The strong stratification in this upper layer inhibits downward heat transfer, 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 (off Seal Island across 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 Center 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. 21. The annual variability in the cross-sectional areas of the CIL are highly correlated between transects (Petrie et al., 1992). In 1996, the CIL area off Bonavista was about 10% below normal compared to 30% above normal in 1995. The CIL area along the Seal Island transect also was below the long-term mean (12% below average) and along the Flemish Cap section, the CIL area fell below normal (by 4%) for the first time since 1981. At Seal Island and Bonavista transects, the CIL area increased relative to 1995 while on the Flemish Cap section there was a very slight decrease. The minimum temperatures observed in the core of the CIL off Seal Island was near -1.57°C in 1996 which is about normal for Bonavista but colder by 0.1°C along Flemish Cap. Across the central portion of the Grand Bank on the Flemish Cap transect, minimum temperatures have remained below the 1961-90 average since the late 1980s. In general, periods of colder than normal core temperatures are highly correlated with larger than normal CIL areas.

The CIL area in autumn along the Bonavista transect shows similar interannual trends as in summer, however, the average area is smaller by approximately 25% due to vertical mixing from above and below. During the autumn of 1996 it was about 10 km^2 compared to about 7 km^2 in 1995 and 26 km^2 in 1994. The CIL area in autumn off Seal Island is more variable and of smaller magnitude than the more southerly Bonavista transect, and in some years there is no water below 0°C. The average CIL area during the autumn along this transect was about 13 km^2 with a standard deviation of about 11 km^2. There was no water at this section less than 0°C in 1996.

Data are available to estimate the total volume of CIL water (<0°C) over the 2J3KL area since 1980 (Fig. 22). Maximum volumes occurred during the cold periods of the mid 1980s and early 1990s. Since 1990, the summertime volume has been decreasing and by 1996 was relatively low, being similar to that recorded in the early 1980s and from 1986 to 1989. The 1996 volume was well below the mean over the period 1980-1994 of just over 4 x 10^4 km^3 which is roughly one-third the total volume of water on the shelf. Compared to summer, the volume in autumn shows similar interannual trends but its absolute value is about a half that observed in the summer. The 1996 value was the lowest in the autumn time series.

Horizontal Temperature Distributions Near Surface and Bottom in 2J3KL

The 1996 autumn temperature and temperature anomalies near bottom over the shelf from southern Labrador to the Grand Banks are shown in Fig. 23 (bathymetry line is 200). The bottom temperatures over most of the northeast Newfoundland shelf (2J3K) ranged from <1°C inshore, to 3°C offshore at the shelf break. Over most of the Grand Bank it varied from -0.5°C immediately to the east of St. John's to 3°C at the shelf break. In general, bottom isotherms reflect the bathymetry. The percentage area of water <-0.5°C over the Grand Bank was lower than the long-term mean while there was a complete absence of sub-zero water on the northeast Newfoundland Shelf and southern Labrador Shelf in 1996. These both represent less cold water than normal and a substantial decrease from the large area of very cold water from 1990 to 1994.

Temperature and Salinity over Flemish Cap

The dominant features in the smoothed time series of temperature anomalies on Flemish Cap at standard depths to 200 m are the 3 major cold periods previously identified elsewhere, i.e. the 1970s, the mid-1980s and the late 1980s to early 1990s (Fig. 24). The upper layer waters exhibited colder-than-normal temperature anomalies beginning around 1971 which continued until 1977. At 200 m, temperature anomalies in the 1970s near the bottom at 200 m were near normal. From 1978 to 1984 the anomalies showed a high degree of variability in the upper water column with a stronger tendency towards positive anomalies. By 1985, intense negative temperature anomalies had returned in the top 100 m with peak amplitudes reaching near -3°C over the top 50 m. The temperatures warmed slightly in 1987 but declined again by 1988. Since 1995, upper layer temperatures have been warming although below normal conditions still exist throughout the water column except at 50 m.

Salinity anomalies exhibited large fresher-than-normal conditions from 1971 to 1976 and from 1983 to 1986 in the upper 100 m with peak amplitudes reaching 0.5 psu below normal. Salinities during the early 1990s range from slightly below normal in 1992 (from 20 to 100 m) to slightly above normal in 1995 and 1996. In general, the temperature and salinity anomalies on Flemish Cap display a temporal pattern very similar to that at Station 27 and elsewhere on the Newfoundland and Labrador continental shelves.

Temperature off Southern Newfoundland

Low-pass filtered temperature anomalies from St. Pierre Bank are shown in Fig. 25 at standard depths of 0, 20, 50 and 75 m. They are characterized by large variations with amplitudes ranging from ± 1°C and with periods between 5 to 10 years with some higher frequency variations in the upper water column. The cold periods of the mid-1970s and the mid-1980s are coincident with severe meteorological and ice conditions in the Northwest Atlantic and colder and fresher oceanographic anomalies over most of the continental shelf surrounding Newfoundland. During the cold period beginning in 1984 temperatures decreased by up to 2°C in the upper water column and by 1°C in the lower water column and continued below normal until 1990. After 1991, temperatures moderated over the top 50 m but remained well below average at 75 m depth. During 1992 to 1996 temperatures varied about the norm in the top 20 m but were colder than average near bottom. Conditions in these deeper waters during 1996 do appear to be moderating slightly, however.

The 1996 bottom temperatures and their anomalies for April within 3Ps and 3Pn are shown in Fig. 26. In general, the bottom isotherms follow the bathymetry around the Laurentian Channel and the Southwestern Grand Bank increasing from 2°C at 200 m depth to 5°C in the deeper water. In 1996 April bottom temperatures ranged from near 5°C in the Laurentian, Burgeo and Hermitage Channels to about 3°C to 4°C on Rose Blanche Bank and on Burgeo Bank and from 0°C on the eastern side of St. Pierre Bank to 2°C on the western side. This resulted in generally cold conditions over the shelf and warm in the Laurentian Channel. The coldest water was found inshore. In spite of the cold conditions, the waters they have warmed slightly relative to 1995, possibly signifying a return to warm conditions in the near future.

Gulf of St. Lawrence

Cabot Strait Deep Temperatures

Bugden (1991) investigated the long-term temperature variability in the deep waters of the Laurentian Channel in the Gulf of St. Lawrence from data collected between the late 1940s to 1988. The variability in the average temperatures within the 200-300 m layer in Cabot Strait was dominated by low-frequency (decadal) fluctuations with no discernible seasonal cycle. A phase lag was observed along the major axis of the channel such that events propagated from the mouth towards the St. Lawrence Estuary on time scales of several years. The updated time series based primarily upon ice forecast cruises conducted by the Bedford Institute in November-December show that temperatures declined steadily between 1988 and 1991 to their lowest value since the late 1960s (near 4.5°C and an anomaly exceeding -0.9°C; Fig. 27). Temperatures then rose dramatically reaching 6.0°C (anomaly of 0.6°C) in 1993. By 1994 temperatures had begun to decline although anomalies remained positive. Temperatures continued to fall in 1995 and were near normal by November. In 1996, temperatures fluctuated about the long-term mean ending up near the end of the year above normal. The temperature pattern at Cabot Strait is believed to reflect changes in the slope water characteristics near the mouth of the Laurentian Channel (Bugden, 1991; Petrie and Drinkwater, 1993). The near normal values in 1996 are in contrast to the deep waters in Emerald Basin where temperatures remained higher-than-average.

CIL

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 1996, the CIL thickness (defined by waters <0°C) decreased by approximately 40% relative to 1995. This decline was not uniform over the Gulf with the percent decrease becoming progressively larger as one moves towards Cabot Strait. An exception to this was off western Newfoundland where the CIL is thickest. There, no change in the CIL thickness was observed. Gilbert and Pettigrew (1997), in a study of the CIL layer, produced a Gulf-wide index of core temperatures for mid-July based upon observed data from different dates and the mean measured warming rate. Their index shows temperature anomalies having an approximate 5-8 year periodicity prior to 1985 (Fig. 28). Since then, temperatures in the CIL have been extremely cold with some slight increase during the last two years. The mid-summer core CIL temperature in 1996 was -0.45°C (representing an anomaly of approximately -0.55C). Gilbert and Pettigrew (1997) found high correlations between the variability in the CIL core temperatures and air temperatures along the west coast of Newfoundland, suggesting the importance of atmospheric forcing although advection of cold waters from off the Labrador Shelf through Belle Isle Strait may also contribute. The temperature pattern in the Gulf is similar to that observed in the deep waters on St. Pierre Bank (Fig. 25).

Bottom Temperatures on the Magdalen Shallows

Annual groundfish surveys of the Magdalen Shallows in the southern Gulf of St. Lawrence have been carried out by Canada during September since 1971. Similar to past years, bottom temperatures during the 1996 survey were lowest in the central region of the Magdalen Shallows and increased shoreward and toward the deeper Laurentian Channel (Fig. 29). Temperature anomalies near-bottom were below normal except in shallow regions such as around the Magdalen Islands (Fig. 29). Swain (1993) developed indices of near bottom temperature defined as the area covered by waters <0°C and <1°C. These two indices show strong similarity (Fig. 30). Since 1990, the areas have been well above the mean and at or near maximum values. In 1996, the areas remained high, indicative of continuing cold conditions. Both indices did decreased relative to 1995, however. This large area of cold bottom waters over the Magdalen Shallows is consistent with the colder-than-normal CIL since the CIL is in direct contact with the bottom over much of the shallows region.

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. Mean temperatures and salinities were then calculated by layers (0-30, 30-100, 100-200 and 200-300 m) within each of the 17 areas defined by Petrie (1990) and were compared to his monthly mean values. In the surface layer the average temperature ranged from <5°C in the St. Lawrence Estuary to >14°C off eastern Prince Edward Island. This represents slight warming compared to 1995 over the northern Magdalen Shallows but cooling elsewhere with largest decline off Cape North in Cape Breton. Relative to the long-term mean, the temperature anomalies in this layer were positive on the northern Magdalen Shallows and off western Newfoundland with the rest of the Gulf being negative. In the 30-100 m layer, which encompasses most of the CIL, temperatures only varied from -0.3°C to the north of Anticosti Island to 2.4°C off northern Cape Breton. These were colder-than-normal for this time of the year with the largest negative anomaly (-1.6°C) off western Newfoundland. In most areas there was little change relative to 1995. Temperatures in the 100-200 m layer ranged from 0.6°C along the north shore of Quebec to 2.5°C in the Estuary while in the deep layer (200-300 m) temperatures were within 0.7°C of 5°C everywhere in the Gulf. They were also similar to those observed in 1995. In the 200-300 m layer, temperatures were generally near normal with little change from 1995. The time series of the average temperature in the lower three layers indicates that the warmest conditions were observed in the early to mid-1980s and that for 30-200 m, 1996 conditions remained relatively cool (Fig. 31).

Scotian Shelf and Gulf of Maine

Coastal Sea Surface Temperatures

Monthly averages of sea surface temperature (SST) derived from continuous thermograph records or twice daily readings are available from Halifax Harbour in Nova Scotia, St. Andrews in New Brunswick, and Boothbay Harbor in Maine. The monthly mean temperature anomalies relative to the 1961-90 long-term averages at each of the sites for 1994 and 1995 are shown in Fig. 32. The dominant feature in 1996 at Boothbay Harbor and St. Andrews was the above normal temperatures throughout most of the year. This continued a trend of warm temperatures that began in June of 1994. The 1996 anomalies equalled or exceeded one standard deviation (based upon the years 1961-90) in 7 months at Boothbay Harbor but only in 1 month at St. Andrews. The maximum monthly anomaly was near 1.5°C in March at Boothbay while at St. Andrews it was 0.75°C in October. The lower 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 these warm sea surface anomalies, those at Halifax were predominantly negative. Only in September were significant above-normal anomalies observed. The largest negative anomalies occurred during the spring, reaching -1.2°C in May. The cold temperatures in Halifax also continues a pattern established in 1994.

Time series of annual anomalies show that temperature trends have differed between sites during the last decade (Fig. 32). Surface temperatures at Boothbay Harbor and St. Andrews have generally been warm and on the increase since the late 1980s whereas in Halifax Harbour they have been cold and decreasing. Mean annual SSTs in 1996 were 9.2°C (0.7°C above normal) at Boothbay Harbor, 7.5°C (0.3°C above normal) at St. Andrews, and 7.5°C (0.3°C below normal) at Halifax. These represent a decrease over 1995 temperatures at Boothbay (by 0.6°C) and St. Andrews (0.3°C) but an increase at Halifax (0.3°C), opposite to the recent temperature trends. At Boothbay the temperatures are close to the highest since the early 1950s whereas at Halifax they are nearly as cold as the mid-1960s.

Prince 5

Temperature and salinity measurements have been taken once per month since 1924 at Prince 5, a station off St. Andrews, New Brunswick, near the entrance to the Bay of Fundy. 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 necessarily 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 anomaly features are likely to be real. The general vertical similarity in temperatures over the 90 m water column is due to the strong tidal mixing within the Bay of Fundy.

In 1996, no data were collected in April. Monthly mean temperatures ranged from a minimum of just over 2°C in the upper half of the water column in March to a maximum of over 12°C at the surface in September (Fig. 33). Monthly temperature anomalies tended to be slightly positive, exceptions being the surface waters from March to July and throughout the water column in January and August (Fig. 33). In August, bottom waters reached an anomaly of 1° to 1.5°C below normal. The annual mean temperatures in 1996 at the surface was near normal and near bottom (90 m) was 0.2°C above normal (Fig. 34). These annual means have decreased for the second consecutive year but are still well above 1992 and 1993 values. At both depths, the maximum annual temperature occurred in the early 1950s and the minimum in the mid-1960s.

Salinities at Prince 5 during 1996 were consistently fresher-than-normal (Fig. 33). The lowest salinities (<30 psu) occurred during May resulting in an anomaly of -0.7 psu in the surface waters. The largest negative anomaly (-1 psu) was observed in the near surface waters during December. The highest salinities (>32 psu) appeared near bottom in the autumn, but were also fresher-than-normal. Time series show that the annual salinity anomalies in 1996 fell by approximately 0.2 relative to 1995 values at the surface and 0.5 at 90 m (Fig. 35). The 1996 anomalies represent the lowest salinities recorded at Prince 5 since the record began in the 1920s. This freshening parallels similar events occurring in the deep waters of Jordan and Georges Basin which may be related to offshore forcing from outside the Gulf of Maine (D. Mountain, Woods Hole, personal communication).

Gulf of Maine Temperature Transect

The Northeast Fisheries Science Center 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 any data within these by month at standard depths.

Representative data (January and September) from 1996 are shown together with the site locations (center of the boxes) in Fig. 36. The near surface waters varied between 2° and 6°C in January with warmer water (>6°C) occupying most of the deep basin. The deep waters in the central region of the basin were typically warmer-than-normal by 1-2°C. Similar warm conditions were observed in the deep waters during September and in most other months. The deep water conditions contrast with those in the near surface waters (0-50 m) in the central Gulf of Maine during September when temperatures were colder-than-average, reaching -2°C at approximately 50 m at site 6 in the central Gulf. On the eastern side of the Gulf towards Nova Scotia, temperatures were above normal. Anomalies from the other months (not shown) indicate high variability in the surface waters with the sign and amplitude of the anomalies changing from month to month.

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 center of the Scotian Shelf. They showed that there was high temperature variance at low frequencies (decadal periods). This signal was more visible at depth (below 75 m) where the low-frequency variance was higher and there was less high-frequency (year-to-year) variability. High coherence at low frequencies was found throughout the water column as well as horizontally from the mid-Atlantic Bight to the Laurentian Channel, although year-to-year differences between locations were observed. Temperature anomalies at 250 m in Emerald Basin have been used as a representative index.

In 1996, temperature measurements in Emerald Basin were obtained to depths of 250 m in four separate months with values ranging from 9.8° to 10.0°C. This produced monthly anomalies of 0.5-1.6°C above normal (Fig. 37). The long-term annual average is 8.5°C and the monthly means range from 7.9°C to 9.4°C. The high positive anomalies were generally representative of conditions below approximately 50 to 100 m. The recent warm period in the deep waters of Emerald Basin began with an intrusion of warm slope water late in 1991 or early 1992. These high temperatures are similar to those occurring in deep waters of the Gulf of Maine (Fig. 36).

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. 38). Their analysis has been updated by Petrie et al. (1996). We produced monthly mean conditions for 1996 at standard depths for selected areas (averaging any data within the month anywhere within these areas) and compared them to the long-term averages (1961-90). Unfortunately, data are not available for each month at each area and in some areas the monthly means are based upon only one profile. As a result the series are characterized by short period fluctuations or spikes superimposed upon long-period trends with amplitudes of 1-2°C. The spikes represent noise and most often show little similarity between regions. Thus care again must be taken in interpreting these data and little weight given to any individual mean. The long period trends are similar from area to area, however.

In a previous analysis, 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 and in the cold intermediate layer (CIL) waters in the Gulf of St. Lawrence (Gilbert and Pettigrew 1997). Data in 1994 and 1995 indicated warming of the intermediate layers in the Gulf of Maine but a continuation of colder-than-normal water on most of the Scotian Shelf (Drinkwater et al. 1996). The third main feature was the presence of anomalously warm slope water off the shelf and in the deep basins such as Emerald on the Scotian Shelf and Georges in the Gulf of Maine. This warm deep water appeared to influence the intermediate depth waters above the basins as their anomalies were generally warmer than elsewhere on the shelves.

The general patterns first identified by Drinkwater (1995) have continued into 1996. 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 along the Atlantic coast of Nova Scotia to Lurcher Shoals. Warmer-than-normal conditions were observed in Emerald and Georges Basins below about 50 to 100 m (see Figs. 36 and 37).

On Sydney Bight (area 1 in Fig. 38) monthly mean profiles from 7 different months show highly variable temperature anomalies in the upper 100 m of the water column and especially in the near surface (< 50 m) waters (Fig. 39). Between 100 and 200 m there is a tendency towards negative temperature anomalies, however, in January the anomalies were positive. At depths > 250 m, which lay within the Laurentian Channel or along its slope, temperatures were above their long-term means but by less than 1°C. The time series of the 100 m temperature anomalies show that in recent years temperatures have been upwards of 1.5°C below the long term mean although the amount of data available in this time period is scanty. During 1995 and 1996 temperatures have been primarily below normal but are suggestive of warming with some monthly anomalies above the long-term mean. Monthly mean temperature profiles for Misaine Bank on the northeastern Scotian Shelf (area 5 in Fig. 38) are available for 6 months during 1996. They too show variable upper layer temperatures with the most prominent anomalies during June when near surface anomalies were approximately 4°C above normal (Fig. 40). During several of the other months temperatures in the top 50 m of the water column were at or below normal. The most consistent feature was the below normal temperatures in the waters >50 m. Temperature anomalies were typically between 0 and -2°C. The time series of the 100 m temperature anomalies show that these negative values have persisted since approximately the mid-1980s (Fig. 40). Recent years have been the coldest or near coldest since the 1950s and match the cold period of the 1960s. This pattern is indicative of the water column below 50 m. Absolute temperatures at 100 m are typically 1-2.5°C depending upon the time of the year. At Lurcher, data were available in 4 months during 1996. The temperature anomaly profiles were negative for 3 of the 4 months with only February (data collected only between 0 and 30 m) being warmer-than-normal (Fig. 41). The warm water in February is based upon data collected during the XBT transect (Fig. 36). The monthly 50 m temperatures at Lurcher show the cooler-than-normal waters and a decline in 1996 relative to 1995. These temperatures are generally representative of the average thermal conditions throughout the water column at Lurcher because of the strong tidal mixing.

