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Climate and Oceanographic Variability in the Northwest Atlantic During the 1980s and Early-1990s

by

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SYMPOSIUM ON ANOMALOUS OCEANOGRAPHIC CONDITIONS

Abstract

A review of climatic and oceanographic conditions in the northwest Atlantic during the decade 1981-90 and in the early 1990s is presented based upon standard station data and climate indices. Trends in decadal means are described together with the interannual variations. Air temperatures are shown to be linked to the large scale atmospheric circulation patterns which in turn influence sea ice conditions. Subsurface ocean climate variability is influenced not only by local atmospheric forcing but also by the advection of generally colder water from upstream. Offshore exchange between the slope and shelf waters is a primary mechanism for climate changes from the Laurentian Channel to the Middle Atlantic Bight.

Introduction

This paper examines the trends in environmental conditions in the Northwest Atlantic with special emphasis upon the continental shelves off West Greenland, eastern Canada and the northeastern United States. Temporally the focus is on the decade of the 1980s and the first few years of the 1990s. Data from representative sites and environmental indices are described, comparisons are made with past conditions, teleconnections between variables are explored and mechanisms governing the observed changes are discussed. This paper and that by Stein (1994a) maintain the tradition within NAFO, and its predecessor ICNAF, of providing decadal (or slightly longer) environmental reviews (ICNAF 1967, 1972; NAFO 1982). While one of the main aims of this study is to provide information for comparison with fisheries statistics, the links between environmental change and fluctuations in fish stocks will not be discussed within the present manuscript.

The paper relies heavily upon the annual reviews of environmental conditions in the NAFO area presented to the NAFO Environmental Subcommittee since 1982 by myself, R.W. Trites and colleagues (e.g. Trites and Drinkwater, 1984; Drinkwater et al. 1994) but also draws upon other published material and presents some new analyses. Emphasis is placed upon interannual and decadal variability and is expressed primarily in terms of anomalies, i.e. differences from the long-term means. These means have been calculated over the period 1961-90, where possible. This period coincides with that used by meteorologists and roughly corresponds in time with the availability of routine fisheries surveys and VPA analyses for the major groundfish species.

The NAFO area spans over 40° of latitude and 30° of longitude (Fig. 1). In such a large area it is to be expected that interannual and decadal fluctuations will vary from subarea to subarea as a result of differences in atmospheric, hydrological and oceanographic (offshore) forcing. However, there are important linkages between subareas due to advection by the mean currents. Therefore to set the stage, a brief review of the circulation pattern in the NW Atlantic is presented. The discussion of the environmental variability begins with atmospheric conditions, including air temperatures, air pressures and winds. Sea ice and hydrological conditions are then described. This is followed by a description of changes in hydrographic properties, region by region. A summary is provided in the last section.

General Circulation

The circulation in the upper layers of the NW Atlantic is depicted in Fig. 2. It is based upon numerous published charts including those by Smith et al. (1937), Hachey et al. (1954), Hachey (1961), Sutcliffe et al. (1976), Trites (1982) and Chapman and Beardsley (1989). The West Greenland Current, an extension of the cold East Greenland Current and the warmer offshore Irminger Current, flows northward along the west coast of Greenland. The bulk of the transport moves westward upon reaching Davis Strait due to the shallowing topography. A much smaller component, mainly confined to the shelf and comprising waters originating from East Greenland, continues north into Baffin Bay. The latter eventually meets Arctic waters flowing through Nares Strait to form the Baffin Land Current. This current flows southward in western Baffin Bay and upon entering the Labrador Sea is confined inshore of the westward moving West Greenland waters. It enters Hudson Strait where the strong tidal currents cause it to mix with the low salinity waters flowing out from Hudson Bay and deeper waters of West Greenland origin. The resultant mixture flows onto the Labrador Shelf to form the inshore Labrador Current. The extension of the flow from West Greenland that is found along the continental slope of Labrador constitutes the offshore branch of the Labrador Current and contains approximately 80% of the total transport in the Current (Lazier and Wright, 1993). Within both the Labrador Sea and Baffin Bay the circulation patterns are cyclonic. The inshore branch of the Labrador Current, upon reaching the Grand Banks flows through Avalon Channel and then westward towards the Gulf of St. Lawrence. The offshore branch flows along the outer edge of Grand Banks, some moving eastward and passing north of Flemish Cap, but the majority continuing southward along the eastern slope of the Bank to the Tail of the Banks. This water will either flow westward along the southern edge of the Grand Banks or be mixed into the slope water region. The waters that flow into the Gulf of St. Lawrence move clockwise being augmented, at times by transport from the Labrador Shelf through the Strait of Belle Isle and by the freshwater emanating from the St. Lawrence Estuary. The outflow from the Gulf exits on the south side of the Cabot Strait and moves onto the Scotian Shelf. Part rounds the eastern tip of Cape Breton Island remaining on the inner half of the shelf to form the Nova Scotia Current. The remainder flows along the Laurentian Channel, some spreading out over the northeastern Scotian Shelf and some turning at the outer edge of Banquereau Bank and flowing southwestward along the continental slope. Anticyclonic eddies occur over some of the Scotian Shelf banks, e.g. Browns Bank. The flow continues into, and cyclonically around, the Gulf of Maine with some being temporarily diverted into the Bay of Fundy. Upon reaching Cape Cod the current again splits, part moving south and part northeastward where it concentrates along the northern flank of Georges Bank. The latter also splits with one branch moving north to form the Gulf of Maine gyre and the other flowing around Georges Bank to form an anticyclonic gyre. On the Middle Atlantic Bight the flow continues on its southwestward journey eventually reaching Cape Hatteras. Offshore the Gulf Stream moves east-northeast. The area between the shelf and Gulf Stream is occupied by Slope waters which move slowly northeastward. Near the Tail of the Bank the Gulf Stream splits with one branch continuing east to southeast and the other branch northward through the Newfoundland Basin, around Flemish Cap and towards the Labrador Sea. The latter then loops heading eastward towards the Irminger Sea, eventually contributing to the Irminger Current.

Exchange between shelf and offshore waters is a continuous process with enhanced mixing in the southern NAFO area due to the presence of Gulf Stream rings. These are formed from Gulf Stream meanders and interact strongly with the shelf waters.

The above circulation pattern is based primarily upon temperature and salinity distributions, geostrophic computations and only limited direct current measurements. The strength and sometimes even the direction of the flow changes seasonally. As a result of this and higher frequency variability, the flow can differ substantially from that shown in Fig. 2. However, it is clear that the mean circulation provides the linkage between regions within the NW Atlantic. The observed variability in environmental conditions within any area therefore depends not only on local forcing but also upon upstream forcing whose effects are transport downstream by the residual circulation.

Atmospheric Conditions

Air Temperatures

The correlation between annual air temperatures (50-100 y records) at different coastal sites in the NW Atlantic decreases gradually with increasing horizontal separation (Fig. 3). At separation distances of 1000 km the correlations typically exceed 0.6 but fall to 0 or less by 2500 km separation. This implies different air temperature patterns within the NAFO region.

Decadal mean air temperatures were calculated at several sites and expressed as anomalies relative to the average of the 1961-90 decadal means. During the 1980s conditions over the Labrador Sea and Baffin Bay were relatively cold, in contrast to the warmer conditions south from Newfoundland to Cape Hatteras (Fig. 4). The coldest area lay along West Greenland. In Godthaab, where temperature records extend back 12 decades, it was the second coldest decade on record with only the 1880s being colder (Fig. 5). Temperatures at Godthaab rose steadily through the beginning of the century, were relatively high through the 1920s to the 1960s and have declined through the 1970s, into the 1980s and has continued in the early 1990s. Winter temperatures were exceedingly cold in the 1980s although anomalies for all four seasons were below normal. It is interesting to note that the high temperatures in the 1920s and 1930s were due primarily to warm springs and summers whereas in the 1960s it was warm winters and springs. The time series of the annual air temperatures shows high variability within the 1980s with very cold in the early part of the decade, very warm in the middle years and a steadily decline through the later years and into the 1990s.

In the Atlantic provinces of Canada and around the Gulf of Maine, air temperatures in the 1980s and into the early 1990s were generally slightly above their 1961-90 averages but well below the peak temperatures in the 1950s (Fig. 6). This peak was due primarily to warm winters. The warmest decadal anomaly in the 1980s was recorded at Cape Hatteras (Fig. 7). Temperatures rose throughout the 1980s and into the 1990s in all seasons. The lowest decadal anomalies at Cape Hatteras were recorded in the 1960s while anomalies have risen steadily since then. The late part of the last century and the early part of this saw cold conditions but warmed in the 1920s and remained relatively warm through to the 1950s.

The decadal anomalies at Godthaab, Sable Island and Cape Hatteras showed certain similarities, being low in the early 1900s, rising sharply in the 1920s and remaining warm through the 1950s. Since then, however, temperature trends have differed becoming progressively colder in the north whereas in the south the 1960s were cold and conditions have been moderating ever since.

Air Pressures

Air temperatures trends are closely related to the large scale atmospheric circulation patterns. In the North Atlantic these are dominated by the Icelandic (subpolar) Low, the Bermuda-Azores (subtropic) High (Fig. 8). The strengths of the Low and High vary seasonally from a winter maximum to a summer minimum. Year-to-year changes in winds are associated with interannual variations in the intensity of these pressure systems, e.g. a deeper low and higher high result in stronger westerly winds over the North Atlantic and stronger northwesterly winds over the Labrador Sea.

Monthly mean sea-surface pressures over the North Atlantic have been published in *Die Grosswetterlagen Europas* by the German Meteorological Service since 1950. Decadal seasonal anomalies of air pressure relative to the 1961-90 average were calculated. Winter (December to February) exhibits the largest variability. The contrast between the 1960s winter sea level pressure pattern and that in the 1980s is shown in Fig. 9. During the 1960s the Icelandic Low and Bermuda-Azores High were relatively weak (positive and negative anomalies, respectively). The associated anomalous winds (see below) were from the south to southeast over the Labrador Sea and Baffin Bay producing relatively mild conditions. The anomalous winds over southeastern Canada were from the northeast whereas those over the northeastern seaboard would have been from the north to northwest. The latter would have contributed to the cold conditions of the 1960s. In contrast to the 1960s, the pressure systems in the 1980s intensified, causing stronger northerly and northwesterly winds over the Labrador Sea which carried cold Arctic air. The strengthening of the Bermuda-Azores High would have resulted in southerly to southeasterly winds along the coast between Cape Hatteras to the Gulf of Maine producing the warm air temperatures.

The North Atlantic Oscillation (NAO) Index is one measure of the strength of the large scale atmospheric circulation. It is the difference in winter sea level pressures between the Azores and Iceland. A high positive index indicates stronger westerly winds across the North Atlantic and northwesterly in the Labrador Sea region. The decadal anomalies show the 1980s to have a high NAO index whereas the 1960s were a minimum (Fig. 10). These correspond to cold and warm years, respectively, in the Labrador Sea. The 1990s continue to show a high NAO index. Whereas in the last three decades the inverse relationship of NAO to annual air temperature trends over the Labrador Sea has been very strong, the NAO index does not correspond as closely with the annual air temperatures at Godthaab in the early part of this century. This is due, in part, to differences in the importance of the winter temperatures in determining the annual mean. For example, the warming in the 1920s was dominated by warm springs and summers. The NAO index on the other hand is most strongly correlated with winter air temperatures and much less so for other seasons. Correlations between air temperatures at Godthaab and the NAO index decrease from -0.72 in winter to -0.33 in spring and even lower in summer and autumn (based on years 1895-1993). The correlation coefficient with annual air temperatures at Godthaab is -0.50.

Winds

Interannual variability of geostrophic wind stress estimates from 6 hr sea level pressures are available from 25 sites in the NW Atlantic stretching from the northern Labrador Sea to Georges Bank from 1946-91 (Drinkwater and Pettipas 1993). The seasonal means are maximum in winter being from the northwest or west and minimum in summer and from the southwest (Fig. 11). Maximum interannul variability occurs in winter and generally increases northward.

Seasonal wind stress anomalies were calculated and decadal means determined. Large differences between decades are especially noticeable in the winter (Fig. 12). In the Labrador Sea, the warm winters of the 1950s and 1960s coincide with anomalous winds from the southeast. (Note that during these decades the winter winds still were from the northwest but much less than normal.) In contrast the 1980s, and to a lesser extent the 1970s, show enhanced NW winds over the Labrador Sea. During the 1950s when winter air temperatures were highest over the Gulf of St. Lawrence and Scotian Shelf, the anomalous winds were easterly.

The strength of the wind stress amplitude has also increased over the last 3 decades through most of NW Atlantic (Fig. 13). The greatest increase has occurred in the Labrador Sea where wind stresses doubled from the 1960s to the 1980s with the largest increase in winter. This will tend to increase the sensible and latent heat fluxes, especially in winter thereby producing strong cooling of the shelf waters in winter and promote deep convection in the central Labrador Sea.

Ice Conditions

Sea ice occurs seasonally over much of the NW Atlantic (Fig. 14). Local ice formation occurs in most areas although ice in the south is due primarily to advection. Ice duration generally increases northward. Interannually variability of the ice cover is large, especially in the Gulf of St. Lawrence and on the Grand Banks. In some years little to no ice is presence whereas in other years ice extends to the southern Grand Banks and as far south on the Scotian Shelf as Halifax. Air and sea temperatures, winds, and ocean currents all influence the presence or absence of ice.

Interannual variability of ice cover off southern Labrador and Newfoundland from the early 1960s to the early 1990s has been discussed by Prinsenberg and Peterson (1994). They note the strong association between the area of ice extent below 55°N and the NAO index. Increased ice coverage increases with cold air temperatures and strong NW winds, both of which are related to NAO as described above. This association between atmospheric conditions and ice had also been observed earlier by others including Markham (1967) and Agnew (1993). The monthly areal extent of ice south of 55° was obtained from S. Prinsenberg (personal communication, Bedford Institute of Oceanography). The mean annual ice extent during January to March (generally the period of southward advance of the ice) and April to June (northward retreat) show extensive ice in the early 1970s, the mid-1980s and in the 1990s (Fig. 15). These periods coincide with high NAO index, cold air temperatures and strong NW winds. The decadal anomalies indicate greater areal extent in the 1980s relative to the past two decades (note no data were available in the 1961 and 1962). This is consistent with the cold air temperatures and stronger winds in the Labrador Sea during the 1980s. Statistics on the date of the presence of first and last ice together with ice duration at 24 sites off Newfoundland and in the Gulf of St. Lawrence are kept by Ice Central in Ottawa and have been published in the NAFO annual environmental overviews since 1984. The ice duration at 3 sites in each region are shown in

Fig. 16. For Newfoundland the ice duration typically increases inshore and northward but the interannual trends are similar throughout. The duration tends to mirror the ice coverage, i.e. larger ice extent coincides with longer ice duration. Thus the ice stayed longer in the early 1970s, mid-1980s and in the 1990s.

In the Gulf of St. Lawrence the interannual trends in ice duration are similar between sites but differ from those off Newfoundland. Duration shows two distinct minima, one in 1969-70 and the other in the early 1980s. Differences in ice conditions between Newfoundland and the Gulf of St. Lawrence are due to differences in atmospheric conditions during the ice season.

Ice also appears in the northern regions in the form of icebergs. They originate from glaciers on West Greenland and northern Baffin Island, drift in Baffin Bay and eventually the residual currents carry some as far south as the Grand Banks (Anderson 1971). The extent of the drift depends upon the current speed, air and sea temperatures, ice cover and winds. Stronger NW winds tend to help push the icebergs further south while the cold air temperatures delay melting and the heavy sea ice prohibit wave activity, which also decreases the melting rate. The importance of large-scale atmospheric circulation in the number of bergs making to the Grand Bank was noted early (e.g. Smith 1931). Icebergs are monitored by the U.S. Coast Guard who annually report the number of bergs passing south of 48°N each month. The majority (on average over 90%) appear between March and July. In the first half of this century, iceberg counts relied upon ship observations. After WWII directed flights were used to spot icebergs and since 1983 they have been detected on flights with SLAR (Side-Looking Airborne Radar). SLAR is believed to spot more icebergs than the traditional observational methods and direct comparison between the iceberg index derived from the different methods can only be considered as relative. Further, difficulties during the first two years of using SLAR are believed to have resulted in a substantial overestimate of the number of bergs reported south of 48°N. Recognizing these difficulties, the decadal and annual iceberg index is shown in Fig. 17. The high number of icebergs in the 1990s is due, in part, to the enhanced technology. It is save to conclude that relatively low numbers of icebergs were observed in the 1950s and especially in the 1960s. During the 1980s low numbers of bergs were reported in the early years and in the later part of the decade. High numbers were observed in 1983 and 1984 and in the during the early 1990s. The period of high iceberg counts occurred during periods of high NAO index, cold air temperatures, anomalous NW winds and heavy ice.

Hydrological Conditions

Gulf of St. Lawrence

Freshwater runoff plays an important role in the salinity and density structure of the continental shelves in the NW Atlantic. The freshwater discharge from the St. Lawrence River drainage basin exceeds that from all of the US rivers from Maine to southern Florida (Sutcliffe et al. 1976). This discharge regulates the timing of the seasonal salinity minimum in the Gulf of St. Lawrence and on the Scotian Shelf and influences interannual variability in hydrographic properties from the Gulf of St. Lawrence to the Middle Atlantic Bight (Sutcliffe et al. 1976; Manning 1991).

Annual mean discharge rates for the combined runoff from the St. Lawrence, Ottawa and Saguenay Rivers (labelled RIVSUM after Sutcliffe et al. 1976) were determined and decadal means calculated. The discharge during the 1980s was the second highest decade on record (Fig. 18). The highest was in the 1970s with low discharge rates during the 1960s and the 1930s.

Gulf of Maine

The largest and most important river discharging into the Gulf of Maine is the Saint John River. A time series of monthly mean discharge rates were obtained by combining measurements from Pokiok (1921-67) and Mactaquac (1967-1993) in New Brunswick. The decadal mean for the 1980s is near the long-term average (Fig. 19). The highest discharge rates which were observed in the 1970s and the lowest on record in the 1960s. Flows decreased through most of the 1980s but rose dramatically at the end of the decade such that in the early 1990s they have been above normal.

Oceanographic Conditions

West Greenland (Inshore Subarea 1)

Hydrographic conditions off West Greenland are influenced by the relatively cold, low-salinity waters of the East Greenland Current and the warm high-salinity water of the Irminger Current. Interannual variability has been monitored by Greenland (Denmark) and Germany primarily at Fyllas Bank but also routine measurements have been collected at other banks between Cape Farewell and Disko Bay. Conditions during the 1980s in the waters off West Greenland have previously been discussed by several authors including Buch and Stein (1989), Stein and Wegner (1990) and Stein (1993). Updates for the 1990s have been reported by Buch (1993) and Stein (1994b).

To examine decadal trends, I assembled historical hydrographic data from Fyllas Bank (depths < 200 m), interpolated to standard depths where required and averaged the data spatially to obtain monthly means. Long-term (1961-90) averages were determined and subtracted from the data to generate monthly anomalies. All of the monthly anomalies within a year were then averaged to derive an annual anomaly. These annuals were further averaged into decadal means and plotted together with the annual anomalies in Figs. 20 and 21. There is strong similarity between depths. Decadal temperature anomalies show little difference over the last 3 decades but are lower than in the 1950s with the major decline occurring in the 1960s. Within the 1980s, temperatures initially decreased to a minimum, then rose to above normal in the middle of the decade. Temperatures declined in the last two years of the decade (Stein 1993). Similar temperature variability in the 1990s was observed over other banks and in the waters along the continental slope off West Greenland (Buch and Stein 1989; Stein 1993). Salinity anomalies show relatively fresh conditions during the cold period of the 1980s and increasing salt content during the warming period (Fig. 21). The decadal means show that the 1980s were the most saline in the past 4 decades and have been rising since the 1960s. Note that the low salinities in the late 1960s corresponds to the time when the Great Salinity Anomaly pasted through the region (Dickson et al. 1988). During the 1990s temperatures were relatively cold in late spring on Fyllas Bank (Buch 1993) but by autumn have been observed to be warmer than normal (Stein 1994b).

