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Ocean Climate Variability on the Flemish Cap in NAFO Subdivision 3M during 2015

by

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ABSTRACT

Oceanographic observations from seasonal surveys in NAFO Division 3M during 2015 are presented referenced to their long-term means. An analysis of infrared satellite imagery around the Flemish Cap indicates that annual sea-surface temperatures (SST) decreased to about -1.5°C below normal in 2015, the coldest value since 1985. Annual water column temperatures decreased to -3.3°C, -3.2°C, -1.1°C and -0.7°C below normal at depths of 10, 50 and 100 m and bottom, respectively. The results from seasonal surveys along the standard Flemish Cap section at 47°N show the development of an intense cold-intermediate layer (CIL) with T<2°C over the Cap and reaching as low as 0°C during the summer of 2015. Water column temperatures along the section were predominately below normal during spring, summer and fall with values reached between -2° to -3°C below normal. The cold water penetrated to the bottom directly over the Cap with cold anomalies (~-1°C) restricted to the shallow portions of the area. The corresponding salinity cross-sections show relatively fresh upper layer shelf water with some areas <33.5 corresponding to generally fresher than normal conditions in most areas of the water column over the Cap. The spatial extent of the CIL (<3°C) covered the entire survey area during the summer of 2015 for the first time since 1995 and average thickness of the CIL was the highest since 1993 at about 70 m thicker than normal. During the summer of 2015 the CIL minimum observed core temperature was the coldest in the observational record at -2°C below normal. The average CIL temperature was also at a record low of -1°C below normal. In general, data from four surveys conducted in NAFO division 3M on the Flemish Cap during the spring, summer and fall of 2015 show a record cold-fresh water mass over the Flemish Cap that penetrated to the bottom habitat over the central shallow areas while the deeper bottom areas were dominated by warmer North Atlantic Water. The circulation pattern revealed by geostrophic current calculations was particularly dynamic in 2015, resulting in water properties dominated by Labrador Current Water trapped within the anticyclonic circulation around the Flemish Cap.

INTRODUCTION

The Flemish Cap is an isolated bank located east of the Grand Banks of Newfoundland centred at about 47° N, 45° W with minimum water depths of 126-m (Figures 1 and 2). To the west, the Flemish Pass with maximum water depths of about 1100 m separates the Cap from the Grand Banks. The Cap has a diameter of about 200 km at the 500-m isobath for a total area of approximately 30,000 km^2. The water mass over the Flemish Cap is derived from a mixture of Labrador Shelf and Slope water and North Atlantic Current water, the general circulation of which is shown in Fig. 1.

Numerous reviews and studies of the physical oceanography around the Flemish Cap were conducted during the Flemish Cap Project of the late 1970s and early 1980s (Hays et al. 1978, Bailey 1982, Akenhead 1981). More recent reviews of oceanographic conditions in the region by Garabana et al. (2000), Lopez (2001) and Cabanas (2003) and Colbourne (2005) using data collected on the Flemish Cap during the summer from fisheries research surveys conducted by the European Union and by Fisheries and Oceans, Canada.

In the absence of strong wind forcing (mainly summer) the circulation over the Flemish Cap is dominated by a topographically induced anticyclonic gyre over the central portion of the bank (Gil et al. 2004, Colbourne and Foote2000, Kudlo et al. 1984, Ross 1981). The stability of this circulation pattern may influence the retention of ichthyoplankton on the bank and is probably a factor in determining the year-class strength of various fish and invertebrate species, such as cod, redfish and shrimp (Kudlo and Borovkov 1977; Kudlo and Boytsov 1979).

This manuscript presents an updated overview of oceanographic conditions on the Flemish Cap in NAFO subdivision 3M during 2015 in relation to long-term average conditions based on archived data. When possible, the long-term averages were standardized to a 'normal' base period from 1981 to 2010 in accordance with the recommendations of the World Meteorological Organization.

The information presented for 2015 is derived from two main sources: (1) measurements made along the standard NAFO cross-shelf section from seasonal oceanographic surveys by Canada (Fig. 2); and, (2) oceanographic observations made during an annual summer multi-species resource assessment bottom-trawl surveys carried out on Flemish Cap from 1988-2015 by the EU (Fig. 3). Data from other research surveys and ships of opportunity as well as remotely sensed SST data were also used to help define the long-term means and the conditions during 2015.

SATELLITE SEA-SURFACE TEMPERATURE CONDITIONS

The 4 km resolution Pathfinder 5.2 sea surface temperature (SST) database (Casey et al., 2010) archived at BIO was used to provide annual estimates of the SST within a defined area on the Flemish Cap (Fig. 2). This dataset runs from 1981 to 2010. Updated values for 2011 to 2015 were taken from NOAA satellite data provided by the remote sensing group in the Ocean Research and Monitoring Section at the Bedford Institute of Oceanography (BIO). These updates were adjusted by using a least squares fit of the Pathfinder and NOAA temperatures during the period (2001-2010) given by SST (Pathfinder) = 0.989*SST (NOAA) -0.02 with an r^2=0.98 (Hebert et al. 2012).

The Flemish Cap SST climatology together with the 2015 annual cycle is shown in Figure 4. On average SST generally range from 2°C - 4°C during winter and early spring then increase to a maximum of about 13°C in August which subsequently decrease to about 5°C in December. Except for January, February and October the 2015 SSTs were below normal reaching an anomaly of more than -3°C in July (Fig. 5).

