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An assessment of the physical oceanographic environment on the Newfoundland and Labrador Shelf during 2004

Évaluation de l'environment océanographique physique sur la plate-forme continentale de Terre-Neuve et du Labrador en 2004

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Abstract

Oceanographic observations on the Newfoundland and Labrador Shelf during 2004 are presented referenced to their long-term (1971-2000) means. The annual water-column averaged temperature at Station 27 for 2004 remained above the long-term mean and reached the highest value on record. The annual surface temperature at Station 27 was 1^{o}C above normal, also the highest on record, while the annual bottom temperature was the highest since 1966. Water-column averaged annual salinities at Station 27 remained above normal for the 3rd consecutive year. The cross-sectional area of <0^{o}C (CIL) water on the Newfoundland and Labrador Shelf during the summer of 2004 decreased over 2003 remaining below the long-term mean along all sections. Off eastern Newfoundland along the Bonavista Section the summer CIL area was below normal for the 10th consecutive year and the lowest since 1965 and by late fall it was completely eroded. Temperatures along the standard sections, except for some isolated cold surface anomalies, were generally above normal by 1^{o} to 2^{o}C in most areas during spring and summer and in all areas during the fall. Except for slightly negative salinity anomalies over the inner shelf during spring, most areas of the shelf during 2004 experienced generally saltier-than-normal conditions. During the spring of 2004, bottom temperatures over St. Pierre Bank increased significantly over 2003 values with <0^{o}C water restricted to the deeper waters of the approaches to Placentia Bay. Consequently, above normal temperatures were more widespread during 2004 compared to those of 2003, covering most of the bottom areas of the banks in the 3P region with values as high as 1^{o}C above the long-term mean. In Division 3LNO spring bottom temperatures were above normal in all areas of the Grand Banks by 1^{o}C to 1.5^{o}C. As a result the spring of 2004 had the lowest area of <0^{o}C water in Division 3L since the surveys began in the early 1970s. Bottom temperatures during the fall of 2004 were predominately above normal in all areas by 0.5^{o} to 2^{o}C and were the highest on record in Division 2J. In general, water temperatures on the Newfoundland and Labrador Shelf remained above normal, reaching record highs in some areas, continuing the warm trend experienced during the past several years.

Résumé

Des observations océanographiques effectuées en 2004 sur la plate-forme continentale de Terre-Neuve et du Labrador sont présentées en regard des moyennes à long terme (1971-2000). En 2004, la température annuelle moyenne de la colonne d'eau à la station 27 est demeurée supérieure à la moyenne à long terme, affichant la plus haute valeur jamais enregistrée. La température annuelle en surface à la station 27 s'établissait à 1° C au-dessus de la normale, ce qui correspond également à la plus haute valeur jamais enregistrée, alors que la température annuelle au fond était la plus élevée depuis 1966. La salinité annuelle moyenne de la colonne d'eau à la station 27 s'est maintenue au-dessus de la normale pour la troisième année consécutive. L'aire en coupe transversale de l'eau <0 ^{o}C (CIF) sur la plate-forme continentale de Terre-Neuve et du Labrador durant l'été 2004 a diminué par rapport à 2003, demeurant sous la moyenne à long terme le long de tous les transects. Au large de l'est de Terre-Neuve, le long du transect Bonavista, l'aire de la CIF estivale était sous la normale pour la dixième année consécutive et affichait la valeur la plus basse depuis 1965; à la fin de l'automne, elle était complètement érodée. Les températures mesurées le long des transects standard, à l'exception de quelques anomalies isolées de surface froide, étaient généralement supérieures à la normale de 1 à 2° C dans la plupart des secteurs au printemps et à l'été et dans tous les secteurs à l'automne. À l'exception de légères anomalies de salinité négatives sur la plate-forme intérieure au printemps, on a enregistré dans la plupart des secteurs de la plate-forme des conditions généralement plus salées que la normale en 2004. Au printemps 2004, les températures au fond sur le banc Saint-Pierre ont augmenté de façon significative par rapport aux valeurs de 2003, les eaux <0 ^{o}C étant limitées aux eaux plus profondes situées à proximité de la baie de Plaisance. En conséquence, les températures supérieures à la normale ont été plus fréquentes en 2004 qu'en 2003, couvrant la plupart des secteurs de fond sur les bancs de la région 3P avec des valeurs aussi élevées que 1 °C au-dessus de la moyenne à long terme. Dans la division 3LNO, les températures au fond au printemps étaient de 1 à 1,5° C supérieures à la normale dans tous les secteurs du Grand Banc. En conséquence, le printemps 2004 a affiché la plus faible superficie d'eau <0 ^{o}C dans la division 3L depuis le commencement des relevés au début des années 1970. Les températures au fond à l'automne 2004 ont été de façon générale de 0,5 à 2 °C supérieures à la normale dans tous les secteurs et ont affiché les plus hautes valeurs jamais enregistrées dans la division 2J. En général, la température de l'eau sur la plate-forme continentale de Terre-Neuve et du Labrador est demeurée supérieure à la normale, atteignant des sommets record dans certains secteurs et demeurant conforme à la tendance au réchauffement enregistrée depuis plusieurs années.

Introduction

This manuscript presents an overview of physical oceanographic conditions in the Newfoundland and Labrador Regions during 2004, 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 2004 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 and AZMP cross-shelf sections from seasonal oceanographic surveys (Fig. 1), and (3) oceanographic observations made during the spring and fall multi-species research vessel surveys (Fig. 1). Data from other sources are also used to help define the long-term means and conditions during 2004.

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^{o}C in temperature and 0.005 in salinity. The XBT measurements are accurate to within 0.1^{o}C.

Time series of temperature and salinity anomalies were constructed at standard depths using data collected at Station 27. Anomalies were calculated by subtracting a fitted annual cycle composed of three harmonics from each observation. Monthly estimates are based on a varying number of observations; 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 and CIL grids for the Newfoundland Shelf were produced from all available data from the multi-species surveys for the spring and fall of 2004. The CIL values were calculated as the vertical extent of the water mass with temperatures <0^{o}C. The bottom temperature and CIL values for each period were interpolated onto a regular grid and contoured using a geostatistical (2-dimensional Kriging) procedure. Bottom temperature anomaly maps were computed by subtracting the 2004 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 2005.

Near-bottom temperature data from the multi-species assessment surveys (Fig. 1) were also 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^{o}C, 0^o to 1^{o}C, 1^o to 2^{o}C, 2^o to 3^{o}C and ≥3^{o}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

Station 27, located in the Avalon Channel off Cape Spear (Fig. 1), was sampled 49 times (38 CTD profiles, 11 XBT profiles) during 2004 down from the 59 occupations 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, their associated anomalies for 2004 and their annual values are displayed in Fig. 2. The cold near isothermal water column during the winter months has temperatures ranging from near 0^o to –0.5^{o}C. These temperatures persisted throughout the year below 100 m depth and even decreased to <-1.0^{o}C during the summer months. Surface layer temperatures ranged from about 2^o to 0^{o}C from January to mid-April, after which the surface warming commenced. By mid-May upper layer temperatures had warmed to 3^{o}C and to >15^{o}C by August at the surface, after which the fall cooling commenced. These temperatures were about 0.5^o to 1.5^{o}C above normal during the winter months over most of the water column. Temperatures during the spring were above normal over the entire water column. During the remainder of the year, temperatures were above normal (by >1.0^{o}C in surface layers during the summer) except for an isolated cold anomaly at 30-50 m depth in August. Contours of annual anomalies (Fig. 2a bottom panel) show distinct warm and cold periods lasting several years with the most recent 5-6 years showing warmer-than-normal temperatures over the entire water column.

Surface salinities reached maximum values by late winter (>32.2 in mid-March) and decreased to minimum values by late summer (<31.2 in September-October, Fig. 2b). These values were slightly below normal until May after which the anomalies increased to 0.5 above normal by summer and remained above normal during the remainder of the year. In the depth range from 50-100-m, salinities generally ranged from 32.4 to 32.6 and near bottom they varied throughout the year between 32.8 and 33.4. The most significant salinity anomaly during 2004 occurred from May to September in the depth range of approximately 50-150 m when anomalies were about 0.3 below normal. Bottom salinities increased to above normal values (>33.2) during the fall months (Fig. 2b). Contours of the annual salinity anomalies show highly variable conditions over the water column with the past decade or so showing mostly fresher than normal conditions, at least below the surface layer where anomalies have been above normal for the past three years (Fig. 2b, bottom panel).

Monthly temperature anomalies at fixed depths were above normal (maximum of 2.5^{o}C in August at the surface) in all months of 2004 except in August at 50 m depth when temperatures dipped to 0.5^{o}C below normal (Fig. 3 left panels). Monthly surface salinities were near normal until August when they increased to near 0.5 above normal. Minimum salinity anomalies occurred in the depth range of 50-100 m where they reached about 0.4 below normal in June and July (Fig. 3 right panels). The depth averaged 2004 monthly temperatures at Station 27 were above the long-term mean by approximately 1^{o}C in most months except for August when they were about normal (Fig. 4). The stratification index (defined as the density gradient over the top 50 m of the water column) computed from data collected at Station 27 during 2004, except for a slight increase in early April (day 100), was about average until mid-September. From late September until December the stratification values were slightly below the long-term average. The mixed layer depth defined as the depth of maximum density gradient was highly variable and mostly deeper than normal until early June (day 160). During the summer the mixed layer depth was about normal but increased to deeper-than-normal values during the fall (Fig. 4).

The time series of the depth averaged annual temperature (0-175) and salinity (0-50) anomalies generally show cold and fresher-than-normal periods at near decadal time scales since the early 1970s (Fig. 5). Annual temperatures varied considerably during the past decade or so, from a record low during 1991, a near record high during 1996, near normal in 1997 and 1998 and above normal from 1999 to 2004. The 2004 value set an all time record. Upper layer 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, varied about the mean until 2000 and decreased to below normal in 2001. During 2002 and 2004 upper layer 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). 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. The time series of the annual water column stratification values at Station 27 show a general increase in stratification beginning in the late 1960s. During the past 3-years stratification values have returned to the about normal as defined by the 1971-2000 mean (Fig. 5 bottom panel).

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). Four of these sections are occupied during mid-summer on an annual oceanographic survey conducted by DFO's Newfoundland Region. They are (1) the Seal Island section on the southern Labrador coast and Hamilton Bank, (2) the White Bay section which crosses the relatively deeper portions of the northeast Newfoundland Shelf, (3) the Bonavista section off the east coast of Newfoundland and (4) the Flemish Cap section which crosses the Grand Bank at 47°N and continues eastward across the Flemish Cap. As part of an expanded AZMP, the Bonavista and Flemish Cap sections are now occupied during the spring and fall with the addition of the Southeast Grand Bank section. Also, when time permits, sections crossing Makkovik Bank and Nain Bank (Beachy Island) on the mid-Labrador Shelf and the Funk Island Bank on the eastern Newfoundland Shelf are occupied during the summer. We present the physical oceanographic results from these sections for the spring, summer and fall of 2004. The temperature and salinity anomalies referenced to the 1971-2000 data sets are also presented. The levels of confidence in these estimates are not assessed, but are the highest for the summer sections.

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° to 2°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° to 4°C and salinities in the range of 34 to 34.75. Surface temperatures warm to 10° to 12°C during late summer, while bottom temperature remain <0°C over the Grand Banks but increase to 1° to 3°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° to 4°C. 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.

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 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. While the area of the CIL water mass undergoes significant annual variability the changes are highly coherent from Labrador to southern Newfoundland. 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 seasonal heating increases the stratification in the upper layers to a point when 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 cross sections discussed below.

Southeast Grand Bank Section

The Southeast Grand Bank section was sampled twice during 2004 (April and November). Contours of temperature and salinity and their anomalies along this section are shown in Fig. 6 and 7. During both spring and fall of 2004 water with temperatures <0°C was restricted to the Avalon Channel in the inshore area of the section. Upper layer temperatures across the Grand Bank ranged from 1° - 4.5°C during spring and to 7°C during the fall near the surface. Bottom temperatures ranged from 1° - 3°C during the spring and from 1° - 4°C during the fall. These values were above normal across the entire Southeast Grand Bank in the spring but generally below normal in the fall over the central part of the section. Temperatures offshore of the shelf break were 4° - 5°C below normal as the warmer slope water was displaced further offshore during the time of the spring survey.

Upper layer salinities along the section during the spring ranged from <32.5 near shore to >33 in the offshore region. Bottom salinities on the Grand Bank ranged from 32.75-33.0 and from 33-34 over the southeast slope of the Grand Bank. These values were predominantly saltier-than-normal in the inshore areas, near normal over most of the southeast Grand Bank during the spring and generally fresher than normal in the offshore areas. During the fall, salinities increased over spring values to above normal in the inshore, near normal across much of the southeast Grand Bank and above normal along the southeast slopes of the Grand Bank.

Flemish Cap (47° N) Section

The Flemish Cap section was sampled 3 times during 2004 (April, July and November) (Fig 8, 9 and 10). Near surface temperatures along this section over the Grand Bank ranged from 0°-1°C during the spring to 9°-10°C during the summer and 4° - 4.5°C during the fall. Water with temperatures <0°C persisted throughout the year along some areas of the bank, particularly near bottom. 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. During the spring temperatures on Grand Bank, in the Flemish Pass and over the Flemish Cap were above normal by up to 2°C in some areas. Temperatures during the summer and fall continued above normal except for the near-surface layer over the Grand Bank, where they were around 1°C below average. Bottom temperatures over the Grand Bank during spring, summer and fall were above normal. Along the Flemish Cap section the summer CIL area was below the 1971-2000 normal in 2004, a significant decrease over the previous 5-years and the lowest values since 1970 (Fig. 10). The overall section mean temperature decreased slightly over the 2003 values but remained 0.5°C above its long-term mean. Both the CIL mean and minimum temperatures increased over 2003 to above normal values.

Salinities along the section on the Grand Bank (Fig. 9) are characterized 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 over the Grand Bank during 2004 were generally higher than average in the upper layers and near normal below 50-m depth. To the east over the Flemish Cap salinities were also above normal by over 0.5 in the surface layer (Fig. 9). The overall section mean salinity for the summer decreased over 2003 but remained above the long-term mean. Shelf water salinities remained similar to the past couple of years, about normal (Fig. 10). The summer time series of the slope branch of the Labrador Current indicate higher than average transport during the late 1950s and into the 1960s, lower than average values during the cold period of the early 1970s and to a lesser extent during the cold period of the mid-1980s. During the late 1980s the transport increased to above average values, which for the most part continued into the mid-to-late 1990s. During 2004, the transport through the Flemish Pass was similar to the 2002 value, a decreased from the record high value of 2003 but still above the long-term mean (Fig. 10).