The cool periods in the early 1980s corresponds to a time of cold air temperatures (Fig. 5) and strong NW winds, particularly over the eastern Labrador Sea (Drinkwater and Pettipas 1993). Buch and Stein (1989) have suggested that these harsh atmospheric conditions led to the anomalous hydrographic conditions off West Greenland in the early 1980s. However, Malmberg and Kristmannson (1992) noted similar temperature, salinity variations in the northern Icelandic Shelf and linked them to changes in the percent Atlantic waters in the region. Advection therefore may contribute significantly to the variability observed in the waters off West Greenland in the 1980s. Indeed since the long-term temperature trend in the temperatures at Fyllas Bank does not reflect the declining air temperatures and increasing winds, this argues for the importance of advection. The high salinities in the 1980s are consistent with reduced influence of the East Greenland Current due to the anomalous northeastward winds along East Greenland as suggested by the wintertime decadal pressure pattern (Fig. 9).

Labrador Sea (Offshore Subareas 1 and 2)

Lazier (1980) discussed the interannual variability in the central Labrador Sea from data collected at Ocean Weather Station (OWS) Bravo between 1964-1974. Unfortunately, Bravo was removed in the mid-1970s so that observations of changes in the marine climate in the Labrador Sea must now rely upon oceanographic surveys. Two studies have investigated changes in the deep waters of the Labrador Sea during the 1980s. Lazier (1988a) examined the deep (2000-3000 m) and bottom waters in the western Labrador Sea up to 1986. He found relatively low temperatures and salinities in these water masses during the first half of the 1980s with a minor recover during 1986. The amplitude of the decline increased towards the bottom suggesting that the cause was probably changes in the temperature of the Denmark Strait Overflow water which flows into the Labrador Sea near bottom. Myers et al. (1990a) examined changes in salinity of the 500-2000 m depth layer in the vicinity of OWS Bravo from the 1930s on. Based on the scanty data for the 1980s, the salinities were relatively low in the 500-1000 m depth layer but relatively high between 1000-2000 m. Examination of the historical data in the top 1000 m for this site up to the 1990s made as part of the present study confirmed the findings of Myers et al. (1990a) and also indicates that below 250 m temperatures were as cold as the minimum Lazier (1980) found between 1964-74. These cold temperatures and low salinities appear to extend into the 1990s although few data are available. These conditions are believed to reflect deep water formation in the winter down to at least 1000 m due to the very cold air temperatures and strong NW winds.

Labrador Shelf/Grand Banks (Subarea 2 and 3)

Interannual variability of the continental shelf waters from Labrador to southern Newfoundland has been monitored since the late 1940s from occupation of standard oceanographic stations and sections. The conditions at Station 27 in the Avalon Channel just outside St. John's, Newfoundland are monitored by the Northwest Atlantic Fisheries Center and have been reported annually since 1982 in the NAFO environmental overviews (e.g. Trites and Drinkwater 1984; Drinkwater 1994). Studies of interannual variability at Station 27 that have included at least some years during the 1980s have been undertaken by Myers et al. (1990b), Petrie et al. (1992) and Colbourne et al. (1994). Station 27 is located within the inshore Labrador Current but its subsurface long-term fluctuations were found to be correlated with other temperature-related indices at horizontal distances of close to 1000 km (Petrie et al.,1992; Colbourne et al. 1994). Thus Station 27 is believed to reflect the general conditions in the shelf waters from Labrador to the Grand Banks.

Temperature anomalies reveal the 1980s as the coldest decade on record (Fig. 22). Temperatures have been declining since the 1960s maximum. At the beginning of the 1980s temperature anomalies at all depths were relatively warm having climbed steadily from the extremely low values of the early 1970s. This was followed by a drop through to the mid-1980s when negative temperature anomalies matched those of the early 1970s. In the later half of the decade, temperatures again rose, most rapidly in the very near surface layer but also in the waters below 100 m. At 50 m, temperatures began to rise but quickly fell. Since 1989 temperatures at all depths have been declining and anomalies in the 1990s are at or near their lowest value since the late 1940s.

The decadal salinity anomalies for the 1980s were above normal in the upper 100 m but below normal near bottom at 175 m (Fig. 23). The annual salinity anomalies show a decline in the early to mid-1980s and an increase during the second half of the decade. Salinities reached maxima in the late 1980s and have generally declined in the 1990s. The extremely low surface salinities in the early 1970s, mid-1980s and early-1990s are clearly evident (Fig. 23). Negative salinity anomalies occurred throughout the water column but the subsurface salinity variations were of smaller amplitude. These three salinity minima occurred during years of cold temperatures, strong winds and heavy ice (Lazier 1988b; Colbourne et al. 1994).

Another index of the temperature conditions on the Labrador and Newfoundland shelves is the areal extent of the CIL (Cold Intermediate Layer). Atmospheric cooling of the upper 100 to 200 m of water takes place in winter. In summer, solar heating and low salinity surface waters from ice melt form a shallow (30-40 m) upper layer that insolates the winter-cooled water below. On the Newfoundland Shelf this cold water masses lies above warmer water that has penetrated in from offshore. Because of the warmer water both above and below it, this layer has been called the CIL. Off Newfoundland, the CIL has been defined as containing waters less than 0°C. Time series of the cross-shelf areal extent the CIL have been developed at standard transects. Although some differences do occur between different sections, the long-term trends are similar. The transect containing the most complete data is the Bonavista Line.

Temperature data from which the CIL is derived are available on the Bonavista Line since the late 1940s (Fig. 24). The decadal means show a pattern inverse to the temperature anomalies at Station 27 being maximum in the 1980s (cold years) with a minimum in the 1960s (warm years). This is consistent with the close association between CIL area and Station 27 temperatures found by Petrie et al. (1992). The CIL area varied greatly within the decade of the 1980s from low in the early years to the maximum recorded over the entire record in the mid-1980s. The CIL area again decreased through to 1987 and increased to a peak in the early 1990s.

The mid-1980s and the early 1990s were times of cold sea temperatures and low salinity. They correspond with cold air temperatures, strong winds and heavy ice suggesting the importance of local atmospheric forcing as noted by Lazier (1988b). However, a somewhat similar pattern in temperature was observed at Fyllas Bank but lagged by approximately 2 years. This lag matches closely that found by Dickson et al. (1988) during the passage of the Great Salinity Anomaly. Myers et al. (1988) observed significant correlations between hydrographic properties on Fyllas Bank with those at Station 27 with a lag of approximately one and a half years. Stein (1993) also found a strong correlation between both temperature and salinity on Fyllas Bank with the extent of the CIL providing further evidence of a strong advective component to explain the observed properties on the Labrador Shelf. It seems clear that the Labrador Shelf properties are determined by a combination of atmospheric forcing and advection from West Greenland.

Gulf of St. Lawrence (Subarea 4T,R,S)

Bugden (1991) investigated temperature conditions in the deep waters of the Laurentian Channel. Varying proportions of Labrador and Western North Atlantic waters produced temperature changes at the mouth of the Channel that propagated slowly up-channel towards the St. Lawrence

Estuary through a combination of advection and diffusion. He developed an index of temperature change using the 200-300 m average temperature from Cabot Strait. These data have been updated annually in the NAFO environmental overviews (e.g. Drinkwater 1994). The 1980s was the warmest in the last 4 decades (Fig. 25), an almost inverse pattern to temperatures observed at Station 27. At Cabot Strait temperatures rose steadily from the minimum in the 1960s to the peak in the late 1970s. During the 1980s deep water temperatures were generally between 5.5 to 6.5°C. They dropped rapidly in the early 1990s but returned to high levels during the last 2 years. Bugden (1991) also found a close association between his temperature index and the position of the boundary between the shelf and slope waters using data from 1980-88. High temperatures occurred when the slope waters were closer inshore with the temperatures lagging the movement of the front by 2.5 y. However, Drinkwater and Budgen (1994) were unable to confirm this relationship using the data from 1989-1993. The decline and subsequent rise in temperatures in the early 1990s were not triggered by offshore-onshore movement of the shelf/slope front.

Additional information from analysis of historical temperature and salinity data was sought for the Esquiman Channel, the St. Lawrence Esturay, western Cabot Strait and on the Magdalen Shallows. Unfortunately data for St. Lawrence Estuary were too infrequent to make any reliable conclusions about conditions in the 1980s. (Note that the data base was originally derived from the Canadian archives maintained by MEDS (Marine Environmental Data Service) and so data may have been collected but was not sent to the archive). The warm conditions in the 1980s in Cabot Strait extended into the Esquiman Channel at depths below 125 m. Also similar to Cabot Strait, these waters cooled rapidly in the late 1980s and early 1990s but have risen in the last year or two. These results together with the earlier results of Bugden (1991) suggest the Cabot Strait measurements are a reliable index of temperature conditions in the deep channels of the Gulf. Surface temperatures throughout the Gulf appear to have been above normal in the 1980s but near normal in the 50-100 m depth range. The latter temperatures tended to decline through the decade such that the early 1990s were very cold.

Scotian Shelf (Subarea 4V,W,X) and the Gulf of Maine (Subarea 5)

Petrie and Drinkwater (1993) recently examined the low-frequency variability in hydrographic properties of the waters on the Scotian Shelf and in the Gulf of Maine from 1945-1990. They found this period to be dominated by the cooling and freshening of the water from the early 1950s to the mid 1960s with a rapid reversal into the 1970s. Analysis of data from Emerald Basin in the center of the Scotian Shelf revealed strong similarity in the low-frequency trends throughout the water column and horizontally from the Laurentian Channel to the Middle Atlantic Bight. The interannual temperature variability could not be explained by local atmospheric heating (Umoh 1992). Instead they found the origin of the temperature and salinity changes lay in the slope waters along the continental slope and were advected onto the shelf through cross-shelf exchange. This hypothesis of offshore forcing had been proposed earlier by Lauzier (1965). Petrie and Drinkwater (1993) went on to suggest that variations in the transport of the westward flow of the Labrador Current along the slope at depths of 100-300 m was the most likely cause of the observed changes in the temperature and salinity of the offshore slope waters and hence the source of the changes on the Scotian Shelf and in the Gulf of Maine. They found, based upon data collected by the US Coast Guard off the Grand Banks, that during the warm period of the 1950s the transport in the offshore Labrador Current was reduced whereas in the 1960s there was increased transport. A simplified mixing model based upon the differences in transport between the warm and cold years and a constant mixing rate could account for the observed changes in temperature and salinity at Cabot Strait, on the Scotian Shelf and in the Gulf of Maine. Thus advection from the Labrador Sea appears to play a very important role in the interannual variability of regions further south. It is also interesting to note that the larger transport of the Labrador Current occurred during the warm period of the 1960s. Increased geostrophic transport in the Labrador Current in warm years (low NAO index) was also noted by Myers et al. (1989).

The temperature anomalies in Emerald Basin are shown in Fig. 26. Note that they are 2 to 3 times the amplitude of those in the Labrador Sea. Also, as pointed out by Petrie and Drinkwater (1991), the size of the anomalies increases with depth. The cooling from the 1950s to the mid-1960s and the sharp rise into the 1970s is the dominant signal (Petrie and Drinkwater 1993). During the 1980s the deeper waters (below 100 m) were relatively warm while waters above 100 m were relatively colder than the 1961-90 mean. Of particular note is that the trends in the bottom waters (200 m) and shallower layers (< 100 m) seem to be diverging (Fig. 26). Whereas the trends from the late 1940s to 1980 were similar with depth, since the mid-1980s the bottom waters have been relatively warm whereas the upper 100 m have been cooling. Drinkwater (1994) found significant cooling over all of the Scotian Shelf and into the Gulf of Maine in the depth layer of 50 to 100 m. The cooling began around 1985 and continued through into the 1990s. There is some evidence to suggest that similar cold waters were observed on St. Pierre Bank off southern Newfoundland (R.A. Myers, personal communication, NWAFC, St. Johns) and in the Gulf of St. Lawrence. The relative important of advection versus local atmospheric cooling as the source of this cooling is unresolved.

One of the longest operating offshore monitoring site in the NW Atlantic is Prince 5 which began in the 1920s and is sampled once per month by scientists from the St. Andrews Biological Station. It is located at the mouth of the Bay of Fundy where the strong tidal currents reduce the vertical temperature and salinity gradients (Drinkwater 1987). Similarity of low-frequency changes between Prince 5 and other regions of the Gulf of Maine and on the Scotian Shelf have been noted by Lauzier (1965) and Petrie and Drinkwater (1993). This can also be seen by comparing Figs. 27 and 26. During the 1980s, Prince 5 temperatures have been above the 1961-90 mean but in general have been lower than temperatures attained in the 1970s. Cold conditions dominated the 1930s and 1960s with the warmest temperatures in the 1950s. Within the last decade temperatures through the water column were relatively warm but began to decline by the mid-1980s. A large decrease was observed in the early 1990s. This decrease is part of a wide spread phenomenon over the eastern Gulf of Maine and the and at intermediate depths on the Scotian Shelf. Salinities were above the 1961-90 means but dropped relative to the 1970s. The freshest waters appear at the mouth of the Bay of Fundy in the 1960s which was also observed over the Scotian Shelf (Petrie and Drinkwater 1993). The interannual variability in salinity is not related to the fluctuations in the Saint John River discharge.

Middle Atlantic Bight (Subarea 6)

Temperature conditions in the Middle Atlantic Bight from the 1960s to the late 1980s were described by Mountain and Murawski (1992) from measurements taken during spring and bottom-trawl surveys. They report high coherence between surface and bottom temperature anomalies and over geographic scales from Cape Hatteras to and including the Gulf of Maine. The late 1960s was the coolest period, the mid-1970s the warmest, while the late 1970s and early 1980s were intermediate between the two earlier periods. Temperatures increased in the mid-1980s but did not attain those temperatures observed in the mid-1970s. Manning (1990) investigated salinity variability in the Bight from data collected between 1977-87. The shelf waters exhibited large interannual variations with (range of 1 psu) with low salinity in the late 1970s, 1984 and 1988 separated by years of relatively high salinity in 1981 and 1986. He found that river discharge from U.S. (the major rivers flowing into the Bight and the Gulf of Maine) and the Gulf of St. Lawrence (RIVSUM) plus precipitation accounted for 70% of the interannual changes in salinity. Mountain (1991), however, suggested that the hydrographic variability on the Bight were largely a result of changes in the amount of Slope Water that becomes mixed with the shelf water. The waters on the Bight originate from cold, low salinity waters flowing south over the Scotian Shelf and the relatively warm, saline Slope Waters. The latter enters the Gulf of Maine through the NE Channel and mix with the Scotian Shelf waters as they circulate anticlockwise around the Gulf. The resultant water mass is eventually carried by the residual circulation onto the Bight where it continues its journey southward. Warm and saline conditions in the mid-1980s is attributed to the increased inflow through the NE Channel.

Summary

Examination of meteorological, hydrological and oceanographic datasets have shown:

(1) The Icelandic Low and the Bermuda-Azores High intensified (high NAO index) during the 1980s resulting in stronger westerly winds across the northern North Atlantic Ocean and northwesterly winds in the Labrador Sea. These winds carried cold Arctic air down over the Labrador Sea. In the Middle Atlantic Bight area the strengthened Azores high induced southerly winds carrying warm air masses.
(2) In the north, sea ice formed earlier and it spread more rapidly resulting in the greatest areal extent over the length of the record (3 decades).
(3) Off West Greenland temperatures averaged over the decade were cool relative to the 1950s but were near those observed during the 1960s and 1970s. Salinities were the highest in four decades. On the western side of the Labrador coast temperatures were the coldest and the cross-shelf area of the CIL was the highest in four decades.

(4) In the deep waters of the Gulf of St. Lawrence, the Scotian Shelf and the Gulf of Maine temperatures were the highest in four decades.

(5) Surface waters in the Gulf of St. Lawrence and the Middle Atlantic Bight were slightly warmer than normal while the intermediate waters (approximately 50-100 m) cooled significantly in the late 1980s on the Scotian Shelf and in the Gulf of Maine and Gulf of St. Lawrence.

(6)Along-shelf and across-shelf advection plays an important role in climate change in the NW Atlantic. The latter promotes exchange and mixing of shelf and slope waters especially in subareas 4 to 6.

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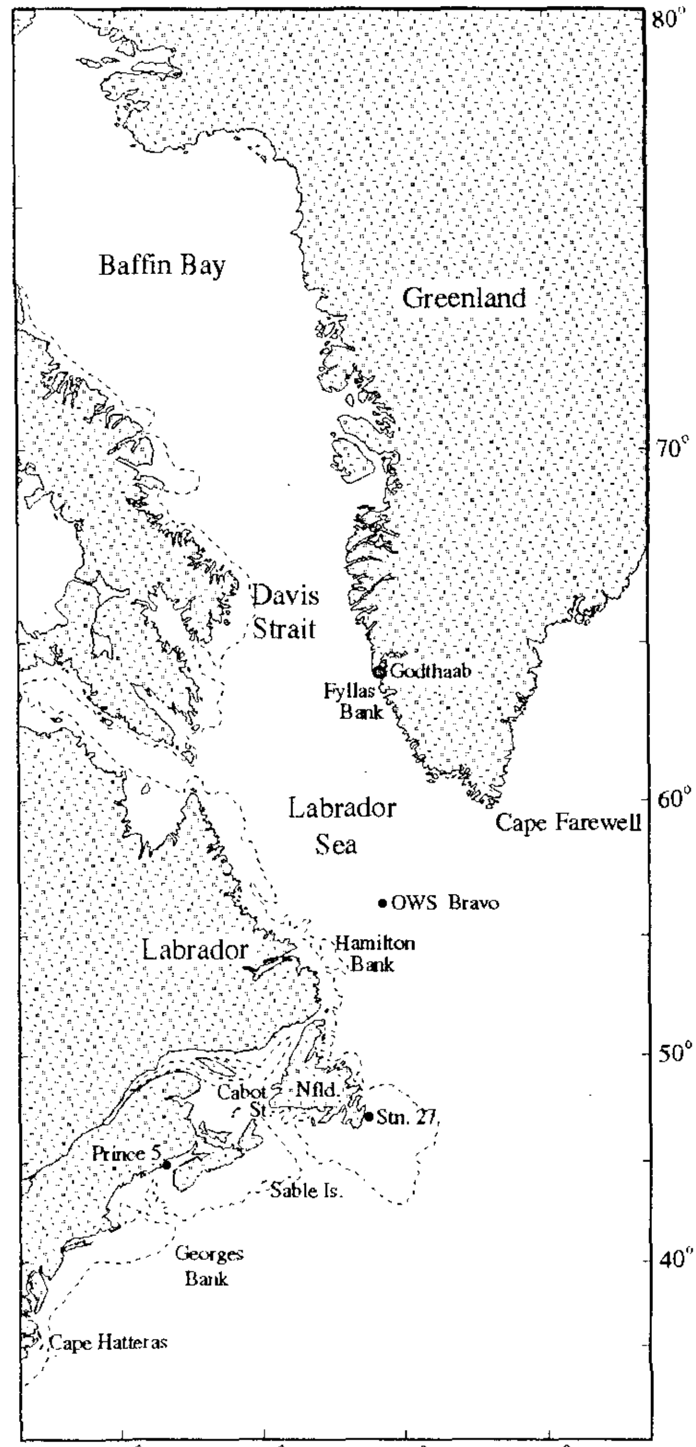


Fig. 1. The NW Atlantic study area.