Since the cold period of the early 1990s annual average SST have been generally increasing, reaching a peak of 1.8°C above normal in 2006, 1.5°C above normal in 2012 then decreasing to -0.6°C below normal in 2014 and to about -1.5°C in 2015 (Fig. 6). Since 1995, only 6 out of the past 20 years had below normal values, however, 2015 had the lowest value since 1985.

LONG-TERM TEMPERAUTE TRENDS

Time series of annual temperature anomalies on the central Flemish Cap based on all archived historical data at depths of 10, 50, 100 m and near-bottom are shown in Fig. 7 and 8. All data within the central Cap area at each depth were averaged by month and the annual anomalies were then computed from the monthly values. Data were not available for every month and in fact some annual estimates are based on as few as 3 monthly values. As a result the time series can show spikes that correspond to high frequency temporal or spatial variability and may poorly represent annual means in any given year. Therefore caution should be used when interpreting short time scale features of these series. The long-term trends however, generally show real features.

At 10 m depth the time series of temperature anomalies show a high degree of variability since 1980 unlike the SST values shown in Figure 6 which show a consistent trend. Since 2012 values have been decreasing reaching a series record low in 2015. At a depth of 50 and 100 m there are clear trends with a cold period from about 1985 to the mid-1990s, a warm period from 1997-2012 and colder than normal conditions during the past 2 years with the 2015 values reaching the second lowest in the series.

During the early 1990s bottom temperature anomalies on the central Flemish Cap ranged from 1°C - 2°C below normal. During the past decade and a half temperatures on the Flemish Cap were either near-normal or above normal reaching a peak of >2°C above normal in 2010, the highest in the series. Since the peak in 2010 bottom temperatures on the Flemish Cap have been decreasing with both 2014 and 2015 showing the lowest value since 1994 at -0.7°C below normal. At 10, 50 and 100 m depth temperatures were below normal by -3.3°C, -3.2°C and -1.1°C, respectively in 2015.

TEMPERATURE AND SALINITY VERTICAL STRUCTURE

In the early 1950s several countries of the International Commission for the Northwest Atlantic Fisheries (ICNAF) carried out systematic monitoring along sections in Newfoundland and Labrador Waters. In 1976, ICNAF standardized a suite of oceanographic monitoring stations along sections in the Northwest Atlantic Ocean from Cape Cod (USA) to Egedesminde (West Greenland) (ICNAF 1978). Since 1998 the Atlantic Zone Monitoring Program (AZMP) of the Canadian Department of Fisheries and Oceans has sampled a subset of these sections on a regular seasonal basis.

In 2015, the Flemish Cap section was sampled by the AZMP during April, July and November. This section crosses the Grand Bank, Flemish Pass and Flemish Cap at 47°N. In this manuscript we present the seasonal cross sections of temperature and salinity and their anomalies for the Flemish Cap portion of the section during 2015 (Figures 9 and 10).

The source waters for the Flemish Cap area consist of Labrador Current Slope Water and North Atlantic Current Water resulting in a water mass that is generally warmer and saltier than the sub-polar Newfoundland Shelf waters with a temperature range of 3°C – 4.5°C and salinities in the range of 34-34.9. In general, the water mass characteristics along the standard Flemish Cap section (Fig. 2) undergo seasonal modification from seasonal cycles of air-sea heat flux; wind forced vertical mixing and through advection and subsequent mixing of Labrador shelf and slope waters with warmer waters to the south. The seasonal changes are highlighted in Figures 9 and 10 along the Flemish Cap portion of the section with the colder Newfoundland Shelf and Labrador Slope waters (T < 3°C) (LSW) as the dominate thermal feature in the upper water column reaching the bottom over the shallow portion of the Cap. In the deeper water the thermal conditions are dominated by North Atlantic Current water (NAW) with temperatures >4°C. The development of a well-defined cold-intermediate layer (CIL) with T<3°C over the Cap was strong during the summer and fall of 2015. In the spring these cold waters extended from the surface to the bottom over the Cap.

The corresponding salinity cross-sections show the relatively fresh upper layer shelf water originating from the Labrador Shelf with values <33.5 extending out over the Cap contrasting to the saltier Labrador Slope water (34<S<34.75) over the Cap and across the region at depths of 100-300 m. In the deeper water >400 m salinities are >34.85 and are derived mainly from North Atlantic Current water from the south (Fig. 10).

During 2015 temperatures along the section were predominately below normal during all seasons with upper layer values reached between 1°C - 3°C below normal. These cold anomalies penetrated to the bottom directly over the Cap with a striking cold anomaly persisting over the water column on the Cap during the fall survey possibly indicating an enhanced gyro circulation with cold (<3°C) Labrador Current water circulating over the central Cap area. There were some exceptions where temperatures were above normal, for example in the deeper layers (>150 m) during all three surveys (Fig. 9).

Spring salinities were lower than normal (>0.5) across the area reaching the bottom over the central Cap during spring, summer and fall. Below about 200 m salinities were near the long-term mean. In general, salinity anomalies were higher in summer decreasing somewhat during the fall (Fig. 10).

TEMPERATURE/SALINITY SPATIAL VARIABILITY

Hydrographic data (CTD) are routinely collected as part of the EU annual bottom-trawl surveys carried out by Spain and Portugal on the Flemish Cap during the period of late June to late July from 1988-2015. Surveys are typically 4-5 weeks duration during which CTD stations were sampled within selected stratum following the randomly stratified survey but more recently on a grid pattern covering most of the Cap. No data were available for 1992 and 1994. The number of CTD profiles varied from 119 in 2002 to only 32 in 2011. A total of 2114 stations were available since 1988 and included in the analysis. From 1988-2002 the survey only covered depths from 125 - 730 m, while in the period 2003-2014 it covered depths to 1491 m. In 2015 the EU bottom trawl survey in Flemish Cap (Div. 3M) was carried out on board R/V Vizconde de Eza from June 23rd to July 22nd. The 2015 survey covered depths up to 1377 m with 68 CTD stations conducted (González-Costas et al. 2015) (Fig.e 3).

