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A Review of the Atmospheric and Sea-Ice Conditions in the Northwest Atlantic During the Decade, 1991-2000[1]

by

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Abstract

The atmospheric and sea ice conditions in the decade 1991-2000 are described. The NAO index in the 1990s was the highest in the past 11 decades and there has been a general increase from the minimum of the 1960s. This was accompanied by increasing southwesterly winds. Mean decadal air temperatures were above their long-term means throughout the NAFO area with the exception of West Greenland with record high decadal means in the Gulf of St. Lawrence and at Cape Hatteras. Air temperatures have generally been increasing since the 1960s from the Scotian Shelf northward. Sea-ice conditions off the Labrador and northern Newfoundland coast, in the Gulf of St. Lawrence and the Scotian Shelf indicate the least amount of ice in the 1960s. From Labrador to the Gulf there was little difference in ice severity between the 1970s, 1980s and 1990s, however, on the Scotian Shelf ice area was less during the 1990s compared to the previous two decades. The decadal mean of the number of icebergs drifting along the Labrador and Newfoundland shelves was at a maximum during the 1990s. There has been large intra-decadal variability in all variables. Within the decade of the 1990s, the early years were characterized by high NAO indices, strong northwesterly winds, cold temperatures from the Labrador Sea to the Gulf of Maine, and extensive ice cover. In 1996, the NAO index experienced its largest annual decline in the over 100-year record. During the remaining years of the 1990s decade, the NAO rose achieving values that even exceeded those of the early years of the 1990s. Of significance during the latter half of the decade was the eastward shift in the anomalous pressure fields. In the Northwest Atlantic, the latter half of the decade saw weaker northwesterly winds, warmer temperatures in the Labrador Sea to the Gulf of Maine, and a reduction in sea-ice.

Introduction

The atmosphere is an important forcing mechanism for both the ocean circulation, its hydrography and marine productivity. It affects temperature through air-sea fluxes (sensible and latent heat) and the vertical distribution of the heat through wind mixing. It also affects salinity directly through precipitation, and indirectly through river runoff. The extent of the vertical mixing determines the timing and strength of the spring bloom of phytoplankton, which is the base of the food chain. Sea-ice also affects the physical and biological components of the marine ecosystem. It restricts atmospheric exchanges including momentum fluxes and removes freshwater during ice formation and releases it during melting. Many fish stocks migrate out of ice-covered regions during the winter and the timing of their return can be determined by the disappearance of the ice (Sinclair and Currie, 1994). Changes in the atmosphere and sea-ice conditions can substantially impact the physical oceanography and subsequently its biology.

The atmospheric and sea ice conditions in the NAFO area of the Northwest Atlantic are known to undergo variability at a variety of time scales from days to centuries. The largest variance typically is at the annual cycle. For example, the yearly cycle accounts for >85% of the total variability in the time series of monthly mean air temperatures. Although smaller than the annual cycle, there still is significant variance at time scales from greater than one year to tens of years.

[1] Mini Symposium on "Environmental Conditions in the NAFO Water of the Northwest Atlantic during the Decade of the 1990s".

While there is nothing special in nature about decades, human's fixation upon multiples of 10 (decades, centuries and millennium) usually result in reviews of the previous decade, century or millennium. We, as scientists are no different and decadal reviews of climate conditions or progress within a certain field is common. NAFO has a long tradition of decadal or near decadal reviews, beginning with a review of the 1950s. While it is useful to regularly review what environment conditions in an attempt to synthesize events and to clarify our thinking, it must be remembered that many of the climate trends and processes have much longer time scales than 10 years.

This paper examines meteorological (air pressures, winds, air temperatures) and sea-ice conditions in the Northwest Atlantic during the period 1991-2000, hereafter referred to as the 1990s. It compares this decade to conditions during previous decades and also discusses inter-decadal variability. It forms part of the decadal review of environmental conditions in the NAFO Area.

Data and Methods

The meteorological variables examined include air pressures and the related North Atlantic Oscillation (NAO) index, winds and air temperatures for all NAFO regions. The sea ice conditions are restricted to NAFO Subareas 2 through 4 and include ice area and iceberg numbers that drift down the Labrador and Newfoundland shelves.

Monthly sea pressure data gridded throughout the North Atlantic are from the German Weather Service's monthly publication *Grosswetterlagen Europas.* The monthly 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. These data are published in the NOAA publication *Monthly Climatic Data for the World.* The small number of missing data early in the time series was filled using pressures from nearby stations. The re-analyzed NCEP (National Centre for Environmental Prediction) – NCAR (National Center for Atmospheric Research) winds were obtained from the International Research Institute of the Lamont-Doherty Earth Observatory at Columbia University.

Air temperatures were obtained for eight representative stations throughout the Northwest Atlantic including Nuuk in Greenland, Iqaluit on southern Baffin Island, Cartwright on the southern Labrador Coast, St. John's in eastern Newfoundland, the Magdalen Islands in the central Gulf of St. Lawrence, Sable Island on the Scotian Shelf off Nova Scotia, Boston in the southern Gulf of Maine and Cape Hatteras at the southern tip of the Middle Atlantic Bight. The monthly means from the Canadian sites were taken from the Environment Canada website and for non-Canadian locations from *Monthly Climatic Data for the World*.

Information on the location and concentration of sea ice is available from the daily ice charts published by Ice Service of Environment Canada in Ottawa. These daily charts are digitized onto a grid 0.5° latitude by 1° longitude for Newfoundland (Peterson and Prinsenberg, 1990) and for the Gulf of St. Lawrence and the Scotian Shelf (Drinkwater et al., 1999). The databases begin in the early 1960s and continue to the present. The U.S. Coast Guard publishes the number of icebergs that cross southward of 48°N by month. This latitude approximately delineates the northern edge of the Grand Banks.

Anomalies were calculated by subtracting the 1971-2000 mean, unless otherwise stated. In the case of sea-ice only data during those years ice was present were used.

Results

Air Pressure Patterns and The North Atlantic Oscillation (NAO)

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. The High and Low occur year round but are most intense in winter. Their strengths vary year-to-year with the tendency for both pressure systems to intensify (or weaken) in the same year. This is known as the NAO (North Atlantic Oscillation). It is the most robust of all of the recurrent modes of atmospheric behaviour in the world being present in all months of the year (Barnston and Livezey, 1987). Rogers (1984) defined an NAO index based upon the difference in the average pressure during December, January and February between Iceland and the Azores. Later, Hurrell (1995) used pressure differences between Iceland and Lisbon in Portugal (December through March) in order to extend the time series further back in time. A high NAO index (positive phase) occurs when the pressure systems weaken and a low index (negative phase) when they strengthen. The NAO index varies greatly from year-to-year but with discernible longer period trends. The index, which is a latitudinal pressure gradient, reflects the strength of the westerly winds across the northern North Atlantic. Generally, it also means stronger northwest winds over the Labrador Sea (Drinkwater, 1996). In such years, these northwest winds carry cold Arctic air masses further south causing winter air temperatures to decrease and greater formation of sea ice. (Colbourne et al., 1994; Drinkwater, 1996).

The mean winter (December, January and February) air pressure over the North Atlantic for the 1990s reveals the presence of the Icelandic Low and the Azores High (Fig. 1). Relative to the previous 9 decades, the NAO index in the 1990s was the highest on record and has climbed steadily from the minimum of the 1960s (Fig. 2). This is indicative of an increase in the intensity of the large-scale atmospheric circulation over the North Atlantic Ocean. Within the decade of the 1990s, the index was relative high in the early years (Fig. 2). In 1996, however, it declined rapidly from the previous year's high positive anomaly to a large negative anomaly as the Icelandic Low and Azores High weakened. This was the largest annual decline in the NAO index in its over 100-year record. After 1996, the index rose steadily as the pressure systems intensified. By the late 1990s, the index had returned to values equivalent to those recorded in the early years of the decade. In spite of these changes, the within decade variability of the NAO during the 1990s as measured by the standard deviation was slightly lower than had been observed in each of the previous three decades (Fig. 2).

In addition to the temporal changes in the index, an eastward shift in the spatial pattern of the anomalous pressure patterns occurred after 1995. The centers of the anomalous pressures moved over the northeastern sector of the North Atlantic. This had important ramifications on conditions in the Northwest Atlantic. With the eastward shift of the Icelandic Low, the pressure gradients in the northwest declined and with it the strength of the correlations between the NAO and the atmospheric and sea ice conditions also declined.