Temperatures during the Summer Ground Fish Survey

The most extensive temperature coverage over the entire Scotian Shelf occurs during the Canadian annual groundfish survey, usually in July. In 1996, just under 200 conductivity-temperature-depth (CTD) stations were occupied. Temperatures were interpolated onto a 0.2 by 0.2 degree latitude-longitude grid using an objective analysis procedure known as optimal estimation. The interpolation method uses the 15 "nearest neighbours" and a horizontal 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 300 m as we were only interested in the temperatures over the shelf. In addition, the 1961-90 means for July were estimated onto the same grid in order to calculate temperature anomalies.

Temperatures in 1996 at the surface varied from <8° to >16°C with the dominant pattern being relatively cool waters off southwest Nova Scotia in the Gulf of Maine due to strong tidal mixing, and warmer temperatures on the Scotian Shelf. The coldest waters are on Lurcher Shoals off Yarmouth and the warmest on Sydney Bight and the central Shelf area (Fig. 42a). At 50 m the coldest temperatures (<2 °C) are in the northeast and off Yarmouth (Fig. 42b). Note the cold waters covering most of the northeastern Scotian Shelf and off the "south shore" of the Atlantic coast of Nova Scotia. Warm waters penetrated into the central shelf region of Emerald Basin. The 100 m temperatures show a pattern similar to that for 50 m but with slightly higher temperatures, especially over the Emerald Basin region (Fig. 42c). Bottom temperatures show several typical features (Fig. 42d). First is the large contrast between the northeast and central Scotian Shelf. In the northeast, bottom temperatures were generally cold with minima less than 2°C in the Misaine Bank region. Cool waters were also found off southern Nova Scotia. Temperatures in Emerald Basin exceeded 9°C and those in the central Gulf of Maine >8°C. Relatively high temperatures also were found along the continental slope on the western half of the Shelf and in the upper reaches of the Bay of Fundy.

Temperature anomalies show similar patterns at the 4 depth levels (Fig. 43). The dominant feature is the below-normal temperatures over most of the shelf although its areal extent decreased with depth. In particular, Emerald Basin in the central Scotian Shelf and eastern Jordan Basin in the Gulf of Maine tend to be warmer-than-normal. Maximum negative anomalies in the surface waters were -3° to -4° C. Elsewhere through the water column, anomalies were typically -0.5 to over -1°C. The southwestern end of the Shelf was also cold with surface anomalies of -2°C and deeper anomalies similar to that in the northeast. In contrast, anomalies in the central Scotian Shelf region were above normal except at the surface. The largest positive anomalies were near bottom and had magnitudes of 1-2°C. The warm water in Emerald Basin during the July survey is consistent with the 250 m temperature time series (Fig. 37) and the cold temperatures in the northeast and southwest during the survey with the temperature time series observed on Misaine Bank (Fig. 40) and off Lurcher (Fig. 41), respectively.

Differences between the temperatures in 1995 and 1996 indicate that subsurface waters warmed slightly in the northeastern Scotian Shelf but cooled along most of the outer banks of the Shelf. Over Emerald Basin temperatures at 50 m warmed substantially perhaps due to mixing with the warm deep waters, however, the deep waters cooled between July 1995 and 1996.

SUMMARY

During 1996, a significant change occurred in the large-scale atmospheric circulation pattern. The Icelandic Low which has for over a decade been more intense than the long-term average, weakened. The Bermuda-Azores High also weakened. This resulted in a decline in the NAO index, the single largest annual decrease on record in over 100 years. Associated with the weakening of the Icelandic Low northwest winds would have been weaker than normal over the Labrador Sea which would account for the wintertime air temperatures being, on average, warmer-than-normal and the warmest in approximately a decade. Warmer air temperatures and weaker northwest winds resulted in later-than-normal ice formation, less areal extent of ice and a shorter duration of ice over much of the Labrador/Newfoundland shelves and in the Gulf of St. Lawrence/Scotian Shelf. In turn, the warm temperatures, weak winds and less ice all contributed towards a large reduction in the number of icebergs reaching the Grand Banks in 1996 relative to 1995 and the earlier years of the 1990s. During spring, air temperature anomalies continued to remain above normal consistent with the air pressure pattern and weaker northwest winds over the Labrador Sea. During the summer and autumn, air temperatures tended to fluctuate about their long-term means.

Warmer-than-normal sea temperatures were observed over most of the southern Labrador and Newfoundland regions in 1996, reversing the cooling pattern established in the early to mid-1980s. This included warming throughout the water column at Station 27, less than average amount of CIL waters, and an increase of near bottom temperatures over the Grand Banks in autumn. In contrast, the waters south of Newfoundland, in the Gulf of St. Lawrence and on much of the Scotian Shelf remained colder than normal. The CIL waters in the Gulf of St. Lawrence were still very cold and more of the Magdalen Shallows were covered with cold waters in 1996 than on average. However there were signs of moderating conditions as the temperatures rose slightly and the area of cold water decreased. Cold temperatures continued in the 30-200 m layers throughout the Gulf of St. Lawrence. They were also observed in the CIL layer and near-bottom waters on the northeastern Scotian Shelf, in the near surface waters shore along the Atlantic coast of Nova Scotia as recorded in the sea surface at Halifax and throughout the water column off southwestern Nova Scotia. This continued the cold pattern established in the middle of the 1980s. These cold waters are believed to be advected onto the Scotian Shelf from the Gulf of St. Lawrence and perhaps off the Newfoundland Shelf and to a lesser extent from *in situ* cooling during the winter. The relative importance of each factor has not yet been established. In contrast to these cool conditions, the waters in the central Scotian Shelf over Emerald Basin and along the continental slope, were warmer-than-normal. These conditions have persisted since 1992 and reflect the presence of warm slope water offshore. In the Gulf of Maine, temperatures were predominantly warmer-than-normal which is believed to be due to the influx of slope water into the region through the Northeast Channel.

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TABLE 1. Historical data on presence and duration of sea ice at 24 sites off eastern Canada and ice duration at these sites in the 1995/96 (October-September) ice year with 1994/95 data in parentheses.

				Ice Duration (in weeks)				
				When ice present				
Site	Seasons Studied	# of Yrs	Yrs ice	Min	Max	Mean	Overall Mean	95/96 (94/95)
G-7	67/68-95/96	29	29	6	16	10.8	10.8	8 (14)
G-10	76/77-95/96	20	20	3	17	12.4	12.4	10 (17)
G-12	67/68-95/96	29	29	2	15	11.7	11.7	10 (13)
G-22	76/77-95/96	20	20	7	17	12.3	12.3	12 (17)
G-31	68/69-95/96	28	27	8	17	12.6	12.1	11 (12)
G-33	71/72-95/96	25	25	2	14	10.8	10.8	8 (10)
G-35	59/60-95/96	37	19	1	11	3.5	1.8	0 (0)
G-86	76/77-95/96	20	20	6	23	16.7	16.7	12 (18)
G-87	70/71-95/96	26	25	1	12	7.6	7.3	1 (7)
N-19	66/67-95/96	30	30	17	32	23.9	23.9	20 (25)
N-21	67/68-95/96	29	29	5	28	18.6	18.6	13 (18)
N-23	59/60-95/96	37	31	1	17	5.1	4.2	1 (1)
N-25	59/60-95/96	37	2	1	1	1.0	0.1	0 (0)
N-27	59/60-95/96	37	0	0	0	0.0	0.0	0 (0)
N-62	67/68-95/96	29	29	8	27	18.7	18.7	13 (16)
N-64	59/60-95/96	37	36	3	25	13.2	12.8	8 (13)
N-66	59/60-95/96	37	31	1	17	8.6	7.1	5 (5)
N-68	59/60-95/96	37	17	1	10	3.5	1.6	1 (0)
N-70	60/61-95/96	36	0	0	0	0.0	0.0	0 (0)
N-108	59/60-95/96	37	30	1	17	6.3	5.3	0 (10)
N-110	59/60-95/96	37	29	1	16	5.6	4.6	0 (7)
N-112	59/60-95/96	37	15	1	10	4.1	1.7	0 (0)
N-114	59/60-95/96	37	5	1	2	1.6	0.2	0 (0)
N-228	59/60-95/96	37	25	1	14	5.9	4.1	0 (10)

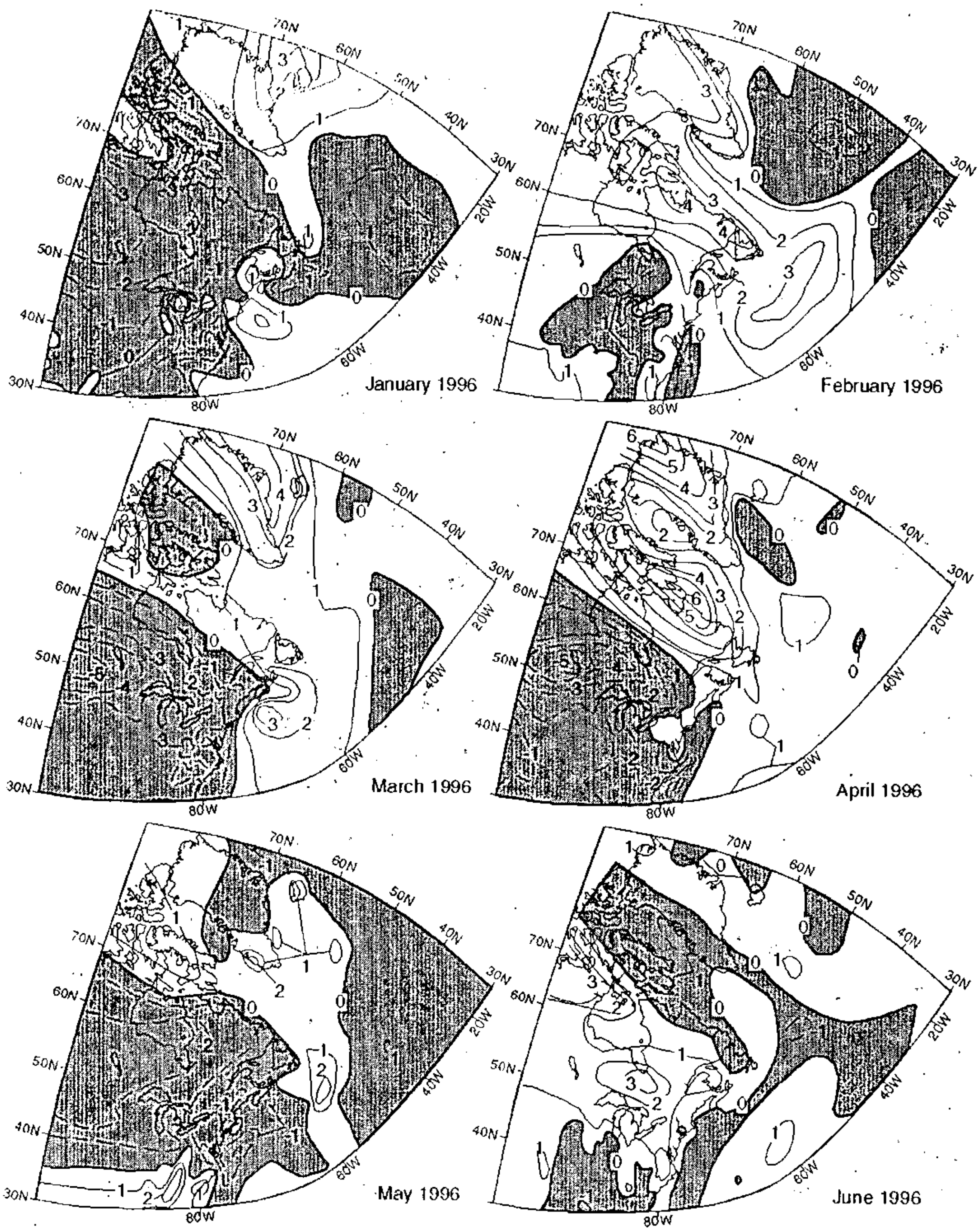


Fig. 1. Monthly air temperature anomalies (in °C) over the Northwest Atlantic in 1996 relative to the 1961-1990 means (from *Grosswetterlagen Europas*). The shaded anomalies indicate areas of below normal temperatures.

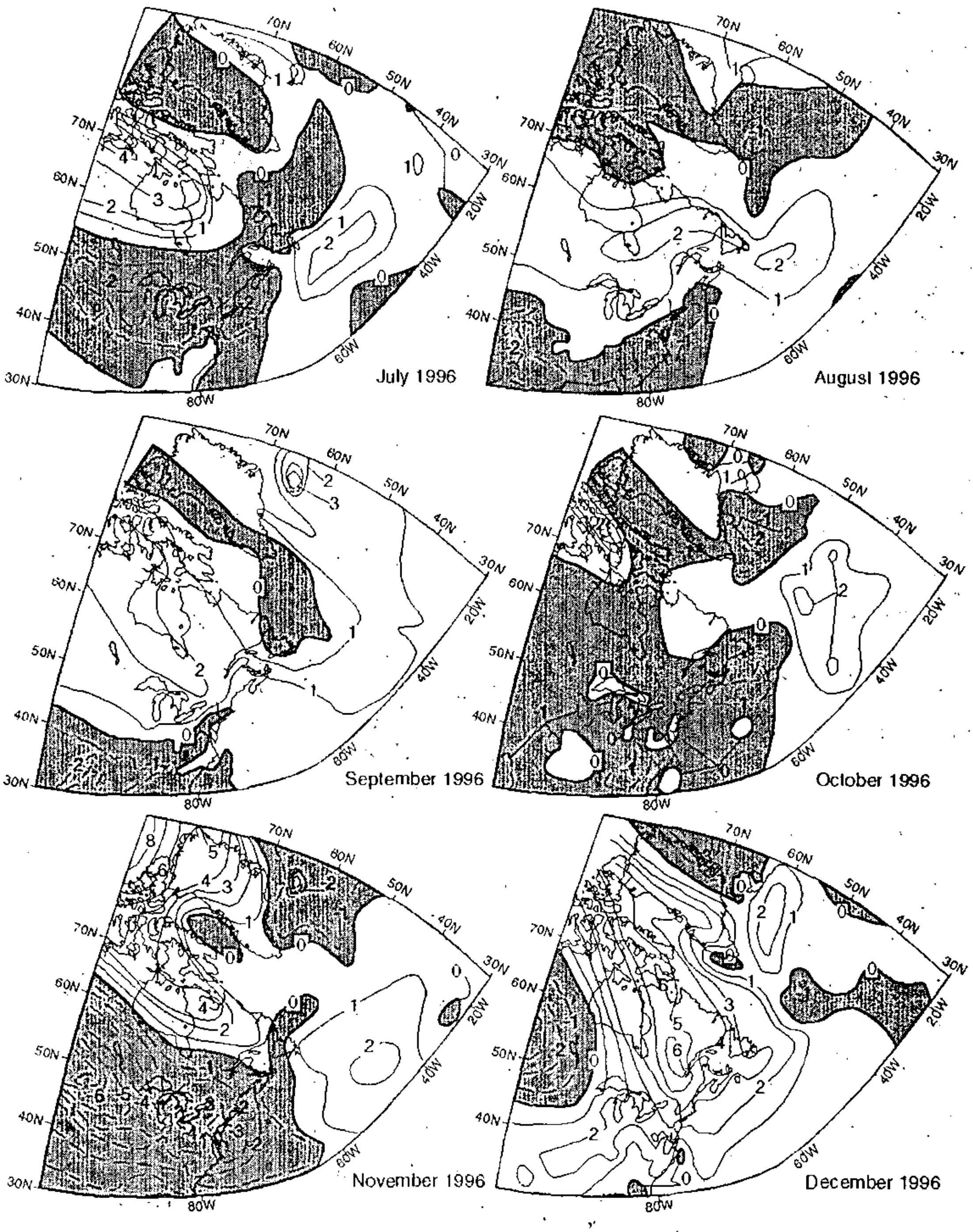


Fig. 1. (Continued) Monthly air temperature anomalies (in °C) over the Northwest Atlantic in 1996 relative to the 1961-1990 means (from *Grosswetterlagen Europas*). The shaded anomalies indicate areas of below normal temperatures.

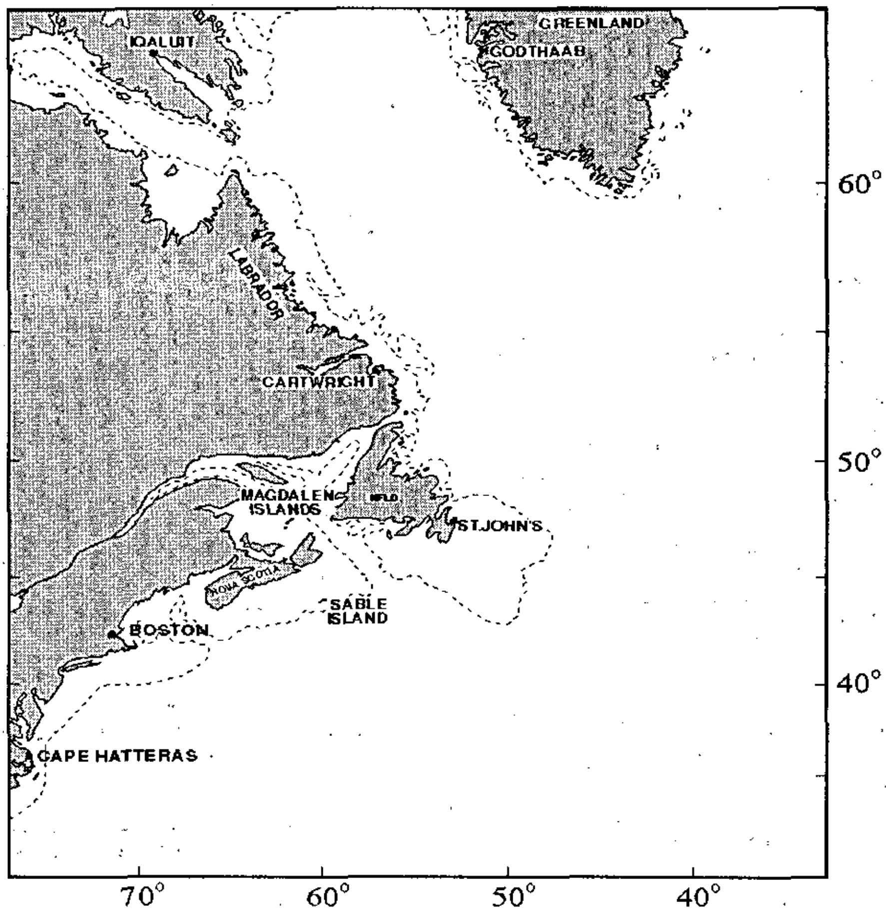


Fig. 2. Northwest Atlantic showing coastal air temperature stations.

