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# An Overview of Meteorological, Sea Ice and Sea-Surface Temperature Conditions in the Eastern Canada during 2002

by

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## ABSTRACT

A review of meteorological, sea ice and sea surface temperature conditions in the Northwest Atlantic in 2002 is presented. During 2002, the NAO index was below normal for the second consecutive year indicating a weakening of the Icelandic Low and Azores High during the winter. Annual mean air temperatures over the northwest Atlantic region were above normal during the year although from Greenland to the Scotian Shelf they decreased on the order of 1ºC compared to 2001. In contrast, over the Gulf of Maine and the Middle Atlantic Bight annual air temperatures rose relative to the 2001 values. The relatively warm winter temperatures in eastern Canada resulted in less ice than normal off Newfoundland and Labrador, and in the Gulf of St. Lawrence. Ice generally arrived late. Its departure was early in the Gulf, causing a shorter duration than usual. Off Newfoundland, although there was less ice than normal, it remained around longer-than-usual and contributed to a longer than average duration of sea ice. Little ice reached the Scotian Shelf for the fifth consecutive year and seaward of Cabot Strait the integrated ice area over the ice season was the 2nd lowest in the 41-year record. The number of icebergs that reached the northern Grand Bank south of 48ºN was 877, significantly higher than 2001 when only 89 bergs were observed on the Banks. The analysis of satellite data indicates that most of the NW Atlantic experienced above normal sea-surface temperatures in 2002.

## INTRODUCTION

This paper examines the meteorological, sea ice and sea surface temperature conditions during 2002 in the Northwest Atlantic (Fig. 1). Specifically, it discusses air temperature trends, atmospheric sea level pressures, winds, sea-ice coverage, iceberg drift and sea surface temperatures (SST). It complements the oceanographic reviews of the waters in and around Newfoundland and the Scotian Shelf and Gulf of Maine, which together constitute the annual physical environmental overviews to the Fisheries Oceanography Committee (FOC). Environmental conditions are compared with those of the preceding year as well as to the long-term means. The latter comparisons are usually expressed as anomalies, i.e. deviations from their long-term mean or normal, and where the data permit, the latter have been standardized to a 30-yr base period (1971-2000). This is in accordance with the convention of North American meteorologists and the recommendations of both the Northwest Atlantic Fisheries Organization (NAFO) and the FOC. Having a standardized base period allows direct comparison of anomaly trends both between sites and between variables.

## METEOROLOGICAL OBSERVATIONS

### *Air Temperatures*

The German Weather Service publishes monthly air temperature anomalies relative to the 1961-1990 means for the North Atlantic Ocean in their publication *Die Grosswetterlagen Europas* (Deutscher Wetterdienstes, 2002). Slightly warmer-than-normal temperatures tended to dominate over most of eastern Canada and its coastal waters during 2002 (Fig. 2A). The highest annual anomalies relative to 1961-1990 were over Georges Bank and the northern region of the Middle Atlantic Bight where they reached >1ºC. Negative annual anomalies extended over the northern Gulf of St. Lawrence, the Grand Banks and northeastern Newfoundland Shelf. Seasonally, predominantly cold air covered much of the Labrador Sea region from January through to April (Fig. 2B). Negative anomalies were as low as -4°C in January near the northern Labrador coast and in February in the Davis Strait region. During this same period, warmer-than-normal air temperatures covered areas from the Gulf of St. Lawrence to the Middle Atlantic Bight. Anomalies of +5°C were recorded in January and again in March in the vicinity of Cape Cod. In June and July, the pattern reversed, with the Labrador Sea region having above normal air temperatures while Newfoundland and marine areas south to Cape Hatteras generally experienced cold conditions. During July to September, inclusive, most of the marine areas off Canada's east coast experienced warmer-than-normal air temperatures but typically only of the order of +1°C or less (Fig. 2C). During October and November, the cold conditions moved into the southern regions, while the Labrador Sea, or large parts of it, maintained warmer-than-normal temperatures. Anomalies in both cases tended to be within 1° of normal. December saw the return of warm air temperature anomalies over the entire region of interest.

Monthly air temperature anomalies for 2001 and 2002 relative to their 1971-2000 mean at eight sites, from Nuuk in Greenland to Cape Hatteras on the eastern coast of the United States, are shown in Fig. 3 (see Fig. 1 for locations). Data from the Canadian sites were available from the Environment Canada website and for non-Canadian locations from *Monthly Climatic Data for the World* (NOAA, 2002). The predominance of warmer-than-normal air temperatures over most of eastern Canadian waters during 2002, noted above, is evident (Fig. 3). At Cape Hatteras, all months but two were warmer-than-normal; on the Magdalen Islands, all but three; and at Iqaluit and Nuuk, all but four. St. John's, Sable Island and Boston had seven months with warmer-than-normal air temperatures while at Cartwright the year was split evenly between positive and negative anomalies. The largest magnitude anomaly was at Iqaluit, where air temperatures were 4.6°C above normal in December. This was part of generally high positive anomalies during the last three months in the northernmost sites of Nuuk and Iqaluit, which contrast with colder-than-normal conditions in the two southernmost sites, Cape Hatteras and Boston.

The mean annual air-temperature anomalies for 2002 were also calculated at all eight sites. For all sites the annual anomalies were above normal. The maximum annual anomaly was recorded at Cape Hatteras with a value of 0.93°C. Slightly lower anomalies were recorded at Nuuk (0.71°C) and Boston (0.67°C). Annual means in 2002 declined substantially compared to 2001 from Nuuk in Greenland to Sable Island on the Scotian Shelf. At most of these sites the decline was over 1°C. This contrasts with Boston and Cape Hatteras where the annual anomalies rose compared to 2001 values. At Hatteras, the increase was almost 1°C. The time series of the annual anomalies are shown in Fig. 4. The positive air temperature anomalies in 2002 are clearly evident. Note that the interannual variability in air temperatures since 1960 at Nuuk, Iqaluit, Cartwright, and, to a lesser extent, St. John's, have been dominated by 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 decline in temperature at most of these sites is consistent with a continuation of this near decadal pattern. Monthly temperature anomalies at the Magdalen Islands and Sable Island contained quasi-decadal fluctuations with minima in the early-1970s (both sites), the mid-1980s (Sable Island only) and in the 1990s (Magdalen Islands only). Air temperatures at Boston and Cape Hatteras have generally been out of phase with the temperature fluctuations in the Labrador region. Thus, for example, the cold temperatures in Labrador during the early-1990s occurred at a time when they were relatively warm along the US seaboard (Fig. 4). Also note that in contrast to these out of phase temperature fluctuations between Labrador and Cape Hatteras on the U.S. seaboard, during the late-1800s and early-1990s, all sites where data are available exhibit cold conditions (relative to the 1971-2000 mean).

Temperatures rose to above normal values between the 1910s and 1950s, the actual timing being site-dependent.

*Sea Surface Air Pressures*

Climatic conditions in the Labrador Sea area are closely linked to 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 (Thompson and Hazen, 1983). 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 2002, relative to the 1971-2000 means, are shown in Fig. 5. Winter includes December 2001 to February 2002, spring is March to May, summer is June to August and autumn is September to November.

In winter, an extensive anomalous low covered eastern Canada with its center (4 mb below normal) located east of Newfoundland. A weaker low (minimum of around -2 mb) was situated to the northeast of Greenland and a high (maximum of over 4 mb) centered over Western Europe. The winter pressure anomalies in 2002 indicate a weakening of both the Iceland Low and the Azores High, i.e. a reduction in the strength of the large-scale atmospheric circulation, similar to 2001. It is noted that the winter pressure anomalies in 2002 were generally weaker than in most other years.

A strong dipole was established in the spring of 2002, with an intense negative pressure anomaly in the northern North Atlantic (minimum –6 mb) and an intense positive pressure anomaly to the south. The presence of a weaker negative anomaly off western Africa contributed to the center of the anomalous high to be located closer to the western side of the ocean than the eastern side. This pressure pattern indicates a strong Iceland Low and Azores High.

As is typical in most years, the pressure anomaly field during the summer of 2002 was weaker than in the other seasons. It has several features similar to that seen in the spring, with a negative anomaly in the northern North Atlantic, a positive anomaly to the south and another negative anomaly over West Africa. No anomaly exceeds an absolute value of much >2 mb.

In the autumn, the pattern switched to predominantly negative anomalies across most of the North Atlantic. The highest value was slightly more than 5 mb below normal and was located in the central North Atlantic. A strong positive anomaly in the sea level pressure field lay to the north and a much weaker one to the south of this band, with maximum values up to 9 mb and 1 mb, respectively.

*NAO Index*

The North Atlantic Oscillation (NAO) Index is the difference in winter (December, January and February) sea level atmospheric pressures between the Azores and Iceland and is a measure of the strength of the winter westerly winds over the northern North Atlantic (Rogers, 1984). A high NAO index corresponds to an intensification of the Icelandic Low and Azores High. Strong northwest winds, cold air and sea temperatures and heavy ice in the Labrador Sea area are usually associated with a high positive NAO index (Colbourne *et al.*, 1994; Drinkwater, 1996). The opposite response occurs during low NAO years. The annual NAO index is derived from the measured mean sea level pressures at Ponta Delgada (up to 1997) or Santa Maria (since 1997) 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 1971-2000 mean.

In 2002, the NAO index was below normal (-3.2 mb anomaly) and rose by 5.1 mb from its 2001 value (Fig. 6). For 2001 and 2002 the levels were similar to those observed during 1996-1997 and well below the higher-than-average indices registered during 1998-2000. As alluded to above, low NAO is usually accompanied by warm air temperatures over the Labrador Sea in winter. This is consistent with observations in 2001 and 2002. However, as described by Drinkwater *et al*. (2001), warm air temperatures accompanied high NAO indices during 1998-2000. The latter was a result of the eastward shift in the location of the anomalous winter pressure field, with weaker gradients over the Northwest Atlantic and the Azores High extending into southeastern Canada in winter, which produced more southerly winds with accompanying warm air.

*Winds*

The re-analyzed NCEP (National Centre for Environmental Prediction) – NCAR (National Center for Atmospheric Research) winds (Kistler *et al*., 2001) are available from the International Research Institute of the Lamont-Doherty Earth Observatory at Columbia University. Based upon correlations with measured data, the vector components of the NCEP winds capture most of the observed variability in the wind field. They are representative of winds measured at a height of 10 m and are gridded at intervals of 1.88° longitude and approximately 1.90° latitude. We have averaged the winds seasonally and obtained anomalies for the gridded wind data covering an area approximately from 40°-68°N and 40°-75°W (Fig. 7). The magnitude of the wind anomalies tend to be larger in the north, hence for presentation purposes, we split the data to show the Labrador Sea separately from regions farther south.

The anomaly of the mean winter winds during 2002 over the Labrador Sea were variable, being primarily northeasterly in the south and weaker, with more directional variability, in the north. Along the northern Labrador coast the wind anomalies were from the north (Fig. 8). Over Atlantic Canada winter wind anomalies were primarily from the north, switching to westerlies over the Grand Bank (Fig. 9). In the Gulf of Maine, the wind anomalies were from the southwest. The anomalous winds in the spring are dominated by northwesterlies in the Labrador Sea, southwesterlies in Atlantic Canada and the Gulf of Maine, and westerlies in the Grand Bank and southern Labrador Sea regions. This is consistent with the intensified low in the north and high in the south (Fig. 5). A similar anomalous wind pattern to that in spring was observed in summer but of much lower amplitude. The autumn winds over the Labrador Sea were predominantly northeasterly to northerly while those over Atlantic Canada were northerly switching to westerly. These seasonal patterns are consistent with those indicated by the sea surface pressure patterns (Fig. 5), assuming geostrophy.

## 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. In the past the long-term median, maximum and minimum positions of the ice edge (concentrations above 10%) were based on the composite for the years 1962 to 1987 taken from Coté (1989). This year new values based on the 1971-2000 data are being used (Canadian Ice Service, 2002). The daily charts represent snapshots of the ice and it must be recognized that the ice edge can vary rapidly over short periods of time due primarily to changes in the winds. We also include an analysis of the time of onset, duration and last presence of sea ice based upon the sea-ice database maintained at the Bedford Institute of Oceanography for the Newfoundland region (Peterson and Prinsenberg, 1990) and for the Gulf of St. Lawrence and the Scotian Shelf (Drinkwater *et al.*, 1999). The weekly concentration and types of ice within 0.5° latitude by 1° longitude areas were recorded through the ice season. The dates of the first and last appearance of ice within these areas, as well as the duration of ice, were determined. The data begin in the early-1960s and continue through to the present. Long-term means (30-years, 1971-2000) of each variable were determined (using only data during years ice was present) and subtracted from the 2002 values to obtain anomalies.

*Newfoundland and Labrador*

*Sea-Ice*. At the beginning of 2002, the only sea ice present lay off the southern Labrador coast in the vicinity of Hamilton Inlet. This was an areal coverage that was less than the long-term median and close to the long-term minimum for the beginning of the year (Fig. 10A). By mid-January, ice had spread south to the Strait of Belle Isle but was confined to a thin strip near the coast. This was slightly more than the long-term minimum but much less than the median. Colder temperatures during the last half of January pushed the ice farther south and farther offshore. The expansion of ice resulted in a distribution by 1 February that was near the median value. Through February the ice continued its southward extension but was slightly less than the median distribution by 1 March. By 1 April, ice was beginning to retreat and continued at a rate that was near average through to the summer (Fig. 10B).