Temperature and salinity grids of the survey area were computed using standard geostatistical techniques by extracting T/S values corresponding to various depth levels. Contour maps of the temperatures climatology, the 2015 temperature and temperature anomaly and the difference from the previous year were derived for 10 m, 50 m and for the bottom. Similar maps for salinity are presented for the bottom only. Anomaly maps were produced by subtracting the average grid from the individual yearly grids.

The temperature climatology, the 2015 temperature along with the 2015 temperature anomalies as well as the difference from 2014 at 10 m depth over the Flemish Cap are displayed in Figure 11. On average upper layer temperatures range from 9°C - 11°C in the southern regions of the Cap to <8°C in the northern regions. In 2015 conditions were much colder with cold LSW flowing to the south on the eastern side and NAW flowing northward on the western side with temperatures >8°C indicating a well-defined anti-cyclonic circulation in the upper layers. The temperature anomaly map shows values colder than normal over the entire survey area with anomalies ranging from -1°C to -4°C below the long term average and a decrease over 2014 values by as much a 4°C to 5°C in the southern areas (Fig. 11).

Similarly, temperature conditions at 50 m depth over the Flemish Cap are displayed in Figure 12. Average temperatures range from 2.6°C -3.4°C in the northern regions of the Cap to 3.6°C to 4.5°C in the south. In 2015 conditions were again much colder with cold LSW dominating with temperature field with values ranging from 0°C to >3°C in limited areas to the east. The temperature anomaly map at this level, while showing more variability than at 10 m depth, also shows colder than normal conditions over most of survey area with anomalies ranging from -1°C to -3.5°C below the long term average. Except for isolated areas these values represent a decrease over 2014 values by 1°C to 2°C in some areas (Fig. 12).

Temperature and salinity conditions near bottom on the Flemish Cap are displayed in Figures 13 and 14. On average bottom temperatures range from 3.5°C to 3.7°C along the periphery and central portions of the Cap. An area of warmer water NAC with temperatures >3.7°C appears to wrap around the central part of the Cap. This pattern of bottom water temperature distribution highlights the anti-cyclonic circulation around the Cap. Average salinities range from 34.85-34.9 around the deeper portions of the Cap and are typical of NAW. Over the central portions of the Cap Labrador Shelf water is dominant with salinities ranging from 34.5-34.7 (Fig. 14).

In 2015, bottom temperatures ranged from 2.4°C to 3°C in the shallow area of the centre of the Cap which was up to -1°C below the long-term average. In deeper waters around the Cap temperatures ranged from 3.6°C to 4.4°C which were 0.2°C to 0.6°C above normal except for outer periphery where they were about normal (Figure 13). Salinities during 2015 show relatively low values (<34.25) over the centre part of the Cap compared to 34.8-34.9 in deeper waters. These bottom values were lower than normal over the shallow portions of the Cap and near-normal elsewhere. Salinities decreased slightly over 2014 values (Fig. 14).

Thus it appears that while most of the water column experienced record cold temperatures in 2015 the cold water anomaly only impacted the bottom area over the shallow portions (<200 m) of the Cap, similar to that observed during 2014. This is in contrast to conditions observed in 1993 when the entire bottom area of the

Flemish Cap was covered by Labrador Slope and Shelf water with temperature <3.7°C (Colbourne and Perez-Rodriguez 2015).

COLD INTERMEDIATE LAYER (CIL)

The temperature profiles collected on Flemish Cap from 1988-2015 by the EU bottom trawl surveys were also used to explore the characteristics of the CIL on the Flemish Cap (spatial coverage, CIL minimum temperature, CIL average temperature and the vertical extent or thickness of the CIL) during the June-July period. As described above, the water masses characteristics of the Flemish Cap area are derived from a mixture of Labrador Current Slope Water (LSW) and North Atlantic Current Water (NAW) which produce waters with average temperatures in the range of 3 °C to 4°C. During cold years however, a well-defined CIL layer develops over the Cap (Fig. 9) with T<3°C and indeed as low as 0°C in cold years. The vertical temperature profiles for each survey were analyzed to determine the presence of CIL water (based on thresholds of <2°C and <3°C), the CIL water mass vertical thickness and the CIL minimum and average temperature. The percentage of CTD cast where the CIL was found was then estimated for each survey year and since the CTD stations are well distributed over the bank, this value is approximately proportional to the surface area of the Flemish Cap covered by the CIL water mass.

Contour maps of the spatial extent of the CIL vertical thickness over the Flemish Cap are shown in Figure 15 for average conditions, the 2015 conditions and corresponding 2015 anomalies as well as the difference from 2014. On average CIL thickness range from 30-40 m in the southern areas to 70-80 m in northwestern areas within the Labrador Current extension. In 2015, the CIL was much thicker with values in the range of 150-180 m within the Labrador Current (Fig. 15 top right panel). These values were as much as 100 m thicker than normal and up to 100 m thicker than in 2014 in isolated areas. There were however areas where the CIL was thinner than in 2014 by 20-30 m (Fig. 15 bottom right panel).

