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Marine Environmental Conditions in the Northwest Atlantic During 1997 Potentially Impacting Atlantic Salmon (*Salmo Salar*)

K.F. Drinkwater, J. Helbig, R. Pettipas and L. Petrie

Department of Fisheries and Oceans, Maritimes Region
Ocean Sciences Division, Bedford Institute of Oceanography
Box, 1006, Dartmouth, N.S. B2Y 4A2

Abstract

Marine environmental conditions during 1997 in the Northwest Atlantic that could potentially impact eastern Canadian Atlantic salmon stocks are reviewed from available atmospheric and oceanographic datasets. The Labrador Sea is of particular interest because it is the overwintering site for most of these stocks. In the Labrador Sea, environmental conditions were cooler than in 1996 but generally warmer than the early 1990s. During 1997 above normal winter air temperatures were observed, however, the first half of the winter was very warm while the second half was very cold. The spring air temperatures also tended to be below normal. The air temperatures are linked to the strength of the North Atlantic Oscillation (NAO) which is a measure of the large scale atmospheric circulation pattern. The NAO index increased relative to 1996 but was well below that of the early 1990s. A low NAO index is associated with weaker NW winds over the Labrador Sea and warmer air and sea temperatures. Some of the inner Bay of Fundy salmon stocks are known to overwinter in the Gulf of Maine instead of migrating to the Labrador Sea. In the Gulf of Maine, in situ measurements of surface temperatures were above normal in the winter, cooled in the spring and were generally above normal through the rest of the year. Seasonal sea surface temperature patterns were extracted from the MCSST data set. Anomalies in various regions varied in sign throughout the year, but much of the offshore North Atlantic and Labrador Sea was warmer than normal for most of the year. Over the continental shelves, the Grand Banks was relatively warm while the Scotian Shelf/Gulf of Maine region was characterized by both positive and negative anomalies as was the Gulf of St. Lawrence.

Résumé

Un examen des conditions environnementales du nord-ouest de l'Atlantique en 1997 qui auraient pu influer sur les stocks de saumon de l'Atlantique de l'est du Canada a été réalisé à partir des données atmosphériques et océanographiques déjà obtenues. La mer du Labrador présente un intérêt particulier car c'est à cet endroit qu'hivernent la plupart de ces stocks. Les conditions y ont été plus froides qu'en 1996, mais généralement plus chaudes qu'au début des années 1990. En 1997, la température de l'air en hiver a été supérieure à la normale, mais la première demie de l'hiver a été très peu froide et la deuxième très froide. La température de l'air au printemps a été généralement inférieure à la normale. Les températures de l'air sont fonction de l'oscillation nord-atlantique (ONA) qui est une mesure du régime de la circulation atmosphérique à grande échelle. L'indice ONA a augmenté par rapport à 1996, mais est demeuré bien en deçà de la valeur du début des années 1990. Un indice faible correspond à des vents du NO plus faibles au-dessus de la mer du Labrador et à des températures de l'air et de l'eau plus élevées. Certains des stocks de saumon du fond de la baie de Fundy hivernent dans le golfe du Maine plutôt que de migrer vers la mer du Labrador. Dans le golfe du Maine, la mesure sur place de la température en surface a donné des valeurs supérieures à la normale en hiver, inférieures au printemps et généralement supérieures à la normale pendant le reste de l'année. Le régime des températures saisonnières des eaux en surface a été obtenu à partir des données MCSST. Le signe des anomalies de diverses zones a changé tout au long de l'année, mais une grande partie des eaux hauturières du nord de l'Atlantique et de la mer du Labrador a été plus chaude que la normale pendant la plus grande partie de l'année. Quant aux plateaux continentaux, la température de l'eau des Grands Bancs a été relativement élevée tandis que celle de la région du plateau néo-écossais et du golfe du Maine se caractérisait pas des anomalies positives et négatives, comme dans le golfe du Saint-Laurent.

Introduction

This paper presents atmospheric and physical oceanographic conditions during 1997 that may have influenced Atlantic salmon (*Salmo salar*) stocks during their marine phase. These fish spawn in the rivers of eastern North America and most migrate in the fall to the Labrador Sea where they overwinter (Reddin and Friedland, 1993). Exceptions to this pattern are the inner Bay of Fundy stocks that are believed to overwinter somewhere within the Gulf of Maine region, although the exact location is unknown. Oceanic variability is thought to influence both recruitment survival and growth of several salmon stocks (Reddin and Shearer 1987; Ritter 1989; Friedland et al. 1993) as well as the timing and location of the return migration (Reddin and Friedland, 1993; Narayanan et al., 1995). Similar to last year (Drinkwater et al., 1997), the focus of this review is upon the meteorological, ice and temperature conditions during 1997 in those areas of the Northwest Atlantic where salmon are found during their marine phase. This covers the continental shelf regions from the Gulf of Maine to Labrador and the Labrador Sea (Fig. 1). Climatic conditions within the paper are often expressed as anomalies, i.e. deviations from their long term mean. Where possible, long-term has been standardized to a 30-yr (1961-90) base period in accordance with the convention of meteorologists and recommendations of the North Atlantic Fisheries Organization. We begin with background information on the linkages between the atmospheric and oceanic connections in the Labrador Sea. This is followed by discussion of the 1997 environmental conditions in the Labrador Sea and in the waters around the Maritime provinces of Canada.

Atmospheric and Oceanic Linkages in the Labrador Sea

Friedland et al. (1993) carried out exploratory analysis of sea-surface temperatures in the Northwest Atlantic to identify habitat areas for Atlantic salmon and then compared these with salmon production indices, in particular the number of salmon returning to spawn. They found the distribution of winter (January-March) habitat (defined by the area within 4-8 °C) at the mouth of the Labrador Sea to be critical for North American salmon stocks with higher returns in those years when there was more suitable habitat. They hypothesized that the habitat limits salmon production through intraspecific competition. The area of the 4°C to 8°C winter habitat was also found to be linked with the atmospheric circulation over the North Atlantic Ocean, as revealed by the North Atlantic Oscillation (NAO) index (defined below). A detailed description of the linkages between the NAO index, meteorological conditions, sea ice and ocean temperatures is provided in Drinkwater and Mountain (1997). As background, a brief summary precedes our examination of the 1997 data.

The large-scale atmospheric pressure patterns over the North Atlantic Ocean are dominated by the Icelandic Low, centered between southern Greenland and Iceland, and the Azores High, centered roughly above the Azores (Fig. 2). This pattern occurs year round but is most intense in winter. The strength of the Low and High vary from year-to-year with the tendency for both pressure systems to intensify (or weaken) in the same year. This tendency is known as the NAO (North Atlantic Oscillation). Rogers (1984) defined an NAO index as the winter (December, January, February) sea surface pressure at the Azores minus that at Iceland. A high index corresponds to a deep Icelandic Low and an intense Azores High. The index is a latitudinal pressure gradient and therefore its increase results in corresponding increases in the strength of the westerly winds across the northern North Atlantic. It also means stronger northwest winds over the Labrador Sea (Fig. 3). In such years, these northwest winds carry cold Arctic air masses further south causing winter air temperatures to decrease (Fig. 3). This in turn results in earlier and more ice formation and the stronger northwest winds push the ice further south leading to more extensive ice coverage (Fig. 3). The cold, windy conditions in winter also result in high air-sea heat exchanges leading to extensive cooling of the waters over the shelf and in the Labrador Sea (Cayan, 1992). In years of low NAO, the opposite tends to occur, i.e. weakened Icelandic Low, reduced northwest winds, warmer-than-normal winter air temperatures, later and less extensive ice, reduced heat exchange leading to warmer ocean temperatures. We now turn our attention to conditions during 1997.

Physical Environmental Conditions in the Northwest Atlantic during 1997

NAO Index

The NAO Index was estimated from the measured mean sea level pressures at Ponta Delgada in the Azores minus those at Akureyri in Iceland. In 1997, the NAO anomaly was below normal for the second consecutive year but was above that observed in 1996 (Fig. 4). The 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 atmosphere circulation. However, the decline also fits the pattern of near decadal variability that has persisted since the 1960s, and was therefore anticipated, although its amplitude was much greater than expected. The relatively low NAO index during 1997 corresponds to a weak Icelandic Low and suggests reduced northwest winter winds over the Labrador Sea.

Air Temperatures

A strong association exists between air and sea surface temperatures. The German Weather Service publishes monthly mean air temperature anomalies relative to their 1961-90 means for the North Atlantic Ocean in their publication *Grosswetterlagen Europas*. During January, positive anomalies covered most of our area of interest with temperatures reaching 4°C above normal in Baffin Bay off West Greenland (Fig. 5). Air temperature anomalies on the northern Labrador Shelf exceeded 1°C above normal. Rapid cooling during February resulted in very cold air temperatures over the Labrador Sea with anomalies falling to 3°C below the long-term mean. The 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 air temperature anomalies were above normal by as much as 3-4°C between Cape Cod and New York. 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 that was 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 air temperatures varied spatially and from month to month between above and below normal. 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 or above by December.

Monthly air temperature anomalies for 1996 and 1997 relative to their 1961-90 mean at eight sites in the northwest Atlantic from Godthaab in Greenland to Cape Hatteras on the eastern coast of the United States are shown in Fig. 6 (see Fig. 1 for locations). Data from the Canadian air temperature sites were available from the *Canadian Climate Summaries* published by the 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 are a continuation of the warm air conditions that were established in December of 1996. This was followed by a rapid decline in temperature anomalies in February. Temperatures remained colder-than-normal at most 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, 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 trends, fluctuating about the long-tern 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).

The 1997 annual temperature anomalies at seven of the eight sites declined from the local maximua in 1996, the exception being Cape Hatteras where the annual mean temperature was similar to that recorded in 1996 (Fig. 7). 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. Since 1970, temperature anomalies at these sites were predominantly below normal due to a general downward trend in temperatures that was occurring at the same time as the near-decadal oscillations. By the mid-1990s temperatures had risen continuing the trend of near-decadal fluctuations. 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 declining temperatures 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 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 region. Thus, for example, when the temperatures were very cold in Labrador during the early 1990s, they were relatively warm along the US seaboard (Fig. 7).

Sea Ice

Information on the location and concentration of sea ice for 1997 has been derived from daily ice charts published by Canadian Ice Service of Environment Canada in Ottawa. Comparisons are made with the long-term median, maximum and minimum positions of the ice edge (concentrations above 10%) based on the composite for the years 1962 to 1987 as described by Coté (1989).

Labrador and Newfoundland

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. 8a). 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 coverage than usual and was again caused by much warmer-than-normal air temperatures, especially off southern Labrador. By the first of February, ice coverage was back to near median values as air temperatures cooled to below normal. 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. 8b). Ice off northern Newfoundland was positioned offshore, meaning many of the harbours and coast communities were clear of ice. By 1 May, strong northeasterly winds over southern Labrador and northern Newfoundland pushed 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, personal communication, Bedford Institute) show the peak extent during 1997 increased relative to 1996 and was near but slightly below that of the early 1990s (Fig. 9). The average area during the period of general advancement (January to March) and retreat (April to June) also increased from 1996. These values indicate that the areal coverage on average, however, was less than the early 1990s and was extremely low during the time of retreat. These data indicate 1997 was an average to lighter-than-average ice year on the Labrador and Newfoundland shelves. Note that during January-March there has been a general tendency for an increase in the area of ice over the past 30 y but no such trend exists during the April-June period. Variations of ice area generally 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.

Gulf of St. Lawrence and Scotian Shelf

At the end of December 1996, no ice was present in the Gulf of St. Lawrence and upper St. Lawrence Estuary due to warmer-than-normal air temperatures which delayed ice formation (Fig. 10). By mid-January, ice had formed along the coast from the Gaspé Peninsula to Nova Scotia and throughout the 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 air temperatures remaining above normal through the first half of January. During the second half of the month, northwesterly winds and below normal temperatures over the northwestern portion of the Gulf resulted in rapid spreading of the ice such that the coverage was only slightly less than the long-term median by the beginning of February. The ice was thinner than normal at this time, however. Cold air and strong northwest winds continued during February and by 1 March the Gulf was ice covered except for St. Georges Bay in Newfoundland. The ice edge was very near to its median position. Ice retreated during March so that by 1 April it had left the Estuary and many of the coastal areas of the southwestern Gulf. There was more ice than normal in the Gulf at this time. Ice continued to retreat through April and by 1 May ice was only located in the southern Magdalen Shallows and in the northeast near the Strait of Belle Isle. At this time there was greater areal coverage than normal. The ice from the southern Gulf finally disappeared by 17 May but remained in the northern Gulf until 3 June. The last ice to disappear was located north of Anticosti Island.

Recently an ice database for the Gulf of St. Lawrence and Scotian Shelf was completed and a more comprehensive analysis of the first and last appearance of ice and the ice duration was carried out. The Gulf and Scotian Shelf was divided into 130 areas of dimensions 0.5° latitude by 1° longitude. The weekly concentration and types of ice within each area were recorded through the ice season. The date of the first and last appearance of ice within these areas as well as the duration of ice were determined. Optimal estimation of the gridded data were used to smooth the data. The database begins in the early 1960s and persists to the present. Long-term means (30 years, 1964-1993) of each variable were determined (using only data during the years ice was present) and subtracted from the 1997 values to obtain anomalies. During 1997 within the Gulf (landward of Cabot Strait), first ice formation 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. 11). 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 date of last appearance of ice shows the typical pattern of lasting longest in the southern Magdalen Shallows and along the north shore of Quebec through to the Strait of Belle Isle (Fig. 12). Over most of the region this represented later-than-normal disappearance although in the outer St. Lawrence Estuary and part of the Magdalen Islands the ice actually left earlier than normal. Note the late disappearance of ice north of Anticosti Island where it remained for 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. 13). 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 over the rest of the Magdalen Islands 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 smaller areas off 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 current pattern. Seaward of Cabot Strait, ice first appeared during the first half of February and 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 (Fig. 10). This was later-than-normal by 10 to over 50 days. Most of this ice had disappeared during the later half of April which is 10 to 30 days later-than-normal. 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. Note that durations of less than 10 days are not plotted in Fig. 13. The duration of ice in 1997 was similar to that of the long-term means (Fig. 13).

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 1997 but there was more than in 1996 (Fig. 14). Although number of days of ice seaward of Cabot Strait was above the long-term mean, the integrated ice area (summation of the area times the number of days) was less-than-normal. This indicates that smaller amounts of ice lasted for a longer time on the Scotian Shelf. Note that based upon data collected since the 1960s, the furthest south that the ice has penetrated along the Atlantic coast of Nova Scotia is to just past Halifax. 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, Halifax, personal communication).

Near Surface Ocean Temperatures

Labrador and Newfoundland

Measurements of temperature and salinity have been routinely taken since 1946 at Station 27 located approximately 10 km off St. John's, Newfoundland. This site lies within the inshore branch of the Labrador Current but changes in temperature at this site are considered to be representative of those over the shelf from southern Labrador to the Grand Banks at time scales of interannual to decadal (Petrie et al., 1992; Colbourne et al., 1994). The station was visited 53 times in 1997, but no data were collected in either February or 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 of these depths. For this report we only present the surface values.

The 1997 monthly temperatures at the surface varied from below 0°C in April to almost 13°C (Fig. 15). Anomalies were positive in January, October and November of 1997. During the spring and summer, surface temperatures were colder then normal with anomalies in May and June of around -1.5°C (Fig. 15). The annual temperature anomaly in 1997 at the surface was approximately -0.23°C. This represented a decrease from 1996 but well above the low temperatures of the early 1990s. Temperature trends at the surface at Station 27 generally match those at other depths but with greater amplitude variability and more month-to-month fluctuations.

Gulf of Maine, Scotian Shelf and Gulf of St. Lawrence

Some of the inner Bay of Fundy stocks do not migrate to the Labrador Sea area but instead are believed to stay in the Gulf of Maine region. Thus, knowledge of the temperature field in this area may also be very important. In addition, marine temperatures may be important during the migration from overwintering grounds to the rivers and back.

Monthly averages of sea surface temperature (SST) in 1997 derived from continuous thermograph records or twice daily readings were available from Boothbay Harbor in Maine, St. Andrews in New Brunswick and Halifax in Nova Scotia. The dominant feature in 1997 at Boothbay Harbor and St. Andrews was the above normal temperatures throughout most of the year (8 out of the 12 months at both sites) which continues a trend of warm temperatures that began in June of 1994. The 1997 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 monthly anomaly was near 1.9°C in January at Boothbay while at St. Andrews it was 0.8°C in October. The lower amplitude anomalies at St. Andrews compared to Boothbay are typical, due to the increased vertical mixing by the tides in the Bay of Fundy. In contrast to the Gulf of Maine sites, at Halifax negative sea surface temperature anomalies dominated with 7 of the 12 months being colder-than-normal including March to July inclusive (Fig. 16). These cold anomalies also continue a trend observed at Halifax over the last several years. Temperatures are rising at Halifax, however, with an increasing number of months with positive temperature anomalies compared to recent past years. Only in 2 months did the temperature anomaly at Halifax exceed the long-term standard deviations, those occurring in May and July.

Time series of annual anomalies show that the surface temperature at both Boothbay Harbor and St. Andrews have been above their long-term means in recent years and generally on the increase since a minimum in the late 1980s (Fig. 16). This minimum was as low as that of the mid-1960s at St. Andrews but at Boothbay Harbor the minimum was only slightly below normal. Consistent with the 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 the temperature had fallen relative to 1996 and the recent peak in 1995. This decrease is consistent with the observed year-to-year variability and can not yet be construed as indicative of a downward trend in surface temperatures at longer time scales. In contrast, Halifax temperatures have been below normal since the mid-1980s although there has been a slow but steady warming since the early 1990s. The 1997 annual sea-surface temperature at Halifax was 7.8°C producing an anomaly relative to the 1961-90 mean of -0.2°C.

Temperature and salinity data have also been monitored once per month at Prince 5, a station at the mouth of the Bay of Fundy since the 1920s. Surface temperature anomalies at this station during 1997 showed a somewhat similar pattern to those at St. Andrews. Monthly temperature anomalies were above normal in the winter and into the spring, were below normal in the late spring and early summer and then rose to above normal in the last four months of the year (Fig. 17). Note that no data were available in March. The negative temperature anomalies at Prince 5 were of larger amplitude, began a month later and persisted for longer than at St. Andrews. The annual anomaly was up slightly relative to 1996 but still was near normal. This was below the very warm temperatures in 1994 and above the cold temperatures of the early 1990s (Fig. 17). Prior to 1994, temperatures had been generally declining since the mid-1980s. The two dominant features in the Prince 5 temperature record are the very warm 1950s and the cold 1960s. Similar temperature patterns have been seen in the waters from the Laurentian Channel to the Middle Atlantic Bight (Petrie and Drinkwater, 1993).

