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Decadal Changes in the Ocean Climate in Newfoundland Waters from the 1950s to the 1990s[1]

by

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ABSTRACT

A review of decadal changes in the ocean climate in NAFO waters adjacent to Newfoundland and Labrador are presented based on standard station and section data as well as data from fishery resource assessment surveys. Both the annual trends and decadal means are examined for the decades of the 1950s to the 1990s. The analysis indicates that the 1950s and particularly the 1960s were the warmest decades during the latter ½ of the 20th century and the 1990s represent the 3rd consecutive decade with below normal temperatures on the Newfoundland Shelf. The decadal mean salinity indicates that the magnitude of negative salinity anomaly on the inner Newfoundland Shelf during the 1990s was comparable to that experienced during the 'Great Salinity Anomaly' of the early-1970s. In addition, the decade of the 1990s has experienced some of the most extreme variations since measurements began during the mid-1940s. Ocean temperatures ranged from record low values during 1991 to record highs during 1999 in many areas, particularly on the Grand Bank of Newfoundland. The potential impact of these changes in ocean climate during the past several decades on marine production in Newfoundland waters is discussed.

Introduction

The latter half of the 20th century has been a time period of considerable variability in the physical environment on the Newfoundland Shelf. During the decades of the 1950s and 1960s the ocean environment was dominated by a general warming phase that reached its maximum by the mid- to late-1960s. Beginning in the early-1970s, however, climate conditions in the northwest Atlantic experienced near-decadal oscillations, with a general downward trend in ocean temperatures (Colbourne *et al*., 1994; Drinkwater, 1996). During the most recent decade (1990s) the Northwest Atlantic experienced some of the most extreme variations in ocean conditions since measurements began during the mid-1940s (Colbourne, 2001; Drinkwater *et al*., 2001; Colbourne and Anderson, 2002).

Recognizing the potential importance of ocean climate in determining the distribution and abundance of marine organisms the International Commission for the Northwest Atlantic Fisheries (ICNAF) initiated a series of symposia aimed at reviewing variations in the ocean environment on decadal time scales (ICNAF, 1967, 1972; NAFO, 1982, 1994). The most recent reviews, including the current one, were conducted by the standing committee on fisheries environment (STACFEN) of the Northwest Atlantic Fisheries Organization NAFO. In this manuscript environmental conditions in the northwest Atlantic for the decade of the 1990s are examined in relation to the previous decades. The long-term trends in the physical environment since the 1950s are first reviewed and the mean conditions on decadal time scales are then examined. Finally, variations within the decade of the 1990s are presented in more detail and a brief discussion follows.

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

Data and Methods

The data utilized in this paper were obtained from several sources. The most spatially comprehensive oceanographic data sets for the Newfoundland Shelf are available from the spring and autumn bottom trawl surveys conducted by the Canadian Department of Fisheries and Oceans. Canada has been conducting these stratified random ground fish trawl surveys on the Newfoundland Shelf in NAFO Div. 2J3KLNO since the early-1970s (Doubleday 1981; Bishop, 1994). The random stratified fish samples obtained from these surveys form a basis to determine recruitment and population abundance for demersal fish stock assessments. Oceanographic data were collected during these surveys at most fishing locations either by bathythermographs, (mechanical and expendable MBT/XBT) in the earlier years and by trawl-mounted conductivity-temperature-depths recorders (CTDs) during the decade of the 1990s.

Annual and seasonal oceanographic monitoring surveys along standard sections on the Newfoundland Shelf were initiated by the International Ice Patrol of the US Coast Guard soon after the Titanic disaster in 1912 to monitor variations in the Labrador Current. Since the 1940s, oceanographic data were collected on research surveys along standardized sections (Fig. 1) under the auspices of the International Commission for Northwest Atlantic Fisheries (ICNAF) by several countries and currently for the Northwest Atlantic Fisheries Organization (NAFO). Additionally, as part of an expanded Canadian Atlantic zonal oceanographic monitoring program some of these transects are now sampled on a seasonal basis (Therriault *et al*., 1998).

Collectively, these surveys provided a comprehensive oceanographic data set for the Newfoundland Shelf region with good temporal and spatial coverage for most of the decades since the 1950s. In this paper we present some of the environmental time series as differences from their long-term averages (anomalies) referenced to a standardised base period from 1961-1990 (normal) in accordance with the convention of the World Meteorological Organisation and recommendations of the NAFO scientific council. Oceanographic data from other available sources archived at the Marine Environmental Data Service (MEDS) in Ottawa were also used to define long-term means. The decadal means computed here are for the years 1961-1970, 1971-1980, 1981-1990 and 1991-2000.

Results

Background

The ocean circulation in the Northwest Atlantic has been described many times (Smith *et al*., 1937; Peterson, 1987; Greenberg and Petrie, 1988; Chapman and Beardsley, 1989; Lazier and Wright 1993; Petrie and Anderson, 1983, Drinkwater, 1996 and Colbourne *et al*., 1997) and will not be repeated in detail in this paper. However, to provide a general background of the main features influencing the study area a brief description follows. The main components of the large-scale circulation consist of the West Greenland Current, which flows around Cape Farewell and northward along the west coast of Greenland. A branch of this flow turns eastward and crosses the northern Labrador Sea forming the northern section of the northwest Atlantic sub-polar gyre. Near the northern tip of Labrador, outflow through Hudson Strait combines with the east Baffin Island Current and flows southeastward along the Labrador coast as a strong western boundary current known as the Labrador Current. The flow over the shelf is strongly influenced by the seabed topography, following the various cross shelf saddles and inshore troughs eventually forming a well defined inshore branch by the time the flow reaches the mid-Labrador Shelf. Most of the volume transport however, remains offshore at the edge of the continental shelf centered mainly over the 400-1 200 m isobaths.

Further south, near the northern Grand Bank, the inshore branch becomes broader and less defined with most of the transport combining with the offshore branch most of which flows southward around the southeast Grand Banks and a smaller portion flows eastward and around the Flemish Cap. The remainder of the inshore branch flows through the Avalon Channel around the Avalon Peninsula westward along the Newfoundland south coast. In southern regions the offshore branch flows westward along the continental slope where it is influenced by the Gulf Stream and slope waters to the Laurentian Channel and into the Gulf of St. Lawrence (Hachey *et al*., 1954). Additionally, part of the flow combines with the North Atlantic Current and forms the southern section of the sub-polar gyre. Within this large complex circulation system the Labrador Current is the most important feature influencing the Newfoundland Shelf area, advecting cold, relatively fresh, polar water together with sea-ice and icebergs from the arctic to lower latitudes along the Labrador Coast to the Grand Bank regions. In some years these arctic waters can be traced as far south as the Middle Atlantic Bight in NAFO Subareas 5 and 6.

Seasonal variations in atmospheric forcing (e.g. air temperatures and wind stress) and sea-ice extent leads to strong annual cycles in the water mass properties (Petrie *et al*., 1991) with intense horizontal and vertical gradients, particularly on the continental shelf regions of Newfoundland and Labrador. Interannual changes in these forces coupled with changing advection patterns are responsible for variations in the ocean climate on the Newfoundland Shelf. In particular, the strength of the cyclonic atmospheric circulation over the north Atlantic, especially during the winter months, influences sea-ice conditions, ocean temperatures and shelf stratification particularly in NAFO Subarea 2 (Colbourne *et al*., 1994; Drinkwater, 1996).

A standard meteorological index representing the strength of the winter atmospheric circulation has been termed the North Atlantic Oscillation (NAO) index and is defined as the difference in the winter sea-level air pressure between the quasi-stationary winter high and low pressure cells over the Azores and Iceland, respectively (Rogers, 1984). During decades when the NAO index is predominately negative, warm generally saline ocean conditions prevail in the northwest Atlantic and colder-fresher conditions predominate in the northeast Atlantic; and conversely when the NAO index is high positive. Spatial variations in the positions and extent of the pressure cells sometimes result in significant inter-annual variations in the strength of the winter wind patterns in any one location. Overall however, the decadal trends in the NAO are significantly correlated with trends in the ocean climate in the northwest Atlantic including the Newfoundland Shelf (Colbourne *et al*., 1994, Drinkwater, 1996; Colbourne and Anderson, 2002). In the next section, the long-term trends in various ocean climate indices derived from the data sets described above are reviewed on decadal time scales.

Inter-Decadal Trends

Temperature and Salinity

Ocean temperatures and salinity have been measured routinely during the past 5 decades at a standard hydrographic monitoring station (Station 27, Fig. 1) located in the inshore branch of the Labrador Current on the Newfoundland Continental Shelf (Huyer, and Verney, 1975; Keeley, 1981; Colbourne and Fitzpatrick, 1994). This inshore site is representative of ocean conditions over a wide area of the Newfoundland Shelf down to a water depth of 176 m (Petrie *et al*., 1991). Temperature anomalies at most depth at this site were predominately above normal during the decades of the 1950s and 1960s, reaching their maximum values by the late-1960s. After the late-1960s temperature anomalies declined steadily, reaching near-record low values by the early-1970s before increasing to above normal values from the mid-to-late 1970s and early 1980s. After about 1982 temperatures again declined to below normal values, reaching an all time record low during 1991 in the upper water column. Near bottom, temperatures remained below normal until around 1996, the longest time period of below normal temperatures in the 50-year record (Fig. 2). The decadal mean temperature also displayed in Fig. 2 shows that the 1950s and particularly the 1960s were the warmest decades during the latter ½ of the 20th century and the 1990s represent the 3rd consecutive decade with below normal temperatures. During the decades of the 1970s, 1980s and 1990s temperatures were below normal over the whole water column on the inner Newfoundland Shelf, with the most significant anomalies occurring in the top 50 m of the water column.