An analysis of the first and last presence of ice was also carried out. In 2002, ice appeared along the southern Labrador coast in late December, and gradually spread southward to northeastern Newfoundland waters by late-January (around day 30; Fig. 11). Only small quantities of ice reached the northern Grand Bank. Relative to the long-term mean, ice generally appeared later-than-normal over most of the Labrador and Newfoundland shelves by the order of 1 to 2 weeks (Fig. 11). Ice began to disappear from the offshore and southern sites in late March (day 90; Fig. 12). It did not began to retreat from inshore northern Newfoundland waters and southern Labrador until mid-May (day 135) to mid-June (day 165). Ice lasted in the vicinity of Hamilton Inlet until July. Over much of the region, ice disappeared later-than-normal (positive anomaly). These anomalies tended to be on the order of 1-2 weeks but reached upwards of 4 weeks off Hamilton Inlet (Fig. 12). South of Hamilton Bank and off the Avalon Peninsula ice departed earlier-than-normal. The duration of sea ice is the number of days that ice is present. It ranged from <30 days on the northern Grand Bank to over 200 days in the vicinity of Hamilton Inlet (Fig. 13). 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 greater-than-normal (positive anomaly) over a significant area of the Newfoundland and Labrador Shelves. This generally followed the pattern of the last ice presence with maximum values off northeastern Newfoundland and in the vicinity of Hamilton Inlet. The maximum anomaly in duration was over 40 days.

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 2002 was slightly above that observed in 2001 but not significantly (Fig. 14). Relative to 2001, the average ice area rose slightly during advancement (January to March) and retreat (April to June). During both periods, the average ice area was below the long-term mean, and was much less than in the early-1990s. The monthly means of ice area show that the 2002 coverage was below that of 2001 during January, February, and May, while it was above in March, April and June (Fig. 15). In December and July there was little change. In all months, the ice area was below the long-term average (1971-2000). In summary, 2002 was generally a lighter-than-average ice year on the Labrador and Newfoundland shelves. Although no estimates of ice volume were made for 2002, based upon studies in the Gulf of St. Lawrence (Drinkwater *et al*., 1999), the temporal variability of the ice volume is expected to be similar to that of the ice area.

*Icebergs*. The International Ice Patrol Division of the United States Coast Guard monitors the number of icebergs that pass south of 48°N latitude each year. Since 1983, data have been collected with SLAR (Side-Looking Airborne Radar). During the 2001/2002 iceberg season (October 2001 to September 2002), a total of 877 icebergs were detected south of 48°N. The monthly totals for February to June were 16, 173, 316, 308 and 64, respectively (Fig. 16). No icebergs were spotted between October 2001 and January 2002, inclusive, or in July to September 2002. In 2002, 98% of the icebergs were observed during the primary iceberg season of March to July, which is higher than the 1985-2000 mean of 91.7%. The 1985-2000 period is considered to represent reliable SLAR measurements. A higher percentage of icebergs than usual arrived in March to May in 2002, and a lower percentage in June and later. The total number of icebergs was up dramatically from the 87 icebergs recorded in 2001, and was the 19$^{th}$ highest number recorded in 123 years of data (Fig. 16).

*Gulf of St. Lawrence*

The location of the ice edge within the Gulf of St. Lawrence at various times during the 2001-2002 winter season is shown in Fig. 17. These again represent snapshots and the reader is reminded that the ice edge can vary rapidly over short periods of time. Warm air temperatures in late 2001 slowed ice formation in the Gulf so that there was very little ice at the beginning of 2002. The ice that had formed was restricted to the coastal regions of Prince Edward Island and the St. Lawrence Estuary. By mid-January the ice coverage remained confined to coastal regions such as Northumberland Strait, Chaleur Bay and the Estuary. This was much less than the long-term median coverage. By 1 February ice had extended through to the northern regions of the Gulf and the western shores of the Magdalen Shallows but the majority of the Shallows were open. Ice continued to move southward through February but by 1 March several areas of the Gulf remained open, including off western Newfoundland, in the southern Magdalen Shallows and a small area off the Gaspe. Ice began to break in March and by 1 April ice had disappeared from most of the Gulf, resulting in less ice than normal. The ice continued to break up and melt and by 1 May ice was only in the entrance to the Strait of Belle Isle region, due to ice on the Labrador Shelf (Fig. 10B). Small amounts of ice remained in this area until mid-May.

The times of first presence show ice formed initially in the St. Lawrence Estuary, along the coastal regions of the Magdalen Shallows and the northern shore of Quebec, and covered these areas by mid-January (Fig. 11). By mid-February, ice had covered most of Gulf for at least some period of time. Subtracting the long-term (1971-2000) mean indicates that the time of first ice was later than normal over almost the entire Gulf by 1-2 weeks (Fig. 11). The last presence of ice varied from late March to mid-May, with the result that it disappeared earlier than normal in the central and southern regions of the Gulf by upwards of 15 days off western Newfoundland and the southern Magdalen Shallows (Fig. 12). In the Estuary and along the north shore of the Gulf, ice disappeared later than normal. Over the entire Gulf, ice duration was less than the long-term mean by between 10 and 30 days (Fig. 13).

New this year, we have estimated the monthly mean area of the Gulf covered by ice. The time series shows that in 2002 the peak areal coverage rose compared to 2001 and the previous several years (Fig. 18). Estimates of the duration of ice, however, indicated a value much lower than the long-term mean and the 2$^{nd}$ lowest in the 40-year record (Fig. 18). The 128 days of ice is over a month less than the normal ice duration. This is part of a general decline in ice duration since the mid-1990s. The integrated ice area (summation of the area times the number of days) was also lower than average and the 10$^{th}$ lowest out of 40 years (Fig. 18). This index shows strong low-frequency variability. To summarize, 2002 was a light ice year in the Gulf of St. Lawrence.

*Scotian Shelf*

Sea ice is generally transported out of the Gulf of St. Lawrence through Cabot Strait, pushed by northwesterly winds and ocean currents. In 2002, ice first appeared seaward of Cabot Strait during February, which is slightly later-than-usual (Fig. 11). It maintained a relatively constant presence through late March-early April in the Cabot Strait area. Ice was primarily limited to the Strait and Sydney Bight with little ice reaching the Scotian Shelf. The ice seaward of Cabot Strait disappeared by early April, a departure time that was earlier than normal by 1-2 weeks (Fig. 12). The duration of ice was 10-50 days off eastern Cape Breton Island. This was less than the long-term mean duration by 20-40 days (Fig. 13). Note that durations of less than 10 days are not plotted.

The monthly estimates of the ice area seaward of Cabot Strait since the 1960s show that only small amounts were transported onto the Scotian Shelf during 2002 compared to the long-term mean (Fig. 19, 20). The ice area was, however, slightly lower in magnitude than that observed in 2001. There were significantly fewer days than usual with ice present seaward of Cabot Strait, less than that observed in 2001, and near the 2000 level. It was the third shortest duration in the 41-year record. The integrated ice area was slightly lower than 2001 and remained well below the long-term average (Fig. 19); indeed, it was the second lowest on record. This was the fifth consecutive year of very light ice conditions seaward of Cabot Strait. Note that, based upon data collected since the 1960s, the farthest south that the ice penetrates is along the Atlantic coast of Nova Scotia to just past Halifax. Historical records prior to 1960 suggest that during heavy ice years, ice occasionally penetrated much farther south, for example in the 1880s sea ice was observed in the southwestern Scotian Shelf (Hill *et al*., 2002).

## Remotely-Sensed Sea Surface Temperature

Recently, we obtained access to the satellite-derived Pathfinder sea surface temperature data. This database offers several advantages over the JPL MCSST database that previously was used (see Petrie and Mason, 2000). A uniform algorithm has been applied to the new Pathfinder data across its observation period (1985-2002). The spatial resolution is 9 km compared to the nominal 18 km of the JPL MCSST dataset and the data return from higher latitudes is considerably greater than for the JPL MCSST dataset, which had artificial cut-off boundaries to reduce the amount of data stored. Finally, the MCSST product ended in February 2001. In spite of the differences between the two datasets, preliminary comparisons show they are quite comparable and show similar interannual variability. The satellite data from 1992 and 1994 have been compromised because of volcanic eruptions; these data are still being examined and could be added to the Pathfinder dataset in the future.

Annual anomalies for 23 Subareas, stretching form the Labrador Sea to the Gulf of Maine (Fig. 21), were determined from the averages of monthly anomalies. For display purposes, we have divided the data into six areas: the Labrador Sea, the Labrador Shelf, the Newfoundland Grand Bank, the Gulf of St. Lawrence, the Scotian Shelf and the Gulf of Maine. The results are shown as annual temperature anomalies in Figure 22(A-E). Within each area the time series are very coherent. In 22 of the 23 Subareas, the exception being the NW Gulf of St. Lawrence, annual temperatures were above average in 2002. This is a continuation of a period of generally above normal temperatures that began in the late-1990s and is particularly well defined in the Newfoundland and Scotian Shelf regions (Fig. 22B, D).

## SUMMARY

During 2002, the NAO index was below normal for the second consecutive year. Air temperatures over the northwest Atlantic region were above normal, although from Greenland to the Scotian Shelf they decreased on the order of 1ºC compared to 2001. In contrast, over the Gulf of Maine and the Middle Atlantic Bight air temperatures rose relative to their 2001 values. Seasonal wind patterns varied during the year with no dominant direction during the year. The relatively warm winter temperatures in eastern Canada resulted in less ice than normal off Newfoundland and Labrador, and in the Gulf of St. Lawrence. Ice generally arrived late. The departure was early in the Gulf, causing a shorter duration than usual. Off Newfoundland, although there was less ice than normal, it remained longer-than-usual. Little ice reached the Scotian Shelf for the fifth consecutive year, and seaward of Cabot Strait, the integrated ice area was the 2nd lowest in the 41-year record. The 877 icebergs that reached the Grand Bank was significantly higher than in 2001 when only 89 bergs were observed reaching the northern edge of the Bank. The analysis of satellite data indicates that most of the NW Atlantic experienced above normal sea-surface temperatures in 2002.

## ACKNOWLEDGEMENTS

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## REFERENCES

Canadian Ice Service. 2002. Sea ice climatic atlas: Northern Canadian waters 1971-2000. Environment Canada, Ottawa. 249 p.

Colbourne, E., S. Narayanan and S. Prinsenberg. 1994. Climatic changes and environmental conditions in the Northwest Atlantic, 1970-1993. ICES mar. Sci. Symp. 198: 311-322.

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

Deutschen Wetterdienstes. 2002. *Die Grosswetterlagen Europas*. Vol. 55. Offenbach, Germany.

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

Drinkwater, K.F., E. Colbourne and D. Gilbert. 2001. Overview of environmental conditions in the Northwest Atlantic in 2000. Serial No. 4414, SCR Doc. 01/36, 84 p.

Drinkwater, K.F., R.G. Pettipas, G.L. Bugden and P. Langille. 1999. Climatic data for the Northwest Atlantic: A sea ice database for the Gulf of St. Lawrence and the Scotian Shelf. Can. Tech. Rept. Hydrogr. Ocean Sci. 199: 134 p.

Hill, B.T., A. Ruffman and K. Drinkwater. 2002. Historical record of the incidence of sea ice on the Scotian Shelf and the Gulf of St. Lawrence. p. 16-23, *In* Ice in the Environment, Proceedings of the 16th IAHR International Symposium on Ice, Dunedin New Zealand, 2-6 December, 2002, International Association of Hydraulic Engineering and Research.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne AND M. Firoino. 2001. The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bull. Amer. Meteorolog. Soc.*, 82: 247-267.

NOAA. 2002. *Monthly climatic data for the world*. Vol. 55. National Climate Data Center, Asheville, North Carolina.

Peterson, I. K. and S. J. Prinsenberg. 1990. Sea ice fluctuations in the western Labrador Sea (1963-1988). Can. Tech. Rep. Hydrogr. Ocean Sci. 123: 130 p.

Petrie, B. and C. S. Mason 2000. Satellite measurements of sea-surface temperature: an application to regional ocean climate. CSAS Res. Doc. 2000/061, 24 pp.

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.

Thompson, K.R. and M.G. Hazen. 1983. Interseasonal changes in wind stress and Ekman upwelling: North Atlantic, 1950-80. Can. Tech. Rep. Fish. Aquat. Sci. 1214, 175 p.


Fig. 1. Northwest Atlantic showing coastal air temperature stations. The thin lines denote the 200 m and 1000 m isobaths.