In 2015, 100% of the CTD stations reported CIL water defined by <3°C for the first time since 1995 and 93% reported water <2°C, the 2nd highest in the series after 1993 (Fig. 16). In accordance with the expected negative relationship of the CIL spatial coverage with the average surface and bottom water temperature at the two temperature thresholds (2°C and 3°C), the higher spatial coverage was usually found during those years with negative temperature anomalies, with the exception of 2000 and 2009 (Fig.16). It was also observed that the lower temperature used to define the percentage of CIL coverage, the weaker the negative correlation is between the CIL and surface or bottom temperatures (compare Fig. 16 and Figures 7 and 8).

The average thickness of the CIL (<3°) displayed in Figure 17 show large values during the cold years of the early 1990s, below normal to near-normal values from 1996 to 2013 and a significant increase during the summer of 2014 followed by a further increase in 2015 to highest value since 1993, ranking the 5th highest in the series. For CIL water defined by temperatures <2°C the thickness reached 60 m higher than normal, the highest in the time series. The values observed in 2014 and 2015 were similar to those observed in the cold period of early-mid 1990s (Fig. 17).

The CIL minimum temperature (Fig. 18) shows no significant long term trend, however the 1993, 2004, 2014 and 2015 values all show significantly colder CIL minimum temperatures with the 2015 value showing a remarkably low value at 2°C below the long term average. The average temperature in the core of the CIL (Fig. 18) show similar variations as the minimum temperature time series, again with the 2015 value the coldest in the series at 1°C below normal.

GEOSTROPHIC CIRCULATION

The eastward bifurcation of the LC in the vicinity of the Flemish Pass flows north of the Flemish Cap and then southward east of the Cap. A portion of this flow is entrained by the NAC and the remainder continues to the south and southeast on the southeastern side of the Cap. To the south, a component of the NAC flows north around the western side of the Cap and mixes with the LC water to form a mixed, partially isolated, water mass over the central portions of the Cap. The circulation pattern is enhanced by the topography of the

Flemish Cap and often forms a well defined anti-cyclonic (clockwise) circulation pattern or gyre, particularly during the summer when wind forcing is at a minimum.

In this section we examine the baroclinic component of the circulation around the Flemish Cap solely from the approximate balance between the Coriolis force and the horizontal pressure gradient force arising from density differences over the Cap, referred to as the geostrophic currents. This approximation to the circulation excludes high frequency components such as wind driven events, inertia currents and tides. Another important consideration is that this method depends on an assumed level of motion and in our case we have no information of the deep current velocities so we assume a level of no motion at 400 m depth. Therefore, the geostrophic currents presented here is relative to that at 400 m depth. The temperature, salinity and pressure profiles collected on Flemish Cap from 1988-2015 by the EU bottom trawl surveys were used to calculate density and the dynamic height over the survey area. At CTD stations where the maximum depth is shallower than the reference level the density of the closest station was assigned at the lowest recorded level. Average and annual geostrophic velocities were obtained from the horizontal gradient of the dynamic height profiles objectively projected onto a 0.1° latitude × 0.1° longitude regular grid pattern.

The June-July average dynamic height field and geostrophic velocity vectors at 10 m depth shows a coherent anticyclonic flow around the Flemish Cap with maximum velocities typically <10 cm/s and appear to be associated with the eastward extension of the LC. The centre of the circulation appears at approximately 47° 15' N, 45° 15' W indicated in Figure 19 by the elevated dynamic height anomaly and low-horizontal gradient region of the dynamic height field and the subsequent near-zero geostrophic currents. The rotating water mass extends northward to about 48° 15' N indicating a spatial scale with a diameter of approximately 200 km. Apart from the centre areas of the Cap the weakest currents occur in the southwestern regions where the influence of the LC is weakest.

Geostrophic current maps for individual years shown in Figures 20 and 21 indicate significant annual variability with the early 1990s showing a weak circulation pattern dominated by the LC. During 2009 the flow was much stronger with speeds ranging from 10-15 cm/s around the periphery of the Cap, with a large area of weak currents towards the central region. In 2010 however, the pattern shows a weak well-formed anticyclonic flow around the Cap with speeds ranging from 5-10 cm/s. This corresponds to a maximum re-circulation time of about 70 days. In 2014 and particularly in 2015 however, the circulation was much more dynamic. The patterns shown in 2009 and 2015 represent the strongest baroclinic flows in the 1988-2015 time series. In 2015 the circulation of water masses around the Cap also appears in the temperature and salinity fields shown in Figures 9, 10 and 11. In particular, the fall temperature and anomaly patterns shown in Figure 9 shows what appears to be LC water with temperature anomalies of 2° to 3°C below normal, trapped within the anticyclonic gyro over the Cap.

Research is on-going to examine the properties and variability of the gyre circulation and how it might affect the re-circulation and residence times of passive drifters such as pelagic fish eggs and larvae within the Flemish Cap ecosystem.