Salinity anomalies in the upper 50 m of the water column during the decade of the 1950s varied about the normal but increased to above normal values during most of the 1960s before declining to very low values during the 1970s (Fig. 2). Since then the time series is dominated by three salinity minima, early-1970s, early- to mid-1980s and most of the 1990s. In water depths generally below 50 m the patterns were very similar, but the variations were of a much smaller magnitude. In general, during these three decades cold ocean temperatures and lower-than-normal salinities were associated with strong positive NAO index anomalies, colder-than-normal winter air temperatures, heavy ice conditions and larger than normal volumes of $<0^{o}$C water on the Newfoundland Shelf (Colbourne *et al*., 1994; Drinkwater, 1996). The decadal mean salinity also displayed in Fig. 2 show that during the 1950s salinities were below normal except near bottom and during the decades of the 1960s-1980s the sign of the salinity anomalies were depth dependent. During the decade of the 1990s however salinities were significantly lower-than-normal over all depth ranges, with the most significantly anomaly in the surface waters. The longest single time period of fresher-than-normal salinities on record occurred during the decade of the 1990s (Fig. 2).

Two of the most widely used indices of ocean climate for Newfoundland waters have been the annual vertically averaged temperature and summer upper layer averaged salinity. The vertically averaged temperature is proportional to the total heat content of the water column while the upper layer average summer salinity is a measure of the magnitude of the freshwater pulse from melting sea ice on the Labrador Shelf (Myers *et al*., 1990). This temperature time series shows large amplitude fluctuations at near-decadal time scale, with cold periods during the early-1970s, mid-1980s and early-1990s. During the time period from 1950 to the late-1960s the heat content of the water column was generally above the long-term mean. It reached a record low during 1991, a near-record high during 1996, near normal in 1997 and 1998 and above normal during 1999-2000 (Fig. 3). The decadal mean water column temperature also displayed in Fig. 3 show that the 1950s and the 1960s were warmer-than-normal, while the decades of the 1970s, 1980s and 1990s were all time periods with below normal oceanic heat content on the Newfoundland Shelf.

The salinity data (Fig. 3) show similar trends as temperature, with fresher-than-normal periods generally corresponding to the colder-than-normal conditions up to at least the early-1990s, although the phase of the salinity cycle preceded that of temperature by approximately five years in the late-1960s. Since then the phase difference generally changed over the time series decreasing to one to two years from the late-1970s to early-1990s. The predominance of fresher-than-normal salinities during the latter half of the 1990s corresponds to a significant warming trend is notable. The decadal mean salinity (Fig. 3) indicates that the magnitude of negative salinity anomaly on the Newfoundland Shelf during the early-1990s was comparable or even exceeded that experienced during the 'Great Salinity Anomaly' of the early-1970s (Dickson *et al*., 1988). However, the freshwater was mostly restricted to the shelf regions during the 1990s, unlike the 1970s when it extended throughout much of the Northwest Atlantic (Dickson *et al*., 1988; Myers *et al*., 1989; Colbourne 2000)

Standard Sections

In 1976 the International Commission for the Northwest Atlantic Fisheries (ICNAF) adopted a suite of standard oceanographic monitoring stations along sections in the Northwest Atlantic Ocean from Cape Cod (USA) to Egedesminde (West Greenland) (ICNAF, 1978). The Canadian Department of Fisheries and Oceans samples several of these sections during a mid-summer annual oceanographic survey. The most consistently sampled include the Seal Island section on the southern Labrador Shelf, the Bonavista section off the east coast of Newfoundland and the Flemish Cap section which crosses the Grand Bank at 47°N and continues eastward across the Flemish Cap (Fig. 1).

The most striking feature of the summer temperature structure on the Newfoundland Shelf is the large volume of sub-surface water with temperatures ranging from near freezing at temperatures below -1.5^{o}C to 0^{o}C (Fig. 4). This sub-surface water mass extends in the offshore direction to over 200 km in cold years, with a maximum vertical extent of over 200 m. This cold, relatively fresh (salinities of 32-33), sub-polar shelf water is isolated from the warmer and saltier water (3-4^{o}C, salinities of 34-35) of the continental slope by a frontal region denoted by a strong horizontal temperature and salinity gradient near the edge of the continental shelf (Narayanan *et al*., 1991). At 100 m depth for example, temperatures normally increase from 0-3^{o}C at a rate of 0.03^{o}C /km.

The panels displayed in Fig. 4 show the summer (mid-July to mid-August) decadal average temperature fields along the Bonavista section (Fig. 1) for the 1960s-1990s. It is clear from these plots that the extent of <0^{o}C water during the decade of the 1960s was at a minimum, with near-bottom temperatures >2^{o}C penetrating to within 25 km from the coast. In contrast, during the decade of the 1980s the extent of the cold water mass was at a maximum, but by the 1990s it's vertical extent had decreased slightly. Note also the large area of water with temperatures <-1^{o}C during the past two decades compared to earlier periods. The seasonally heated near-surface layer during the 1990s however, appeared to be colder by up to 2^{o}C, compared to the other decades. Near-bottom temperatures in water depths below 250 m averaged over the decade of the 1990s were comparable to the 1960s, generally 1-3^{o}C.

One of the most robust indices of environmental conditions and indeed of climate conditions on eastern Canadian shelves in general, which is derived from these sections is the extent or area of cold intermediate layer (CIL) of <0^{o}C water overlying the continental shelf. The physical mechanisms leading to the formation of this water mass have been described many times (Petrie *et al*., 1988; Colbourne *et al*., 1994; Drinkwater, 1996). Essentially, the combined effects of seasonal air-sea heat fluxes, intense winter convection and summer shelf stratification are the primary mechanisms. The cold intermediate layer (CIL), usually defined as water with temperatures ≤0^{o}C, during the summer months remains relatively isolated between the seasonally heated upper layer and the deeper shelf-slope water but undergoes a gradual decay during autumn due to intense vertical mixing, particularly during the fall months. The CIL index therefore, is a measure of the strength of seasonal forcing and hence is correlated with the large-scale winter atmospheric circulation (NAO), air temperatures and winter and spring sea-ice cover on the Newfoundland Shelf. For example, the trends in the annual summer Bonavista CIL area and winter NAO is significantly correlated at r=0.41,p=0.0028.

Beginning in the late-1950s the amount of cold water on the Newfoundland Shelf was declining and by the mid-1960s the volume of CIL water on the Newfoundland Shelf reached the lowest value ever observed in the time series (Fig. 5). During the early years of the decades of the 1970s to 1990s however, the CIL area reached very high values, coincident with the negative temperature anomalies observed at Station 27 (Fig. 2). The maximum area of CIL water ever measured on the Newfoundland Shelf was in 1984. In general, the CIL time series for all three sections from the Grand Bank to Hamilton Bank on the southern Labrador Shelf show annual differences but are highly correlated. The decadal mean CIL area for all three sections (Fig. 5) show the below normal values along all three sections in the 1960s and a near normal decadal mean during the 1980 except for the Grand Banks along the Flemish Cap transect. The decade of the 1980s had the highest observed values of <0°C water and during the 1990s, except for the Grand Bank, the amount of <0°C water was about average. The persistent positive anomaly of the CIL on the Grand Bank up to at least 1997 is probably related to the topography of the Grand Banks, which may have restricted any increase in warmer slope-water from penetrating shoreward that may have influenced the CIL area along the deeper sections further north.

Grand Bank Bottom Temperatures

Canada has been conducting stratified random bottom trawl surveys on the Grand Banks in NAFO Subareas 3 since the early-1970s. Each NAFO Division was stratified based on the depth contours of available standard navigation charts. Areas within each division with a selected depth range were divided into strata and the number of fishing stations in an individual stratum are based on an area weighted proportional allocation (Doubleday, 1981). Temperature profiles of the water column are available for most fishing set in each stratum, providing a spatially comprehensive oceanographic data set for the Grand Banks.

The panels in Fig. 6 show the average near-bottom temperature contours for the decades of 1960s, 1970s, 1980s and the 1990s. In general, bottom temperatures on the Grand Banks are strongly influenced by the local bathymetry, with strong thermal gradients over the slope regions where temperatures typically increase from 1-3°C over distances of a few kms. The cold <0°C water, which is mainly restricted to NAFO Div. 3L, is associated with the CIL waters described earlier. The warmer bottom water (1-3°C) in the southern areas of Div. 3NO is associated with shelf-slope intrusions from the south and also from solar heat input on the shallow south-east shoal of the Grand Bank, where water depths are generally less than 75 m. During the decade of the 1960s the amount of <0°C water was at a minimum in NAFO Div. 3L and almost all of the bottom habitat in Div. 3NO had bottom temperatures ranging from 1-3°C. By the 1970s however, the areal extent of <0°C water had expanded significantly and by the 1980s almost completely covered the entire northern Grand Bank. Relatively warm water however persisted in the southern most areas, although slightly less that that observed during the 1960s. Bottom temperature conditions averaged over the decade of the 1990s were very similar to the 1980s, much colder than the 1960s and 1970s.

The spatially averaged bottom temperature for the Div. 3LNO region during the decades of the 1980s and 1990s are displayed in Fig. 7. These estimates show large inter-annual variations, particularly during the early-1980s and a declining trend that started in 1984, which continued until the end of the decade, when the temperatures reached the minimum of the 20-year record. The low temperatures on the Grand Banks continued until at least 1993, after which a slight recovery commenced. Towards the end of the decade of the 1990s bottom temperatures increased over the lows of the early-1990s with the average bottom temperature during the spring of 1999 and 2000 reaching 2°C. The highest temperature in the 25-year record occurred in 1983, when the average temperature was 3.2°C and the lowest temperature of 0.25°C occurred in 1990. In general, the decade of the 1980s was one of declining bottom temperatures in contrast to the generally increasing trend during most of the 1990s (Fig. 7).