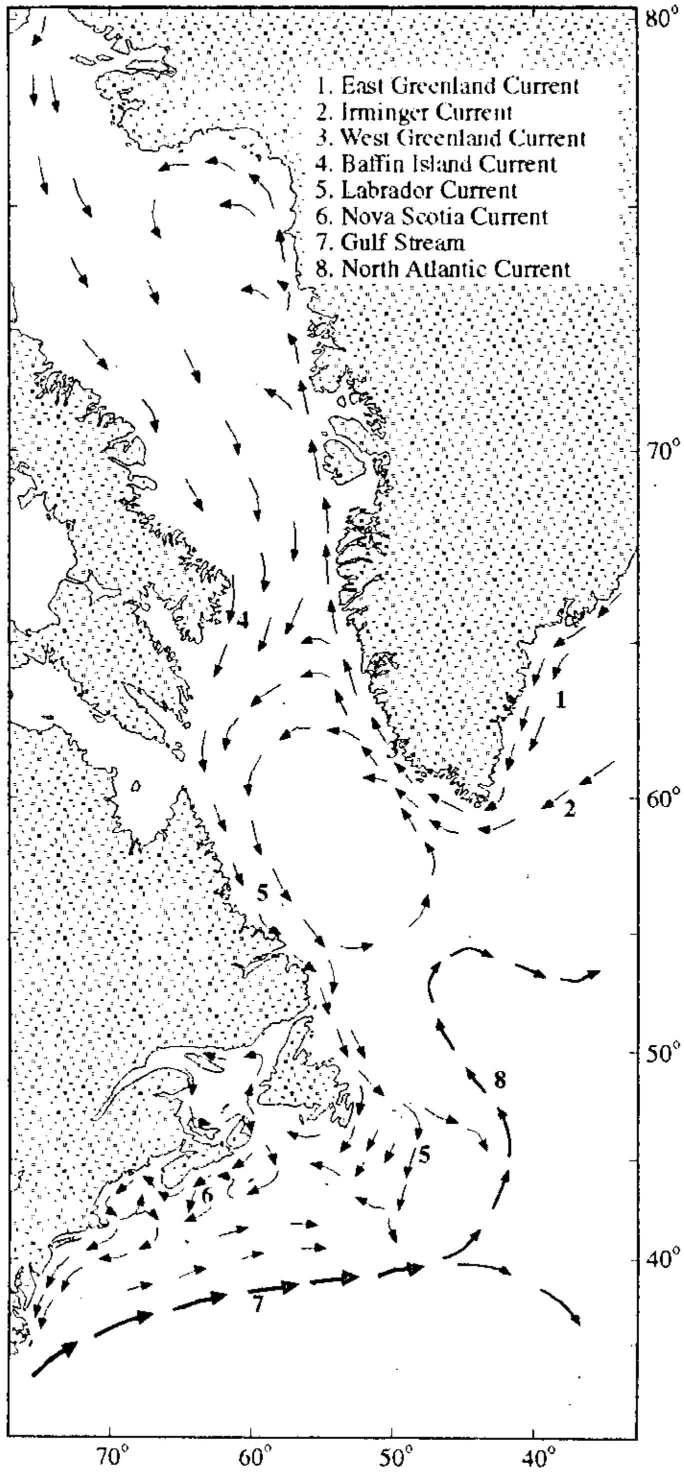


Fig. 2. The near surface circulation pattern in the NW Atlantic.

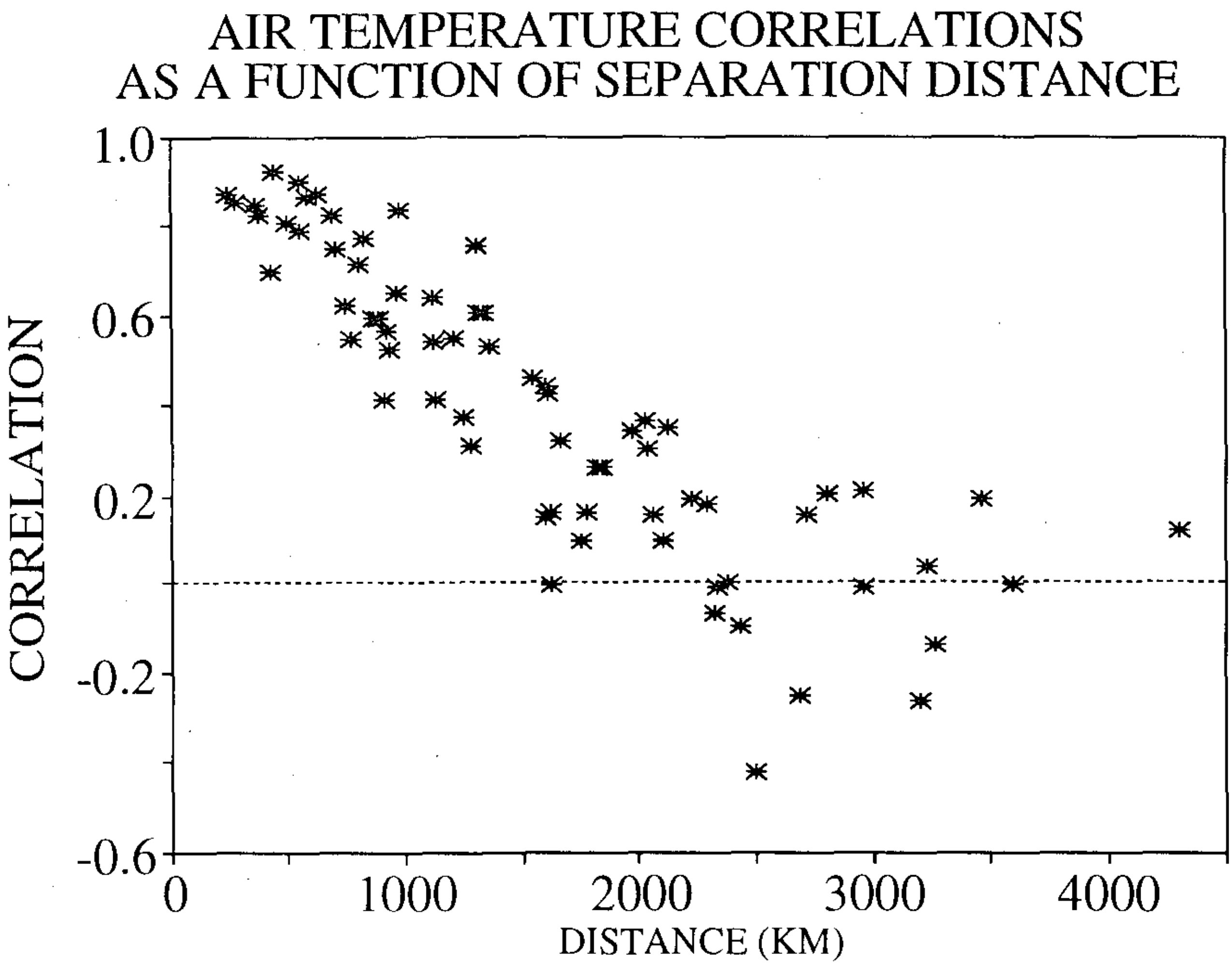


Fig. 3. The correlation of annual air temperature records in the NW Atlantic as a function of separation distance.

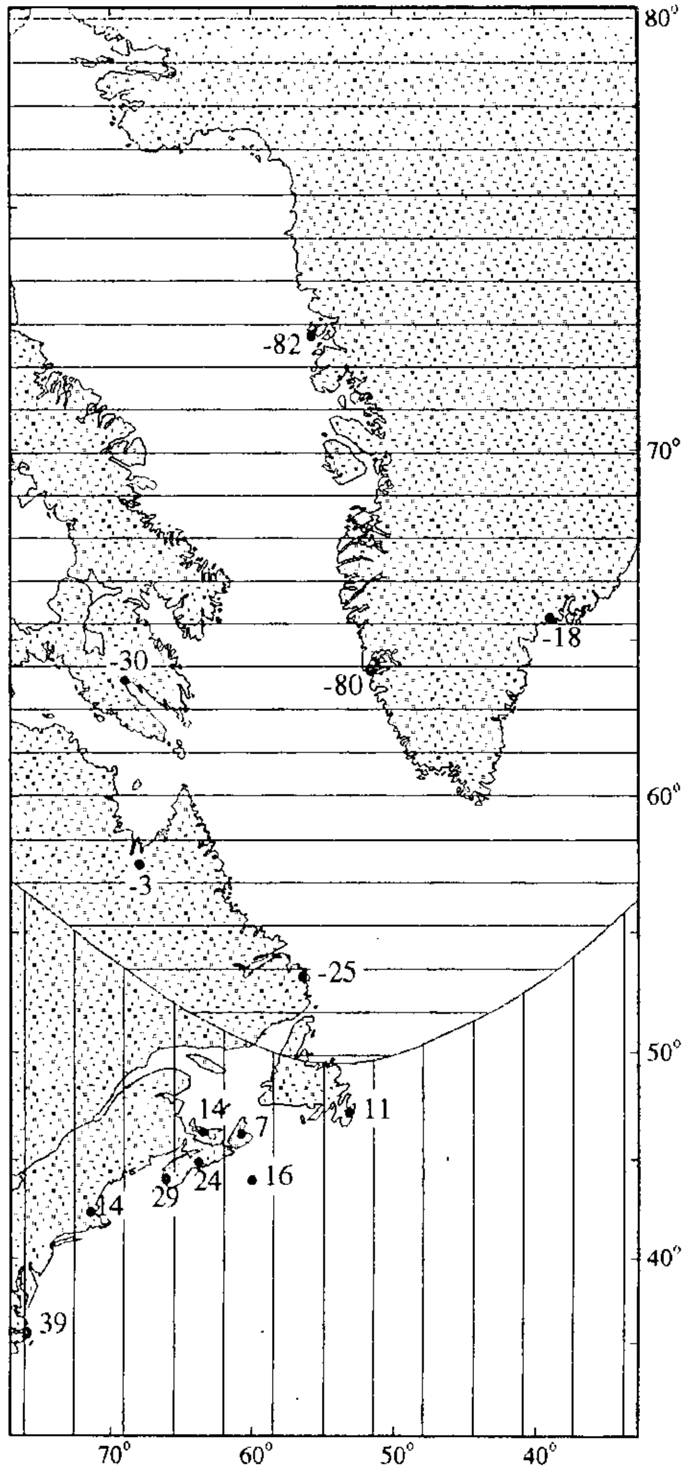


Fig. 4. The 1980s decadal mean air temperature anomaly in hundreds of a degree relative to 1961-90.

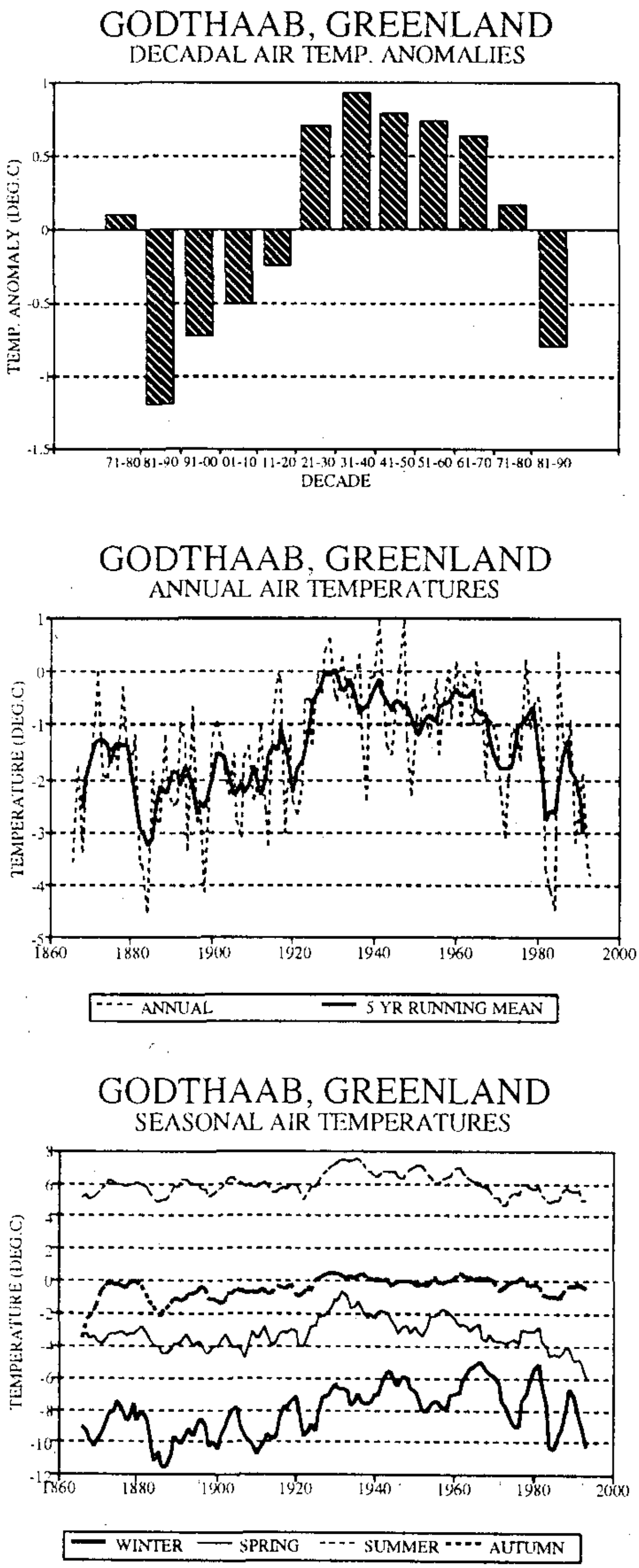


Fig. 5. Godthaab air temperatures. Decadal anomalies (top), annual temperatures (middle) and seasonal means (bottom).

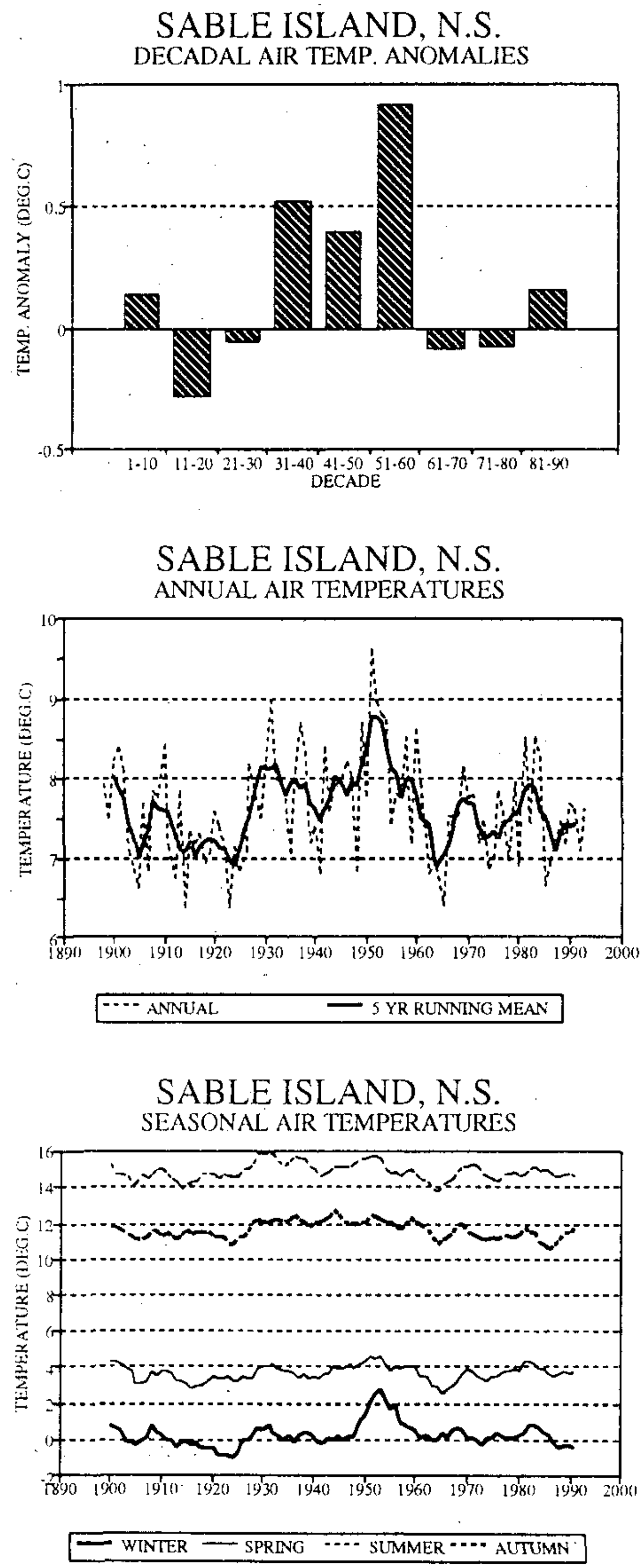


Fig. 6 Sable Island air temperatures. Decadal anomalies (top), annual temperatures (middle) and seasonal means (bottom).

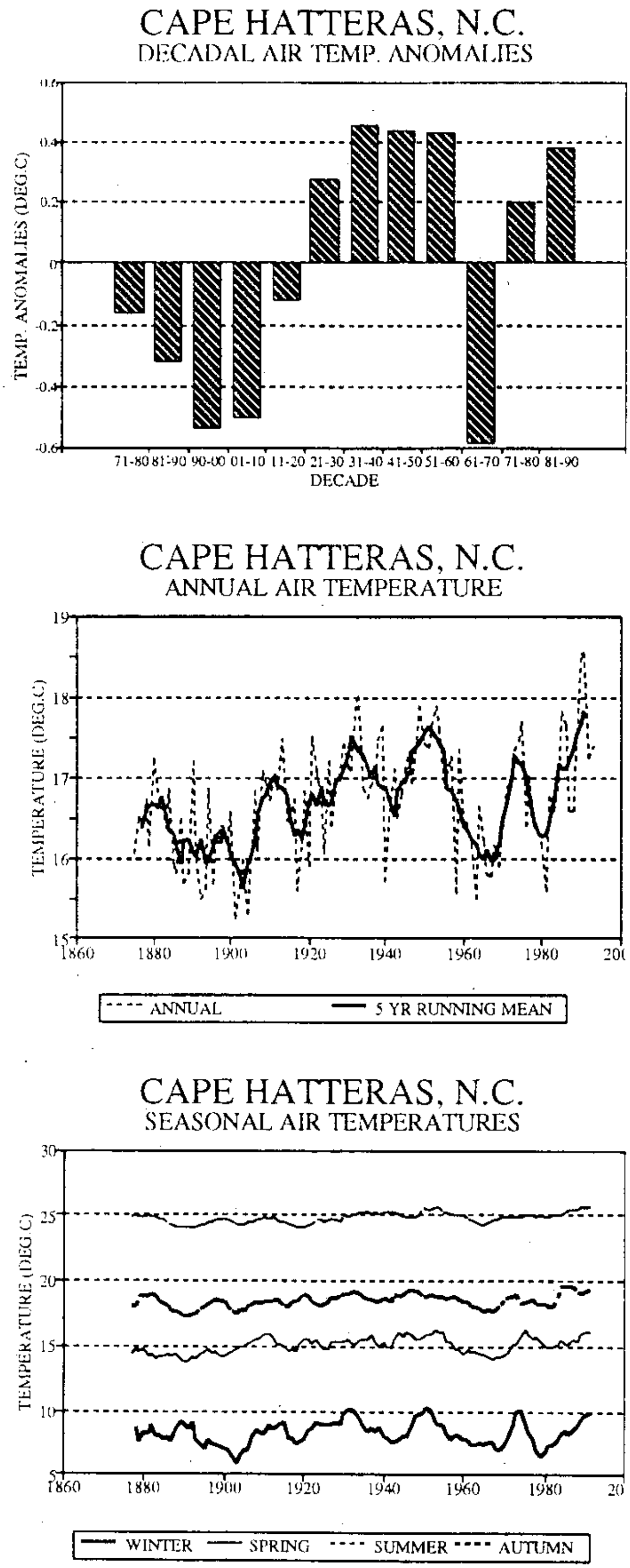


Fig. 7 Cape Hatteras air temperatures. Decadal anomalies (top), annual temperatures (middle) and seasonal means (bottom).