Bonavista Section

The Bonavista section was also sampled 3 times during 2004 (April, July and November) (Fig. 11, 12 and 13). Temperatures along the Bonavista section shoreward of the shelf break in the upper water column ranged from <0°C during spring, reached a maximum of 8-9°C during the summer and decreased to <4°C by late fall. These values were generally above normal (up to 2°C) in most areas during spring and summer and in all areas during the fall. Bottom temperatures over the entire eastern Newfoundland Shelf were above normal by 1° - 2°C. The dominant feature along this section is the cold intermediate layer of <0°C water (CIL) which develops during early spring after intense winter cooling. On average along the Bonavista section during the summer this cold layer extends offshore to over 200 km, with a maximum vertical extent of about 200 m. In 2004, this water mass extended to the surface during the spring, was the smallest since 1965 in the summer and was completely eroded by late autumn (Fig. 11). The CIL area along this section was below normal for the 10th consecutive year ranking the 2nd warmest year in the 56 year time series. The overall section mean temperature increased over the 2003 value to approximately 1.3°C above the long–term mean and the highest value since 1965. Both the CIL mean and minimum temperatures increased over 2003 to just under 0.5°C above normal (Fig. 13).

Salinities along the section on the inner shelf areas are characterized by generally fresh conditions (<33), a strong horizontal gradient at the shelf break separating the saltier (>34.5) slope water offshore along the shelf break. Bottom salinities ranged from 32.5 in the inshore regions, to >34.5 below 300-m depth. Except for slightly negative salinity anomalies at mid depth over the inner shelf during the spring most of the shelf during 2004 experienced generally saltier-than-normal conditions, particularly during the fall (Fig. 12). The overall section mean salinity for the summer increased slightly over 2003 remaining above the long-term mean for the 3rd consecutive year. Shelf water salinities also increased over 2003 similar to 2001 and 2002. The summer baroclinic transport of the slope branch of the Labrador Current during 2004 decreased over 2003 and appeared about normal (Fig. 13).

Funk Island Section

The Funk Island section, which crosses the deeper portions of the eastern Newfoundland Shelf and Funk Island Bank, was sampled in early December of 2004 (Fig. 14). The CIL water during the summer is usually quite extensive along this section but by the late fall of 2004 it was completely eroded. Temperatures over most of the inner shelf and Funk Island Bank ranged from 1.5^o – 2^{o}C during the fall of 2004. Further offshore and in the deep water between the bank and the inner shelf temperatures were generally between 3^o - 4^{o}C. Temperatures along the entire section were above average by 1^o - 2^{o}C during the fall of 2004. Surface salinities ranged from <32.5 in the inshore to near 34 in the offshore region. Bottom salinities ranged from 33 near shore to >34.5 at the edge of the shelf. These values were generally saltier-than-normal except for an area of fresher than normal values at mid-depth near the coast.

White Bay Section

The White Bay section, which crosses the deeper portions of the northeast Newfoundland Shelf, was sampled in August of 2004 (Fig. 15a). The CIL water during the summer is usually quite extensive along this section, with a large area of water with <0^{o}C temperatures extending from the coast to over 300 km offshore. At about mid-shelf temperatures below 200 m increased from 0^{o}C to >3^{o}C at the outer edge of the shelf. Temperatures along this section during the summer of 2004 were generally above average over the entire area except for near-surface values over the inner shelf. Surface salinities ranged from <32.5 in White Bay to over 34 in the offshore region. Bottom salinities ranged from 33.5 near shore to over 34.5 at the edge of the shelf. These values were saltier-than-normal in the surface layer over the northeast shelf and near normal over the outer shelf areas. The CIL area along this section has been decreasing since 1994 and during the summer of 2004 it reached the lowest value since 1978 (Fig. 15b).

Seal Island Section

The Seal Island section, which crosses Hamilton Bank on the southern Labrador Shelf (Fig. 1), was sampled in July of 2004 (Fig. 16 and 17). Upper layer temperatures across the shelf in this region ranged from 0^{o}C at approximately 50-m depth to between 6^{o}to 7^{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-4^{o}C. Temperature anomalies over the shelf were generally above normal except for an isolated cold surface anomaly over Hamilton Bank. In the offshore area particularly along the continental slope region temperatures were up to 1^o to 3^{o}C above normal. Surface salinities along this section ranged from <31.5 inshore of Hamilton Bank to >34.5 in the offshore region. Bottom salinities ranged from 31.5 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. Salinities corresponding to the CIL water mass were about normal. Offshore of the shelf break and along the continental slope regions salinities were above normal by up to 1.0 practical salinity unit.

Along the Seal Island section the area of <0^{o}C (CIL) water decreased slightly over 2003 and except for 1997 was below normal for the 9th consecutive year. The overall section mean temperature has been increasing since the early 1990s and during 2004 it was approximately 1^{o}C above the long–term mean and the highest value since 1965. Both the CIL mean and minimum temperatures increased over 2003 to above normal with a record high CIL minimum temperature. During 2004 the offshore upper-layer transport of the slope branch of the Labrador Current decreased slightly over the 2003 value but still remained above the long-term mean (Fig. 17). In general, the CIL area observed along all sections continue to show a decreasing trend of below normal values since at least 1995. This is in contrast to the near record high values measured during the cold period of the early-1990s on the Newfoundland and Labrador 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 sets 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 2004, in water depths down to 366 m until 1979 and to 548 m since then; 3L in spring from 1971-2004, except 1983 and 1984; 3NO in spring from 1971-2004, 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 1977-2004; 3K in fall from 1978-2004; 3L in fall from 1981-2004, 3NO in fall from 1990-2004. 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.

The hydrographic data collected on these surveys, mainly temperature and salinity, are routinely used to provide an assessment of the spatial variability in oceanographic conditions of the survey regions. A number of data products are now routinely generated to characterize the oceanographic habitat. Among these are contoured maps of the bottom temperature and their anomalies, the thermal habitat areal index, spatial variability in the Cold Intermediate Layer (CIL) and water-column stratification and mixed-layer depth spatial maps of the surveyed area. 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.

Spring Conditions

Bottom temperatures during the spring of 2004 in NAFO Sub-area 3P were generally >3^o in the Laurentian, Burgeo and Hermitage Channels and on Burgeo Bank. On St. Pierre Bank bottom temperatures ranged from near 0^{o}C on the eastern side to 2^o to 3^{o}C on the western side. During the spring of 2004, bottom temperatures over St. Pierre Bank increased significantly over 2003. Values with <0^{o}C water were restricted to the deep approaches to Placentia Bay (Fig.18). Consequently, above normal temperatures were more widespread during 2004 compared to 2003, covering most of the bottom areas of the banks in the 3P region with values as high as 1^{o}C above the long-term mean. In the deeper regions (Laurentian and Hermitage Channels) of 3P temperatures were mostly below the long-term average but still generally >3^{o}C (Fig. 18). The averaged bottom temperature (Fig. 19) of the surveyed area in Division 3P ranged between 2^o to 4^{o}C from 1970 to 1984 but decreased to between 2^o to 2.5^{o}C from 1985 to 1997. During 1999 and 2000 the average bottom temperature increased to over 3^{o}C but decreased to near 2.5^{o}C in 2001 and 2002. During the spring of 2002 the average bottom temperature increased slightly over the 2001 value to 2.6^{o}C but decreased to 2^{o}C by the spring of 2003 making it the 3rd coldest spring in the 34 year time series. During the spring of 2004 the mean bottom temperature rebounded by more than 0.5^{o}C. 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. 19. 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. 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. In 2004 the area of the bottom covered by water with temperatures <0°C was the lowest since 1988 (Fig. 19).

Spring bottom temperatures in Div. 3L ranged from <0°C in the inshore regions of the Avalon Channel, from 0.5°C to 1°C over most of the shallow northern Grand Bank to >3°C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1°C to 3.5°C and generally >3.5°C along the southwest slopes of the Grand Bank in Div. 3O. In general, temperatures were above normal in all areas of the Grand Banks by 1°C to 1.5°C. The average spring bottom temperature time series for the 3LNO region shows large inter-annual variations of about 1°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°C and the lowest temperature of 0.25°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°C. During the spring of 2001 to 2003, the average bottom temperature decreased over the 2000 value to about 1°C in 2003, the 11th coldest in the 28 year record. In 2004 it increased by 1°C to near 2.5°C, the highest since 1983 (Fig. 19). The areal extent of the bottom covered by water in various temperature ranges during spring for the 3LNO region is displayed in Fig. 19. In this region from 1975 to 1983 most of the bottom was covered by water >0°C with approximately 20% covered by <0°C water. From 1984 to 1997 there was a large increase in the area of <0°C water reaching near 60% in some years. Since 1997 there was a significant decrease in the percentage area of the bottom covered by <0°C water and a corresponding increase in the area covered by water ≥1°C. During the spring of 1998 and 1999 water with temperatures >1°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°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. The spring of 2004 had the lowest area of <0°C water in Division 3L since the surveys began in the early 1970s (Fig. 19).

Fall Conditions

Bottom temperatures for the fall of 2004 in NAFO Divisions 2J, 3K and 3LNO are displayed in Fig. 20. During the fall of 2004 bottom temperatures in Div. 2J ranged from <2°C inshore, to >3.5°C offshore at the shelf break. Over Hamilton Bank they ranged from 2° to 3°C about 1.5° to 2°C above the long-term average. The spatially averaged bottom temperatures during the fall in Div. 2J are about 2°C but during the latter half of the 1990s they increased to about 2.5°C. During the fall of 2003 mean bottom temperatures increased over 2002 values to near 3°C and to >3°C during 2004, the highest in the record (Fig. 21). 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. 21. The percentage area of the bottom covered by <0°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 the bottom area covered by water with temperatures >3°C ranged from a low of 15% in 1992 to a maximum of near 50% during 2001 to 2004. Since 1996 the area of the bottom covered with <0°C water decreased to <10%.

Most of the 3K region is deeper than 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 2004 ranged between 2° to 3.5°C, which were approximately 0.5° to 1.5°C above their long-term means. Near the edge of the continental shelf in water depths below 500 m temperatures were generally near normal at 3.5°C. The time series of the spatially average bottom temperature in Div. 3K (Fig. 21) during the fall ranged from 1°C in 1982 to 2.3°C in 1986 with an overall mean of about 2°C. From 1995 to 1999 temperatures increased to above-average values, reaching a maximum of 2.7°C during 1999. After decreasing by approximately

0.5^{o}C in 2000 bottom temperatures have again increased to near-record highs in 2004. 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. In Div. 3K the bottom area covered by water with temperatures >3^{o}C 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 2004 (Fig. 21).

Fall bottom temperatures in Divs. 3LNO generally ranged from <0^{o}C on the northern Grand Bank and in the Avalon Channel to 3^{o}C along the shelf edge. Over the central and southern areas bottom temperatures during 2004 ranged from 1^{o} to 3.5^{o}C and to >3^{o}C along the edge of the Grand Bank. Bottom temperatures were predominately above normal in 2004 except for isolated areas over the central Grand Bank. The spatially average bottom temperature in Divs. 3LNO during the fall decreased from approximately 1.5^{o}C during 1990 to 1^{o}C during 1993 and 1994 then increased to approximately 1.8^{o}C during 1995. These remained relatively constant up to 1998 but then increased to >2.5^{o}C during 1999, the highest in the 15 year record. 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. In 2004 temperatures again increased by approximately 0.5^{o}C (Fig. 21). 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% but decreased again in 2004 to about 15% (Fig. 21).

Summary

The annual water-column averaged temperature at Station 27 for 2004 remained above the long-term mean and reached the highest value on record. The annual surface temperature at Station 27 was 1^{o}C above normal, also the highest on record, while the annual bottom temperature was the highest since 1966. Water-column averaged (0-50 m) annual salinities at Station 27 remained above normal for the 3rd consecutive year.

The cross-sectional area of the water mass with temperatures <0^{o}C (CIL) on the Newfoundland and Labrador Shelf during the summer of 2004 decreased compared to that of 2003. The CIL areas were below normal 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 10th consecutive year. Seasonally, the CIL water mass extended to the surface during the spring, decreased to the smallest since 1965 in the summer and was completely eroded by late autumn of 2004. The areas of the CIL in recent years are in sharp contrast to the near record high values measured during the extremely cold years of the early 1990s on the Newfoundland and Labrador Shelf.

Temperatures along the standard sections, except for some isolated cold surface anomalies, were generally above normal by 1^{o} to 2^{o}C in most areas during spring and summer and in all areas during the fall. Except for slightly negative salinity anomalies at mid depth over the inner shelf during the spring most areas of the shelf during 2004 experienced generally saltier-than-normal conditions, particularly during the fall.

During the spring of 2004, bottom temperatures over St. Pierre Bank increased significantly over 2003 values with <0^{o}C water restricted to the deep approached to Placentia Bay. Consequently, above normal temperatures were more widespread during 2004 compared to 2003, covering most of the bottom areas of the banks in the 3P region with values as high as 1^{o}C above the long-term mean. In Division 3LNO spring bottom temperatures were above normal in all areas of the Grand Banks by 1^{o}C to 1.5^{o}C. As a result the spring of

2004 had the lowest area of <0°C water in Division 3L since the surveys began in the early 1970s. Bottom temperatures during the fall of 2004 were predominately above normal in all areas by 0.5° to 2°C and were the highest on record in Division 2J.

In summary, water temperatures on the Newfoundland and Labrador Shelf remained above normal, reaching record highs in some areas, continuing the warm trend experienced during the past several years. Shelf water salinities which increased to the highest observed in over a decade during 2002 also remained above normal in 2004 in the upper water column.

Acknowledgements

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 crews of the CCGS Teleost, Templeman and Hudson for three successful oceanographic surveys during 2004.