Changes in the thermal habitat of a region can be estimated by computing the % area of the bottom for example covered by water in selected temperature ranges. During the 1980s the % area of the Grand Banks with <0°C water increased from 20% in 1981 to near 50% during the latter half of the decade (Fig. 7). At the beginning of the decade of the 1990s the area of <0°C water was at an all time maximum, well over 50%, which remained relatively constant between 40-50% until 1995. Beginning in 1995 the % area of <0°C water began to decline reaching an all time low of near 10% by 1999. During this time period there was a corresponding increase in the area covered by water ≥1°C reaching 50-60% by the spring of 1998 and 1999, the largest area of relatively warm water on the Grand Bank since the late-1970s (Colbourne, 2001).

The Decade of the 1990s

During the first half of the 1990s the NAO index was well above its long-term mean, reaching the third highest value of this century by 1995. During the winter of 1996 it underwent a sharp reversal, decreasing to the lowest value since 1979 and one of the 10^{th} most negative values this century (ICES, 2001). In response to the oscillations in the NAO, the climate conditions in the northwest Atlantic and the ocean environment on the eastern Canadian Continental Shelf during the decade of the 1990s experienced some of the most extreme variations since measurements began during the mid-1940s. Annual air temperatures increased from near record lows during the early-1990s to above normal values in 1996, and to record highs in 1999, setting a 126-year record over Newfoundland and a 65 year record over Labrador (Drinkwater *et al*., 2000). Sea ice extent on the Newfoundland Shelf decreased rapidly from the heavy ice years of 1990-1994 to the lightest ice-year since 1969 by 1996. Below normal sea ice extend and duration continued to the end of the decade (Drinkwater *et al*., 2001).

The changes in the heat content of the water column as a result of the extreme variations in meteorological and ice conditions is evident by comparing the annual temperature fields at Station 27 and along the Bonavista section during the most extreme years of the 1990s (Fig. 8 and 9). At Station 27 for example, the annual surface warming (comparing the 1^oC contour) was delayed by 1.5 months during 1991 compared to 1999. The peak late summer surface temperatures were up to 4^oC colder in 1991 compared to 1999 and the sub-surface values ranged from $1\text{-}2^oC$ colder in 1991. Temperatures in the near-surface waters (0-25 m) along the Bonavista section during 1991 ranged from $2^o\text{-}5^oC$ compared to $5^o\text{-}10^oC$ during 1999. In the near-bottom zone temperatures below 200-m depth ranged from $-1.5^o\text{-}2^oC$ on the inner shelf, within 100 km from the coast, compared to $0^o\text{-}3^oC$ during 1999 (Fig. 8). Bottom temperatures on the outer shelf areas were very similar ($>3^oC$) during both 1991 and 1999. In addition, there were significant changes in the area or volume of CIL waters on the Newfoundland Shelf within the 1990s. For example, along the Seal Island section (Fig. 1) the area of the CIL ranged from the third highest ever-recorded in 1991 to the third lowest in 1999 (Fig. 5, 8, and 9). The 1999 CIL area was the lowest measured since 1978, a 22-year record. Off eastern Newfoundland along the Bonavista section, the CIL was the 2^{nd} highest ever recorded, in 1991 and among the lowest ever recorded during the latter years of the decade.

The thermal habitat of many demersal fish species on the eastern Canadian Shelf, particularly on the Grand Banks of Newfoundland, also shifted from one extreme to the other during the past decade. Off eastern Newfoundland and on the southern Labrador Shelf bottom temperatures decreased to $<0^oC$ by the early-1990s reaching a minimum of -1^oC by 1993 on Hamilton Bank and to -0.5^oC on the southern Newfoundland Shelf at Station 27 (Fig. 10). During 1994 bottom temperatures began to increase reaching positive values by 1996, a trend that continued to the end of the decade (Fig. 10). During the cold years of the early-1990s most of the Grand Bank (except the deeper slope regions) and the southern most areas were covered by $<0^oC$ water with a large area of the northern half of the banks covered with $<-1^oC$ water (Fig. 11). During these years temperatures for the most part were below normal over the entire region, with anomalies reaching at least 0.5^oC below normal, but as low as 2^oC below normal in some regions (Colbourne, 2001). By the late 1990s the area of $<0^oC$ water began to retract and by 1999 was restricted to a small area near the coast. Areas of the bottom with water temperatures $<-1^oC$ had completely disappeared by the end of the decade of the 1990s. In the southern regions of the Brand Banks during the spring of 1999 for example, temperatures reached over 3.5^oC and to over 8^oC during the fall. As a result above normal conditions persisted over the entire Grand Banks with temperatures up to 1^oC above average in northern areas and up to 4^oC above normal on the southern Grand Banks during the fall (Colbourne, 2001).

Discussion and Summary

The latter half of the 20^{th} century has been a time period of considerable variability in the physical environment in NAFO waters of the Northwest Atlantic. During the decades of the 1950s and 1960s the ocean environment was dominated by a general warming phase that reached its maximum by the mid- to late-1960s. Beginning in the early-1970s however climate conditions in the Northwest Atlantic experienced near-decadal oscillations, with a general downward trend in ocean temperatures. The decadal mean temperature indicates that the 1950s and particularly the 1960s were the warmest years in the 50-plus year record and the decade of the 1990s was the 3^{rd} consecutive decade with below normal temperatures on the Newfoundland Shelf. The decadal mean salinity indicates that the magnitude of negative salinity anomaly on the inner Newfoundland Shelf during the decade of the 1990s was comparable to that experienced during the 'Great Salinity Anomaly' of the early-1970s.

In summary, during the last several decades, water properties (temperature/salinity) on the Newfoundland Shelf showed extreme variability, often exhibiting different phase responses during different time periods both within and between decades. During the most recent decade (1990s) for example, the northwest Atlantic experienced some of the most extreme variations in ocean conditions since measurements began during the mid-1940s. Off eastern Newfoundland and on the southern Labrador Shelf bottom temperatures ranged from near record lows during 1991 to some of the highest values ever recorded by the late-1990s. The extreme variability in water properties is due to differences in the phase and amplitude in the seasonal cycles of solar heat input, sea ice dynamics and variations in advection rates. The sea-surface pressure fields from which the NAO index is derived and is one of the largest scale forcing mechanisms affecting the ocean climate in the north Atlantic also experienced extreme spatial variability during the end of the 1990s. This resulted in a breakdown in the expected ocean response in the Northwest Atlantic to changes in the NAO patterns, particularly during 1999 and 2000 (ICES, 2001; Colbourne and Anderson, 2002).

One common trend in the ocean climate during the past three decades however, is the extremely cold-water temperatures during the early part of each decade and generally warmer conditions during the second half of each decade. This was especially true during the decade of the 1990s. For example, the three highest CIL areas ever recorded on the Newfoundland Shelf occurred during 1972, 1984 and 1991 along all three sections shown in Fig. 1. On the other hand there was a significant difference in the trends in salinity between the decade of the 1990s compared with the pervious 2 decades on the inner Newfoundland Shelf. Salinities during the 1990s at most depths remained below normal throughout the decade, in contrast to the previous 2 decades when salinities increased more or less in phase with the increasing temperature trends during the latter ½ of the decade. The source of the freshwater observed at Station 27 during the early-1990s was assumed to be due to increased amounts of fresh water from melting sea-ice off Labrador. However, the source of the increased amounts of freshwater during the latter part of the 1990s needs to be investigated. The record high air temperatures experienced in northern regions during the late-1990s may have led to increased amounts of sea ice melting at higher latitudes, resulting in larger amounts of freshwater flowing south throughout most of the year.

The NAFO waters of the northwest Atlantic and particularly the Newfoundland and Labrador shelf regions are a habitat to many marine species of demersal fish and crustacean populations. Many of these species are at the northern limit of their distributions within a very limited thermal habitat. It is not unreasonable therefore, to expect variations in the thermal habitat at this northern limit as probably one of the most important physical variables influencing biological production in this region. Indeed many studies have suggested that variations in the physical ocean environment influences growth, recruitment and distribution of many marine organisms in Newfoundland waters (deYoung and Rose, 1993; Myers *et al*., 1993; Rose *et al*., 1994; Rose *et al*., 1995; Taggart *et al*., 1994; Narayanan *et al*., 1994; Colbourne *et al*., 1997; Carscadden *et al*., 2001, Parsons and Lear, 2001; Colbourne and Anderson, 2002). The interactions between the marine environment and production however is complicated, usually non-linear and operate through complex mechanisms throughout several trophic levels of the ecosystem over a broad range of time and space scales. These interactions are further complicated by variations in fishing mortality. Therefore, the significance of correlations between individual environmental indices and measures of marine production are most often marginal at best and often break down as different factors predominate.

The analysis presented here suggest that the ocean climate on the Newfoundland Shelf has changed on decadal time scales with the last three decades all showing significantly lower average temperatures compared to the 1950s and 1960s. Coincident with these climate variations many commercial fish species have shown dramatic changes in distribution and abundance on similar time scales. Recruitment in Newfoundland cod stocks, for example, declined almost steadily since the 1960s, reaching historical low values by the early-1990s (Stansbury *et al*., 1999; Lilly *et al*., 1999). The correlations shown in Fig. 12 between the air temperatures the area of CIL water and Atlantic cod (*Gadus morhua*) recruitment with the NAO are consistent with the scenario outlined by Mann and Drinkwater (1994) on the physical mechanisms that lead to ecosystem productivity. We find strong correlations between the NAO with air temperatures and the amount of CIL water on the Newfoundland Shelf. Furthermore, recruitment in the southern Grand Bank cod (Div. 3NO) is associated with negative NAO anomalies and generally warmer ocean climate conditions.