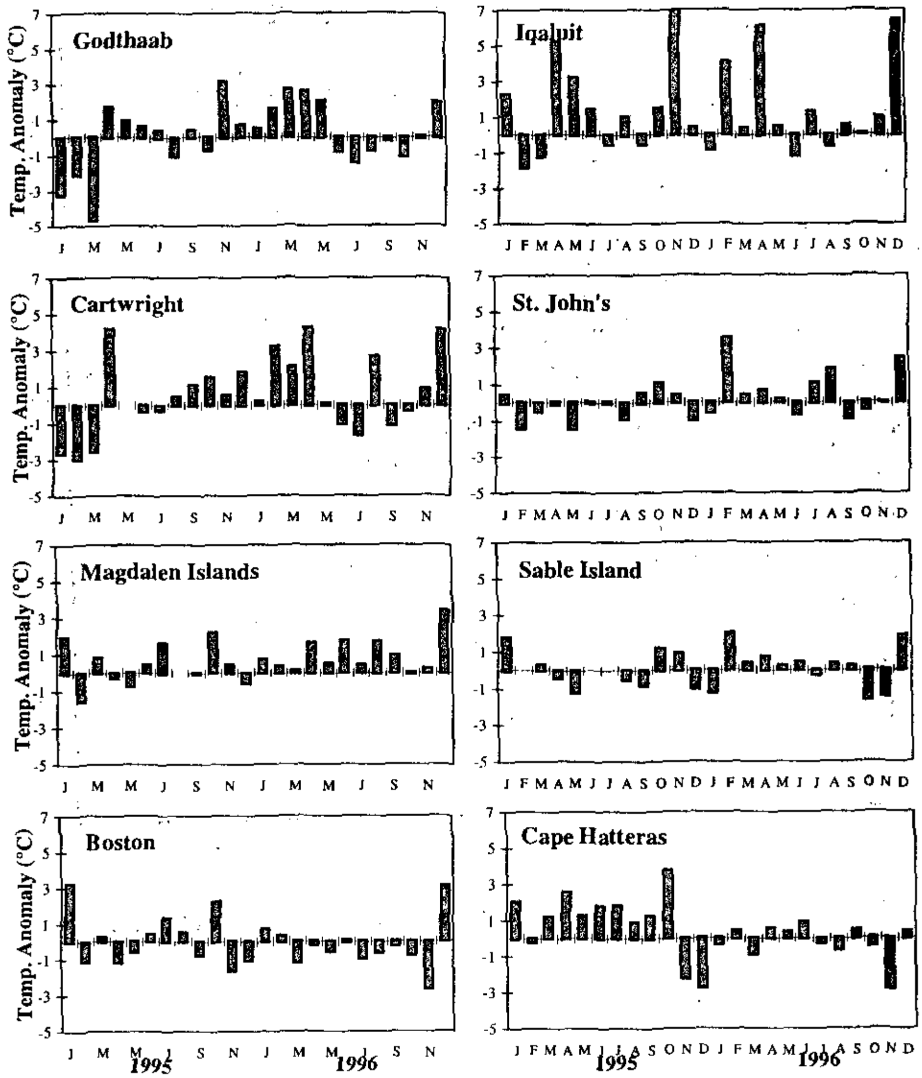


Fig. 3. Monthly air temperature anomalies in 1995 and 1996 at selected coastal sites (see Fig. 2 for locations.

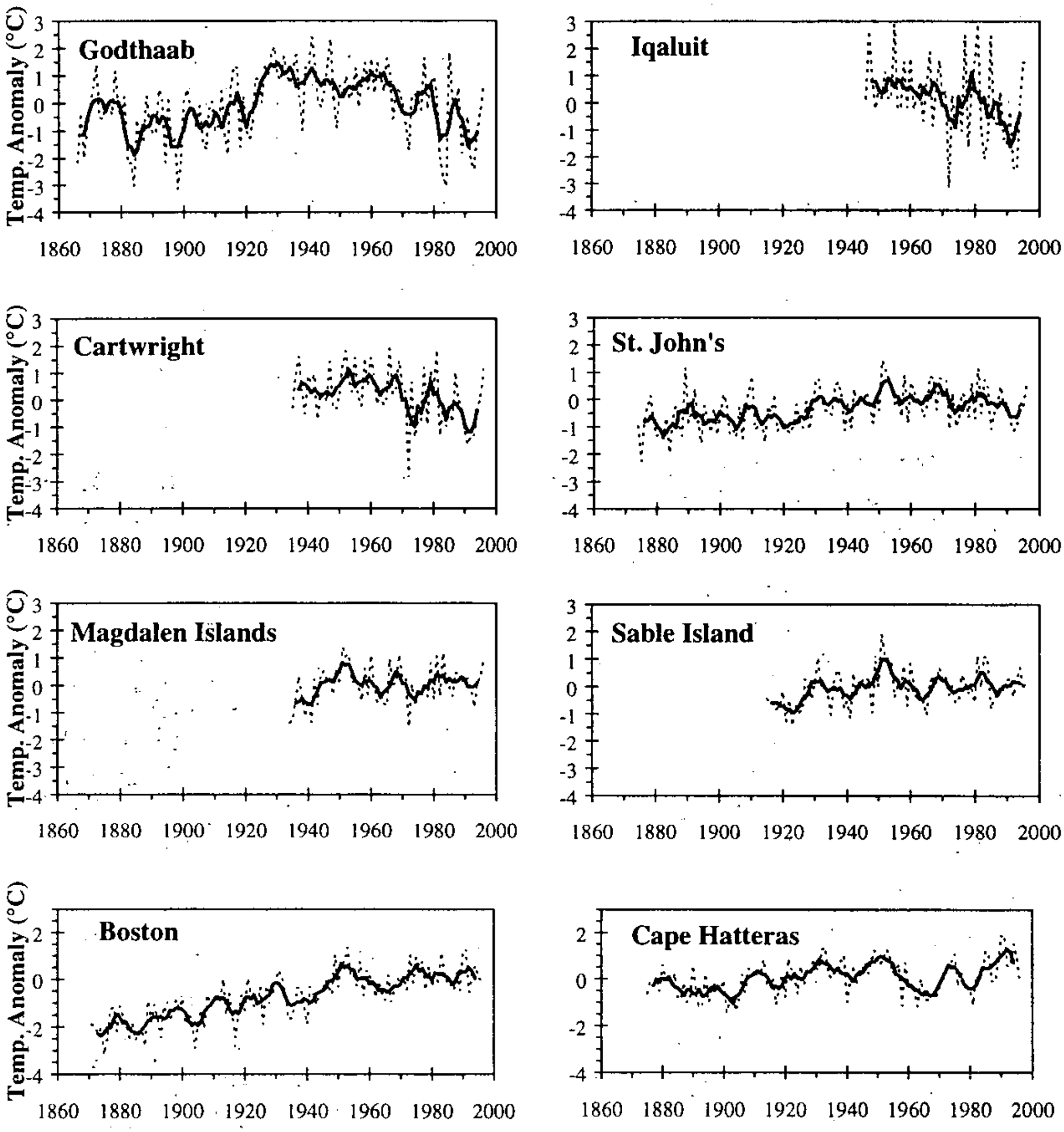


Fig. 4. Annual (dashed) and 5-year running (solid) means of the air temperature anomalies at selected sites.

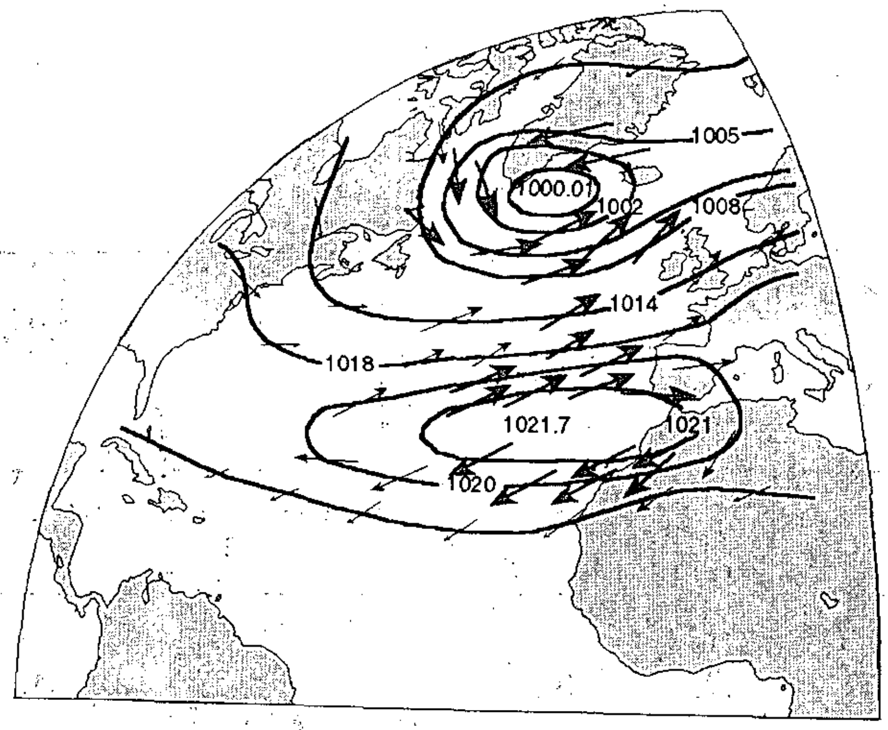


Fig. 5. The long-term (1961-90) mean sea surface pressures during winter (average of December, January and February). A schematic of the wind field associated with the mean pressure is also shown.

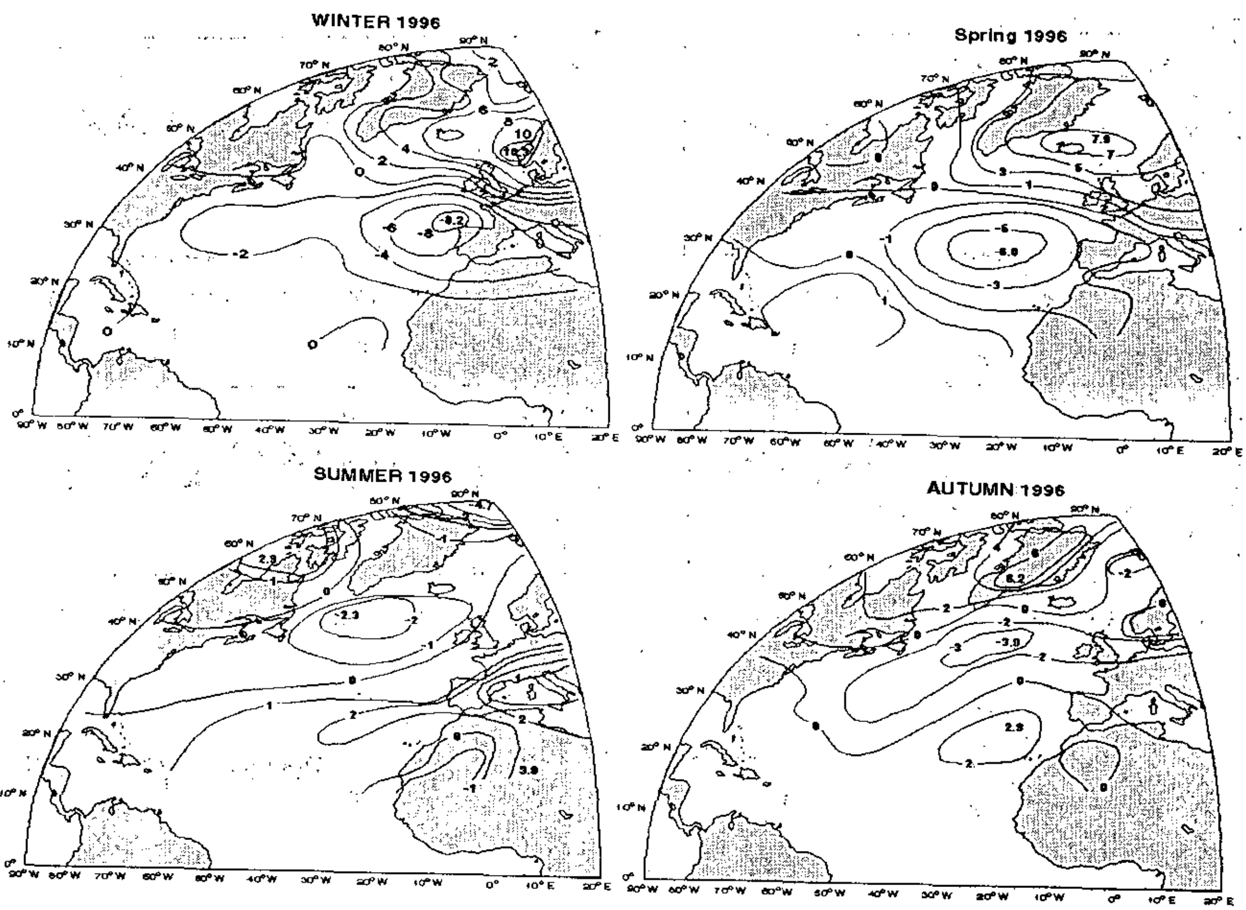


Fig. 6. Seasonal sea-surface air pressure anomalies (mb) over the North Atlantic in 1996.

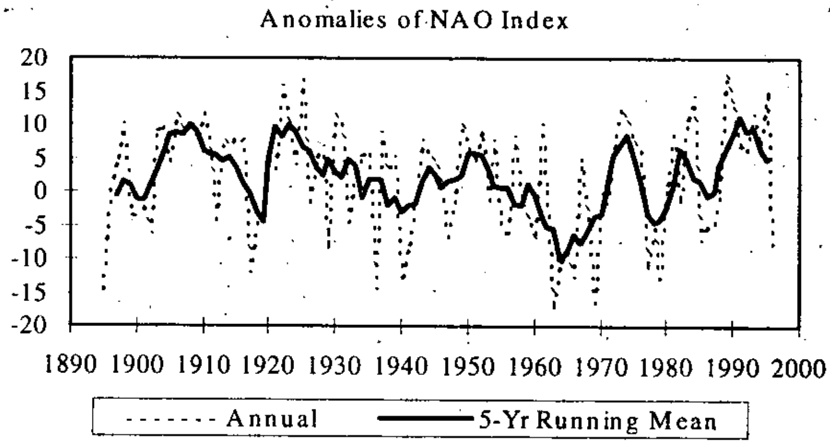


Fig. 7. Anomalies of the North Atlantic Oscillation Index.

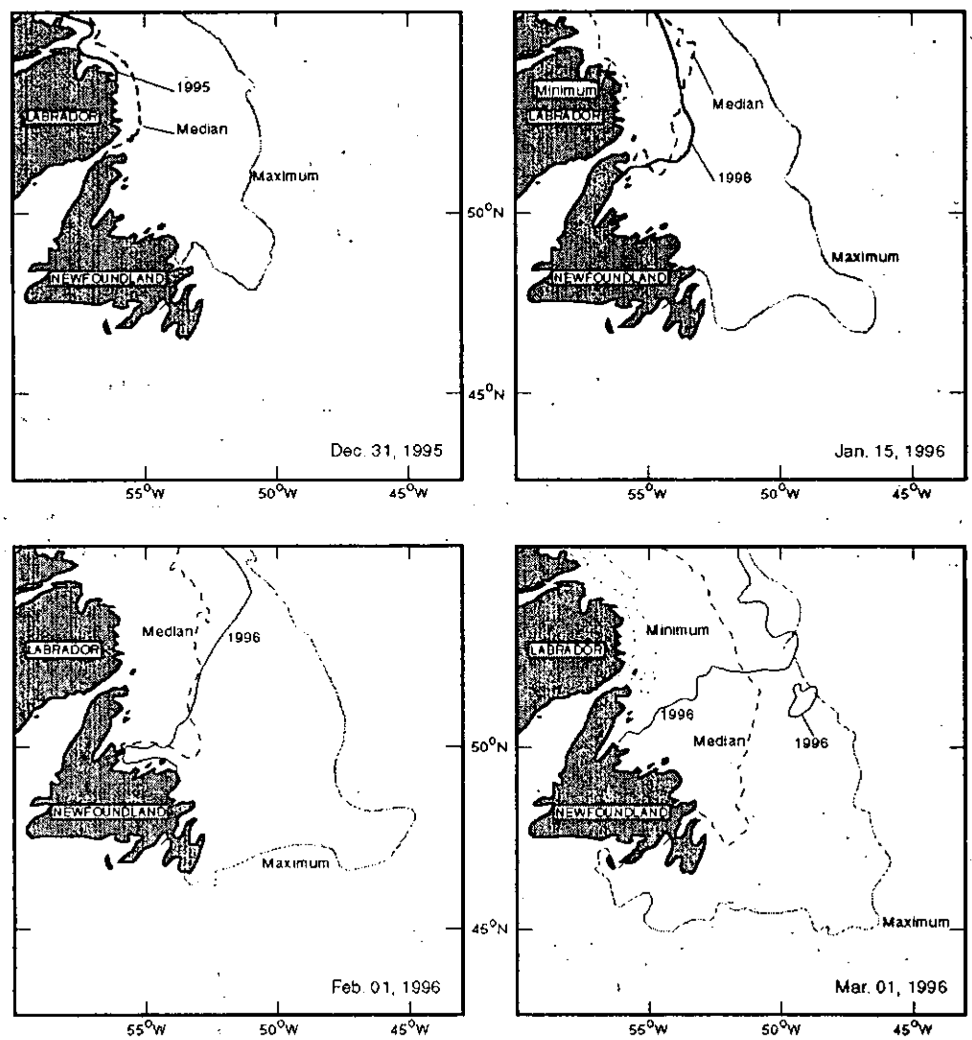


Fig.8a. The location of the ice edge (>10% concentration) together with the historical (1962-87) median and maximum positions off Newfoundland and Labrador at selected dates between December 1995 and March 1996.

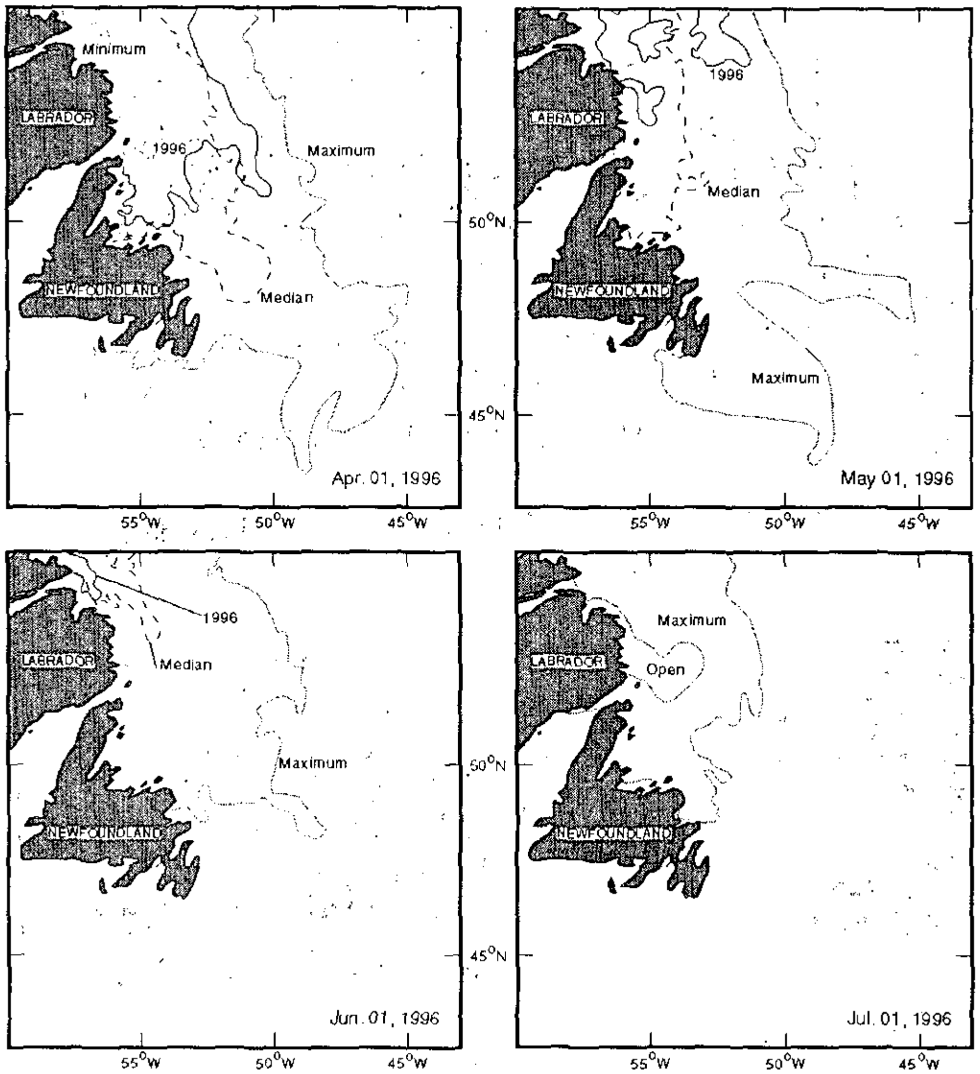


Fig.8b. The location of the ice edge (>10% concentration) together with the historical (1962-87) median and maximum positions off Newfoundland and Labrador at selected dates between April and July 1996.