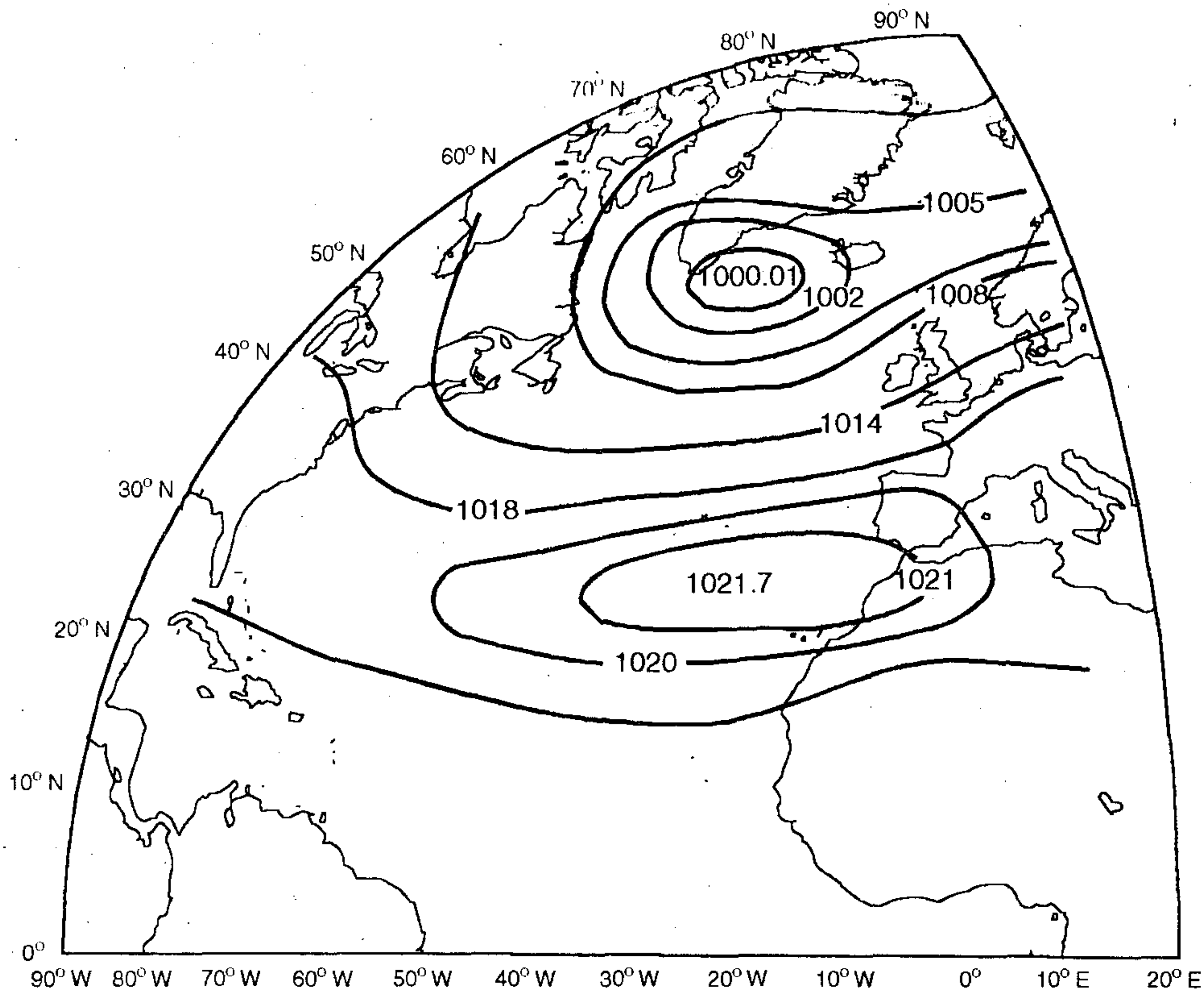


Fig. 8. The 1961-90 mean sea level pressure field over the North Atlantic Ocean during the winter (in mb). The pattern is dominated by the Icelandic Low and the Bermuda-Azores High.

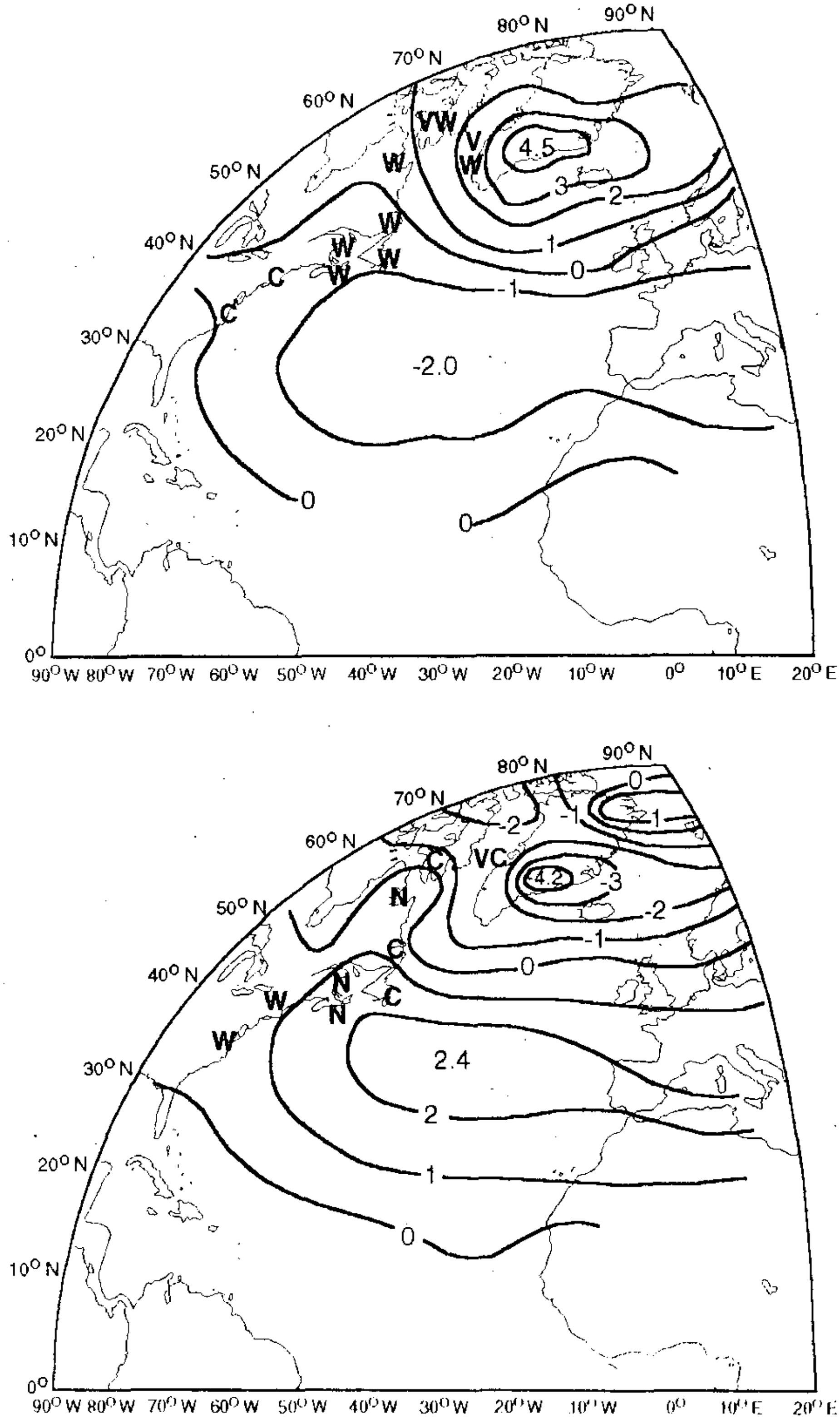


Fig. 9. Winter sea level pressure anomaly patterns during the 1960s (top) and 1980s (bottom). The decadal mean air temperatures at several sites in the NW Atlantic are labelled as very warm (VW), warm (W), near normal (N), cold (C) or very cold (VC).

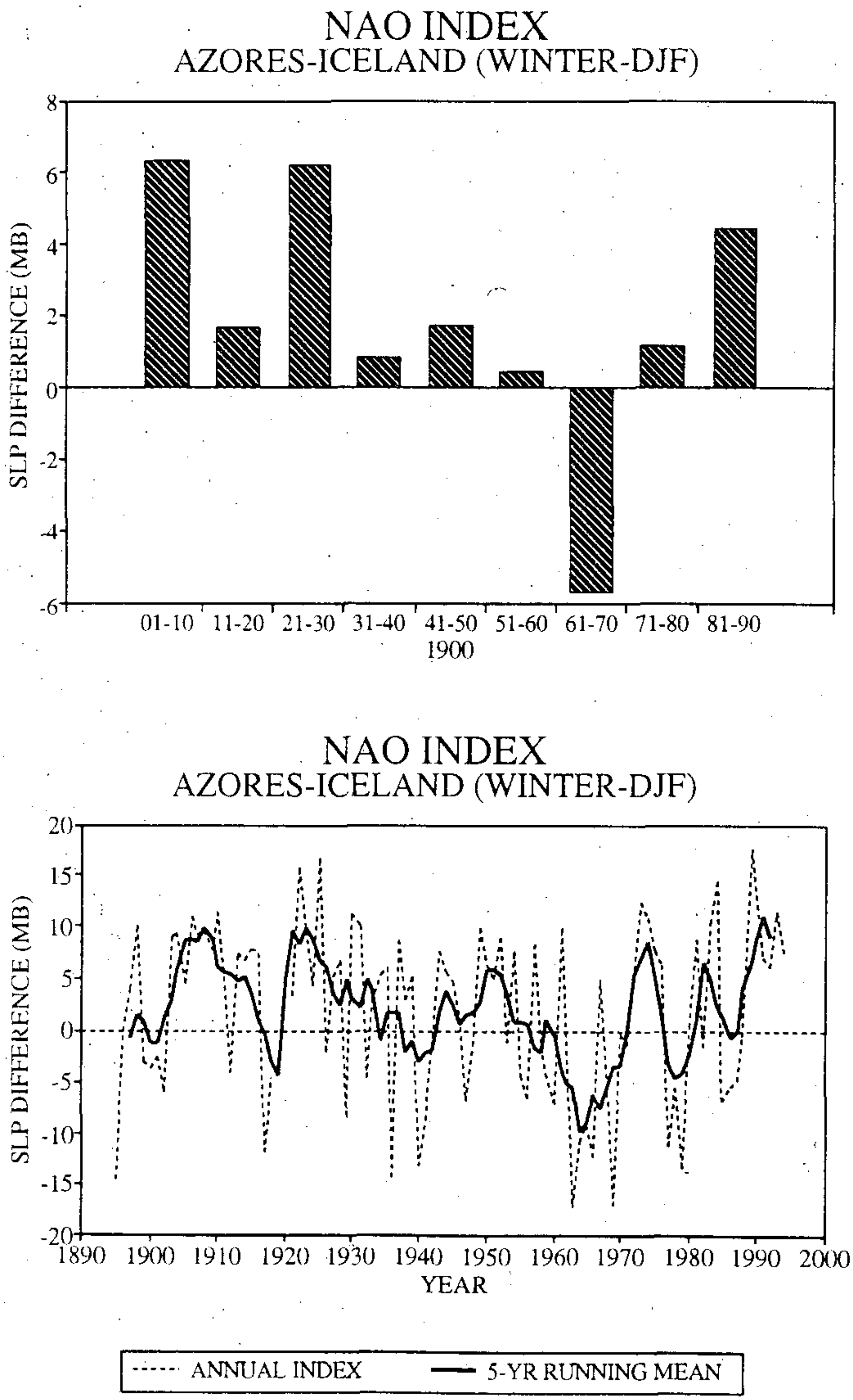


Fig. 10. The decadal (top) and annual (bottom) anomalies of the NAO Index.

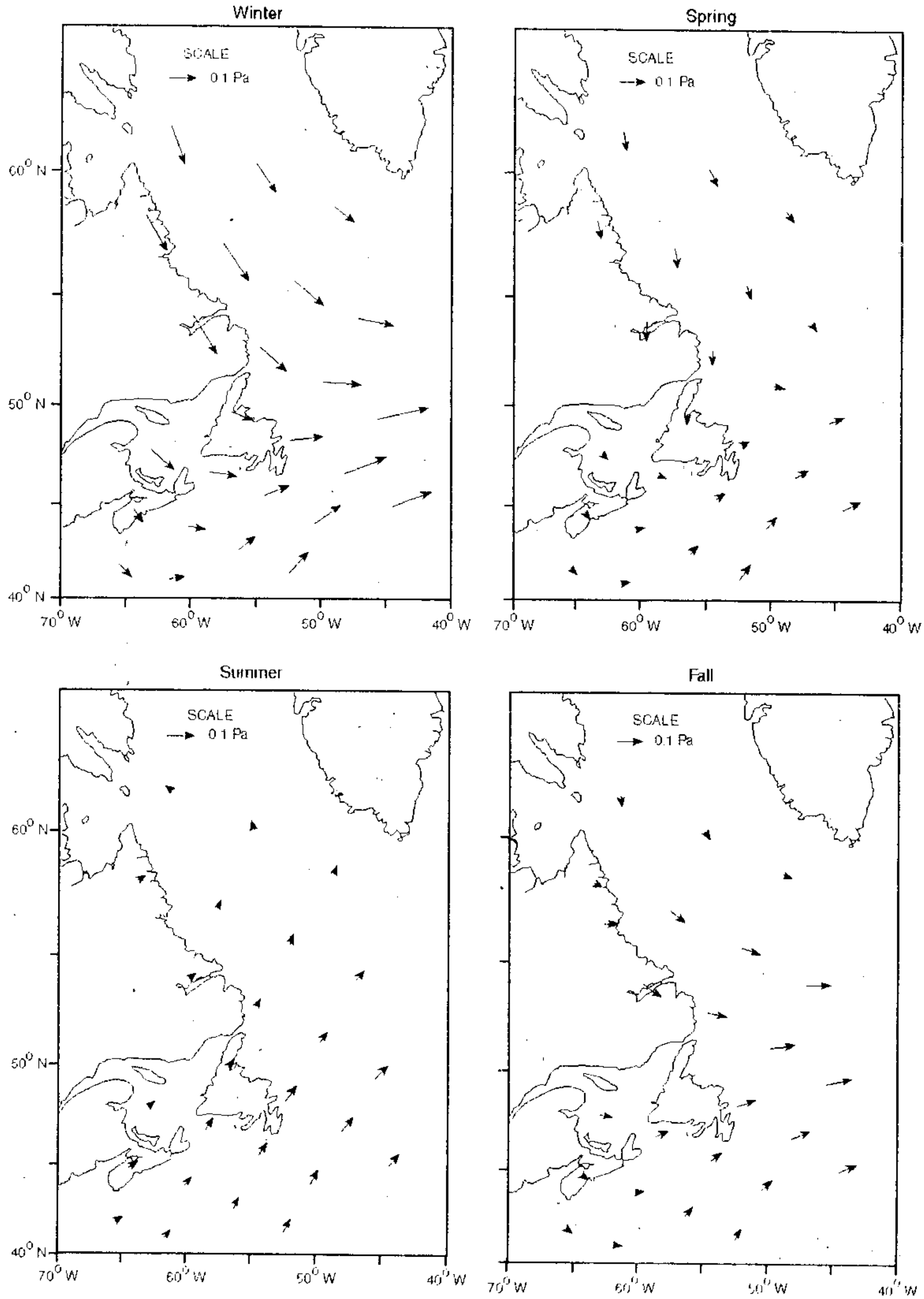


Fig. 11. The seasonal mean (1961-90) geostrophic wind stresses at 25 sites off the east coast of Canada.

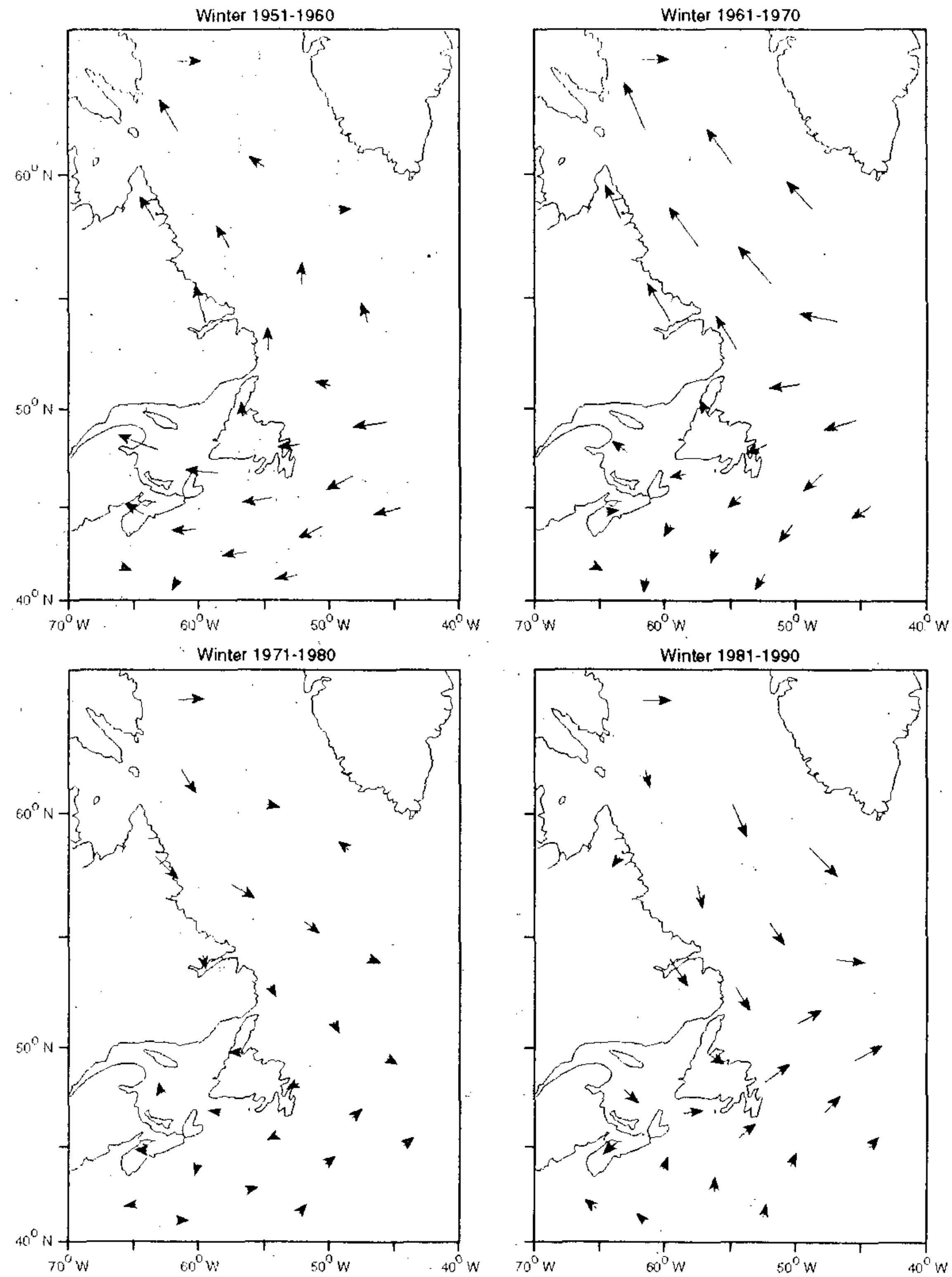


Fig. 12. The winter wind stress anomalies for the 1950s, 1960s, 1970s and 1980s.