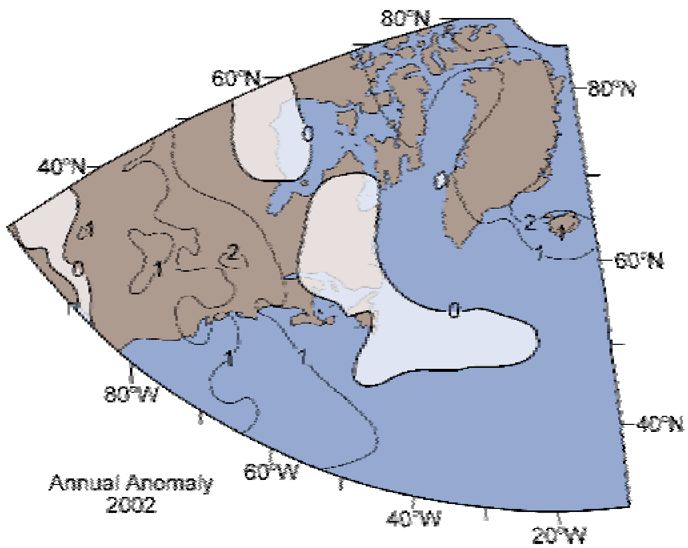



Fig. 2A. The 2002 annual anomaly of air temperature (ºC) over the Northwest Atlantic, relative to 1961-1990 means. The white shaded areas are colder-than-normal. (Redrawn from Grosswetterlagen Europas).

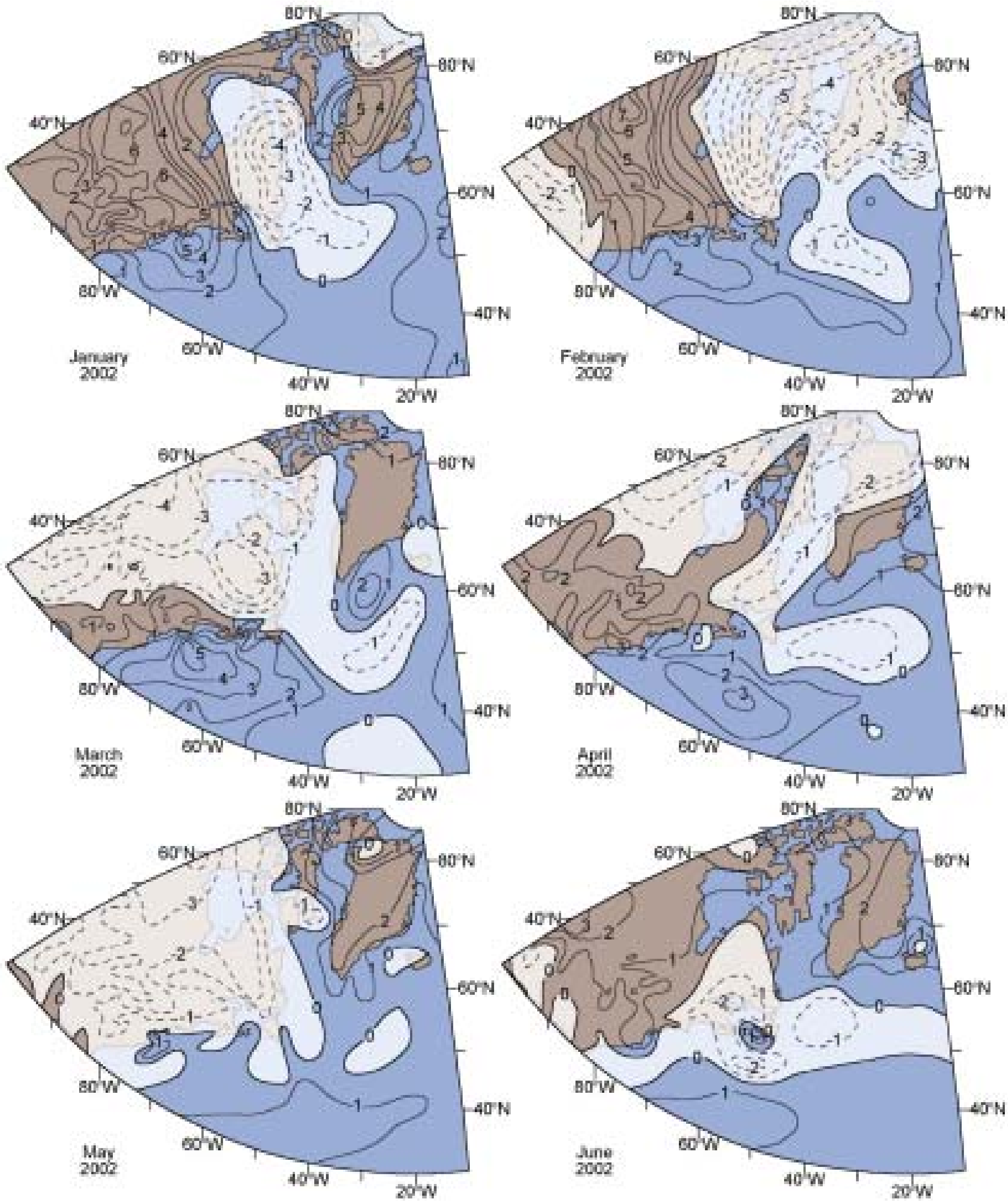



Fig. 2B. Monthly air temperature anomalies (°C) over the Northwest Atlantic from January to May of 2002 relative to their 1961-1990 means. The white shaded areas are colder-than-normal. (Redrawn from *Grosswetterlagen Europas*)

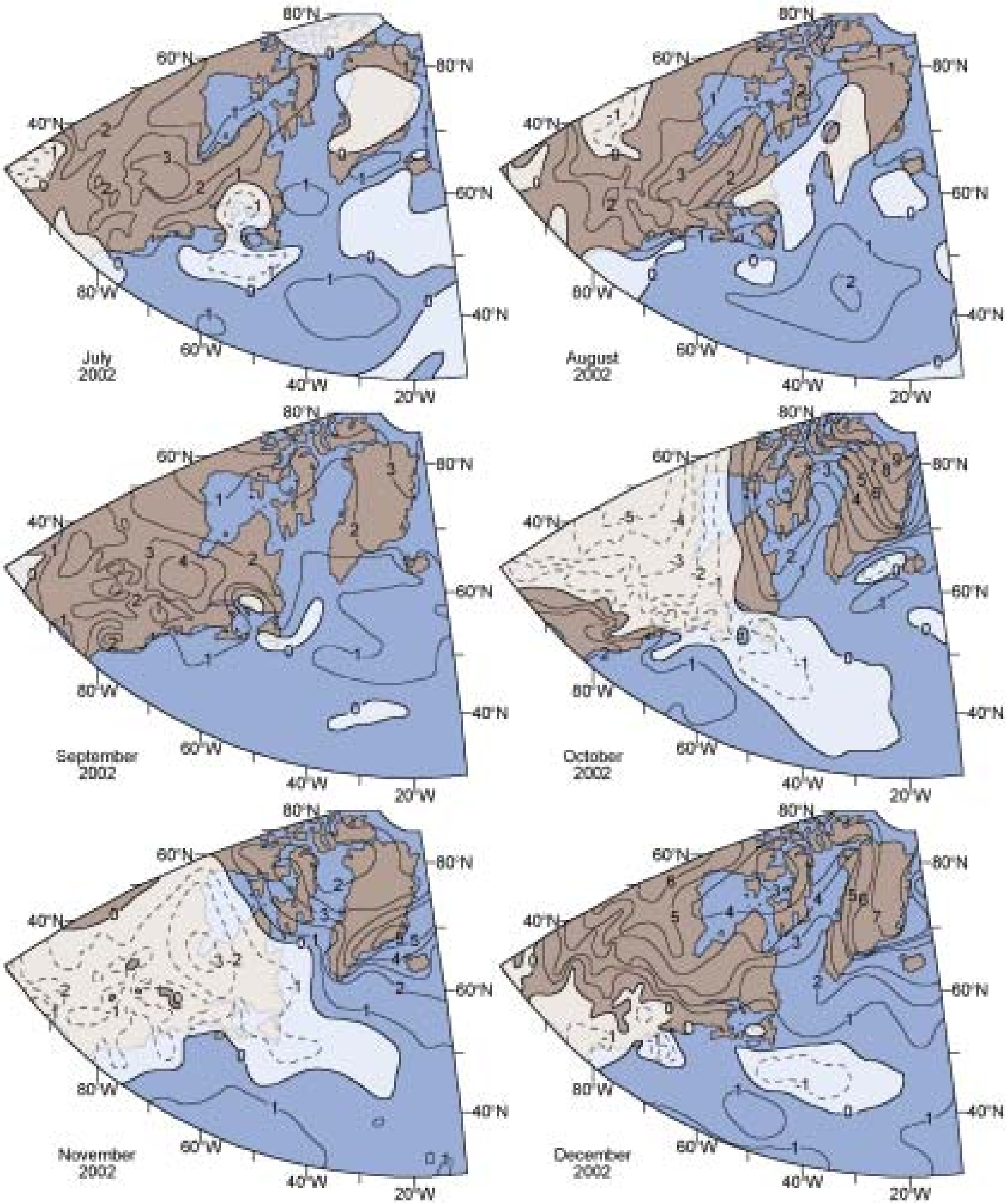



Fig. 2C. Monthly air temperature anomalies (°C) over the Northwest Atlantic from July to December of 2002 relative to their 1961-1990 means. The white shaded areas are colder-than-normal. (Redrawn from *Grosswetterlagen Europas*)

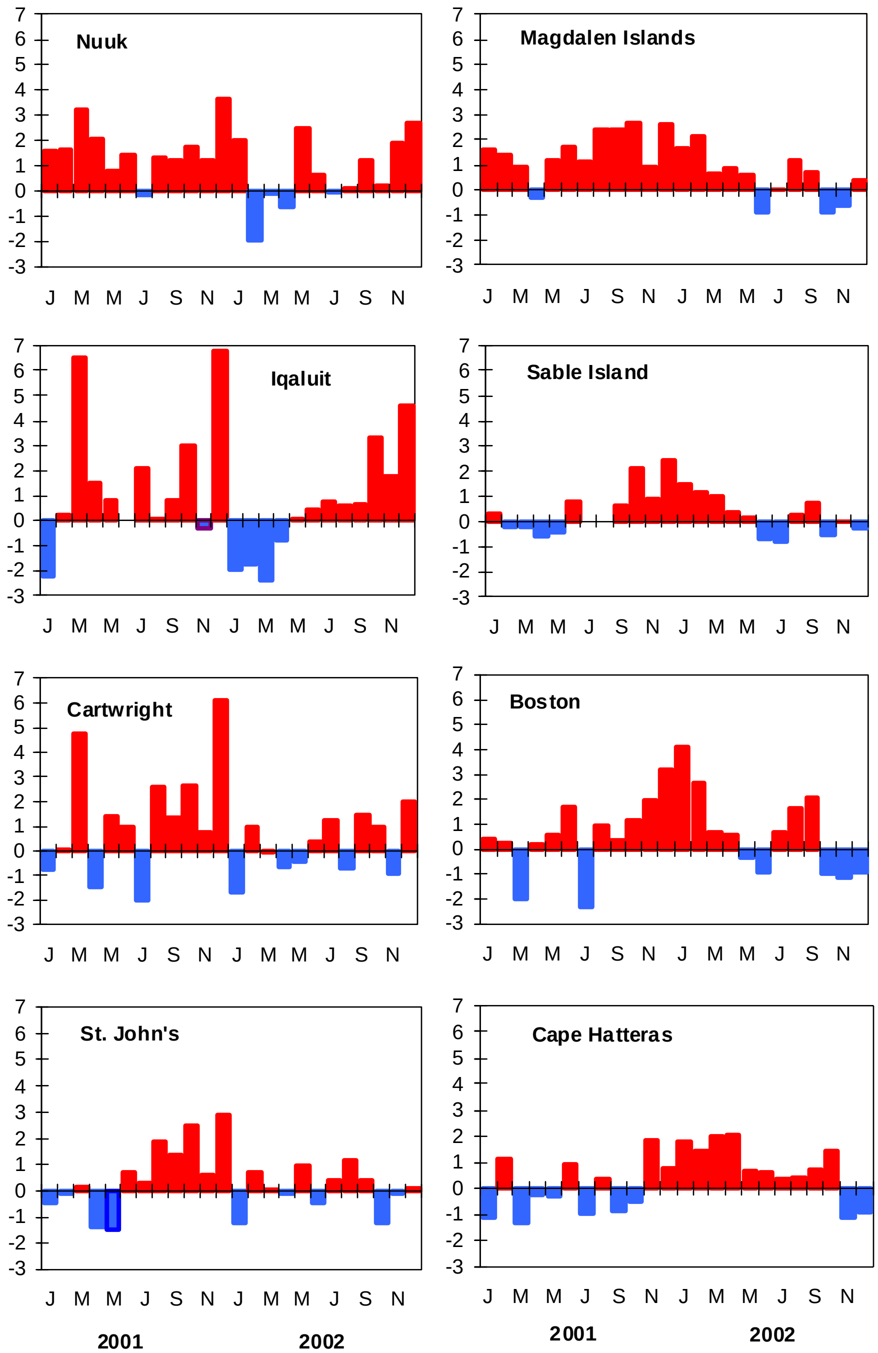



Fig. 3. Monthly air temperature anomalies in 2001 and 2002 at selected coastal sites (see Fig. 1 for locations).