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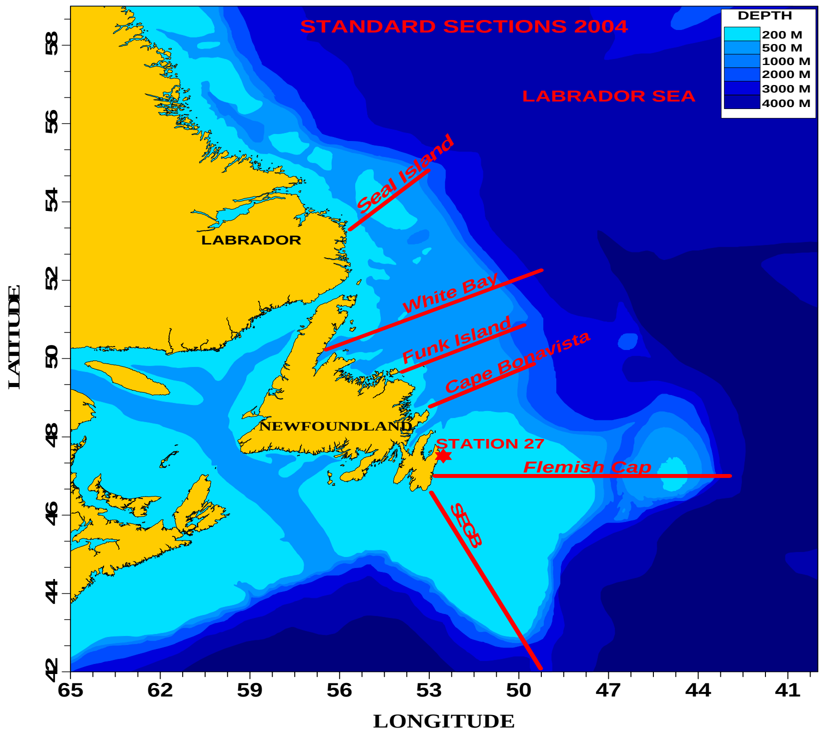


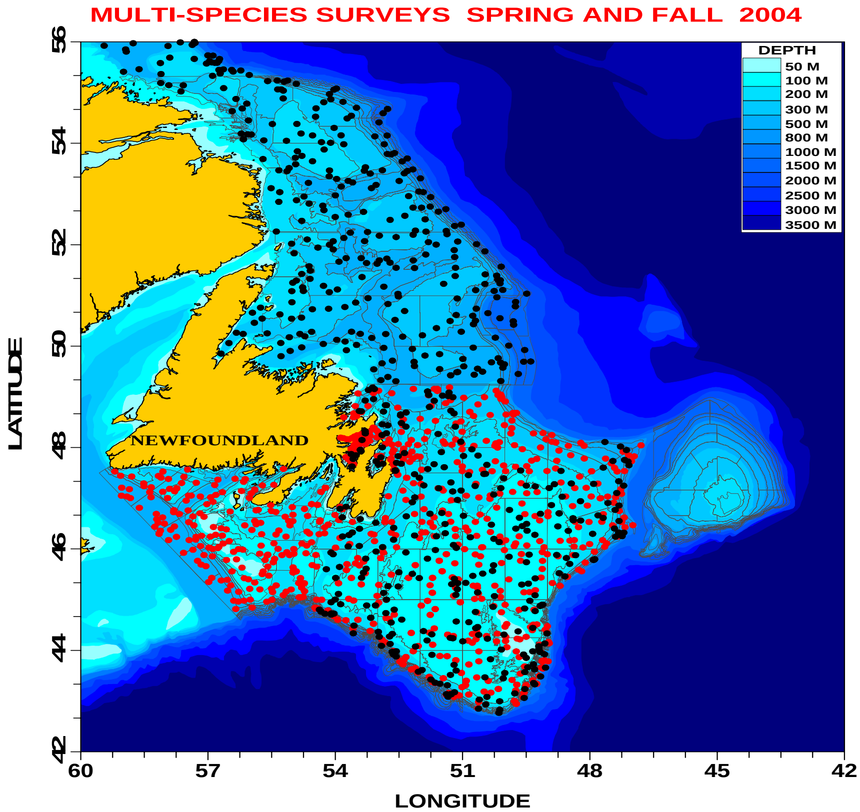


Fig. 1. Location maps showing Station 27 and the standard monitoring sections sampled on the NL Shelf during 2004 (top panel) and the positions of fishing sets with oceanographic data from the multi-species surveys during the spring (red) and fall (black) of 2004.

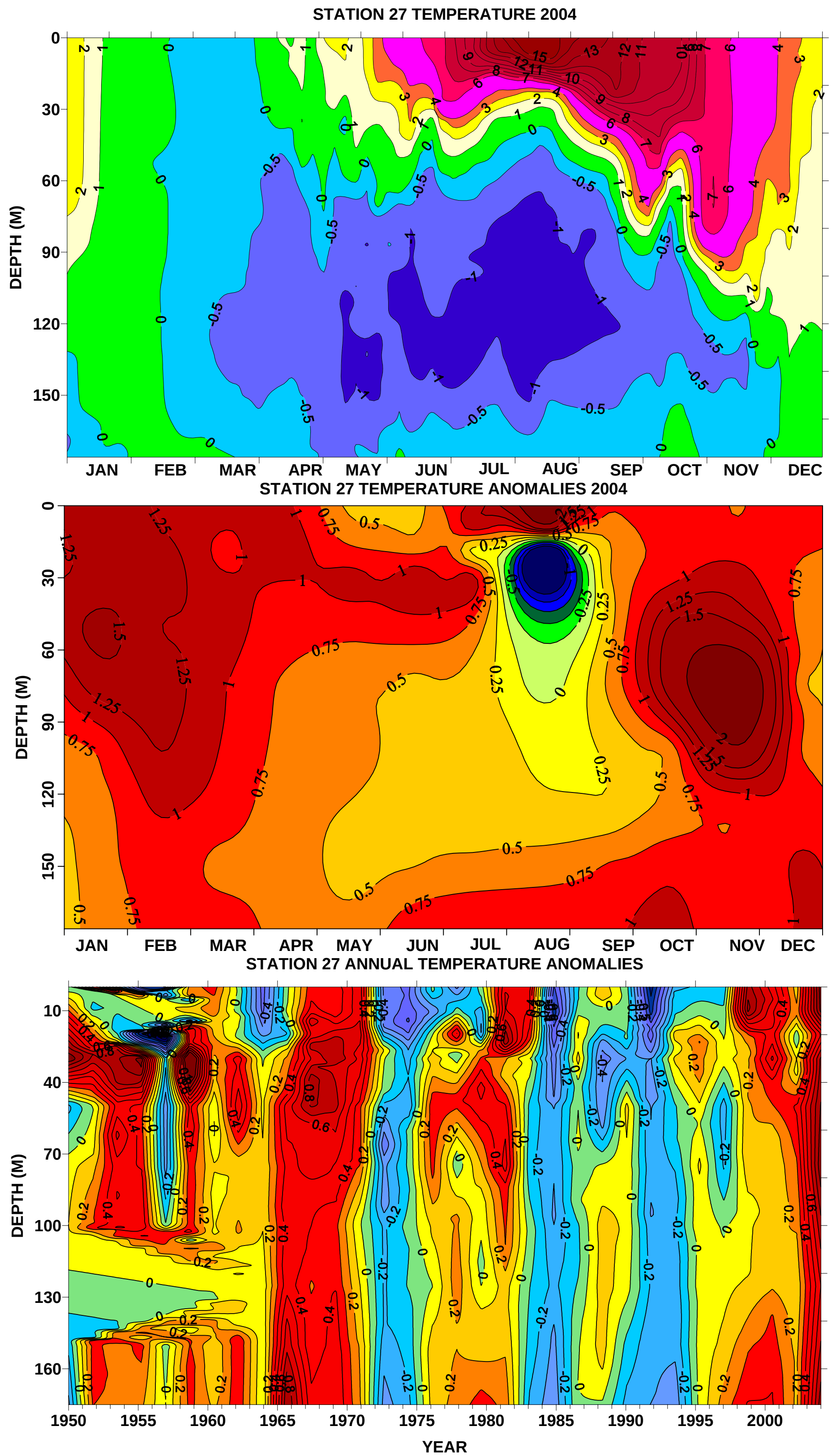


Fig. 2a. Contours of daily temperature (top panel), monthly temperature anomalies (centre panel) and annual temperature anomalies (bottom panel) in °C as a function of depth at Station 27.

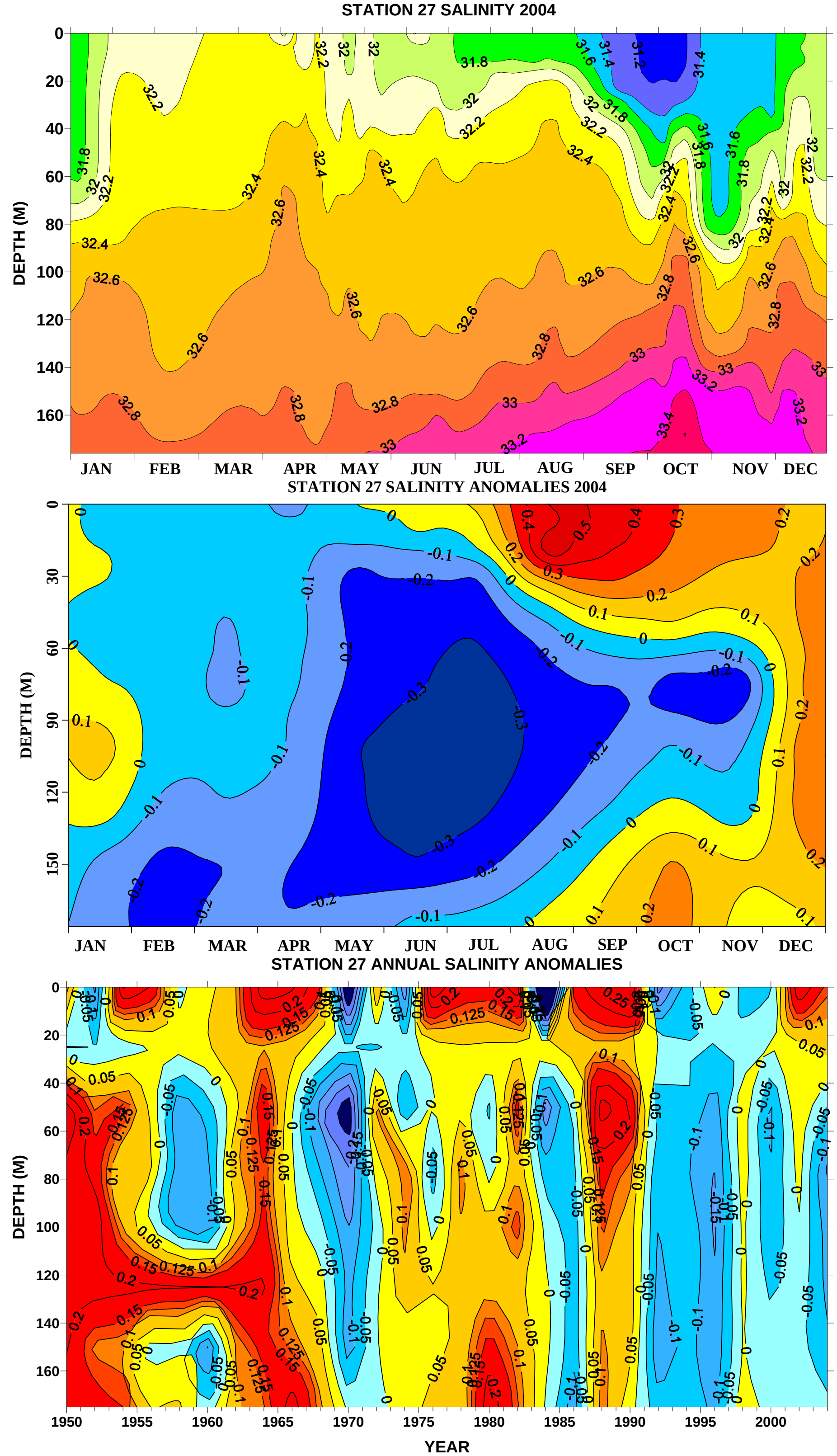


Fig. 2b. Contours of daily salinity (top panel), monthly salinity anomalies (centre panel) and annual salinity anomalies (bottom panel) as a function of depth at Station 27.

STATION 27 TEMPERATURE AND SALINITY ANOMALIES

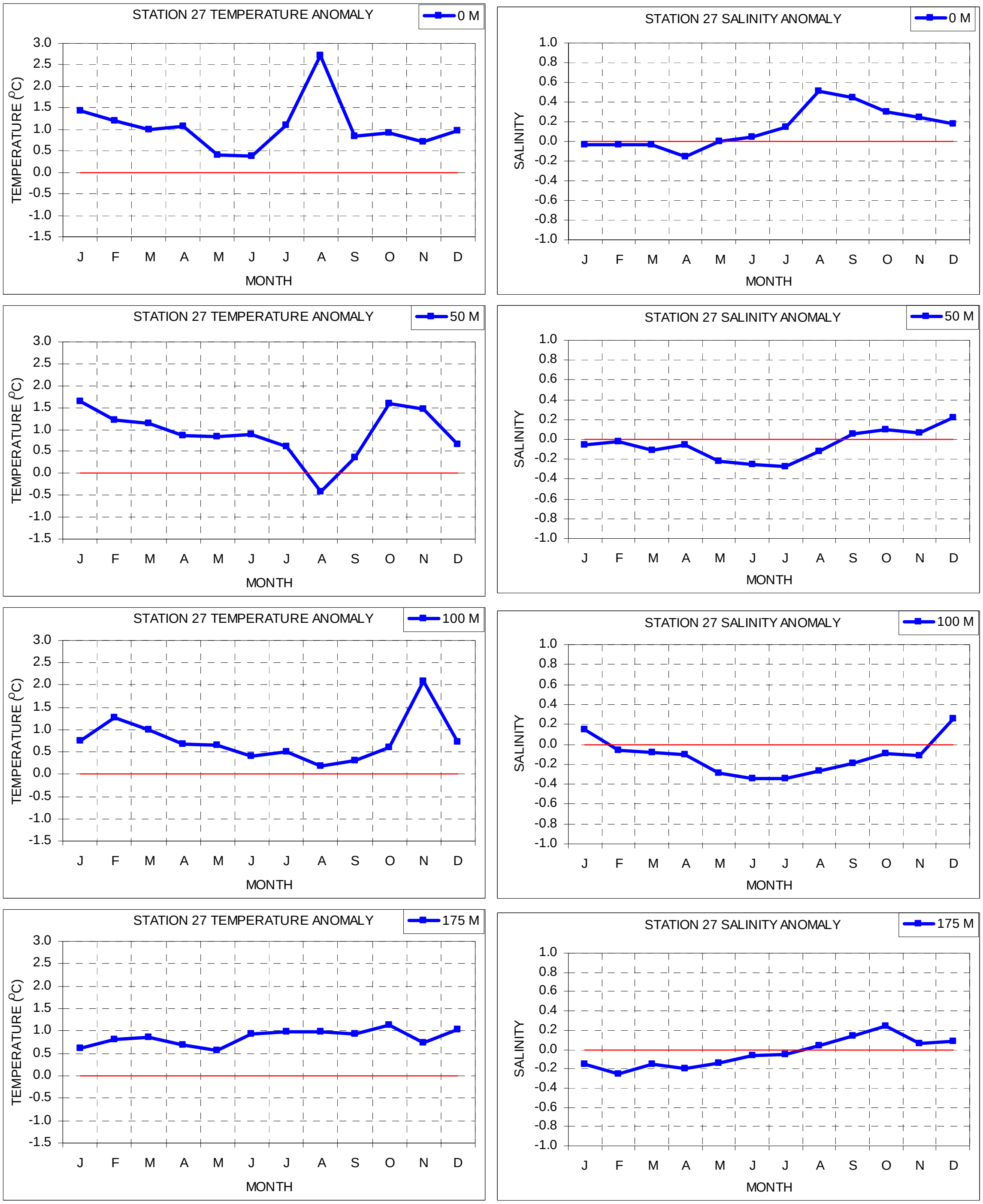


Fig. 3. Monthly temperature (left panels) and salinity (right panels) anomalies at Station 27 during 2004 at standard depths.