Surface salinities at Prince 5 during 1997 were fresher-than-normal during January and February by over 0.5 psu (Fig. 17). By the spring salinities were above normal, again fell below during the summer and by the end of the year were slightly more salty then the long-term mean. Time series show that the annual salinity anomalies in 1997 rose by approximately almost 0.4 relative to 1996 values at the surface (Fig. 17). The 1996 anomalies represented the lowest salinities ever recorded at Prince 5. The decline in salinity has been occurring since the late 1970s. The recent low values parallel salinity events occurring in the deep waters of Jordan and Georges Basin and appear to be related to advection from areas further to the north (P. Smith, BIO, personal communication).

Good spatial coverage of the temperatures in our coastal waters from ship surveys are rare. However, the summer groundfish surveys in July on the Scotian Shelf and in September for the southern Gulf of St. Lawrence are exceptions. Extensive CTD (conductivity-temperature-depth) profiles are taken. We interpolated these temperature data onto a standardized grid that is 0.2° by 0.2° of latitude and longitude for the Scotian Shelf and 0.1° by 0.1° in the Gulf of St. Lawrence. The temperatures at the surface were contoured and anomalies from the long-term 1961-90 mean determined. The July survey shows surface temperatures of 13° to 16°C over most of the shelf with the warmest waters on Sydney Bight and in the central Shelf region (Fig. 18). The coldest temperatures (<9°C) were found at the mouth of the Bay of Fundy. These reflect enhanced vertical mixing due to the strong tidal currents and high tidal elevations. Note that no data were collected on the Lurcher Shoals during this survey. Temperature anomalies at the surface show generally weak, spatially-varying anomalies except in the Bay of Fundy which was below normal by greater than 1°C (Fig. 18).

In contrast to the Scotian Shelf in July, the surface waters in the southern Gulf of St. Lawrence during September were warmer than normal over most of the Magdalen Shallows (Fig. 19). Temperatures ranged from 13°C off the Gaspe to 17°C in St. Georges Bay, Nova Scotia. Over most of the Magdalens temperatures were 15°-17°C. This represented positive anomalies of up to 4°C and generally greater than 2°C in the northern half of the Shallows (Fig. 19). Negative anomalies were observed in eastern Northumberland Strait, off eastern Prince Edward Island and also along one section of its northern coast. Relative to 1996, September surface temperatures warmed in the northern half of the Shallows and especially off Cape Breton where very cold water had been observed in 1996. Colder temperatures were found around Prince Edward Island, especially the eastern end. One must remember, however, that surface temperatures and temperature anomalies can vary substantially on time scales of days to months.

Sea Surface Temperatures from Satellite Imagery

Patterns of sea surface temperature (SST) for the spring 1996 to spring 1997 period were generated from the MCSST (multi-channel SST) data set maintained by the Jet Propulsion Laboratory (JPL). These data are derived from the daytime passes of the NOAA series of polar orbiting weather satellites and are given as weekly SST averages on an 18° latitude by 18° longitude, equal angle grid (JPL.PODAAC Product 016) for the period of 1982 to the present. The accuracy of this data set is difficult to assess, but quoted values generally fall in the range of 0.5°-1.0°C. However, accuracy varies with both space and time, and a comprehensive examination has yet to be carried out for the region of interest here. Further information is contained in Dempson et al. (1998).

Cloud is opaque to infrared radiation, so that some areas suffer from low data return as will be clear in the figures. Compounding this problem is an uneven level of effort assigned by NOAA to various geographical regions. To overcome these limitations, we present SST images averaged over 3 month periods (beginning with winter defined as the Jan-Mar period).

Grand seasonal mean SSTs (Fig. 20-23) obtained by averaging over the full 16 year data set display the expected seasonal progression of SST due to atmospheric forcing. They also reveal a surprising amount of detail including: the cold Labrador Current that follows the Labrador and Newfoundland continental slopes; an isolated centre of relatively warm water over Flemish Cap that separates two branches of the Labrador Current; the cold East Greenland Current; and tidally induced upwelling of cold water along the southern Nova Scotian coast.

An example of an individual seasonal average (spring 1996) is shown in Fig. 24. Next to its obvious similarity to the mean spring field (Fig. 21), its most striking feature is the large number of pixels that had an insufficient number of passes to form a meaningful average (arbitrarily defined here as a minimum of 4 weeks per 13 week season). These pixels form a box-like pattern that is a direct result of the relatively low priority assigned to the Labrador Sea area by NOAA.

Figures 25-29 display SST anomalies for spring 1996 to spring 1997 defined relative to their respective long-term 1982-1997 means. In spring 1996 (Fig. 25), much of the Labrador Sea was warmer-than-normal (in some cases > 1°C) as were the Grand Banks and the northern Scotian Shelf. The southern Scotian Shelf and the Gulf of Maine, however, were cooler-than-normal, while the Gulf of St. Lawrence showed both warm and cold zones. Finally, the northern half of the North Atlantic was anomalously warm whereas the southern half was cool.

By summer (Fig. 26), most of the study area was warmer than average, with the exception of the Scotian Shelf/Gulf of Maine. Most of these warm areas disappeared by autumn (Fig. 27) although the northern half of the North Atlantic remained warm. The Scotian Shelf/Gulf of Maine continued cooler than normal whereas the Gulf of St. Lawrence remained warm. Data coverage in winter (Fig. 28) was poor, especially over the Labrador Sea. However, most of the region appeared to be warmer-than-normal including the Scotian Shelf/Gulf of Maine. Finally, in spring 1997 (Fig. 29) the northern North Atlantic, the Labrador Sea, and parts of the eastern Grand Banks were anomalously warm while the Scotian Shelf/Gulf of Maine returned to cooler-than-normal conditions.

Summary

During 1997, the wintertime large-scale atmospheric circulation (Icelandic Low and Bermuda-Azores High) remained weaker-than-normal for the second consecutive year. This resulted in a lower-than-average NAO index, and well below the high values of the earlier 1990s. Associated with the weakening of the Icelandic Low, the northwest winds would have been weaker-than-normal over the Labrador Sea and wintertime air temperatures were, on average, warmer-than-normal. Relative to 1996, the NAO index strengthened and air temperatures cooled. Notable was a significant change in winter air temperatures from very warm temperature anomalies in the first half of the season to very cold in the latter half. Ice formed late, but as cold conditions and strong winds developed during the latter half of the winter the ice spread quickly. Ice lasted longer-than-normal in much of the Gulf and on the Scotian Shelf but not on the Newfoundland and Labrador shelves. In spite of the long lasting ice the areal extent of ice on the Scotian Shelf was below normal. During spring, air temperature anomalies were generally below normal during 1997, consistent with the air pressure pattern and weaker northwest winds over the Labrador Sea. During the summer, air temperatures anomalies tended to be relatively small, fluctuated about their long-term means, and varied spatially.

In 1997, from *in situ* measurements of near surface temperatures at Station 27 off St. John's, warmer-than-normal conditions during the early winter were replaced by cool temperatures in spring and summer. This represents a cooling from the warm conditions of 1996 but much warmer than the early 1990s. In the Gulf of Maine and Bay of Fundy, annual temperatures were near to slightly above normal, although the spring was cooler-than-normal by upwards of 1°C. Seasonal sea surface temperature patterns were extracted from the MCSST data set. Anomalies in various regions varied in sign throughout the year, but much of the offshore North Atlantic and Labrador Sea was warmer-than-normal for most of the year. Over the continental shelves, the Grand Banks was relatively warm while the Scotian Shelf/Gulf of Maine region was characterized by both positive and negative anomalies, as was the Gulf of St. Lawrence.

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References

Battisti, D.S., U.S. Bhatt and M.A. Alexander. 1995. A modeling study of the interannual variability in the wintertime North Atlantic Ocean. J. Climate 8: 3067-3083.

Cayan, D.R. 1992. Latent and sensible heat flux anomalies over the northern oceans: the connection to monthly atmospheric circulation. J. Climate 5: 354-369.

Coté, P.W. 1989. Ice limits eastern Canadian seaboard. Environment Canada, Ottawa. 39 p. (Unpublished Manuscript)

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.

Dempson, J.B., D.G. Reddin, M.F. O'Connell, J. Helbig, C.E. Bourgeois, C. Mullins, T.R. Porter, G. Lilly, J. Carscadden, G.B. Stenson, and D. Kulka. 1998. Spatial and temporal variations in Atlantic salmon abundance in the Newfoundland-Labrador region with emphasis on factors that may have contributed to low returns in 1997. DFO Atl. Fish. Res. Doc. 98/114.

Drinkwater, K.F. 1996. Marine environmental conditions in the northwest Atlantic during 1995 potentially impacting Atlantic salmon (*Salmo salar*). DFO Atl. Fish. Res. Doc. 97/137.

Friedland, K.D., D.G. Reddin and J.F. Kocik. 1993. Marine survival of North American and European Atlantic salmon: effects of growth and environment. ICES J. mar. Sci. 50: 481-492.

Narayanan, S., J. Carscadden, J.B. Dempson, M.F. O'Connell, S. Prinsenberg, D.G. Reddin, and N. Shackell. 1995. Marine climate off Newfoundland and its influence on Atlantic salmon (*Salmo salar*) and capelin (*Mallotus villosus*), p. 461-474. *In* R.J. Beamish [ed.] Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

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., J.W. Loder, S. Akenhead and J. Lazier. 1992. Temperature and salinity variability on the eastern Newfoundland Shelf: The residual field. Atmosphere-Ocean 30: 120-139.

Reddin, D.G. and K.F. Friedland. 1993. Marine environmental factors influencing the movement and survival of Atlantic salmon. p. 79-103. *In* D. Mills [ed.] Salmon in the sea. Blackwell Sci. Pub., London, UK.

Reddin, D.G. and W.M. Shearer. 1987. Sea-surface temperature and distribution of Atlantic salmon in the northwest Atlantic Ocean. Amer. Fish. Soc. Symp. 1: 262-275.

Ritter, J.A. 1989. Marine migration and natural mortality of North American Atlantic salmon (*Salmo salar* L.). Can. Manu. Rep. Fish. Aquat. Sci. 2041.

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.

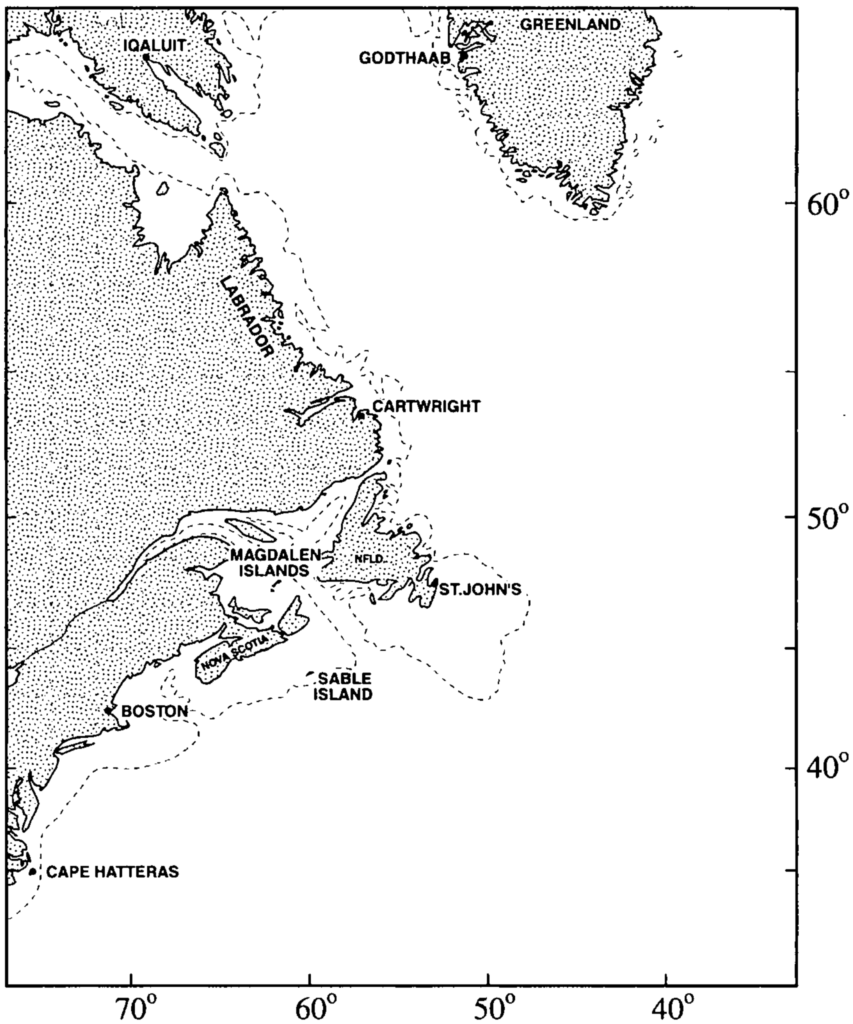

Fig. 1. Northwest Atlantic showing coastal air temperature stations.

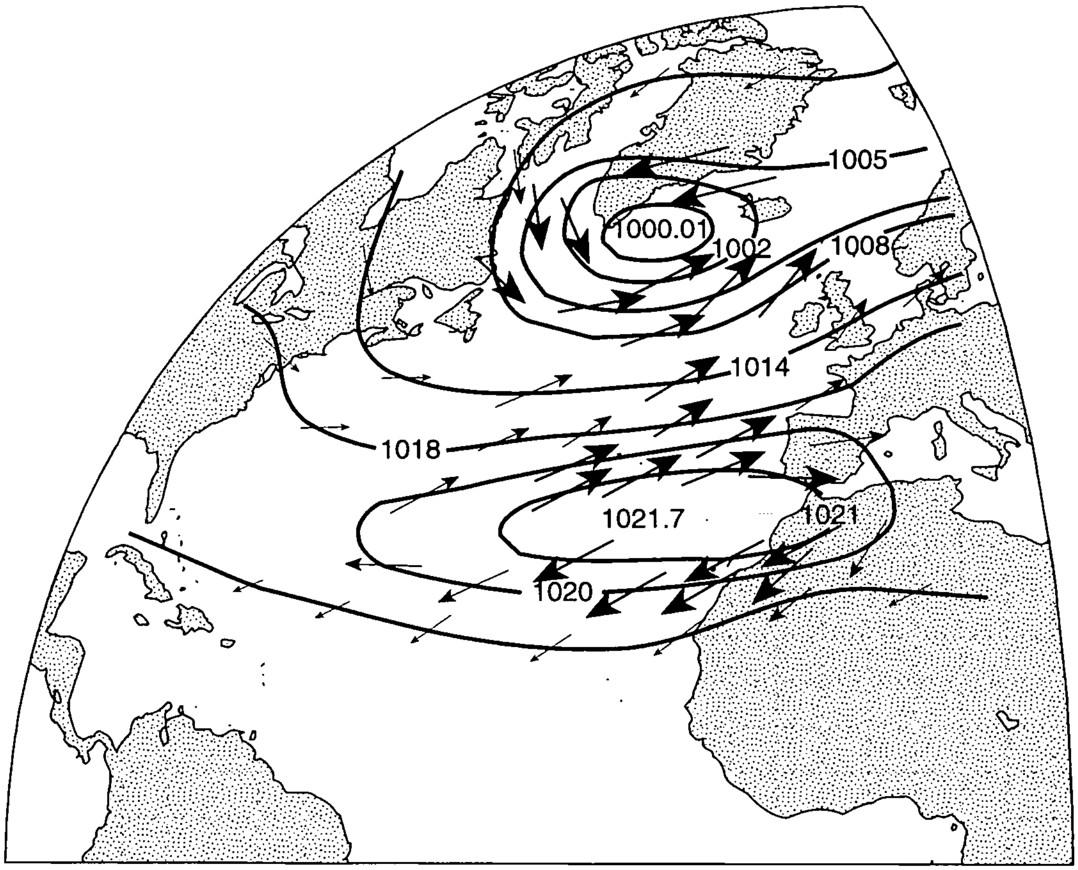

Fig. 2. Mean (1961-1990) sea surface pressure in winter showing the Icelandic Low in the north and Azores High in the south. Winds are shown schematically.