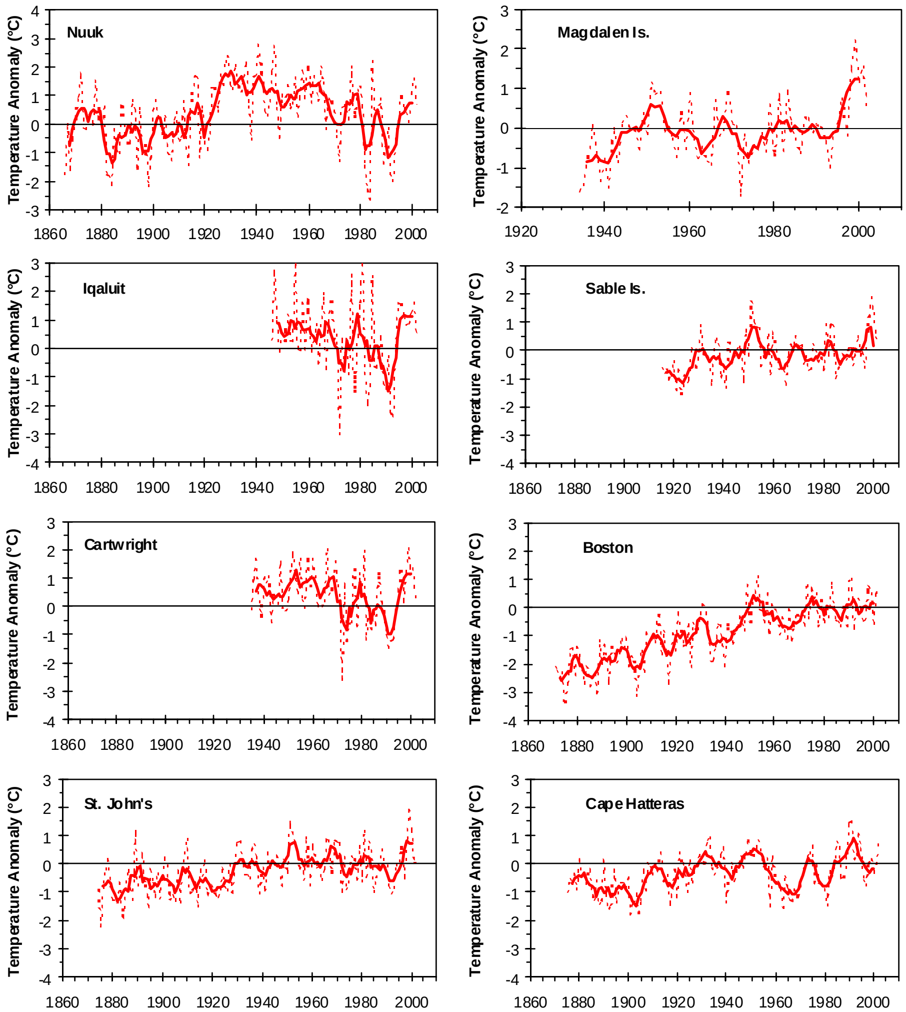



Fig. 4. Annual air temperature anomalies (dashed line) and 5-yr running means (solid line) at selected sites.

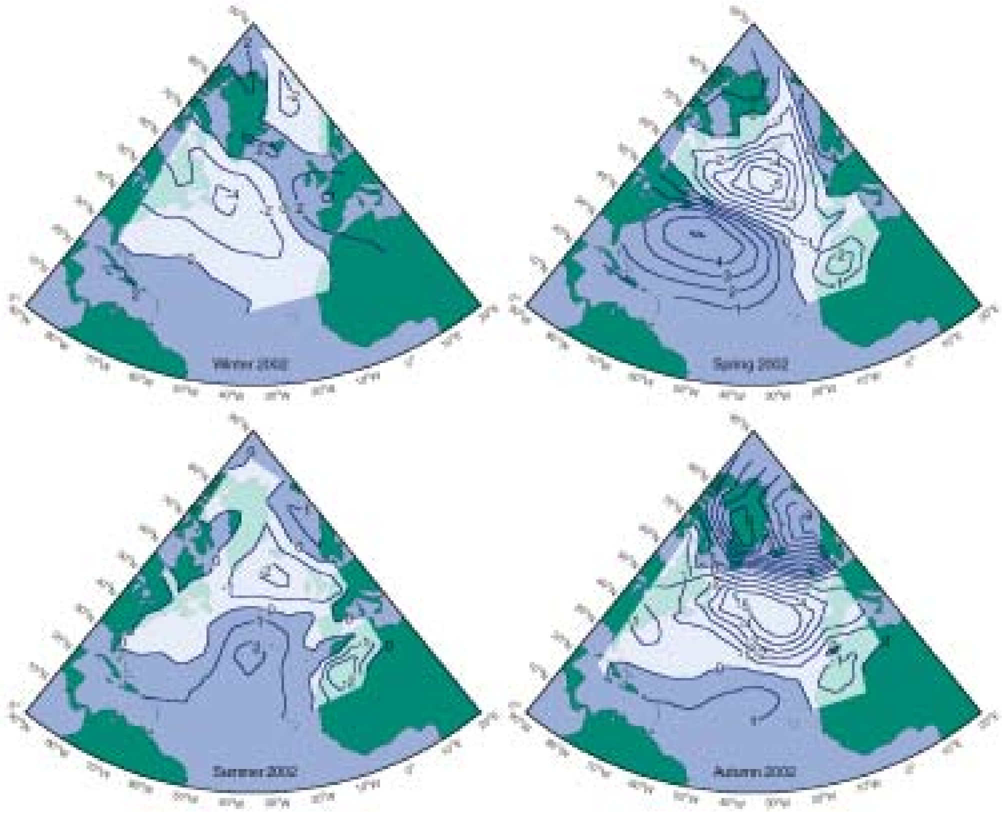



Fig. 5. Seasonal sea-surface air pressure anomalies (mb) over the North Atlantic in 2002 relative to the 1971-2000 means.

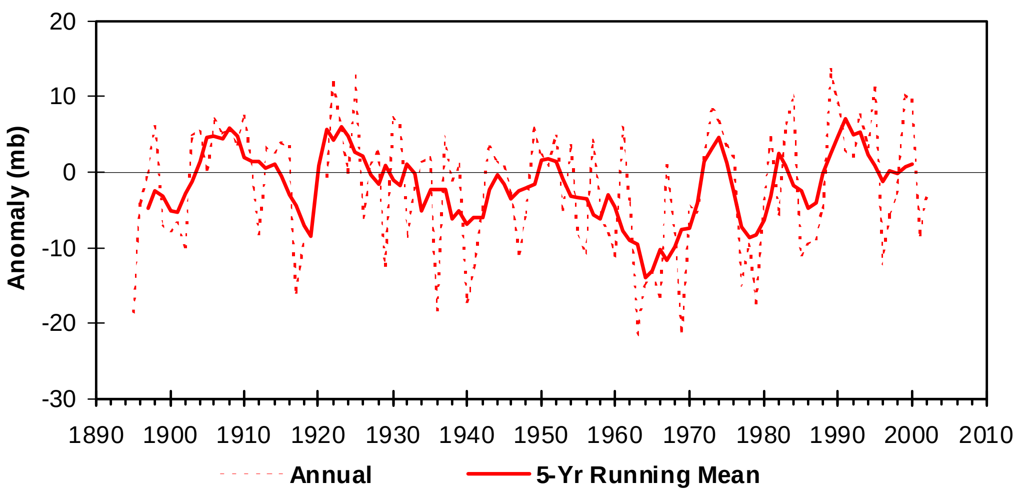



Fig. 6. Anomalies of the North Atlantic Oscillation Index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1971-2000 mean.

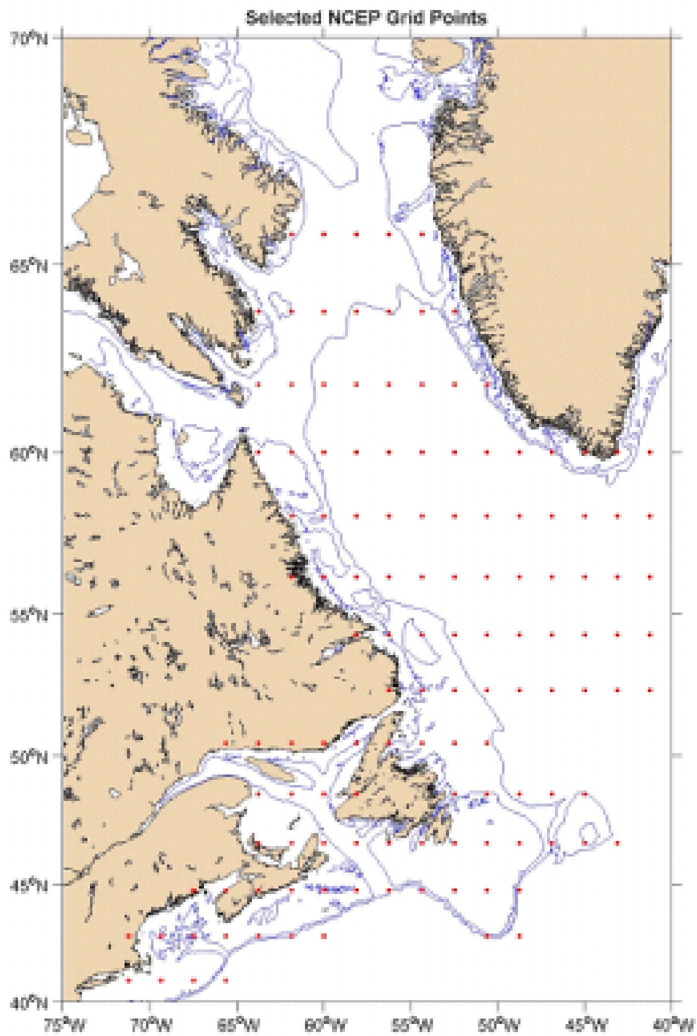



Fig. 7. The Northwest Atlantic showing the NCEP wind grids used in our study.

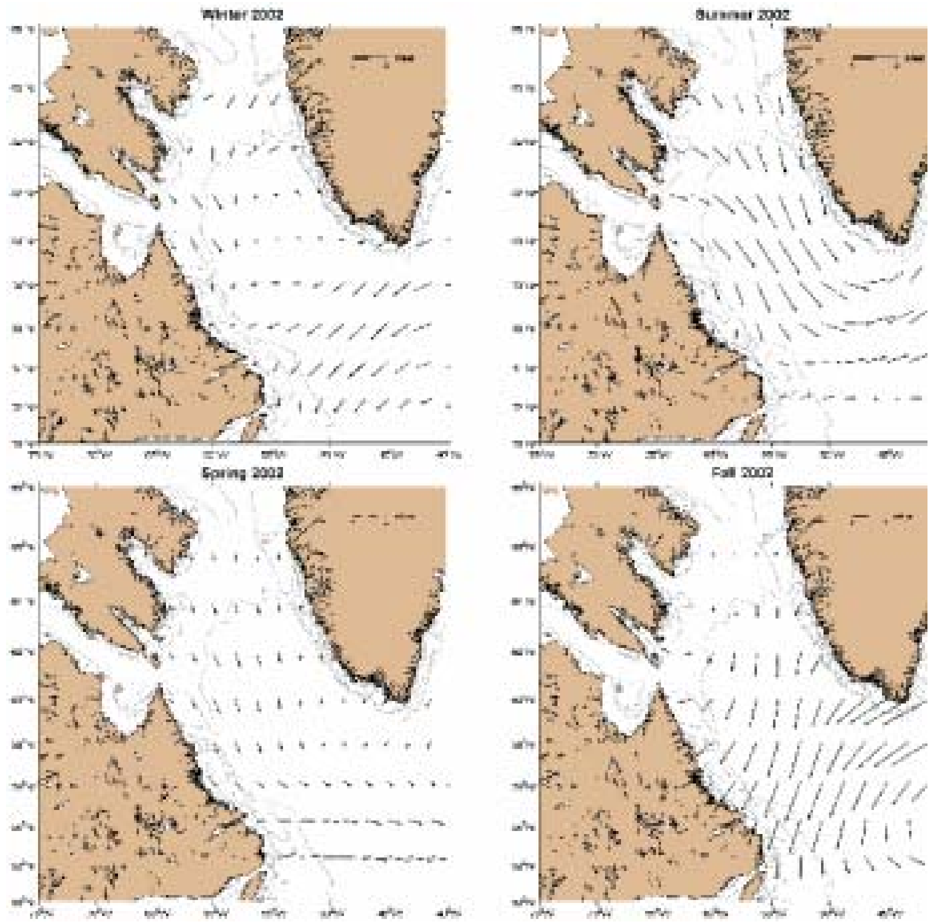



Fig. 8. The seasonal wind anomalies for the northern region during 2002.