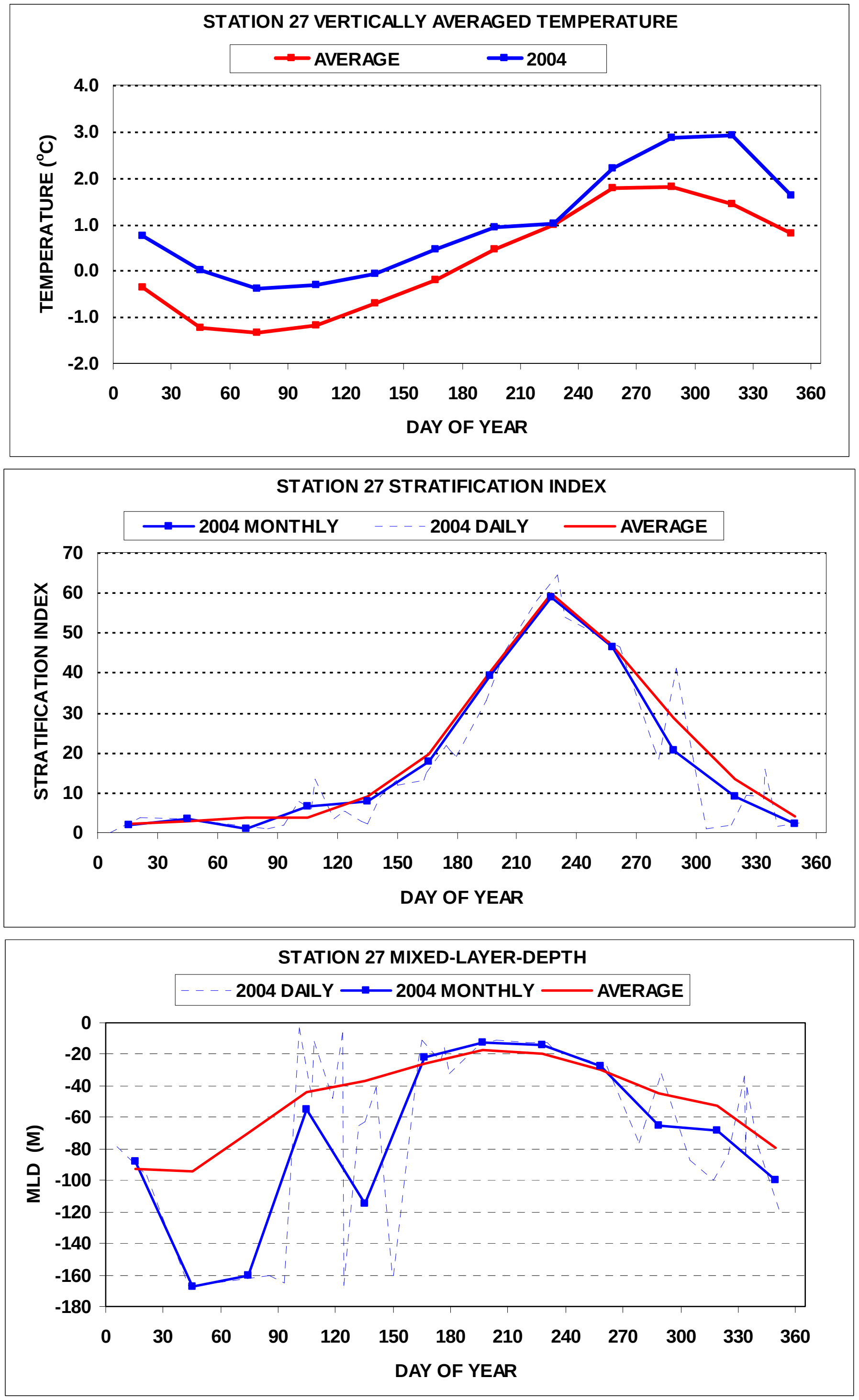


Fig. 4. The Station 27 2004 vertically temperature (top panel), stratification index (centre panel) and mixed-layer-depth (bottom panel).

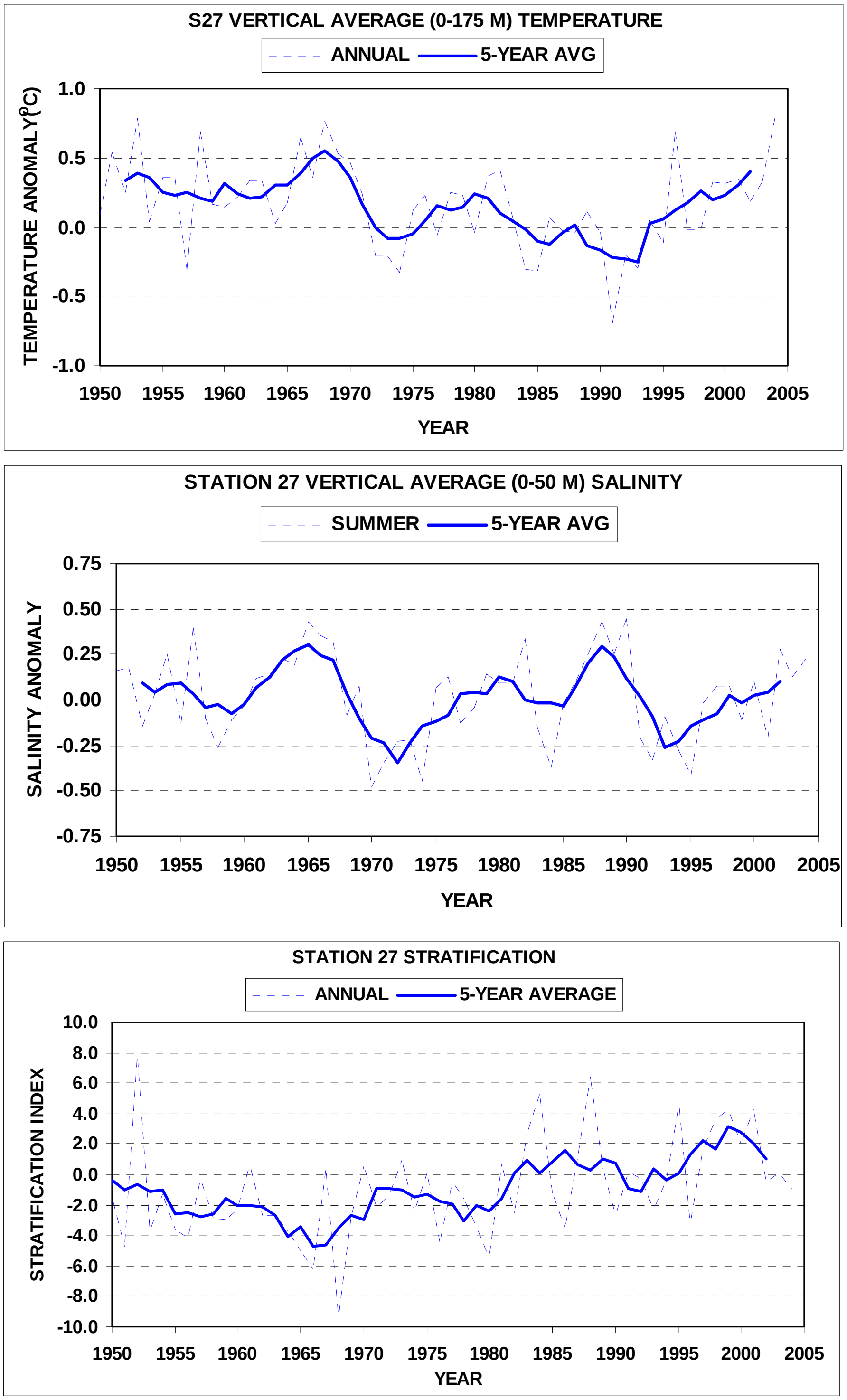


Fig. 5. Time series of the annual vertically averaged temperature (top panel), salinity (centre panel) and stratification index (bottom panel) anomalies at Station 27.

SOUTHEAST GRAND BANK SECTION (SPRING 2004)

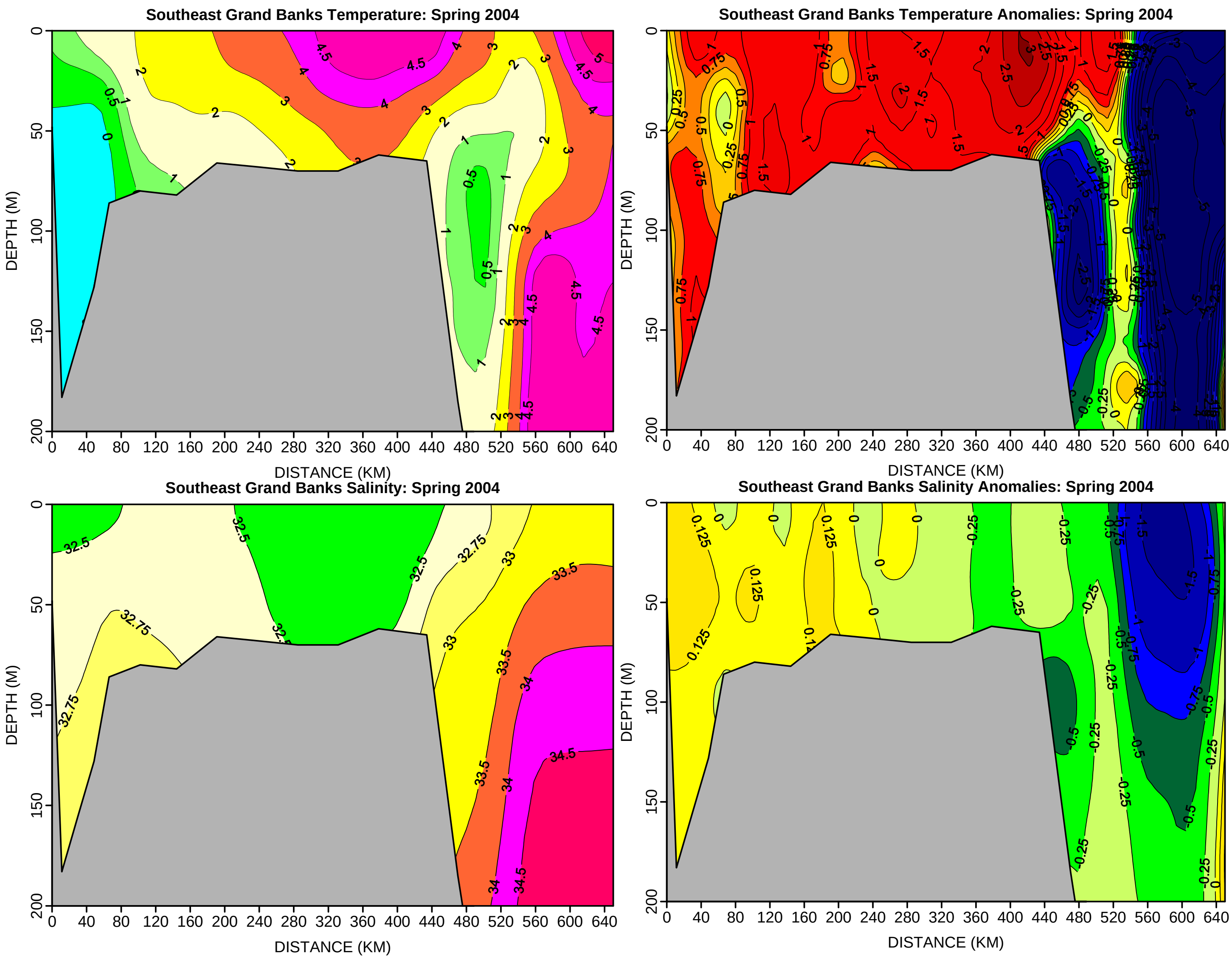


Fig. 6. Contours of temperature (in ^{o}C) and salinity and their anomalies along the Southeast Grand Bank Section (Fig. 1) during the spring of 2004.

SOUTHEAST GRAND BANK SECTION (FALL 2004)

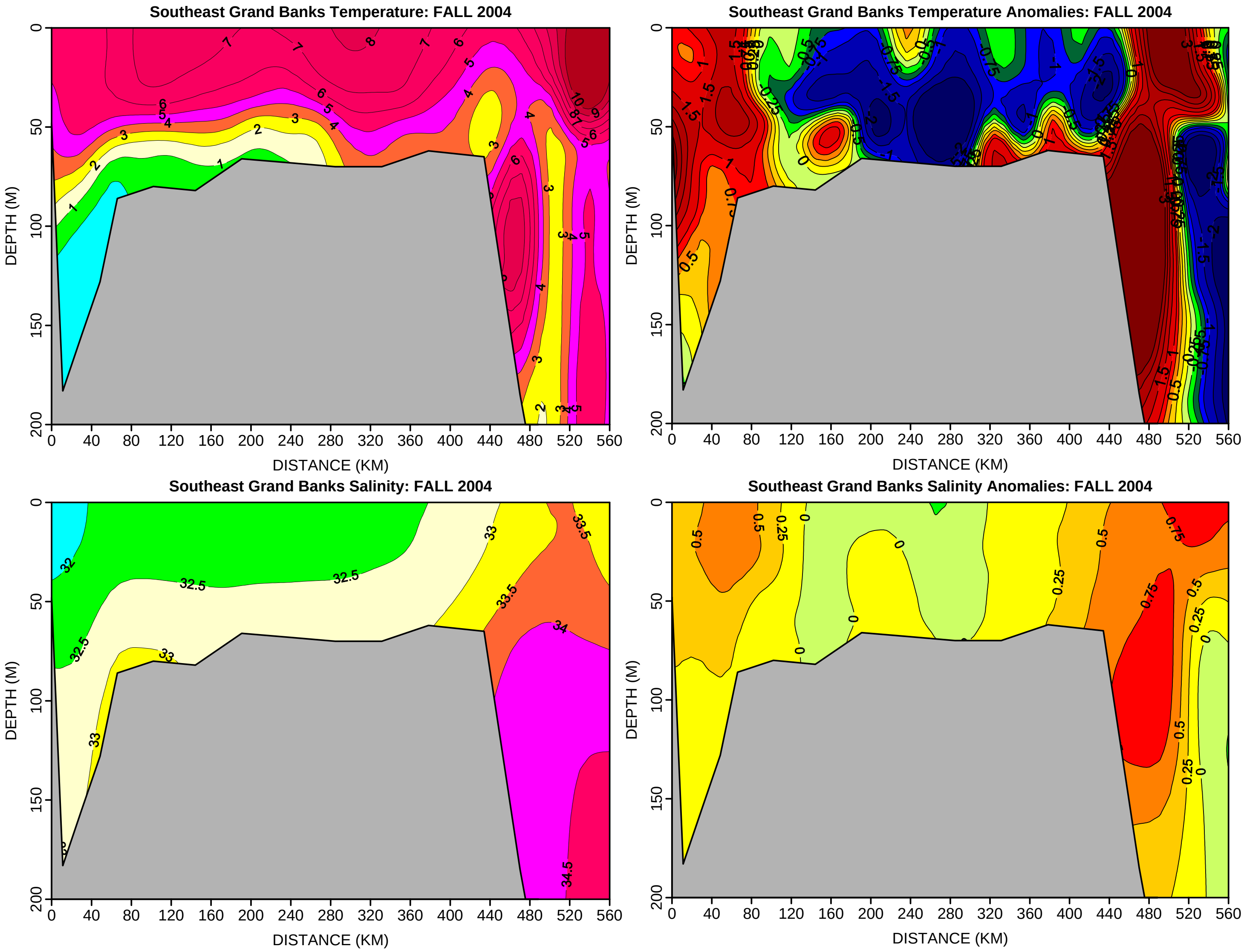


Fig. 7. Contours of temperature (in ^{o}C) and salinity and their anomalies along the Southeast Grand Bank Section (Fig. 1) during the fall of 2004.