Winds

Winds are important in driving ocean currents and ice drift, promoting heat exchange between the atmosphere and the ocean, and causing vertical mixing of the water column. They are also related to the air pressure fields through geostrophy, i.e. winds tend to blow perpendicular to the pressure gradients with the high pressure on the right looking downwind. Thus, winds move clockwise around a high and counterclockwise around a low.

Seasonally, the winter winds tend to be the most intense. They determine the extent of the winter mixing, including the depth of convection in the Labrador Sea. During the 1990s, the winter winds in the northern Labrador Sea and in the Gulf of Maine and southwestern Scotian Shelf were predominantly northwesterly (Fig. 3). Elsewhere the winds were shifted more westerly. Relative to the previous four decades, these winds were generally more westerly (Fig. 4).

Five sites were chosen to represent winds over the Labrador Sea. These included ones in central Davis Strait, central Labrador Sea, the southern entrance to the Labrador Sea, one half way up on the Labrador side and another near Fylla Bank on the West Greenland side. A time series of winter winds was developed by averaging the wind components resolved along 315 and 45 degrees, which lay approximately along and across the axis of the Sea, respectively. The predominant winds are from the northwest with a long-term mean wind speed near 4 ms^{-1} (Fig. 5). These show near equal decadal means for all decades except the 1960s when it was below 3 ms^{-1}. The largest change came in the cross-sea component where the southwesterly wind component increased steadily from the 1960s from near zero to 1.5 ms by the 1990s.

Again, however, the decadal means hide significant intradecadal variability (Fig. 5). The northwesterly winds were stronger during the early years of the 1990s, declined dramatically in 1996 when the NAO also declined significantly and then rose in the later years of the 1990s but never recovering to the levels of the early part of the decade. The similarity of the winds with the NAO is consistent with earlier periods with approximately 50% of the variance in the winter northwesterly winds being accounted for by the NAO (Fig. 6). For the cross-sea component, the winter winds throughout the decade were southwesterly. They were of higher magnitude in the early years of the decade, declined in the middle years and rose again towards the end. Although the NAO also accounts for some of the variability in the cross-sea component of the wind stress, it is less (30%) than for the along-sea component.

Air temperatures

Annual air temperatures were selected at eight sites throughout the NAFO area (Fig. 7). Decadal means at the eight sites show several interesting features. First, the 1990s were above the 1971-2000 mean at all sites except for Nuuk (Fig. 8). The amplitude of the anomalies was between 0 and 0.5°C. At two sites, the Magdalen Islands and Cape Hatteras, the 1990s set decadal highs. In the case of the latter, the time series spans 13 decades. The decadal means show the consistent cold period in the 1800s and into the first few decades of the 1990s in the southern sites. Also, the dramatic warming in the northern North Atlantic during the 1920s and 1930s are evident at Nuuk and follow later at several of the other northern sites.

The within decade variability during the 1990s differs between sites. At most of the sites the early part of the decade experienced cold conditions but warmed substantially towards the latter half (Fig. 9). During 1999, historic high annual means were observed from southern Labrador to the Gulf of Maine and significantly higher at some sites such as the Magdalen Islands. At the southern sites, this trend reverses and at Cape Hatteras, for example, the annual air temperatures were highest in the early years of the 1990s and declined through to the later years (Fig. 9). The year 1999 experienced below normal air temperatures, in contrast to the historic highs of some of the northern sites.

Sea Ice

Newfoundland

The monthly mean areal extent of the sea ice on the Newfoundland Shelf was determined for each decade from the 1960s when the records began. These show that the 1990s were similar to the 1970s and 1980s but were well above the 1960s (Fig. 10). The later decade had peak areas approximately two-thirds those of the other decades. As with the air temperatures and winds, the decadal means mask large intradecadal variability (Fig. 10). Ice area was most extensive during the early years of the 1990s but declined to relative low levels in the latter half of the decade. These are consistent with the air temperatures and winds, with cold temperatures and stronger northwesterly winds accompanying years of greater ice extent and warmer temperatures and weaker northwesterly winds during years of smaller sea ice extent. The time series is dominated by peaks in the early 1970s, 1980s and 1990s, which also correspond to periods of coldest temperatures and strongest northwest winds in winter.

Gulf of St. Lawrence

The area of ice with the Gulf of St. Lawrence by month and averaged by decade also shows a pattern similar to that seen in Newfoundland waters, although the total area is much less. The 1960s again stands out from the other decades, there being much less ice in the sixties (Fig. 11). The 1990s were slightly more distinguishable from the 1970s and 1980s than off Newfoundland, being slightly later in forming than during the other two decades. The within decade variability also shows similarity with Newfoundland with the maximum ice extent during the decade occurring in the early years of the 1990s and declining to relatively low levels in the later half of the decade (Fig. 11). The latter were the lowest amount of sea ice in the Gulf since the 1960s. The peak ice extent occurred in the early 1970s and between the late 1980s and early 1990s.

Scotian Shelf

The area of ice seaward of Cabot Strait, shows the lowest values during the decade of the 1960s (Fig. 12). However, unlike Newfoundland and the Gulf, there was much less sea ice during the 1990s than in the 1970s and 1980s. Although the total area of sea-ice is much less than in Newfoundland and the Gulf of St. Lawrence, the variability is much larger. This is perhaps not surprising given that the Scotian Shelf is at the southern limit of sea ice in the western North Atlantic and will depend much more upon advection than ice formation. The advection will depend upon wind strength and direction and the ocean currents while whether the ice melts or not will depend upon the ocean and air temperatures and wind-induced waves. Similar to Newfoundland and the Gulf, however, the largest areal extent of ice on the Scotian Shelf was during the early years of the 1990s and then declined to relatively low values in the latter half of the decade. These latter years have been the longest extended period of reduced ice extent since the 1960s.

Icebergs

The number of icebergs that have been observed to cross south of 48°N has been recorded since the late 1800s. The decadal means of the numbers that cross during the months March through July, which typically is 95% of the total number of icebergs that cross 48°N, reveal relatively equal numbers from the late 1800s until the 1950s (Fig. 13). During that decade and the 1960s, the number of icebergs declined but then increased steadily through to the maximum number in the 1990s. Indeed, the average number of icebergs increased by almost a factor of two from the 1980s to the 1990s. Within the decade the iceberg numbers fluctuated interannually but with a general decreasing trend (Fig. 13). The numbers in 1999, which was the warmest year on record in the southern Labrador and Newfoundland area, were the lowest since 1980.

Summary

This paper has examined the meteorological and sea ice conditions in the Northwest Atlantic, with emphasis upon the period 1991-2000. Decadal means were used to compare conditions during this decade with past decades. The NAO index in the 1990s was the highest in the past 11 decades and there has been a general increase in the NAO index from the minimum of the 1960s. The high in the 1990s indicates a stronger atmospheric circulation with an intensified Icelandic Low and Azores High. While there was little change in the strength of the northwesterly wind component over the Labrador Sea during the 1990s compared to other decades, there was a significant increase in the southwesterly wind component. Mean decadal air temperatures were above their long-term means throughout the NAFO area with the exception of West Greenland. Indeed, record high decadal means were observed in the Gulf of St. Lawrence (Magdalen Islands) and at Cape Hatteras (southern Middle Atlantic Bight). At most sites, air temperatures have been increasing since the 1960s. Two dominant features of the decadal means are the low temperatures during the late 1800s and early decades of the 1900s throughout the NAFO area and the very warm temperatures in the northern sites, especially on West Greenland, beginning in the 1920s and extending at some sites into the 1970s. Sea-ice conditions off the Labrador and northern Newfoundland coast, in the Gulf of St. Lawrence and the Scotian Shelf indicate the least amount of ice in the 1960s. From Labrador to the Gulf there was little difference in ice severity between the 1970s, 1980s and 1990s, however, on the Scotian Shelf ice area was least during the 1990s compared to the previous two decades. The decadal mean number of icebergs drifting along the Labrador and Newfoundland shelves was at a maximum during the 1990s.

There has been large intra-decadal variability in all variables. Within the decade of the 1990s, the early years were characterized by high NAO indices, strong northwesterly winds, cold temperatures from the Labrador Sea to the Gulf of Maine and extensive ice cover. In 1996, the NAO index experienced its largest annual decline in the over 100-year record. During the remaining years of the 1990s decade, the NAO rose achieving values that even exceeded those of the early years of the 1990s. Of significance during the latter half of the decade was the eastward shift in the anomalous pressure fields. In the Northwest Atlantic, the latter half of the decade saw weaker northwesterly winds, warmer temperatures in the Labrador Sea to the Gulf of Maine, and a reduction in sea-ice.