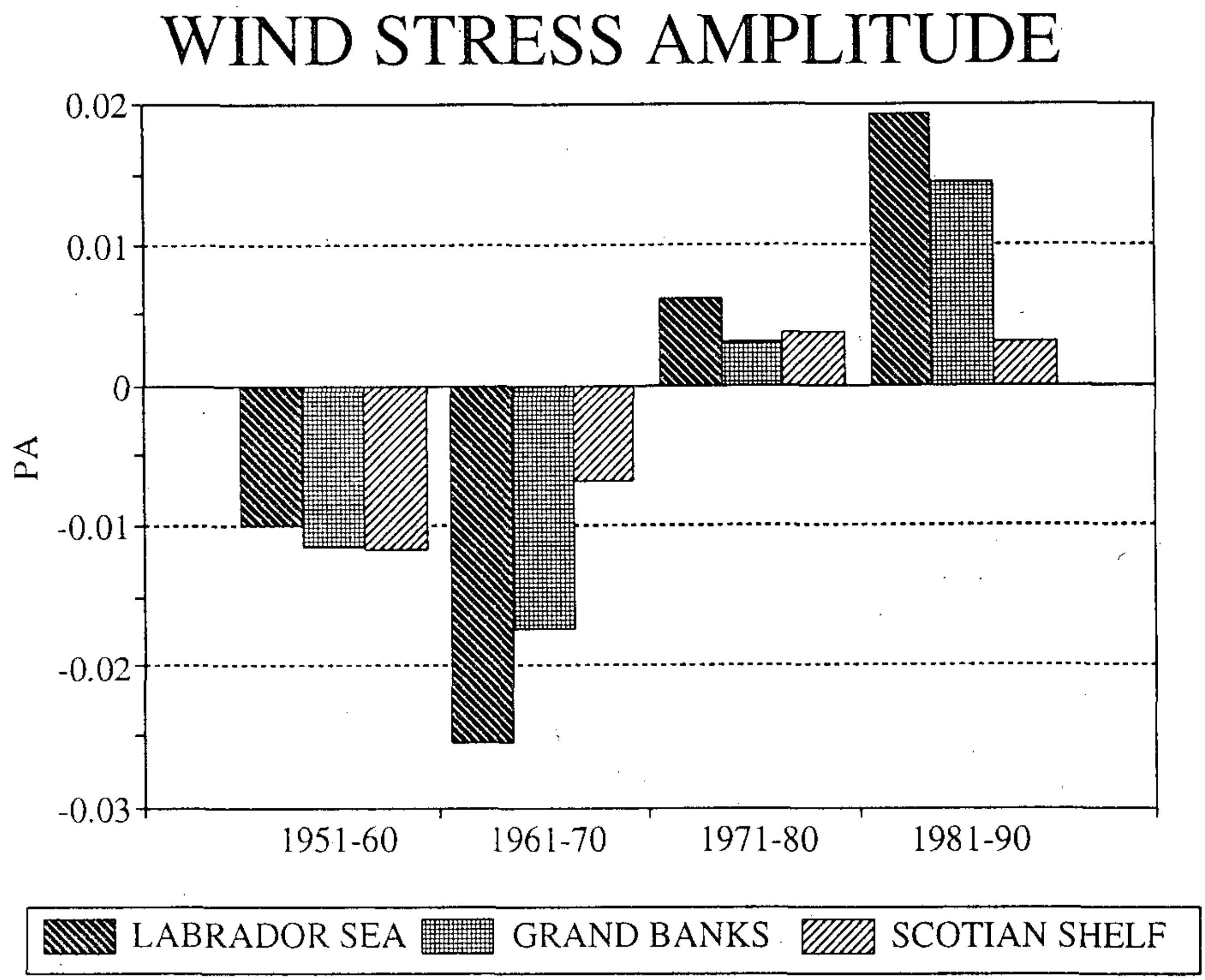


Fig. 13. The decadal amplitudes of the wind stress over the Labrador Sea, the Grand Banks (including the northern Newfoundland Shelf) and the Scotian Shelf (including the Gulf of St. Lawrence).

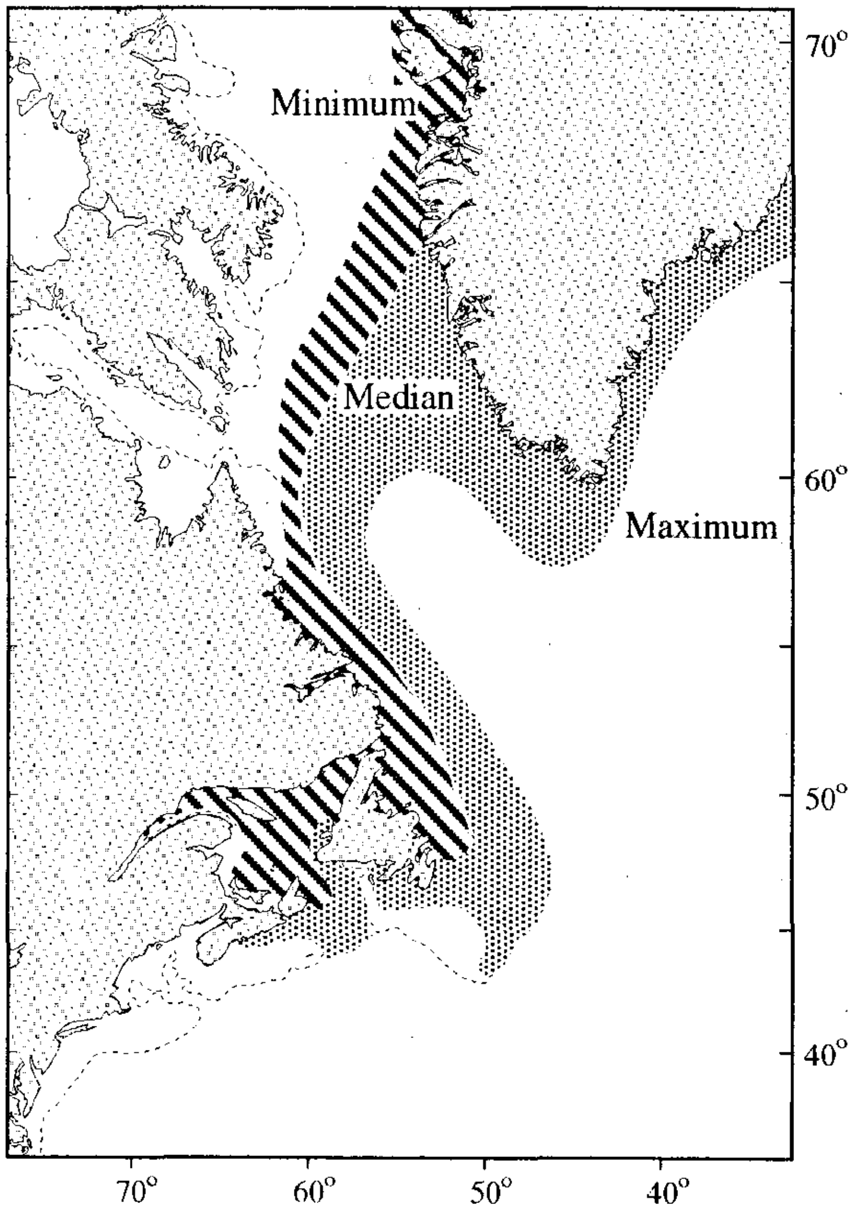
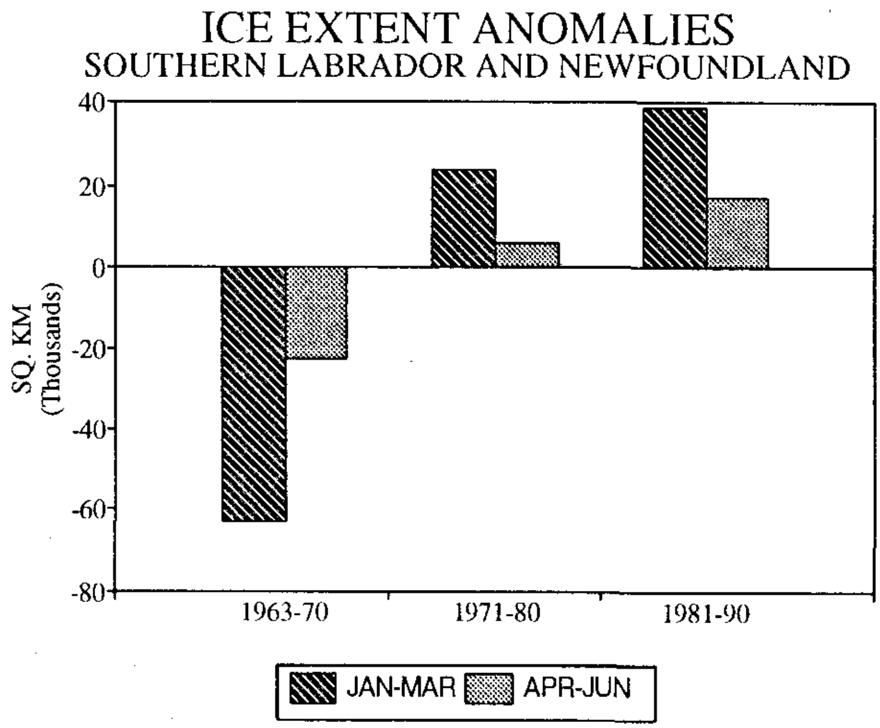


Fig. 14. The approximate location of the interannual minimum, median and maximum position of the edge of the sea ice (10% concentration) during the peak ice season (based upon Coté (1989) and Agnew (1993)).



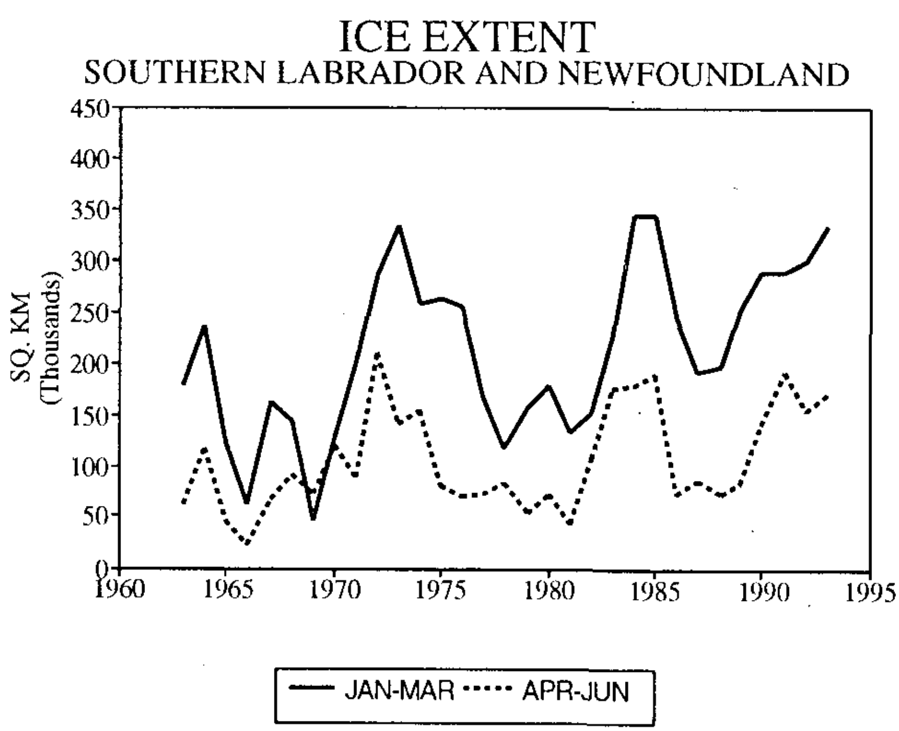
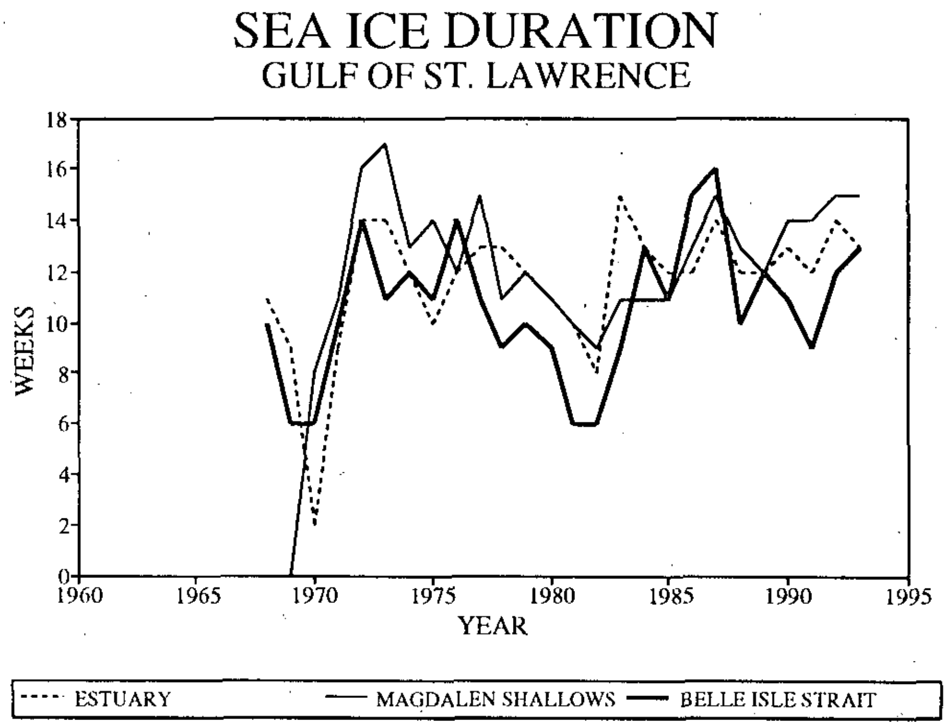


Fig. 15. The decadal (top) and annual (bottom) variability in the average ice extent during January to March (ice advance) and April to June (ice retreat).



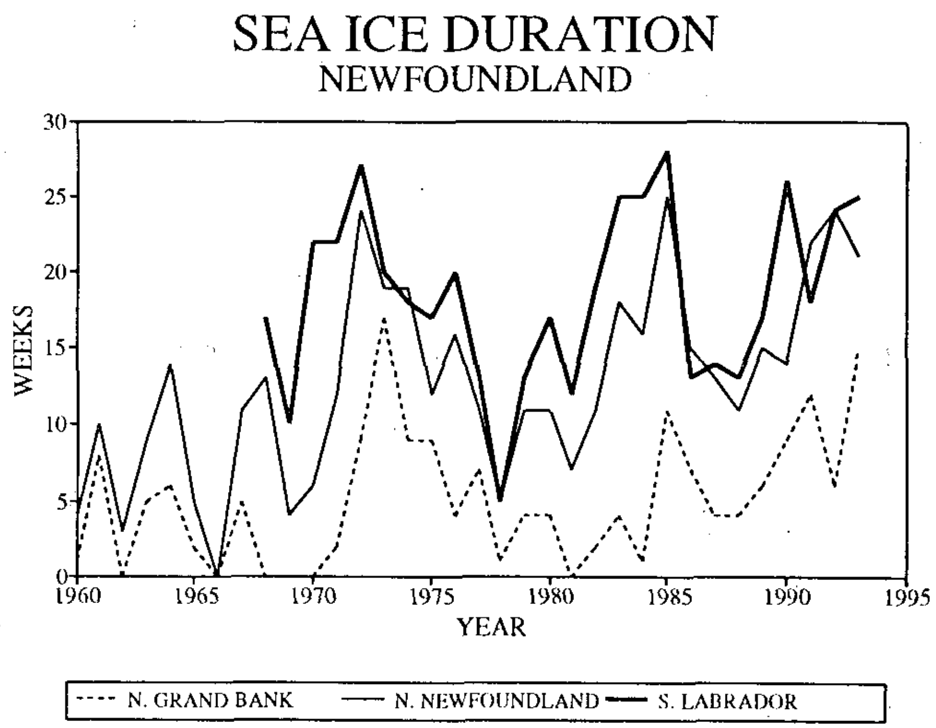
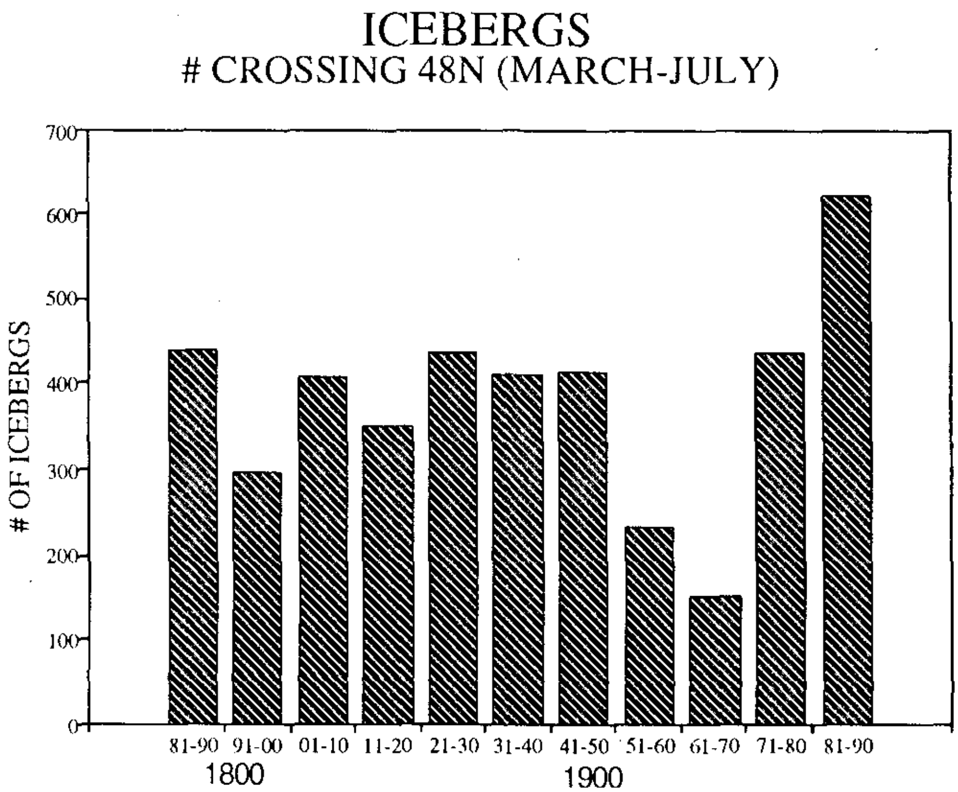


Fig. 16. The annual duration of sea ice at three locations off both Newfoundland (top) and in the Gulf of St. Lawrence (bottom).