FLEMISH CAP SECTION (SPRING, SUMMER AND FALL 2004)

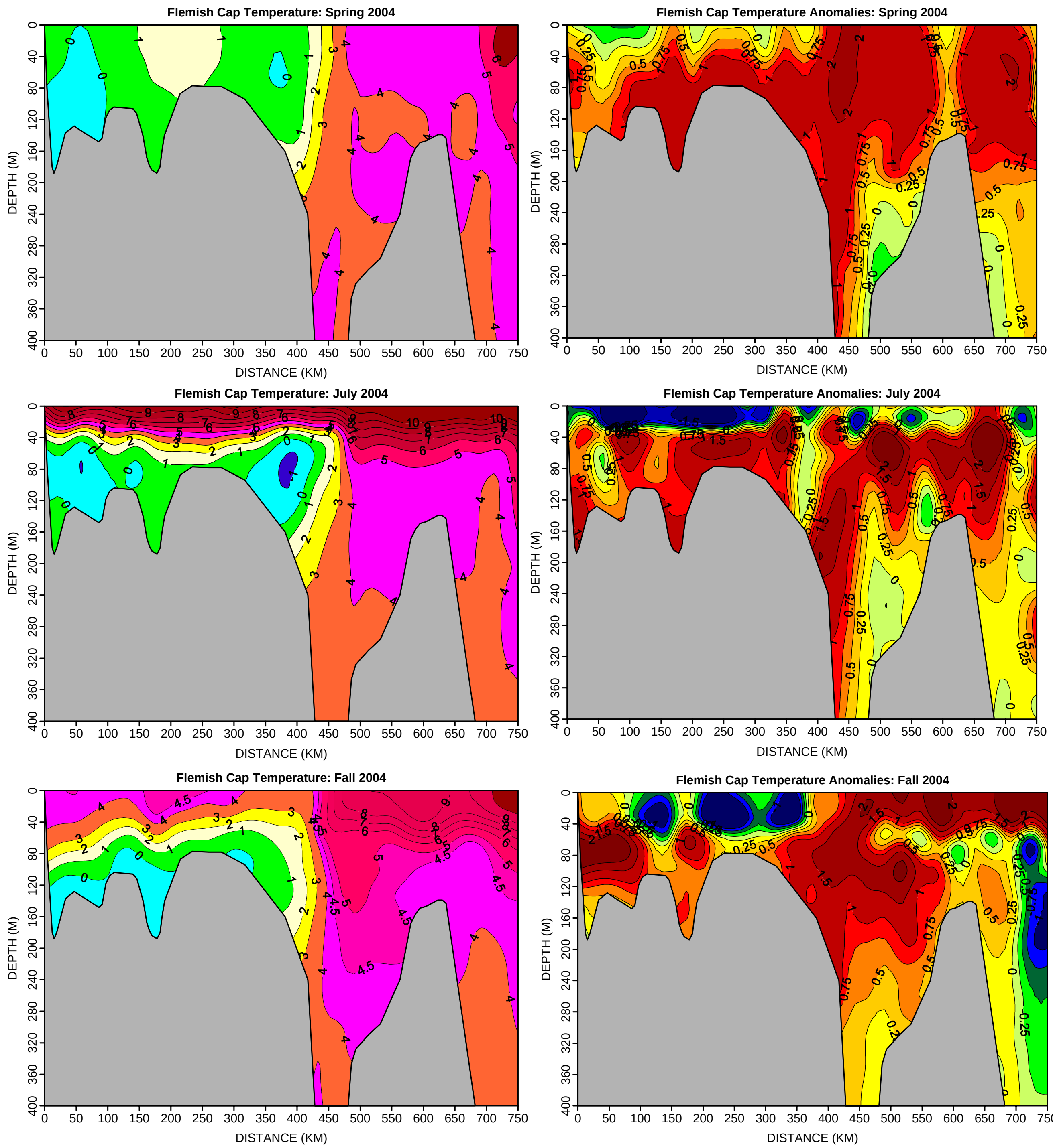


Fig. 8. Contours of temperature and temperature anomalies (in °C) along the Flemish Cap Section (Fig. 1) during the spring, summer and fall of 2004.

FLEMISH CAP SECTION (SPRING, SUMMER AND FALL 2004)

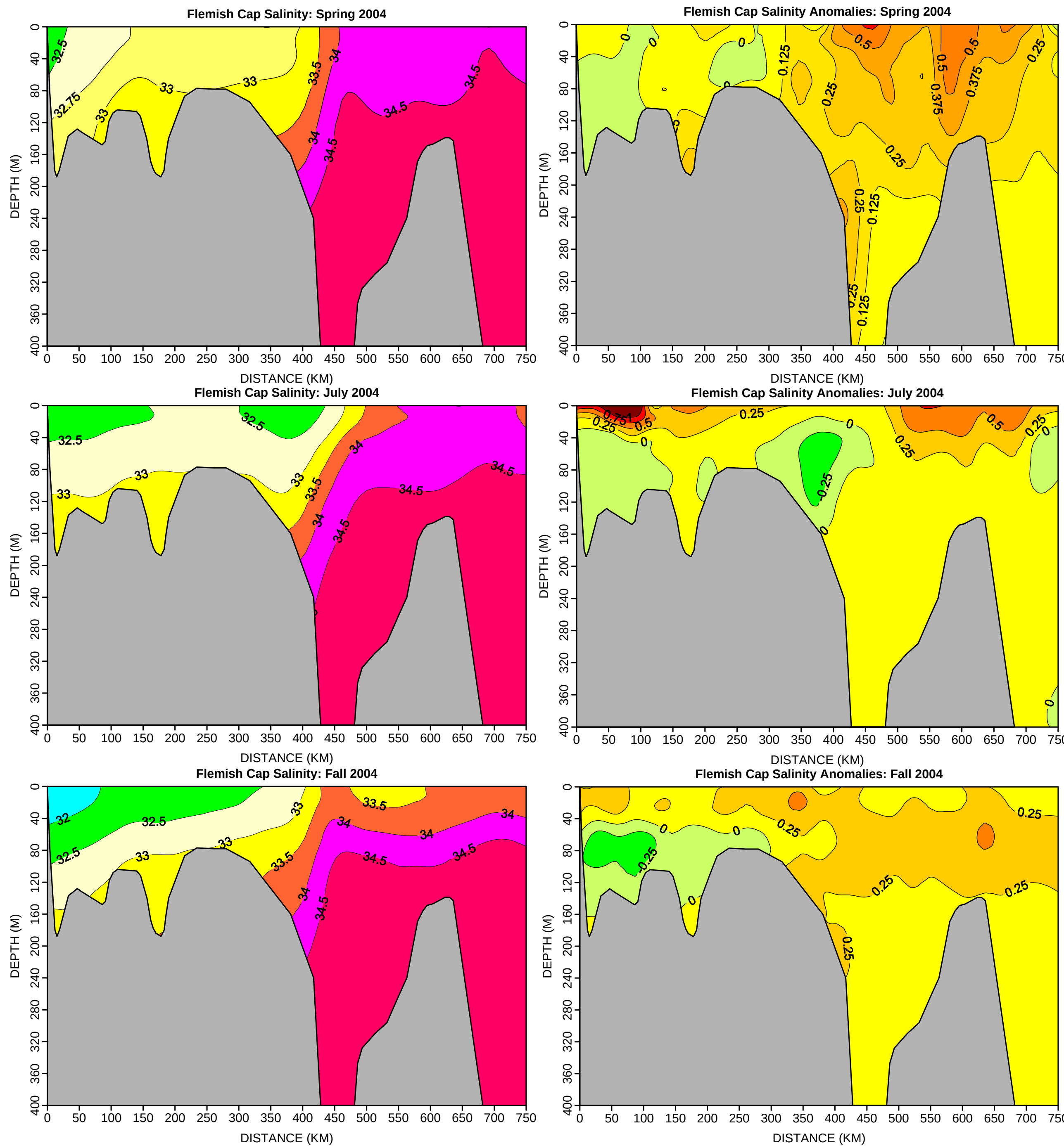


Fig. 9. Contours of salinity and salinity anomalies along the Flemish Cap Section (Fig. 1) during the spring, summer and fall of 2004.

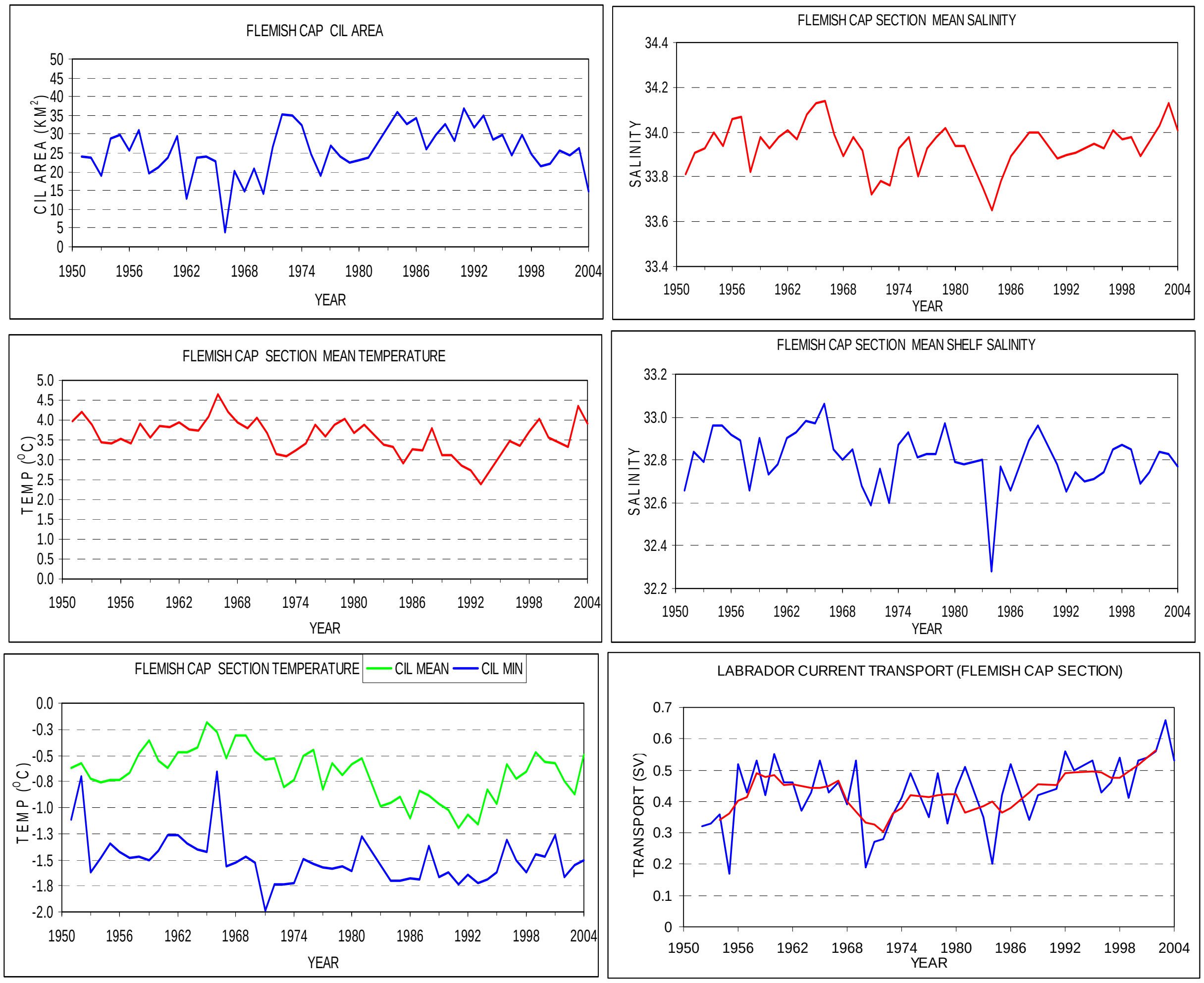


Fig. 10. Flemish Cap Section summer estimates of the Cold-Intermediate-Layer (CIL) cross sectional area, the section mean temperature (<500 m), the CIL mean and minimum temperatures, the section mean salinity (<500 m), the Grand Bank (<400 km) mean salinity and the transport of the offshore branch of the Labrador Current referenced to 135 m.