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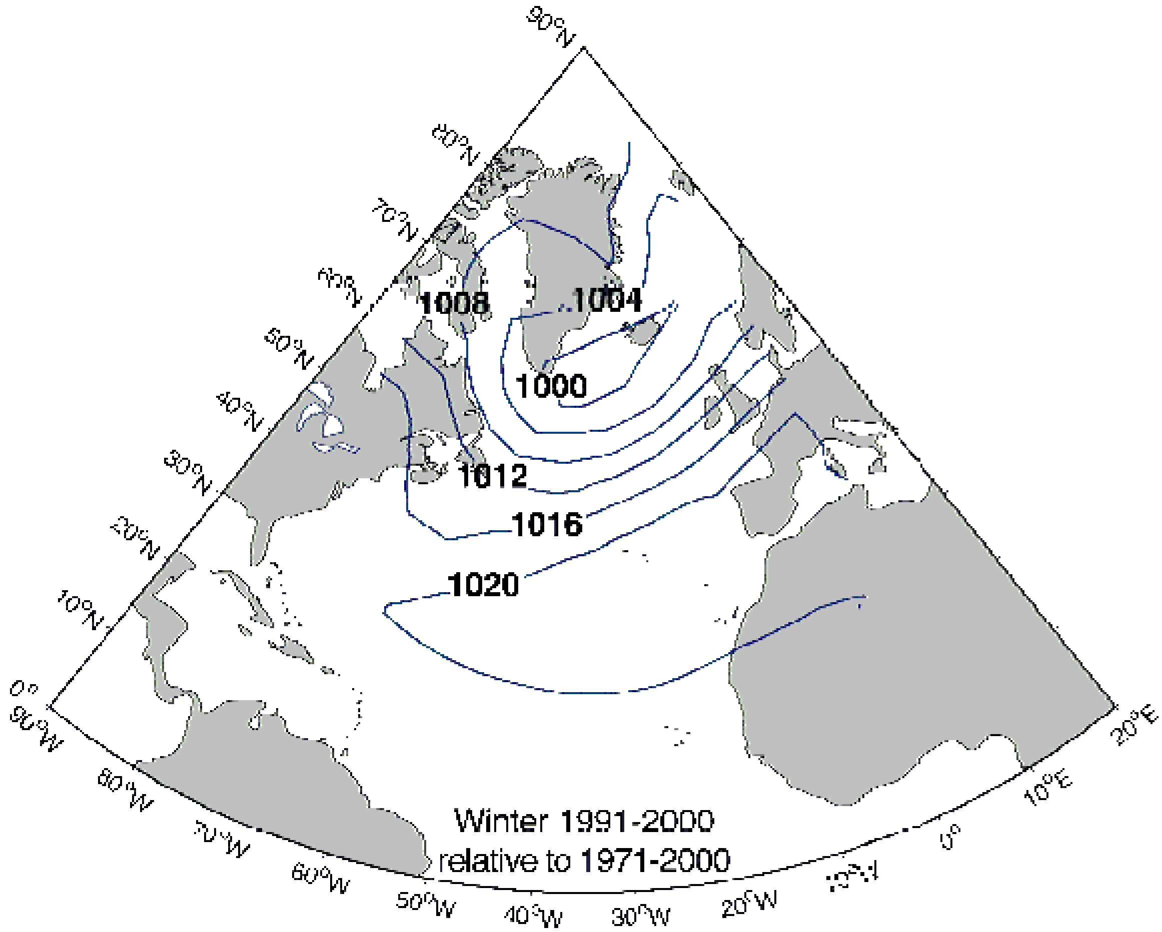


Fig. 1. The winter sea level pressure field over the North Atlantic Ocean averaged over 1991-2000 showing the Icelandic Low and the Azores High.

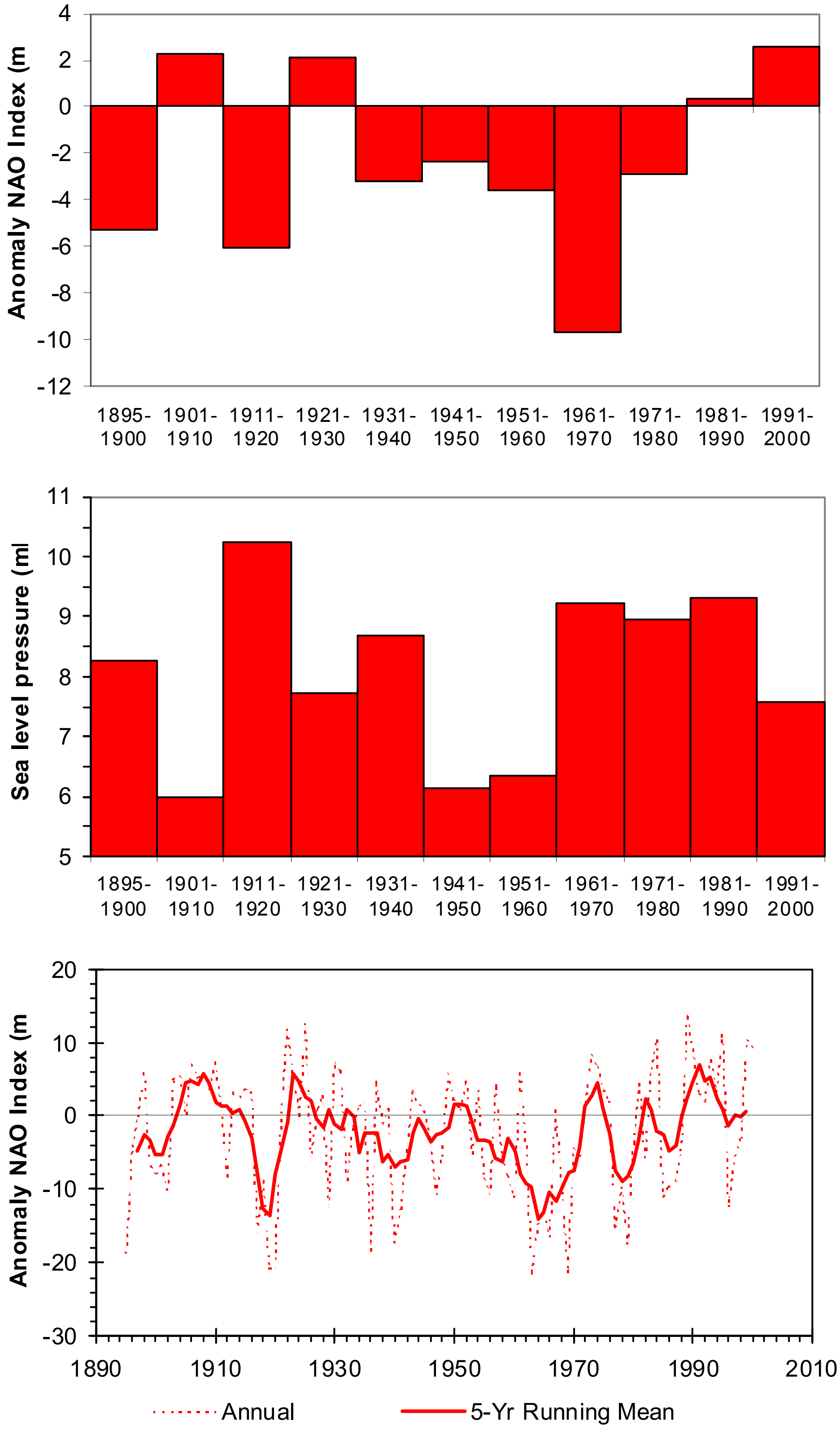


Fig. 2. The decadal anomalies (top) and their within decade standard deviation (middle) along with the annual anomalies (bottom) of the NAO Index in mb.