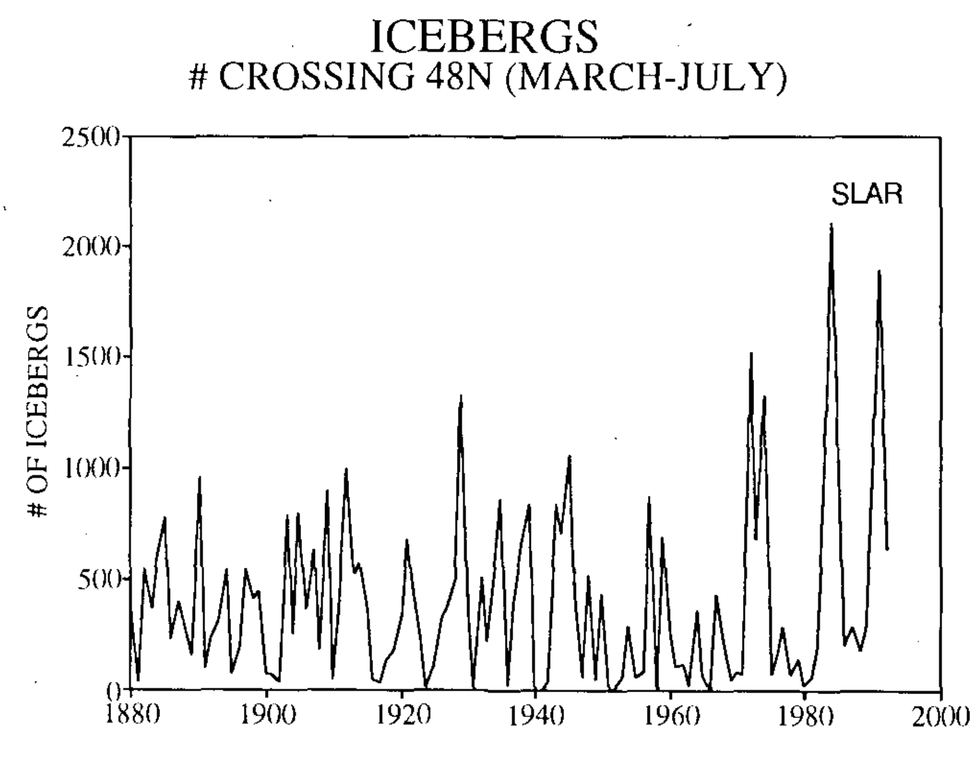
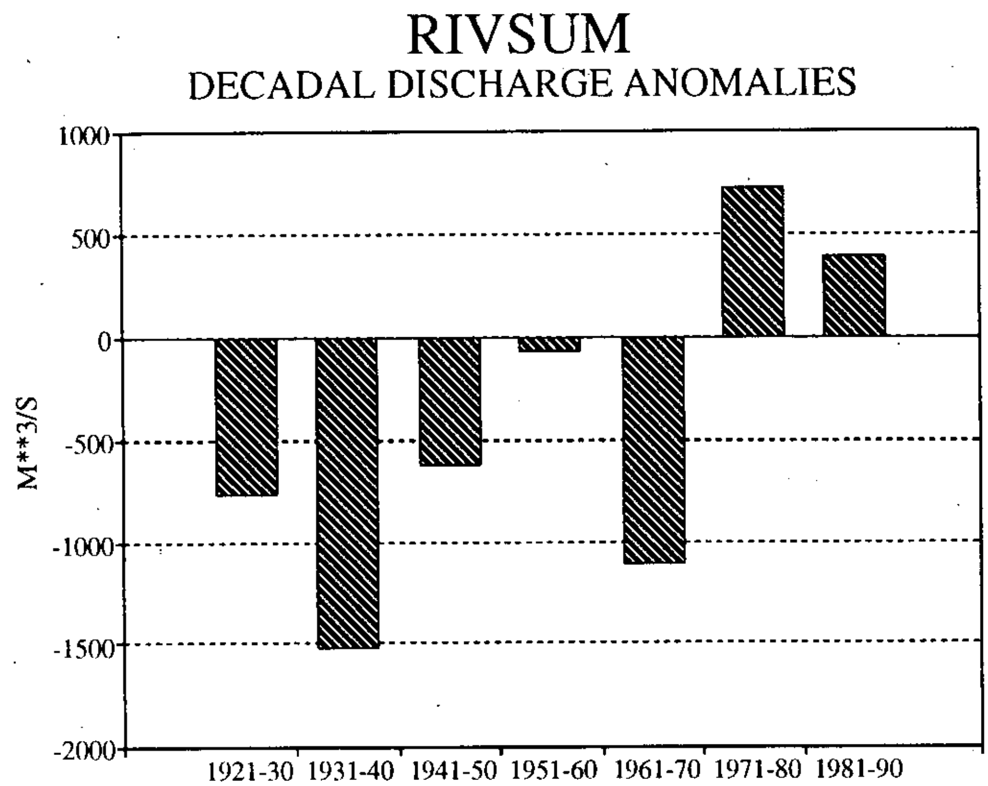


Fig. 17. The annual number of icebergs crossing south of 48°N.



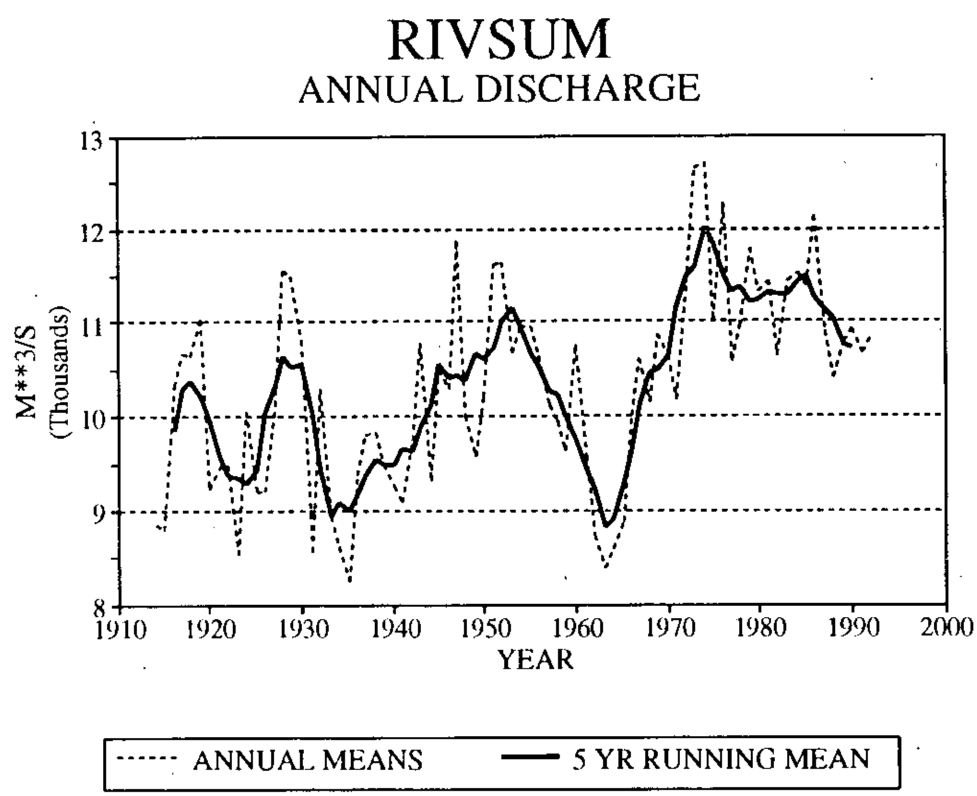
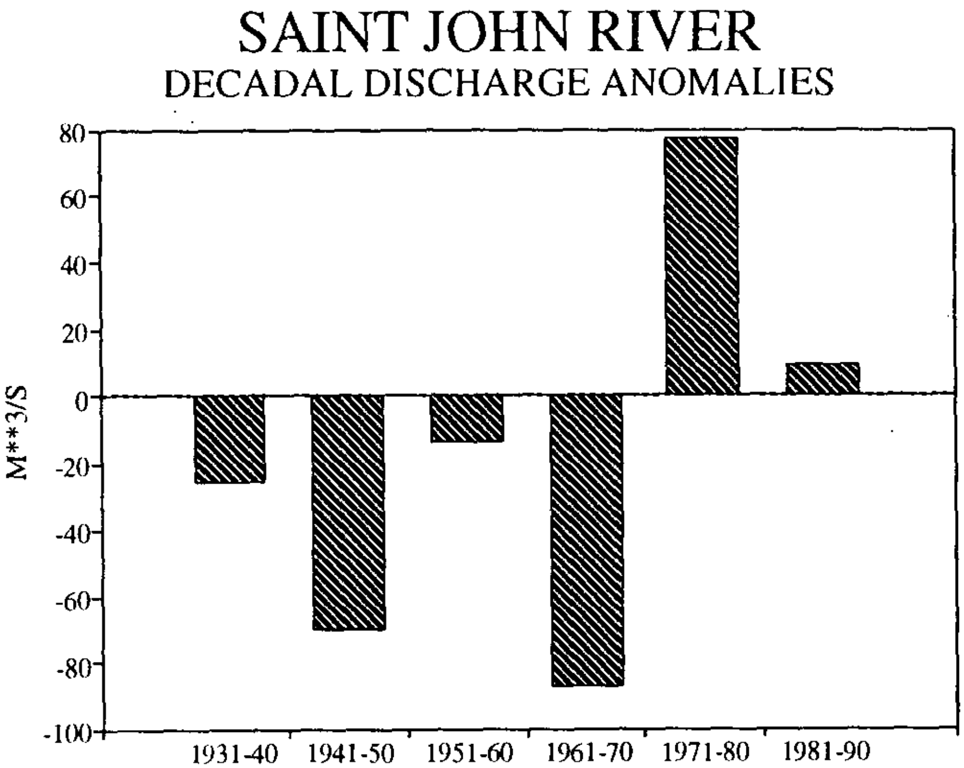


Fig. 18. The decadal (top) and annual (bottom) discharge from the combined St. Lawrence, Ottawa and Saguenay rivers (RIVSUM).



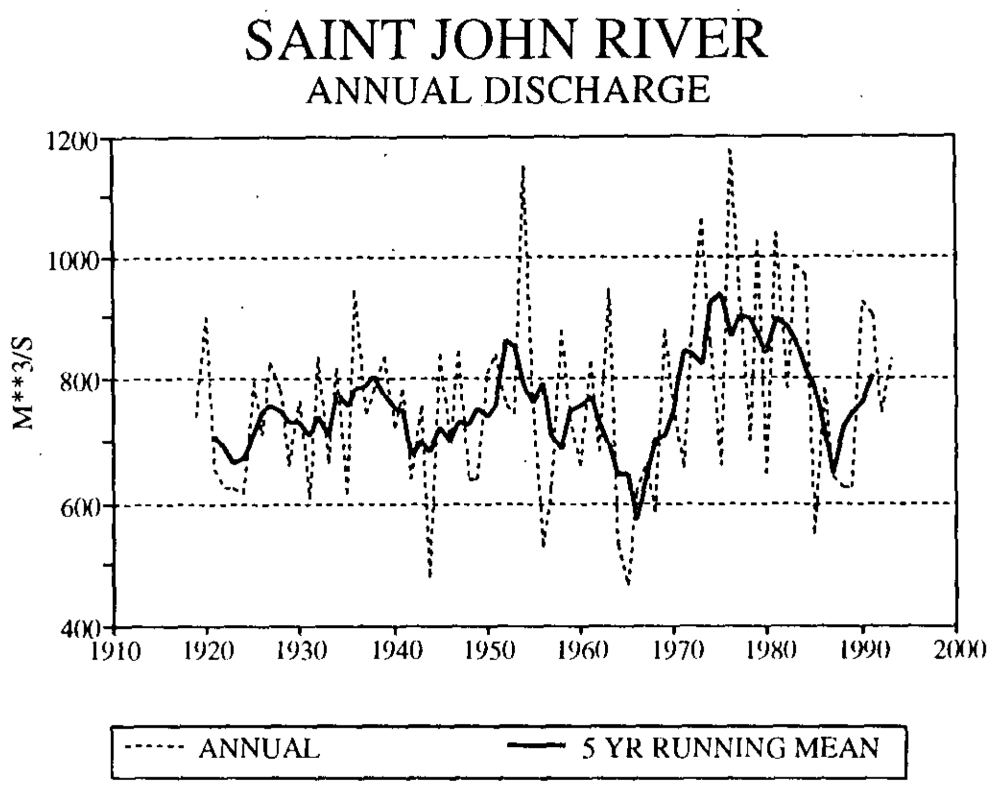
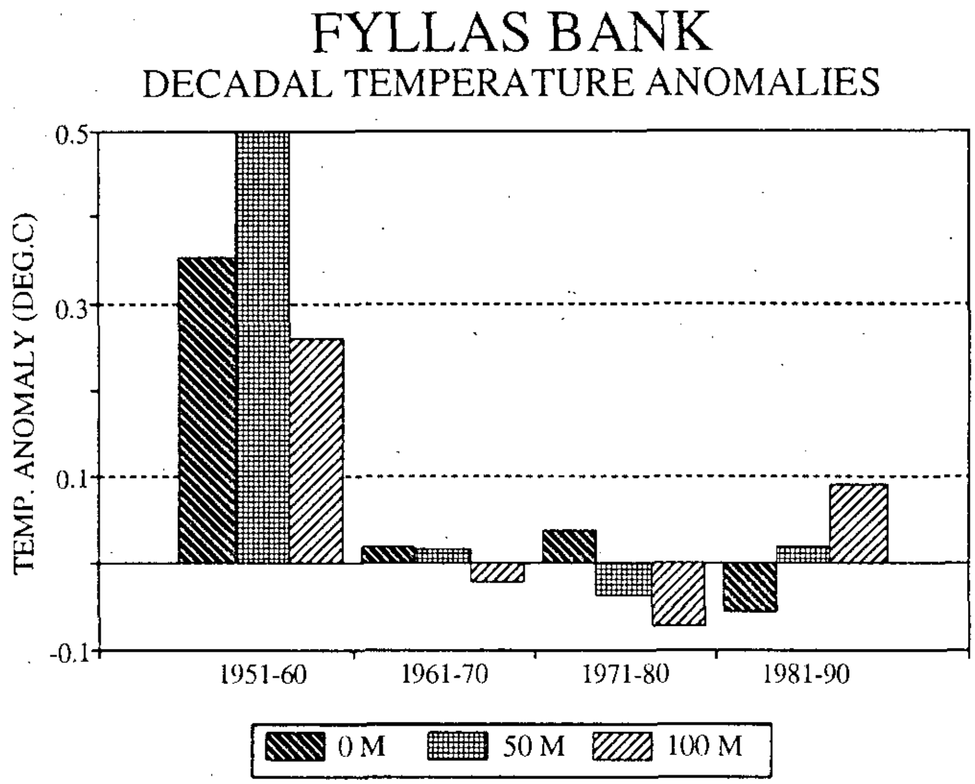


Fig. 19. The decadal (top) and annual (bottom) discharge from the Saint John River.



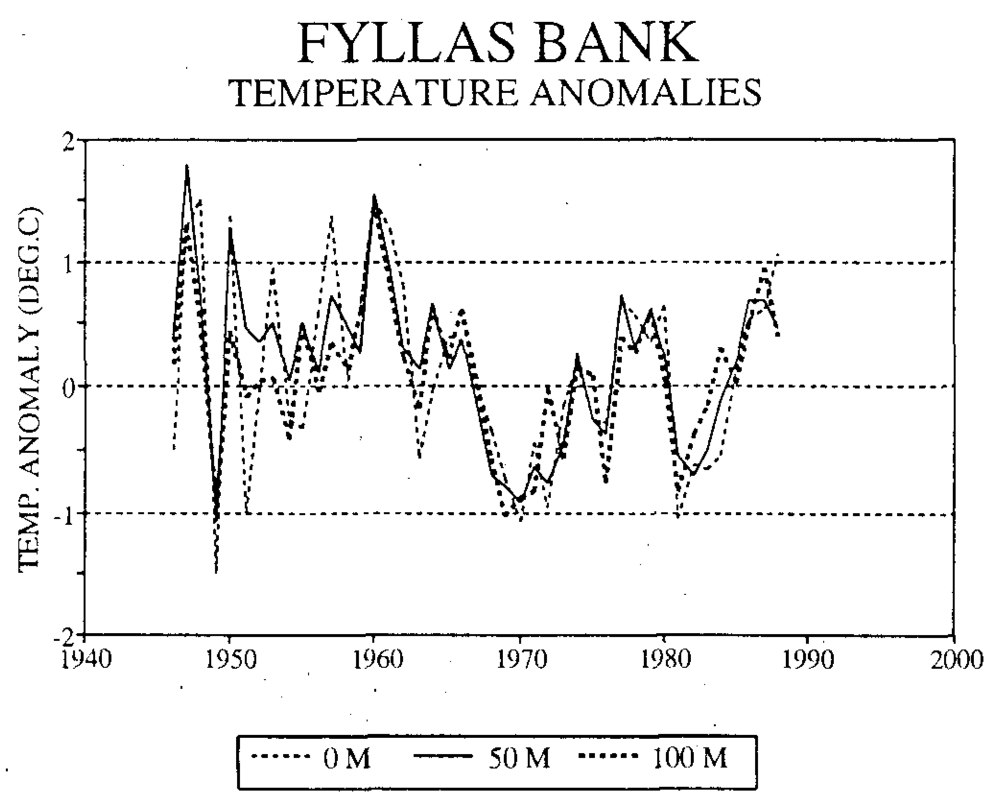
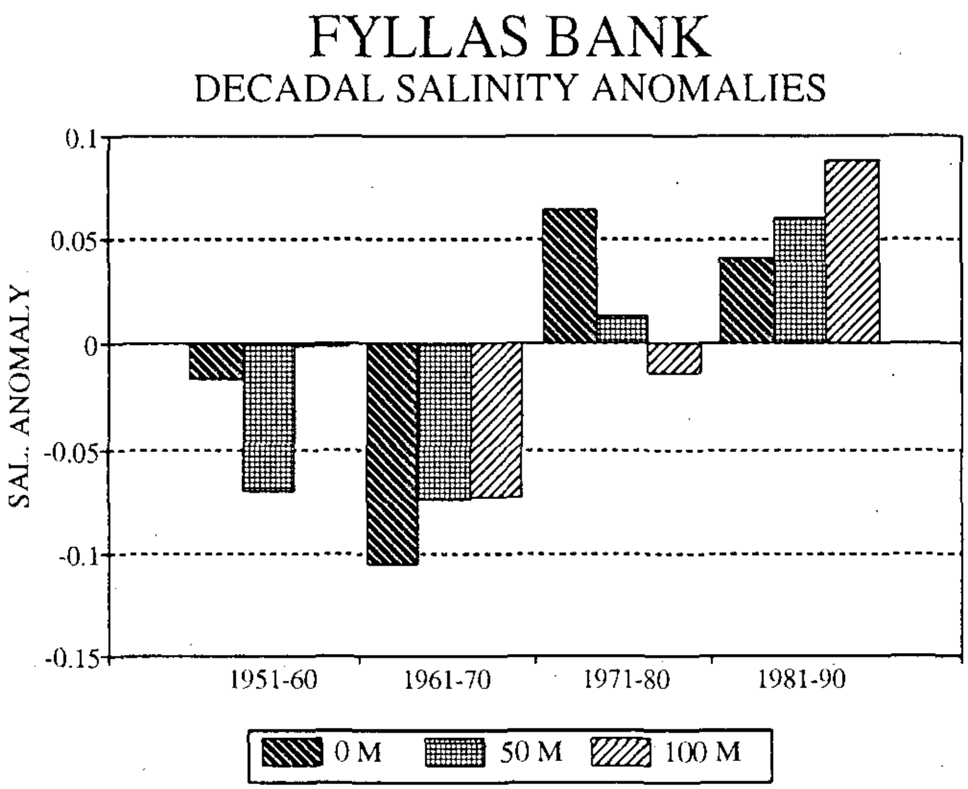


Fig. 20. The decadal (top) and annual (bottom) temperature anomalies at 0, 50 and 100 m depth over Fyllas Bank.