BONAVISTA SECTION (SPRING, SUMMER AND FALL 2004)

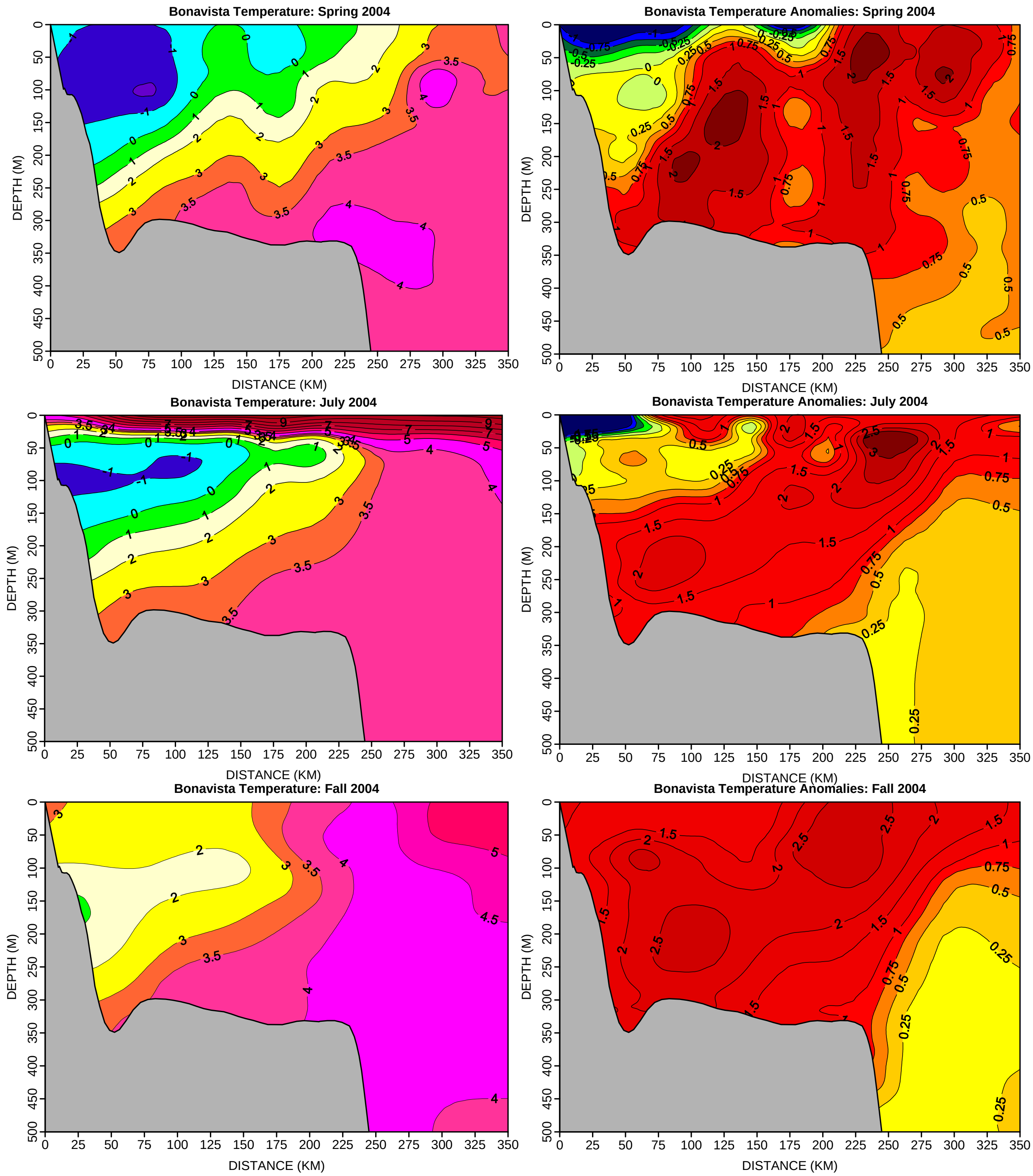


Fig. 11. Contours of temperature and temperature anomalies (in ^{o}C) along the Bonavista Section (Fig. 1) during the spring, summer and fall of 2004.

BONAVISTA SECTION (SPRING, SUMMER AND FALL 2004)

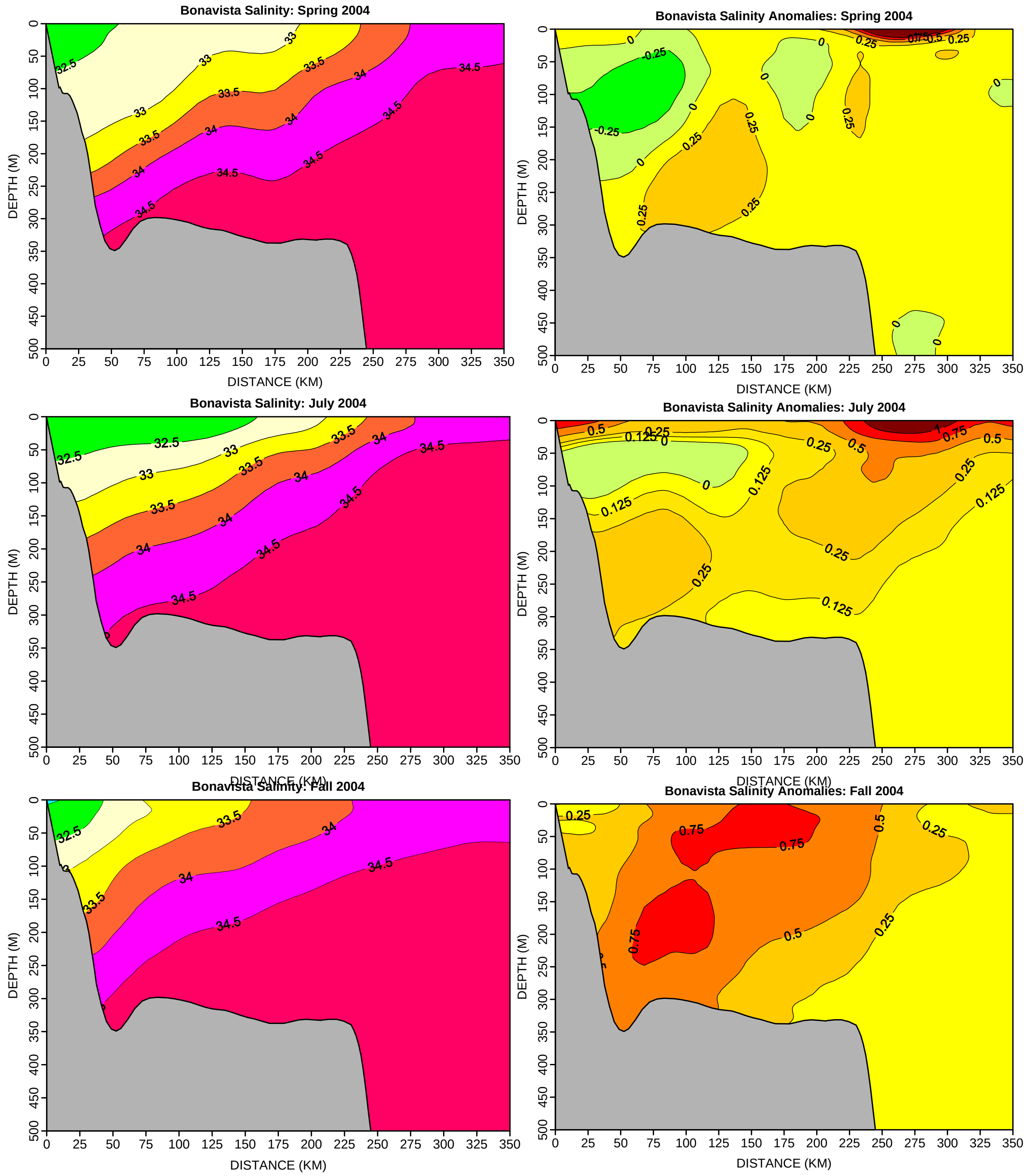


Fig. 12. Contours of salinity and salinity anomalies along the Bonavista Section (Fig. 1) during the spring, summer and fall of 2004.

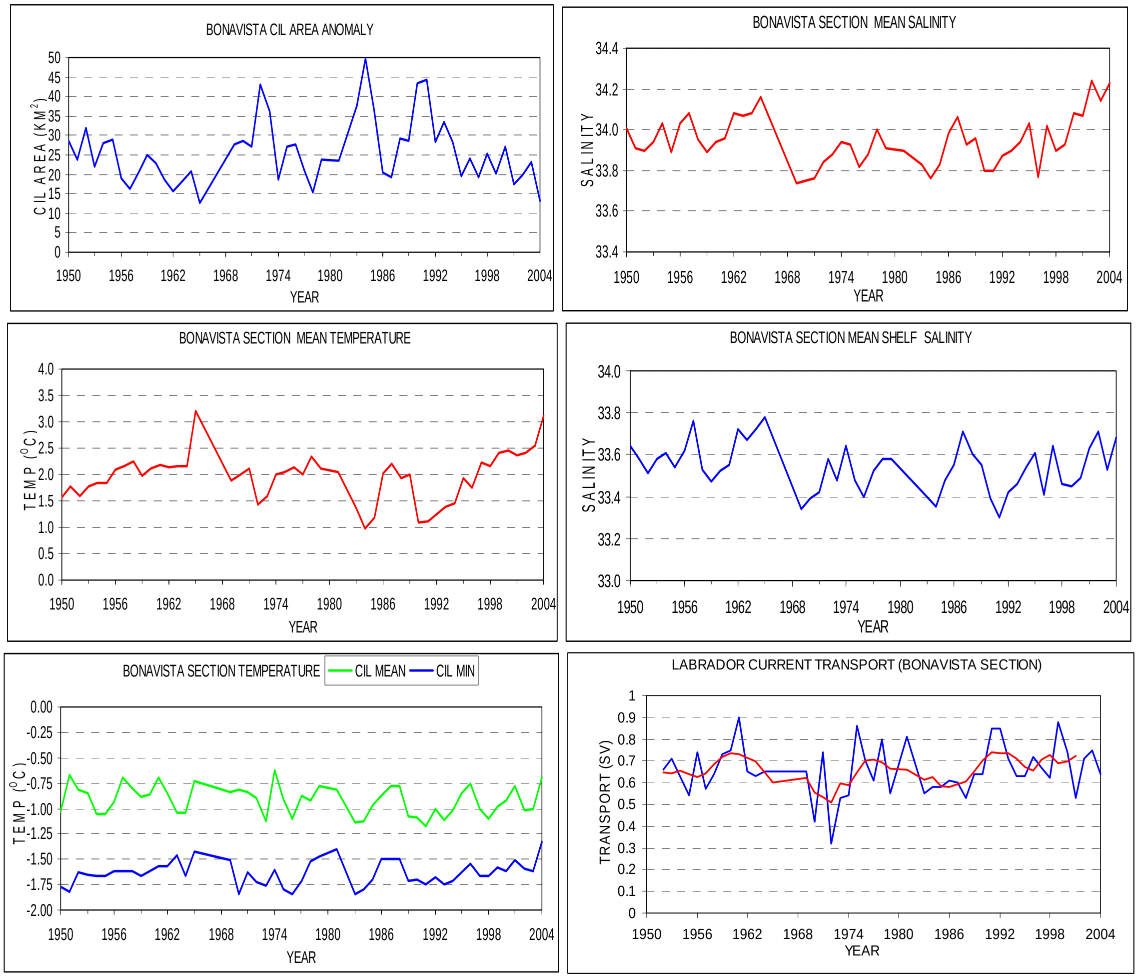


Fig. 13. Bonavista Section summer estimates of the Cold-Intermediate-Layer (CIL) cross sectional area, the section mean temperature (<500 m), the CIL mean and minimum temperatures, the section mean salinity (<500 m), the eastern Newfoundland Shelf (<200 km) mean salinity and the transport of the offshore branch of the Labrador Current referenced to 135 m.

FUNK ISLAND SECTION (FALL 2004)

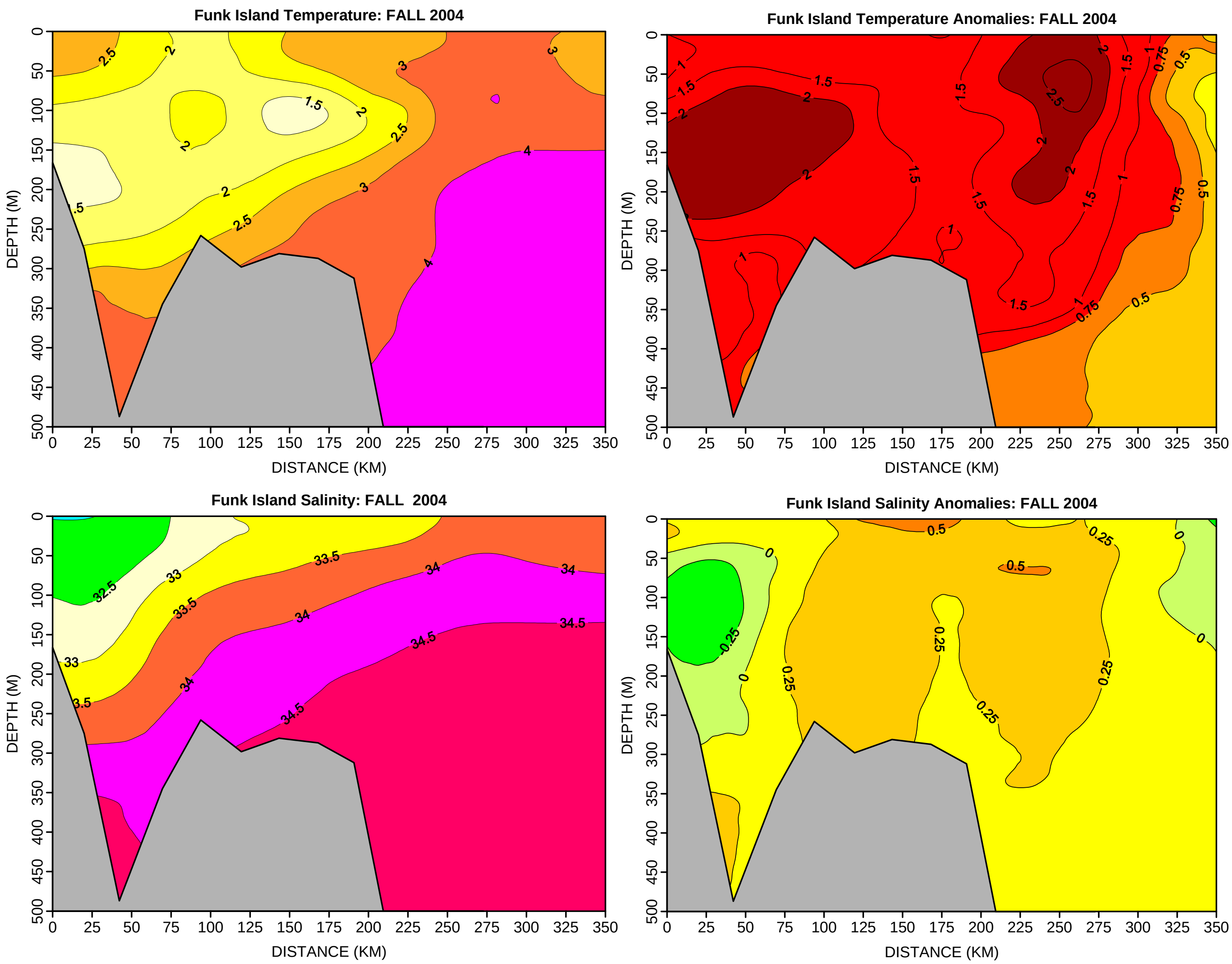


Fig. 14. Contours of temperature (in ^{o}C) and salinity and their anomalies along the Funk Island Section during the fall of 2004.