Within the decade of the 1990s water properties in the Newfoundland region have experienced extreme variations from record low ocean temperatures during the first half of the decade to record high by the late-1990s. This shift in the thermal habitat from the Arctic-like conditions of the early-1990s to the more temperate conditions of the late-1990s most likely contributed to the observed changes in the pelagic ecosystem, which showed a significant increase in the nekton biomass during the late-1990s (Anderson *et al*., 1999, Dalley *et al*., 2000, Colbourne and Anderson, 2002). In addition, data from the annual multi-species bottom trawl surveys of the Div. 2J3KLNO region while showing only a slight increase in the biomass of cod from 1995 to 1997 showed a 70% increase from 1998 to 1999 during the fall survey (DFO, 2000). Finally, the recently observed expansion in the spatial distribution and increase in abundance of yellowtail flounder (*Limanda ferruginea*) on the Grand Bank coincided with the improved thermal environment during the latter half of the 1990s (Walsh *et al*., 2000; Colbourne and Bowering, 2001). In conclusion, the progressive decline in ocean temperatures, particularly during the past 2 decades, coincided with the general decline in fish production in Newfoundland waters. However as noted above fish production in general depends on many other complex physical and biological processes in addition to changing fishing mortality.

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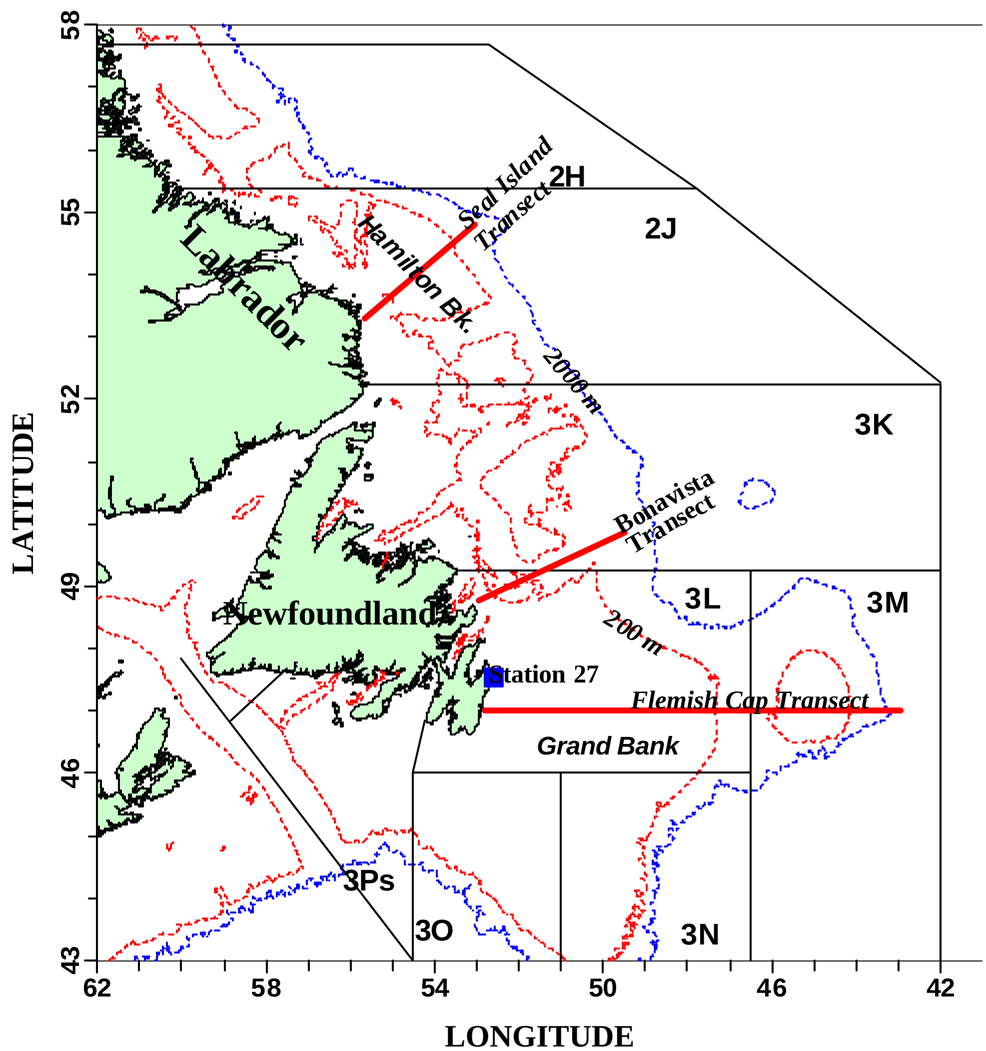

Fig. 1. Regional map showing the positions of standard monitoring transects, Station 27 and the statistical fish management areas established by the Northwest Atlantic Fisheries Organization (NAFO).

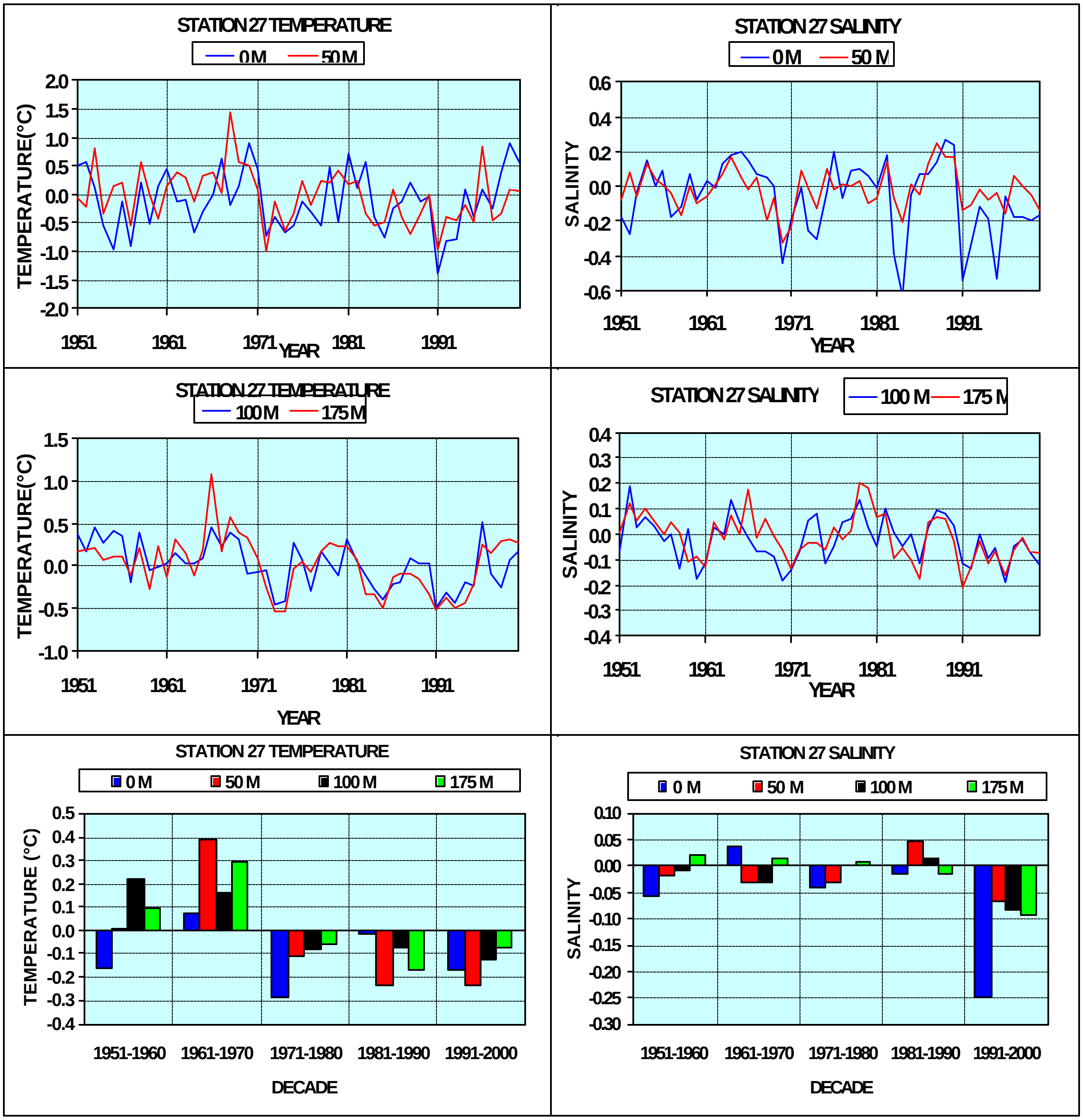

Fig. 2. Station 27 annual temperature and salinity anomalies at selected depths (top panels) and their decadal means (bottom panels).