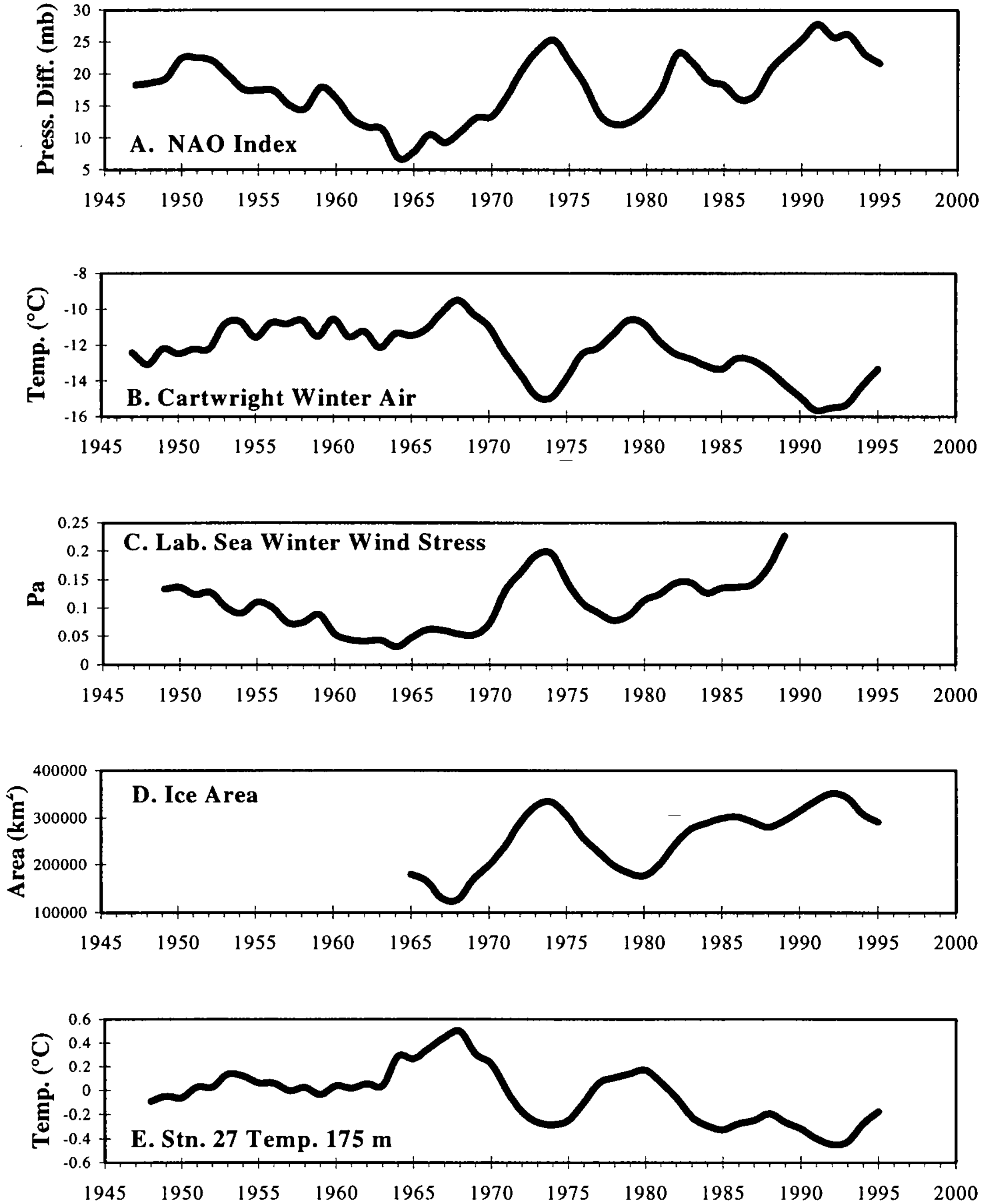

Fig. 3. The 5-y running mean of the annual values of the NAO index (A), the winter (January, February and March) air temperatures at Cartwright on the Labrador coast (B), the NW wind stress over the Labrador Sea (C), ice area off southern Labrador and Newfoundland in February (D) and near-bottom temperatures at Station 27 off St. John's, Newfoundland (E).

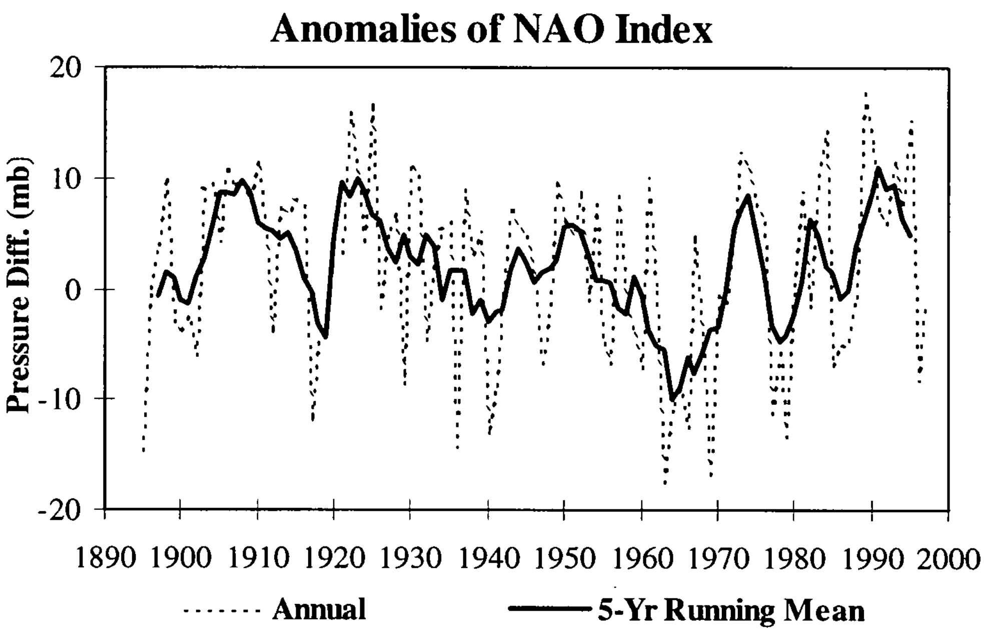

Fig. 4. Anomalies of the North Atlantic Oscillation (NAO) Index, defined as the winter (December, January, February) sea level pressure at Ponta Delgada in the Azores minus Akureyi in Iceland, relative to the 1961-90 mean.

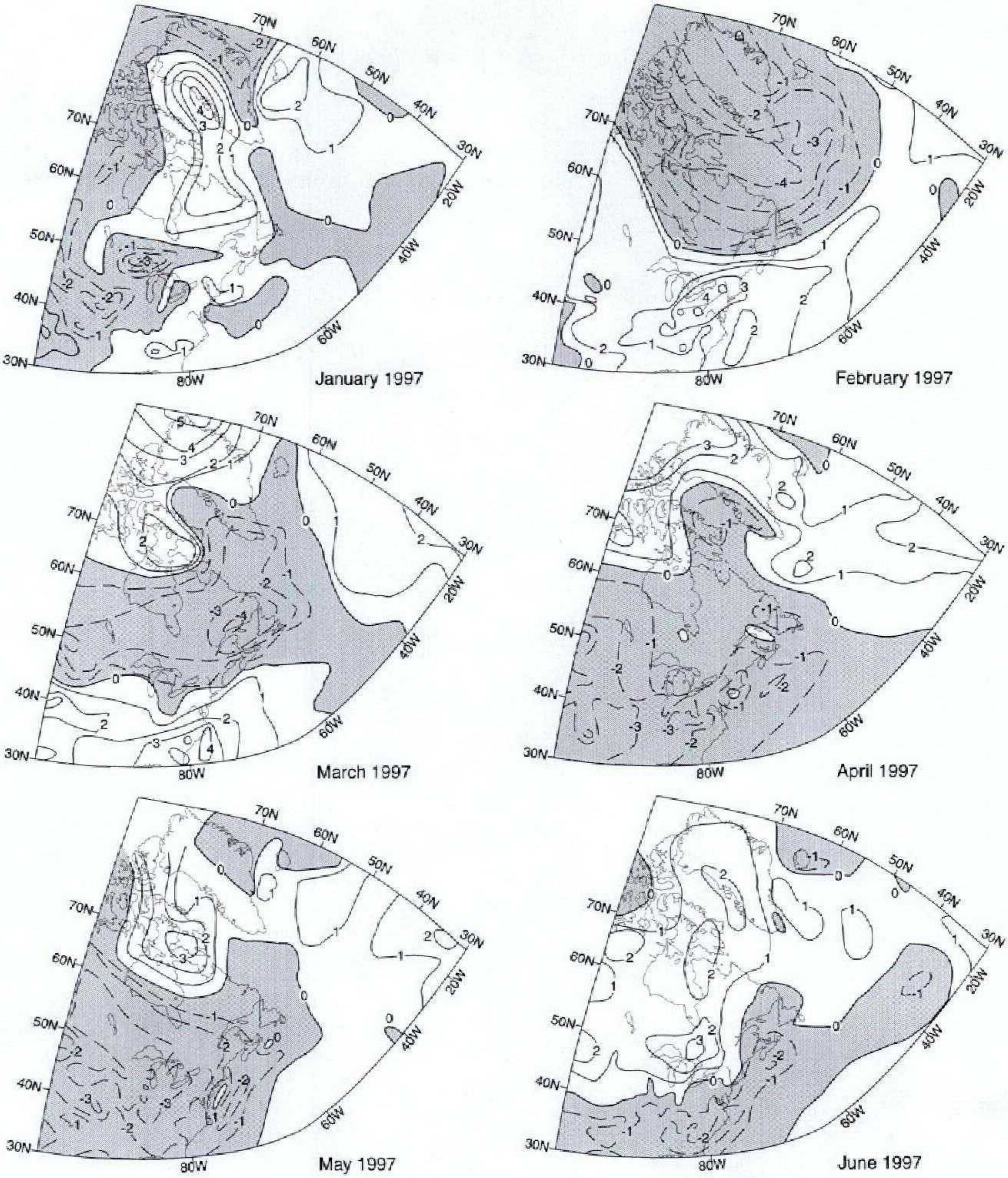

Fig. 5. Monthly air temperature anomalies (°C) over the Northwest Atlantic and eastern Canada in 1997 relative to the 1961-90 means. Shaded areas are negative anomalies. (From *Grosswetterlagen Europas*)

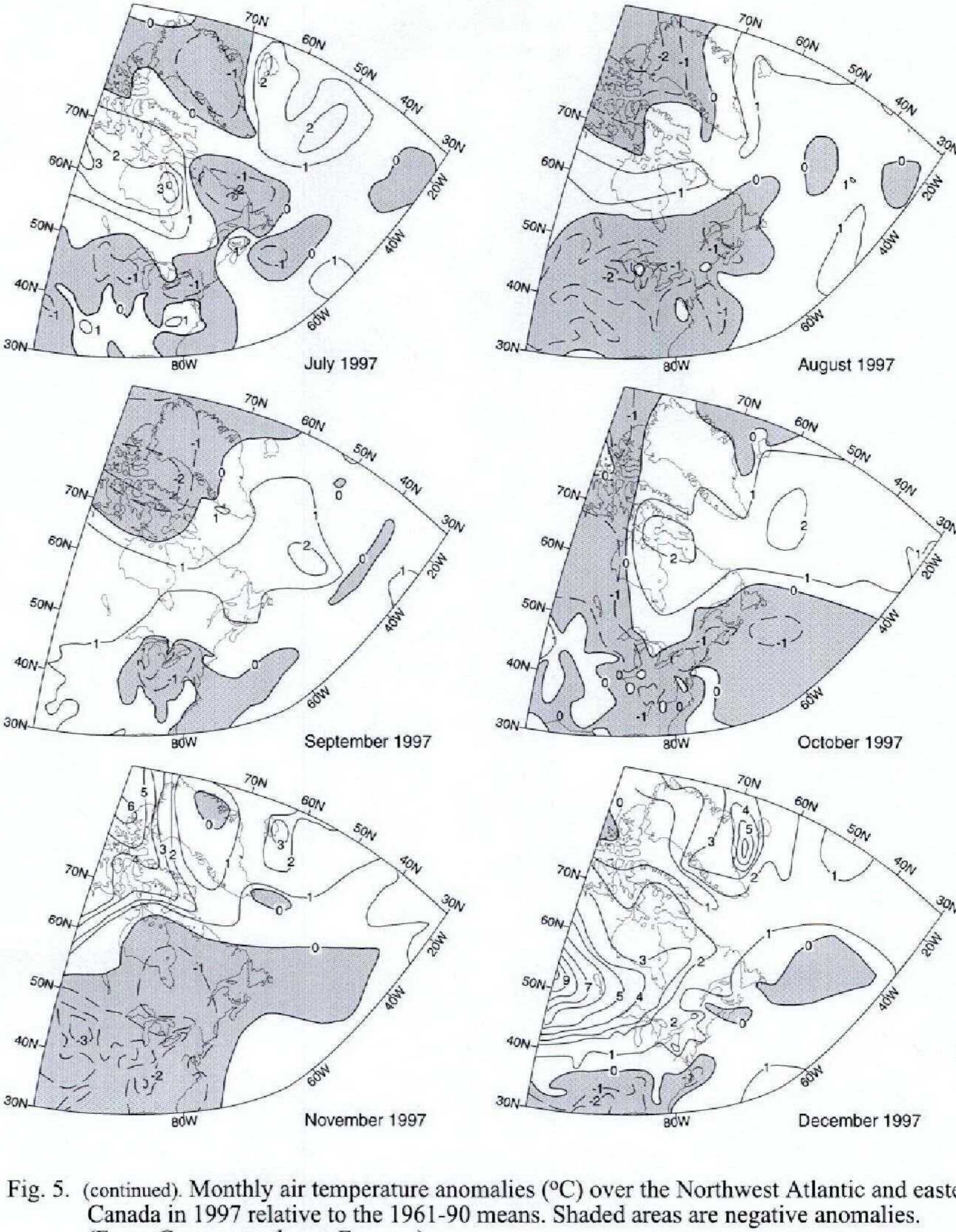

Fig. 5. (continued). Monthly air temperature anomalies (°C) over the Northwest Atlantic and eastern Canada in 1997 relative to the 1961-90 means. Shaded areas are negative anomalies. (From *Grosswetterlagen Europas*)

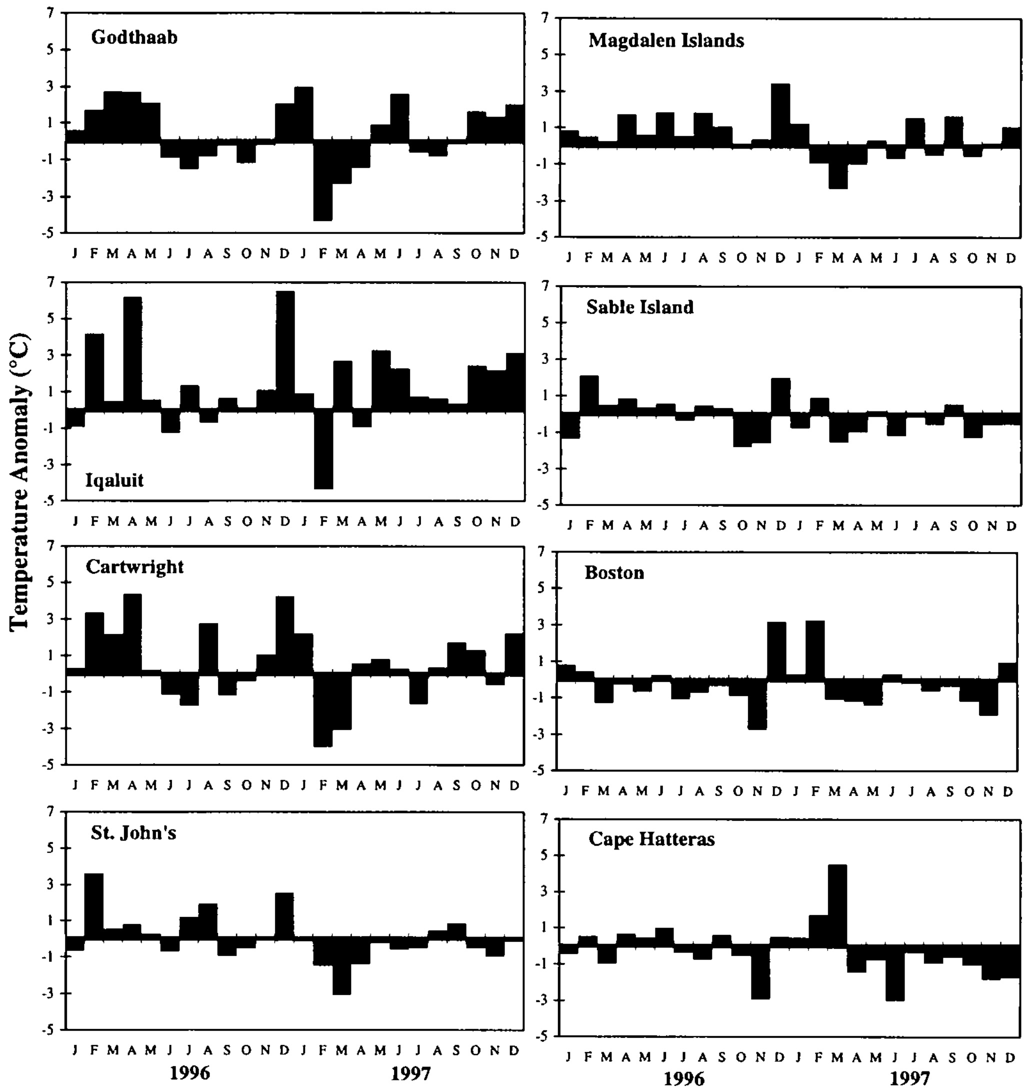

Fig. 6. Monthly air temperature anomalies in 1996 and 1997 at selected coastal sites (see Fig. 1 for locations.)

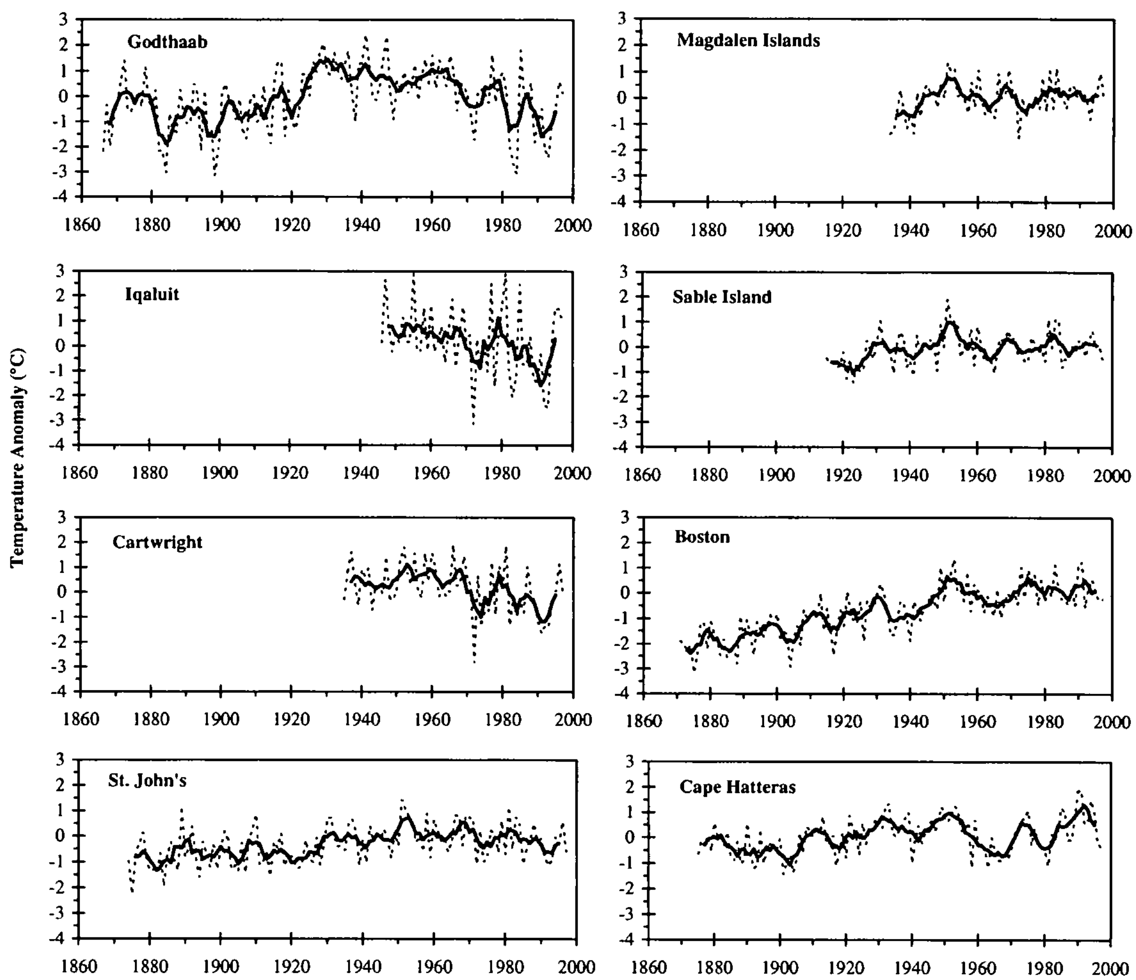

Fig. 7. Annual air temperature anomalies (dashed line) and 5-yr running means (solid line) at selected sites.

