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An Assessment of Physical Oceanographic Conditions in NAFO Sub-areas 2 and 3 for 2003

by

E. B. Colbourne, C. Fitzpatrick, D. Senciall, P. Stead, W. Bailey, J. Craig and C. Bromley

Fisheries and Oceans, Canada
P. O. Box 5667, St. John's Newfoundland, Canada A1C 5X1

Abstract

Oceanographic observations in NAFO Sub-areas 2 and 3 during 2003 are presented referenced to their long-term (1971-2000) means. The annual water-column averaged temperature on the inner Newfoundland Shelf (Station 27) for 2003 remained above the long-term mean and increased over 2002 values at all depth ranges. Annual salinities measured at Station 27 remained above normal, similar to 2002 values which were the highest in over a decade. The cross-sectional area of <0°C (CIL) water on the Newfoundland and Labrador Shelf during the summer of 2003 increased slightly over 2002 values but remained below the long-term mean along all sections, in some cases for the ninth consecutive year. In general, the below normal temperatures observed along standard sections off the east coast of Newfoundland during the spring moderated by summer and were generally above normal by fall. Bottom temperature anomalies in southern areas of the Grand Bank and St. Pierre Bank during the spring of 2003 were generally below normal. In fact temperatures during the spring of 2003 were 3rd coldest in the 34 year time in 3P. Fall bottom temperatures for the shallow waters of the southeast Grand Bank where similar to 2002, up to 2°C below normal however in Divs. 3L, 3K and 2J they were above normal, up to 2°C on Hamilton Bank and up to 1°C on Funk Island Bank. In summary, 2003 was a year of extremes in many areas, with below normal temperatures in early spring but increased to above normal values through the year. In general both 2002 and 2003 were cooler than 1999-2000 values, but remained above normal over most areas continuing the trend established in 1996. Ocean salinities on the Newfoundland Shelf which reached near-record lows in the early 1990s remained below normal throughout most of the 1990s up to and including 2001, however, during 2002 and 2003 there was a significant increase with surface values the highest observed in over a decade.

Introduction

This manuscript presents an overview of physical oceanographic conditions in the Newfoundland and Labrador Regions during 2003, with a comparison to long-term average conditions based on historical data. Where possible the long-term averages were standardised to a base period from 1971-2000 in accordance with the recommendations of the World Meteorological Organization. Most of the time series presented had good temporal coverage between the years 1971-2000. The information presented for 2003 is derived from three principal sources; (1) observations made at Station 27 throughout the year from all research and assessment surveys, (2) measurements made along standard NAFO cross-shelf sections from annual oceanographic surveys (Fig. 1), and (3) oceanographic observations made during the spring and fall multi-species research vessel surveys (Fig. 2). Data from other sources are also used to help define the long-term means and conditions during 2003.

Data Sources and Analysis

Oceanographic data are available from archives at the Marine Environmental Data Service (MEDS) in Ottawa and maintained in databases at the Bedford Institute of Oceanography (BIO) in Dartmouth, Nova Scotia and at the Northwest Atlantic Fisheries Centre (NAFC) in St. John's Newfoundland. Since 1977 (in Div. 2J), and from

1981 (in Div. 3KL) to 1989 the bulk of the fall data were collected during random stratified groundfish surveys. From 1971 to 1988 these surveys collected temperature data using bottles at standard depths and/or bathythermographs, mechanical or expendable (MBT/XBT), which were deployed usually at the end of each fishing set. Since 1989 net-mounted conductivity-temperature-depth (Seabird model SBE-19 CTD systems) recorders have replaced XBTs. This system records pressure, temperature and salinity data during trawl deployment and recovery as well as for the duration of the tow. Data from the net-mounted CTDs are not field calibrated, but are checked periodically and factory calibrated when necessary, maintaining an accuracy of 0.005°C in temperature and 0.005 in salinity. The XBT measurements are accurate to within 0.1°C.

Time series of temperature and salinity anomalies were constructed at standard depths from Hamilton Bank, Station 27 and the Flemish Cap. Anomaly time series were constructed by subtracting either the monthly mean or a fitted annual cycle from each observation. Except for Station 27 these anomalies are based on data collected over relatively large geographical areas and therefore may exhibit variability due to spatial differences. Additionally, the annual values may be based only on a few monthly estimates for the year. Caution therefore should be used when interpreting short time scale features of these series. The long-term trends however, generally show real features.

Bottom temperature grids for the Newfoundland Shelf were produced from all available data from 1971 to 2000 and for the spring and fall of 2003. All bottom-of-the-cast temperature values for each time period (except those for which the cast depths were not within 10% of the total water depth) were interpolated onto a regular grid and contoured using a geostatistical (2-diminsional Kriging) procedure. Bottom temperature anomaly maps were computed by subtracting the 2003 temperature grid from the average grid. Some temporal and spatial biasing may be present in the analysis given the large area and wide time interval over which the surveys were conducted. For example, the annual fall multi-species survey, which starts in early to mid-October normally, finishes around mid-December but was not completed this year until the end of January 2004.

Near-bottom temperature data from the multi-species assessment surveys (Fig. 2)`were used to compute a time series of the area of the bottom covered by water in selected temperature ranges. The mean near-bottom temperature for each grid element was calculated as described above and its area integrated to produce a yearly estimate of the percentage of the total area within each temperature range. The mean near-bottom temperature time series was also constructed for each region. The selected temperature ranges were ≤0°C, 0° to 1°C, 1° to 2°C, 2° to 3°C and ≥3°C. A potential source of error in this analysis is the temporal biasing arising from the wide time interval during which a typical survey is conducted. This source of error is probably small however, given the low magnitude of the annual cycle at most of the near-bottom depths encountered. An additional source of error that can potentially affect the results, particularly along the shelf edge, occurs when the spatial scales of temperature variations are shorter than the grid size. This error will be small over the Banks where the topography is relatively flat and larger along the slopes.

Time Trends in Temperature and Salinity

Station 27 (NAFO Division 3L)

Station 27, located in the Avalon Channel off Cape Spear (Fig. 1), was sampled 59 times (50 CTD profiles, 9 XBT profiles) during 2003. The data from this time series are presented in several ways to highlight seasonal and inter-annual variations over various parts of the water column. Depth versus time contour maps of the annual cycle in temperature and salinity and their associated anomalies for 2003 are displayed in Fig. 3a. The cold near isothermal water column during the winter months has temperatures ranging from 0° to –1.5°C. These temperatures persisted throughout the year in the bottom layers. Surface layer temperatures ranged from about –1° to 0°C from January to mid-April, after which the surface warming commenced. By mid-May upper layer temperatures had warmed to 2°C and to >13°C by August at the surface, after which the fall cooling commenced. These temperatures were about 0.25° to 0.5°C above normal during the winter months over most of the water column. Temperatures during the spring were generally below normal. During the remainder of the year, temperatures were above normal (by >1.5°C in surface layers during the summer) except for a mid-depth cold anomaly during the fall. Surface salinities reached maximum values by late winter (>32.4 in mid-March) and decreased to minimum values by late summer (<31.3 in September). These values were generally above normal throughout the year in the upper water column, reaching a maximum of about 0.4 above normal during the fall months. In the depth range from 50-100-m, salinities generally ranged from 32.4 to 32.8 and near bottom, they varied throughout the year between 32.8 and 33. Except from May to July bottom salinities were near normal during most of 2003 (Fig. 3a).

The annual time series of temperature and salinity anomalies generally show cold and fresher-than-normal periods at near decadal time scales since the early 1970s (Fig. 3b, 4 and 5). Figure 3b in particular shows an extended cold period lasting from the mid-1980s to the mid-1990s and a fresher-than-normal period that lasted most of the decade of the 1990s. At the surface negative temperature anomalies reached a minimum in the early 1990s, began to moderate to near-normal conditions by the summer of 1994 and have continued at normal to above normal up to 2003. Near bottom at 175-m depth, temperatures were generally below normal from 1983 to 1994, the longest continuous period on record. During 1994 and 1995 bottom temperatures started to warm and by 1996 were above the long-term average. Annual bottom temperatures from 1998 to 2003 have remained above the long-term mean. Monthly surface and bottom temperatures were above normal in all months of 2003 except during the spring (Fig. 4 right panels). The depth averaged (0-175 m) annual temperature varied considerably during the past decade, from a record low during 1991, a near record high during 1996, near normal in 1997 and 1998 and above normal from 1999 to 2003 (Fig. 4 bottom panel).

Near-surface salinity anomalies (Fig. 5) show the large fresher-than-normal anomaly that began in early 1991 had moderated to near normal conditions by early 1993 but returned to fresher conditions by the summer of 1995. Annual salinities approached near normal values during 1996 but decreased to mostly below normal values from 1997 to 2001. During 2002 and 2003 surface salinities increased to above normal and to the highest in over a decade. In general, during the past several decades cold ocean temperatures and fresher-than-normal salinities were associated with strong positive NAO index anomalies, colder-than-normal winter air temperatures, heavy sea-ice conditions and larger than normal summer cold-intermediate-layer (CIL) areas on the continental shelf (Colbourne et al. 1994, Drinkwater 1996). During the past several years (up to 2001) however, salinities have remained below normal during a time period of warm air temperatures and lower than normal ice conditions. During 2003 surface salinities were above normal for 11 of 12 months, near-bottom however, they were slightly below normal in most months especially during spring and summer (Fig. 5 right panels). The depth averaged (0-50 m) salinity time series (Fig. 5 bottom panel) show similar variability as the temperature time series, with fresher-than-normal periods generally corresponding to the colder-than-normal conditions up to at least the early 1990s. The magnitude of negative salinity anomaly on the inner Newfoundland Shelf during the early 1990s is comparable to that experienced during the 'Great Salinity Anomaly' of the early 1970s (Dickson et al. 1988), however, the spatial extent of the anomaly was mainly restricted to the inner Newfoundland Shelf. From 1991 to 2001 annual salinities were below normal on the inner Newfoundland Shelf. During 2002 and 2003 salinities increased over 2001 values and were the highest in about 12 years in the upper water column.

Flemish Cap (Division 3M)

Temperature anomalies on the Flemish Cap (Fig. 6) are also characterised by cold periods during the 1970s, mid-1980s and the late 1980s to the mid-1990s. The cold period, beginning around 1971, continued until 1977 in the upper layers, while temperature anomalies at 150-m depth were of a much lower magnitude. From 1978 to 1984 the temperature anomalies showed a high degree of variability in the upper water column with a tendency towards positive anomalies. By 1985 in the top 100-m of the water column, negative temperature anomalies had returned. This cold period moderated briefly in 1987 but returned again by 1988 and continued into the early 1990s. By 1995 temperatures moderated and were above normal at most depths from 1997 to 2002. Surface temperatures during 2003 were about normal, while values at deeper levels were similar to those of 2002, generally above normal. It should be noted that the annual estimate for 2003 was based on only three observations.

The time series of salinity anomalies on the Flemish Cap (Fig. 6, right panels) show large fresher-than-normal conditions from 1970 to 1975 with peak amplitudes reaching near 1-pratical salinity unit below normal at the surface. Negative salinity anomalies also occurred during the mid-1980s and mid-1990s, however the amplitude was much smaller than the great salinity anomaly of the early 1970s. The trend in salinity values during the latter half of the 1990s ranged from slightly above normal at the surface to near normal at deeper depths. In general, the long-term trends in temperature and salinity anomalies on the Flemish Cap are very similar to those at Station 27 and elsewhere on the continental shelf over similar depth ranges (Colbourne and Foote 2000). Annual salinity anomalies in 2003 continued the increase noted in 2002 over all depths reaching >0.5 above normal at the surface.

Hamilton Bank (Division 2J)

Time series of temperature and salinity anomalies from 1951 to 2003 on Hamilton Bank are shown in Fig. 7 at selected depths. The annual values show a high degree of variability, which may in part be due to the different station locations between years coupled with the spatial variability of the hydrographic properties over the bank at the same depth level. It should also be noted that these annual estimates are calculated from a variable number of observations. A low frequency trend was calculated by a 5-year running mean that suppresses the high frequency variations and gives a general indication of long-term trends.

The temperature anomaly time series is characterised by amplitudes ranging from near $\pm 2^{o}C$ and with periods ranging from 2 to 10 years. The cold periods of the early 1970s, the mid-1980s and the early 1990s are apparent, but the amplitude of the anomalies varied considerably with depth. The long-term trend indicates that temperatures on Hamilton Bank have moderated, particularly in the deeper layers, being above normal since the mid-1990s, similar to conditions further south at Station 27. Temperatures were above normal during 2003 increasing sharply over 2002 values in the upper water column and remained similar to 2002 values in deeper layers. The salinity time series, while very noisy, show similar trends as elsewhere on the shelf with fresher-than-normal conditions particularly in the early 1970s at the surface, and to some extent during the early 1990s. Salinities from 1995-2003 varied about the long-term mean with near-normal values during 2003 in the upper water column and slightly below normal below 100-m depth.