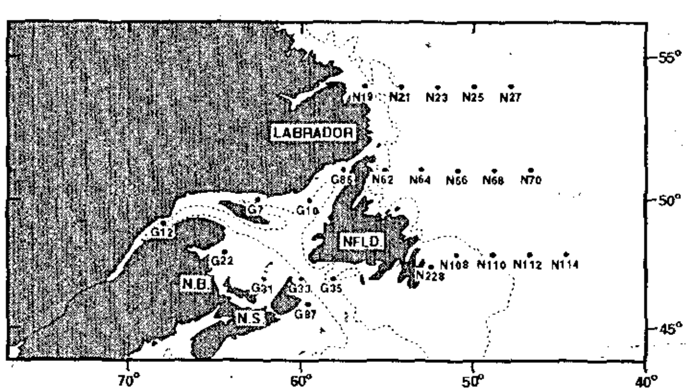


Fig. 9. Location of 24 grid points in the Northwest Atlantic where ice statistics have been extracted from ice charts.

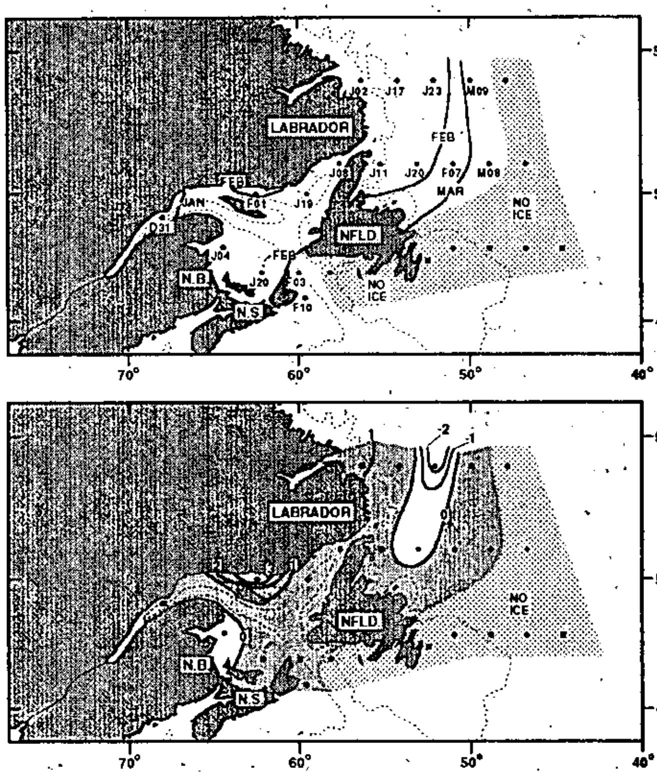


Fig.10. The date during the 1995/96 ice season at which ice first appeared (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded negative anomalies indicates ice appeared earlier than normal which is generally associated with a cold year.

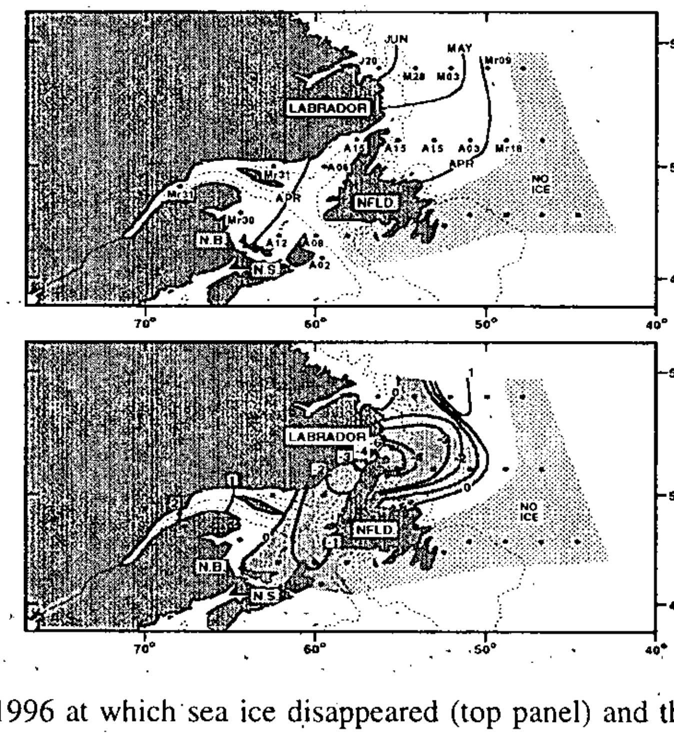


Fig.11. The date in 1996 at which sea ice disappeared (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded positive anomaly indicates ice disappeared later than normal which is generally associated with a colder year.

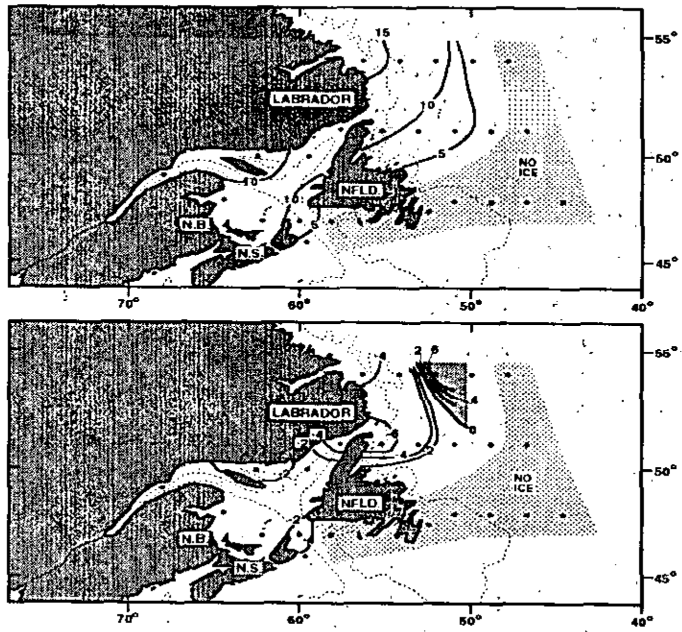


Fig.12. The duration of sea ice during the 1996 (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded positive anomaly indicates ice duration was longer-than-normal which is generally associated with a colder year.

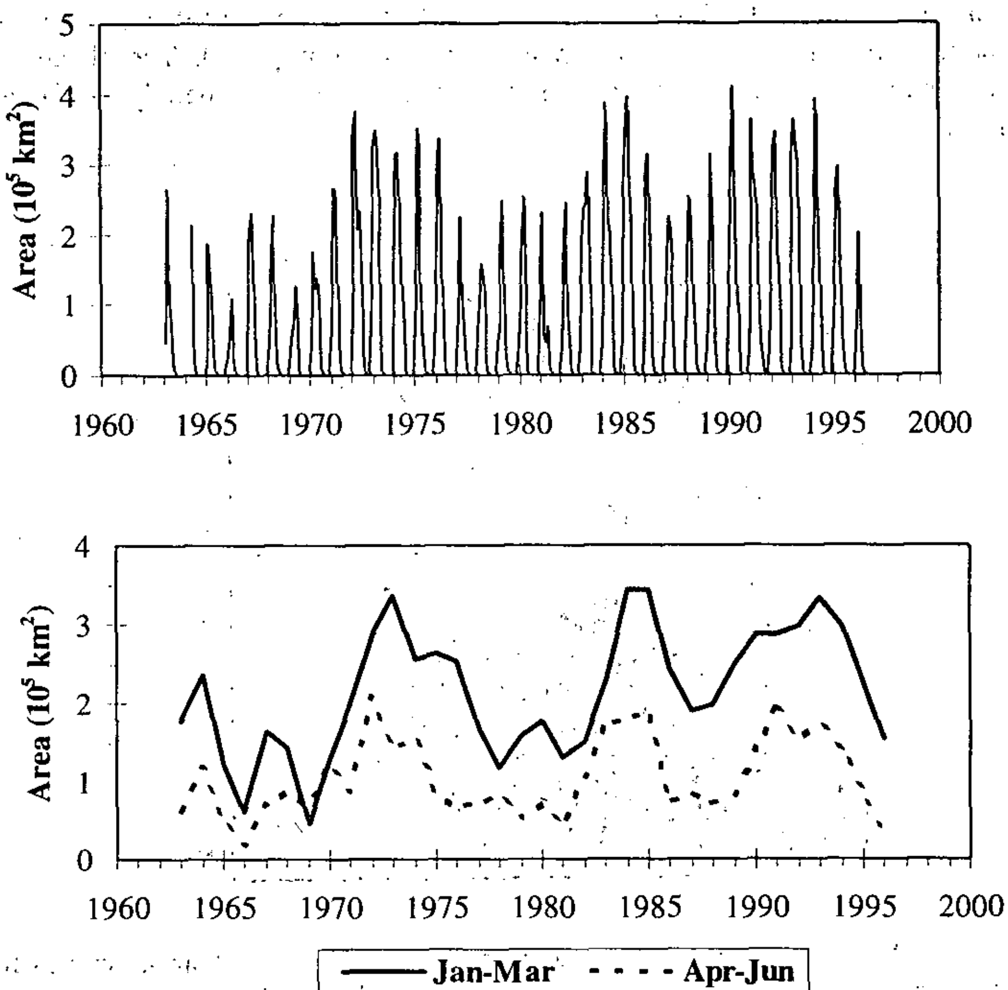


Fig.13. The time series of the sea ice area by month (top panel) and during ice advance (Jan-Mar) and ice retreat (Apr-Jun) on the southern Labrador and Newfoundland shelves.

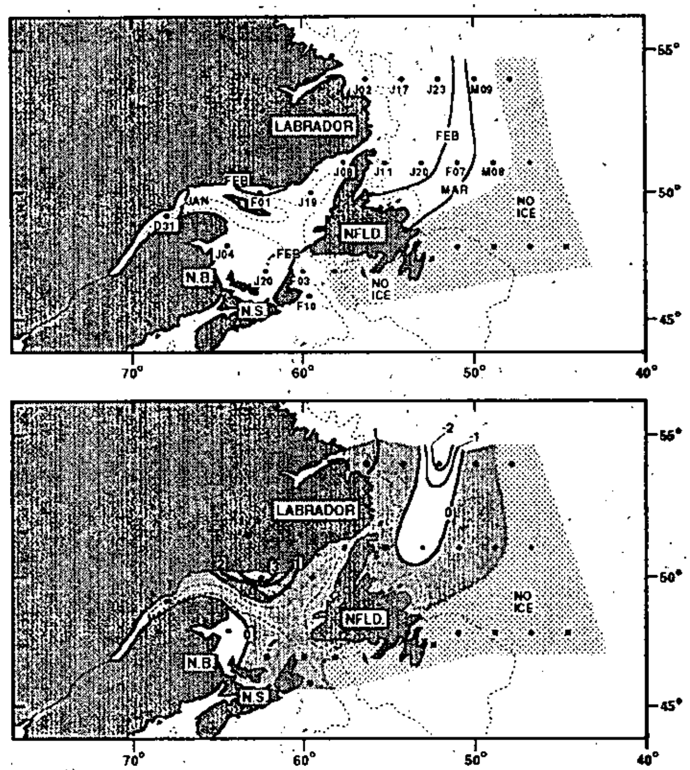


Fig.10. The date during the 1995/96 ice season at which ice first appeared (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded negative anomalies indicates ice appeared earlier than normal which is generally associated with a cold year.

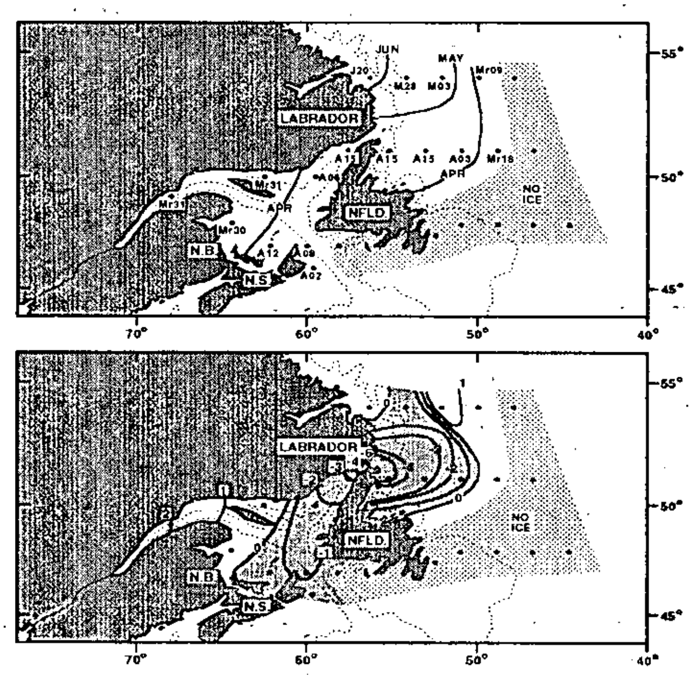
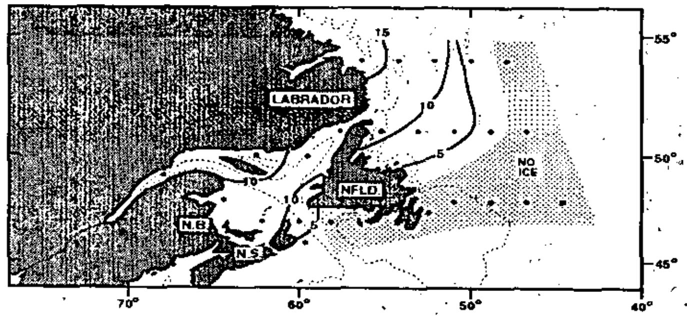


Fig.11. The date in 1996 at which sea ice disappeared (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded positive anomaly indicates ice disappeared later than normal which is generally associated with a colder year.



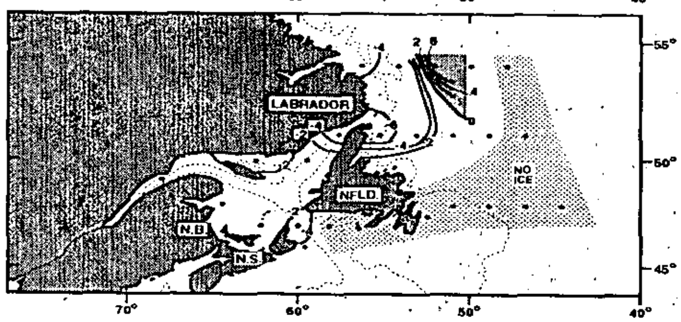
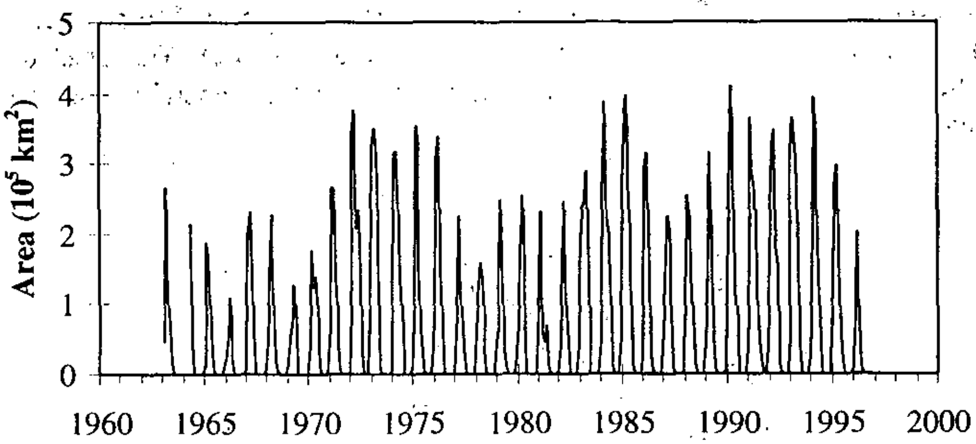


Fig.12. The duration of sea ice during the 1996 (top panel) and their anomalies from the long-term mean in weeks (bottom panel). The shaded positive anomaly indicates ice duration was longer-than-normal which is generally associated with a colder year.



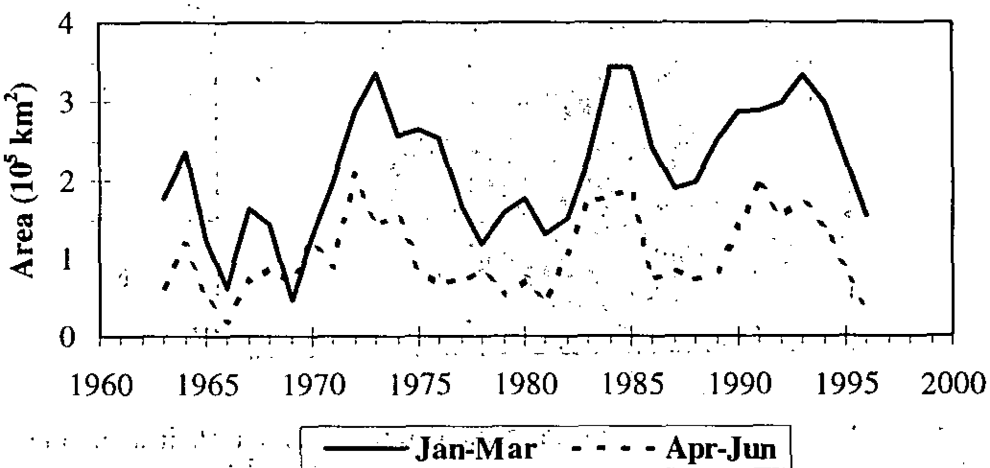


Fig.13. The time series of the sea ice area by month (top panel) and during ice advance (Jan-Mar) and ice retreat (Apr-Jun) on the southern Labrador and Newfoundland shelves.

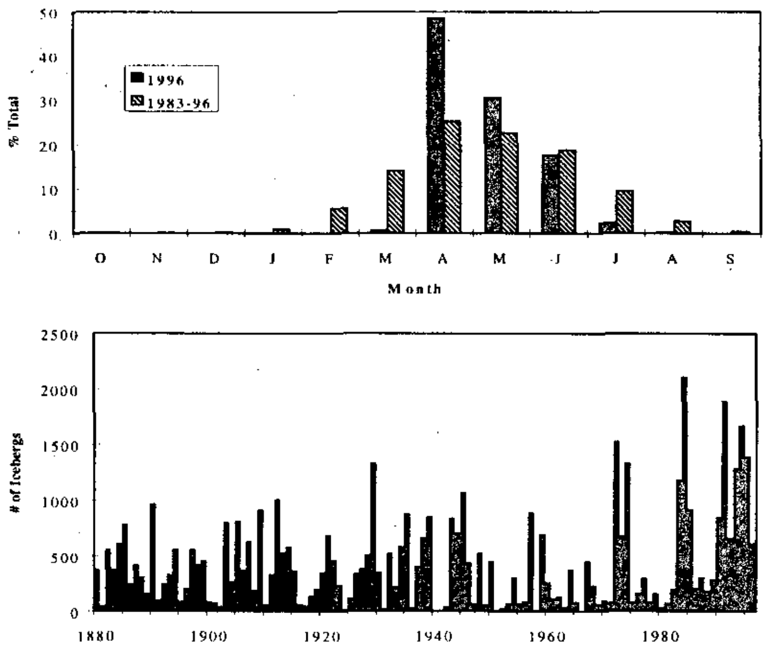


Fig.14 The percentage of the total number of icebergs crossing south of 48°N by month during the 1995/96 and the 1983-96 iceberg seasons (top) and the number of icebergs during March to July from 1945 to 1996.