SUMMARY

A summary of selected temperature and salinity time series and CIL indices for the years 1988-2015 based on the EU data set are displayed in Figure 22 as colour-coded normalized anomalies. The anomalies were normalized by dividing the values by the standard deviation of the data time series over the base period 1988–2015. A value of 1.5 in the table for example indicates that the index was 1.5 standard deviations higher than its long-term average. The normalized values are presented in coloured boxes with gradations of 0.5 standard deviations (SD). Shades of blue represent cold-fresh environmental conditions and reds warm-salty conditions (Fig. 22). In some instances (CIL for example) the sign of the anomalies are reversed to reflect the either warm or cold conditions. To further visualize the trends following Petrie et al. (2007) a mosaic or composite climate index was constructed from the 14 time series as the sum (red line) of the standardized anomalies with each series contribution shown as stacked bars (Fig. 23). The composite index is can be interpreted as a measure of the overall state of the Flemish Cap climate system with positive values representing warm-salty conditions and conversely negative values representing cold-fresh conditions. The plot also indicates the degree of correlation between the various measures of the environment. In general, most time series are correlated, but there are some exceptions as indicated by the negative contributions during a given year with an overall positive composite index and conversely during a year with a negative composite index. The cold/fresh climatic conditions of the early 1990s are apparent as is the warming trend from mid-1990s that continued (with the exception of 2009) throughout the 2000s reaching a record high in 2011. Since 2012 a cooling trend developed with the composite index decreasing to a strongly negative value in 2014 and a further decrease to a record low value in 2015, indicating record cold/fresh water column conditions (Fig. 23). In general, data from four surveys in NAFO division 3M on the Flemish Cap during 2015 indicate an unprecedented cold-fresh water mass over the Flemish Cap during spring, summer and fall. The cold/fresh conditions penetrated to the bottom habitat over the central Cap area in water depths generally less than 200 m, while the deeper regions were dominated by warmer NAW. A preliminary examination of the geostrophic currents show a very dynamic circulation pattern in 2015 that was strongly influenced by the LC resulting in intense negative temperature and salinity anomalies in the Flemish Cap region.

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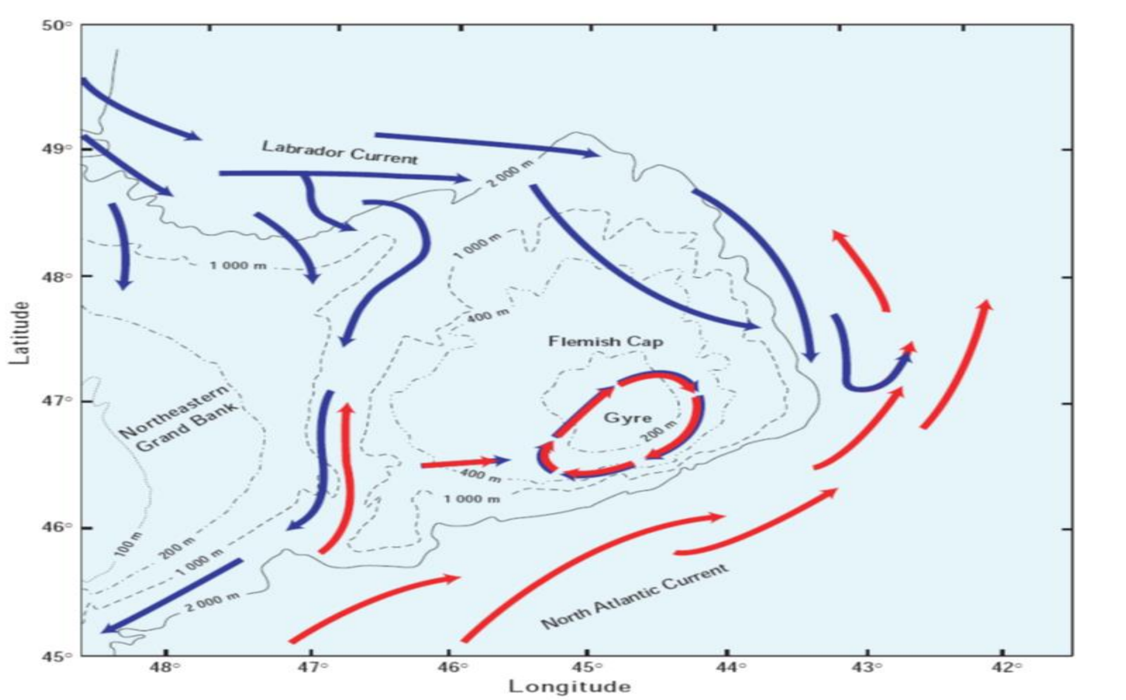

Fig. 1. Areal map showing the local bathymetry and major circulation features around the Flemish Cap area.