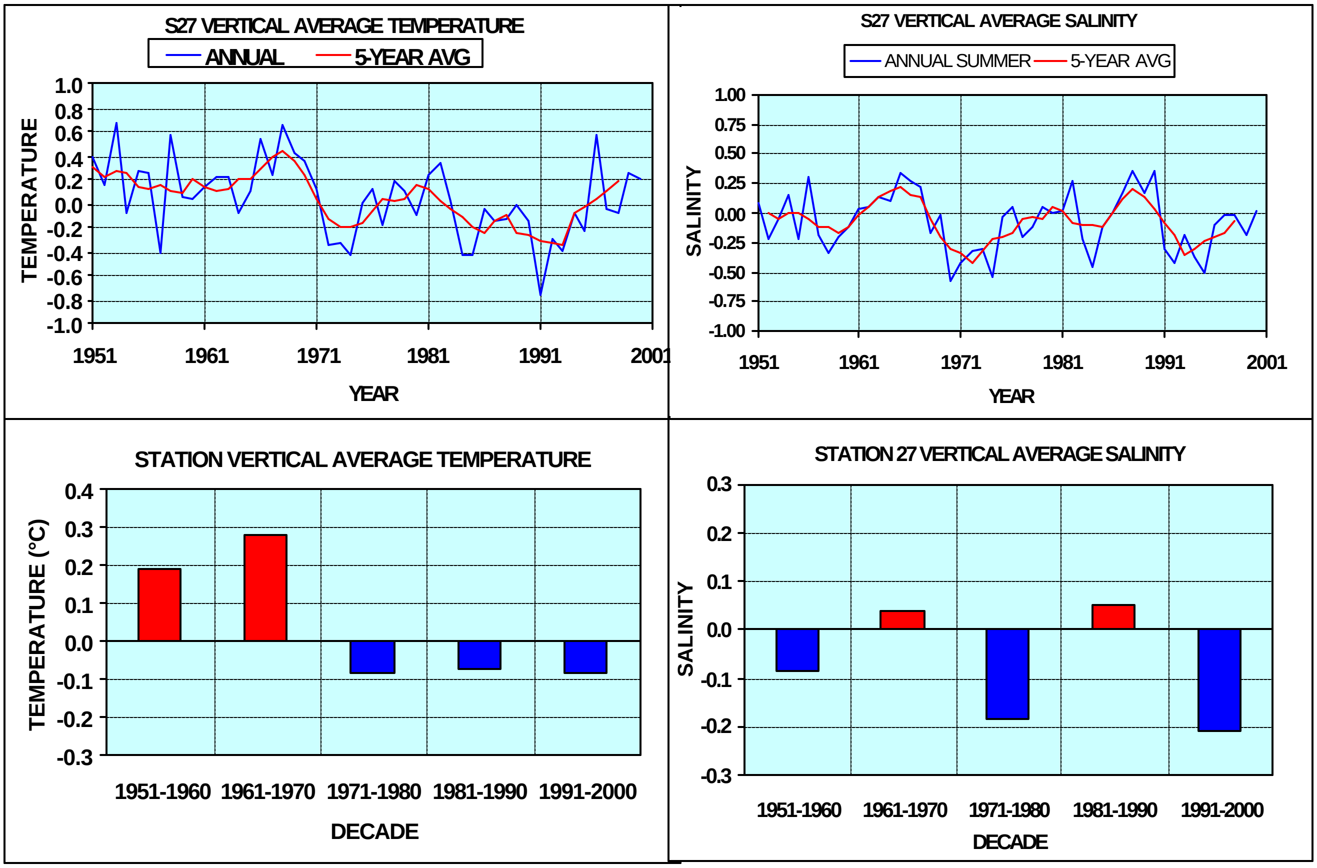

Fig. 3. Station 27 vertically averaged (0-176 m) annual temperature anomalies and the Station 27 vertically averaged (0-50 m) summer salinity anomalies (top panels). The heavy lines are the 5-year running means. The bottom panels are their decadal means.

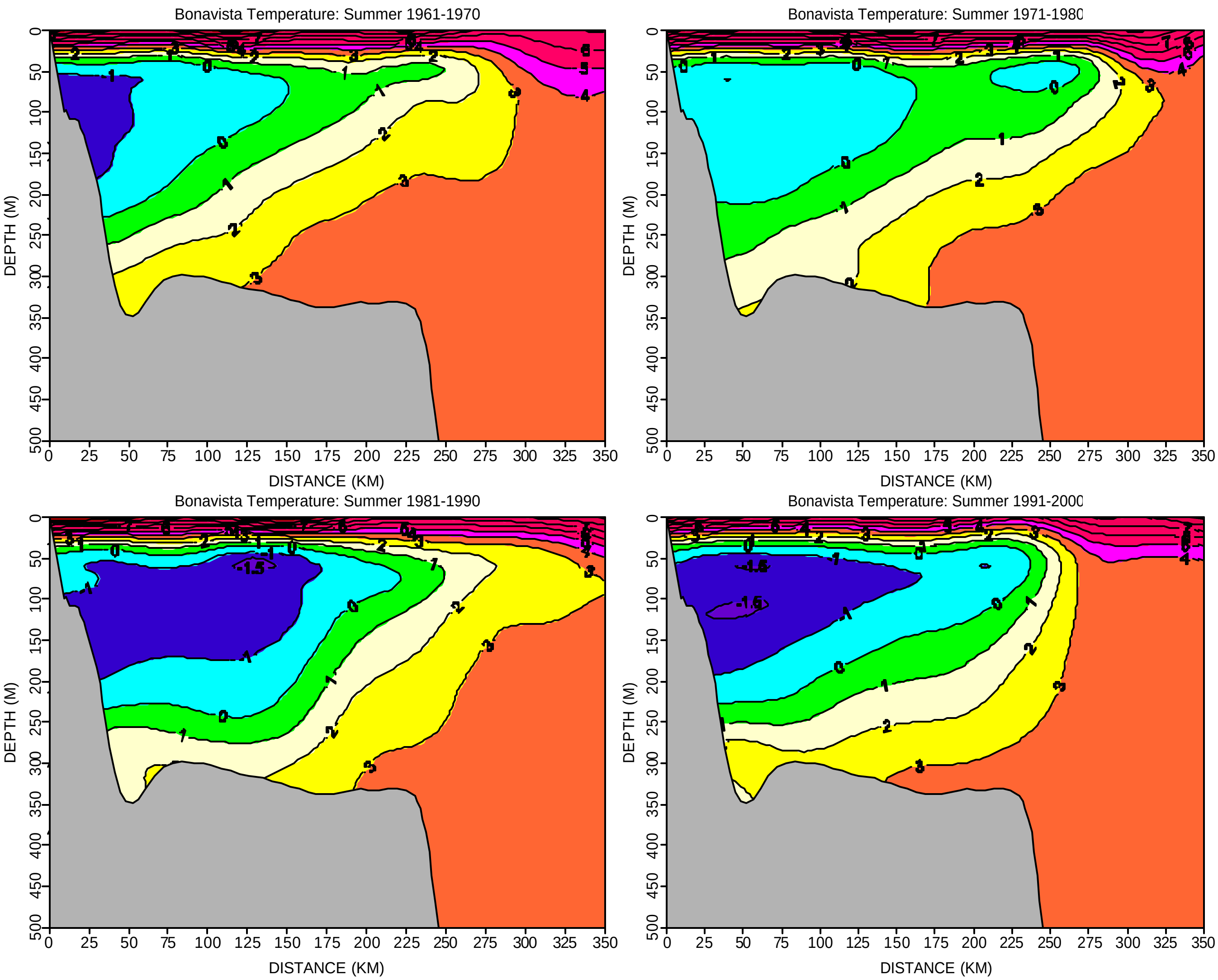

Fig. 4. The averaged vertical temperature field observed along the standard Bonavista section (Fig. 1) for the decades of the 1960s, 1970s, 1980s and 1990s.

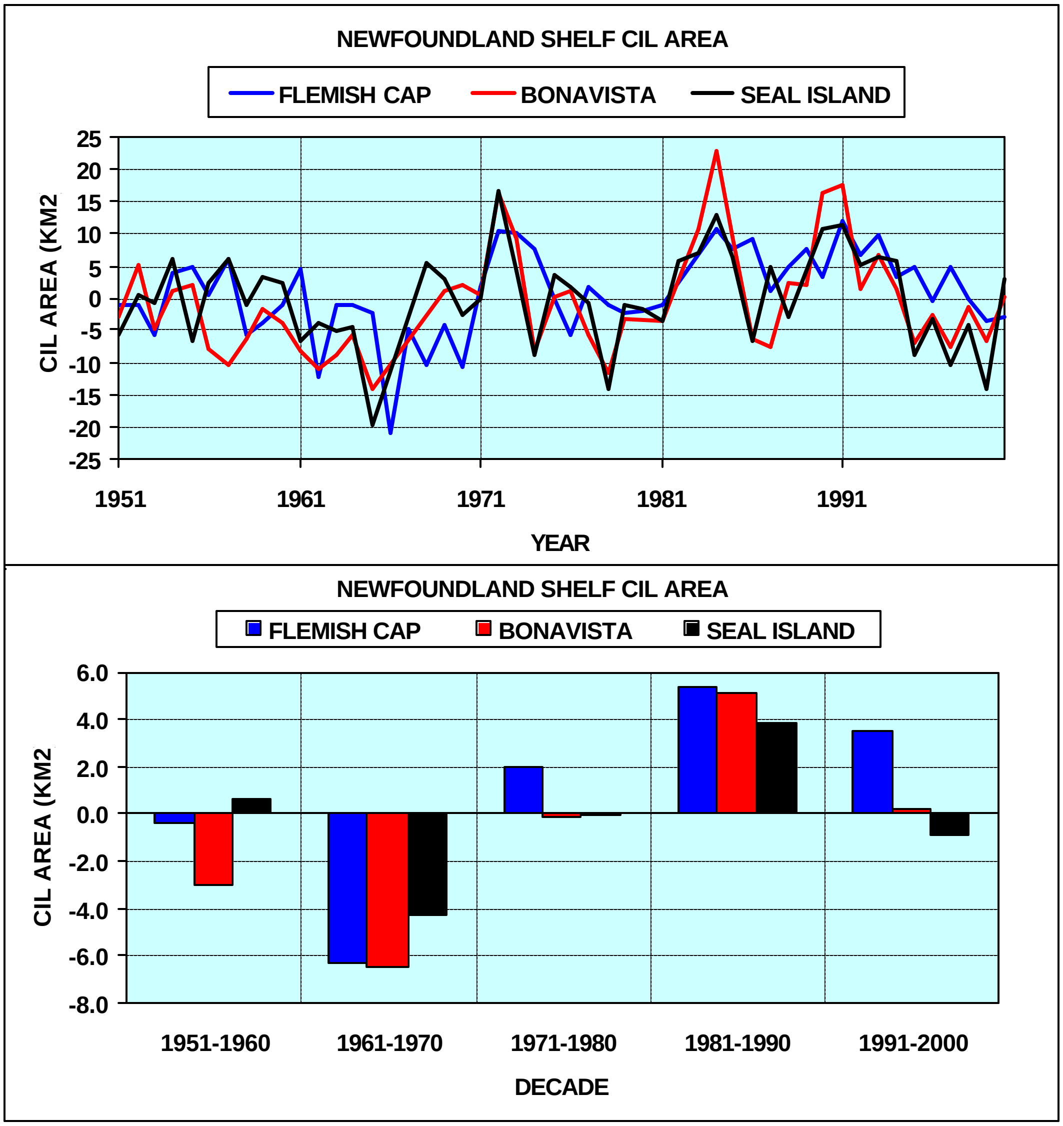

Fig. 5. Annual summer CIL cross-sectional area (top panel) anomalies along the Flemish Cap, Bonavista and Seal Island standard sections and their decadal means (bottom panel).