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). Several of these sections are occupied annually during mid-summer on an annual oceanographic survey conducted by the Fisheries and Oceans Canada (Fig. 1). The sections with the longest historical record include, the Seal Island section on the southern Labrador coast crossing Hamilton Bank, 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. The temperature and salinity data along these sections for the summer of 2003 are presented. The anomalies are referenced to the 1971-2000 historical data sets.

The water mass characteristics observed along the standard sections crossing the Newfoundland and Labrador Shelf (Fig. 1) are typical of sub-polar waters with a sub-surface temperature range of -1^{o} to $2^{o}C$ and salinities of 32 to 33.5. Labrador Slope Water flows southward along the shelf edge and into the Flemish Pass region, this water mass is generally warmer and saltier than the sub-polar shelf waters with a temperature range of 3^{o} to $4^{o}C$ and salinities in the range of 34 to 34.75. Surface temperatures warm to 10^{o} to $12^{o}C$ during late summer, while bottom temperature remain $<0^{o}C$ over the Grand Banks but increase to 1^{o} to $3^{o}C$ near the shelf edge below 200-m. In the deeper waters of the Flemish Pass and across the Flemish Cap bottom temperatures generally range from 3^{o} to $4^{o}C$. Throughout most of the year the cold relatively fresh water overlying the shelf is separated from the warmer higher density water of the continental slope region by a strong temperature and density front. This water mass is generally referred to as the cold intermediate layer (CIL) which is formed during the winter months and is discussed in more detail below. In general the water masses found along the standard sections undergoes seasonal modification in its properties due to the seasonal cycles of air-sea heat flux, wind forced mixing and ice formation and melt leading to intense vertical and horizontal gradients particularly along the frontal boundaries separating the shelf and slope water masses.

Flemish Cap (47^{o} N)

Near surface temperatures along the Flemish Cap section (Fig. 1) during the summer of 2003 ranged from 7^{o} to $10^{o}C$ while $<0^{o}C$ water was present below 60-m depth to the bottom over most of the Grand Bank. The coldest water is normally found in the Avalon Channel and at the edge of the Grand Bank corresponding to the inshore and offshore branches of the Labrador Current (Fig. 8). Temperatures were generally above normal over most areas along this section during the summer except for isolated areas near the surface and in the deeper waters of the Flemish Pass. To the east of the Flemish Cap temperatures were higher than normal by $>8^{o}C$. Salinities along the section on the Grand Bank (Fig. 9) are characterised by generally fresh conditions on the bank (<33), a strong horizontal gradient at the shelf break separating the saltier (>34.5) slope water offshore in the Flemish Pass. Salinity anomalies during 2003 were generally higher than average in the upper layers and near normal below 50-m depth. To the east of the Flemish Cap salinities were above normal by over 1 practical salinity unit (Fig. 9).

Bonavista

The dominant water mass feature along this section during the summer months is the cold intermediate layer of <0^{o}C water (CIL) which develops during early spring after intense winter cooling (Fig. 8). Temperatures along the Bonavista section during the summer of 2003 in the upper water column ranged from 7^{o}to 8^{o}C. These values were above normal in the extreme inshore areas, below normal at mid-shelf and generally above normal in the offshore areas. The offshore area of the Labrador Current appeared warmer-than-normal as did the near bottom areas across most of the eastern Newfoundland Shelf. Intermediate depth waters corresponding to the CIL were colder than normal (Fig. 8). Salinities along the Bonavista section generally range from <32.5 near the surface in the inshore region to >34 in the offshore region (Fig. 9). Bottom salinities ranged from 32.5 in the inshore regions, to 34.75 at about 325-m depth near the shelf edge. Similar to the Flemish Cap section salinities were generally above normal throughout the section, with the magnitude of the anomalies decreasing with depth. In general, salinities along the Bonavista section during 2002 and 2003 increased over values observed in 2001.

Seal Island

The Seal Island section, which crosses Hamilton Bank on the southern Labrador Shelf (Fig. 2), was also sampled in July of 2003 (Fig. 8 and 9 bottom panels). Upper layer temperatures across the shelf in this region ranged from –0.5^{o}C at approximately 50-m depth to between 7^{o}to 8^{o}C at the surface. Temperatures below 50-m depth were generally <0^{o}C over most of the shelf, corresponding to the CIL water mass, except near bottom where they range from 0^{o} to 1^{o}C due to the influence of warmer slope water. Near the shelf break in Labrador slope water, bottom temperatures increase to 2^{o}-3^{o}C. Temperature anomalies in the surface and near-bottom layers were up to 1^{o} to 2^{o}C above normal over most of the shelf. At intermediate depths corresponding to the CIL water mass, anomalies generally varied about the mean. Surface salinities along this section ranged from <31.5 inshore of Hamilton Bank to >34 in the offshore region. Bottom salinities ranged from 32.5 near the coast of Labrador to 34.5 at the edge of the shelf in water depths >300-m. Near-surface salinities were saltier-than-normal particularly in the inshore area and about normal over the remainder of the water column. Offshore of the shelf break however, salinities were below normal in the upper water column.

Cold Intermediate Layer (CIL) Time Series

As discussed above with reference to the cross-shelf contour plots, the vertical temperature structure on the Newfoundland Continental Shelf during late spring through to the fall is dominated by a layer of cold <0^{o}C water trapped between the seasonally heated upper layer and warmer slope water near the bottom. This water mass is commonly referred to as the cold intermediate layer or CIL (Petrie *et al*., 1988) and is generally regarded as a robust index of ocean climate conditions off the eastern Canadian continental shelf. The cold, relatively fresh, shelf water is separated from the warmer saltier water of the continental slope by a frontal region denoted by a strong horizontal temperature and salinity gradient near the edge of the continental shelf. It usually remains present throughout most of the year as the seasonal heating increases the stratification in the upper layers to a point where heat transfer to the lower layers is inhibited, although it undergoes gradual decay during the summer reaching a minimum during the fall. The spatial extent of this winter chilled water mass is evident in the section plots of the temperature contours, for example along the Seal Island section (Fig. 8) the CIL extends offshore to over 200 km, with a maximum vertical extent of approximately 150 m. This corresponds to a cross-sectional area of around 25 km^{2}. The annual summer CIL cross-sectional area anomalies defined by the 0^{o}C contour for the Flemish Cap, Bonavista and Seal Island sections are displayed in Fig. 10. Along the Flemish Cap section the CIL area was below the 1971-2000 normal in 2003, similar to conditions observed during the past 5-years but a slight increase over 2002. Off Bonavista the CIL area was also below normal for the 9th consecutive year ranking the 22nd warmest year in the 55 year time series. Along the Seal Island section the area of <0^{o}C water increased slightly over 2002 but was still below normal. In general, the CIL area observed along all sections, while showing a slight increase over 2002, it continued the trend of below normal values observed since 1995. This is in contrast to the near record high values measured during the cold period of the early-1990s on the Newfoundland Shelf.

Multi-Species Survey Results

Canada has been conducting stratified random bottom trawl surveys in NAFO Sub-areas 2 and 3 since 1971. Each NAFO Div. has been 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 were based on an area-weighted proportional allocation (Doubleday 1981). Temperature profiles of the water column are available for fishing set in each stratum. Surveys have been conducted for the following NAFO Divisions, time periods and depth ranges: 3P in winter and/or spring from 1972 to 2003, in water depths down to 366 m until 1979 and to 548 m since then; 3L in spring from 1971-2003, except 1983 and 1984; 3NO in spring from 1971-2003, except 1983 in 3N and 1972, 1974 and 1983 in 3O, in water depths down to 366 m in most years and more recently to 548 m; 2J fall from 1977-2003; 3K in fall from 1978-2003; 3L in fall from 1981-2003, 3NO in fall from 1990-2003. These surveys provide 2 spatially comprehensive oceanographic data sets on an annual basis for the Newfoundland Shelf, one during the spring from 3Pn in the west to 3LNO on the Grand Bank and one during the fall period from 2J in the north, to 3NO in the south. In this section an analysis of the near-bottom temperature fields and their anomalies based on these data sets are presented for the spring and fall surveys. Inter-annual variations are then examined by computing the areal extent of the bottom covered with water in various temperature ranges as described earlier. The objective of this analysis is to provide some indication of potential changes in any temperature dependent near-bottom habitat for various species of marine organisms.

Spatial Temperature Maps

Bottom temperatures during the spring of 2003 in NAFO Sub-area 3P ranged from 4^o to 5^{o}C in the Laurentian, Burgeo and Hermitage Channels to about 1^o to 3^{o}C on Burgeo Bank. On St. Pierre Bank bottom temperatures ranged from near -1^{o}C on the eastern side to 2^o to 3^{o}C on the western side. During the spring of 2003, bottom temperatures over St. Pierre Bank decreased significantly over 2002 values with <0^{o}C water covering most of the Bank and regions to the east (Fig.11). Consequently, below normal temperatures were more widespread during 2003 compared to 2002, covering most of the bottom areas in the 3P region with values as low as 1^{o}C below normal (Fig. 11). In general, the area of the bottom covered by below normal temperatures increased significantly during the spring of 2003, compared to 2002.

Bottom temperature maps and their anomalies for NAFO Div. 3LNO during the spring and fall of 2003 are displayed in Fig. 12. In the northern areas of the Grand Bank spring bottom temperatures ranged from <0^{o}C in the inshore regions of the Avalon Channel to >3^{o}C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1^{o}C to 2^{o}C on the Southeast Shoal and to 4^o to 5^{o}C along the slopes of the Grand Bank in Div. 3O. During the spring of 2003 <0^{o}C water was mostly restricted to Div. 3L, although there was an increase in the amount of <0C water in the northern portions of 3NO. In general, temperatures were mostly above normal in northern areas and below normal in southern regions. Fall bottom temperatures generally ranged from <0^{o}C on the northern Grand Bank and in the Avalon Channel, to 3^{o}C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1^o to 3^{o}C during 2003 on the Southeast Shoal and to >3^{o}C along the edge of the Grand Bank. These values were above normal on the northern Grand Bank and along the edge of the Grand Bank by up to 0.5^o to 1^{o}C. Bottom temperature anomalies in 3NO were quite variable except for the southeast shoal where they ranged from 0.5^o to 2^{o}C below normal.

Bottom temperatures and their anomalies for NAFO Div. 3K during the fall of 2003 are shown in Fig. 13. Most of the 3K region has water depths >200-m. As a result, relatively warm slope water floods through the deep troughs between the northern Grand Bank and southern Funk Island Bank and between northern Funk Island Bank and southern Belle Isle Bank. Bottom temperatures on these banks during the fall of 2003 ranged between 2^o to 3^{o}C, which were about 0.5^o to 1^{o}C above their long-term means. Near the edge of the continental shelf in water depths below 500-m temperatures are generally around 3.5^{o}C, which was about normal. Bottom temperatures and their anomalies for NAFO Div. 2J during the fall of 2003 are displayed in Fig. 14. Temperatures generally ranged from <1^{o}C inshore, to >3.5^{o}C offshore at the shelf break. Bottom temperatures over Hamilton Bank ranged from <2^{o}C on the inshore portion of the bank, to near 3^{o}C on the southern portion. Bottom temperature anomalies were about 1^o to 2^{o}C above normal on Hamilton Bank and about normal along the edge of the shelf. The negative anomalies apparent near the coast may be due to under-sampling of the extreme inshore regions.

Bottom Temperature Time Series

The spatially averaged spring bottom temperature of the surveyed area in NAFO Div. 3P ranged between 2^o to 4^{o}C from 1970 to 1984 and decreased to between 2^o to 2.5^{o}C from 1985 to 1997. During 1999 and 2000, the average near-bottom temperature increased to >3^{o}C but decreased to near 2.5^{o}C in 2001. During the spring of 2002 the average bottom temperature increased slightly over the 2001 value to 2.6^{o}C but fell to 2^{o}C by the spring of 2003 making it the 3rd coldest spring in the 34 year time series (Fig. 15, top panel). The average spring bottom temperature time series for the 3LNO region shows large inter-annual variations of about 1^{o}C amplitude and a downward trend that started in 1984. This trend continued until the early-1990s. The highest temperature in the 25-year record occurred in 1983 when the average temperature was 3.2^{o}C and the lowest temperature of 0.25^{o}C occurred in 1990. Recently, temperatures have increased over the lows of the early-1990s with the average bottom temperature during the spring of 1999 and 2000 reaching 2^{o}C. During the spring of 2001 to 2003, the average bottom temperature decreased over the 2000 value to about 1^{o}C in 2003, the 11th coldest in the 28 year record (Fig. 15, top panel).