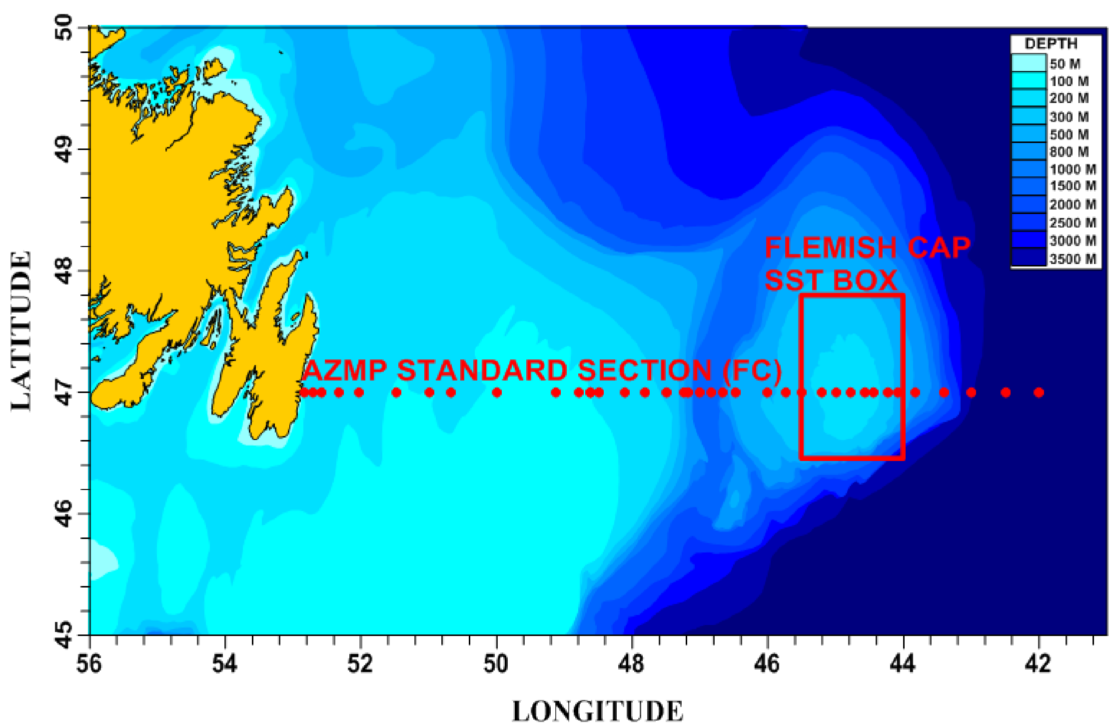

Fig. 2. Areal map showing the standard Flemish Cap (47°N) oceanographic sampling section and the Flemish Cap sub-areas where satellite SST time series were constructed. The red dots show the positions of the stations along the section.

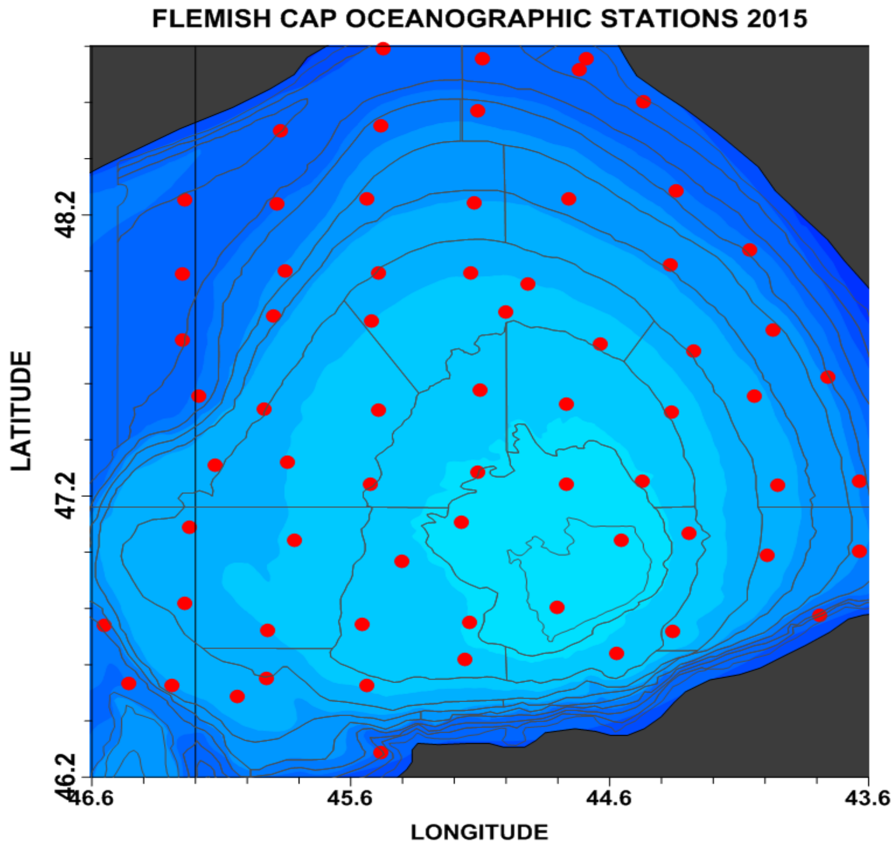

Fig. 3. Map showing the positions of CTD profiles obtained from the summer EU stratified random multispecies survey of the Flemish Cap area during June-July of 2015.