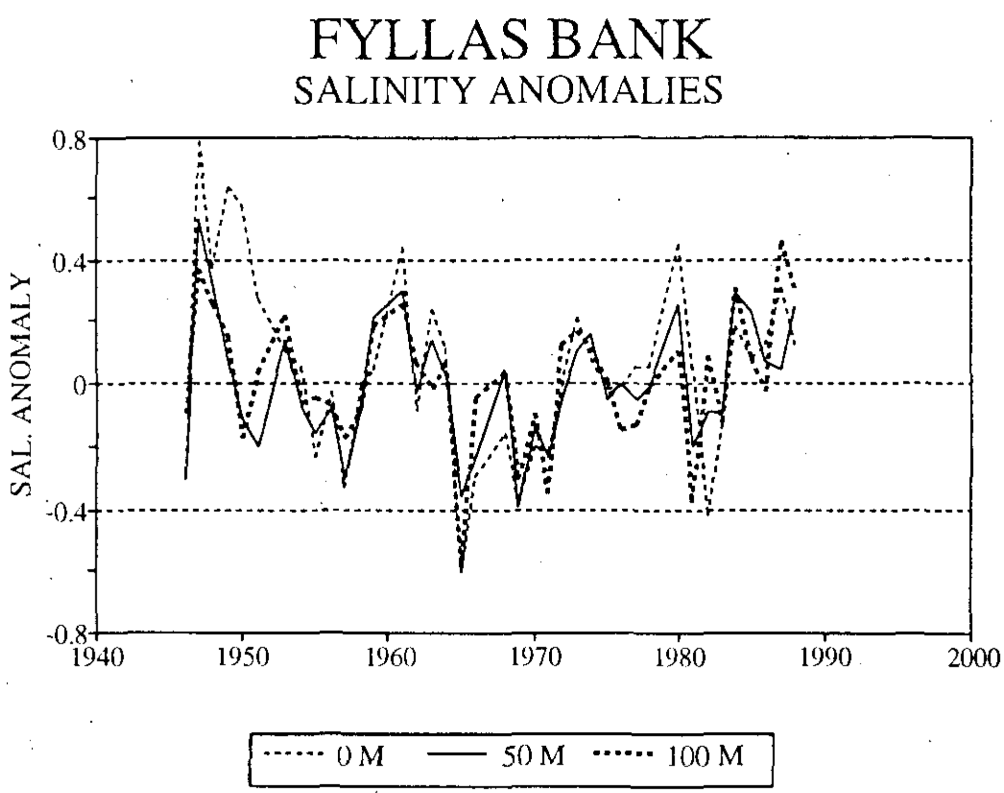
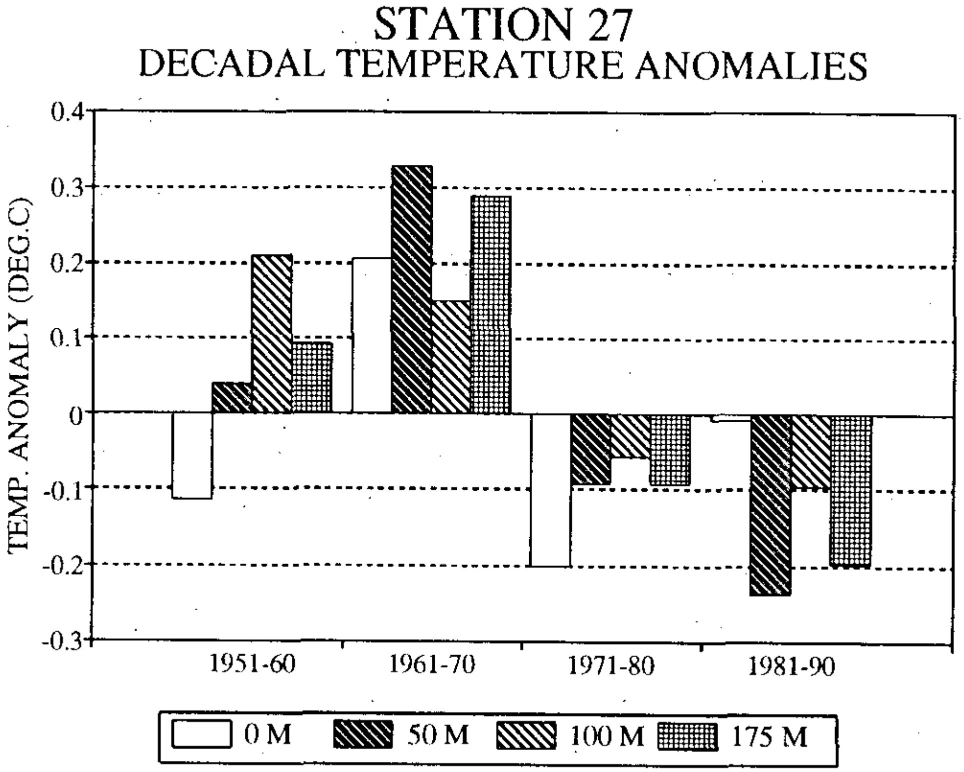


Fig. 21. The decadal (top) and annual (bottom) salinity anomalies at 0, 50 and 100 m depth over Fyllas Bank.



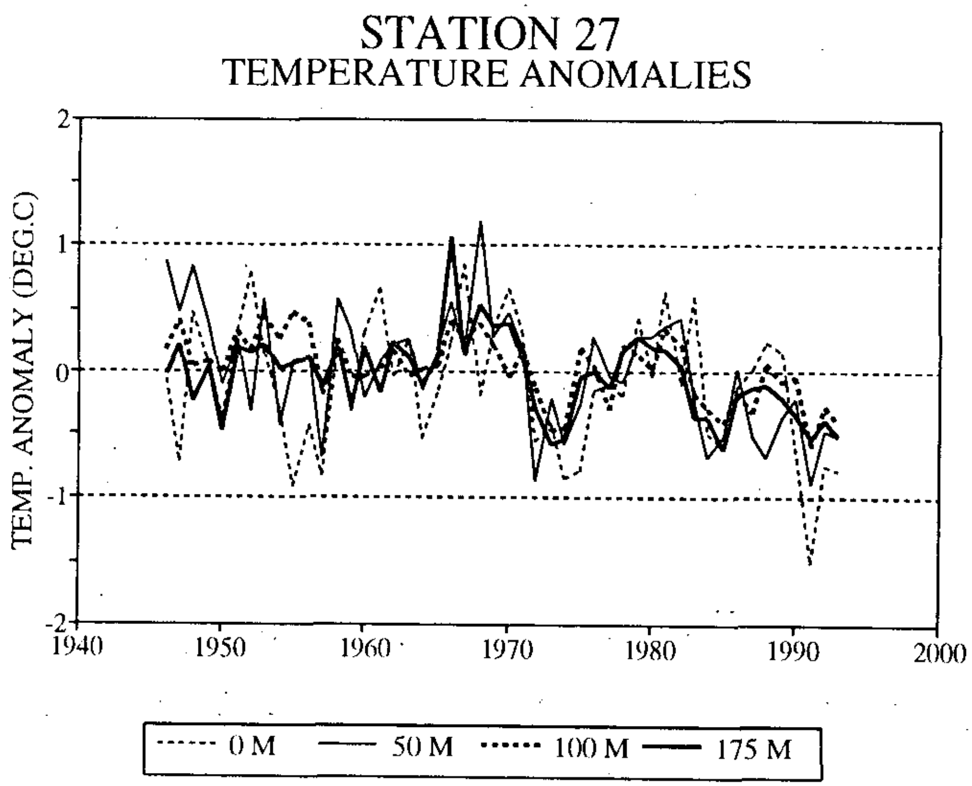
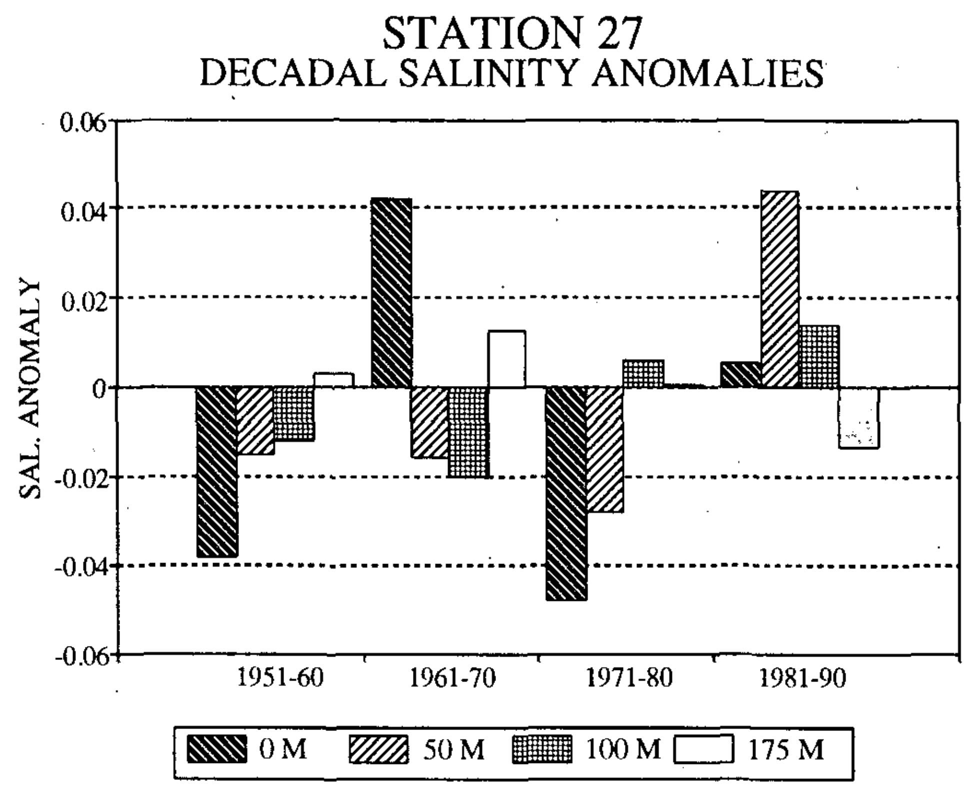


Fig. 22. The decadal (top) and annual (bottom) temperature anomalies at 0, 50, 100 and 175 m at Station 27.



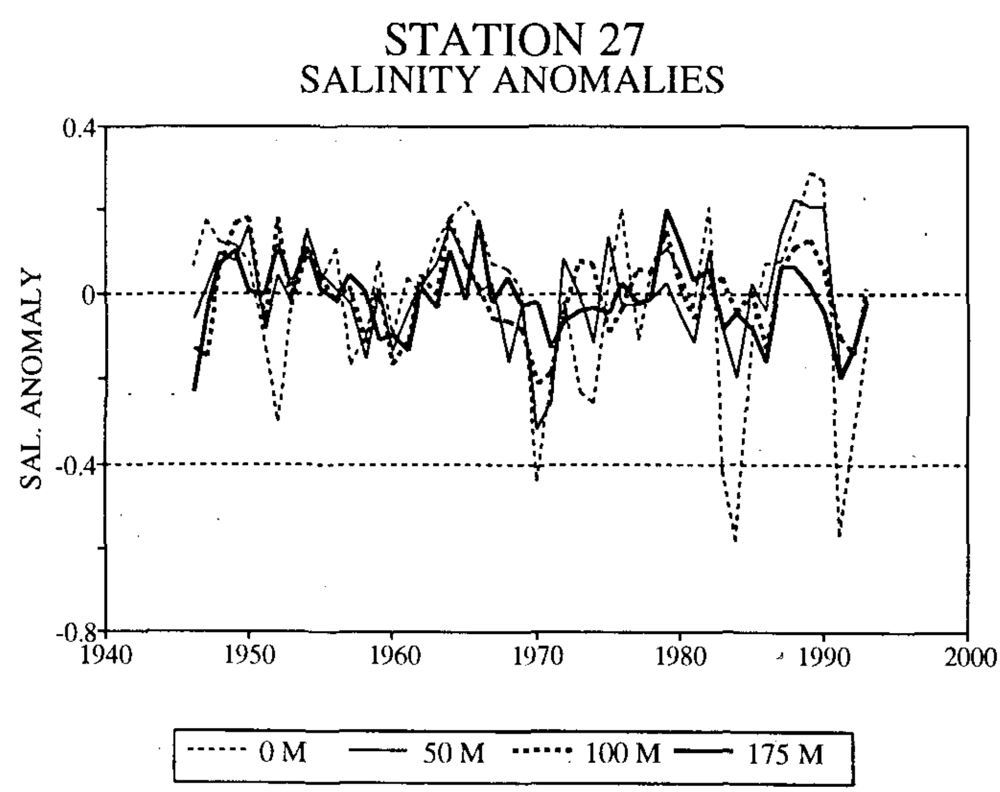
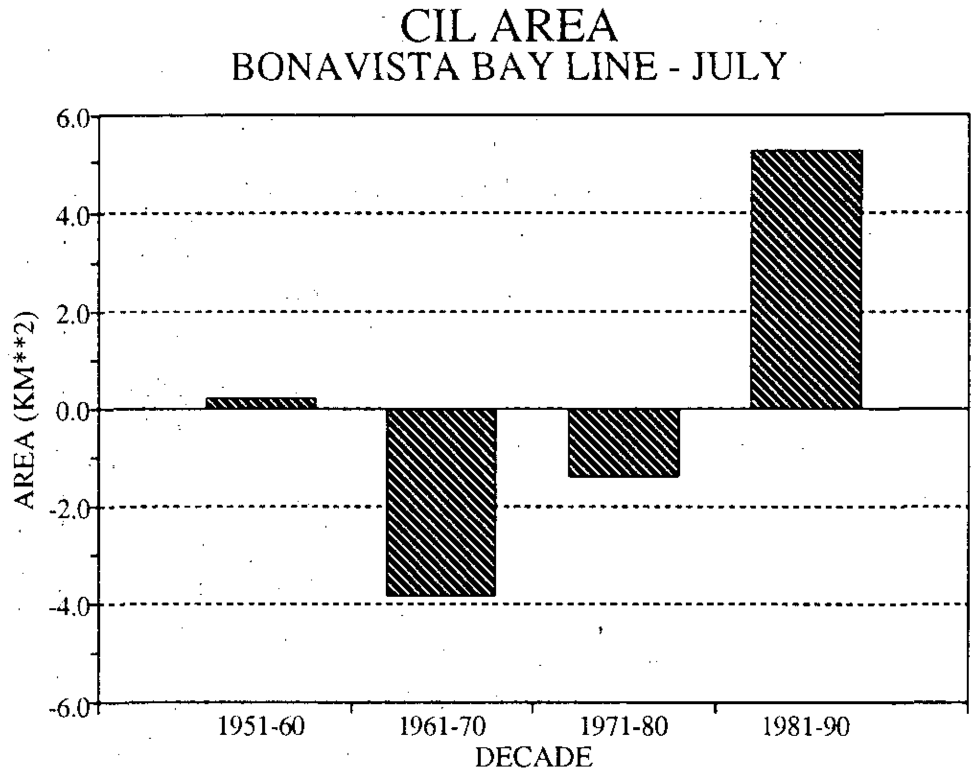


Fig. 23. The decadal (top) and annual (bottom) salinity anomalies at 0, 50 , 100 and 175 m at Station 27.



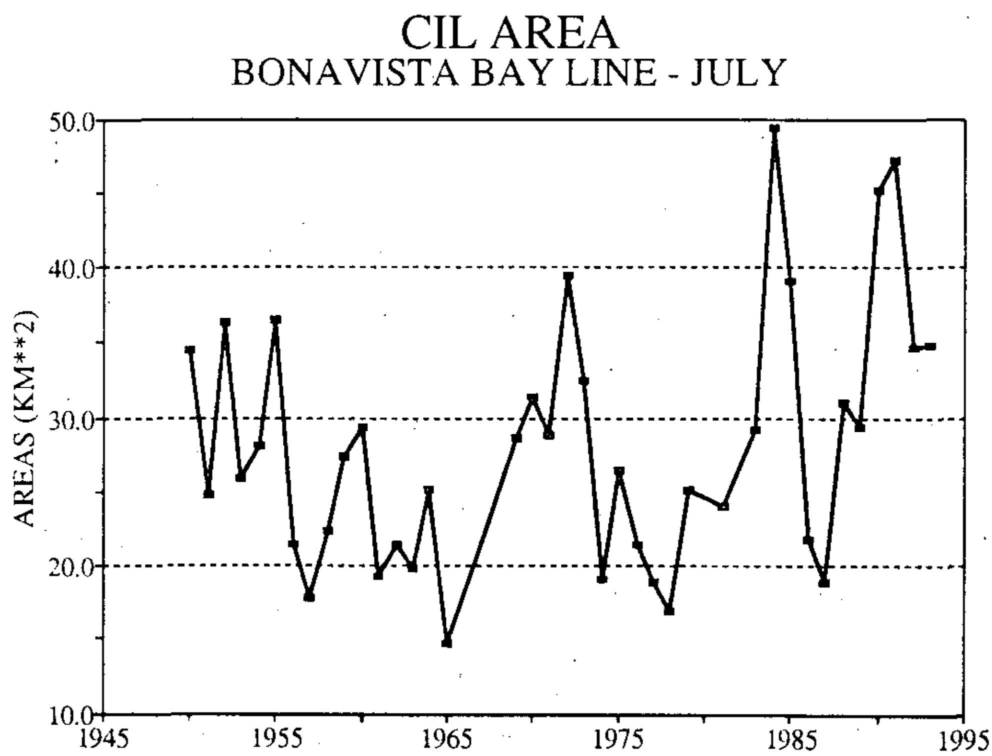
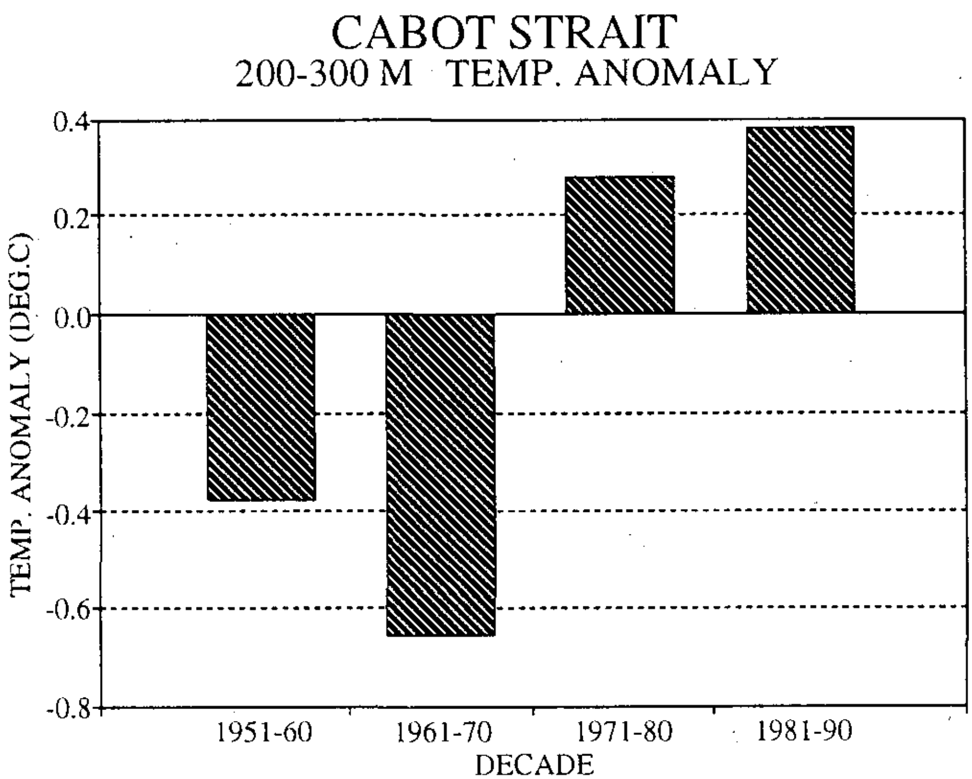


Fig. 24. The decadal (top) and annual (bottom) areal extent of the CIL on the Bonavista Bay Line in July.