During the fall the average bottom temperature in Div. 3LNO decreased from approximately 1.5^{o}C during 1990 to 1^{o}C during 1993 and 1994, and then increased to approximately 1.8^{o}C during 1995. Temperatures remained relatively constant up to 1998 but then increased to over 2.5^{o}C during 1999, the highest in the 10 year record (Fig. 15, bottom panel). During the fall of 2000 to 2003 the mean bottom temperature decreased by nearly 1^{o}C over the 1999 value, but was still above the cold condition of the early-1990s. The average bottom temperature in Div. 3K (Fig. 15 bottom panel) during the fall ranged from 1^{o}C in 1982, to 2.3^{o}C in 1986, with an overall average of about 2^{o}C. From 1995 to 1999 they increased to above-average values reaching about 2.7^{o}C during 1999. During the fall of 2000 to 2003 bottom temperatures were lower than in 1999, but remained relatively warm between 2.2^{o} to 2.5^{o}C. Bottom temperatures during the fall in Div. 2J generally average about 2^{o}C, but during the latter half of the 1990s they increased to about 2.5^{o}C. During 1999 to 2002 mean bottom temperatures remained relatively constant slightly >2.5^{o}C. During the fall of 2003 the average temperature increased to the highest in the record to near 3^{o}C.

Spring Thermal Habitat Index

The areal extent of the bottom covered with water in the temperature ranges of <0^{o}C, 0^{o} to 1^{o}C, 1^{o} to 2^{o}C, 2^{o} to 3^{o}C and >3^{o}C for NAFO Div. 3P is displayed in Fig. 16. Note the large increase in the percentage area of the bottom covered by <0^{o}C water in 1985 that persisted well into the mid-1990s, with the exception of 1988. The percentage area covered by <0^{o}C water during the spring of 1998 decreased to pre-1985 levels and to less than 10% during 2000, but increased to over 25% during 2001 and 2002 and to near 40% in 2003. The bottom area covered with water between 0-1^{o}C, except for 1979 and 1988, has remained below 20%. The bottom area with temperatures >1^{o}C before 1985 was approximately 70 to 80% and from 1984 to 1995 had been nearly constant between 50 to 70%. Since 1995, except for 1997 this area has been increasing and approached pre-1985 values during 1999 and 2000. During the spring of 2001 however, this area decreased to between 50 to 60%, increased slightly in 2002 and decreased again in 2003. During the spring of 1999 and 2000 <0^{o}C water had essentially disappeared from the St. Pierre Bank, but reappeared during 2001, reaching near 30% coverage in 2002 and over 90% coverage in 2003. The area of near-bottom water on the banks with temperatures >1^{o}C increased from about 50% in 1998 to near 85% during 2000, the first significant amount since 1984 (Colbourne 2001).

The areal extent of the bottom covered by water in various temperature ranges during spring for the 3LNO region is displayed in Fig. 16. In this region from 1975 to 1983 most of the bottom area was covered by water above 0^{o}C with only approximately 20% covered by <0^{o}C water. From 1984 to 1997 there was a large increase in the area of <0^{o}C water with percentages reaching near 60% in some years. Since 1997 there was a significant decrease in the percentage area of the bottom covered by <0^{o}C water and a corresponding increase in the area covered by water ≥1^{o}C. During the spring of 1998 and 1999 water with temperatures >1^{o}C covered 50 to 60% of the bottom area on the Grand Bank. The 1998 and 1999 values represent the largest area of relatively warm water on the Grand Bank since the late 1970s. During 1999 the area of <0^{o}C water on the Grand Bank decreased to about 10%, the lowest since 1978. During 2000 the area of cold water began to increase reaching 30% by 2002 and to 40% by 2003.

Fall Thermal Habitat Index

The areal extent of the bottom covered by water in the selected temperature ranges during the fall for the 3LNO region is displayed in Fig. 17. In general, the percentage area of the bottom covered by <0^{o}C water decreased significantly during 1995 to roughly one-half the value during the first half of the 1990s. A corresponding increase in the areal extent of water ≥1^{o}C occurred during 1995. From 1995 to 1998 this remained relatively constant at about 50%, but increased to over 70% during 1999. During the fall of 2000 the area of <0^{o}C water remained below the values of the early-1990s but increased over 1999 values to near 40%. During 2003 the area of <0^{o}C water increased slightly over 2002 to about 30%.

The areal extent of the bottom covered by water in the selected temperature ranges during the fall for Div. 3K is displayed in Fig. 17. The percentage area of the bottom covered by $<0^{o}$C water in this region is generally <30% and in many years <10%, with significant amounts appearing only during the cold periods of the early- to mid-1980s and 1990s. For temperature $>3^{o}$C, the bottom area in 3K covered has been relatively constant ranging from 20 to 35% from 1979 to 1995 after which it increased to near 40 to 50% from 1997 to 2003. The areal extent of the bottom covered by water in the selected temperature ranges during the fall for Div. 2J is also displayed in Fig. 17. The percentage area of the bottom covered by $<0^{o}$C water in Div. 2J is normally very low during the fall with significant amounts appearing only during the cold periods of the early- to mid-1980s and early-1990s, when it ranged between 20 to 30%. In 2J for temperatures $>3^{o}$C the bottom area covered ranged from a low of 15% in 1992 to a maximum of near 50% during 2001 to 2003. Since 1996 the area of the bottom covered with $<0^{o}$C water decreased to <10%.

Summary

The annual water-column averaged temperature at Station 27 for 2003 remained above the long-term mean and increased over 2002 values at all depth ranges. The annual surface temperature at Station 27 was 0.7^{o}C above normal, while the annual bottom temperature remained similar to 2002 at 0.2^{o}C above normal. Bottom temperatures were above normal during January and February, below normal during spring and above normal during the remainder of the year. Water-column averaged annual salinities at Station 27 remained above normal, similar to 2002 values, the highest in over a decade. Surface salinities at Station 27 were above normal for 11 of 12 months, while bottom salinities were generally below normal, particularly during the period April to July.

The cross-sectional area of $<0^{o}$C (CIL) water on the Newfoundland and Labrador Shelf during the summer of 2003 increased slightly over 2002 values but remained below the long-term mean. The CIL areas were below normal along all sections from the Flemish Cap section on the Grand Bank, to the Seal Island section off southern Labrador. Off Bonavista for example, the CIL area was below normal for the ninth consecutive year. In general, the cold temperatures observed along the standard sections during the spring moderated by summer and were generally above normal by fall.

Bottom temperature anomalies in southern areas of the Grand Bank and St. Pierre Bank during the spring of 2003 were generally below normal. Fall bottom temperatures for the shallow waters of the southeast Grand Bank where similar to 2002, up to 2^{o}C below normal, however, in Divs. 3L, 3K and 2J they were above normal by up to 2^{o}C on Hamilton Bank and up to 1^{o}C on Funk Island Bank. The spatially averaged spring bottom temperature during 2003 in NAFO Divisions 3PLNO continued to decline while fall values remained above normal. In general, over all areas of the Newfoundland Shelf the near-bottom thermal habitat continued to be warmer than that experienced from the mid-1980s to the mid-1990s.

In summary, the below-normal trends in temperature and salinity, established in the late 1980s reached a minimum in 1991. This cold trend continued into 1993 but started to moderate during 1994 and 1995. During 1996 temperature conditions were above normal over most regions, however, summer salinity values continued to be slightly below the long-term normal. During 1997 to 1999 ocean temperatures continued to warm over most areas, with 1999 one of the warmest years in the past couple of decades. During 2000 to 2002 ocean temperatures were cooler than 1999 values, but remained above normal over most areas continuing the trend established in 1996. The past year was one of extremes in many areas, with the below normal temperatures during the spring increasing to above normal values by fall. From 1991 to 2001 the trend in salinities on the Newfoundland Shelf was mostly below normal, however, during 2002 there was a significant increase with surface values the highest observed in over a decade. Annual salinity measurements at Station 27 during 2003 continued to show above normal values.

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We thank the many scientists and technicians at the Northwest Atlantic Centre for collecting and providing much of the data contained in this analysis and to the Marine Environmental Data Service in Ottawa for providing most of the historical data. We also thank the captain and crew of the CCGS Teleost and Hudson for three successful oceanographic surveys during 2003.

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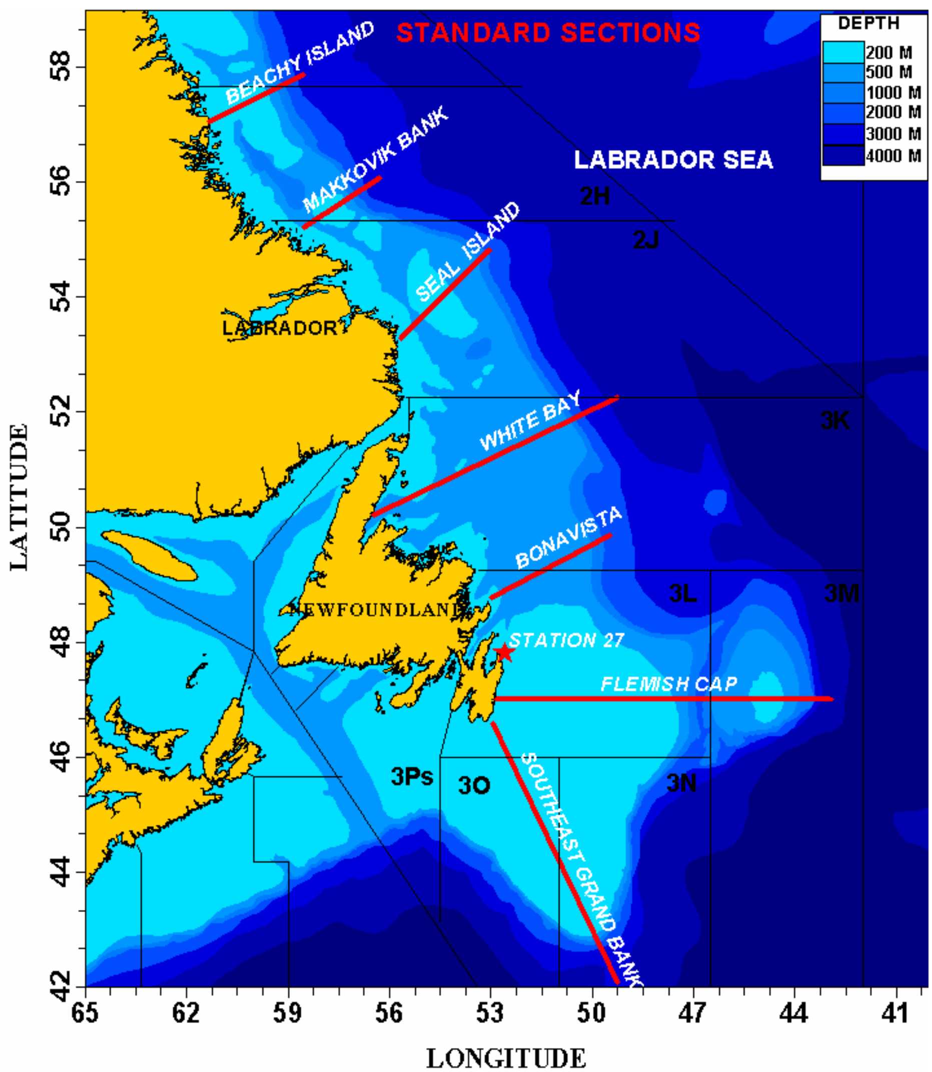


Fig. 1. Location map showing Station 27 and the standard monitoring sections on the Newfoundland and Labrador Shelf.