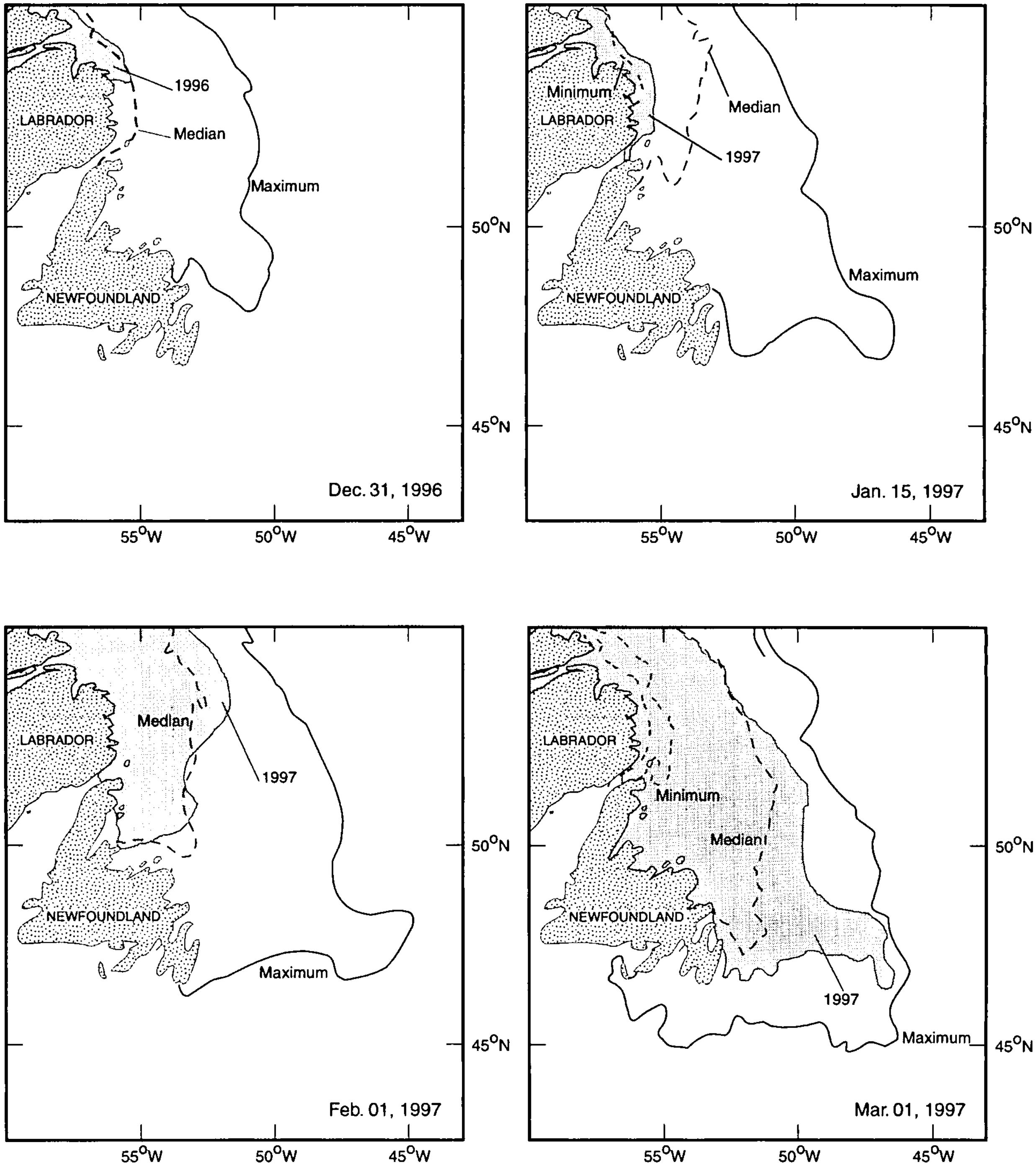

Fig. 8a. The location of the ice edge together with the historical (1962-1987) median and maximum positions off Newfoundland and Labrador between December 1996 and March 1997.

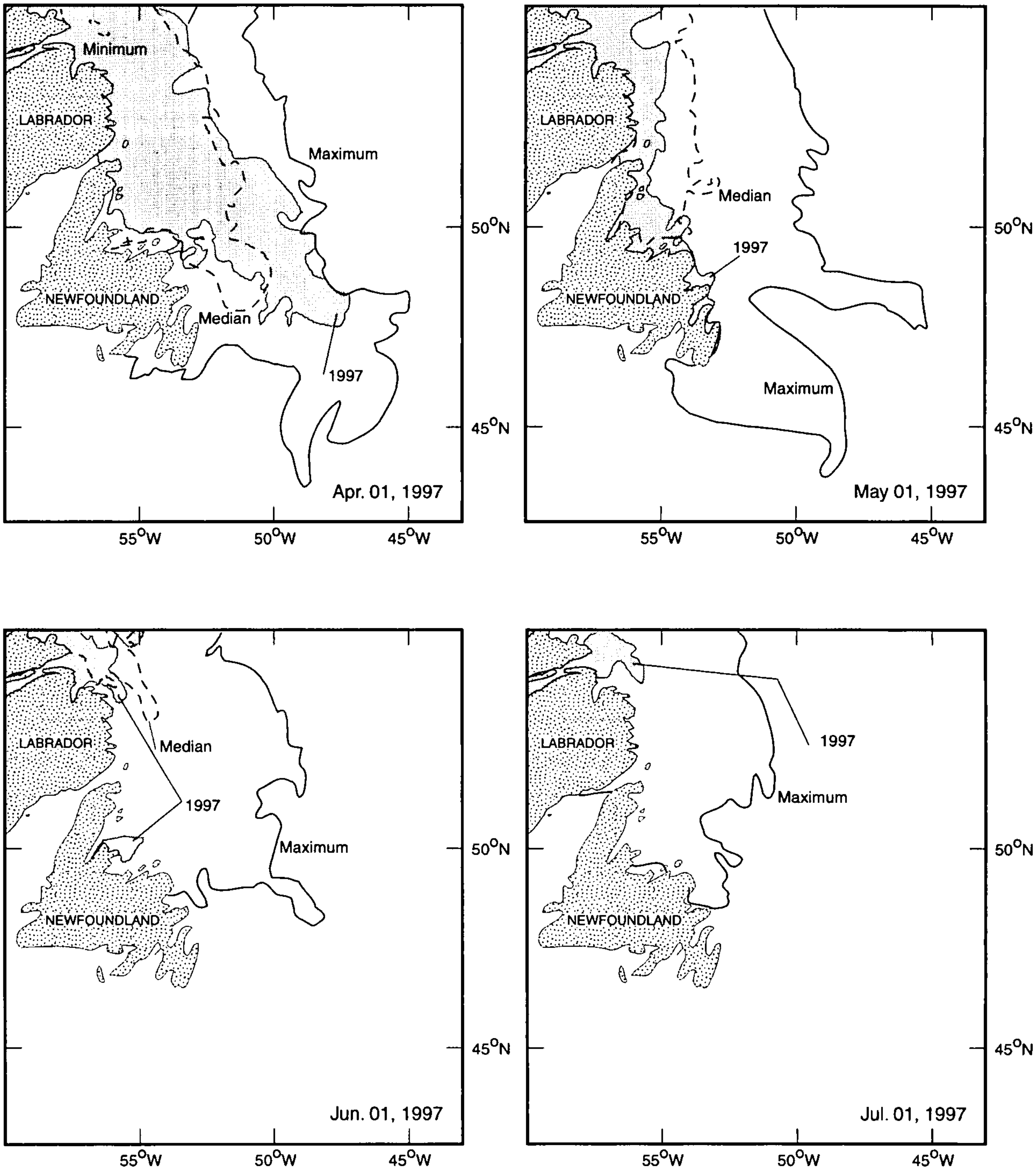

Fig. 8b. The location of the ice edge together with the historical (1962-1987) median and maximum positions off Newfoundland and Labrador between April and July 1997.

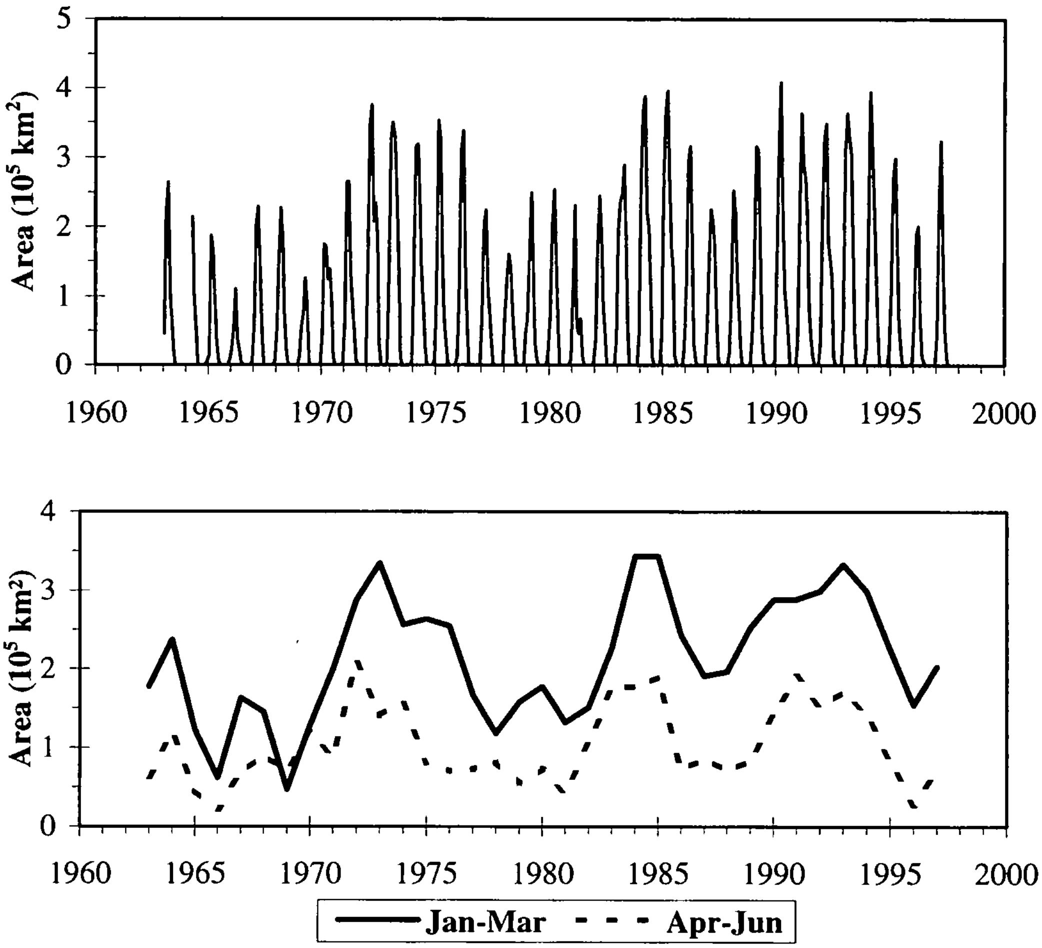

Fig. 9. Time series of the monthly mean ice area off Newfoundland and Labrador between 45°N-55°N (top panel) and the average ice area during January-March and April-June (bottom panel).

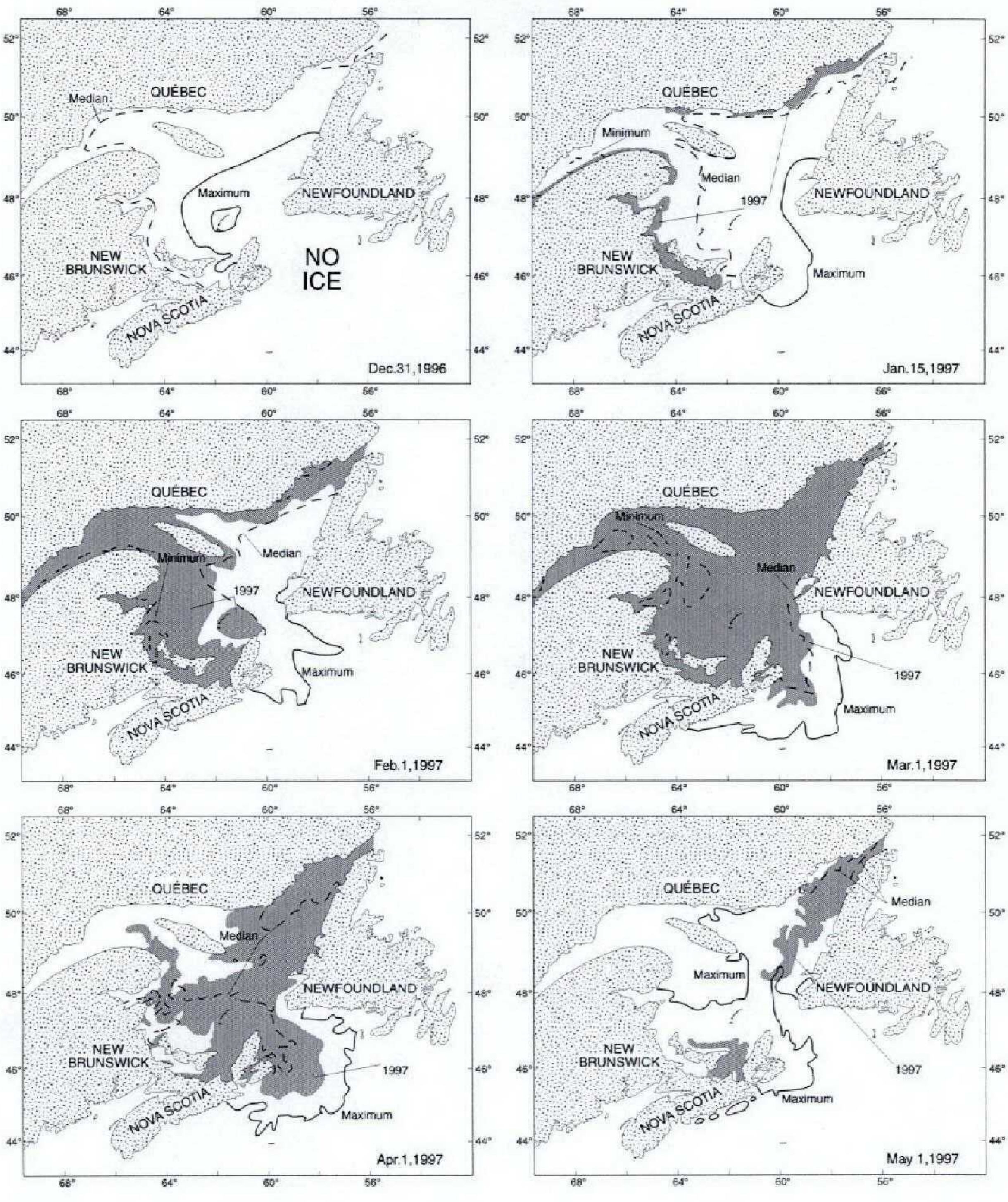

Fig. 10. The location of the ice edge together with the historical (1962-1987) median and maximum positions in the Gulf of St. Lawrence from December 1996 to May 1997.