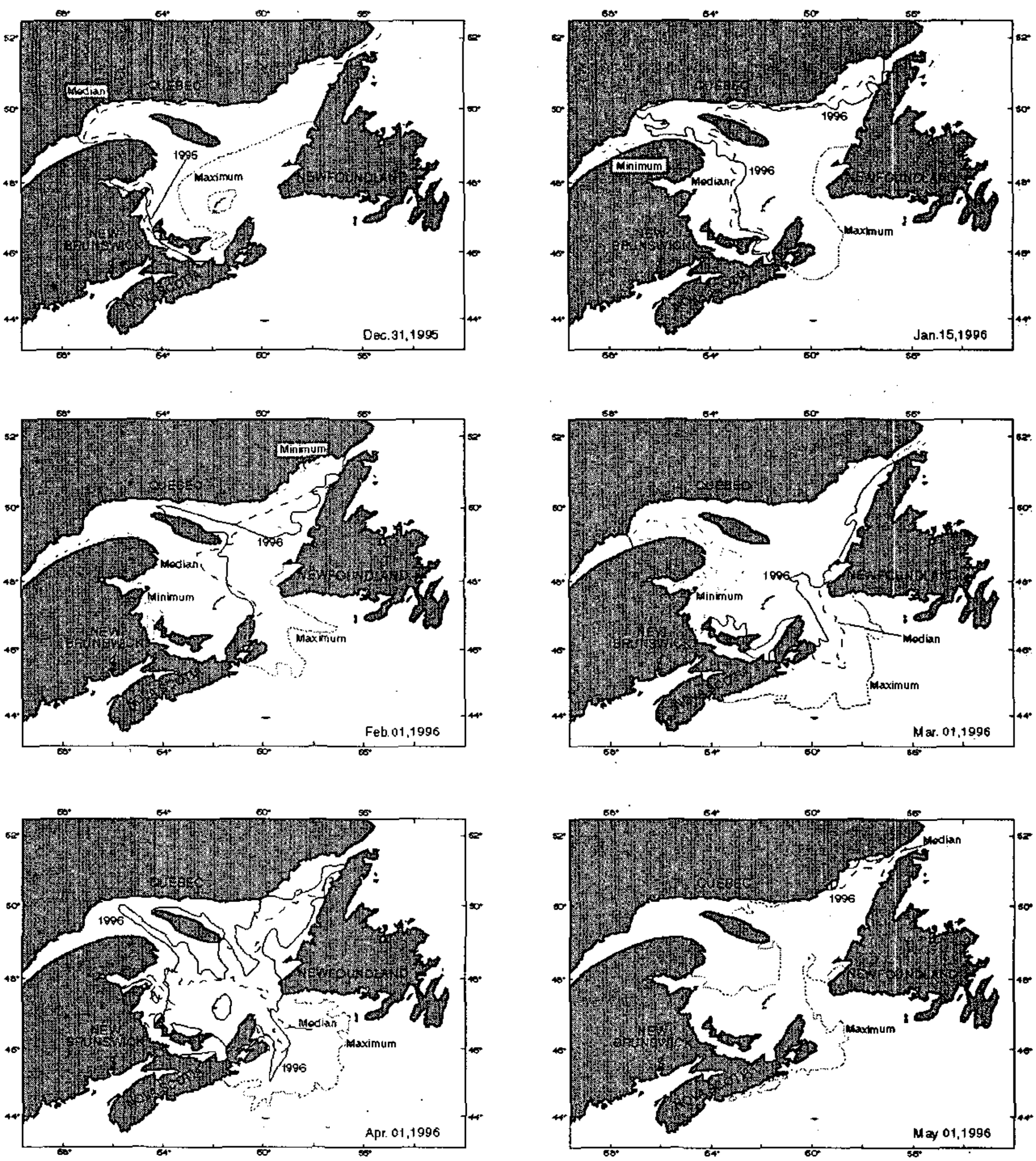


Fig.15. The location of the ice edge (>10% concentration) together with the historical (1962-87) median and maximum positions in the Gulf of St. Lawrence at selected dates between December 1995 and May 1996.

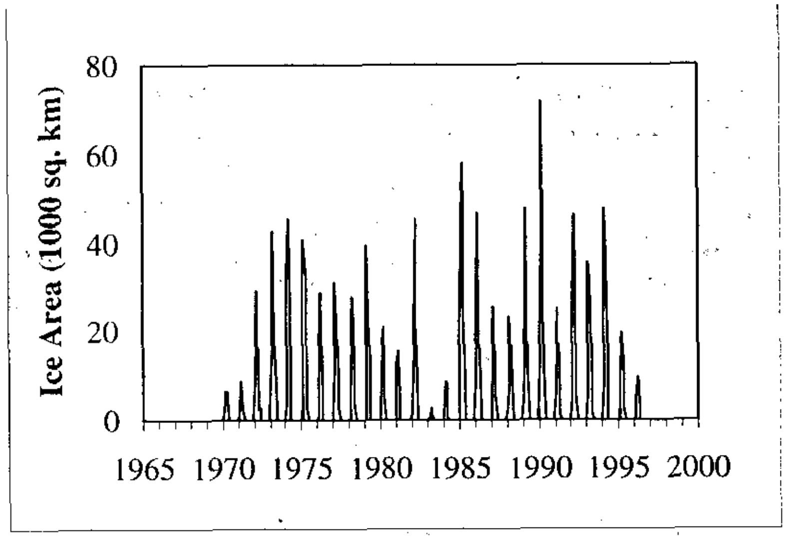


Fig. 16. Time series of the monthly mean area of sea ice seaward of Cabot Strait.

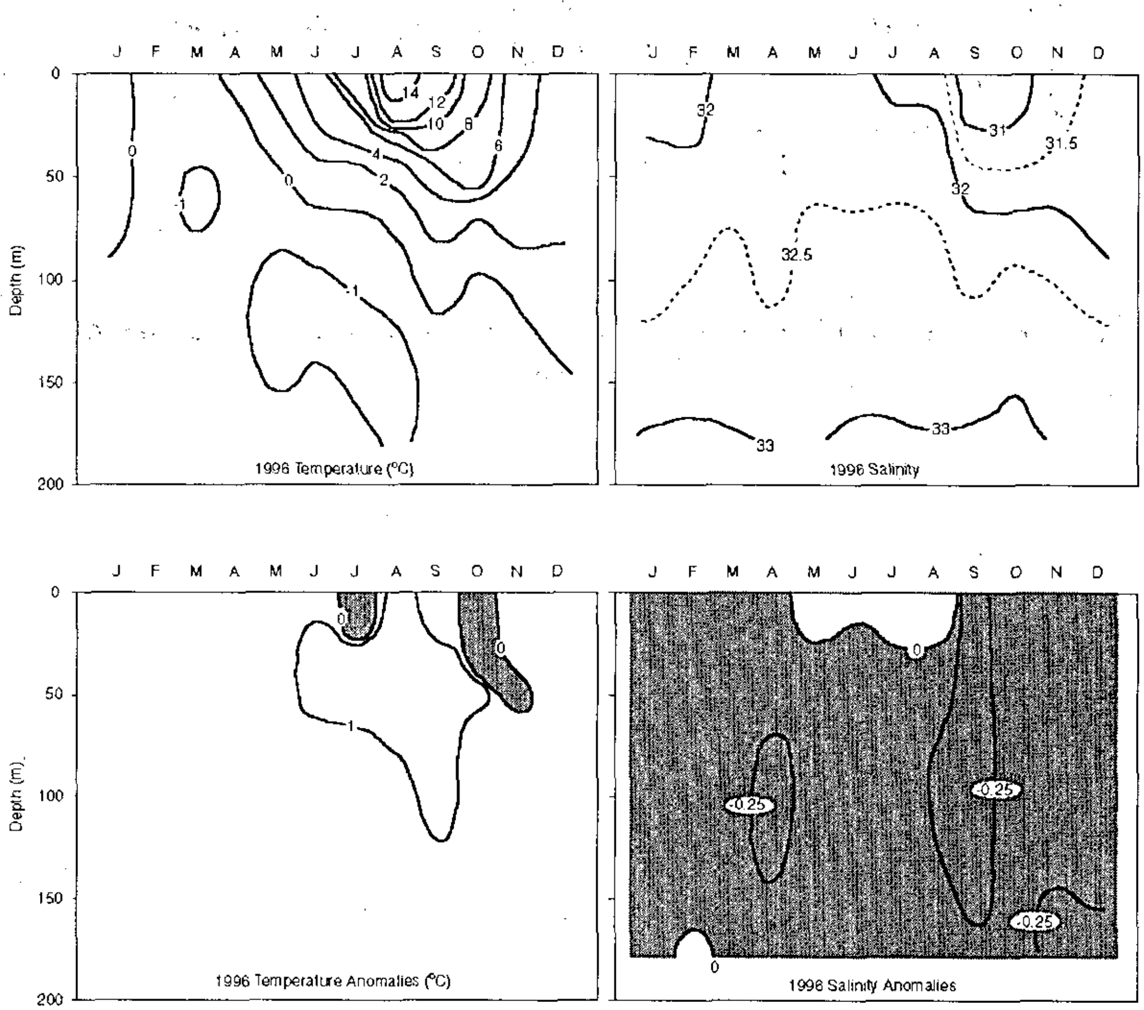


Fig. 17. The monthly mean and anomalies of temperature and salinity at Station 27. The negative (cold, fresher) anomalies are shaded.

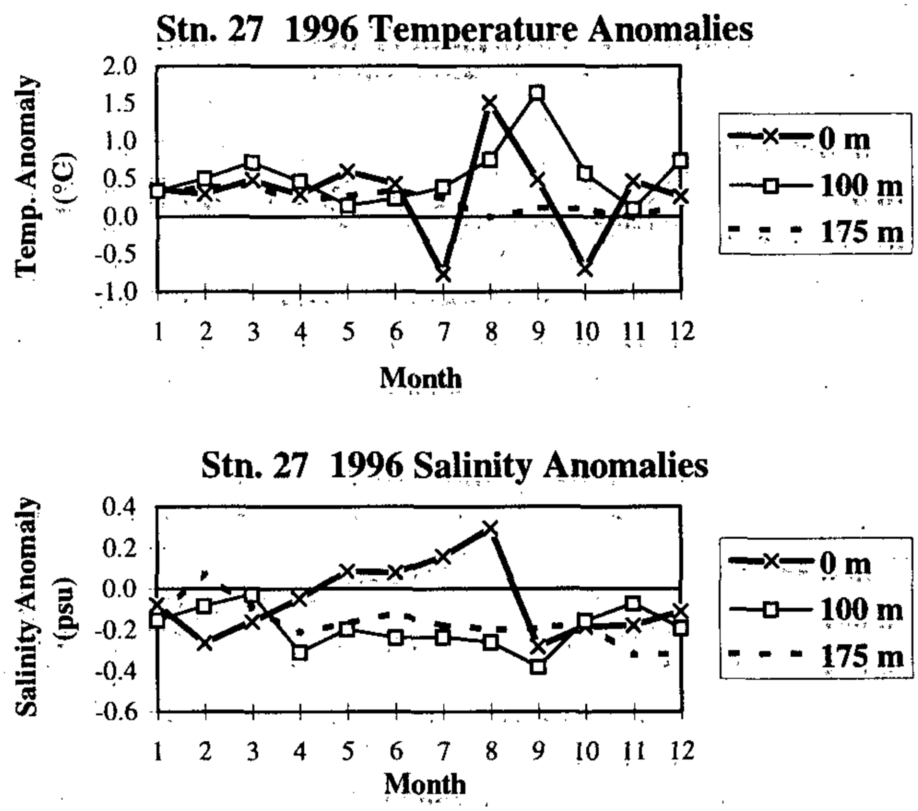


Fig. 18. Monthly temperature (top panel) and salinity (bottom panel) anomalies at 0, 100 and 175 m at Station 27 during 1996.

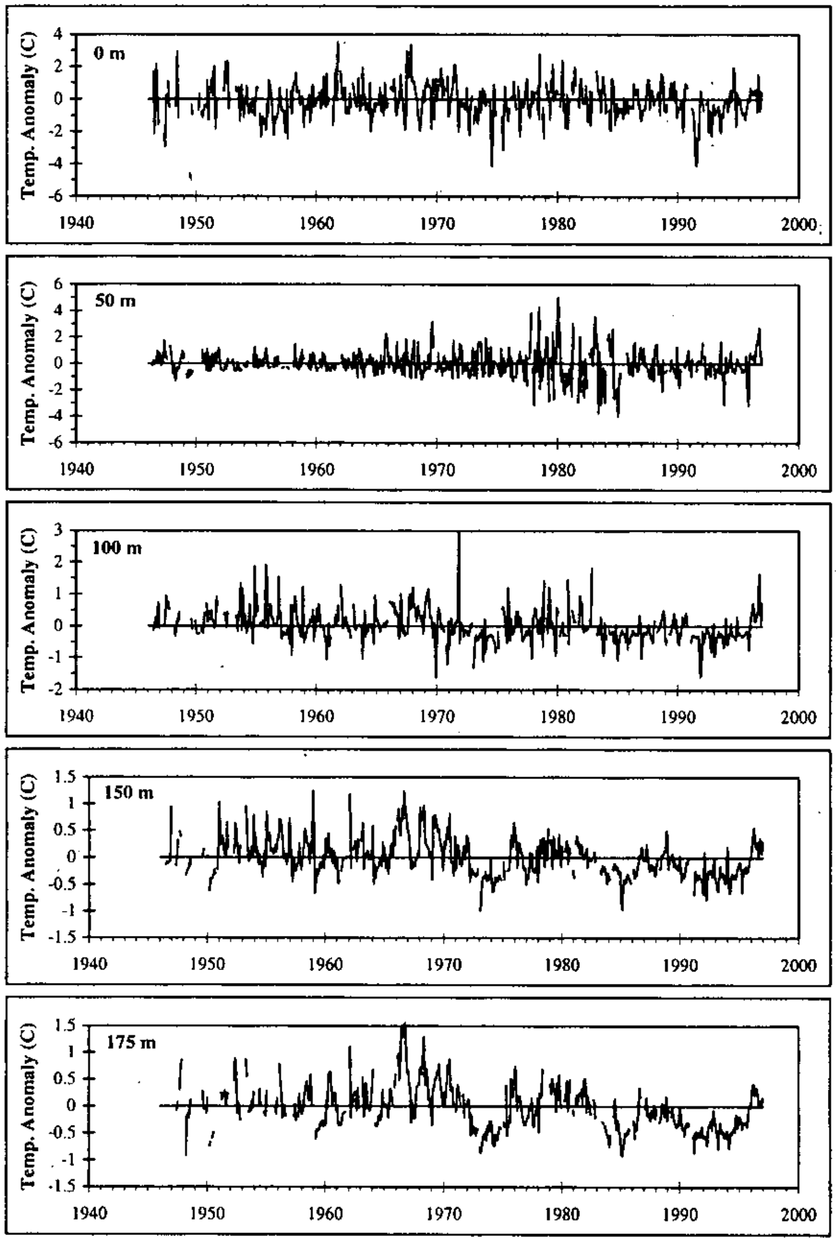


Fig. 19. Monthly mean temperature anomalies at selected depths from Station 27.

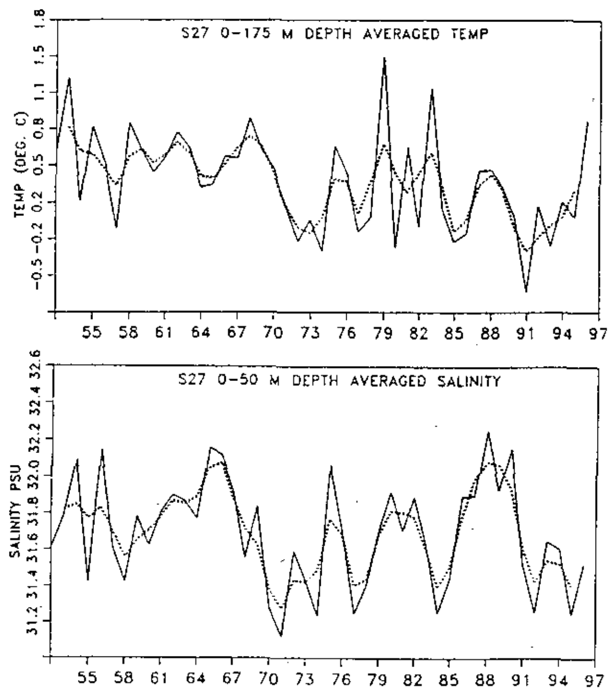


Fig. 20. Vertically-averaged salinity and temperature from Station 27.

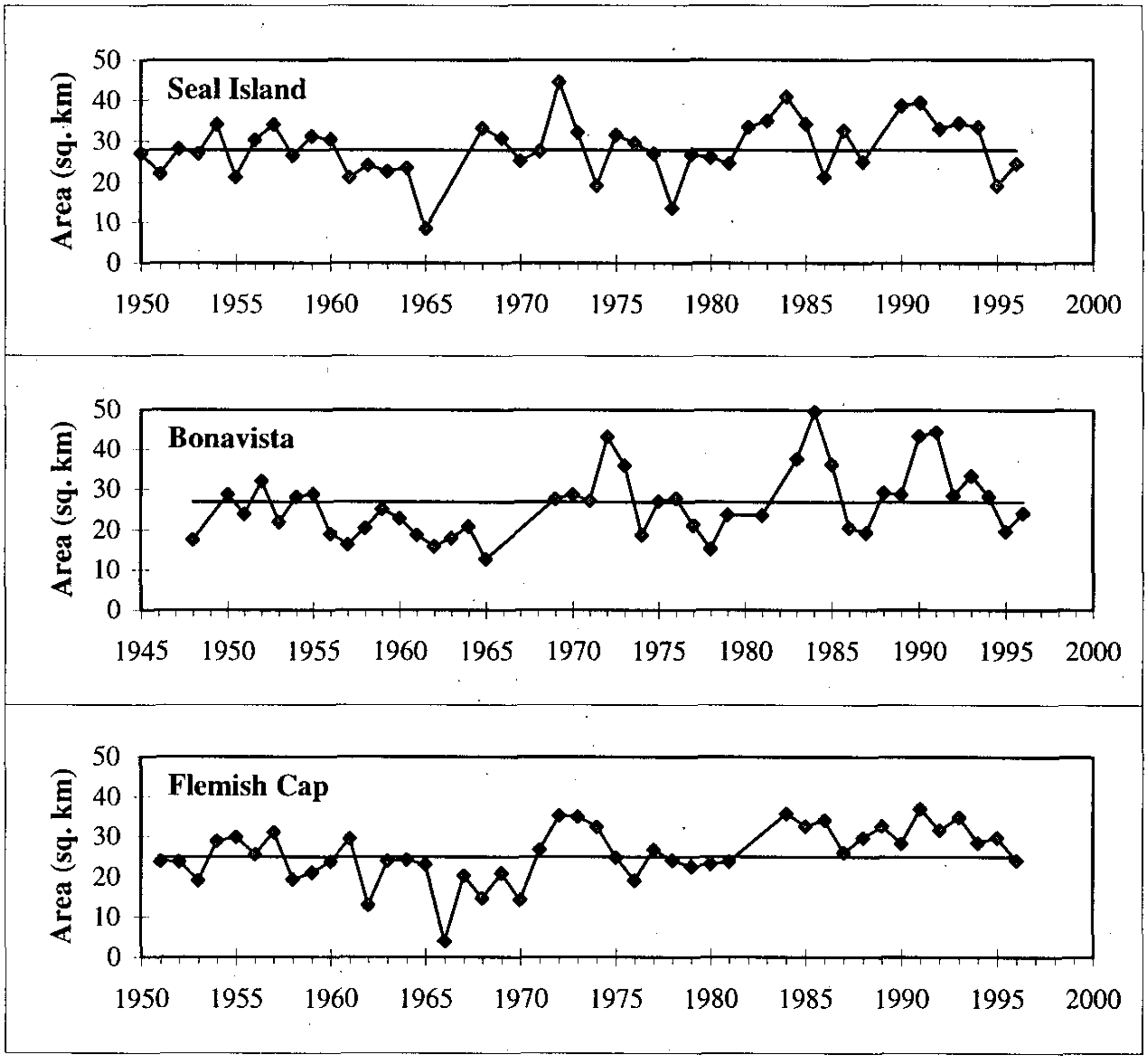


Fig.21. The CIL area (in km^2) during the summer along transects off Seal Island (southern Labrador), Bonavista Bay (northern Newfoundland) and Flemish Cap (Grand Banks).