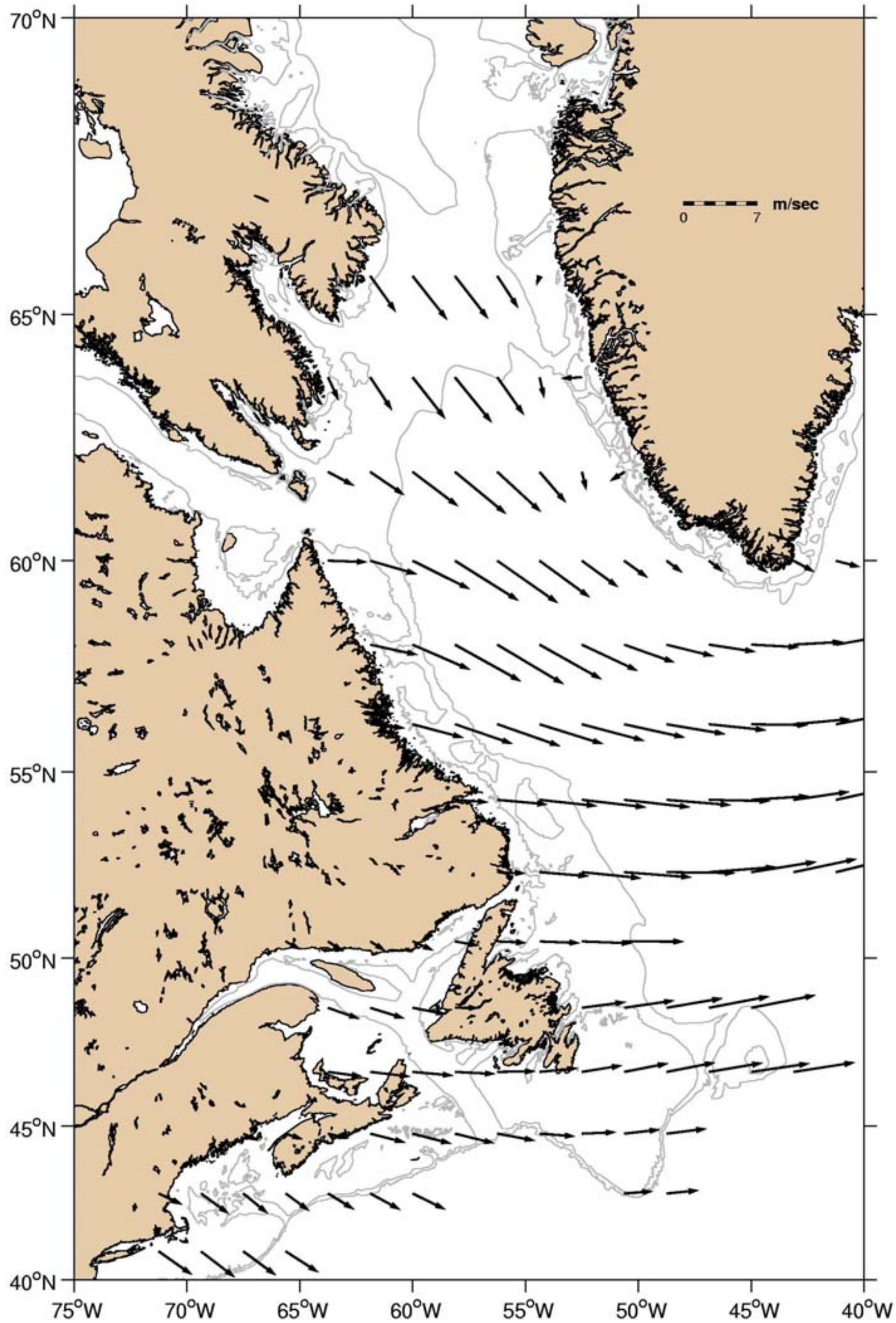


Fig. 3. The mean winter winds during the 1990s.

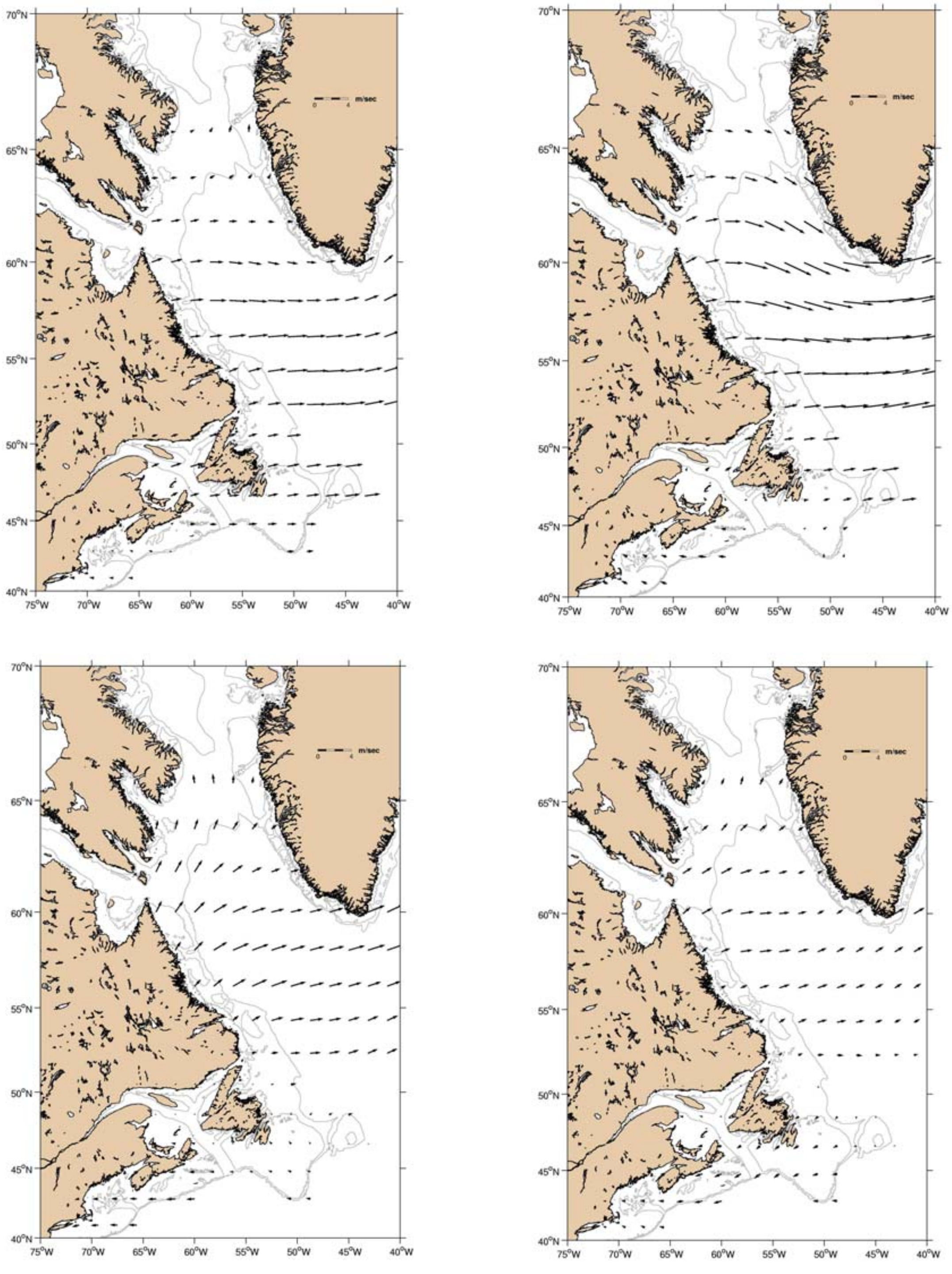
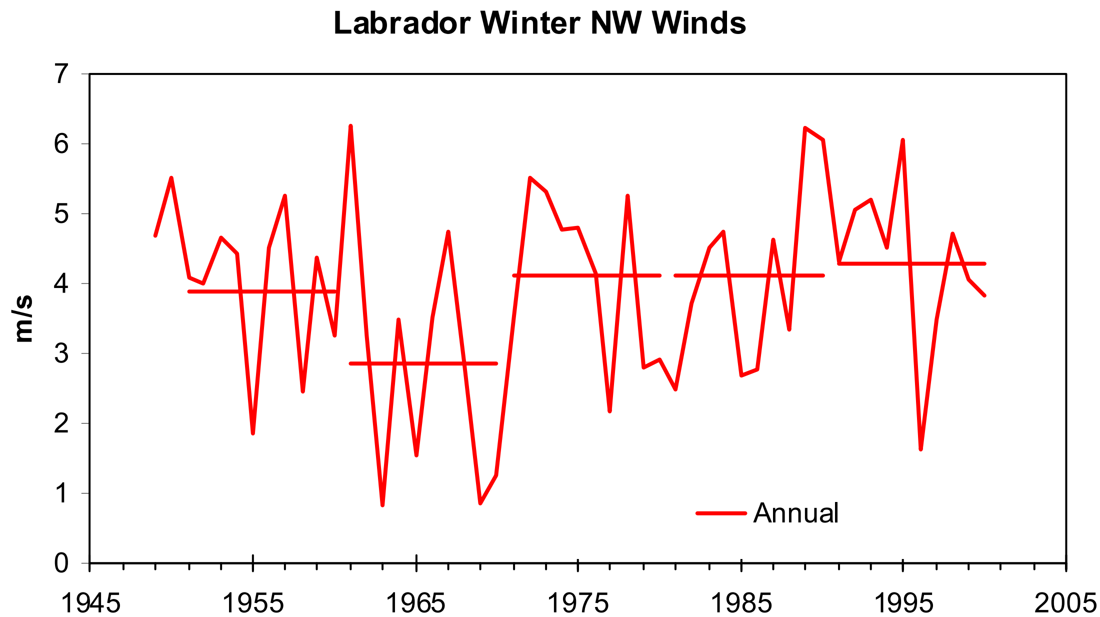


Fig. 4. The difference in mean winds between the 1990s and the previous decades; the 1950s (upper left), the 1960s (upper right), the 1970s (lower left) and the 1980s (lower right).