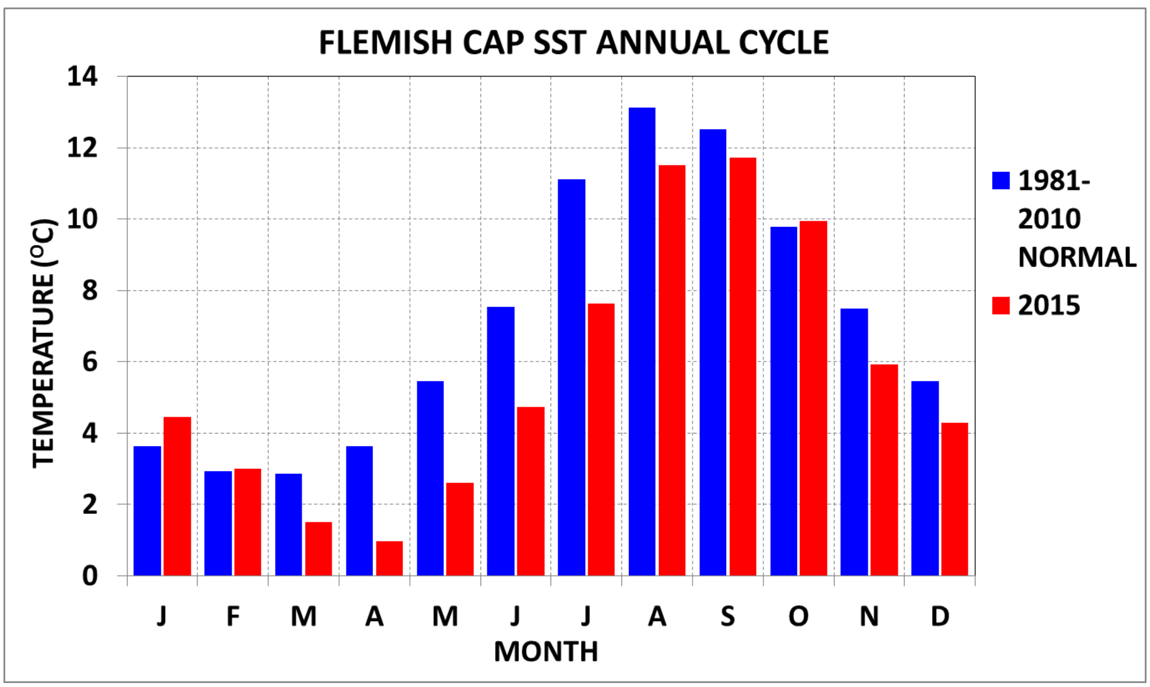

Fig. 4. Sea surface temperatures from the Flemish Cap sub-area (Figure 2) showing the monthly 1981-2010 normal and the 2015 monthly values.

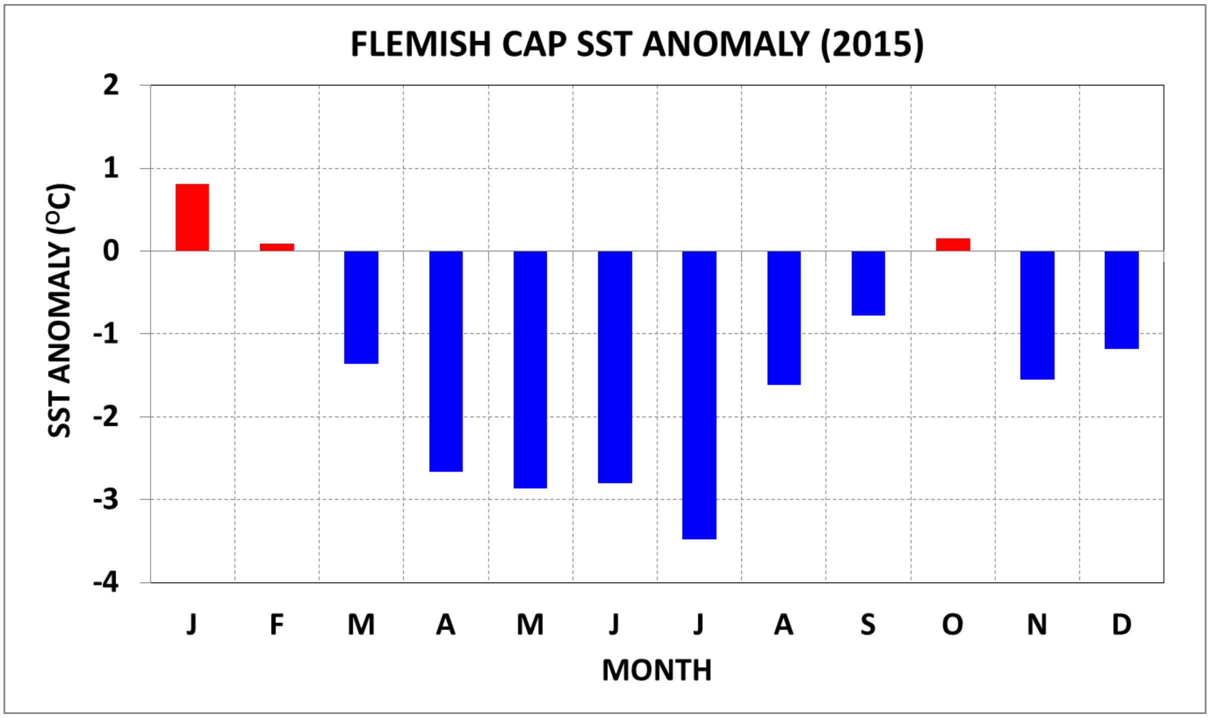

Fig. 5. Monthly sea surface temperature anomalies from the Flemish Cap sub-area (Figure 2) referenced to the 1981-2010 normal.