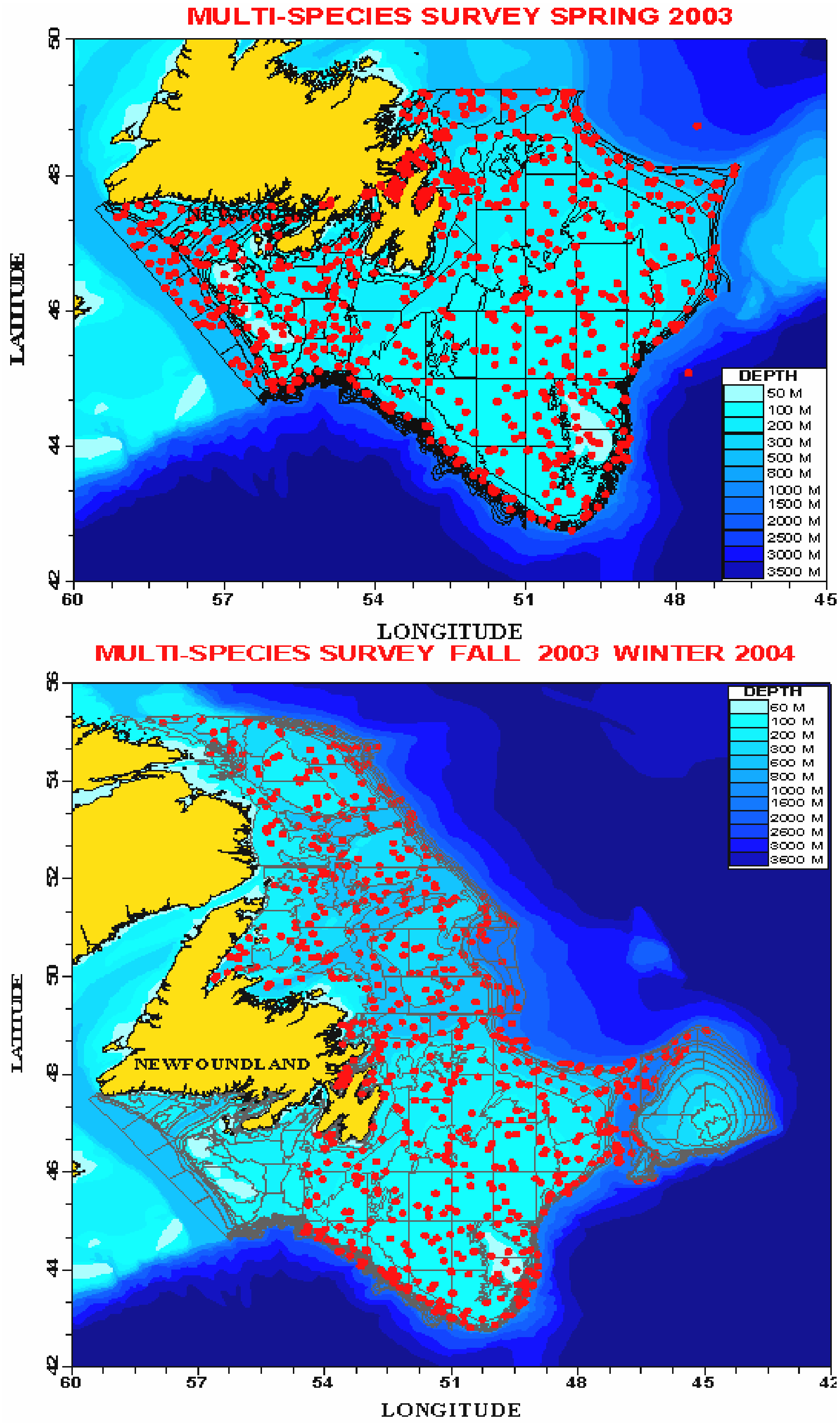


Fig. 2. Location maps showing the positions of sets with oceanographic data from the multi-species surveys during the spring and fall of 2003.

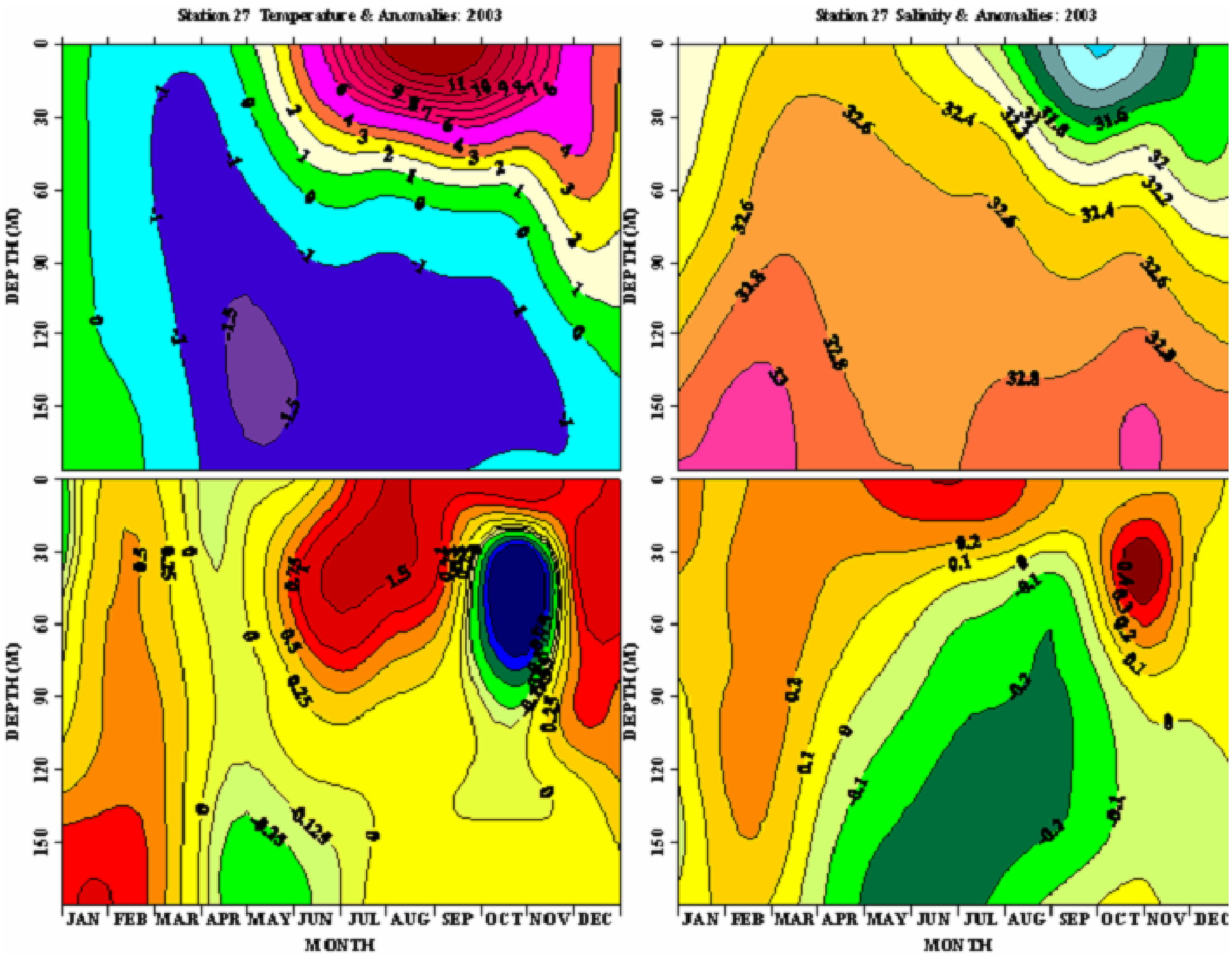


Fig. 3a. Contours of the annual cycle of temperature and temperature anomalies (in °C) (left panels) and salinity and salinity anomalies (right panels) as a function of depth at Station 27 for 2003.

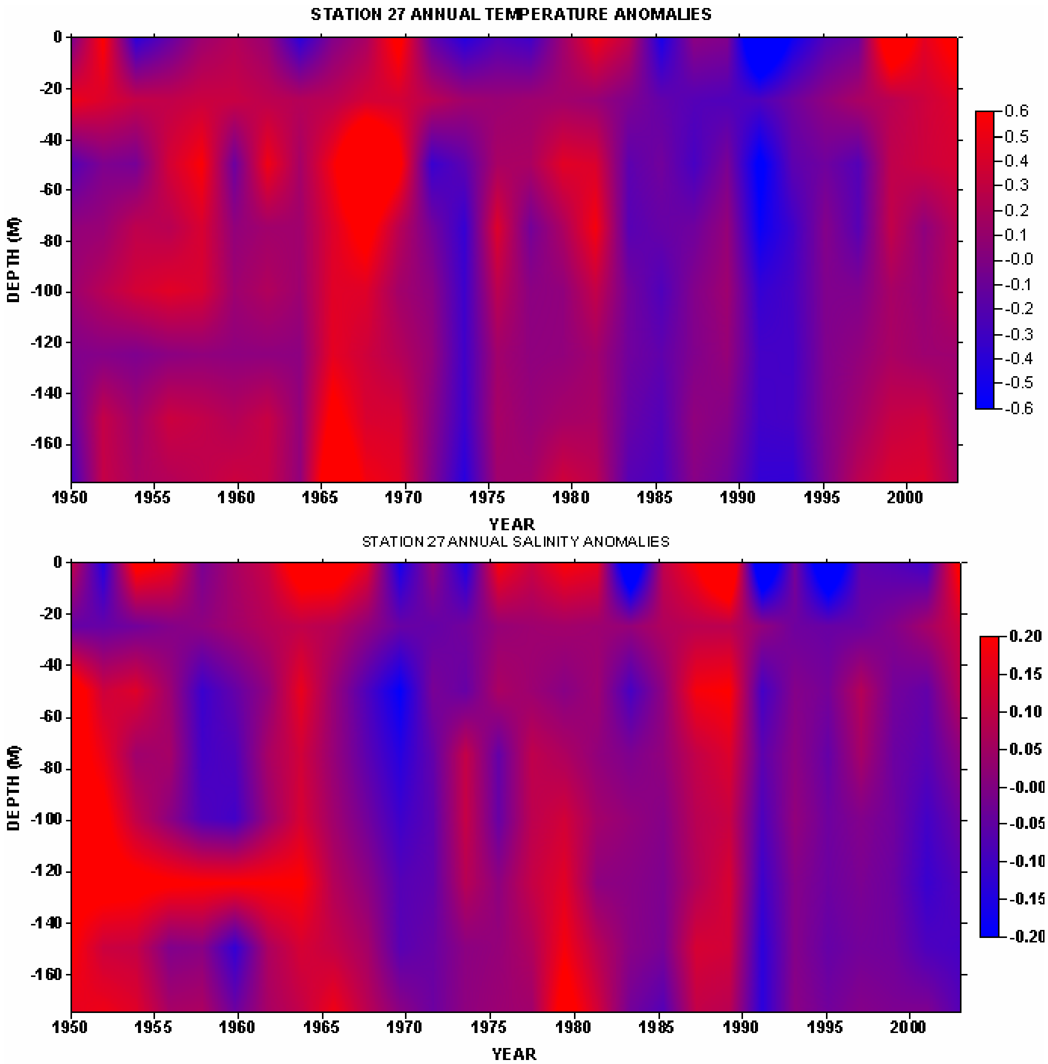


Fig. 3b. Time series of annual temperature (in ^{o}C) and salinity anomalies as a function of depth at Station 27.