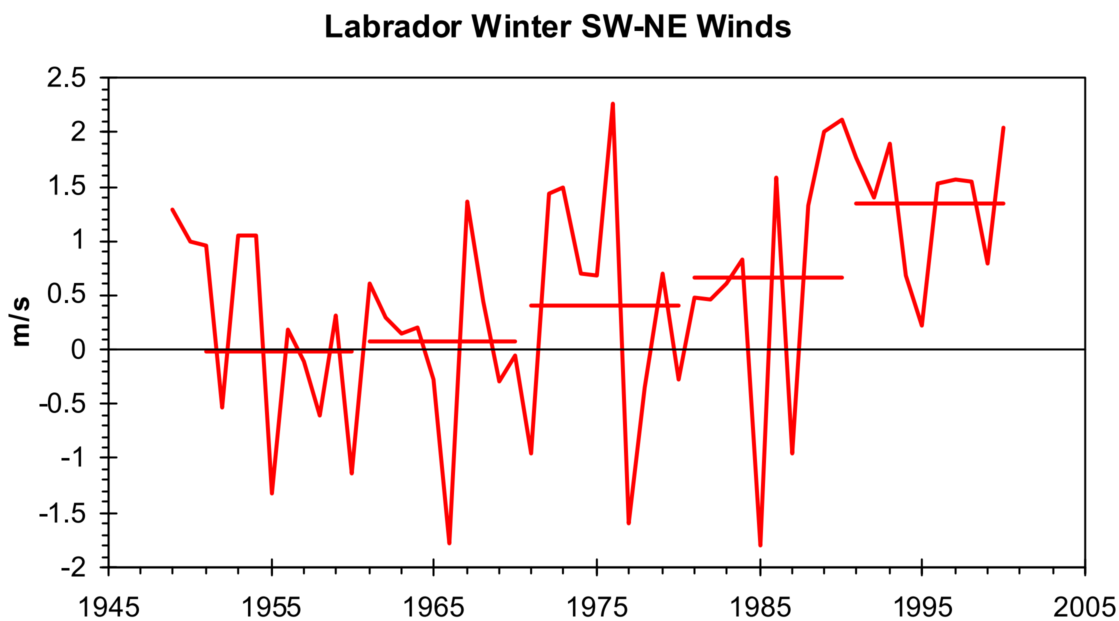
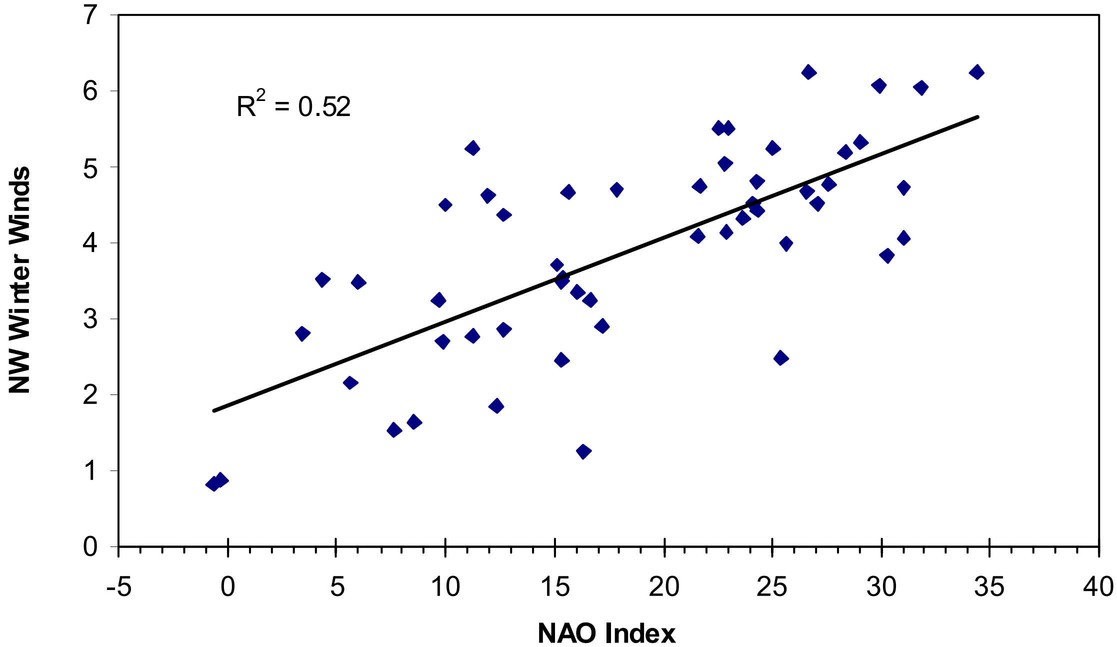


Fig. 5. The strength of the mean winter wind components for the Labrador Sea. The horizontal lines represent the decadal means.



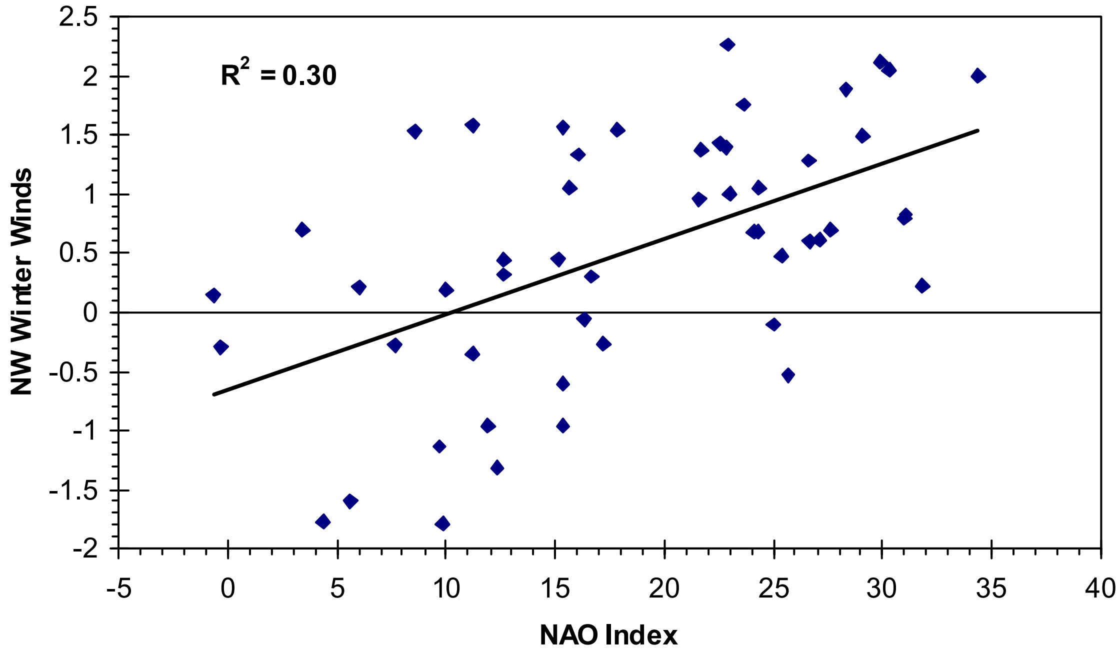


Fig. 6. The relationship between the two wind components and the NAO index.