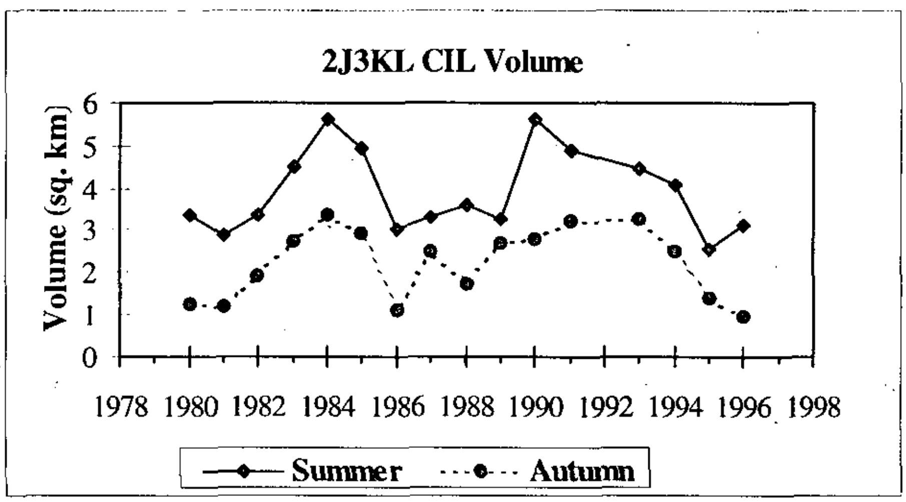


Fig. 22. The CIL volume in the summer and autumn within div. 2J and 3KL.

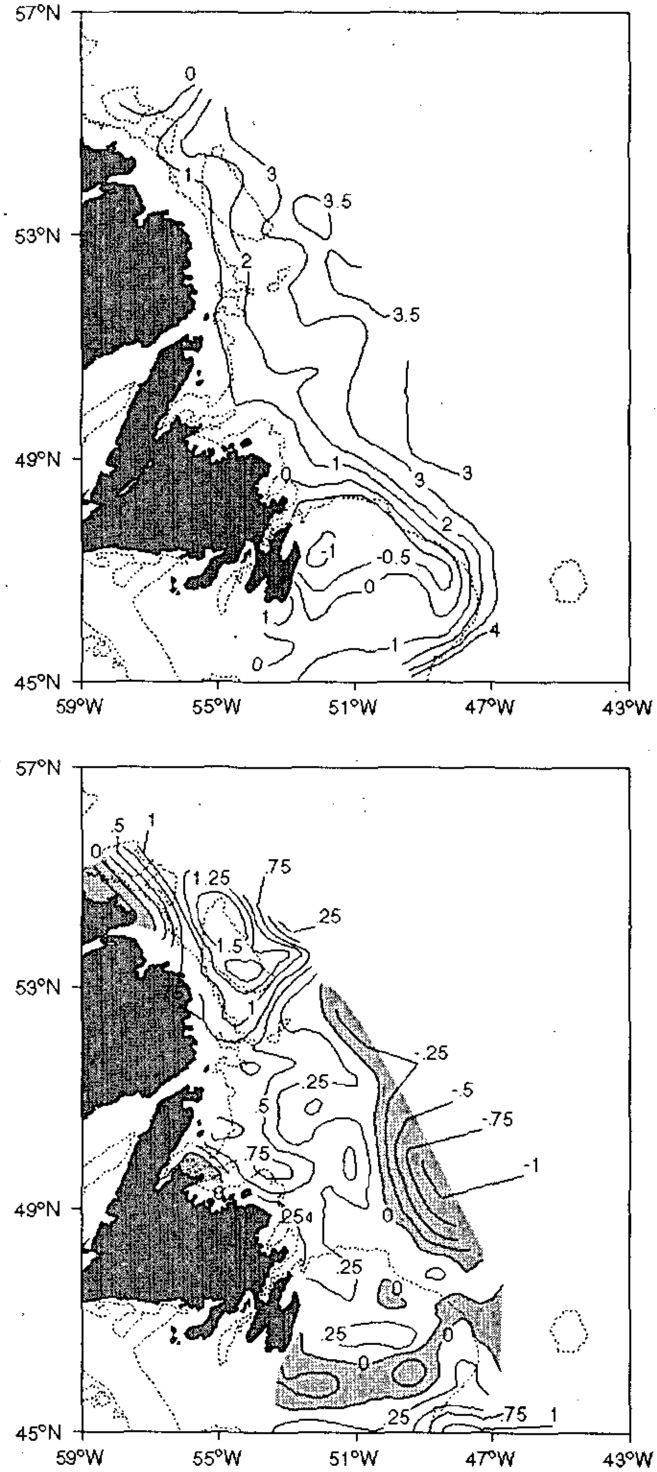


Fig.23. The horizontal distribution of bottom temperature (top panel) and their anomalies (bottom panel) during the autumn 1996 off Newfoundland. Negative anomalies are shaded and the dotted line represents the 200 m isobath.

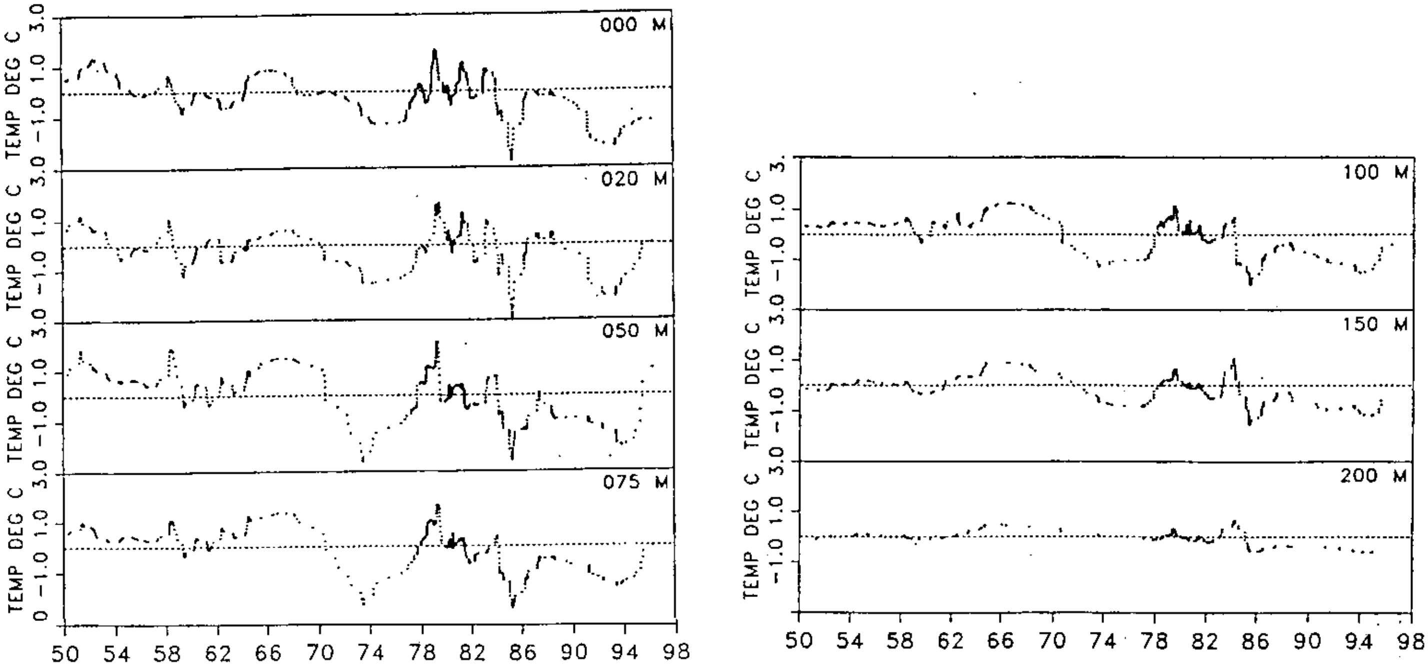


Fig. 24. Smoothed time series of temperature anomalies at standard depths over Flemish Cap.

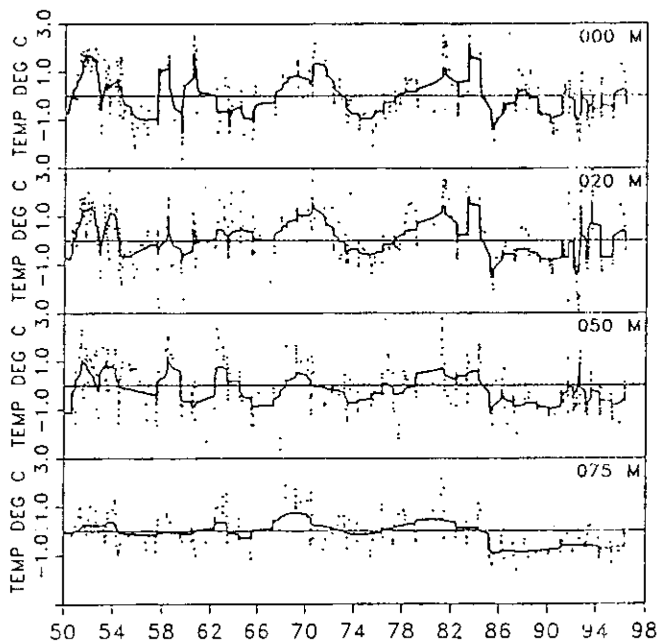


Fig.25. Smoothed time series of temperature anomalies at standard depths over St. Pierre Bank. The apparent vertical lines in the plots are surveys conducted over a day or two and thus reflect both spatial and temporal variability over the Bank.

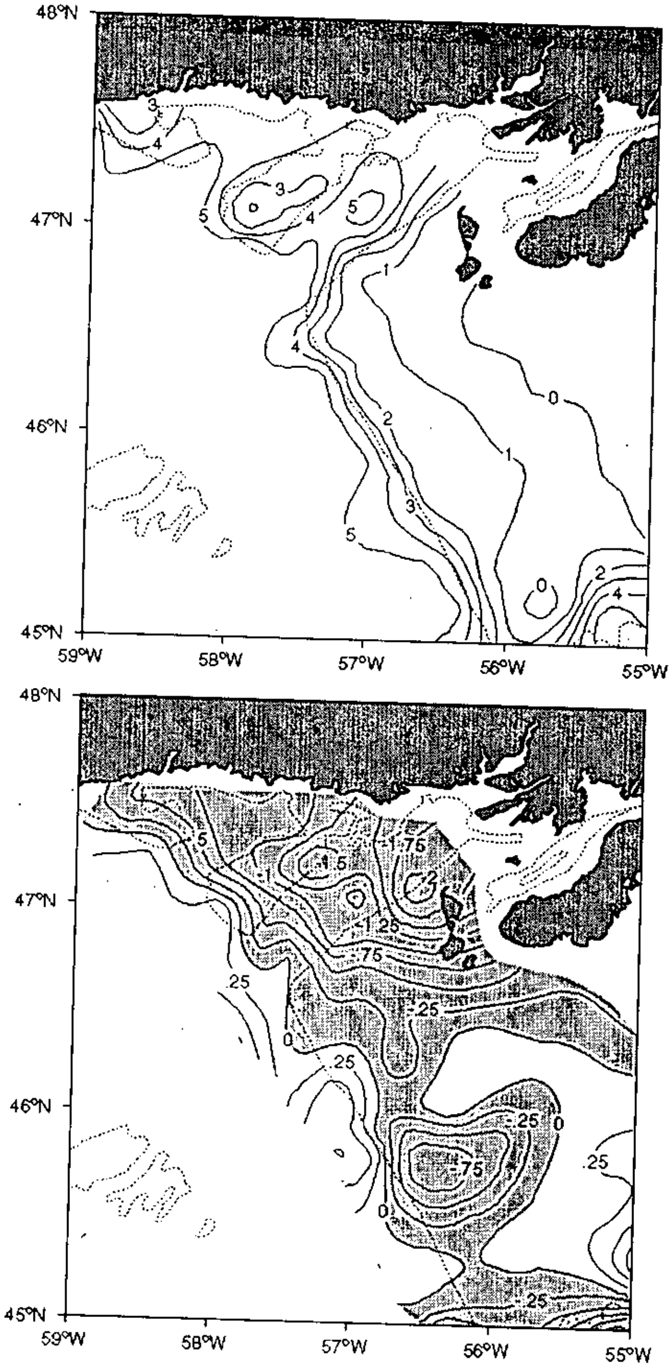


Fig. 26. The horizontal distribution of bottom temperature (top panel) and their anomalies (bottom panel) off southern Newfoundland during April 1996. Negative anomalies are shaded and the dotted line represents the 200 isobath.

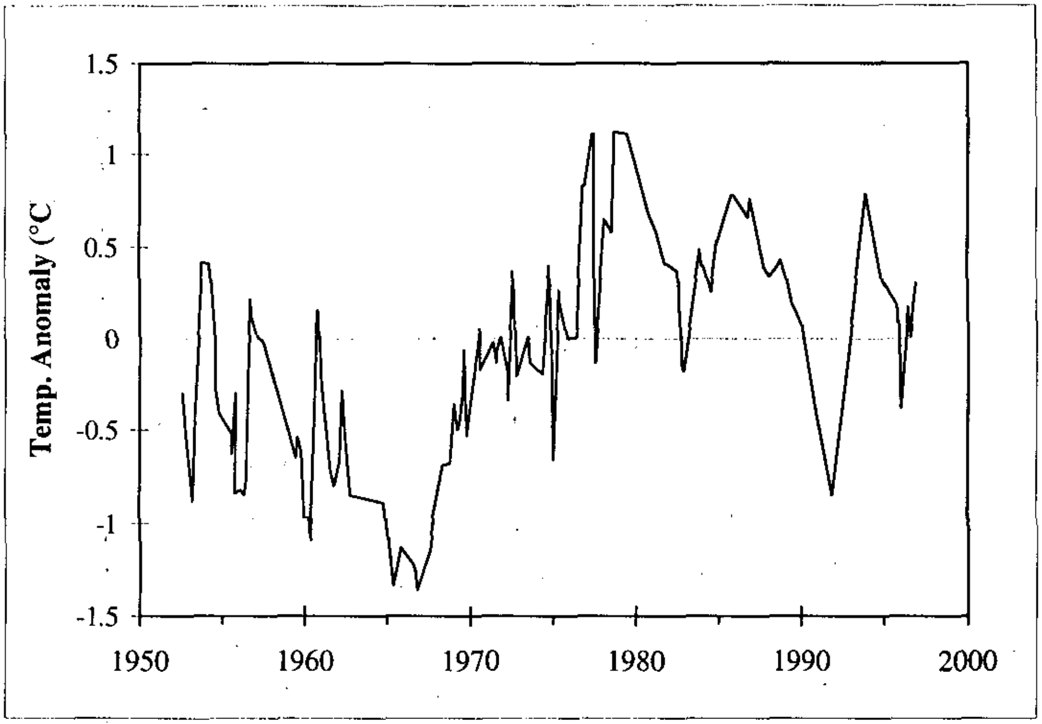


Fig. 27. Anomalies in the average temperature in the 200-300 m layer in Cabot Strait.

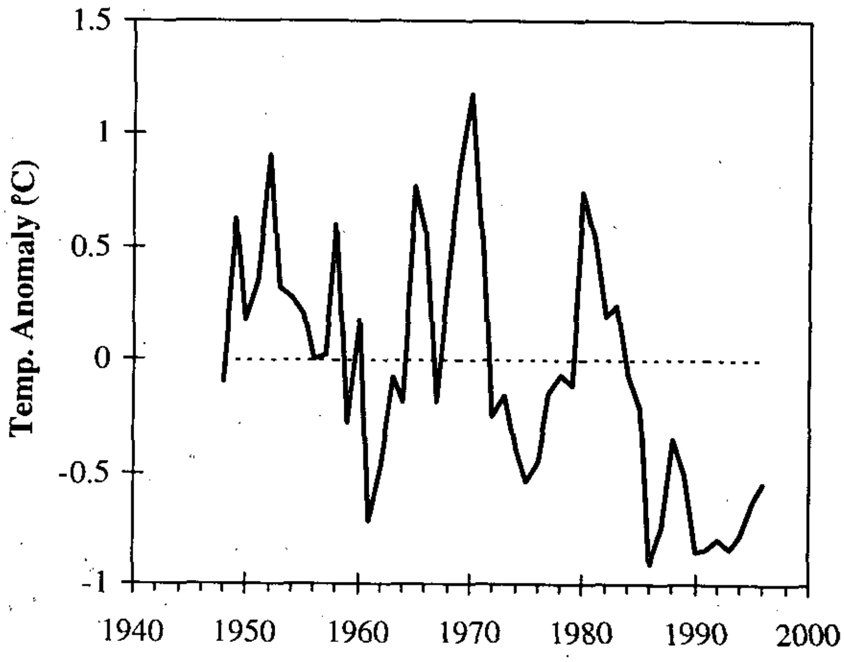


Fig.28. Anomalies of the CIL core temperatures (extrapolated to July 15) for the Gulf of St. Lawrence from the 1948-94 mean (0.8°C).