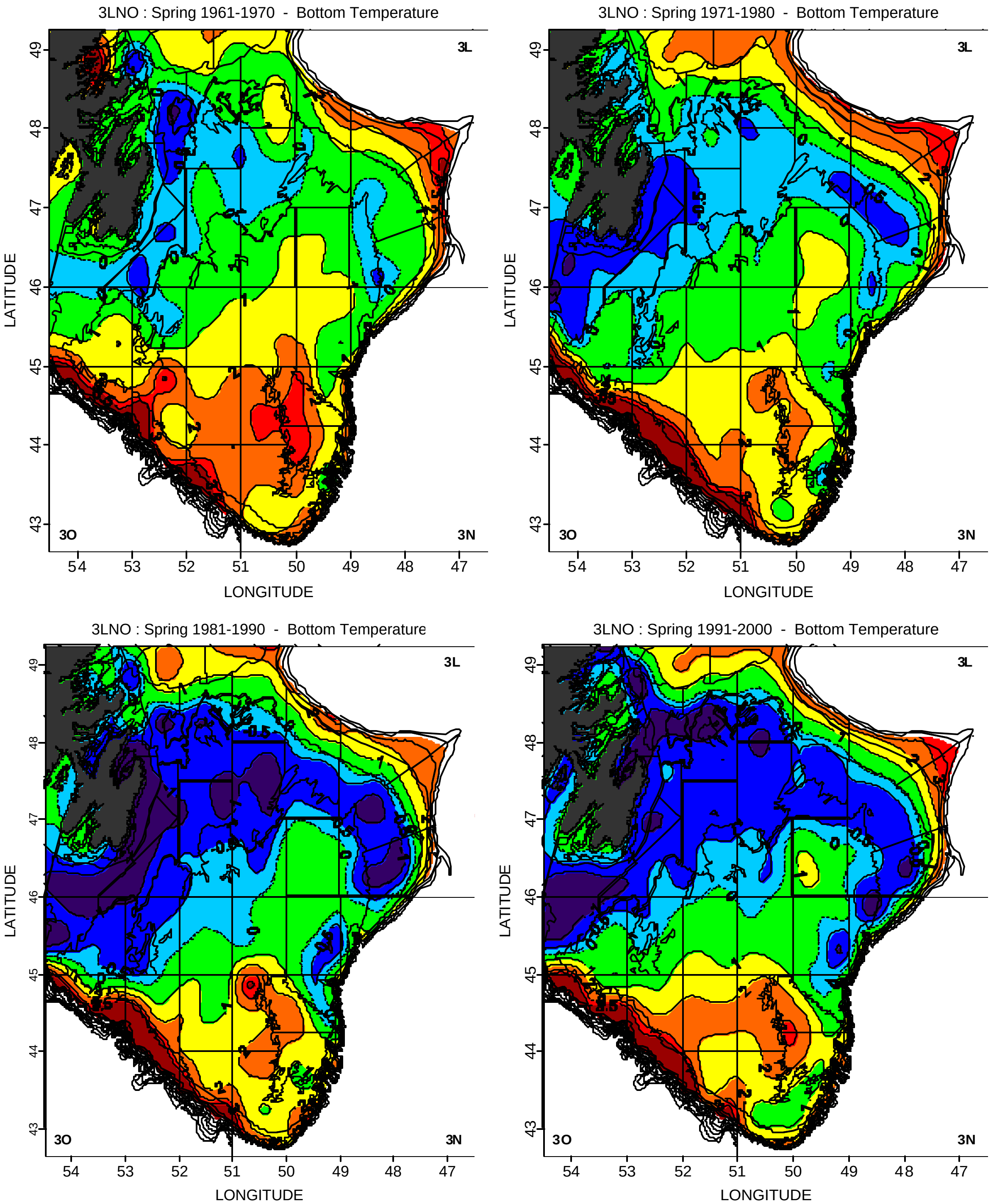

Fig. 6. Contours of spring bottom temperature (in °C) based on all available data collected during the decades of the 1960s, 1970s, 1980s and the 1990s for NAFO Div. 3LNO.

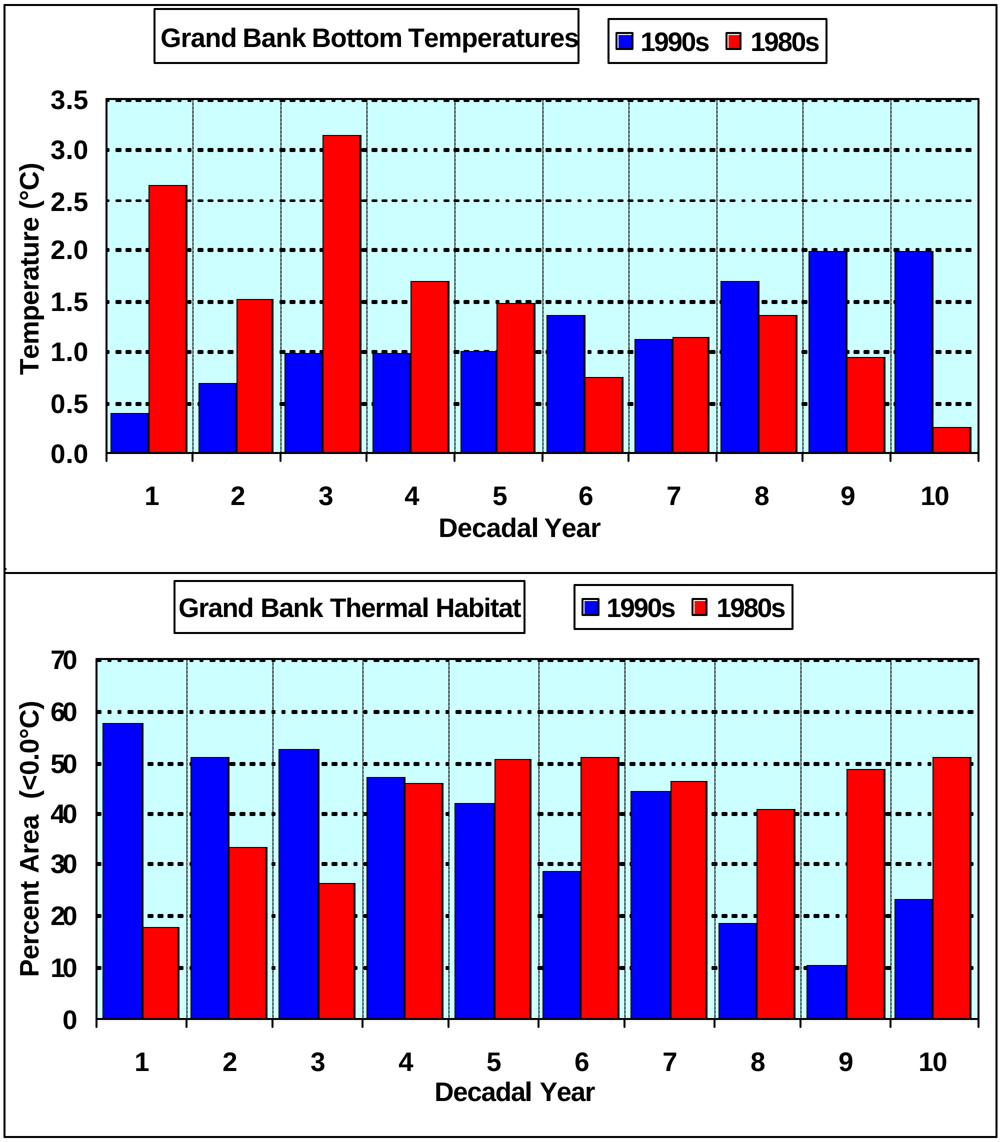

Fig. 7. The annual spatially averaged spring bottom temperature in NAFO Div. 3LNO for the decades of the 1980s and 1990s (top panel) and the area of the bottom covered with water at temperatures <0°C (bottom panel).