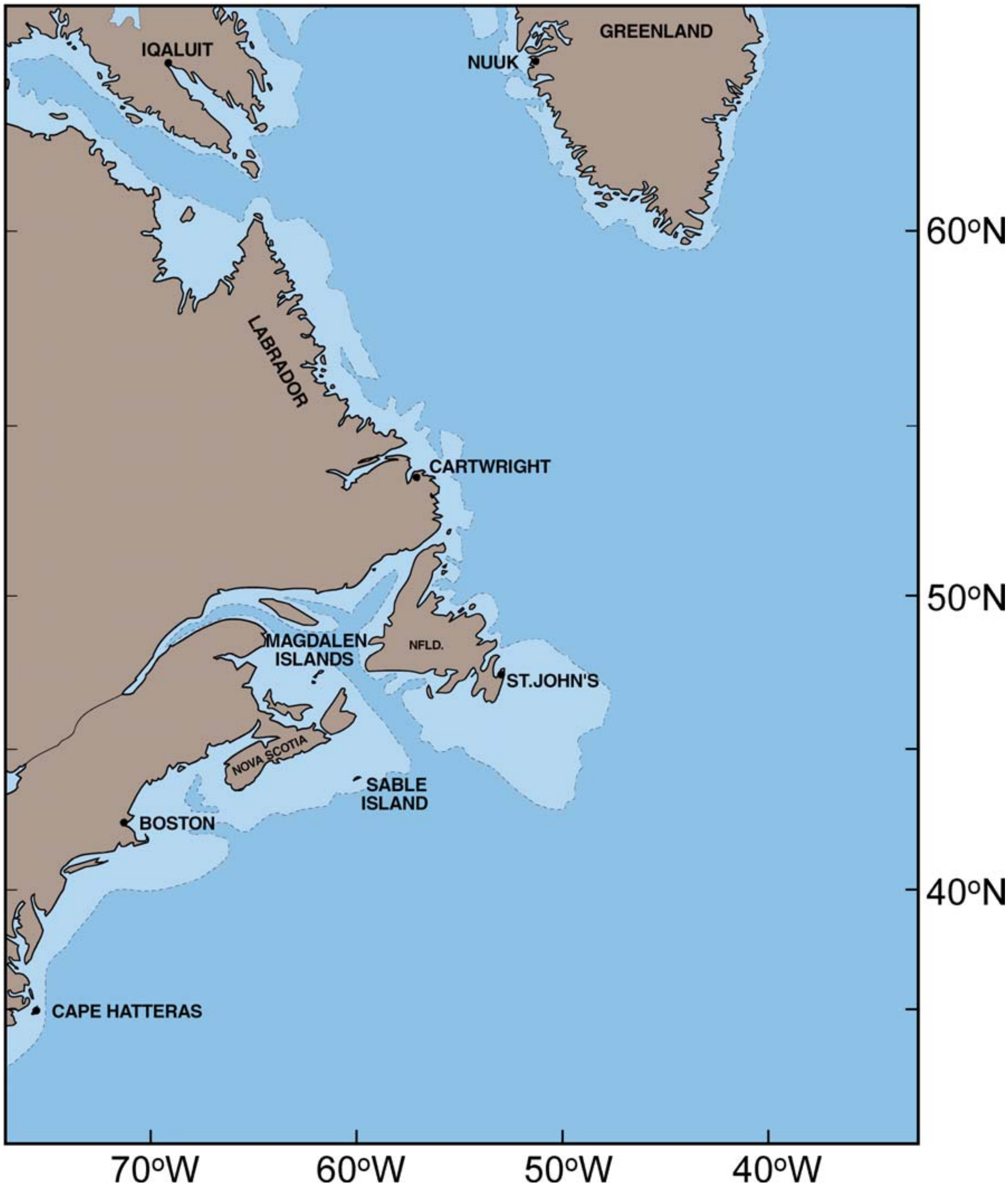


Fig. 7. The map of the Northwest Atlantic showing the air temperature sites.

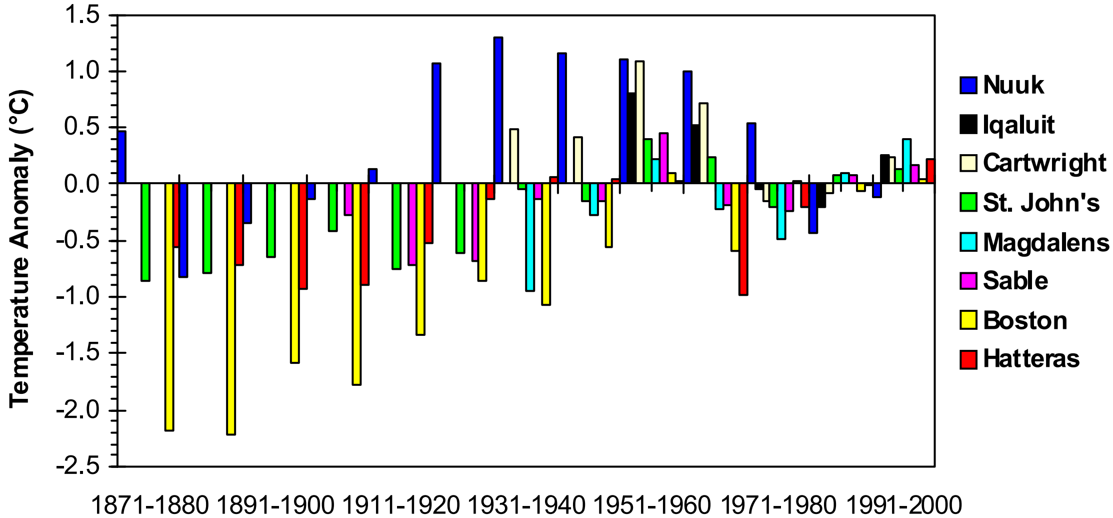


Fig. 8. The decadal means of the temperature anomalies for the 8 air temperature sites in Fig. 7.

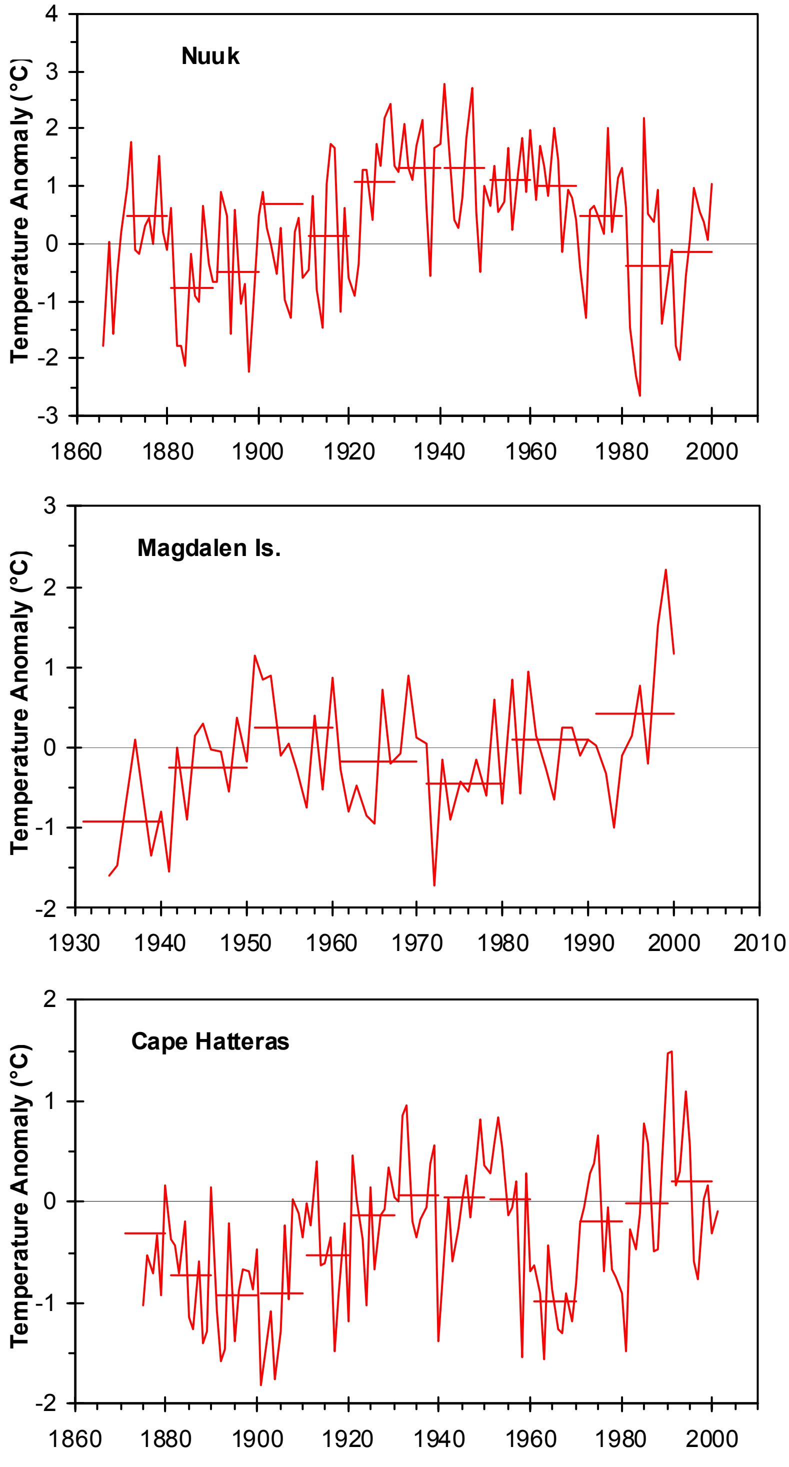


Fig. 9. The annual mean air temperature anomalies from Nuuk (top), Magdalen Islands (middle) and Cape Hatteras (bottom). The horizontal lines represent the decadal means.