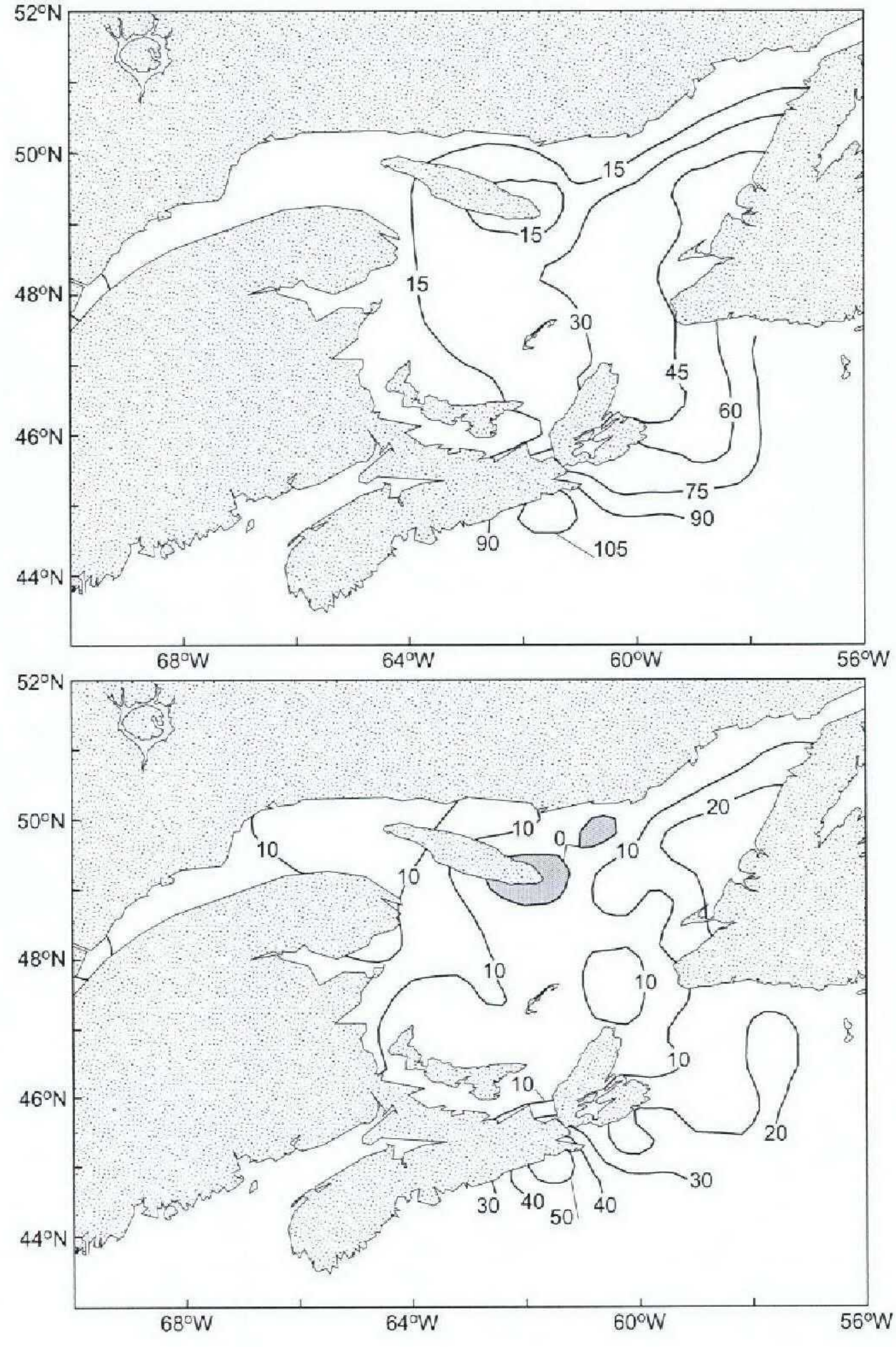

Fig. 11. The date at which ice first appears in the Gulf of St. Lawrence and the Scotian Shelf in days from the beginning of the year (top) and their anomaly in days from the long term mean (bottom). The shaded negative anomaly indicates ice appeared earlier-than-normal which is generally associated with a cold year.

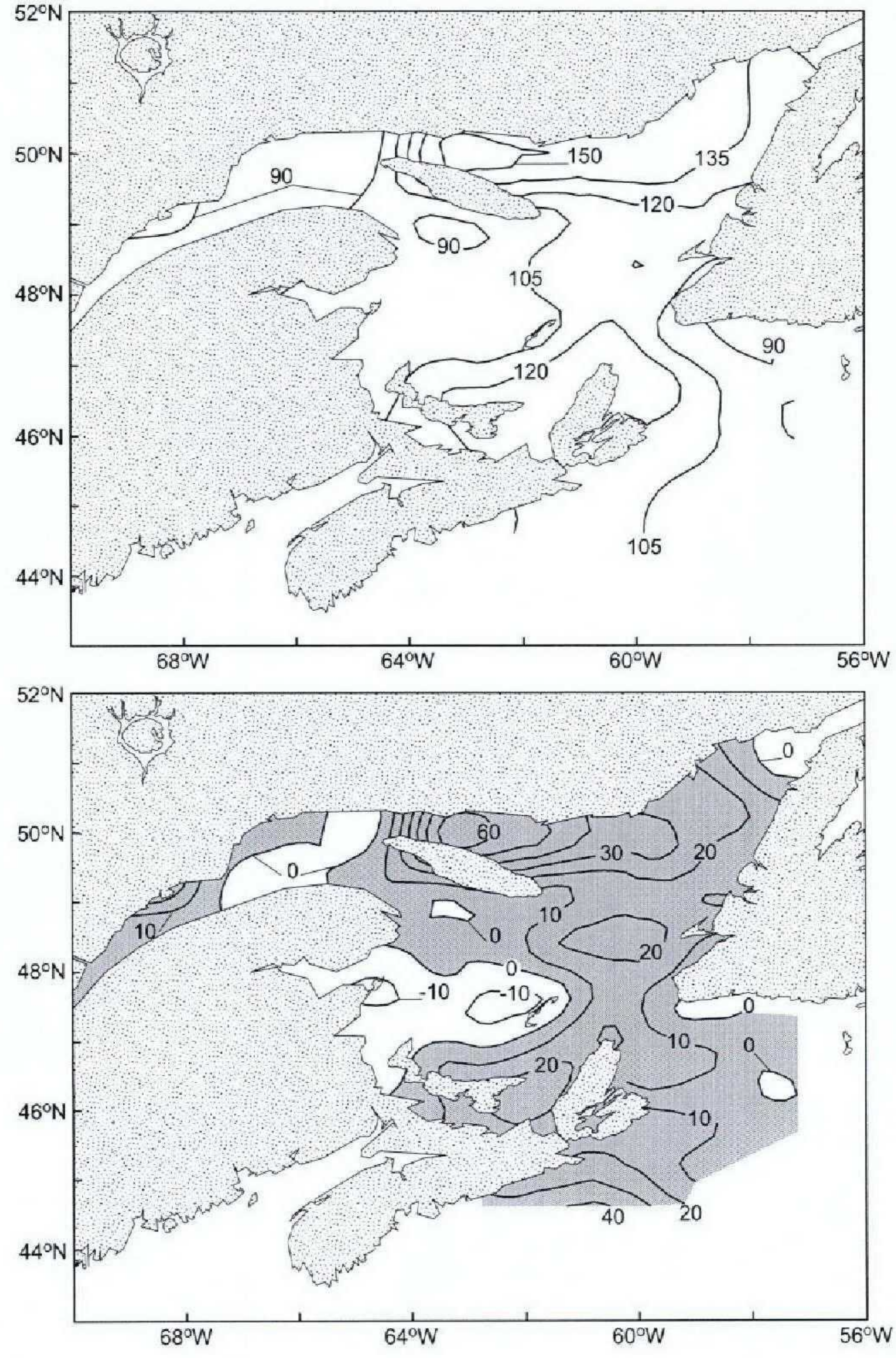

Fig. 12. The date at which ice last appears in the Gulf of St. Lawrence and the Scotian Shelf in days from the beginning of the year (top) and their anomaly in days from the long term mean (bottom). The shaded positive anomaly indicates ice lasted longer-than-normal which is generally associated with a cold year.

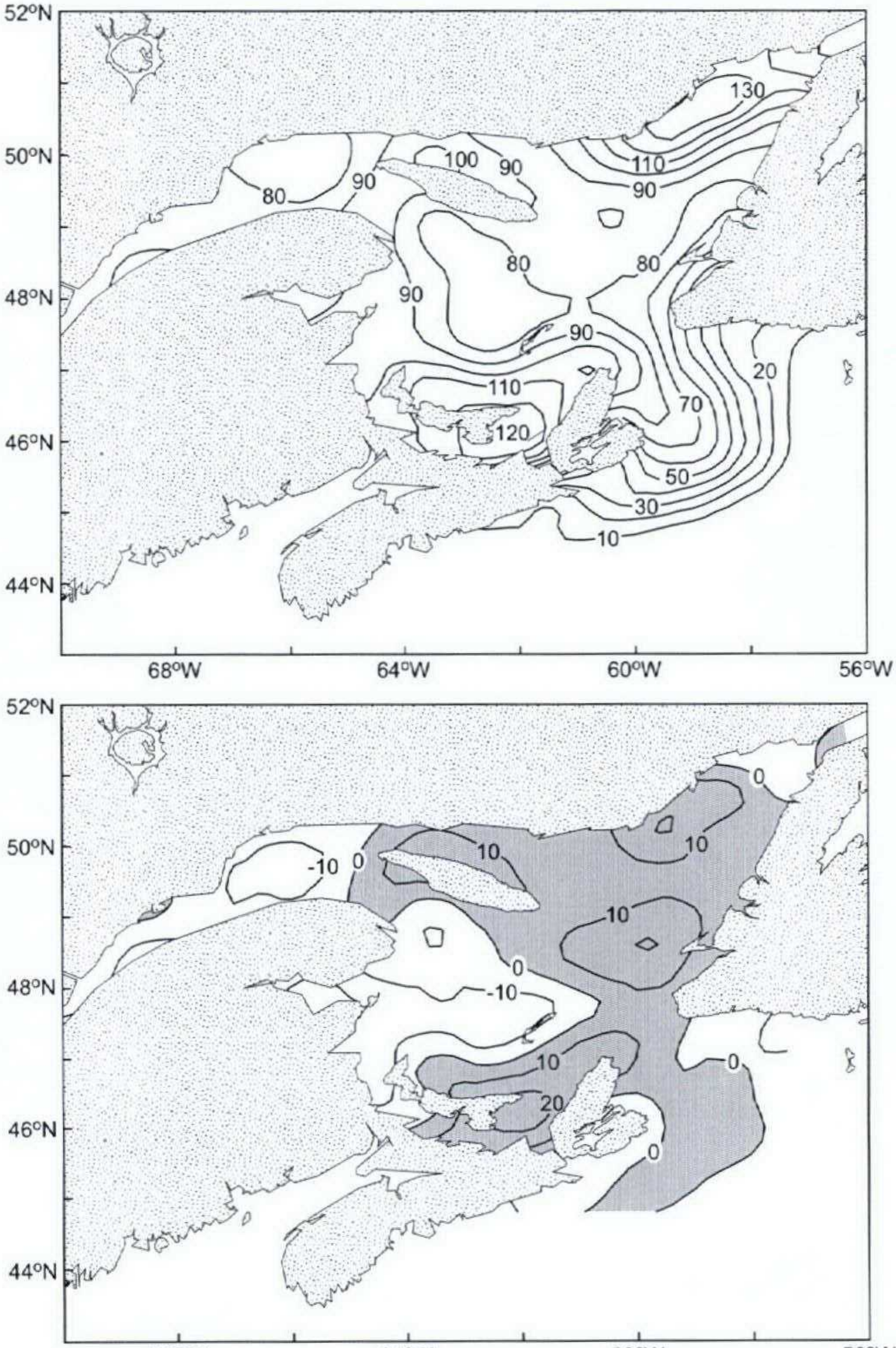

Fig. 13. The duration of ice in the Gulf of St. Lawrence and the Scotian Shelf in days (top) and their anomaly in days from the long term mean (bottom). The shaded positive anomaly indicates a duration longer than the mean which is generally associated with a cold year.

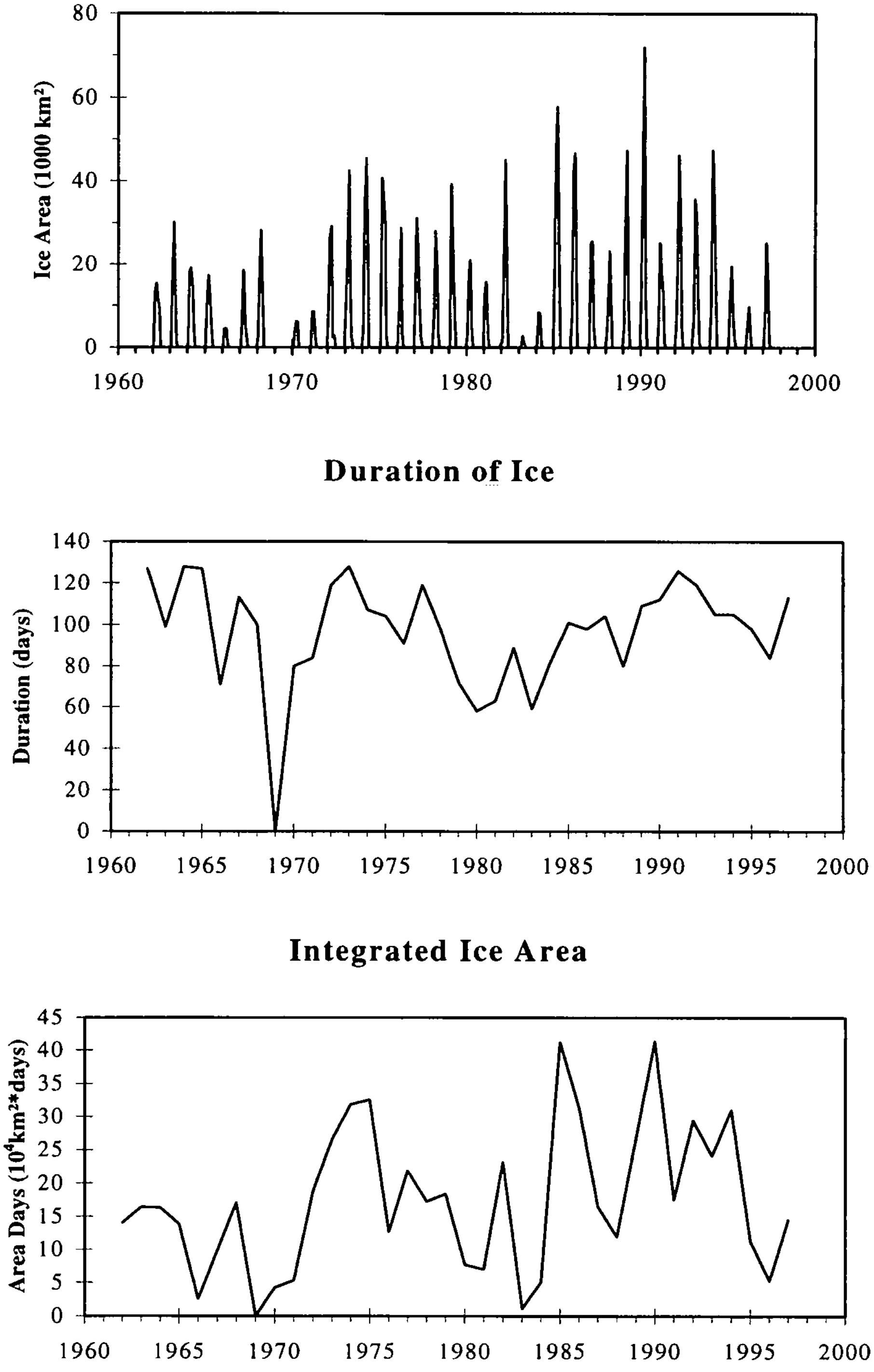

Fig. 14. For the region seaward of Cabot Strait, the time series of the monthly mean ice area (top panel), the duration of ice (middle panel) and the annual integrated ice area (summation of the area times the number of days; bottom panel).

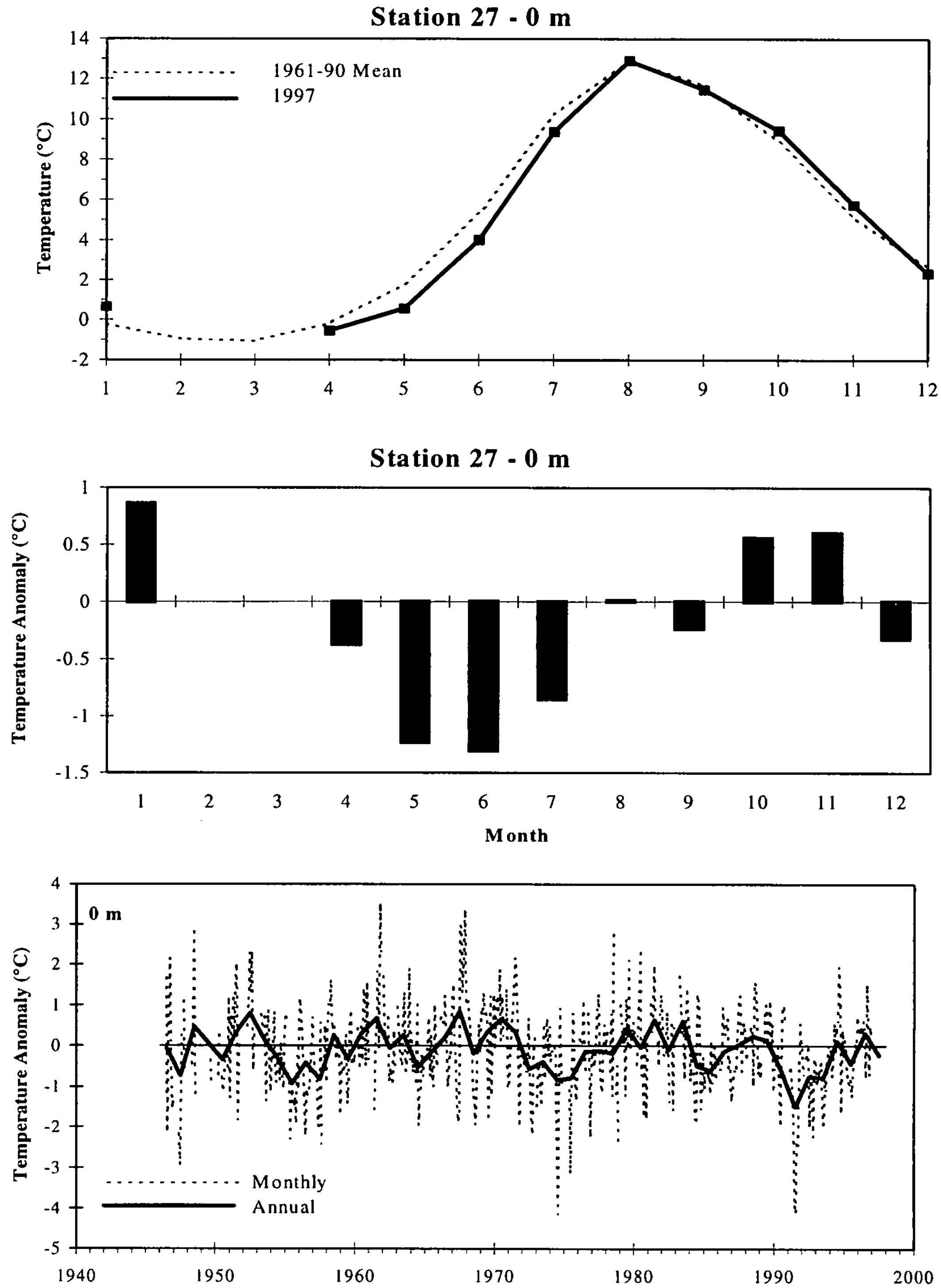

Fig. 15. The 1997 monthly means and long-term means (top panel), the 1997 monthly anomalies relative to the long-term means for 1961-90 (middle panel) and the time series of the monthly and annual means of temperature at Station 27 at the surface.