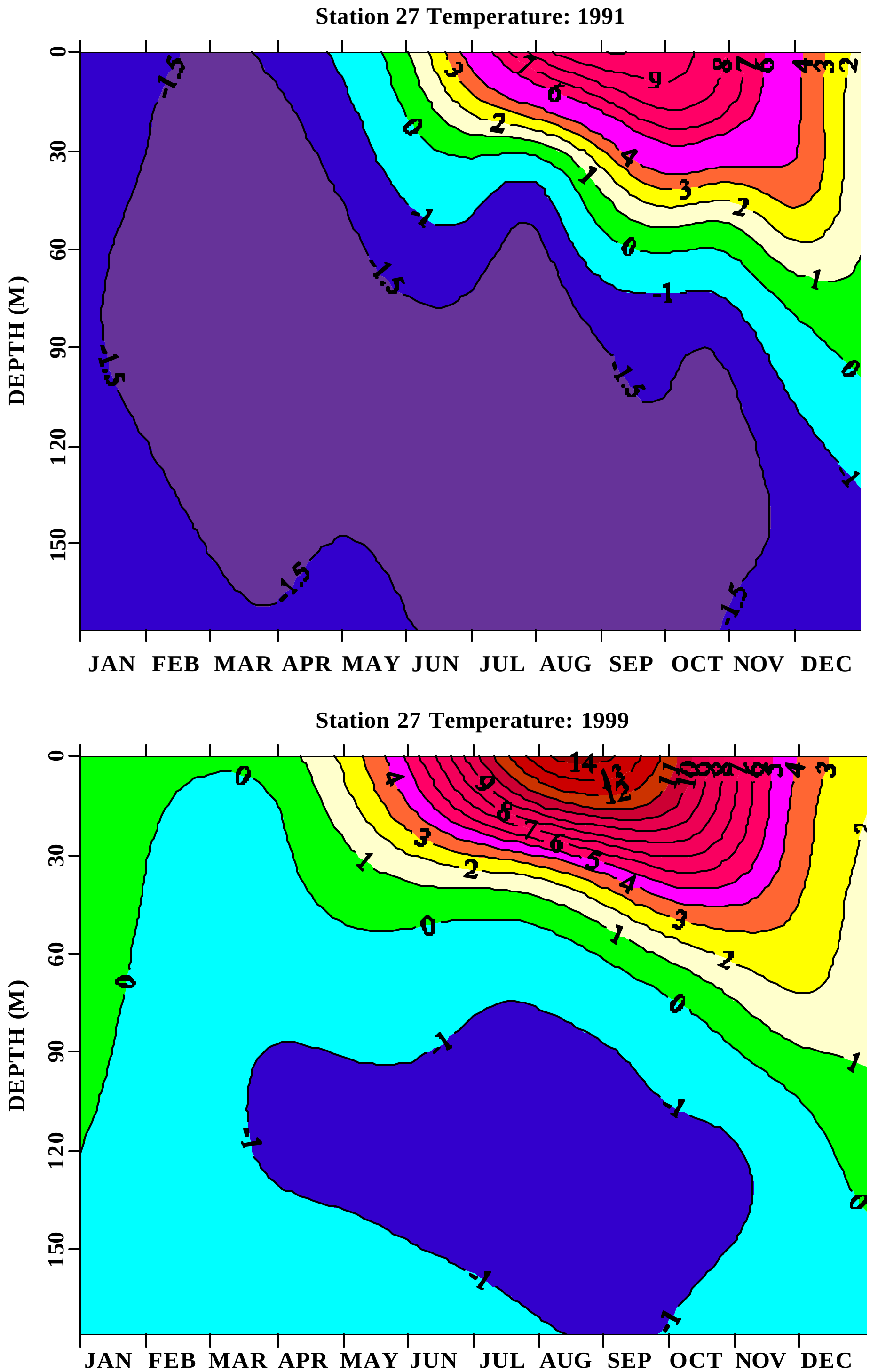

Fig. 8. Monthly temperatures as a function of depth observed at Station 27 (Fig. 1) for 1991 and 1999.

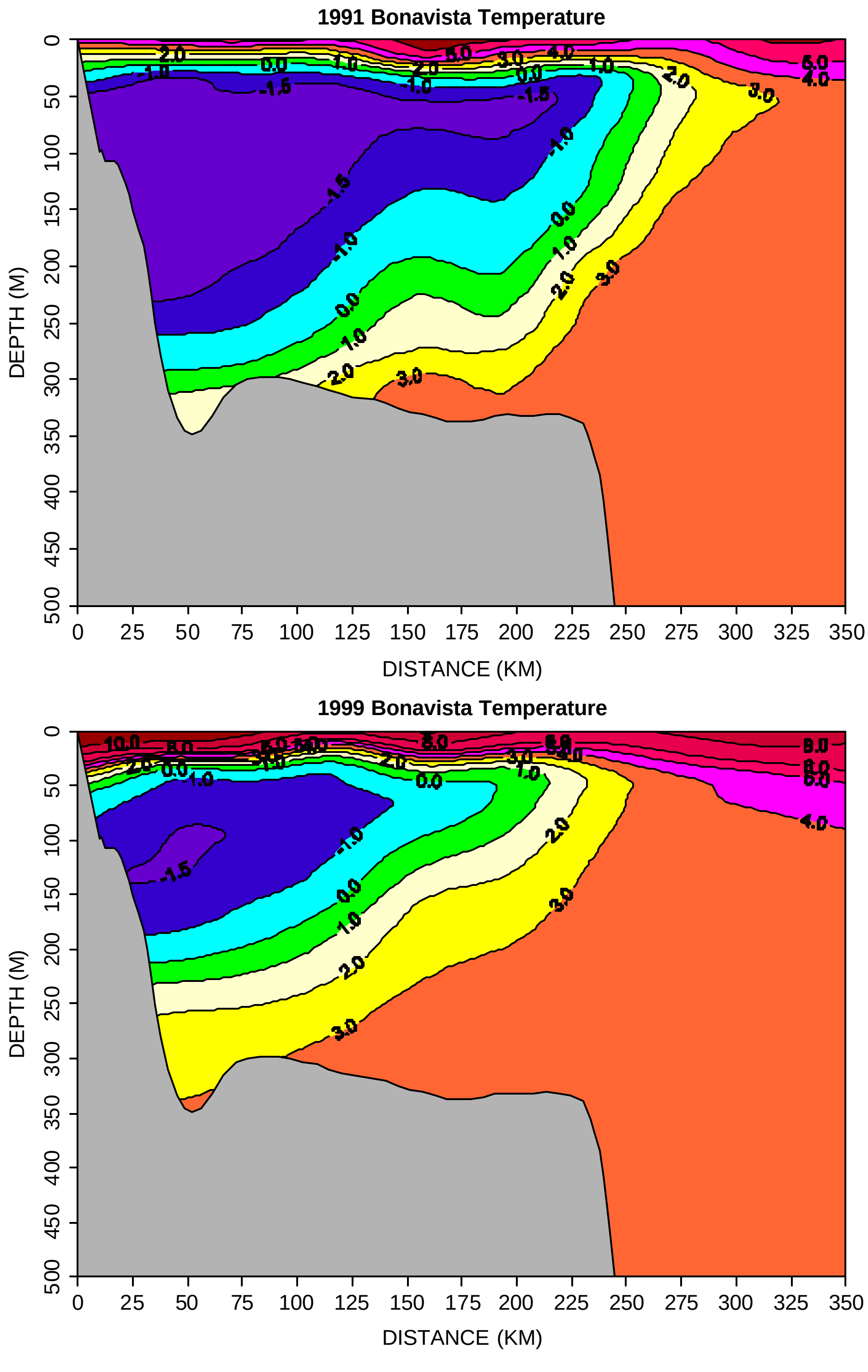

Fig. 9. The vertical temperature structure observed along the standard Bonavista section (Fig. 1) for the summers of 1991 and 1999.