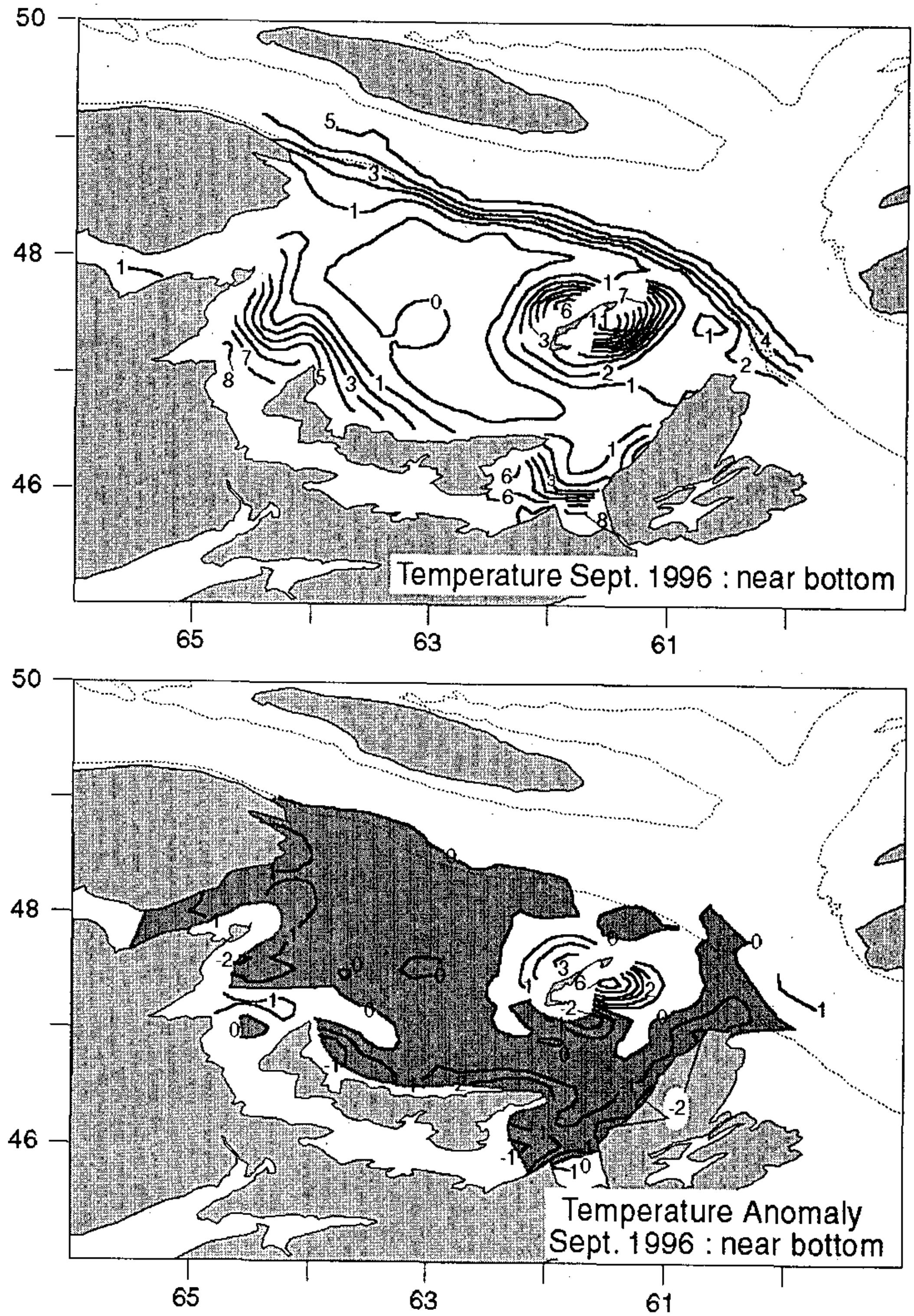


Fig.29. Temperature (top panel) and temperature anomalies (bottom panel) in the southern Gulf of St. Lawrence in September 1996. Negative anomalies are shaded and the dotted line represents the 200 m isobath.

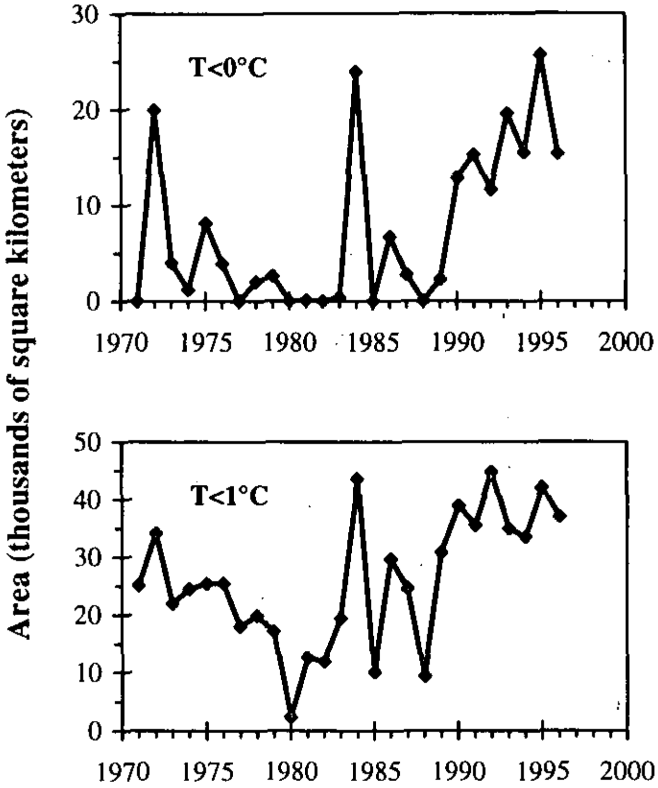


Fig. 30. Area of the Magdalen Shallows with bottom temperatures <0°C and <1°C during September.

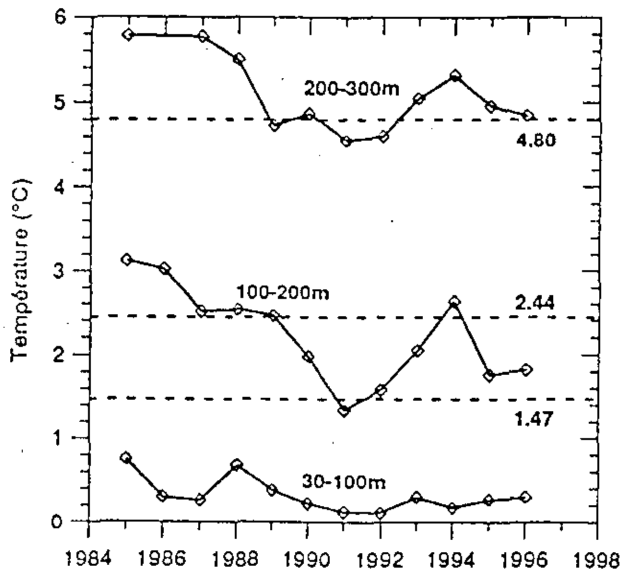


Fig. 31. Temperatures in the 30-100 m, the 100-200 m and the 200-300 m layers in the Gulf of St. Lawrence during August-September. The dashed lines indicate the long-term averages based on Petrie (1990).

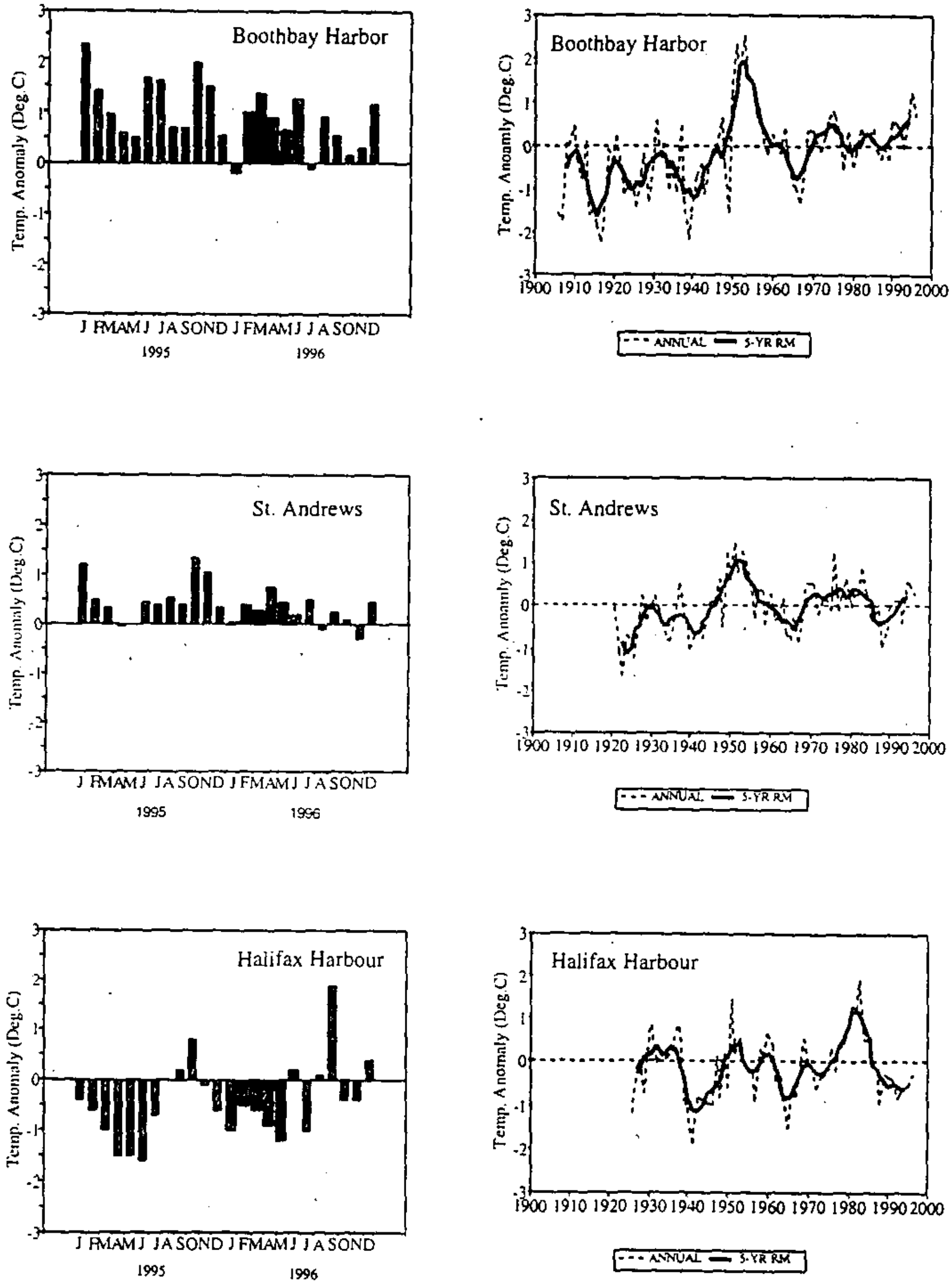


Fig.32. Monthly sea surface temperature anomalies during 1995 and 1996 (left) and the annual temperature anomalies and their 5 year running means (right) for Boothbay Harbor, St. Andrews and Halifax.

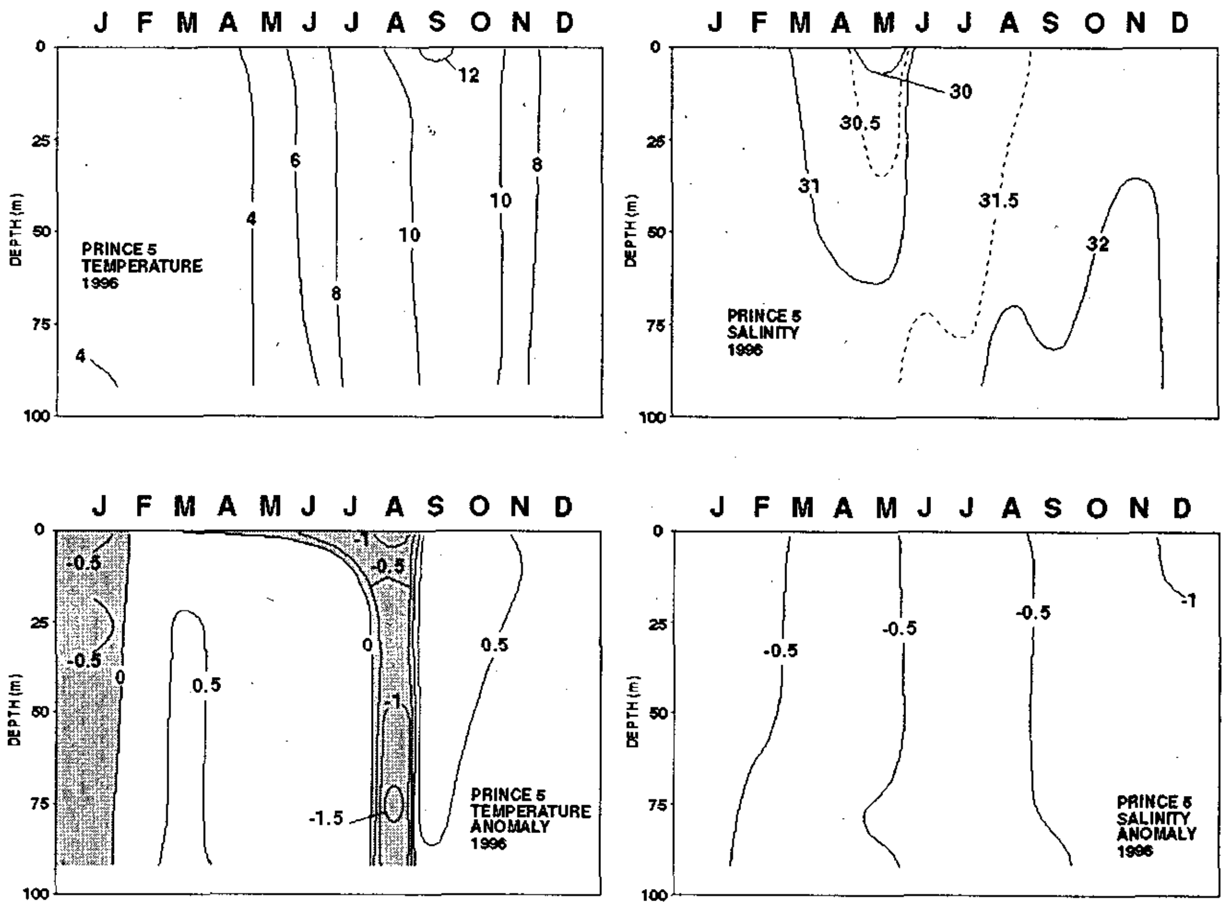


Fig.33. Monthly mean temperatures and salinities and their anomalies at Prince 5 as a function of depth during 1996. Shaded areas are negative anomalies.

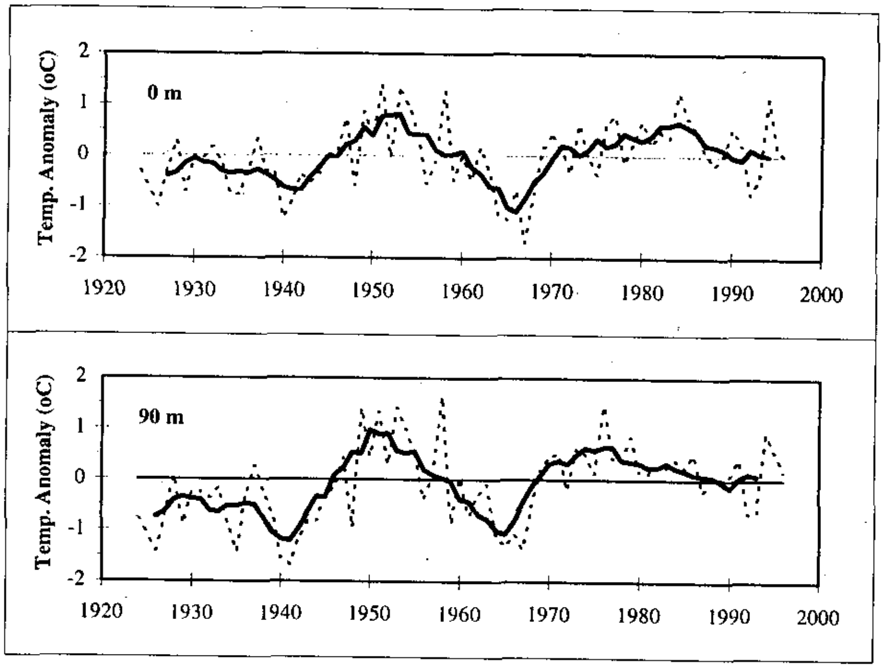


Fig. 34. Annual and 5 yr running means of temperature anomalies at Prince 5, 0 and 90 m.

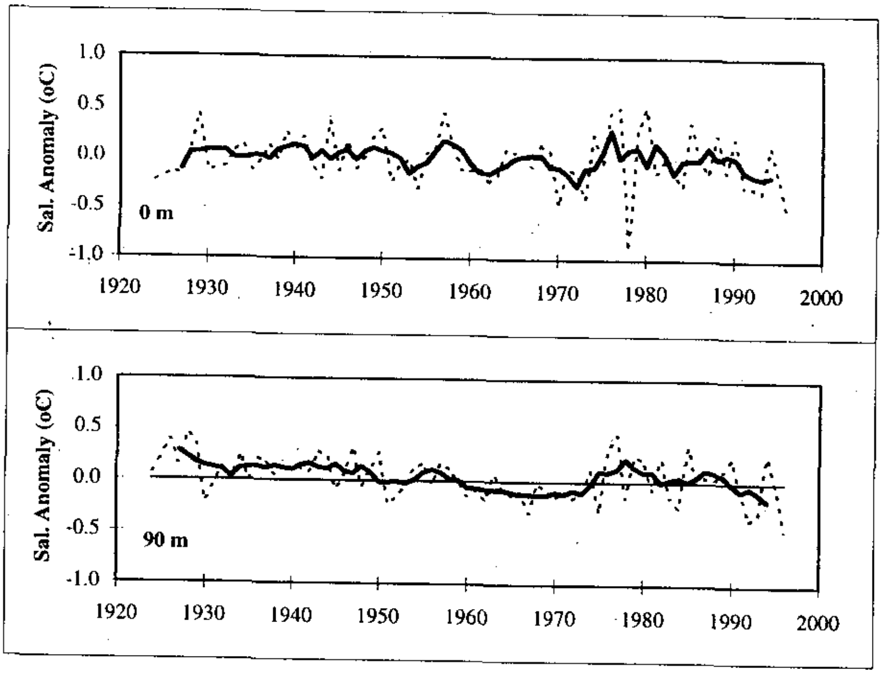


Fig. 35. Annual and 5 yr running means of salinity anomalies at Prince 5, 0 and 90 m.