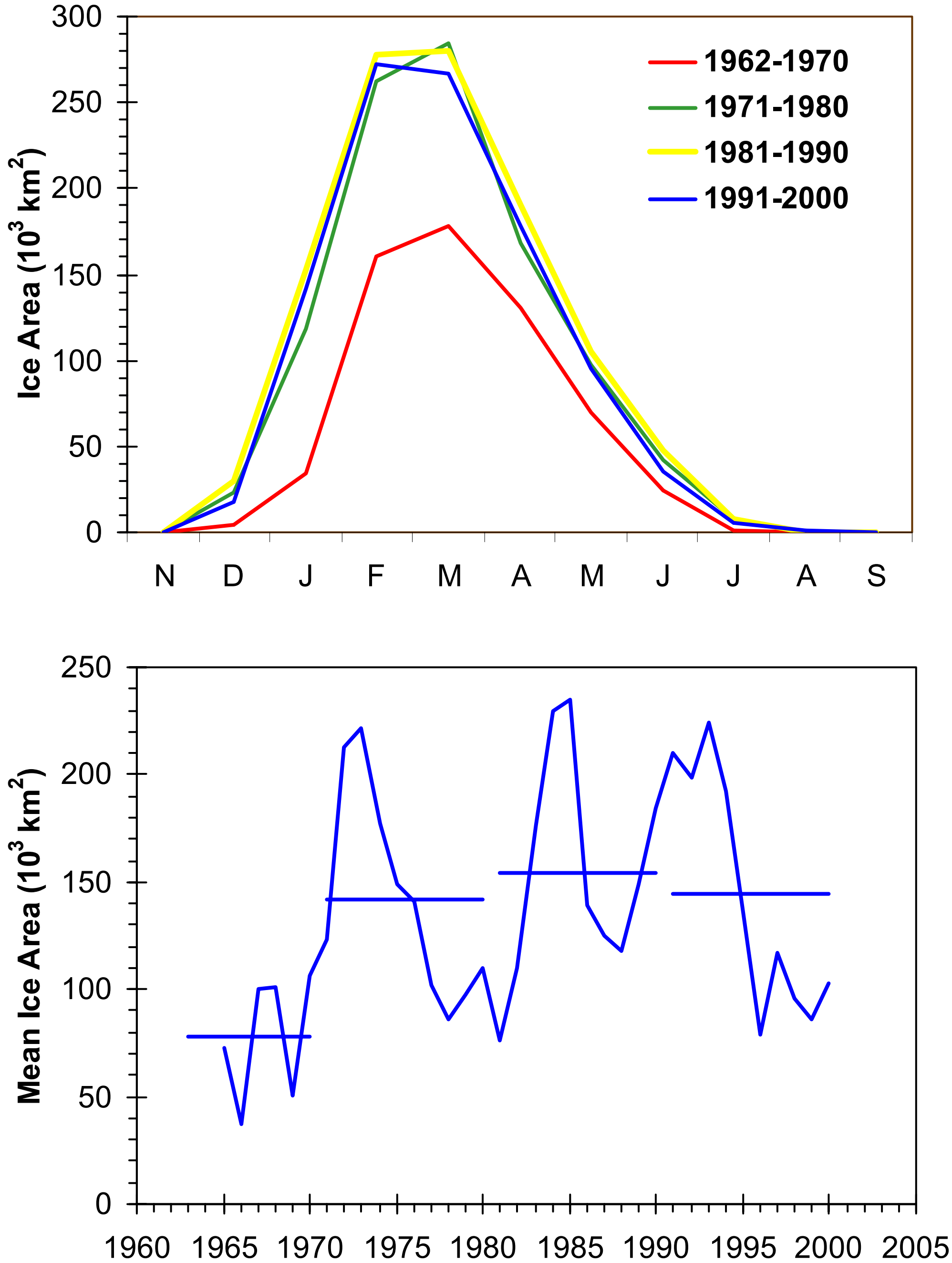


Fig. 10. The monthly mean area of ice averaged by decade (top) and the time series of the daily mean ice area (bottom) for the Labrador and Newfoundland shelves.

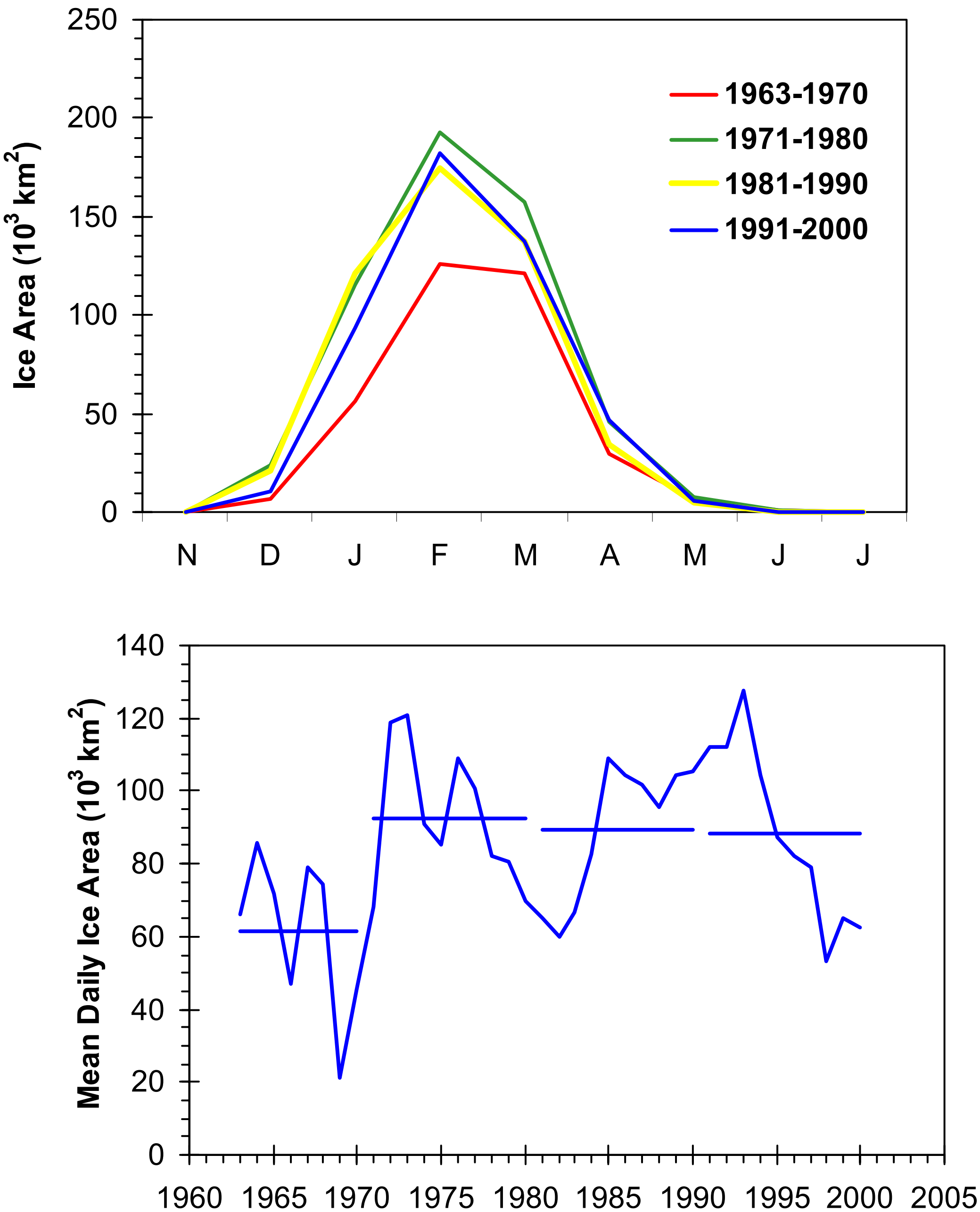


Fig. 11. The monthly mean area of ice averaged by decade (top) and the time series of the daily mean ice area (bottom) for the Gulf of St. Lawrence.