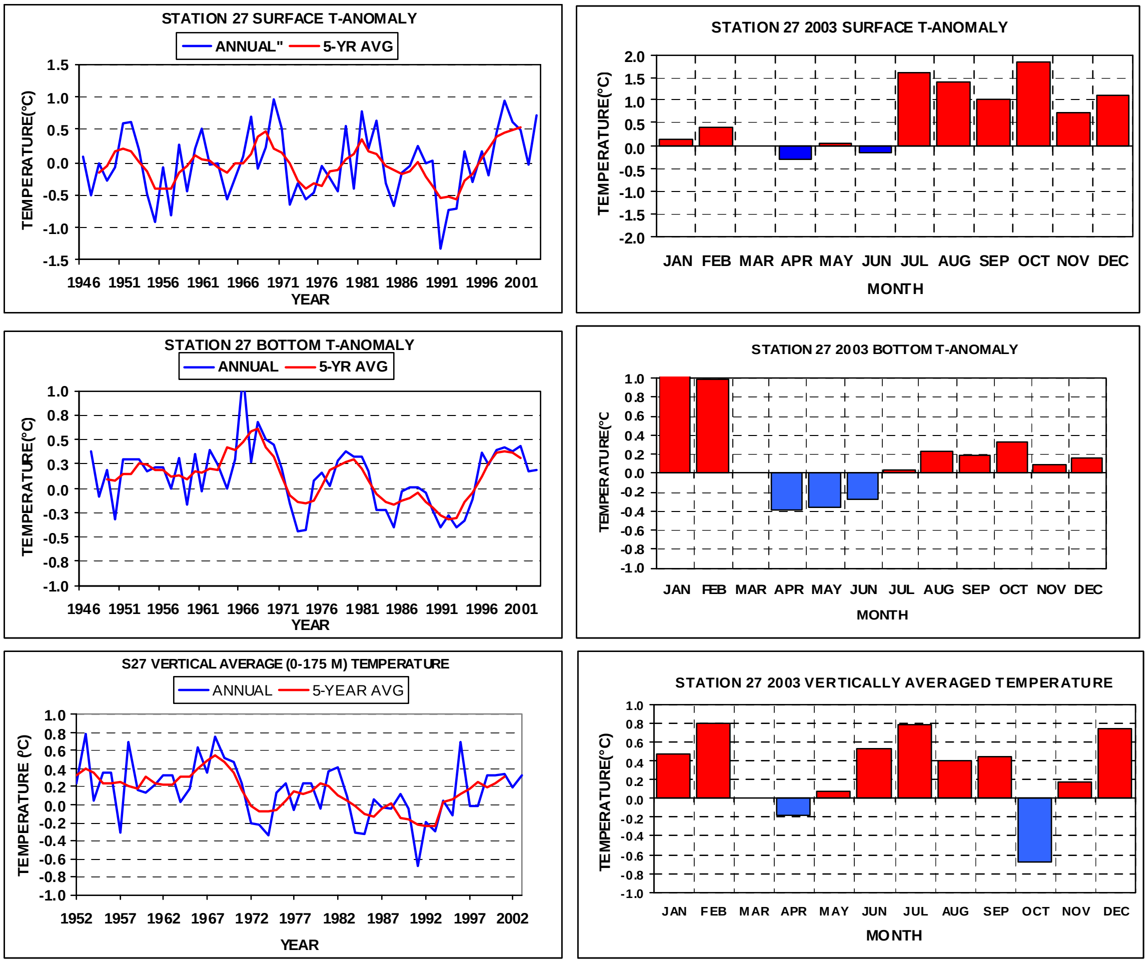


Fig. 4. Monthly surface, bottom and depth-averaged temperature anomalies at Station 27 during 2003 (right panels) and their annual anomalies with 5-year running means (left panels).

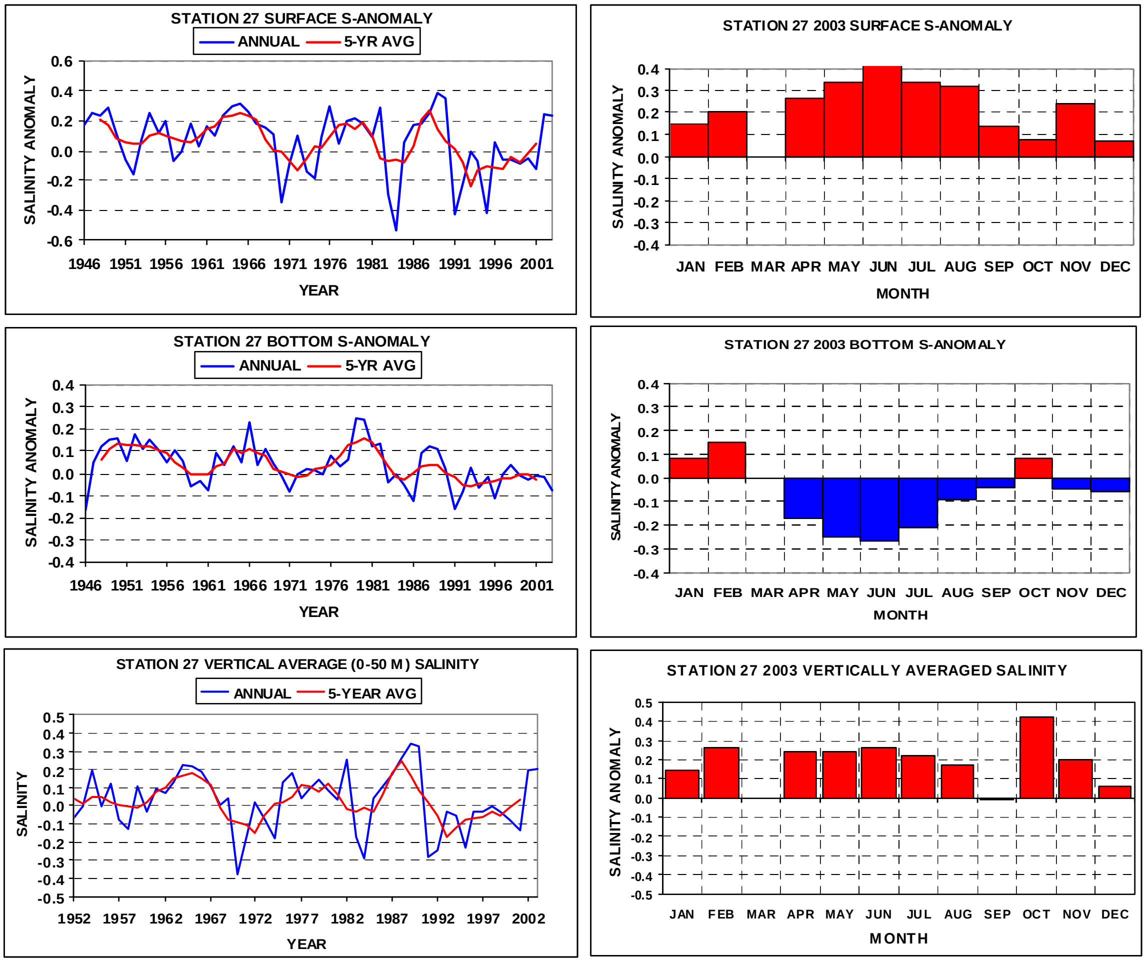


Fig. 5. Monthly surface, bottom and depth-averaged salinity anomalies at Station 27 during 2003 (right panels) and their annual anomalies with 5-year running means (left panels).

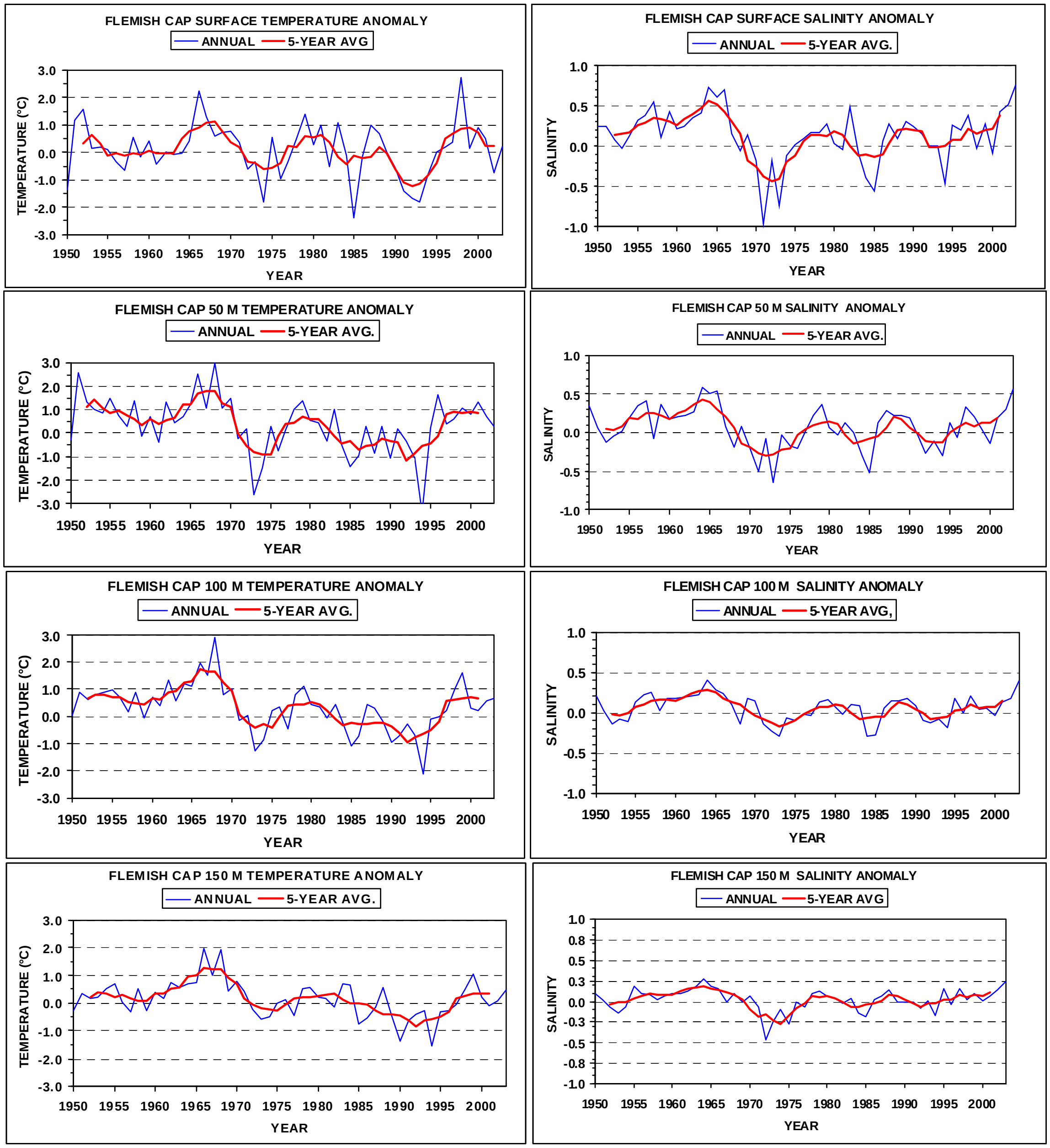


Fig. 6. Annual temperature anomalies (left panels) and salinity anomalies (right panels) on the Flemish Cap in NAFO Division 3M at selected water depths. The heavy lines are the 5-year running means

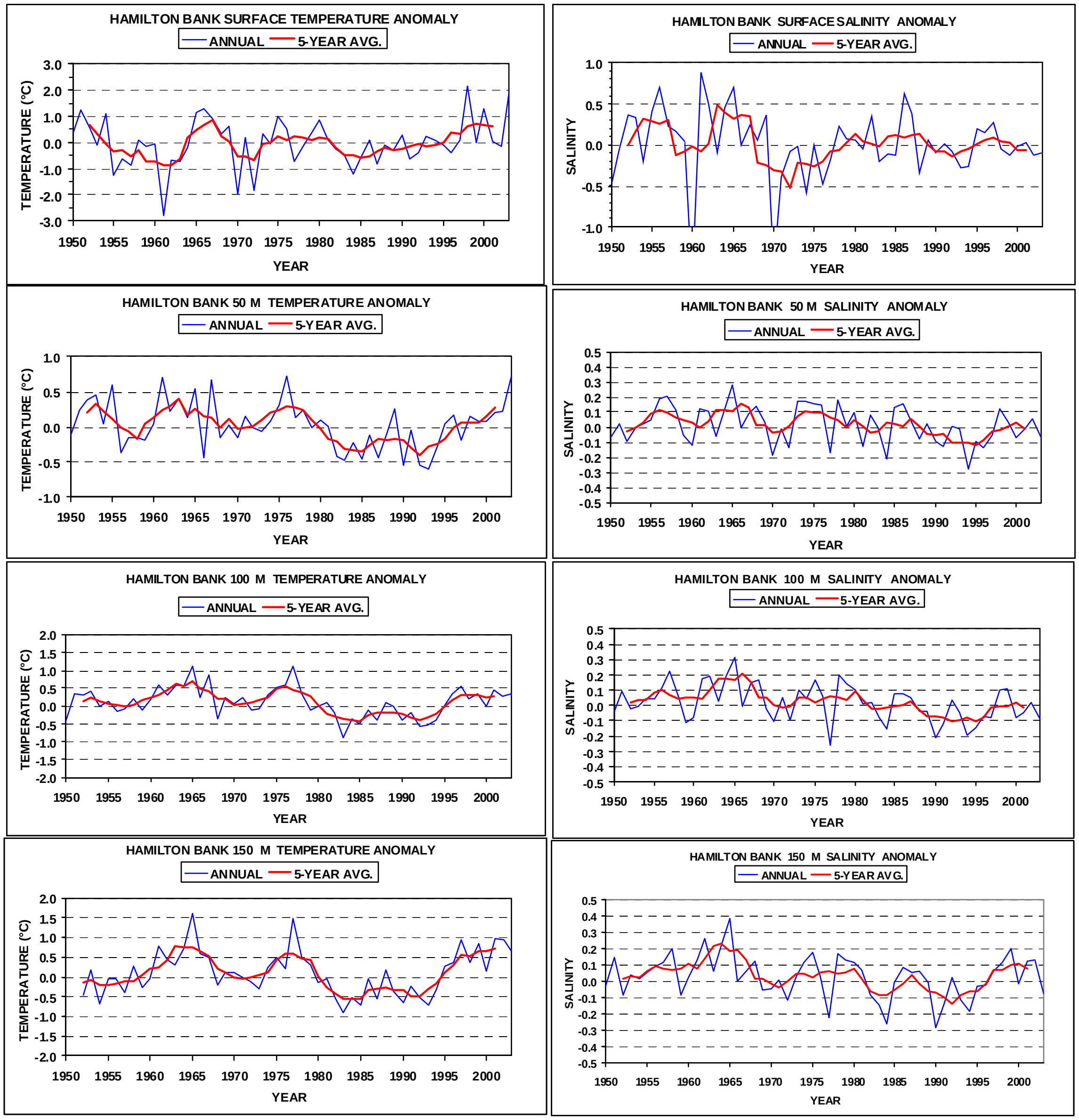


Fig. 7. Annual temperature anomalies (left panels) and salinity anomalies (right panels) on Hamilton Bank in NAFO Division 2J at selected water depths. The heavy lines are the 5-year running means.