WHITE BAY SECTION (SUMMER 2004)

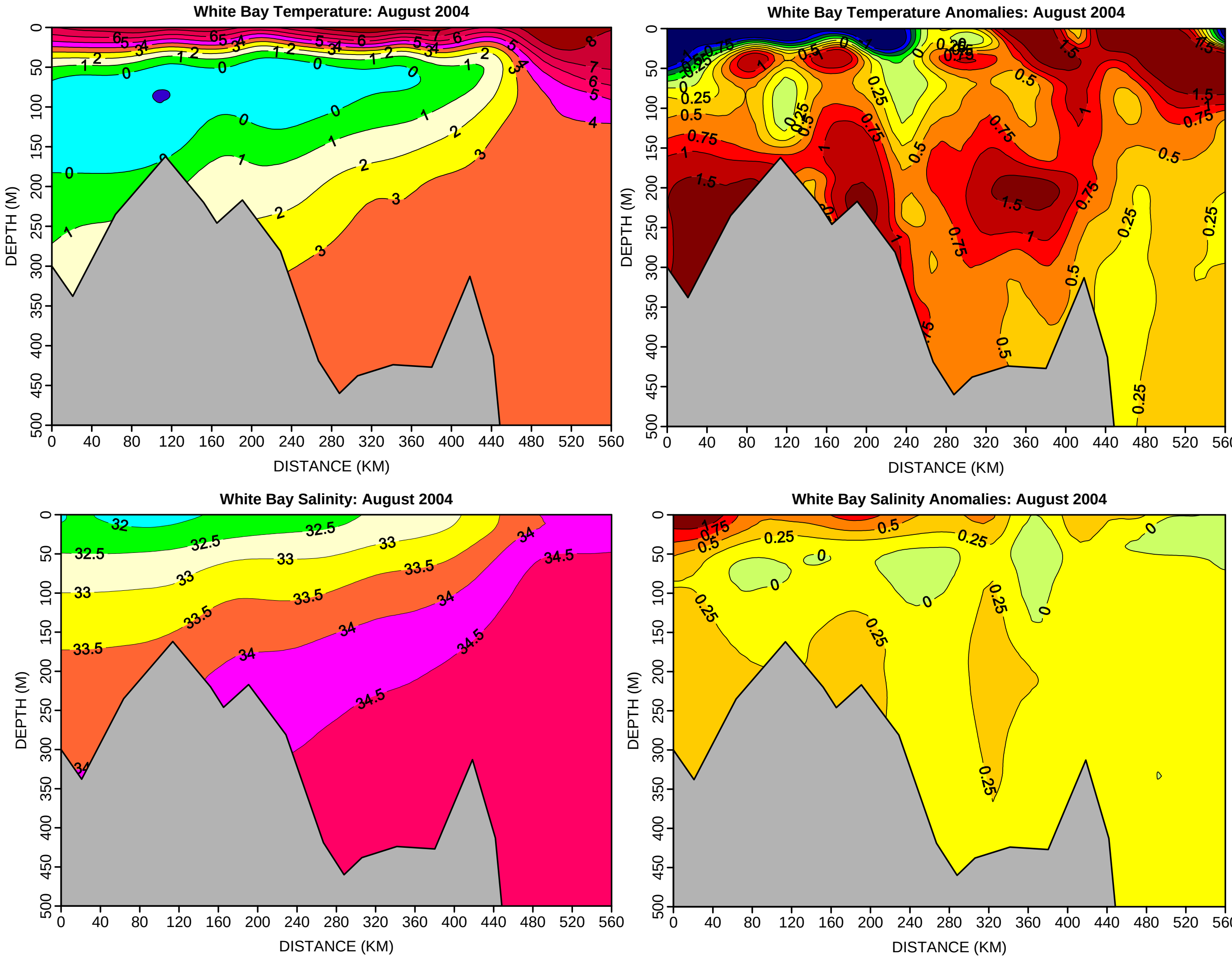


Fig. 15a. Contours of temperature (in ^{o}C) and salinity and their anomalies along the White Bay Section (Fig. 1) during the summer of 2004.

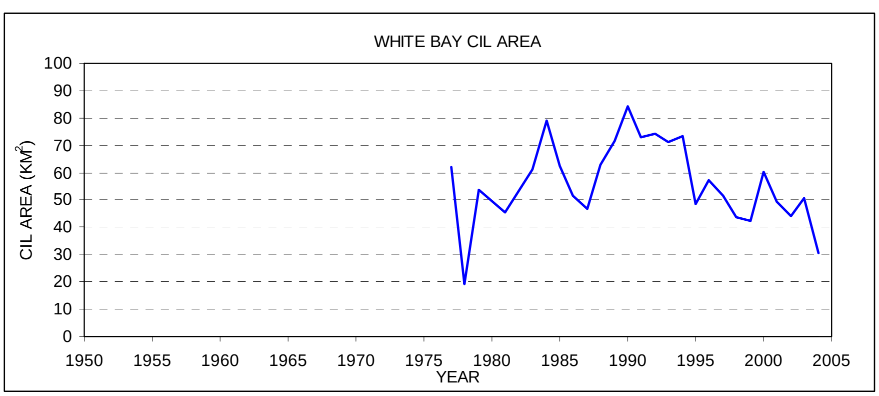


Fig. 15b. Annual summer CIL cross sectional areas along the White Bay Section.

SEAL ISLAND SECTION (SUMMER 2004)

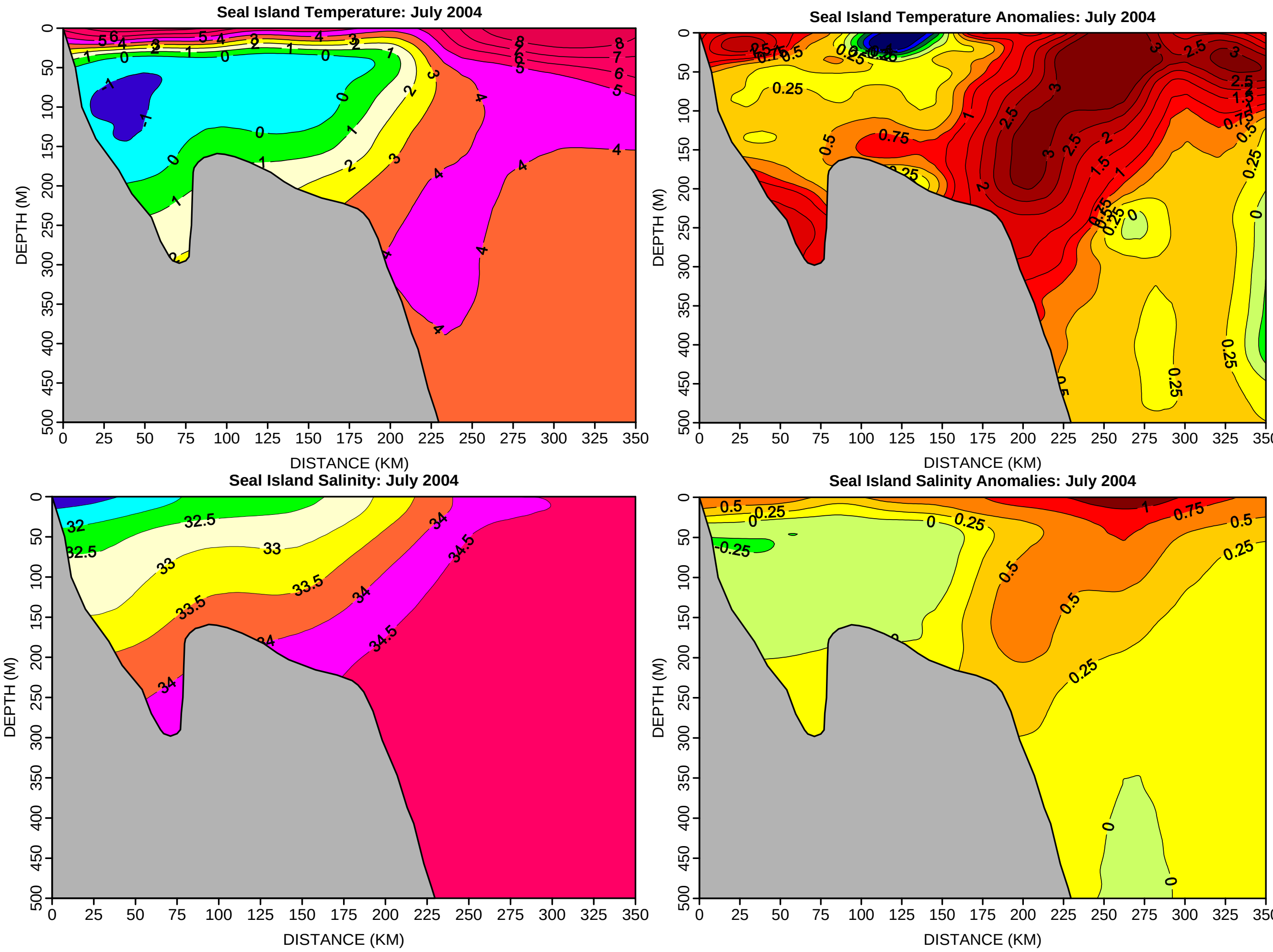


Fig. 16. Contours of temperature (in °C) and salinity and their anomalies along the Seal Island Section (Fig. 1) during the summer of 2004.

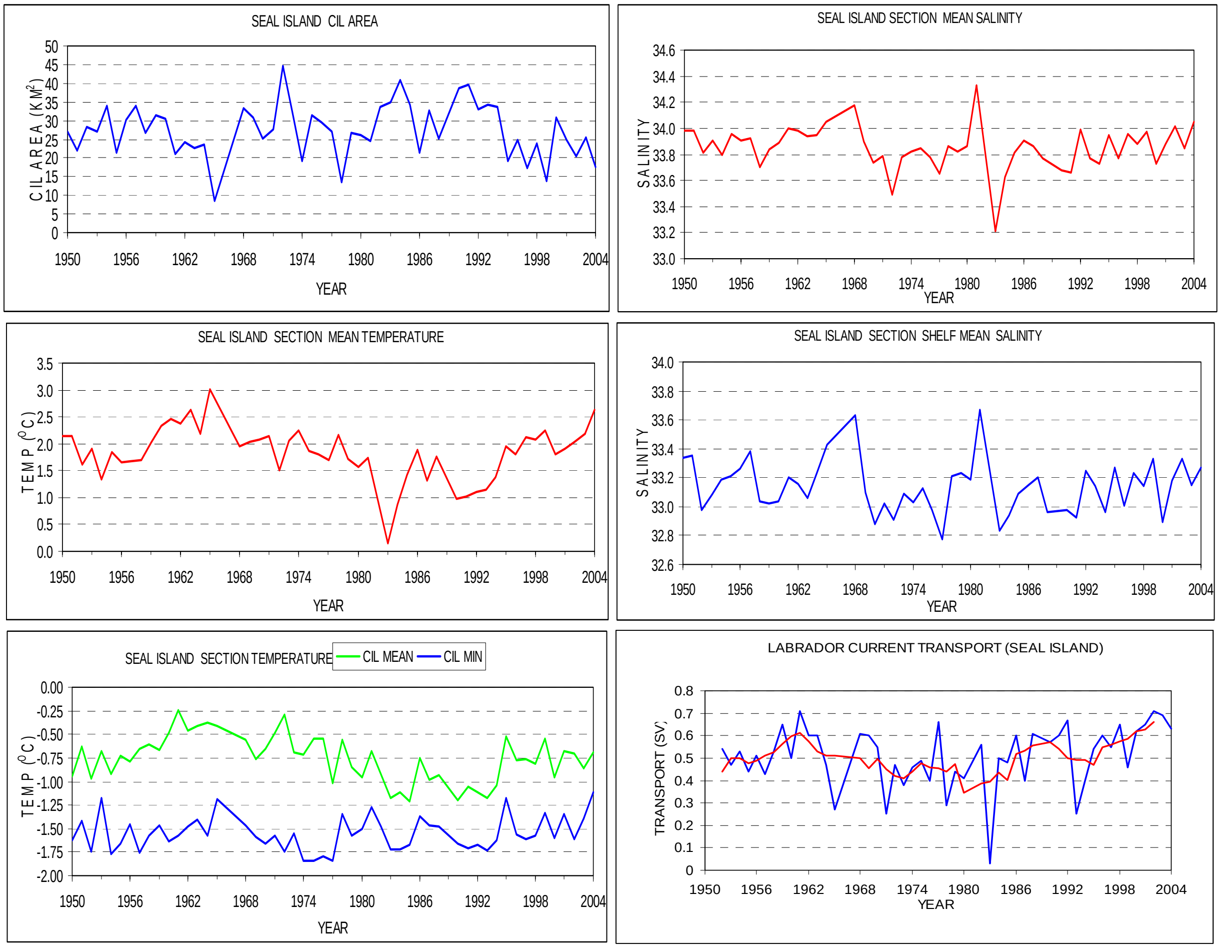
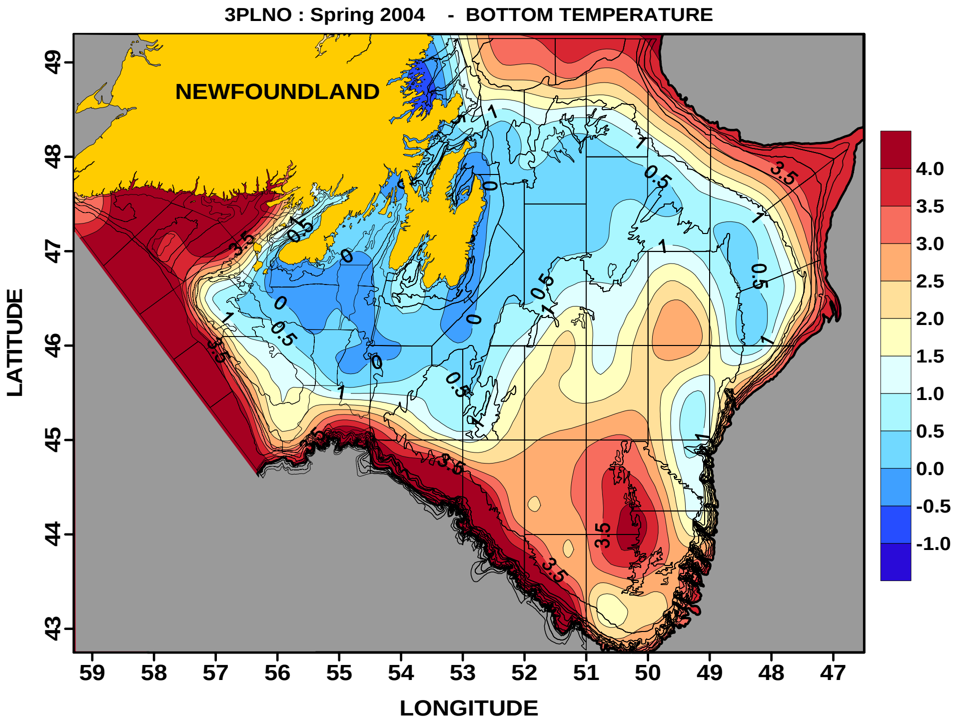


Fig. 17. Seal Island Section summer estimates of the Cold-Intermediate-Layer (CIL) cross sectional area, the section mean temperature (<500 m), the CIL mean and minimum temperatures, the section mean salinity (<500 m), the southern Labrador Shelf (<200 km) mean salinity and the transport of the offshore branch of the Labrador Current referenced to 135 m.