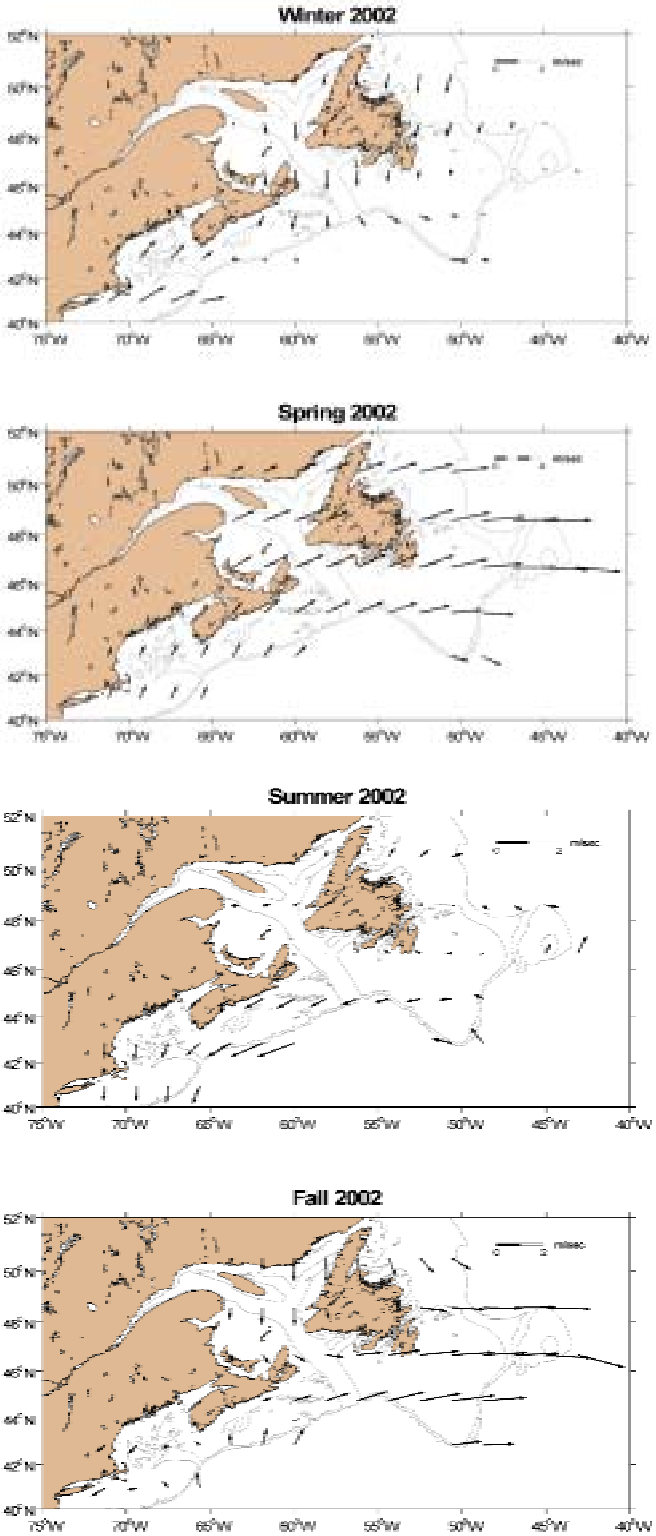



Fig. 9. The seasonal wind anomalies for the southern region during 2002.

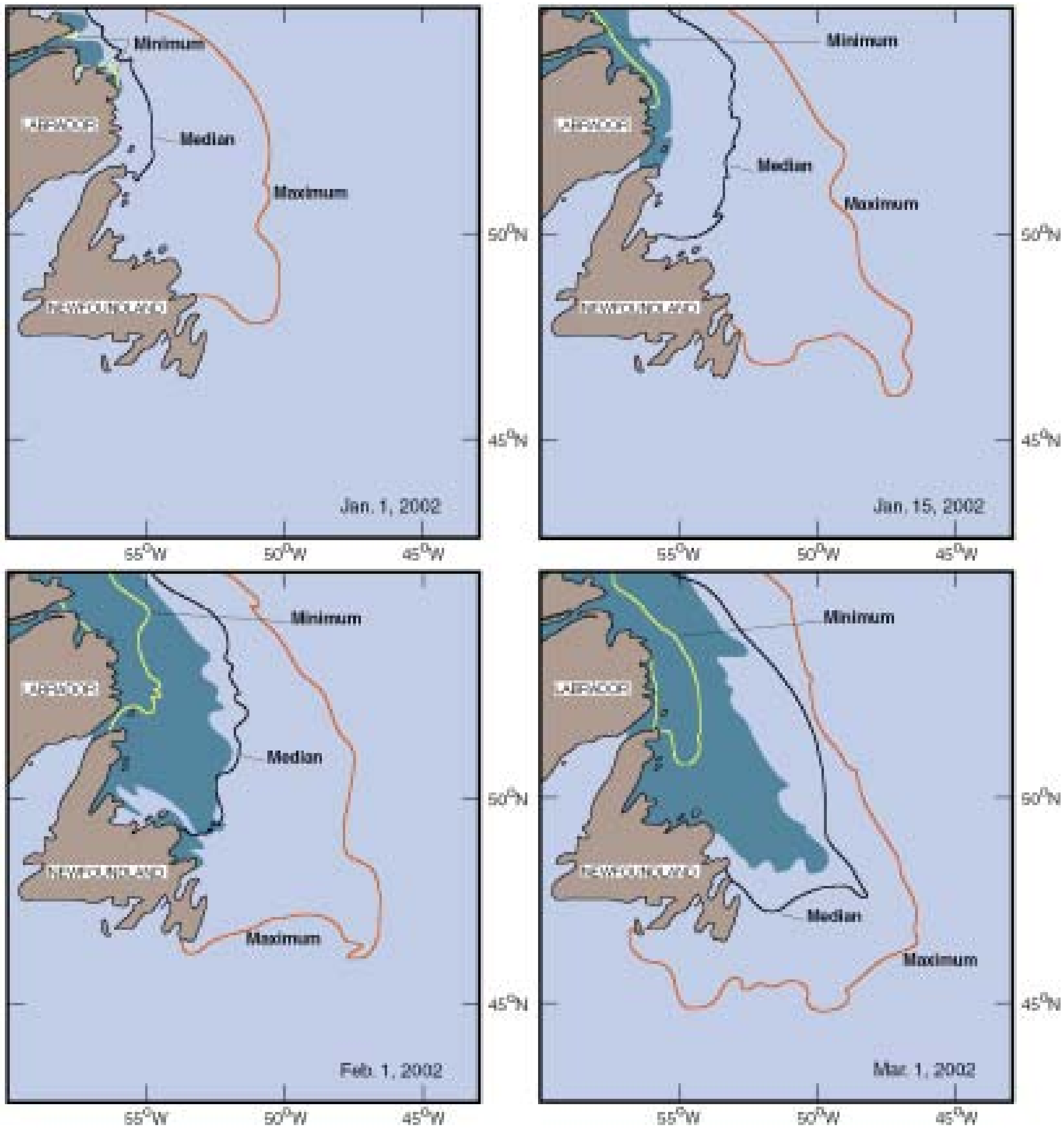



Fig. 10A. The location of the ice (shaded area) between January and March 2002 together with the historical (1971-2000) minimum, median and maximum positions of the ice edge off Newfoundland and Labrador.

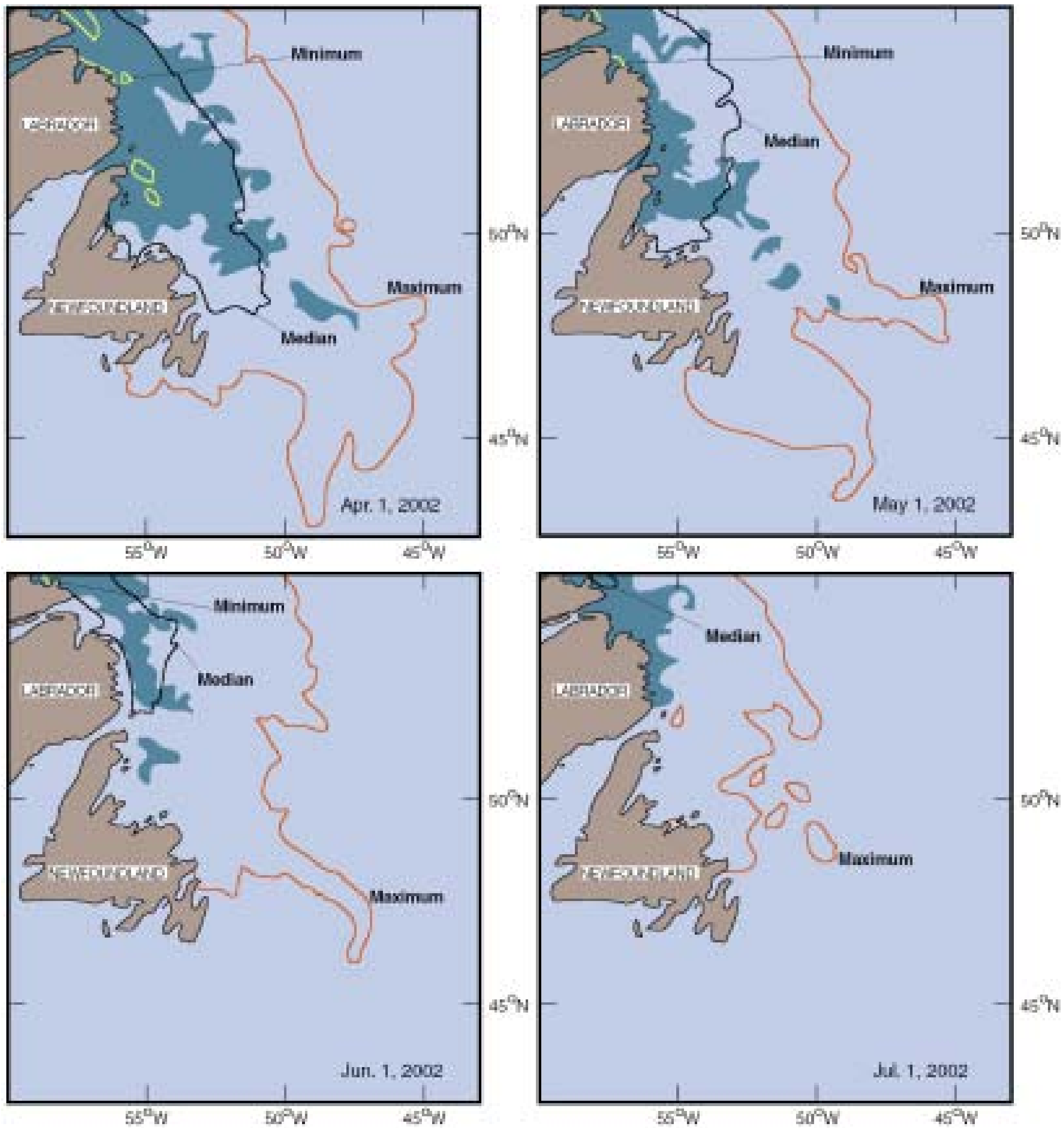
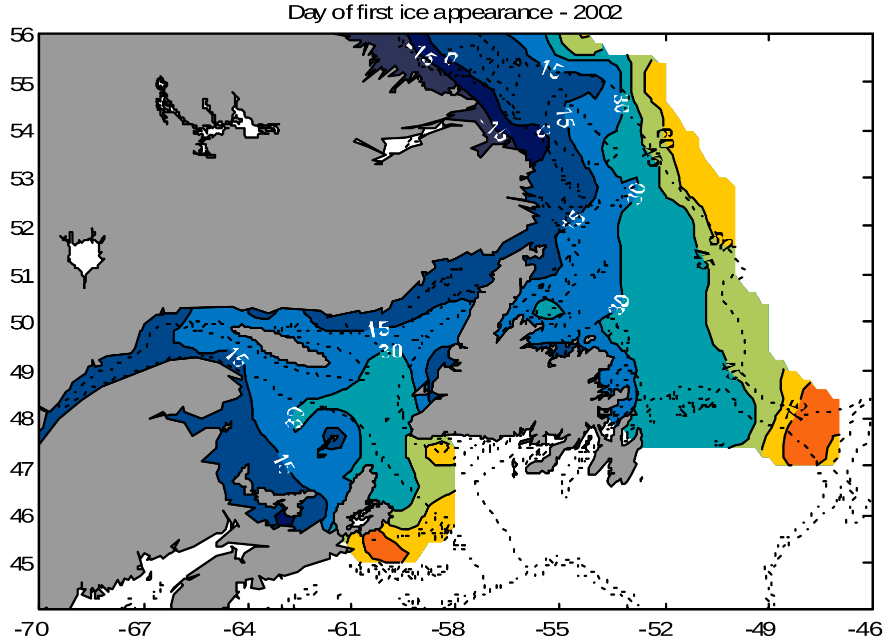



Fig. 10B. The location of the ice (shaded area) between April and July 2002 together with the historical (1971-2000) minimum, median and maximum positions of the ice edge off Newfoundland and Labrador.