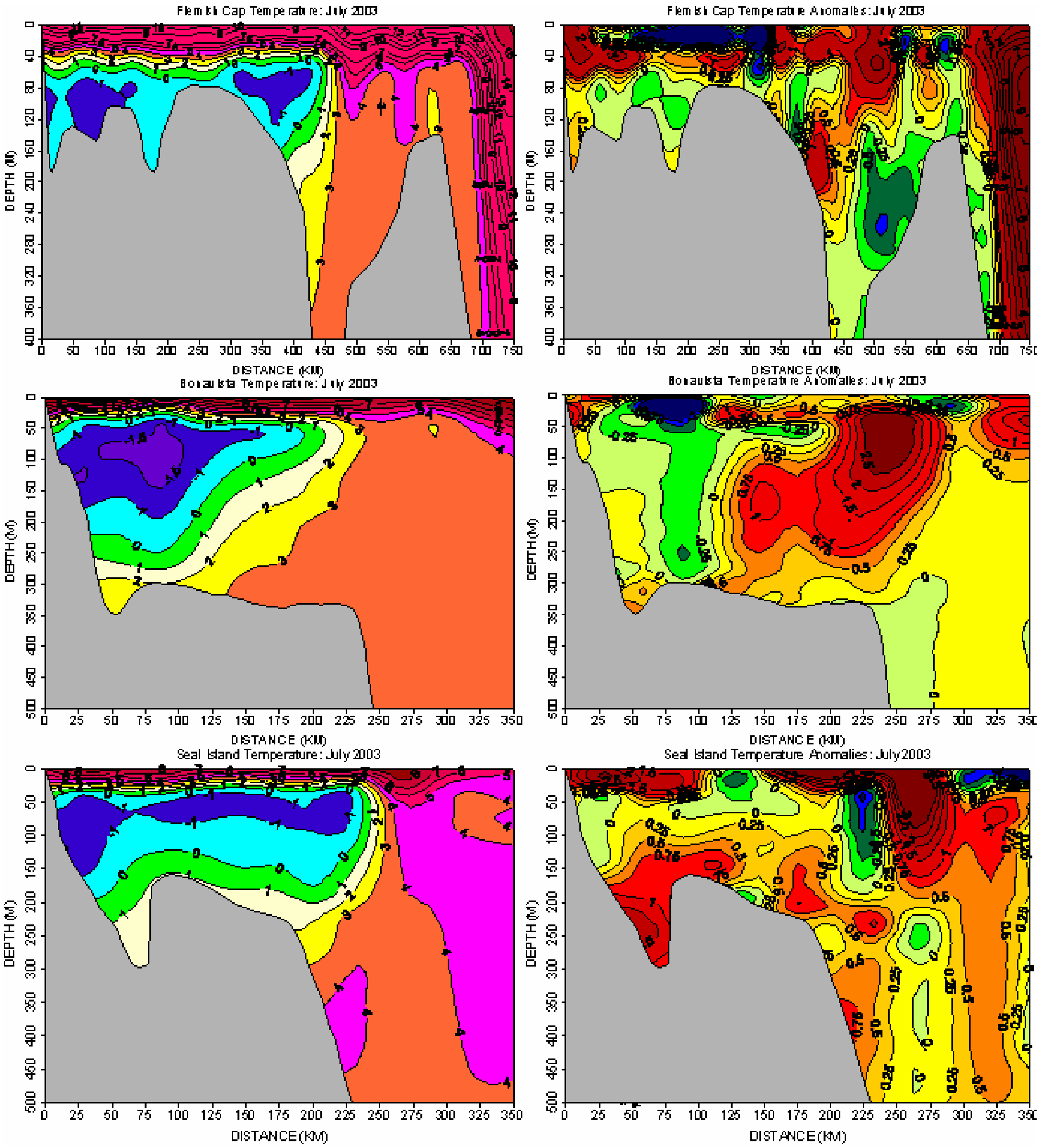


Fig. 8. Contours of temperature and temperature anomalies (in ^{o}C) along the Flemish Cap, Bonavista and Seal Island sections (Fig. 1) during the summer of 2003.

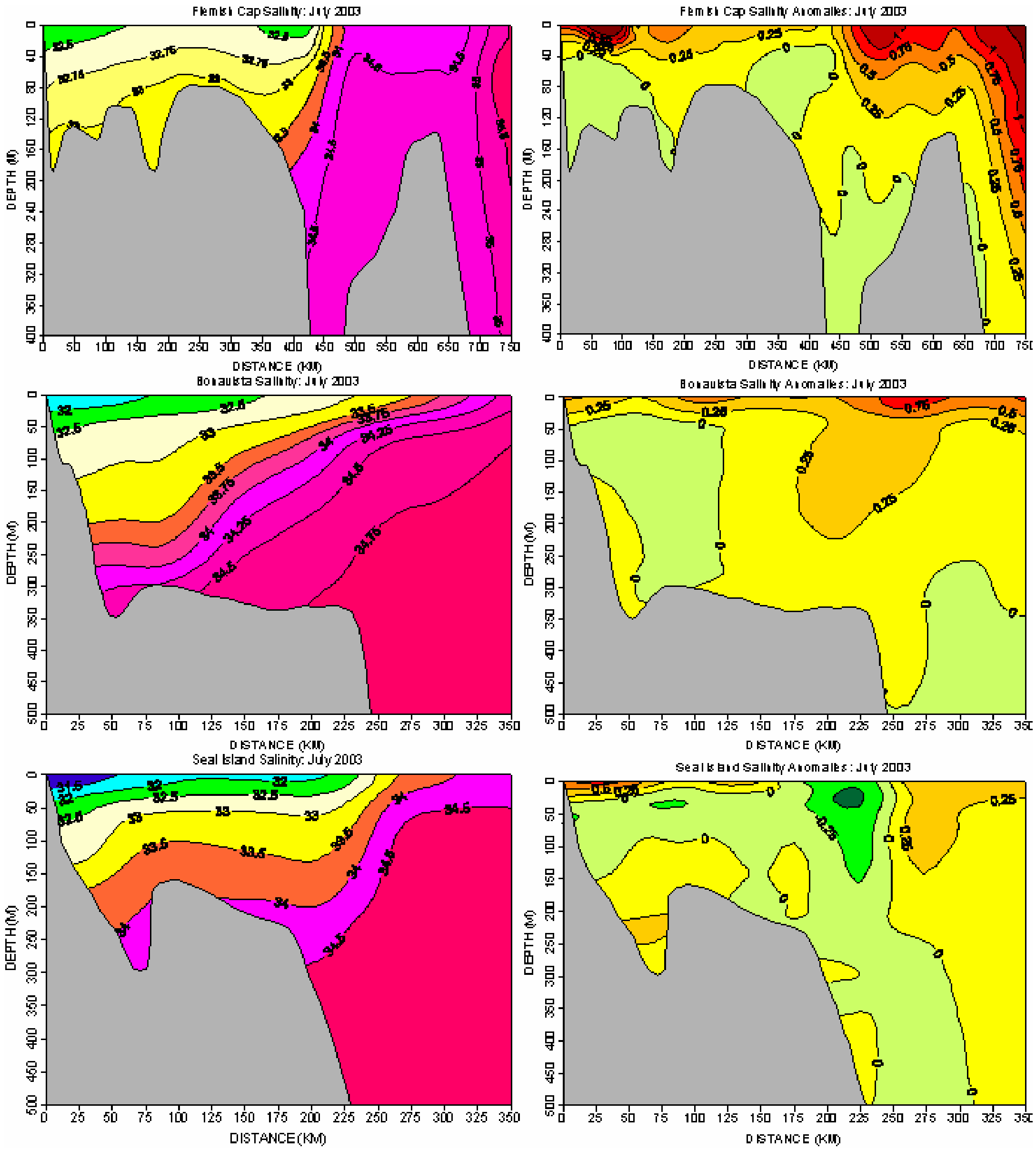


Fig. 9. Contours of salinity and salinity anomalies along the Flemish Cap, Bonavista and Seal Island sections during the summer of 2003.

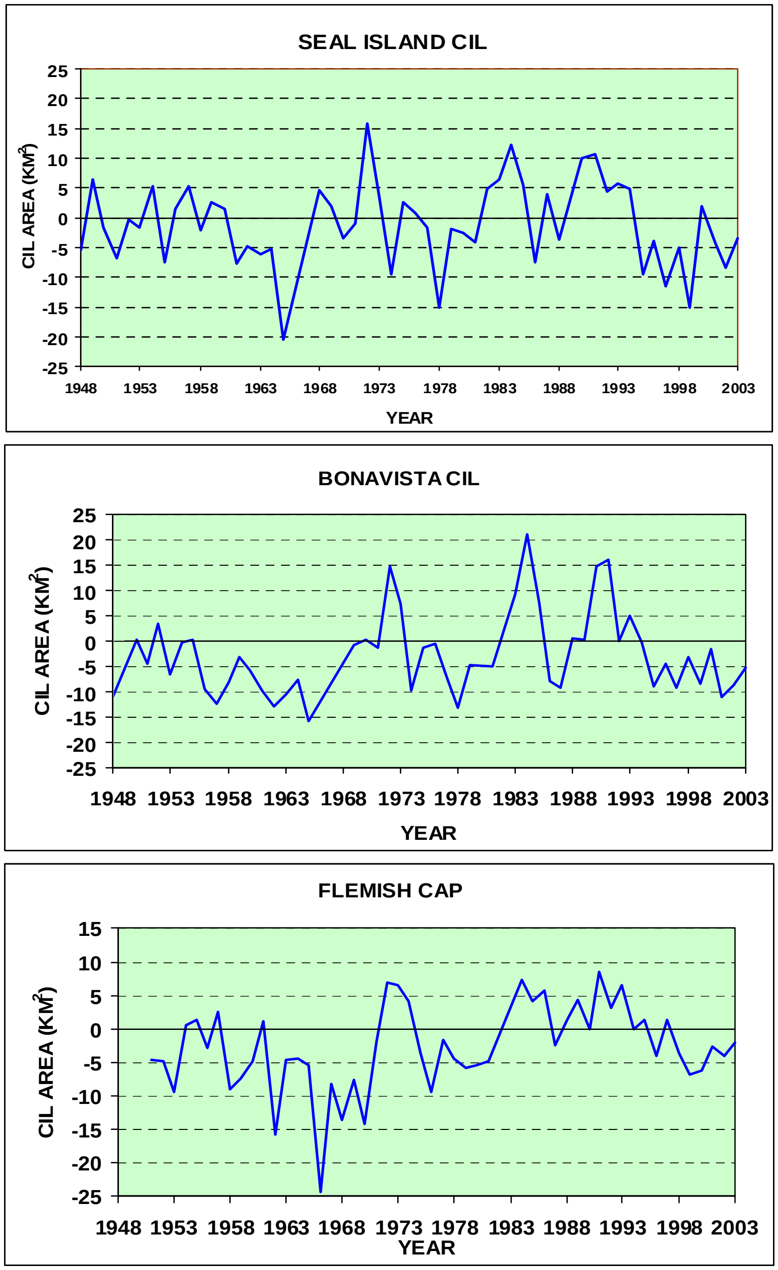


Fig. 10. Annual summer CIL cross-sectional area anomalies along the Flemish Cap, Bonavista and Seal Island sections. The anomalies are references to the 1971-2000 means.