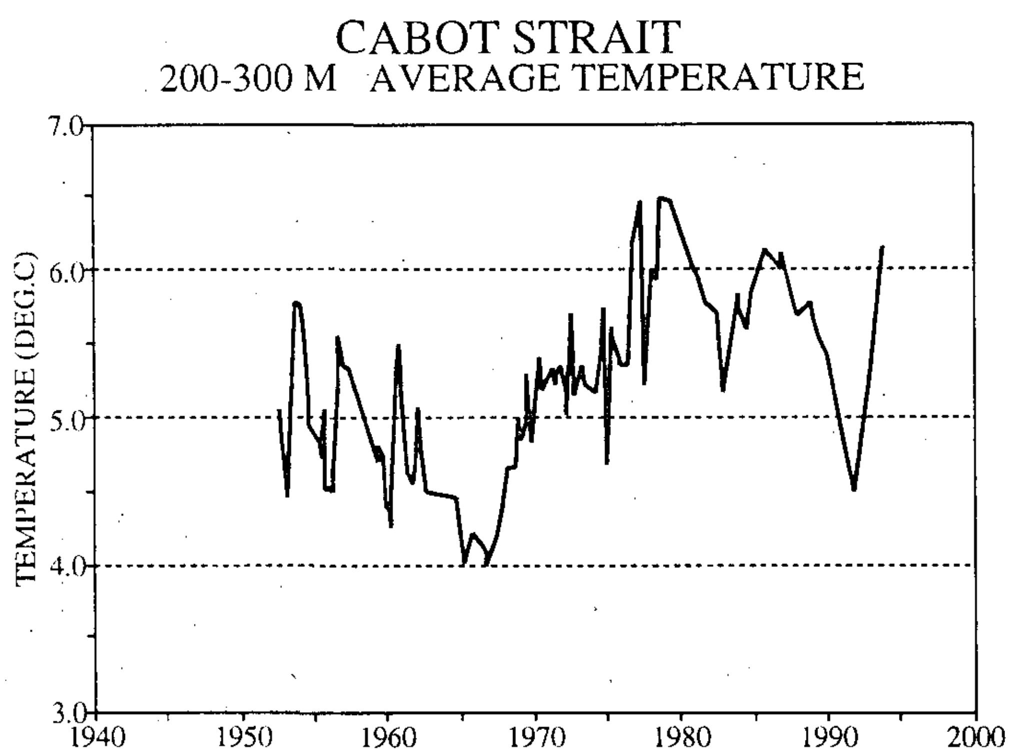
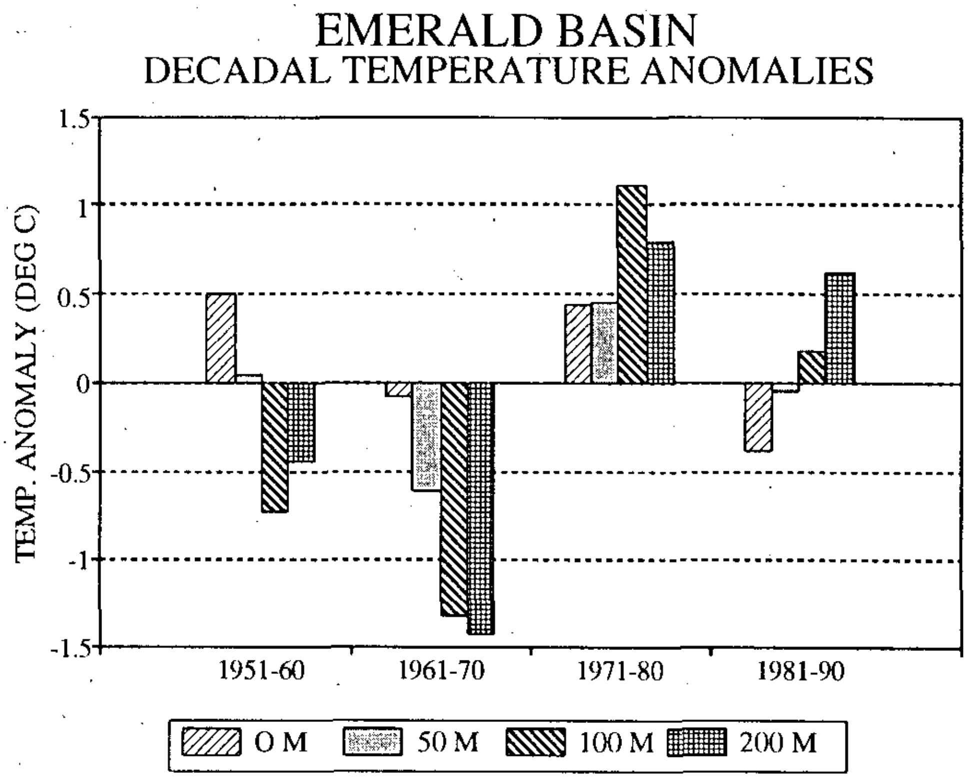


Fig. 25. The decadal (top) and annual (bottom) temperature in the 200 to 300 m depth layer in Cabot Strait.



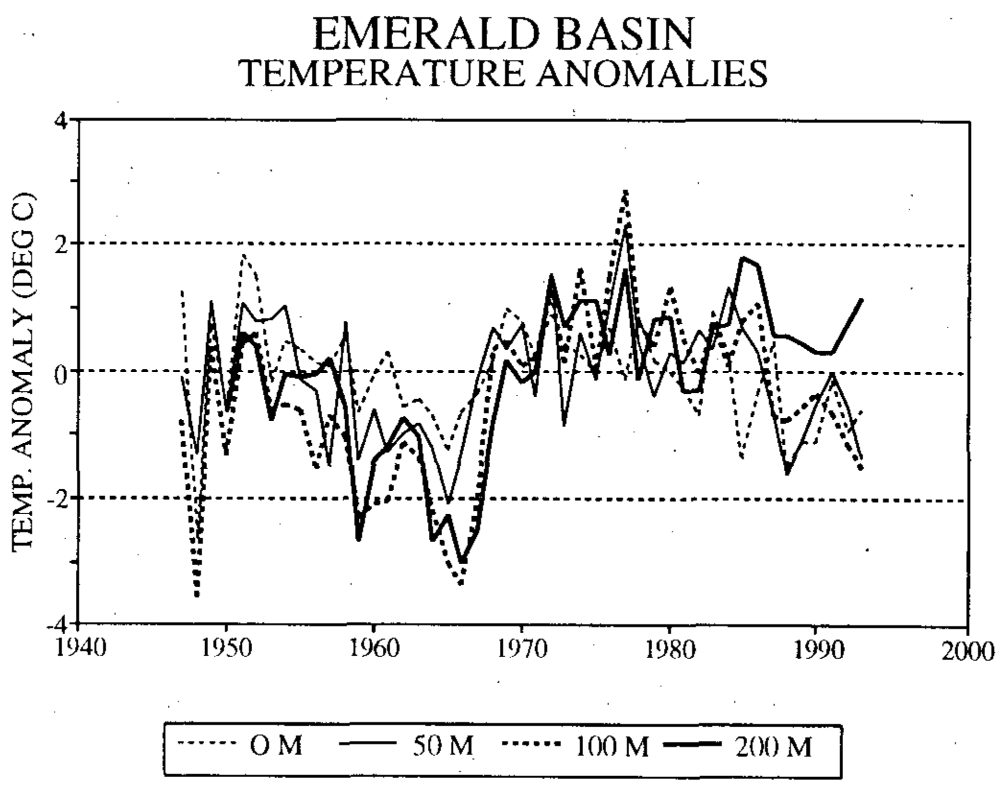
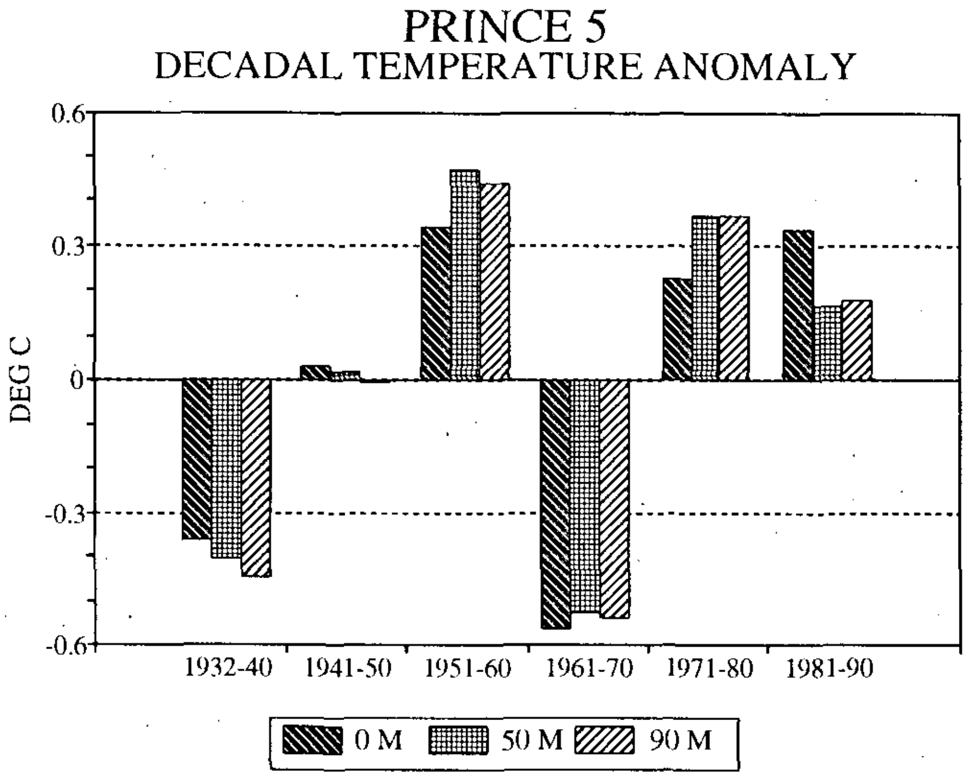


Fig. 26. The decadal (top) and annual (bottom) temperature anomalies at 0, 50, 100 and 200 m in Emerald Basin



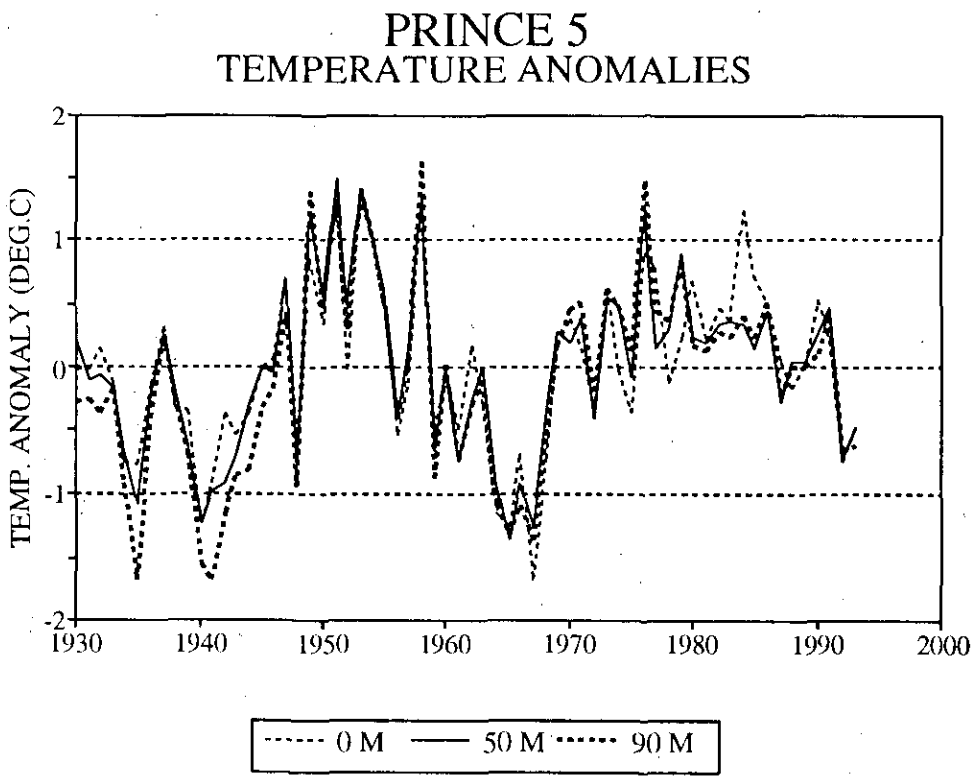
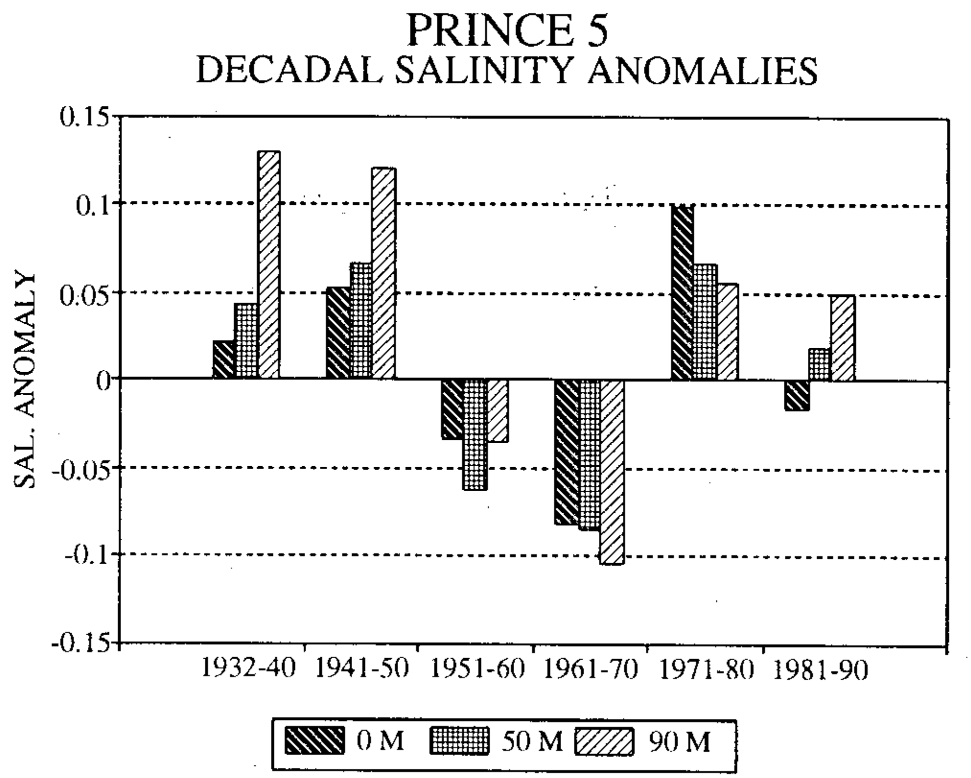


Fig. 27. The decadal (top) and annual (bottom) temperature anomalies at 0, 50, and 90 m at Prince 5.



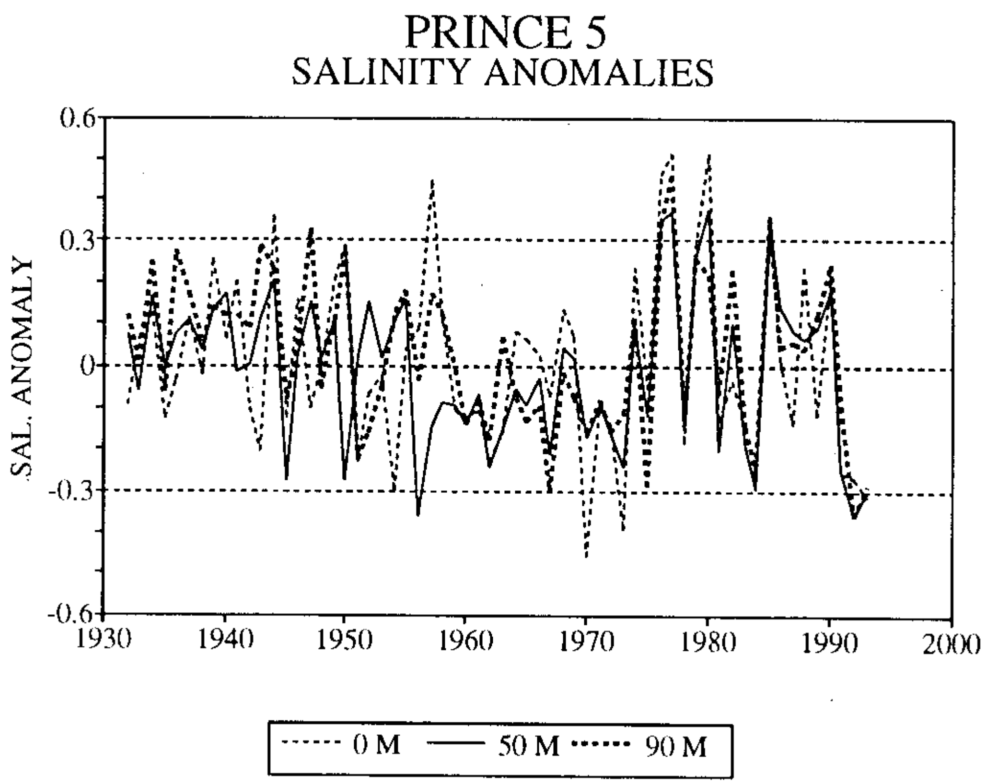


Fig. 28. The decadal (top) and annual (bottom) salinity anomalies at 0, 50, and 90 m at Prince 5.