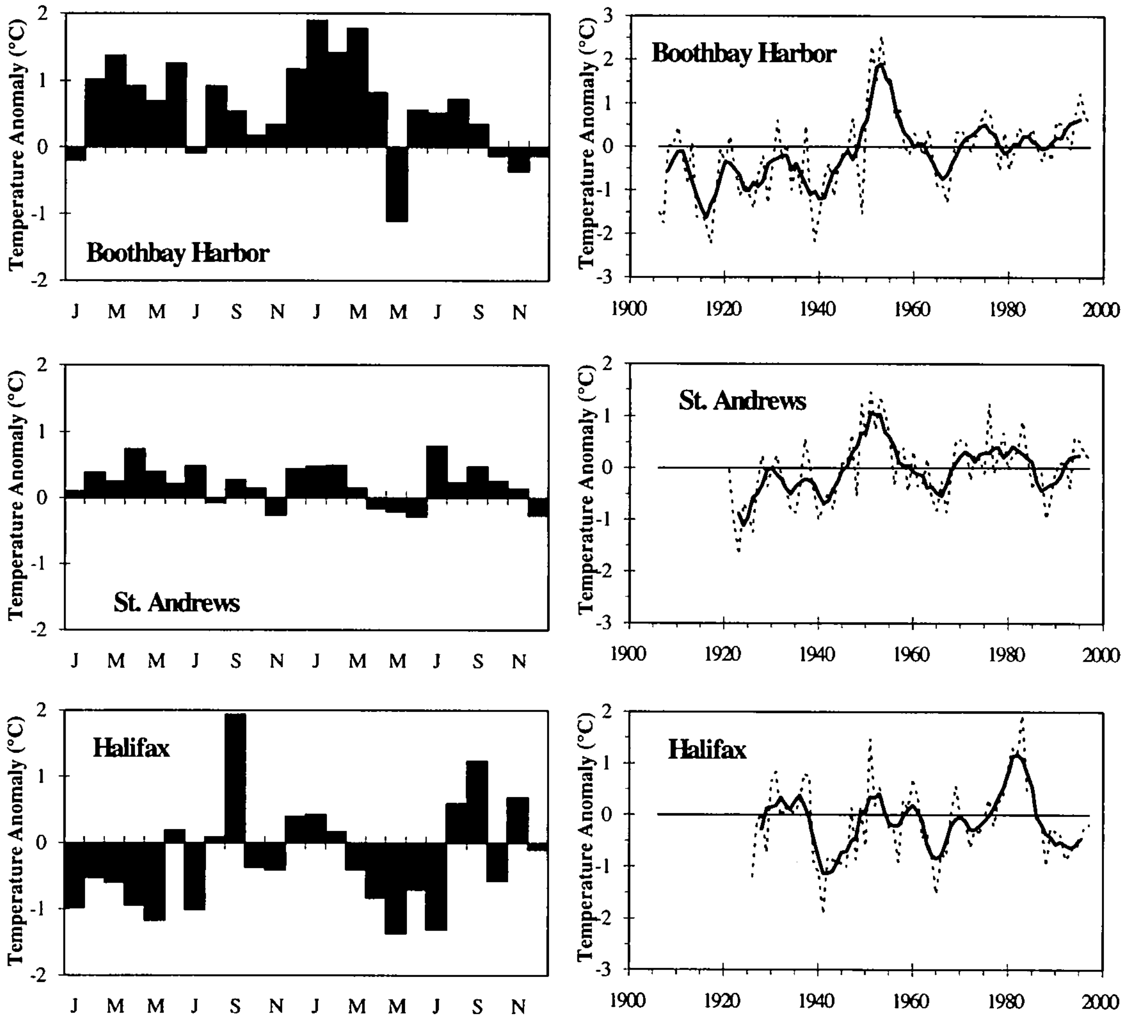

Fig. 16. The monthly sea surface temperature anomalies during 1996 and 1997 (left) and the annual temperature anomalies and their 5-year running means (right) for Boothbay Harbor, St. Andrews and Halifax. Anomalies are relative to the 1961-90 means.

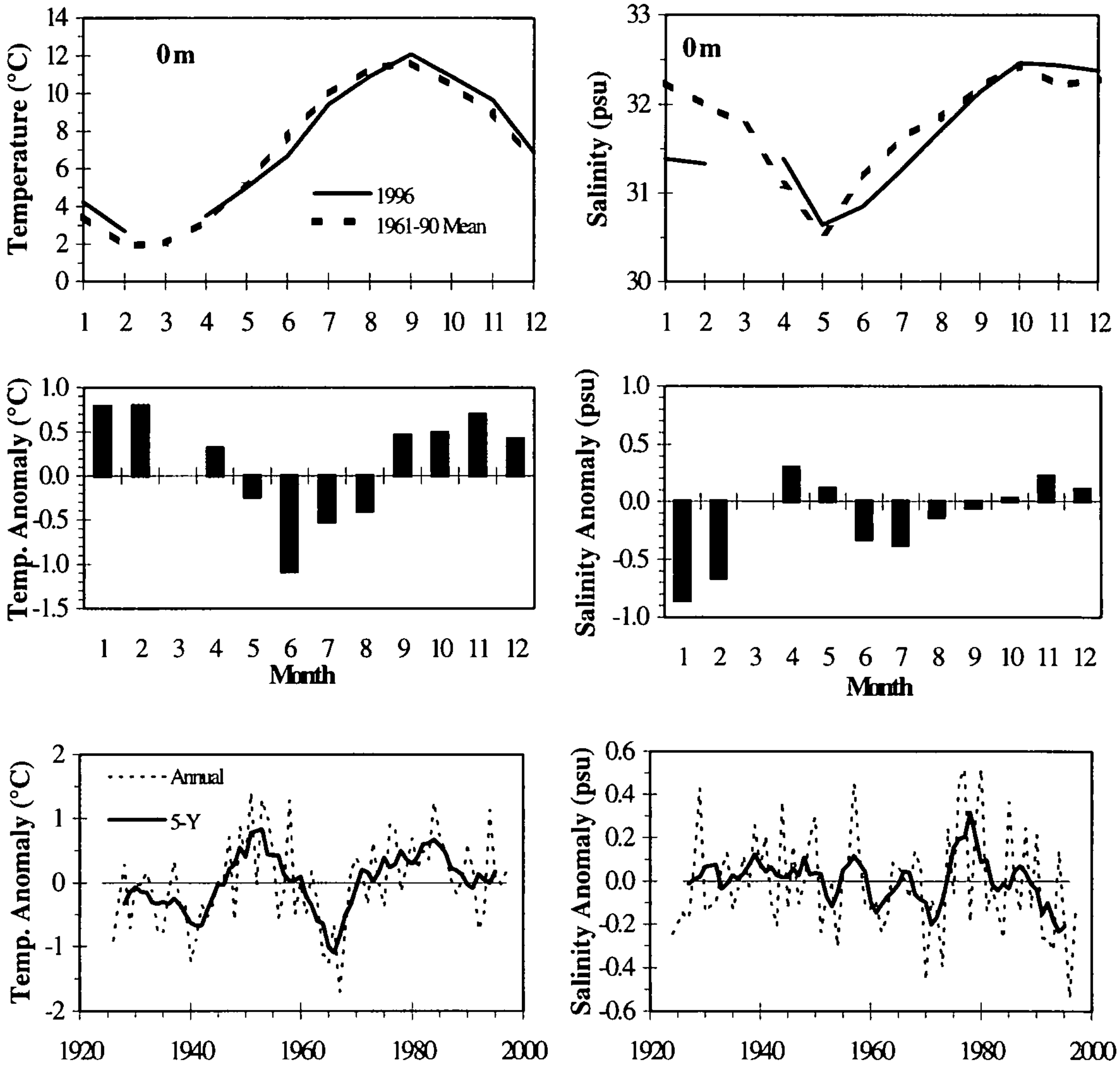

Fig. 17. The 1997 monthly means and long-term means (top panels), the 1997 monthly anomalies relative to the long-term means (middle panels) and the time series of the annual and 5-year running means of the annual anomalies for Prince 5 at the surface of temperature (left) and salinity (right)

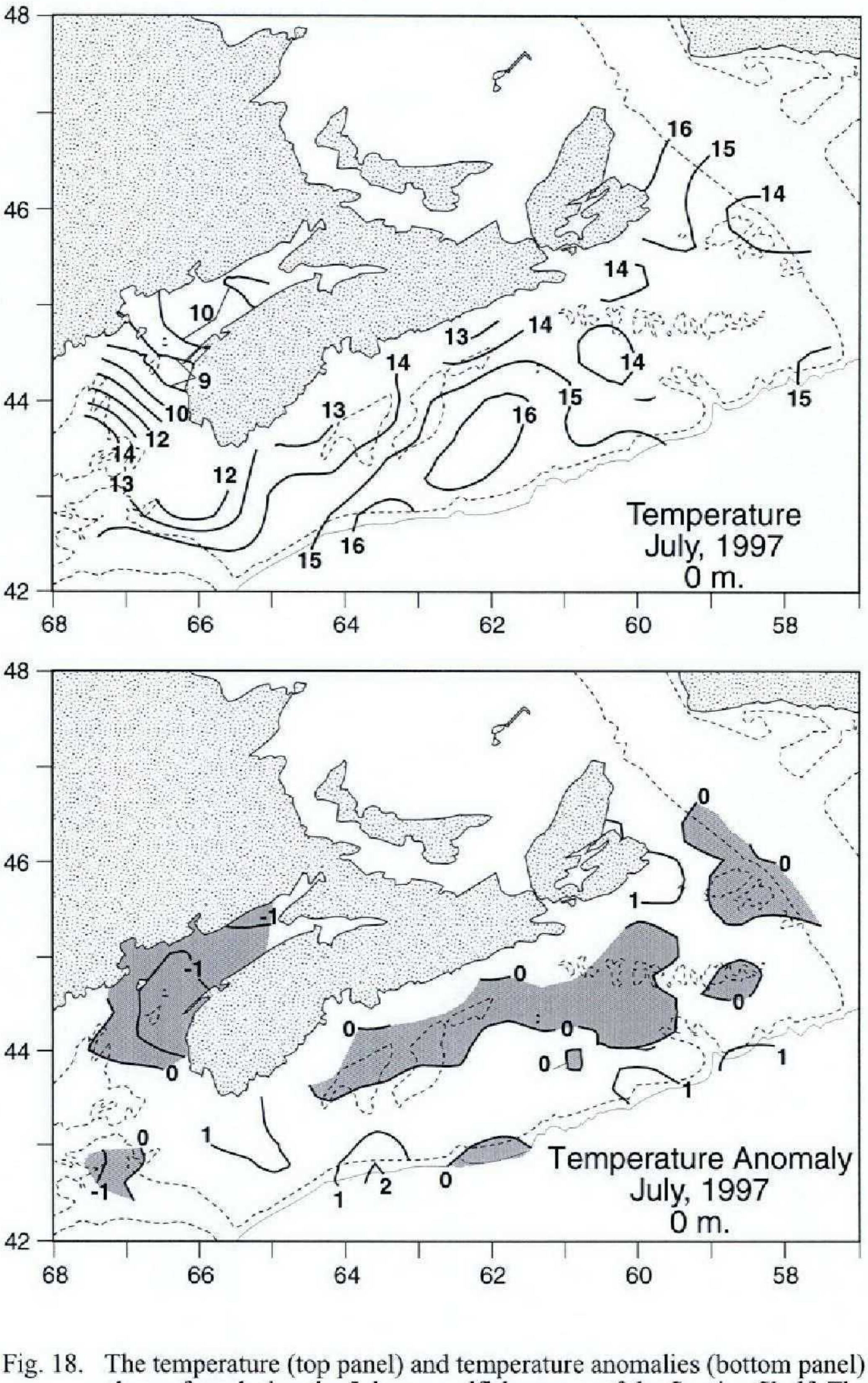

Fig. 18. The temperature (top panel) and temperature anomalies (bottom panel) at the surface during the July groundfish survey of the Scotian Shelf. The negative anomalies indicating colder-than-normal temperatures are shaded.

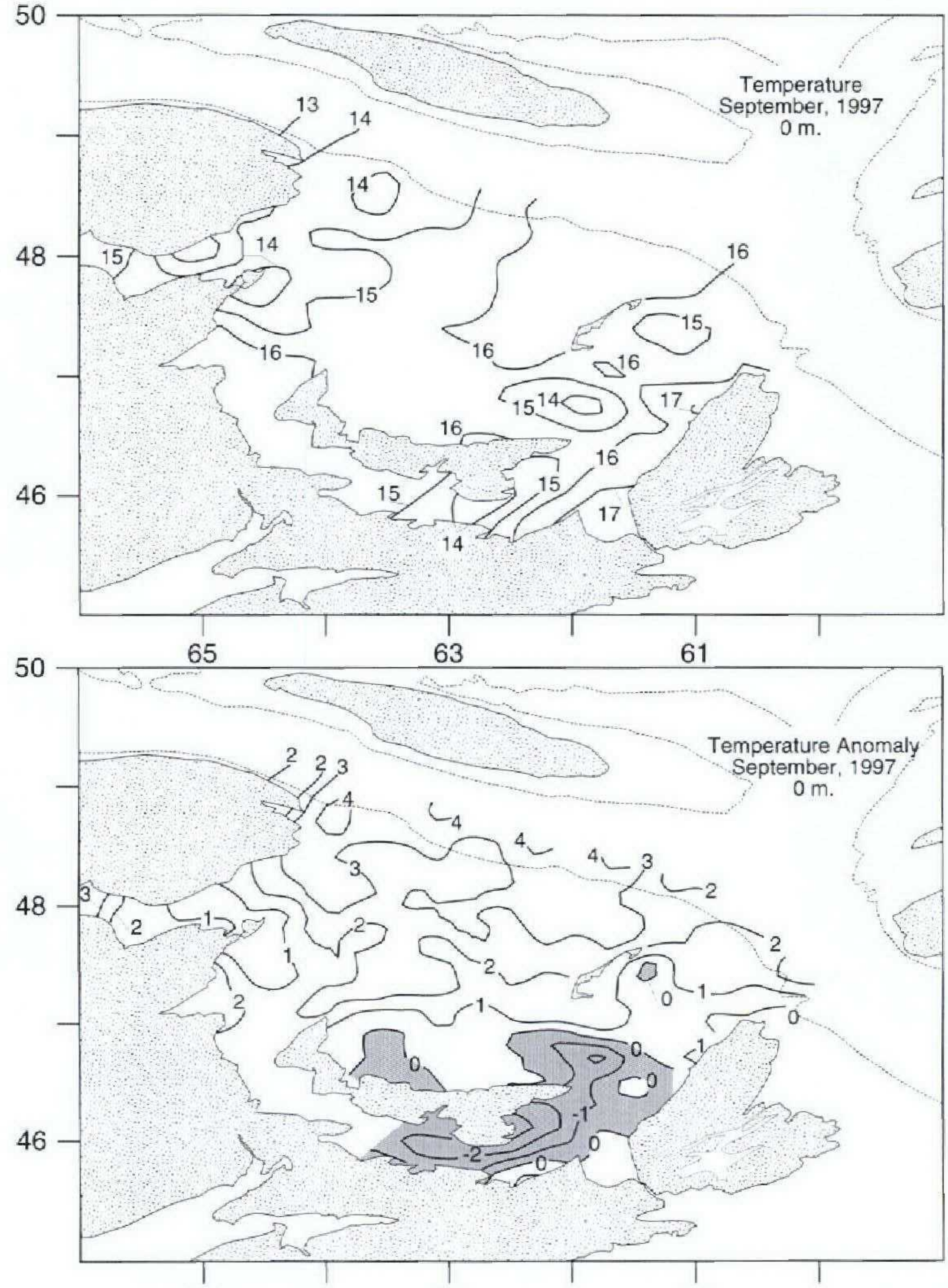

Fig. 19. The temperature (top panel) and temperature anomalies (bottom panel) at the surface during the September groundfish survey of the Magdalen Shallows. The negative anomalies indicating colder-than-normal temperatures are shaded.

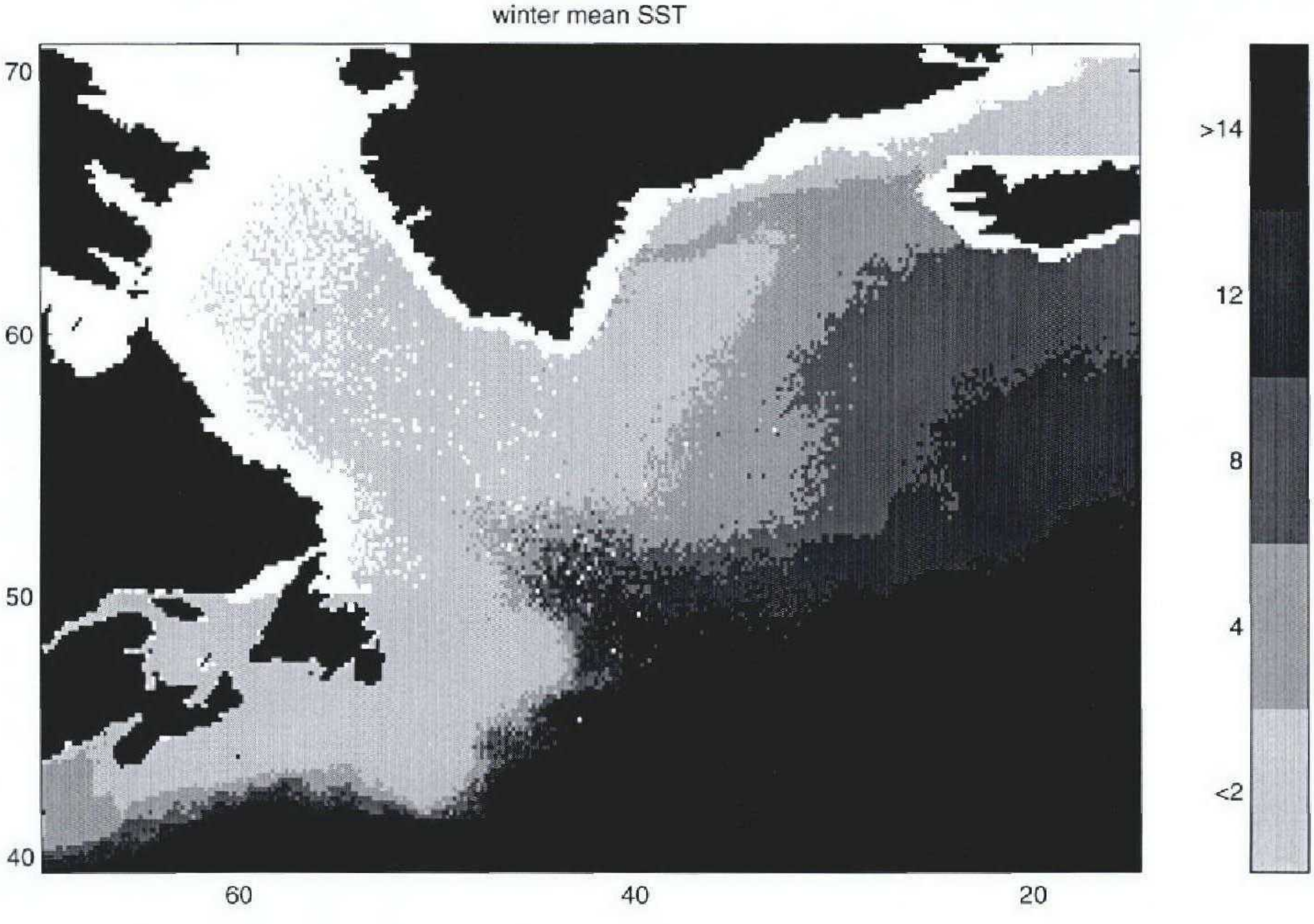

Fig. 20. Seasonal mean SSTs for winter derived from the full 1982-1997 MCSST data set.