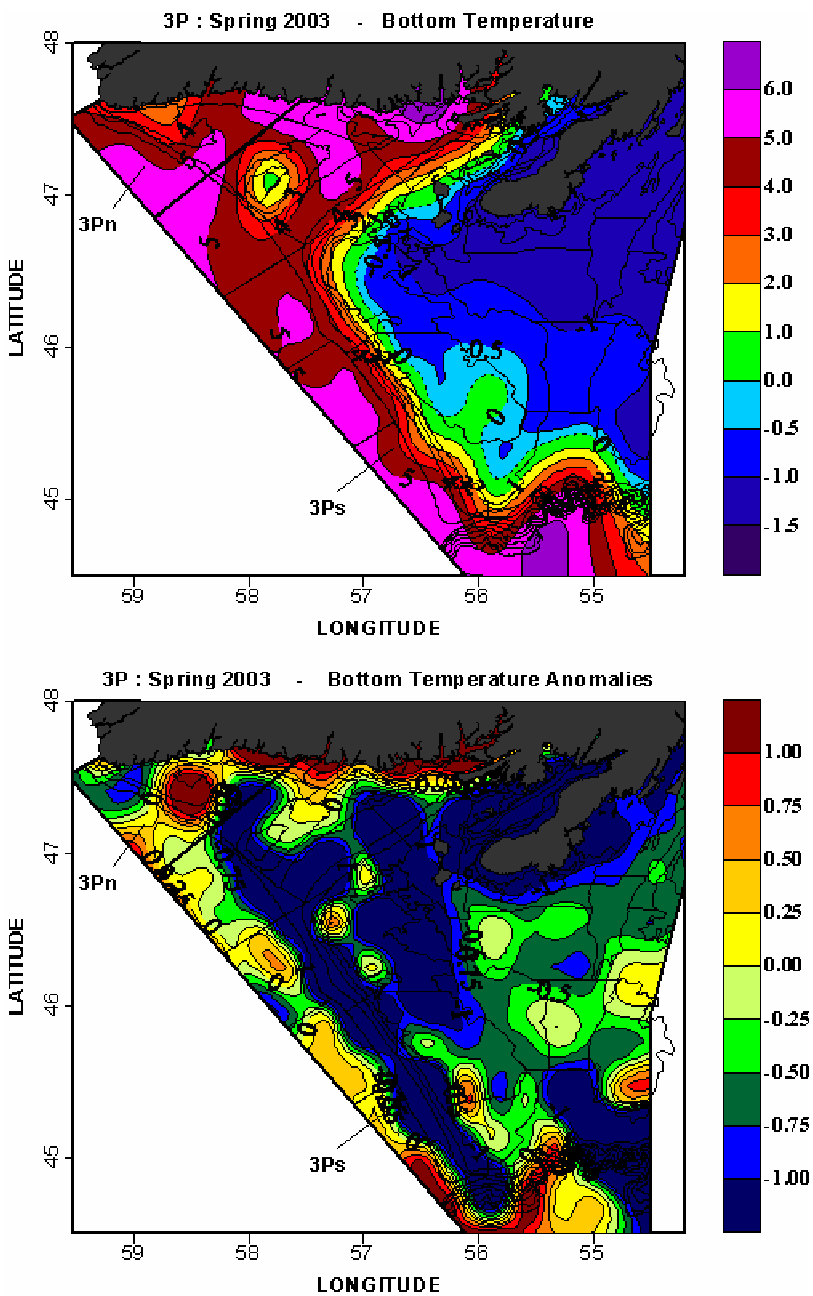


Fig. 11. The April 2003 bottom temperature and anomalies (in °C) in NAFO Subdivisions 3Pn and 3Ps. The anomalies are referenced to the 1971-2000 average.

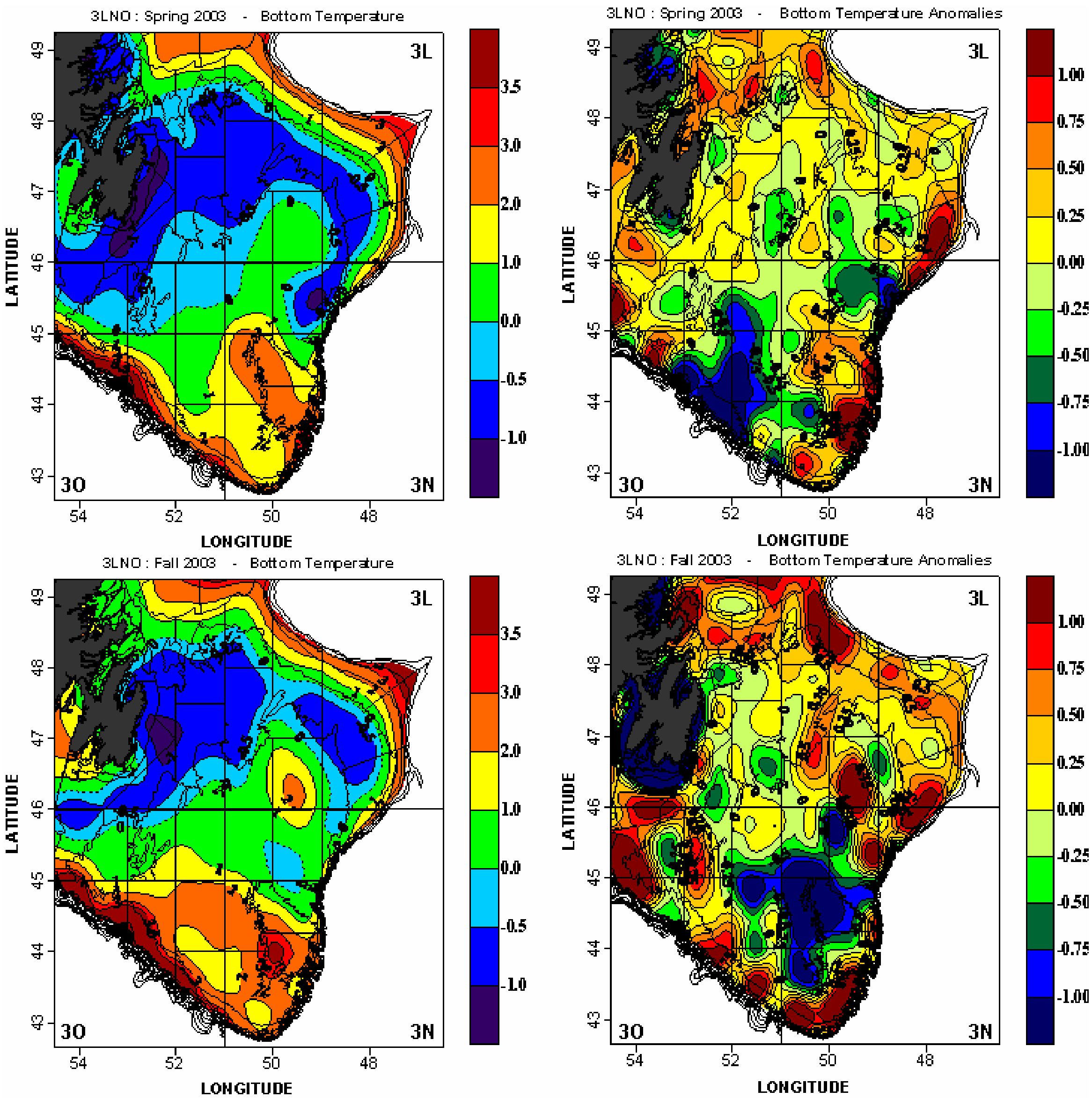


Fig. 12. Contours of bottom temperature and their anomalies (in °C) for the spring and fall of 2003 from the multi-species survey of NAFO Div. 3LNO.

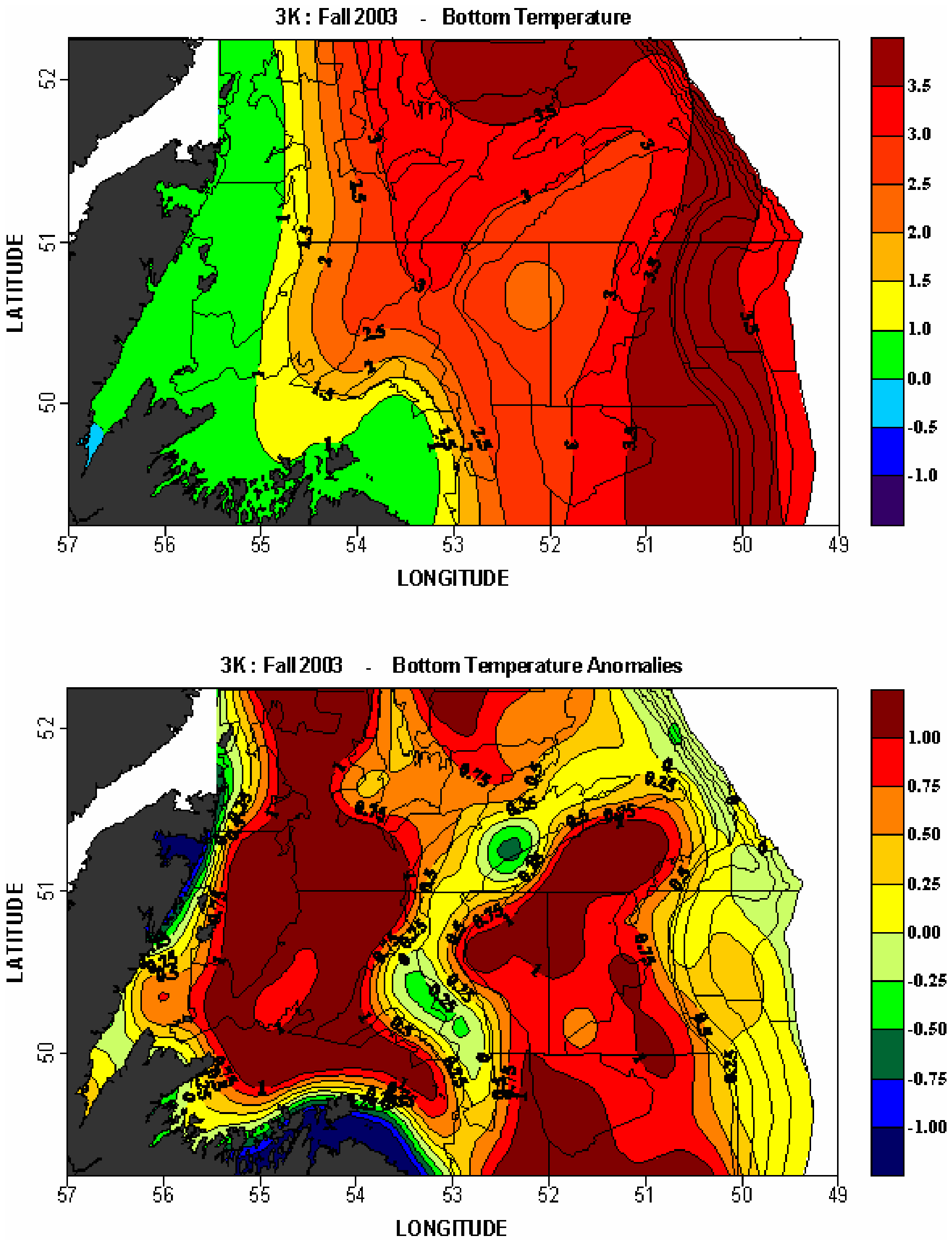


Fig. 13. Contours of bottom temperature and their anomalies (in °C) for the fall of 2003 from the multi-species survey of NAFO Div. 3K.