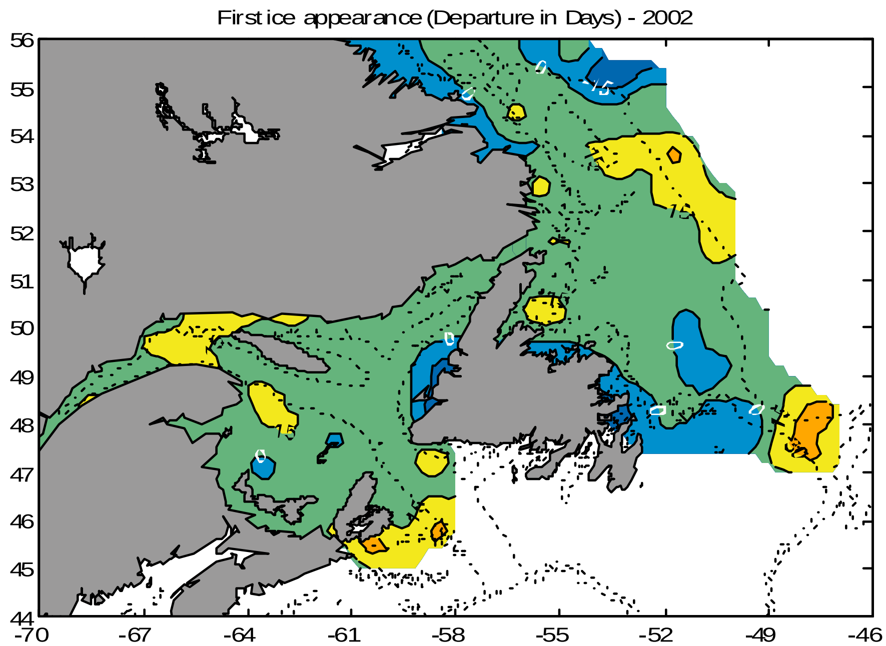




Fig. 11. The time when ice first appeared during 2002 in days from the beginning of the year (top panel) and its anomaly from the 1971-2000 mean in days (bottom panel). Negative anomalies indicating earlier than normal appearance are shaded blue.

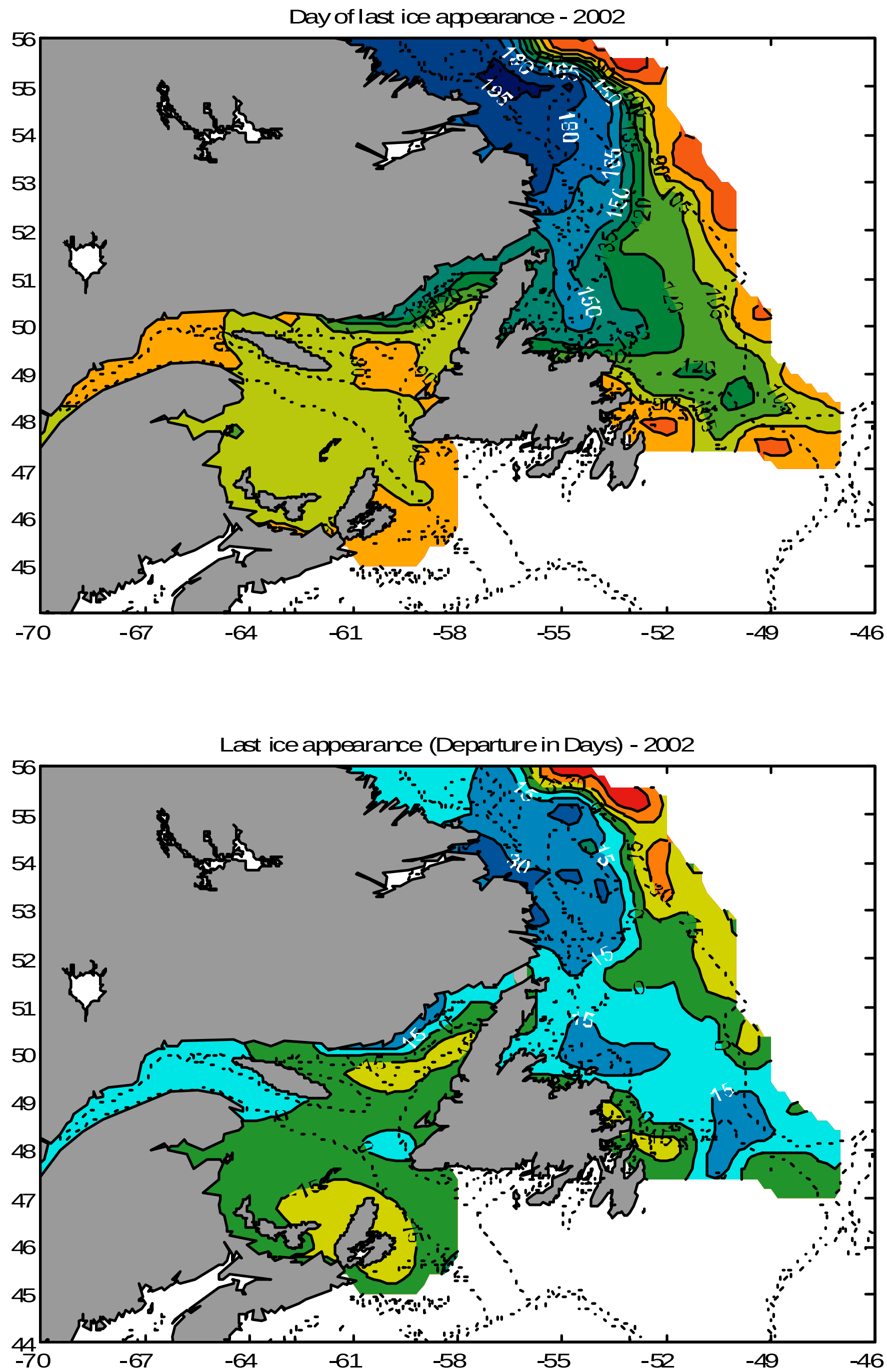



Fig. 12. The time when ice last appeared during 2002 in days from the beginning of the year (top panel) and its anomaly from the 1971-2000 mean in days (bottom panel). Negative anomalies, indicating later-than-normal disappearance, are shaded blue.

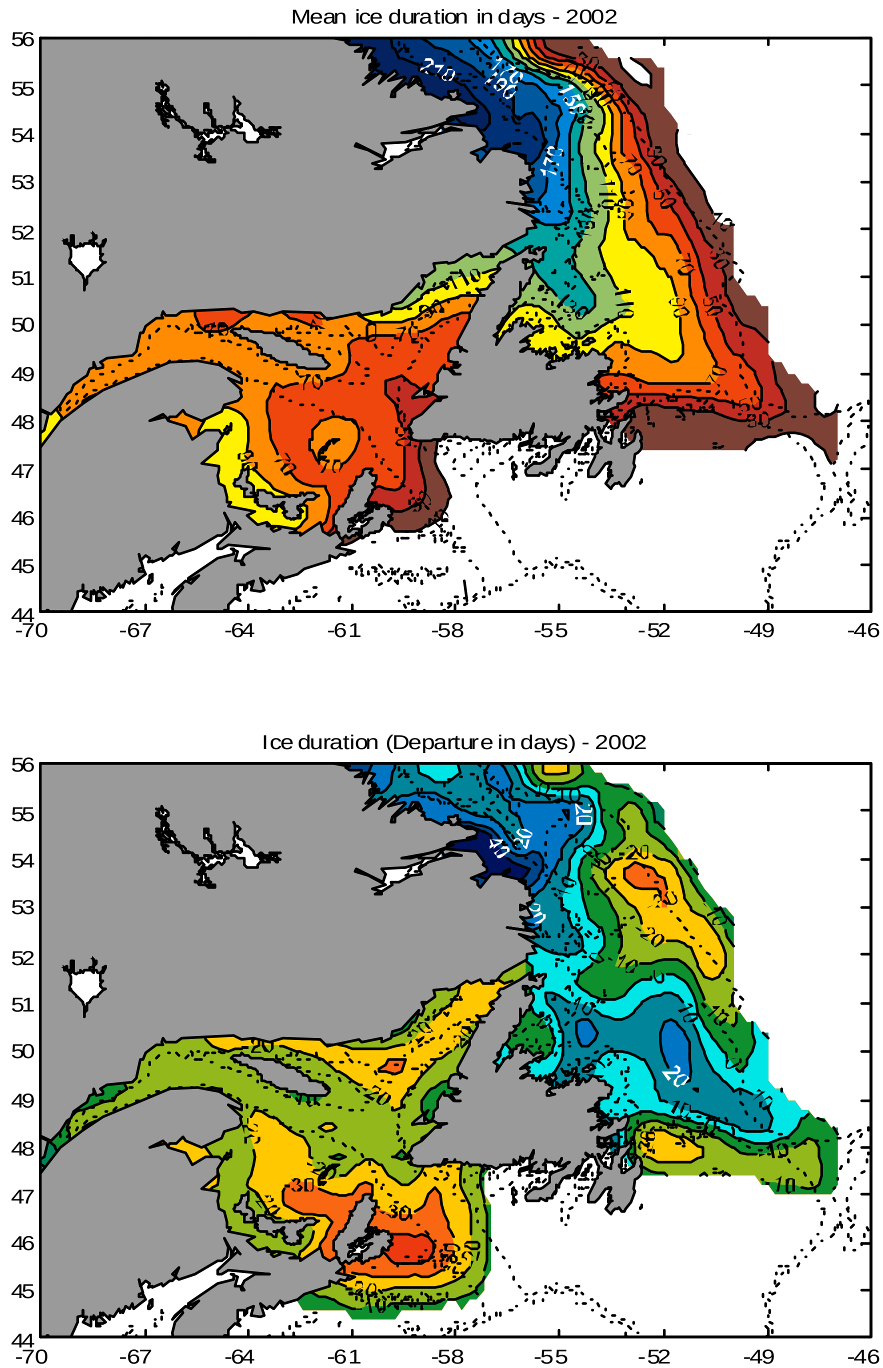



Fig. 13. The duration of ice in days (top panel) during 2002 and their anomaly from the 1971-2000 mean in days (bottom panel). The positive anomalies, which indicate durations longer than the mean, are shaded blue.

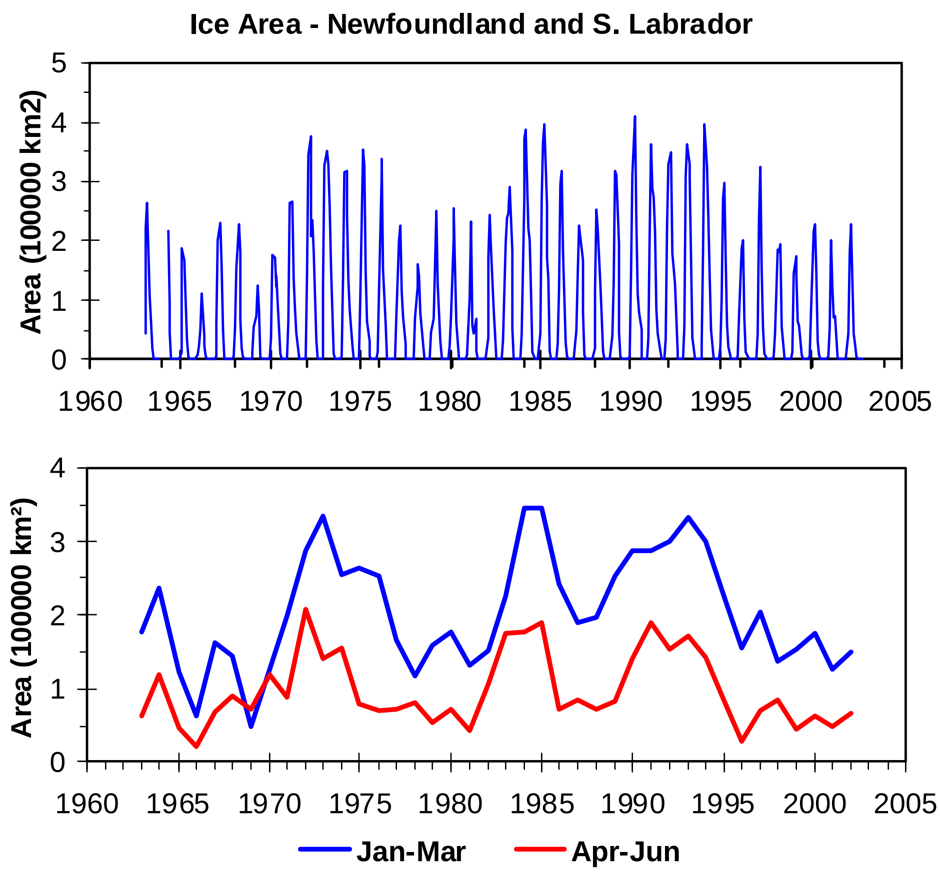



Fig. 14. Time series of the monthly mean ice area off Newfoundland and Labrador between 45°N-55°N (top panel) and the average ice area during the normal periods of advancement (January-March) and retreat (April-June) (bottom panel).