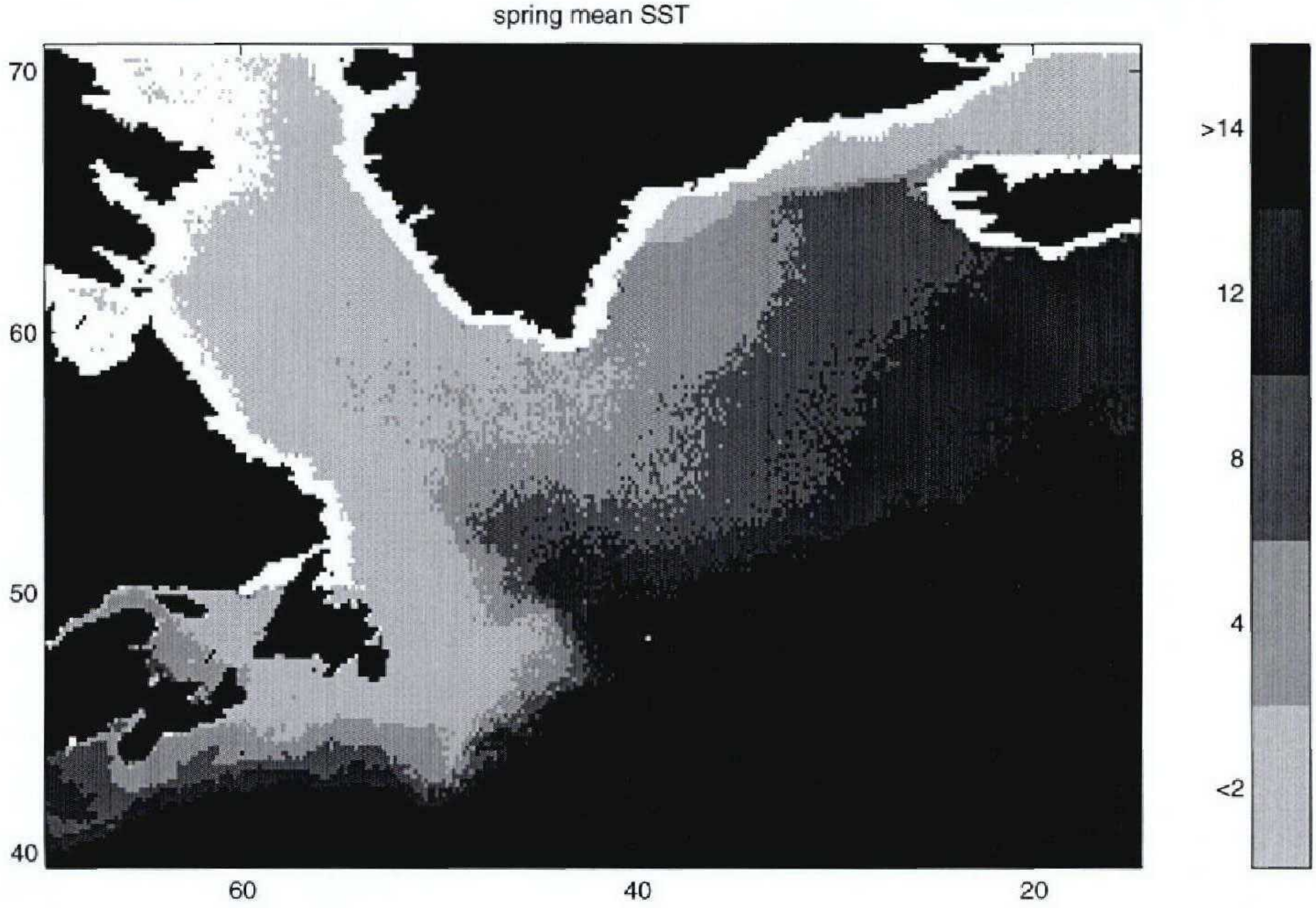

Fig. 21. Seasonal mean SSTs for spring derived from the full 1982-1997 MCSST data set.

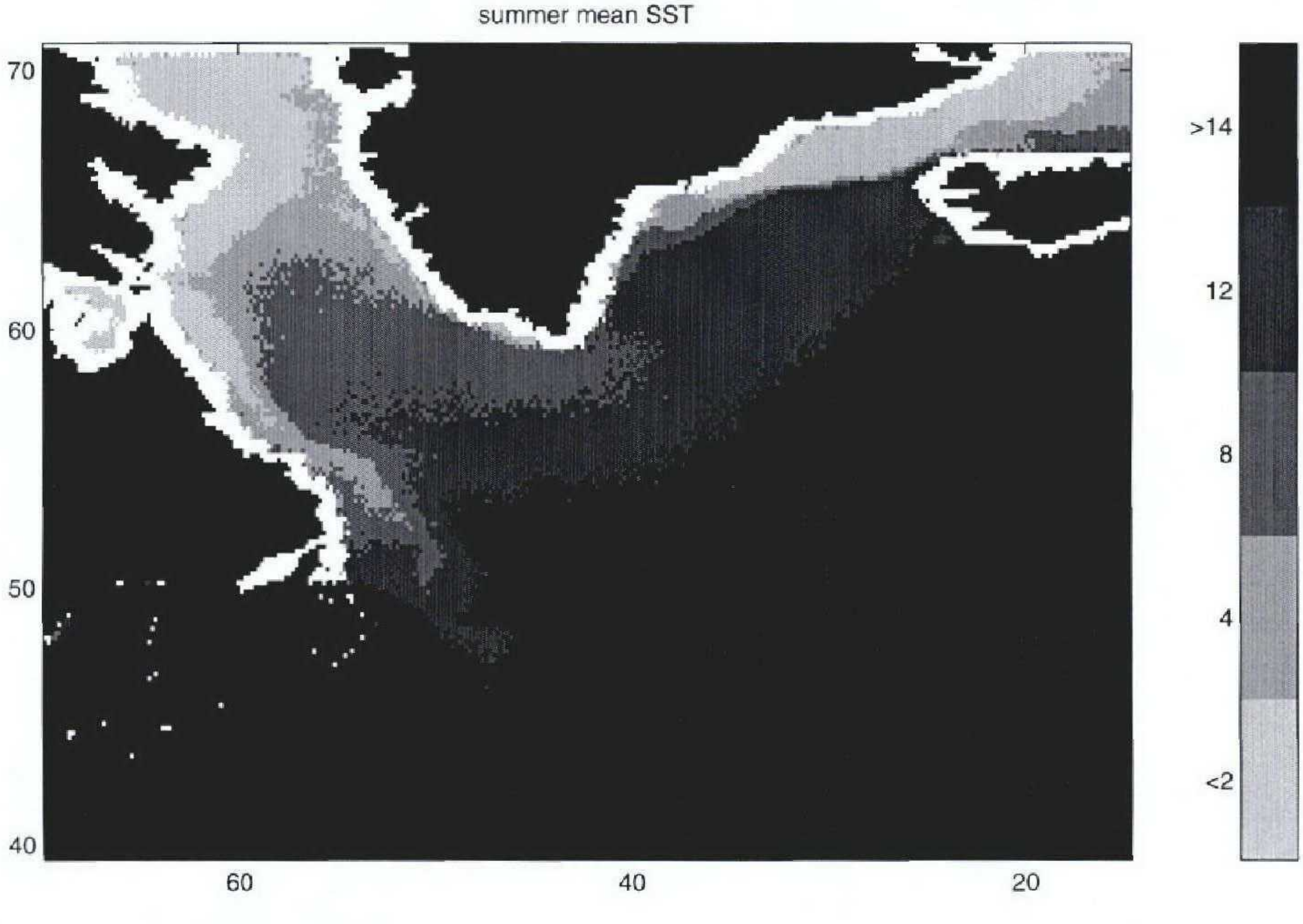

Fig. 22. Seasonal mean SSTs for summer derived from the full 1982-1997 MCSST data set.

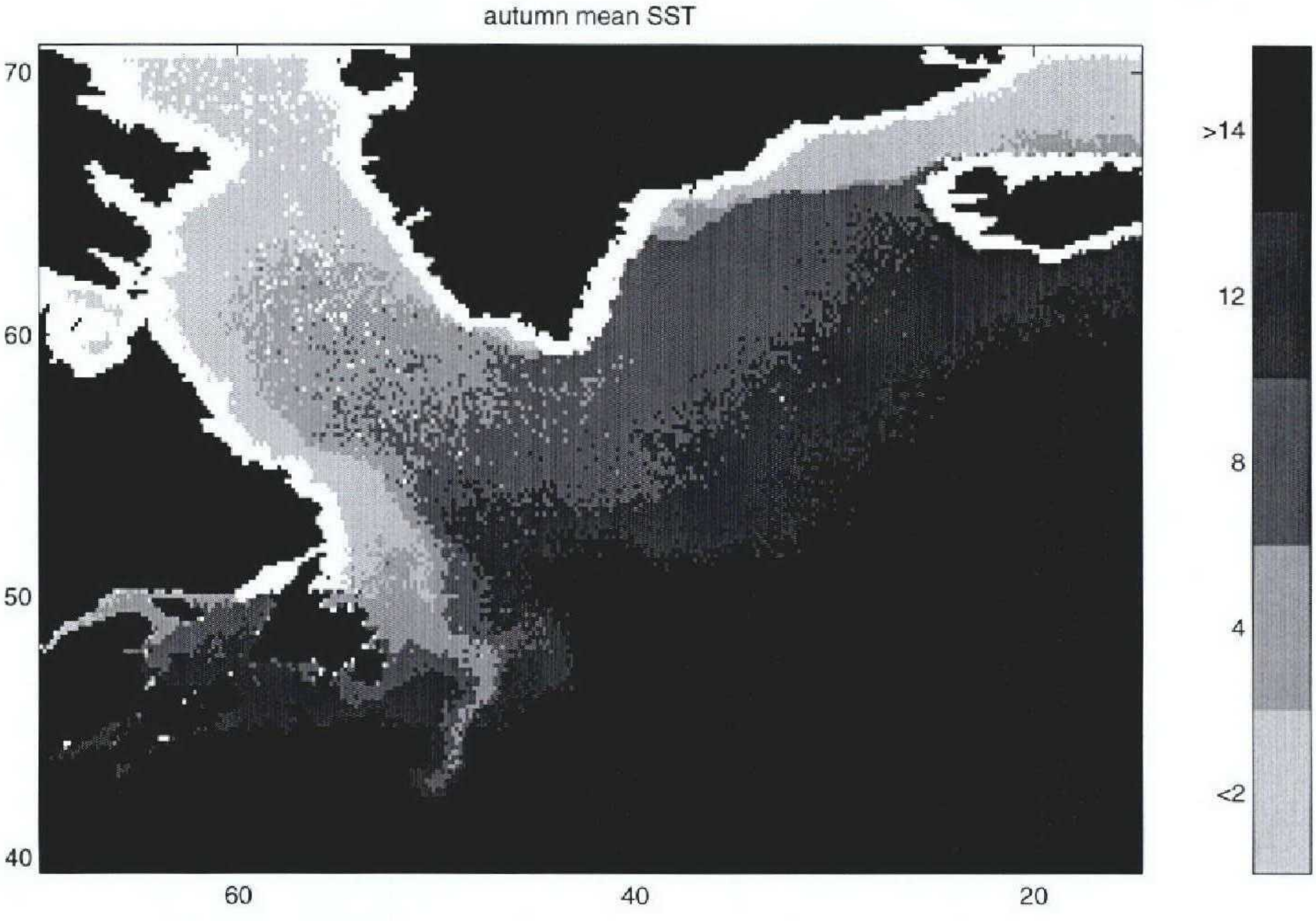

Fig. 23. Seasonal mean SSTs for autumn derived from the full 1982-1997 MCSST data set.

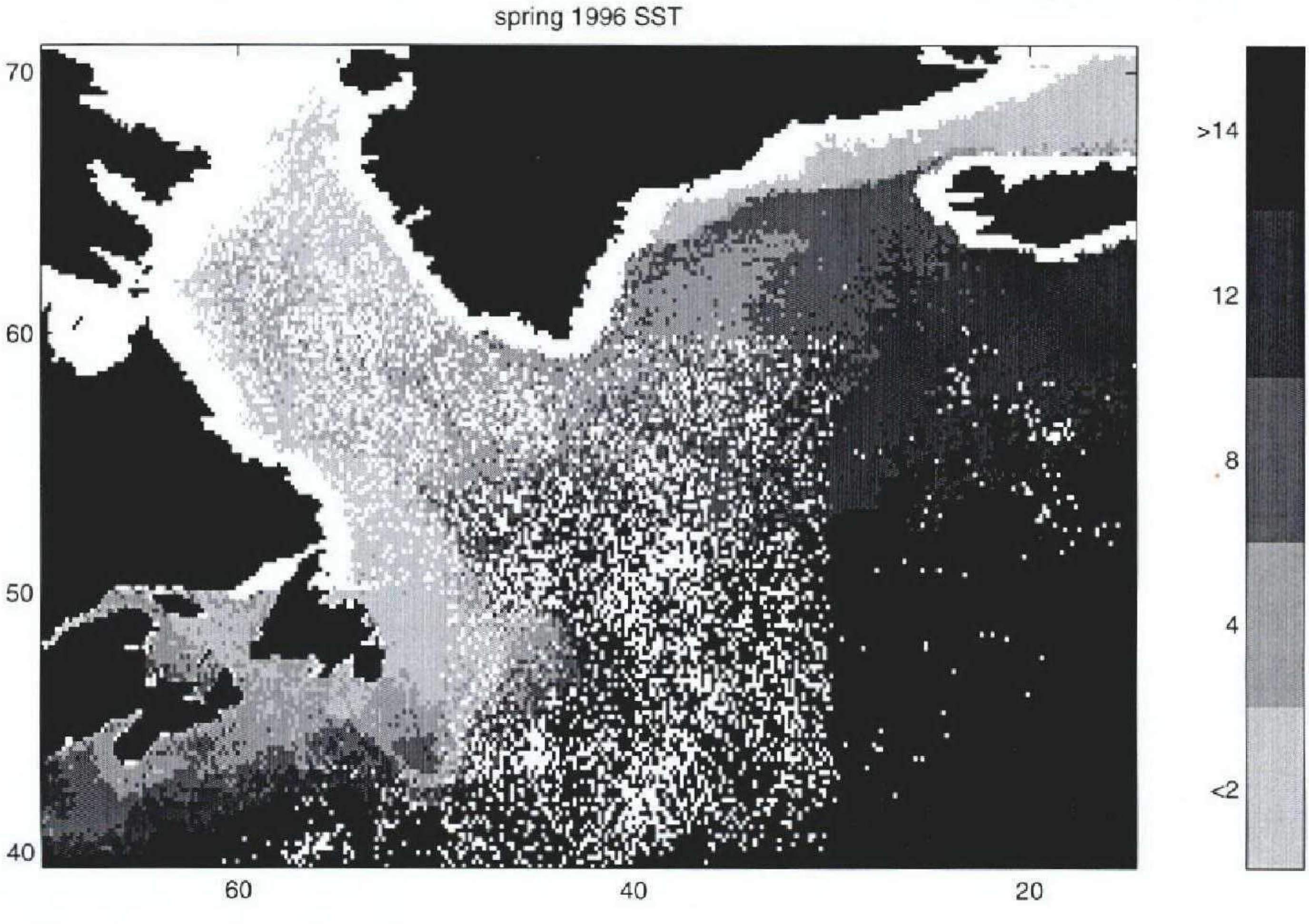

Fig. 24. Seasonal mean SSTs for spring 1996.