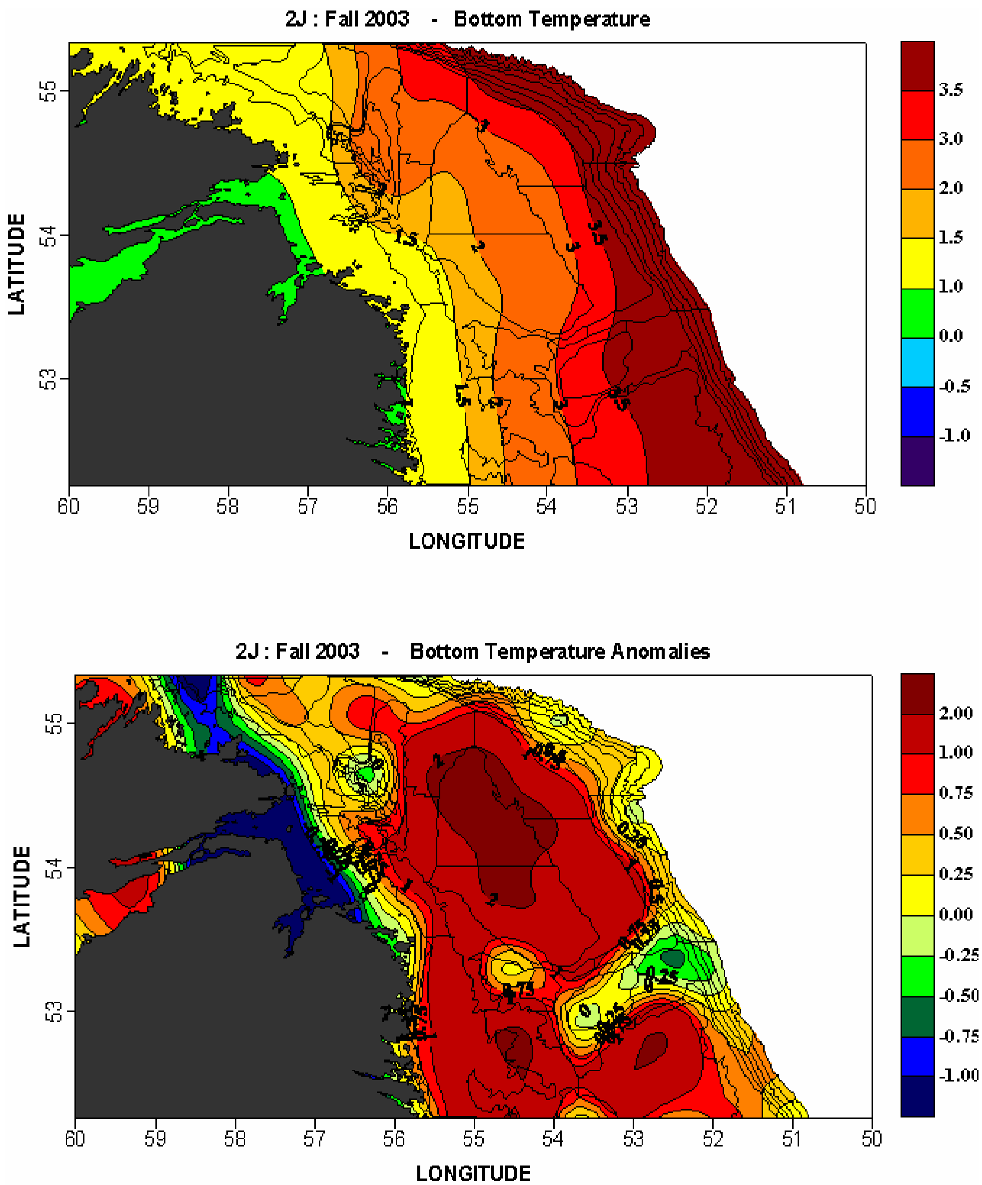


Fig. 14. Contours of bottom temperature and their anomalies (in °C) for the fall of 2003 from the multi-species survey of NAFO Div. 2J.

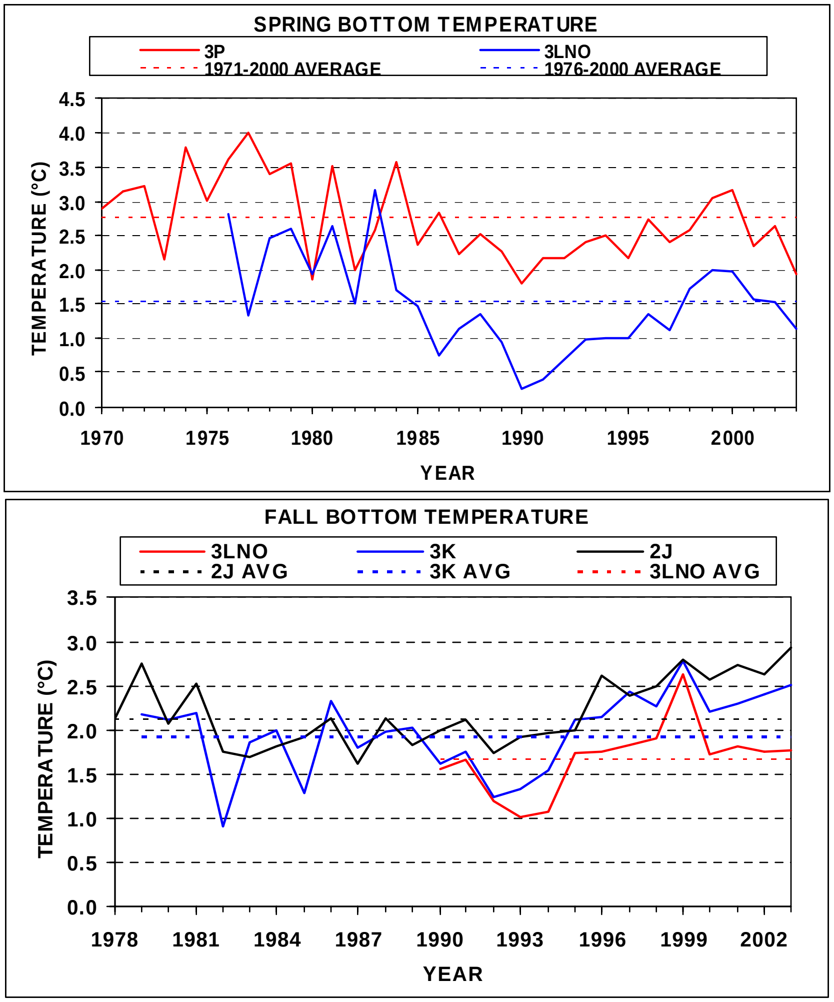
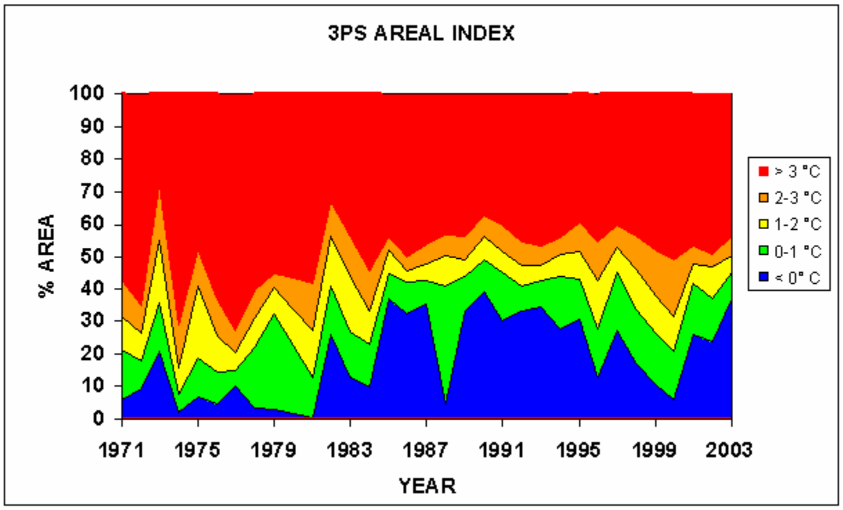


Fig. 15. Time series of the spatially averaged bottom temperatures during the spring (top panel) and fall (bottom panel) in NAFO Div. 3P, 3LNO, 3K and 2J.



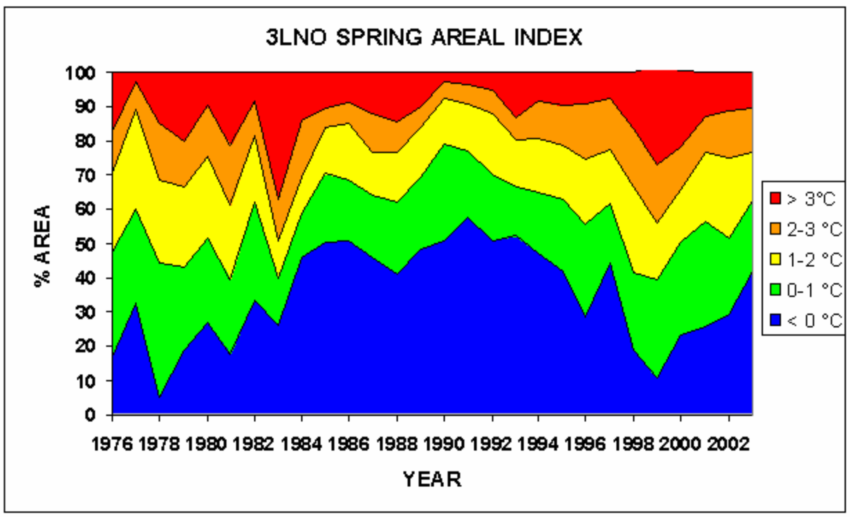


Fig. 16. Time series of the percentage area of the bottom in NAFO Div. 3P (top panel) and in Div. 3LNO (bottom panel) covered by water with temperatures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥3°C during spring.

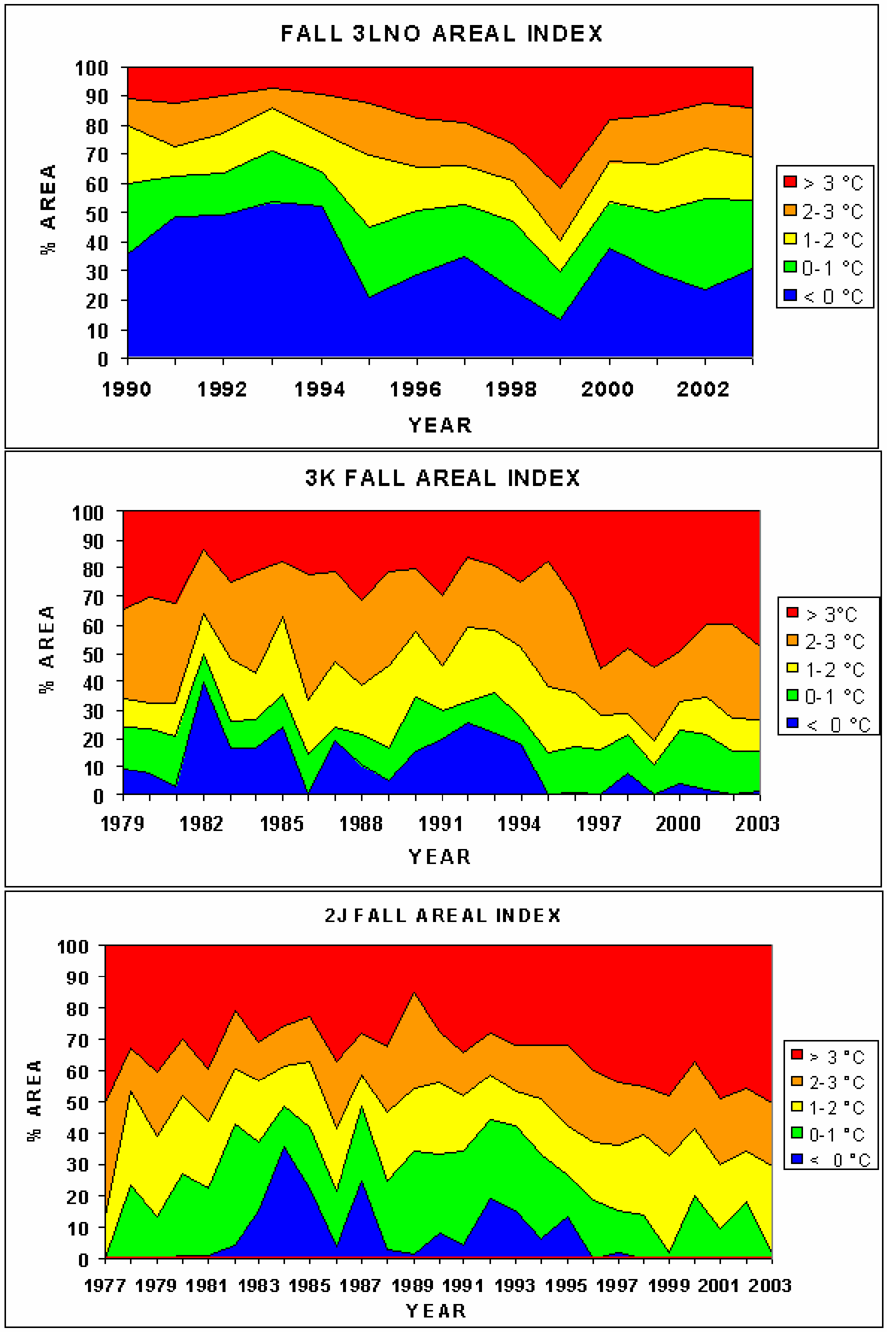


Fig. 17. Time series of the percentage area of the bottom in NAFO Div. 3LNO, 3K and 2J covered by water with temperatures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥3°C during the fall.