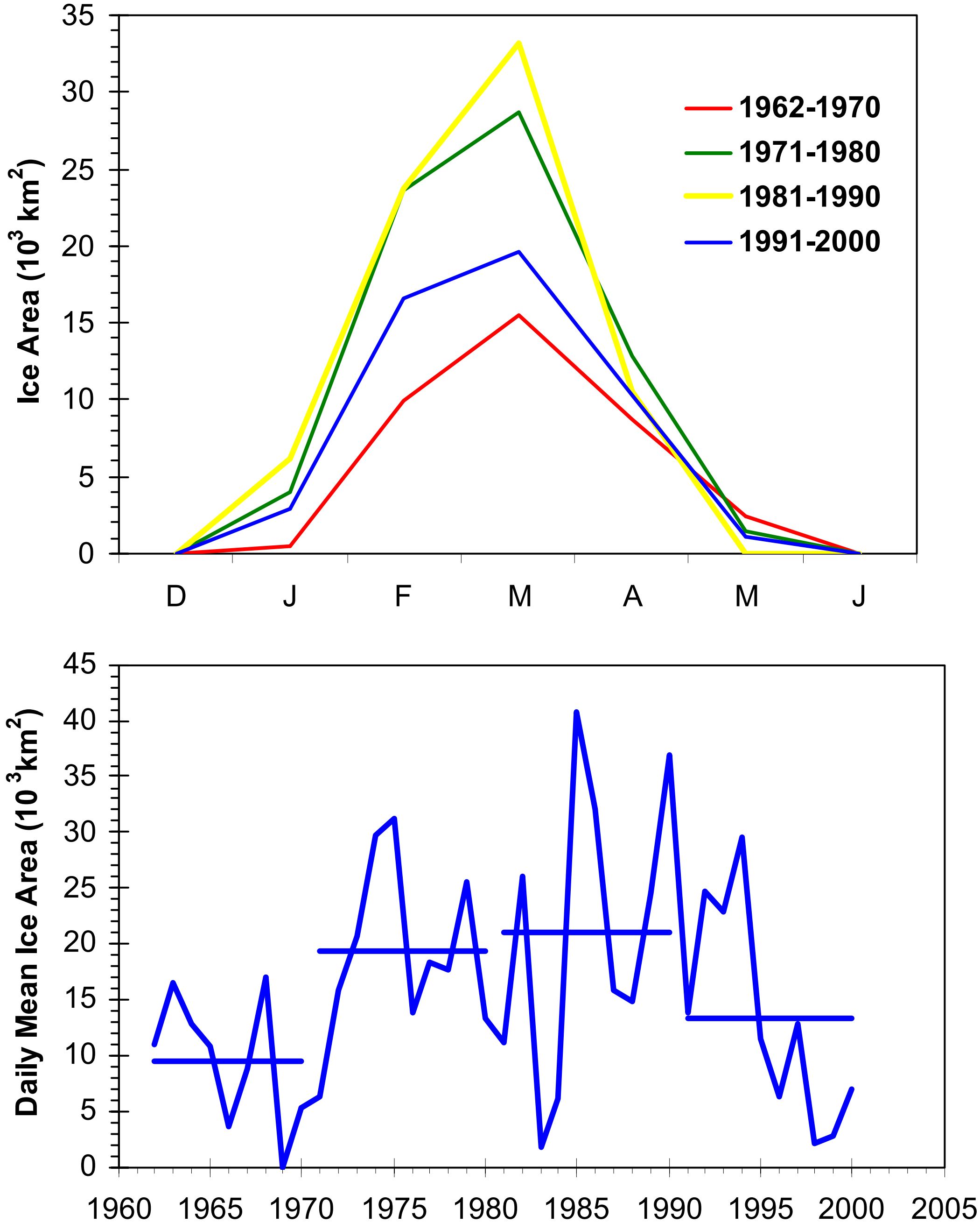


Fig. 12. The monthly mean area of ice averaged by decade (top) and the time series of the daily mean ice area (bottom) for the Scotian Shelf.

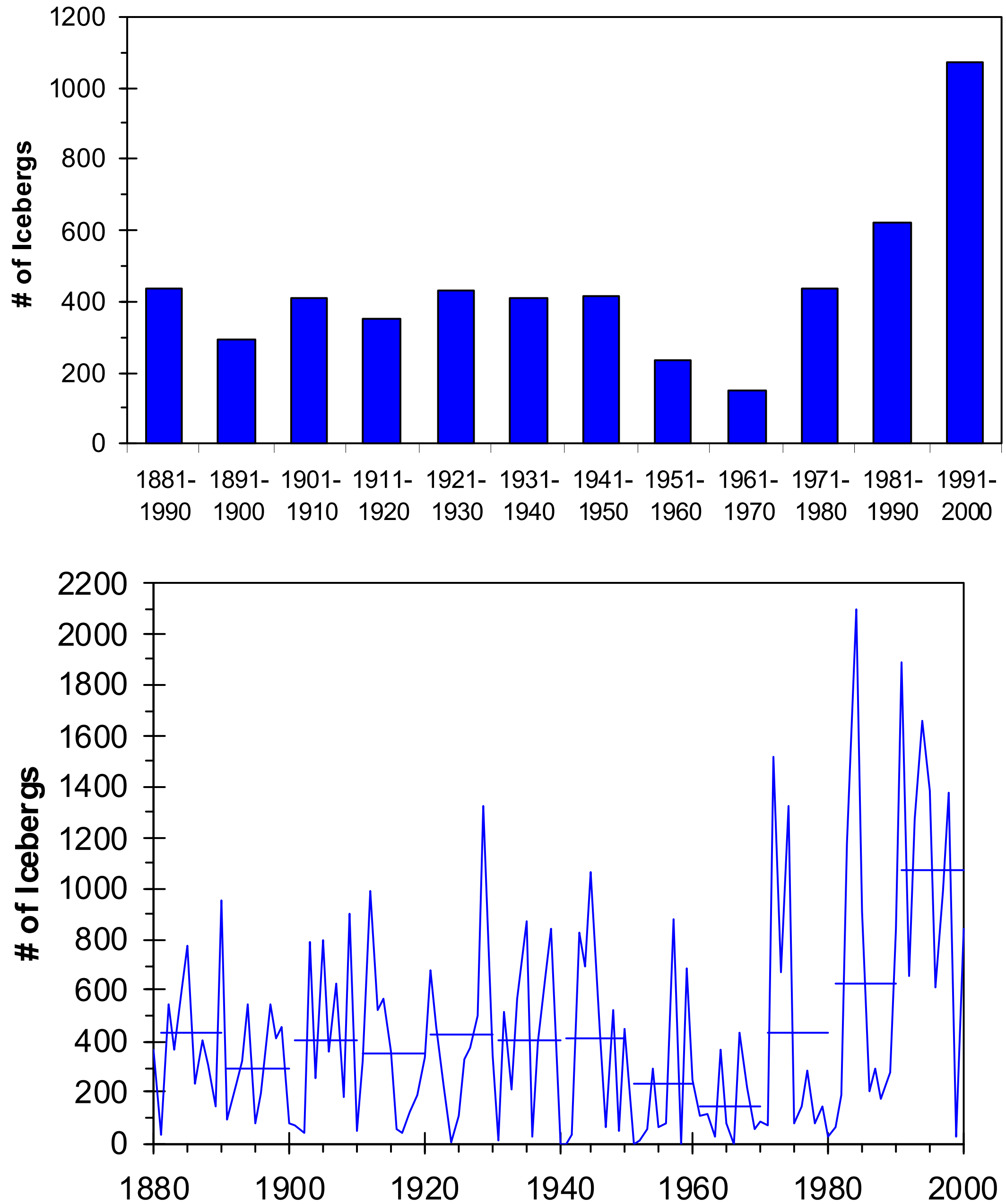


Fig. 13. The decadal means of the number of icebergs crossing south of 48°N (top) and the time series of the annual numbers (bottom). The horizontal lines in the bottom plot are the decadal means.