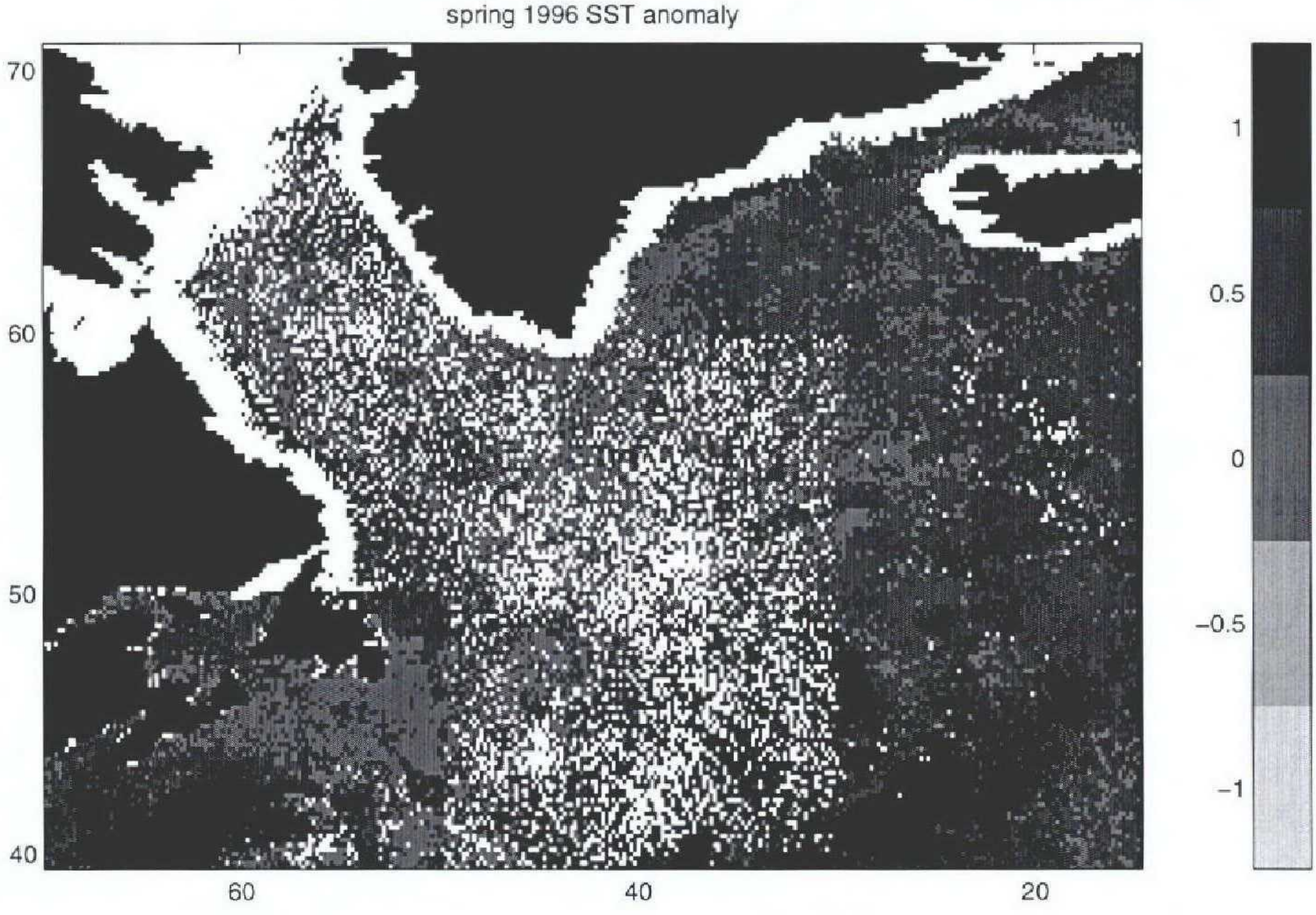

Fig. 25. Seasonal SST anomalies for spring 1996.

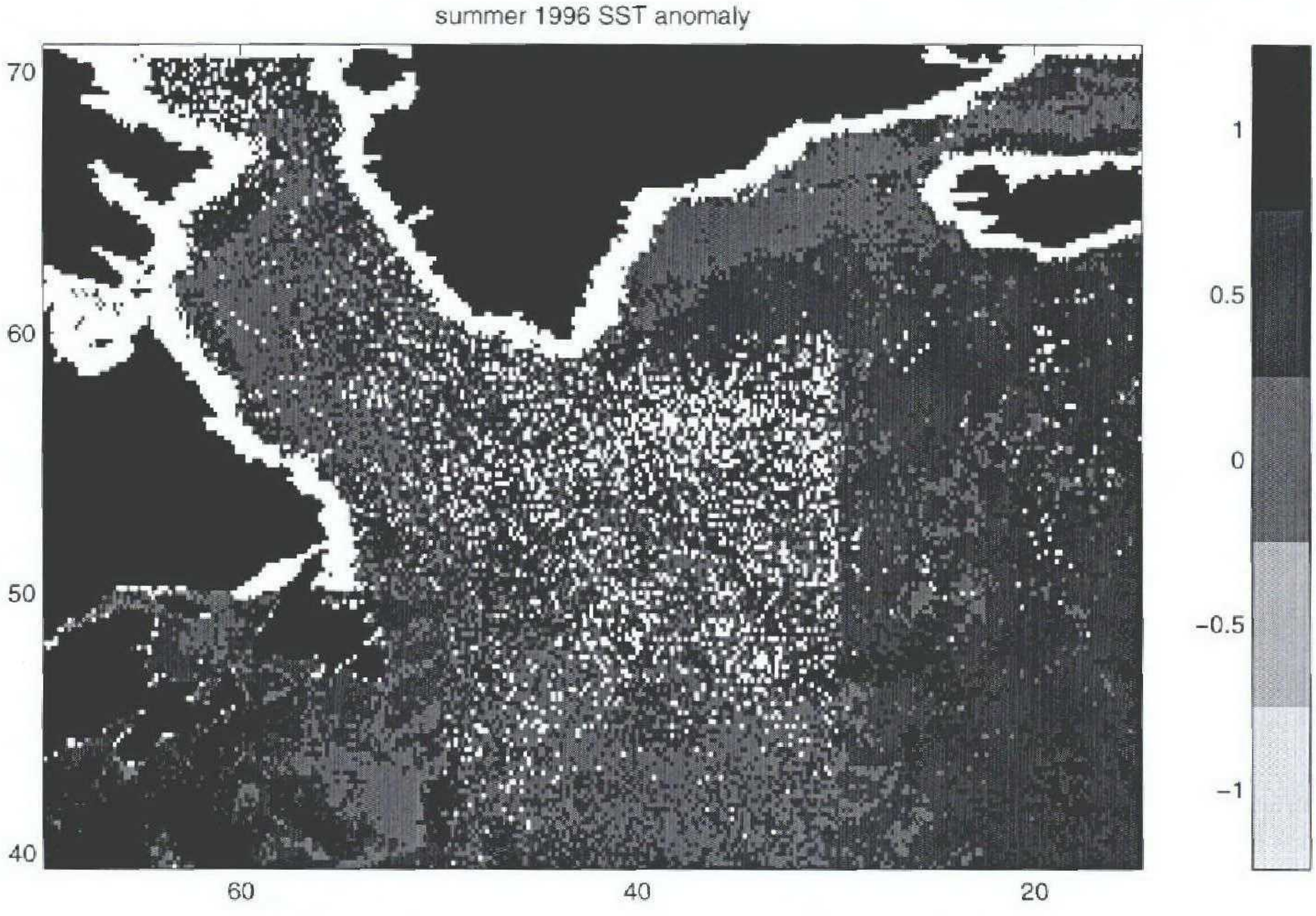

Fig. 26. Seasonal SST anomalies for summer 1996.

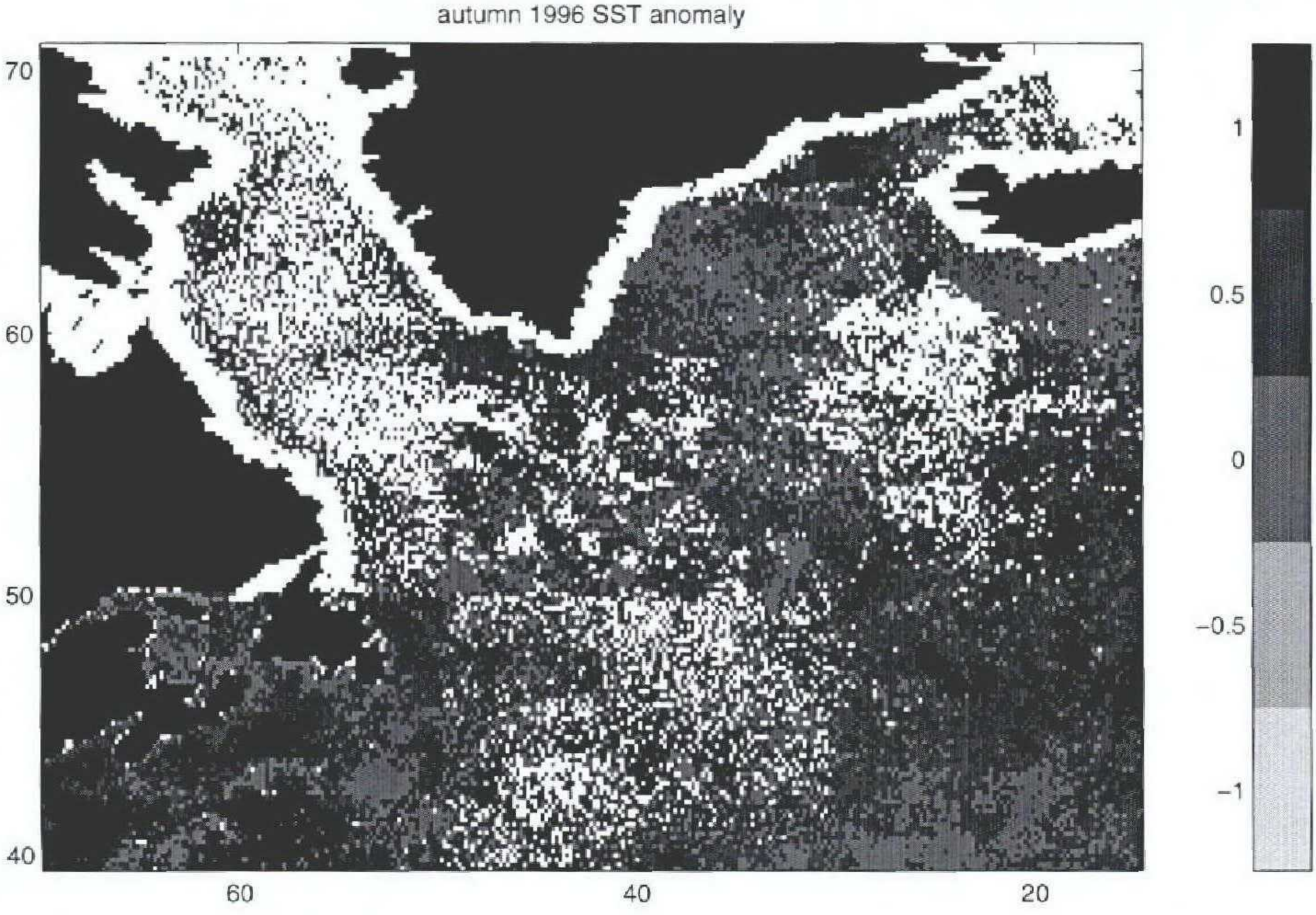

Fig. 27. Seasonal SST anomalies for autumn 1996.

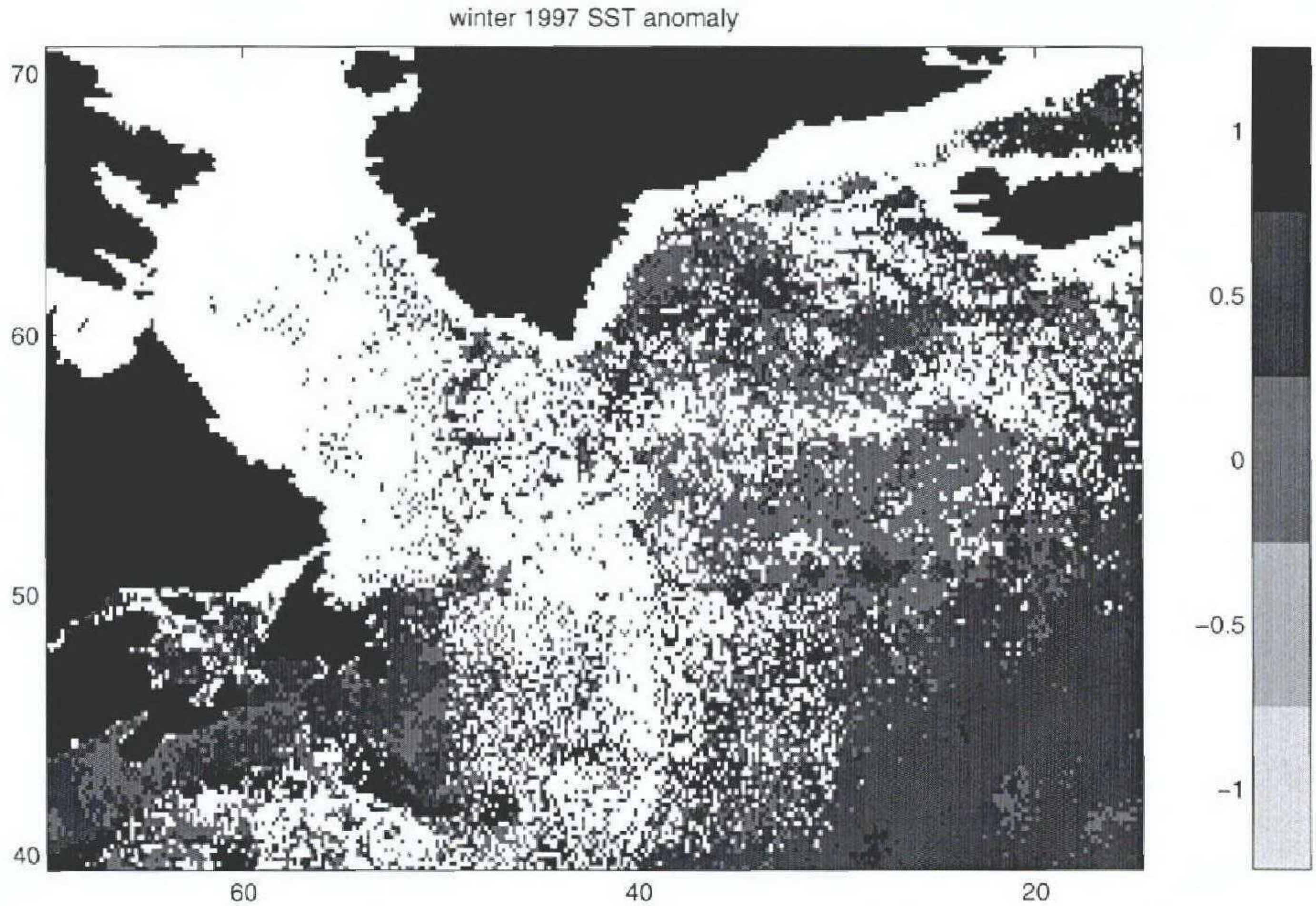

Fig. 28. Seasonal SST anomalies for winter 1997.

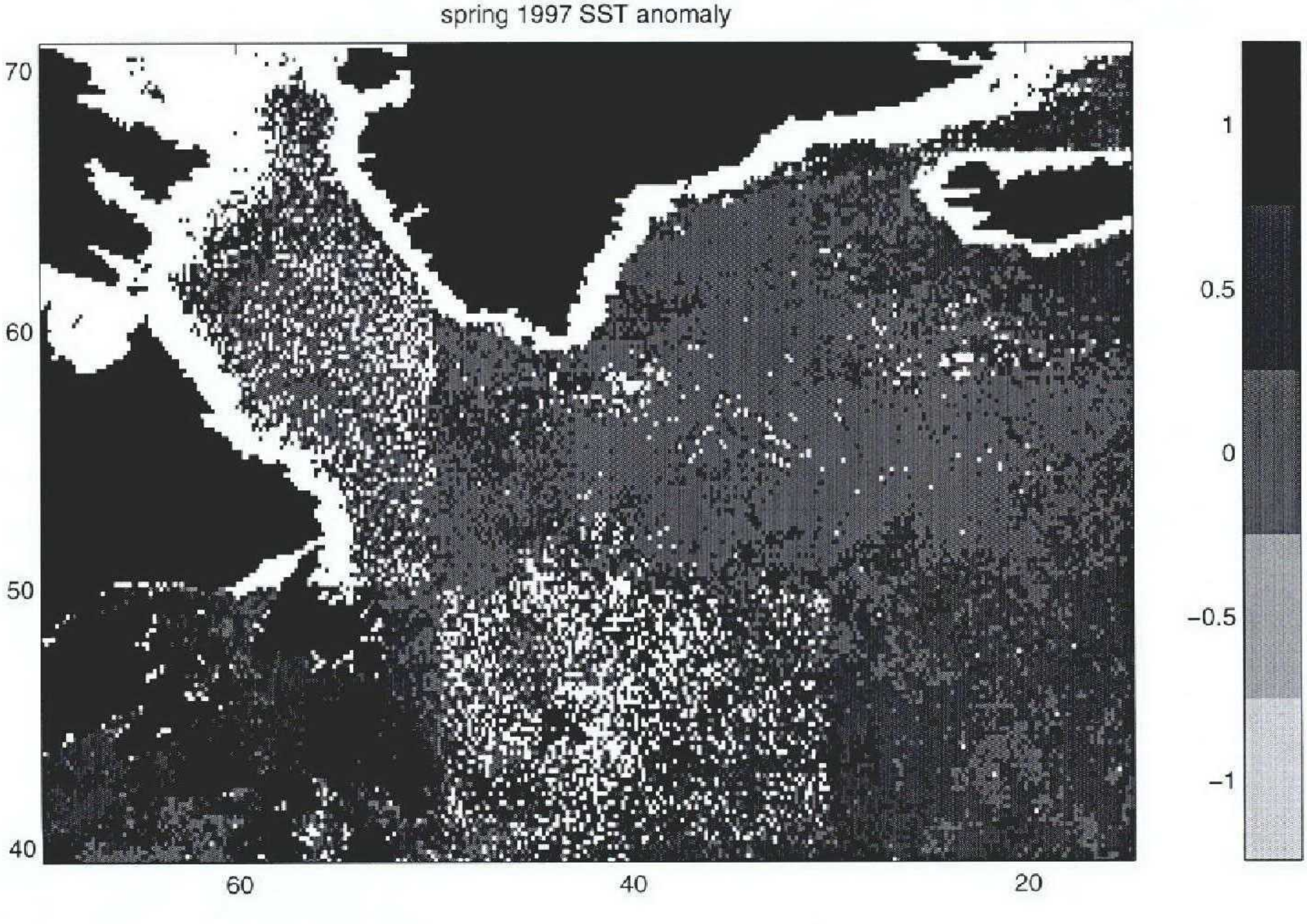

Fig. 29. Seasonal SST anomalies for spring 1997.