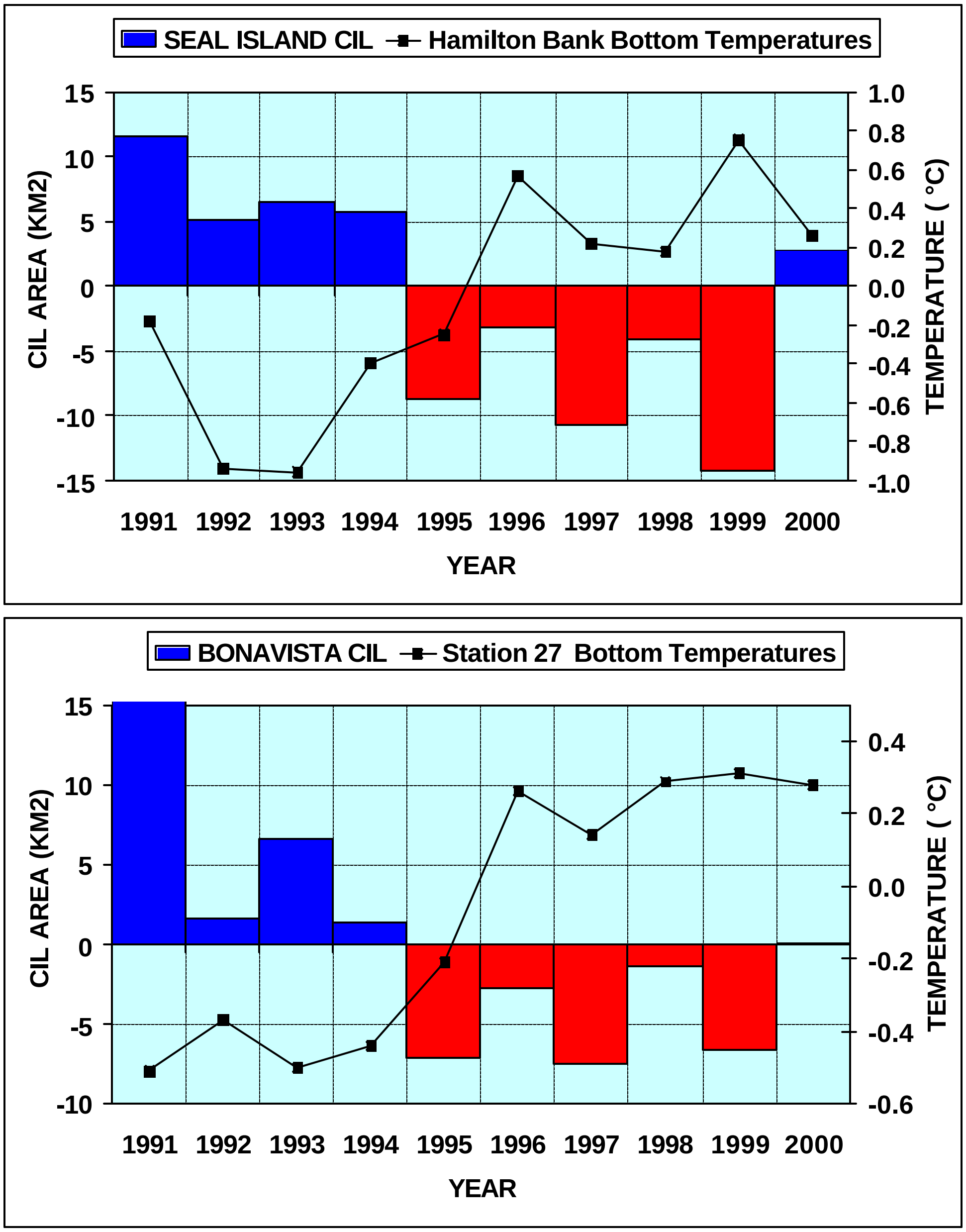

Fig. 10. The CIL area anomalies for the Seal Island standard section and the Hamilton Bank mean fall bottom temperature for the decade of the 1990s (top panel) and the CIL anomalies for the Bonavista section together with the Station 27 bottom temperature for the 1990s (bottom panel).

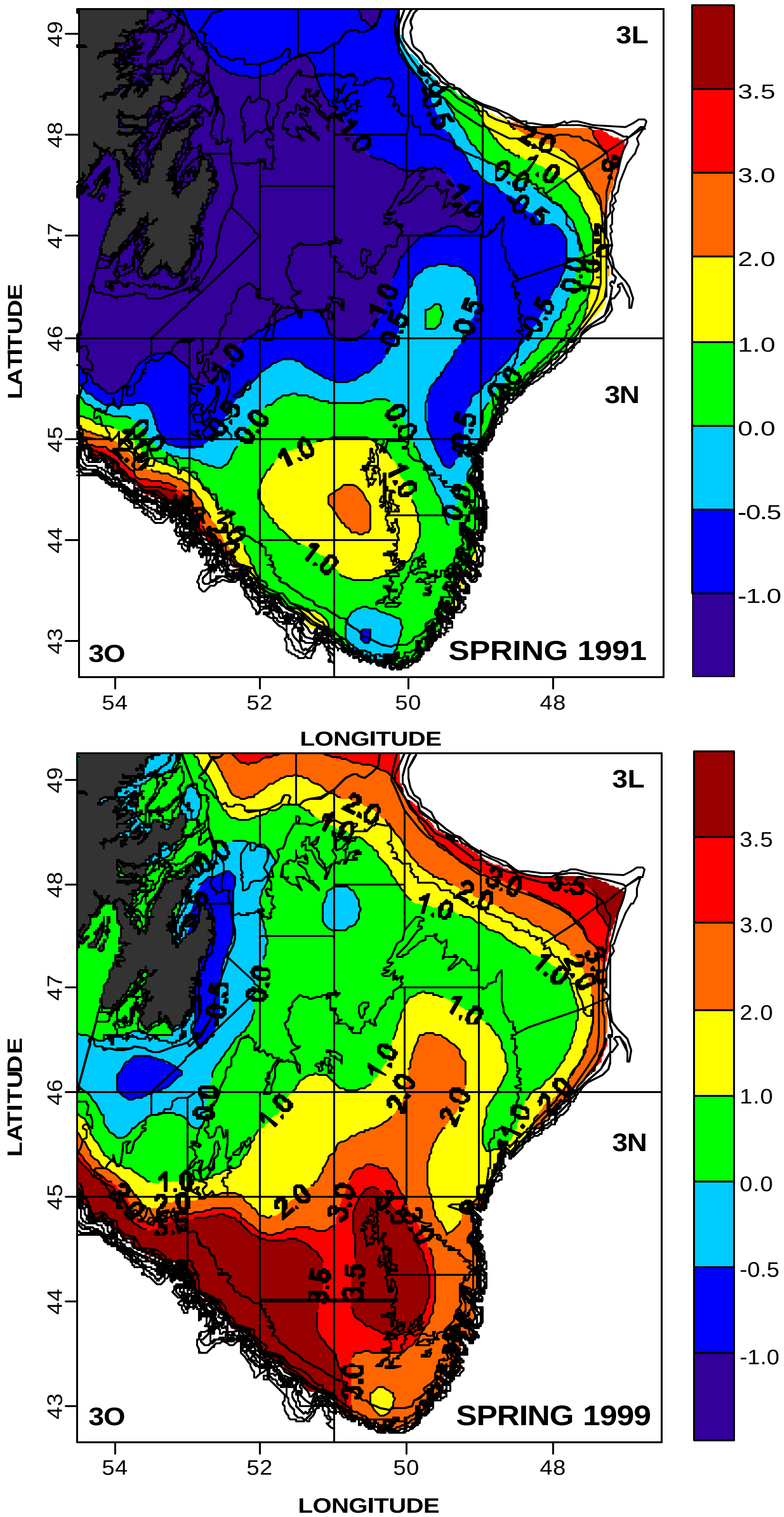

Fig. 11. Contours of spring bottom temperature (in °C) based on data collected during the multi-species surveys in NAFO Div. 3LNO for 1991 and 1999.

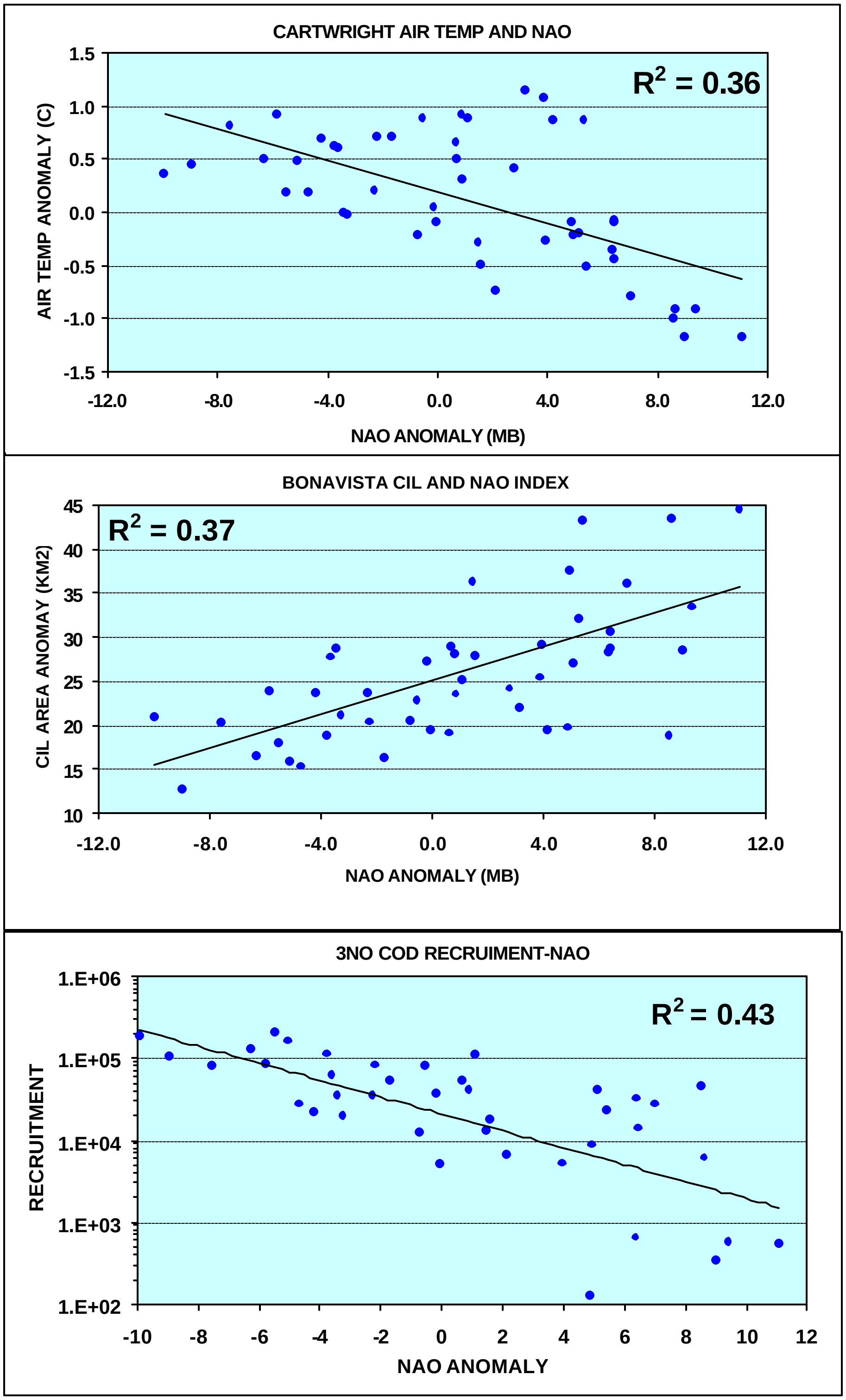

Fig. 12. Correlations between the trends in Labrador air temperatures, Newfoundland Shelf extent of cold <0°C water and recruitment in Grand Bank (Div. 3NO) cod with the NAO index anomaly.