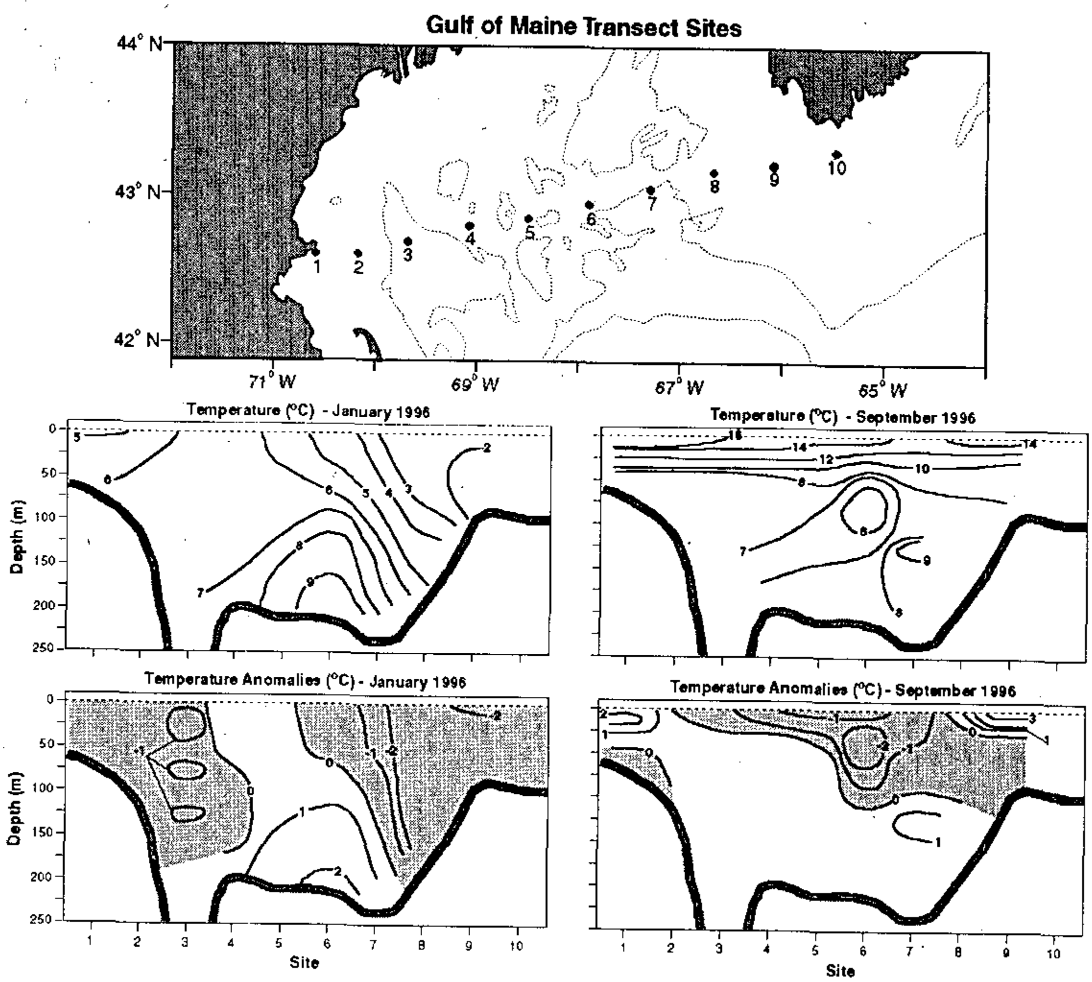


Fig.36. The temperature (middle panels) and temperature anomalies (bottom panels) in °C along a XBT transect (top panel) across the Gulf of Maine during January and September 1996.

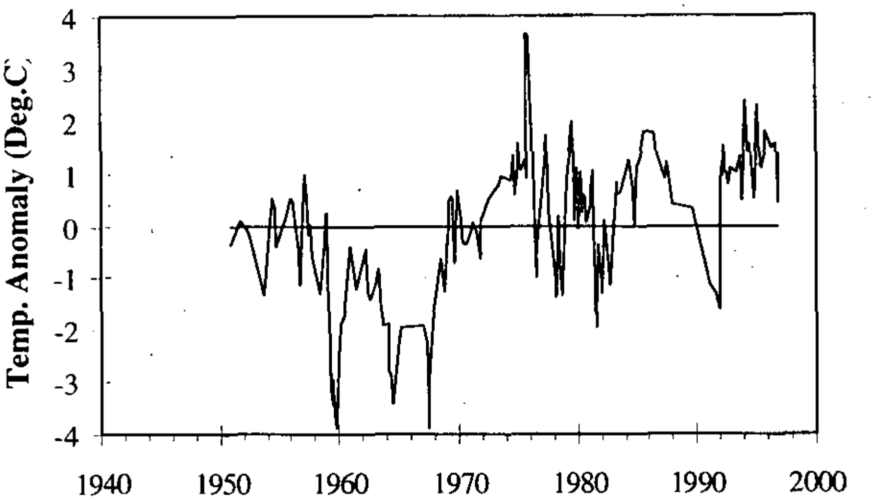
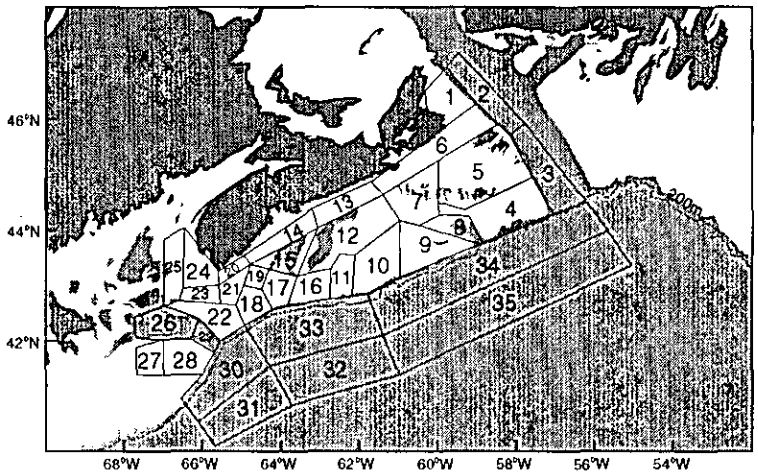


Fig.37. Anomalies of the average temperature in the 200-300 m depth layer in Cabot Strait. The mean temperature is 5.4 °C.



1. Sydney Bight
2. N. Laurentian Channel
3. S. Laurentian Channel
4. Banquereau
5. Misaine Bank
6. Canso
7. Middle Bank
8. The Gully
9. Sable Island
10. Western Bank
11. Emerald Bank
12. Emerald Basin
13. Eastern Shore
14. South Shore
15. Lahave Basin
16. Saddle
17. Lahave Bank
18. Baccaro Bank
19. Roseway Bank
20. Shelburne
21. Roseway Basin
22. Browns Bank
23. Roseway Channel
24. Lurcher Shoals
25. E. Gulf of Maine
26. Georges Basin
27. Georges Shoal
28. E. Georges Bank
29. N.E. Channel
30. Southern Slope
31. Southern Offshore
32. Central Offshore
33. Central Slope
34. Northern Slope
35. Northern Offshore

Fig.38. The areas in which monthly mean temperature and temperature anomalies were estimated.

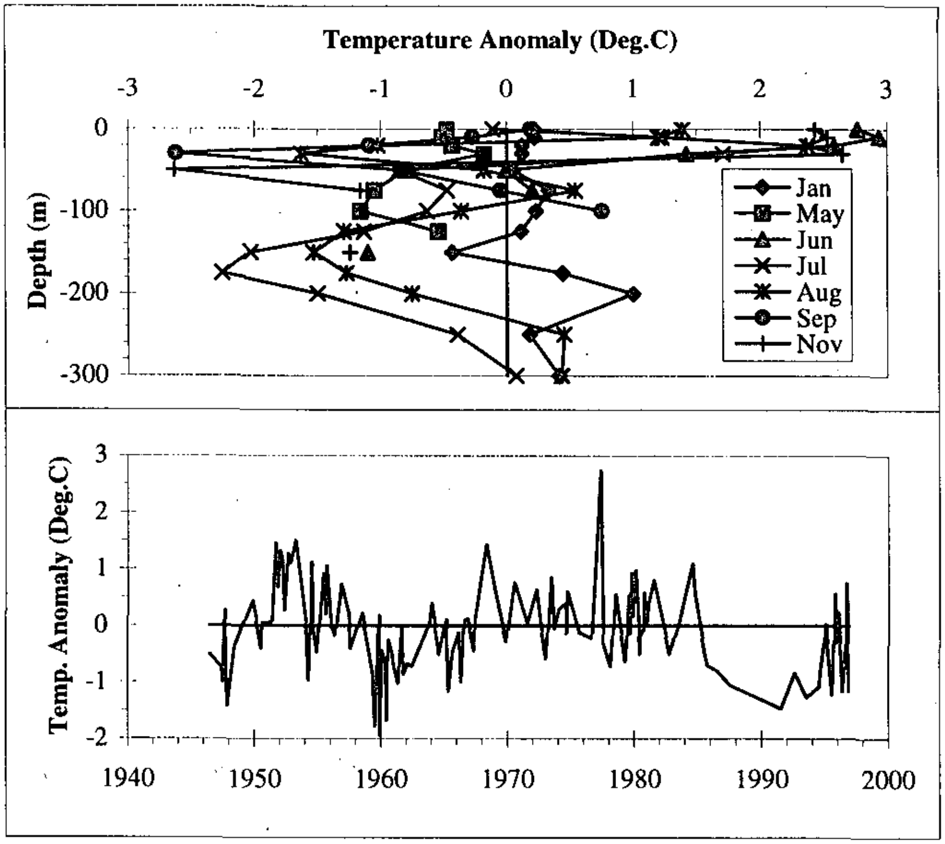


Fig. 39. The 1996 monthly temperature anomaly profiles (top) and temperature anomaly time series at 100 (bottom) for Sydney Bight (area 1 in Fig. 38).

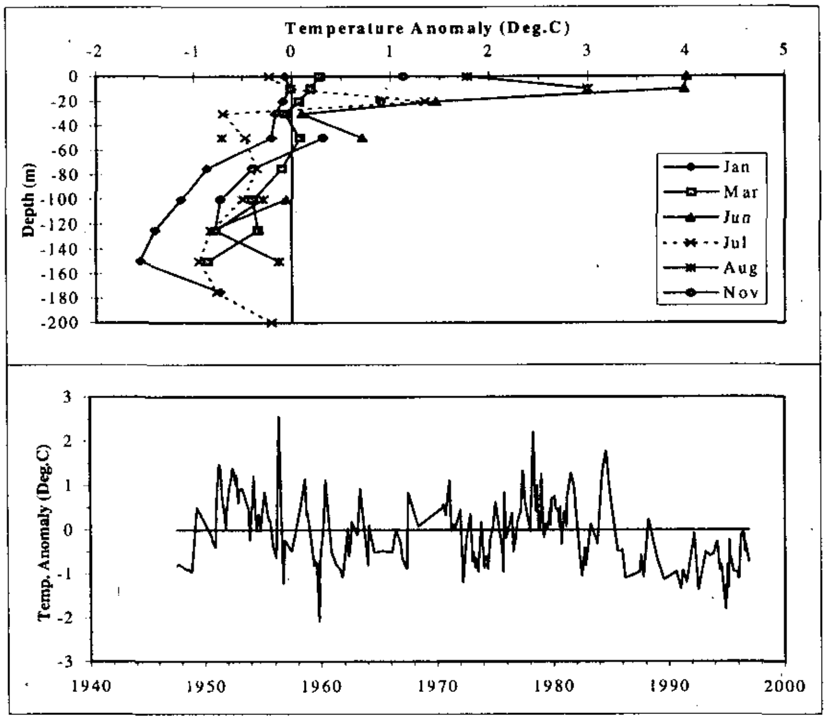


Fig. 40. The 1996 monthly temperature anomaly profiles (top) and temperature anomaly time series at 100 m (bottom) for Misaine Bank (area 5 in Fig. 38).

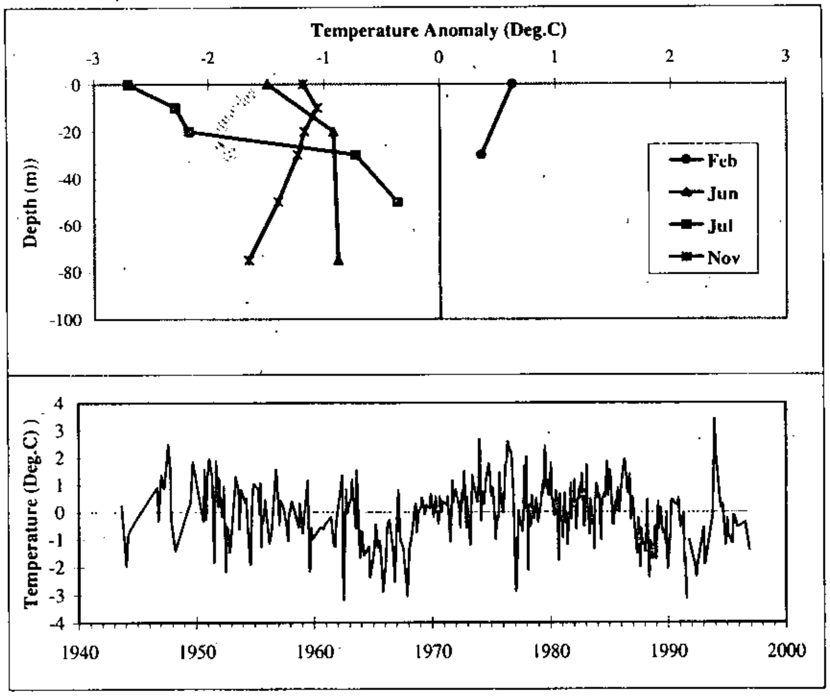


Fig. 41. The 1996 monthly temperature anomaly profiles (top) and temperature anomaly time series at 50 m (bottom) for Lurcher Shoals (area 24 in Fig. 38).

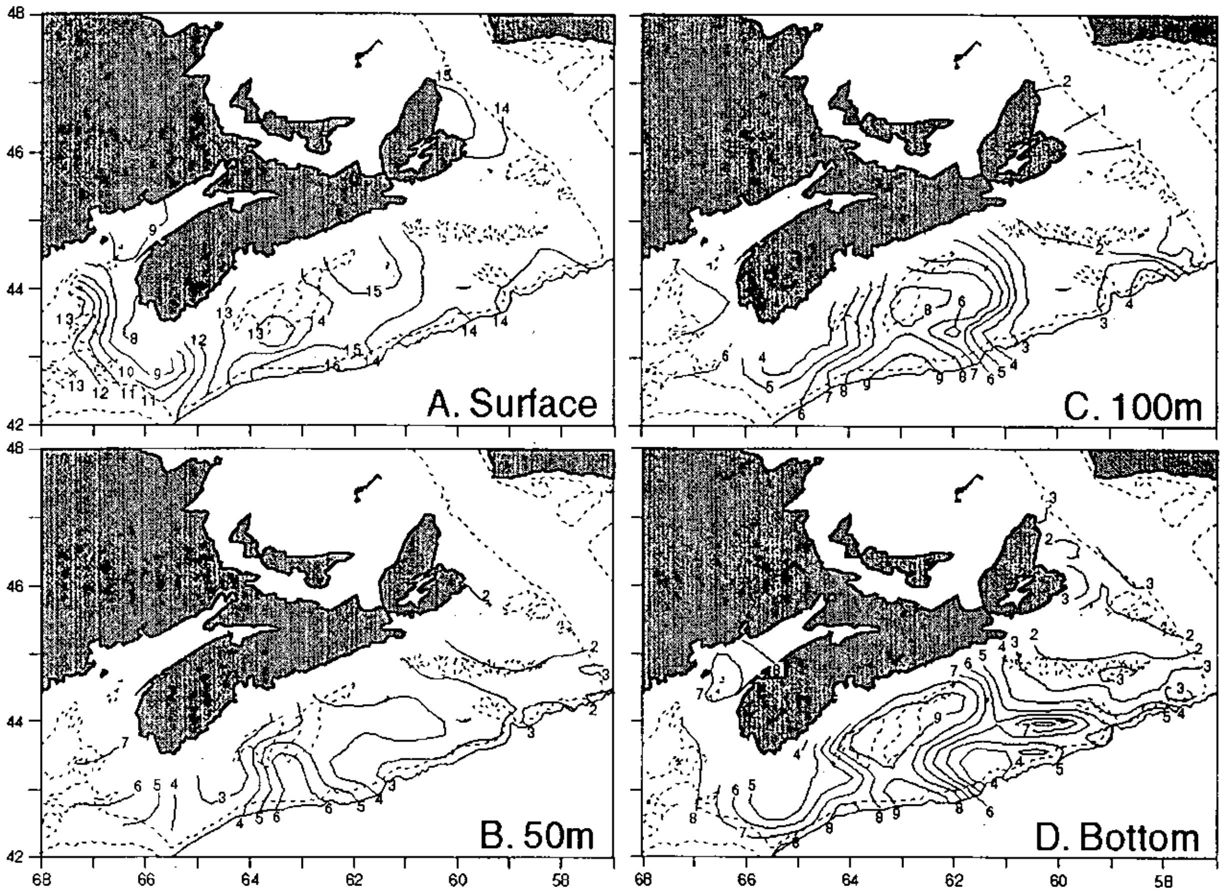


Fig.42. Temperatures contours at different depth levels during the 1996 Canadian July groundfish survey.

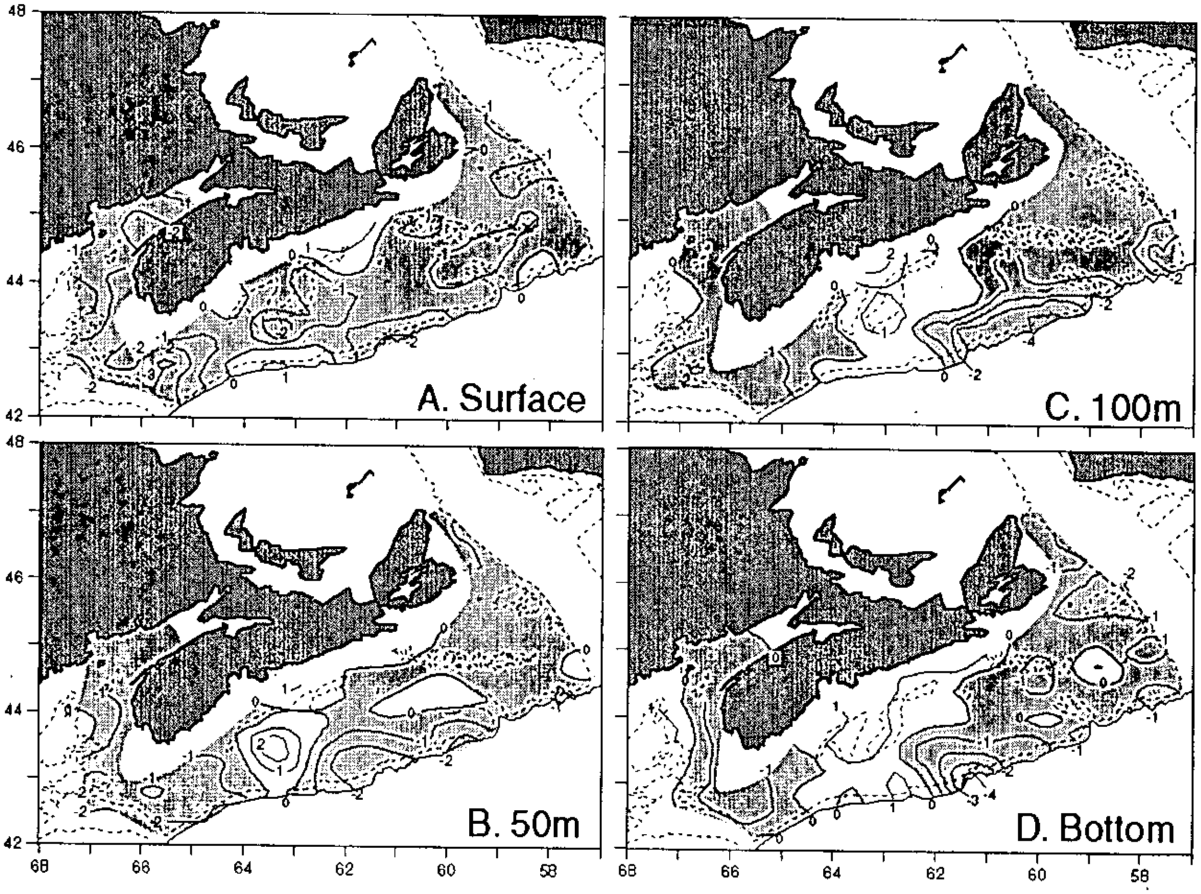


Fig. 43. Temperature anomaly contours at different depth levels calculated from data taken during the 1996 Canadian July groundfish survey.