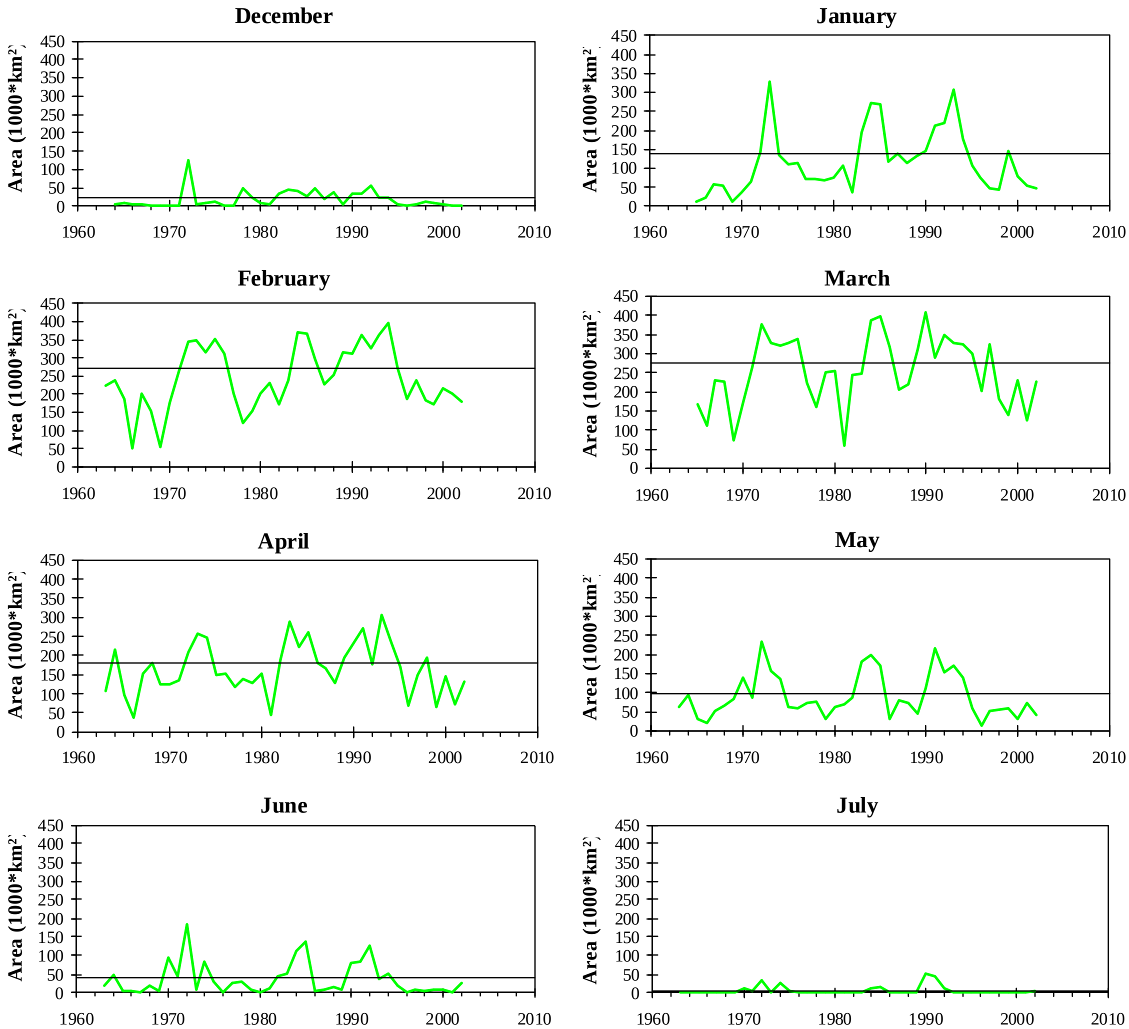



Fig. 15. The time series of ice area off Newfoundland and Labrador, by month. The horizontal lines represent the long-term (1971-2000) means.

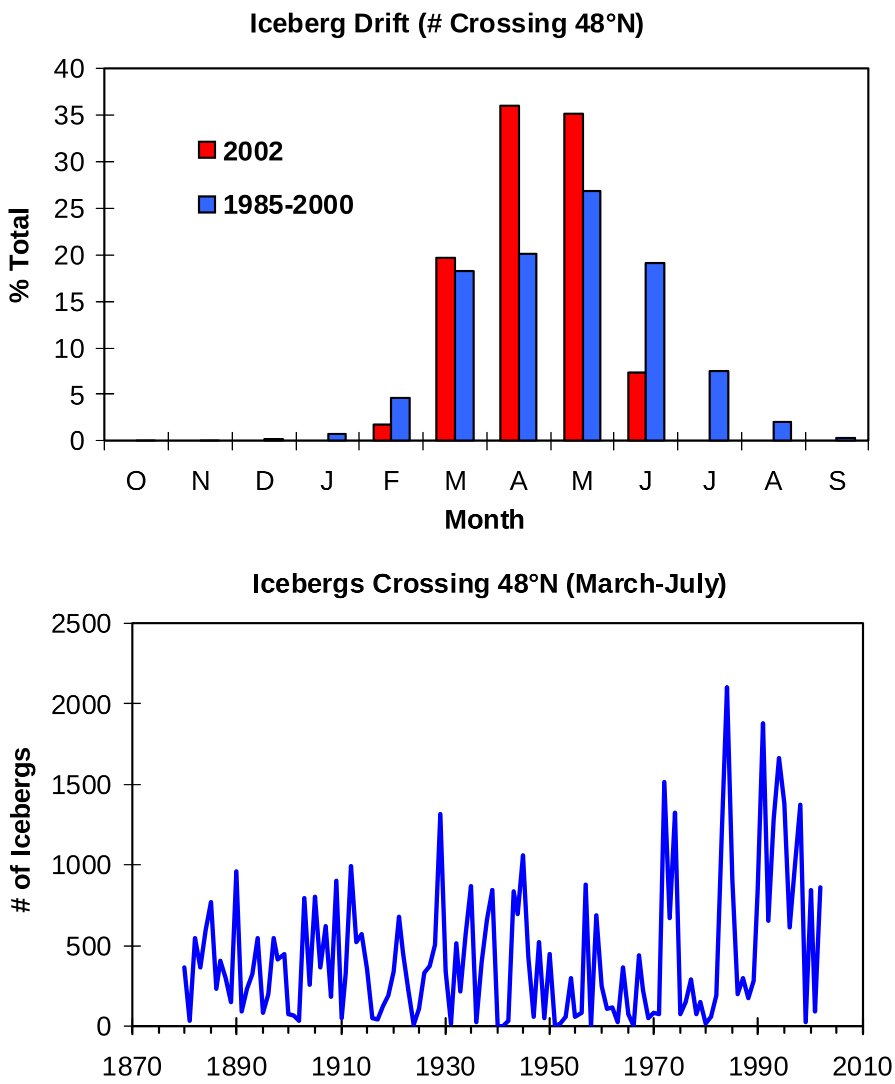



Fig. 16. The number of icebergs crossing south of 48°N during the iceberg season 2001/2002 expressed as a percent of the total by month compared to the mean during 1985-2000, the years SLAR has been used (top panel) and the time series of total number of icebergs observed during March to July (bottom panel).

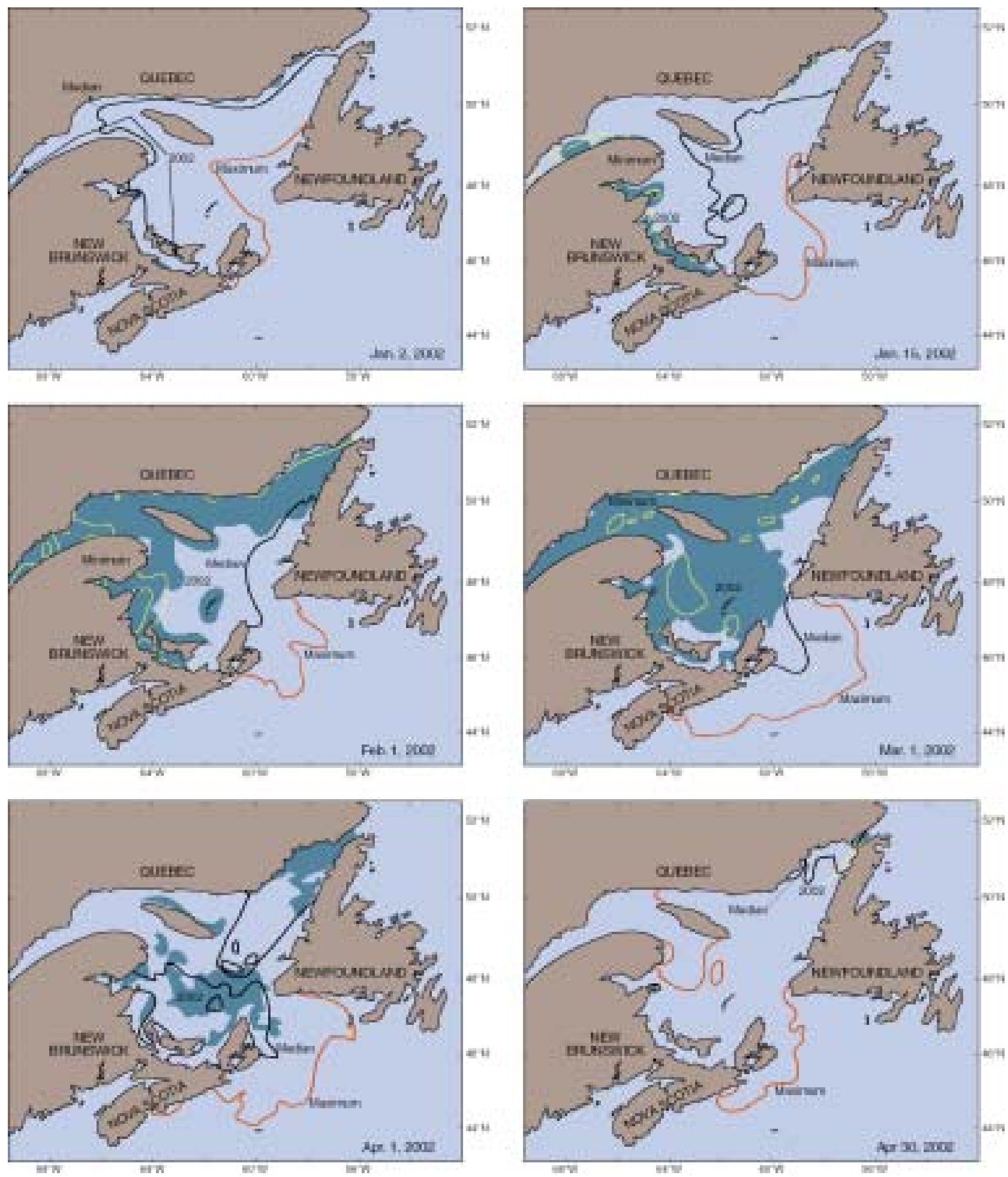



Fig. 17. The location of the ice (shaded area) between early January and late April 2002 together with the historical (1971-2000) minimum, median and maximum positions of the ice edge in the Gulf of St. Lawrence.

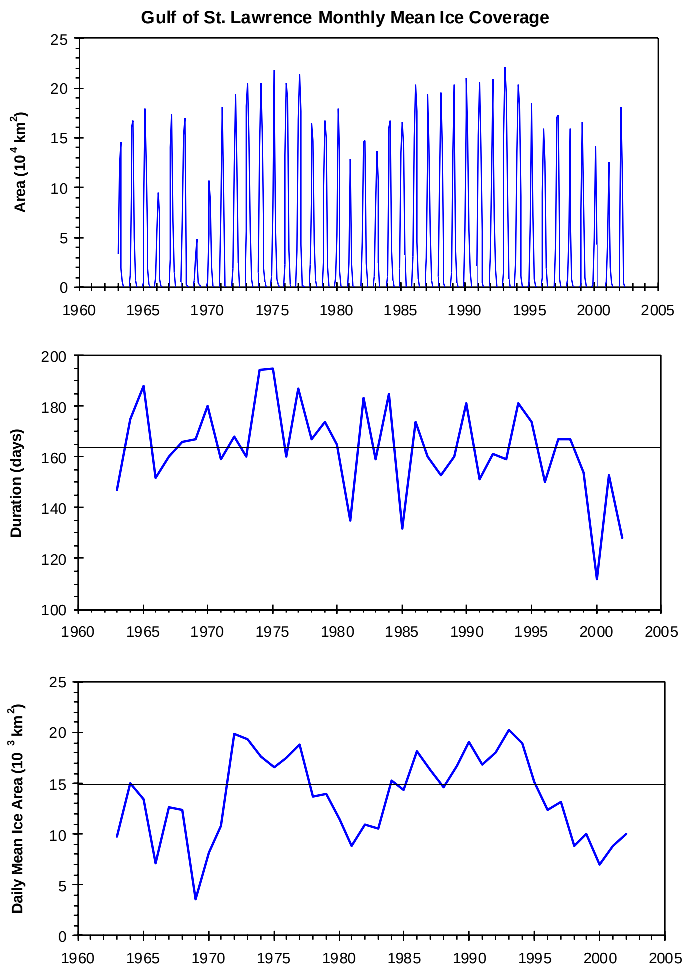



Fig. 18. For the Gulf of St. Lawrence, the time series of the monthly mean ice area (top), the duration of ice (middle) and the annual integrated ice area (summation of the area times the number of days). The horizontal lines represent the long-term (1971-2000) means.