SPRING MULTI-SPECIES SURVEYS



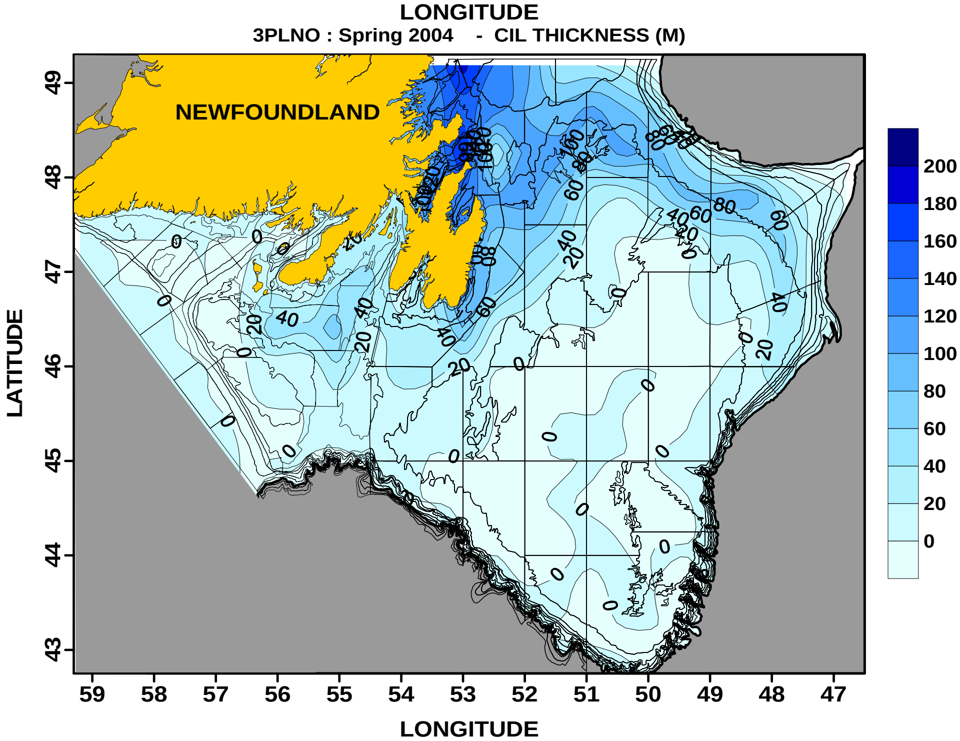


Fig. 18. Bottom temperature (in °C) and CIL thickness (in m) during the spring of 2004 in NAFO Divisions 3PLNO.

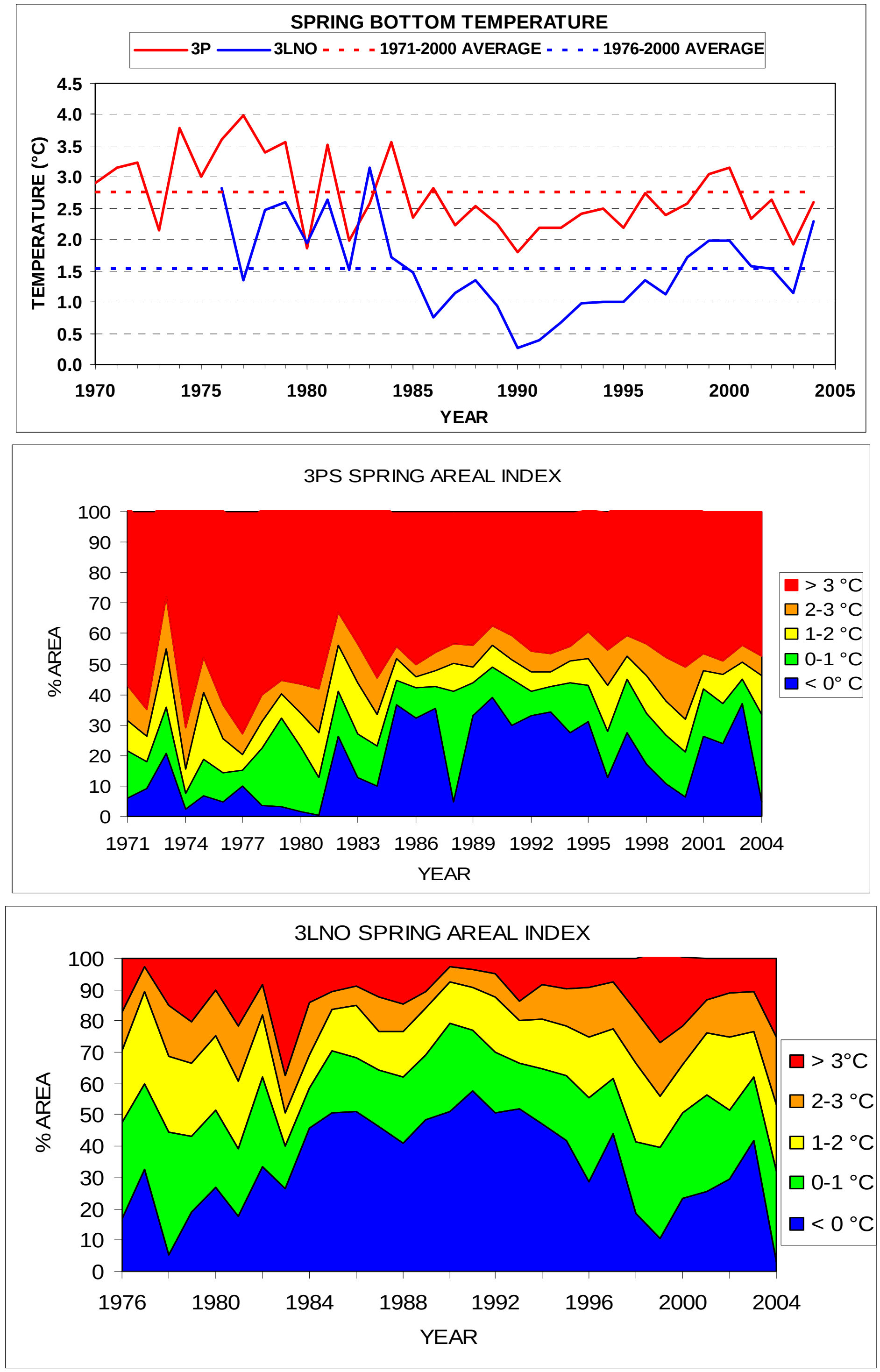


Fig. 19. Time series of the spatially averaged bottom temperatures during the spring in NAFO Div. 3P, and 3LNO and the percentage area of the bottom covered by water with temperatures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥3°C.

FALL MULTI-SPECIES SURVEYS

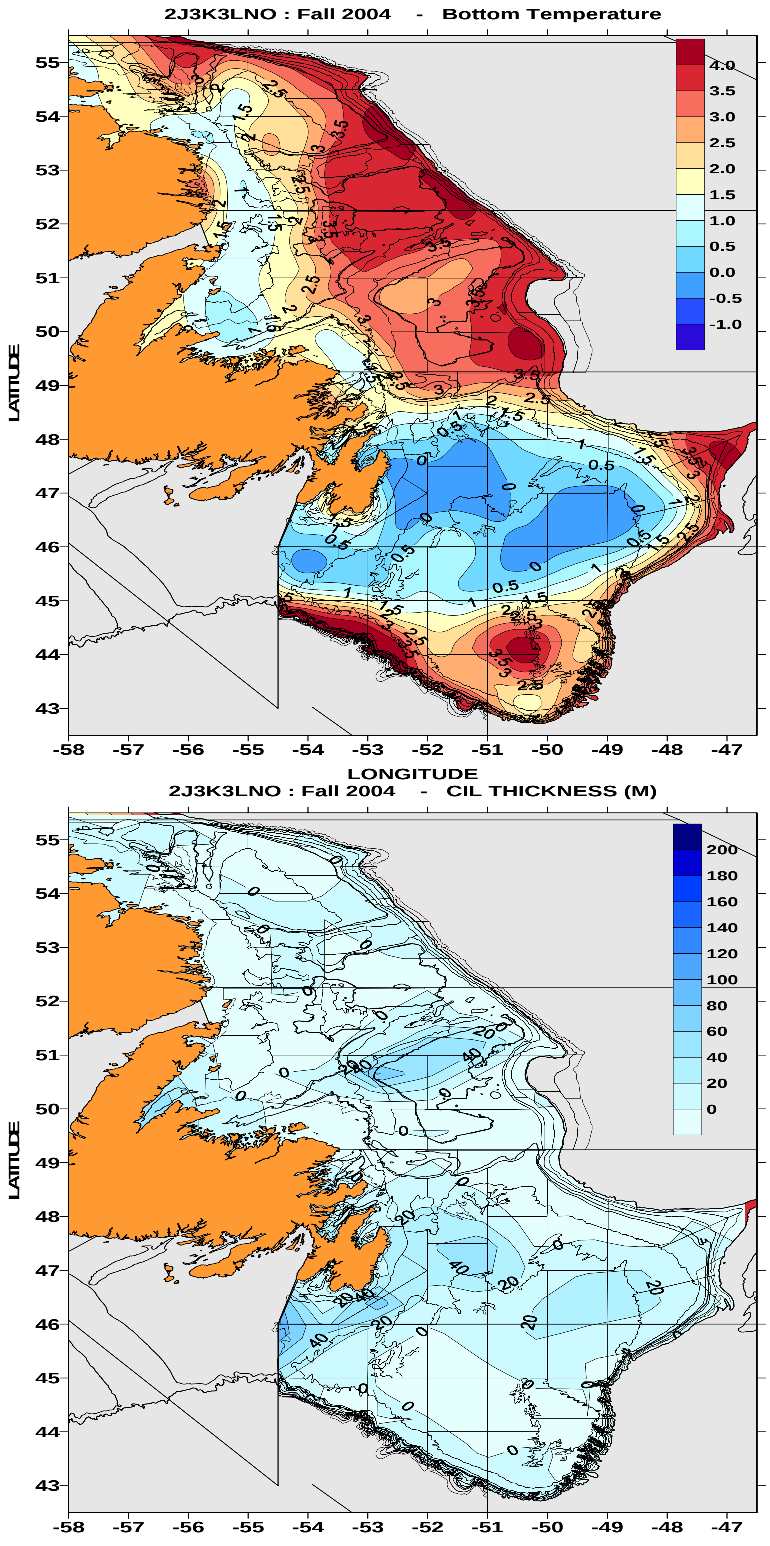


Fig. 20. Bottom temperature (in °C) and CIL thickness (in m) during the fall of 2004 in NAFO Divisions 2J, 3K and 3LNO.

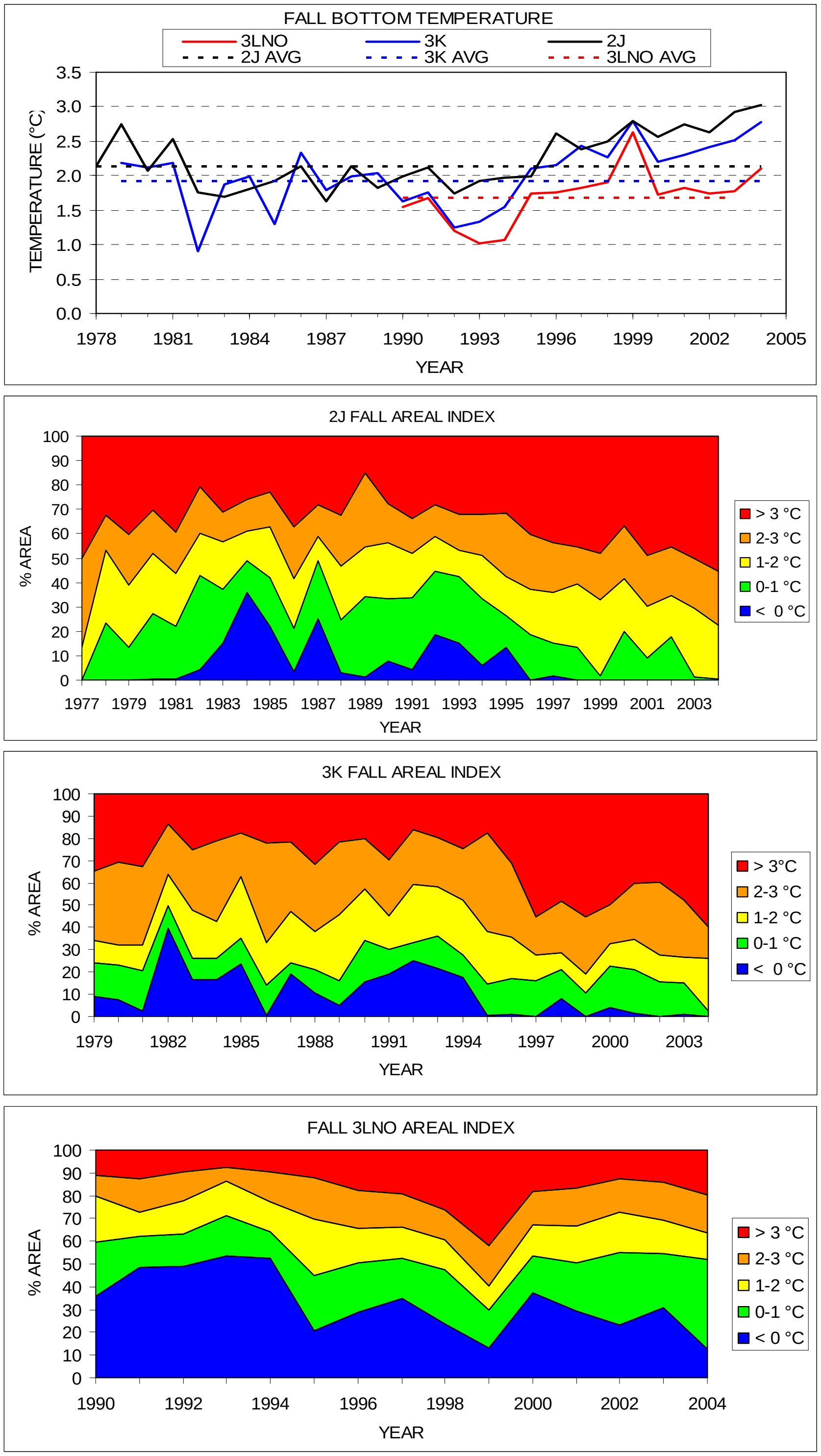


Fig. 21. Time series of the spatially averaged bottom temperatures during the fall in NAFO Div. 2J, 3K and 3LNO and the percentage area of the bottom covered by water with temperatures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥3°C.