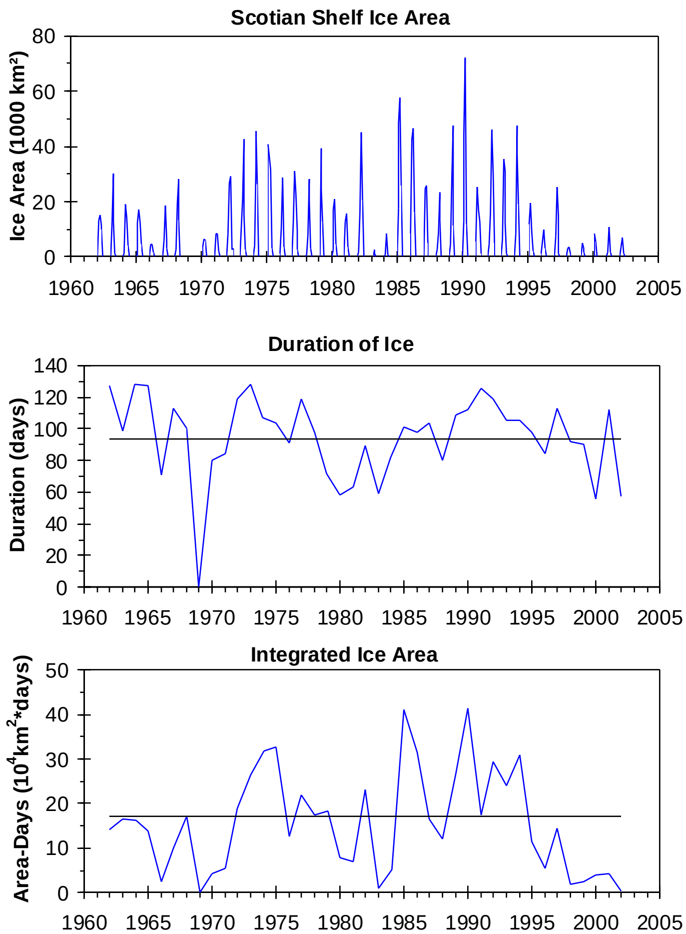



Fig. 19. For the region seaward of Cabot Strait, the time series of the monthly mean ice area (top), the duration of ice (middle) and the annual integrated ice area (summation of the area times the number of days). The horizontal lines represent the long-term (1971-2000) means.

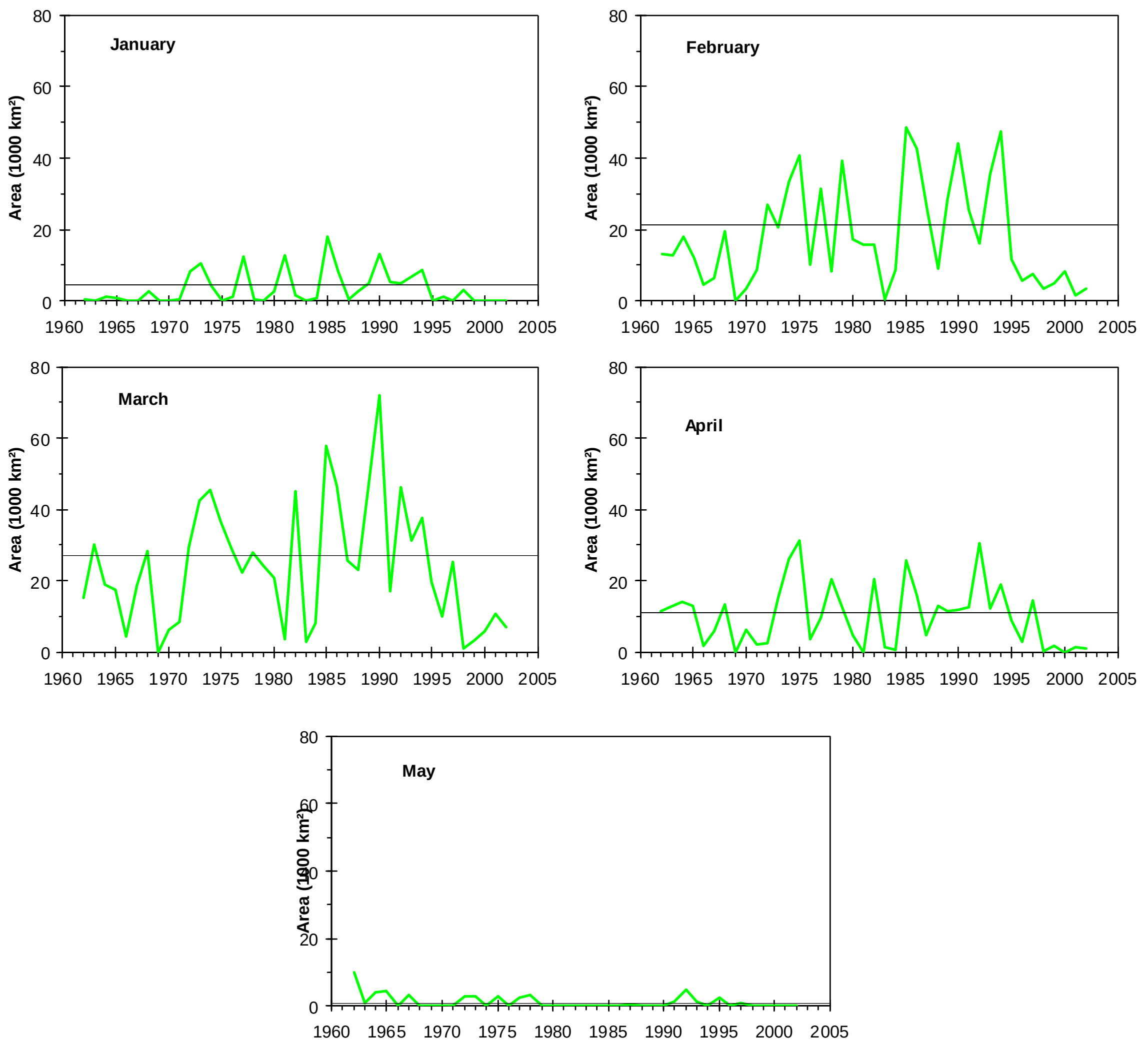



Fig. 20. The time series of ice area seaward of Cabot Strait, by month. The horizontal lines represent the 1971-2000 means.

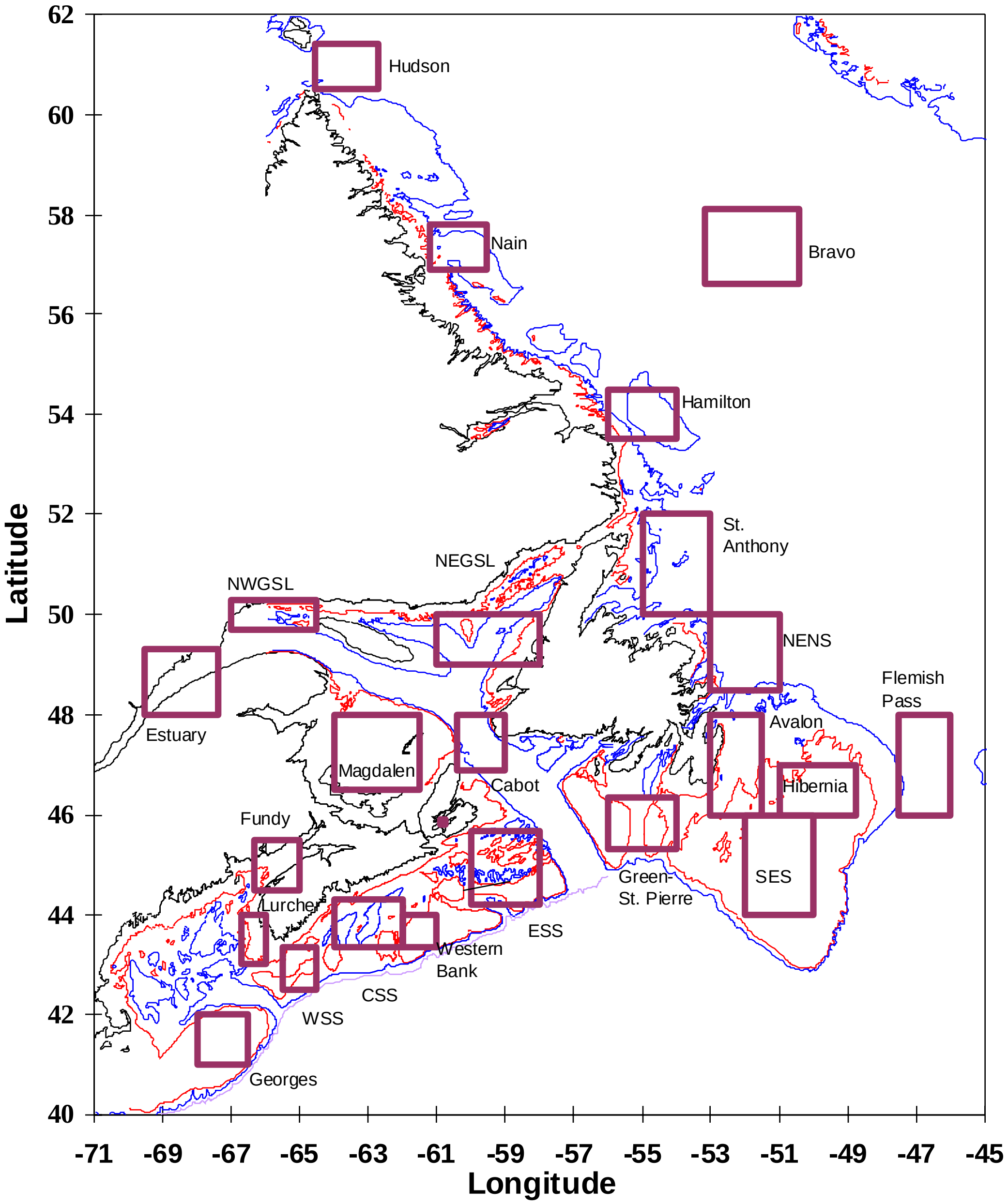



Fig. 21. The areas in the Northwest Atlantic used for extraction of sea-surface temperature.

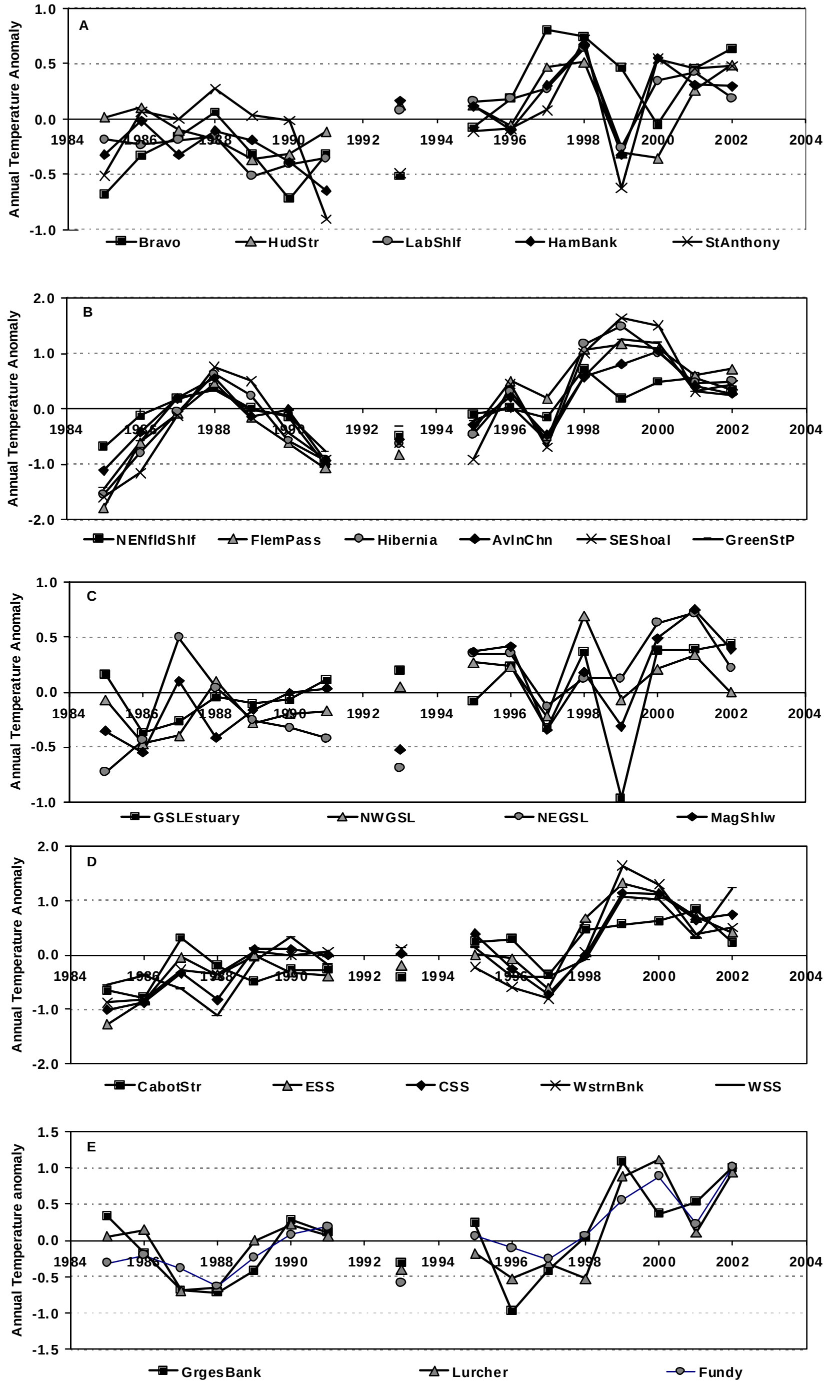



Fig. 22. The time series of sea surface temperature anomalies derived from satellite imagery compared to their long-term means: (A) Labrador, (B) Newfoundland, (C) Gulf of St. Lawrence, (D) Scotian Shelf and (E) Gulf of Maine.