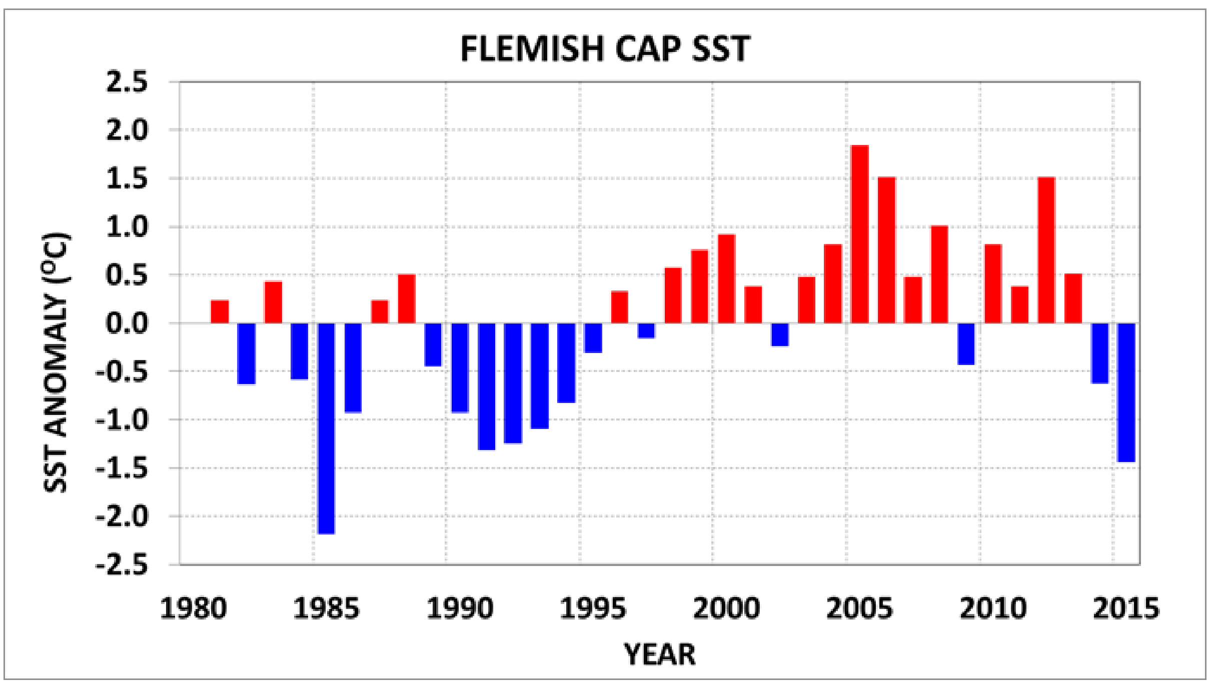

Fig. 6. Annual sea surface temperaures from the Flemish Cap sub-area (Figure 2) referenced to the 1981-2010 mean.

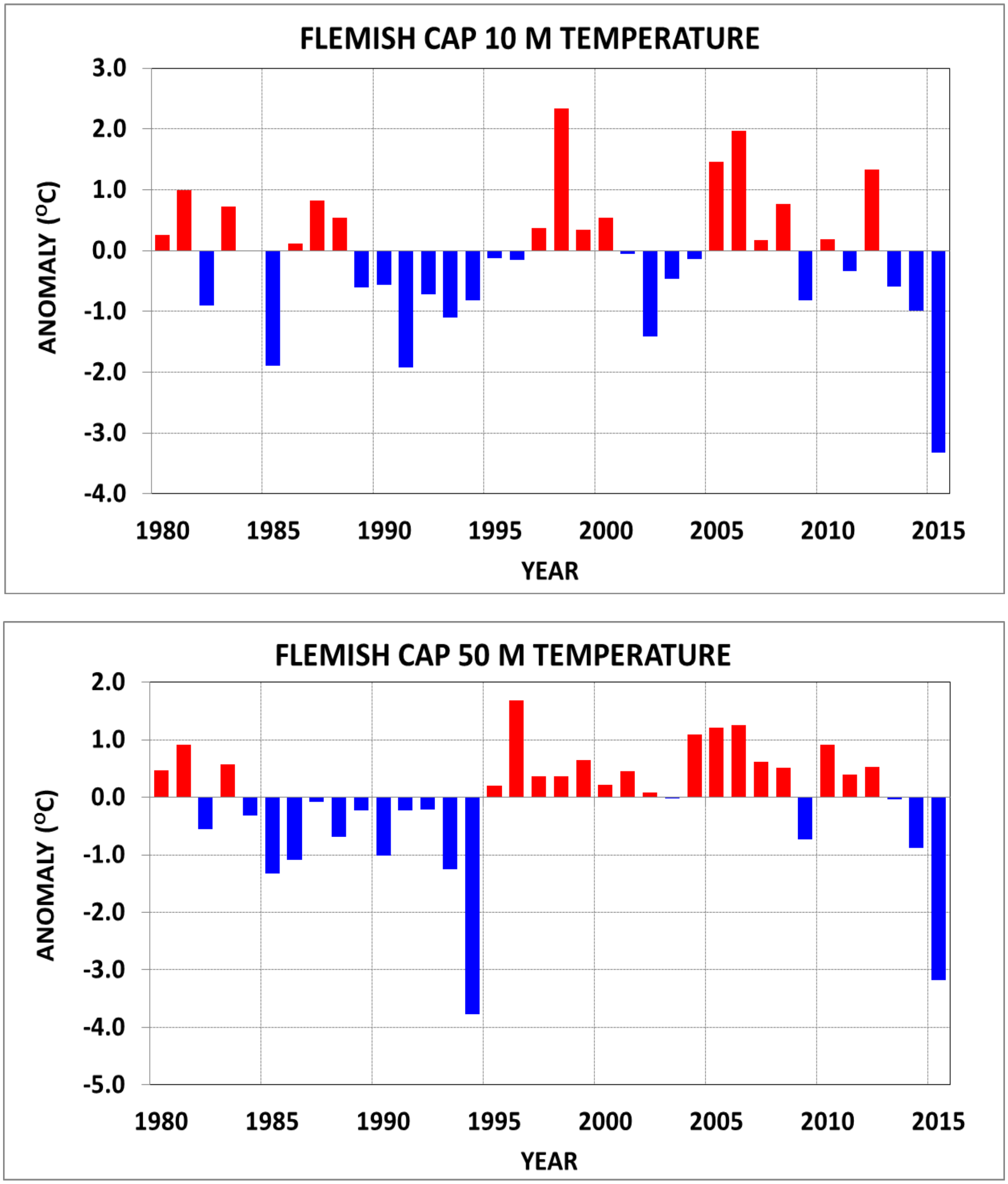

Fig. 7. Annual 10 and 50 m temperature anomalies from the central Flemish Cap referenced to the 1981-2010 mean.

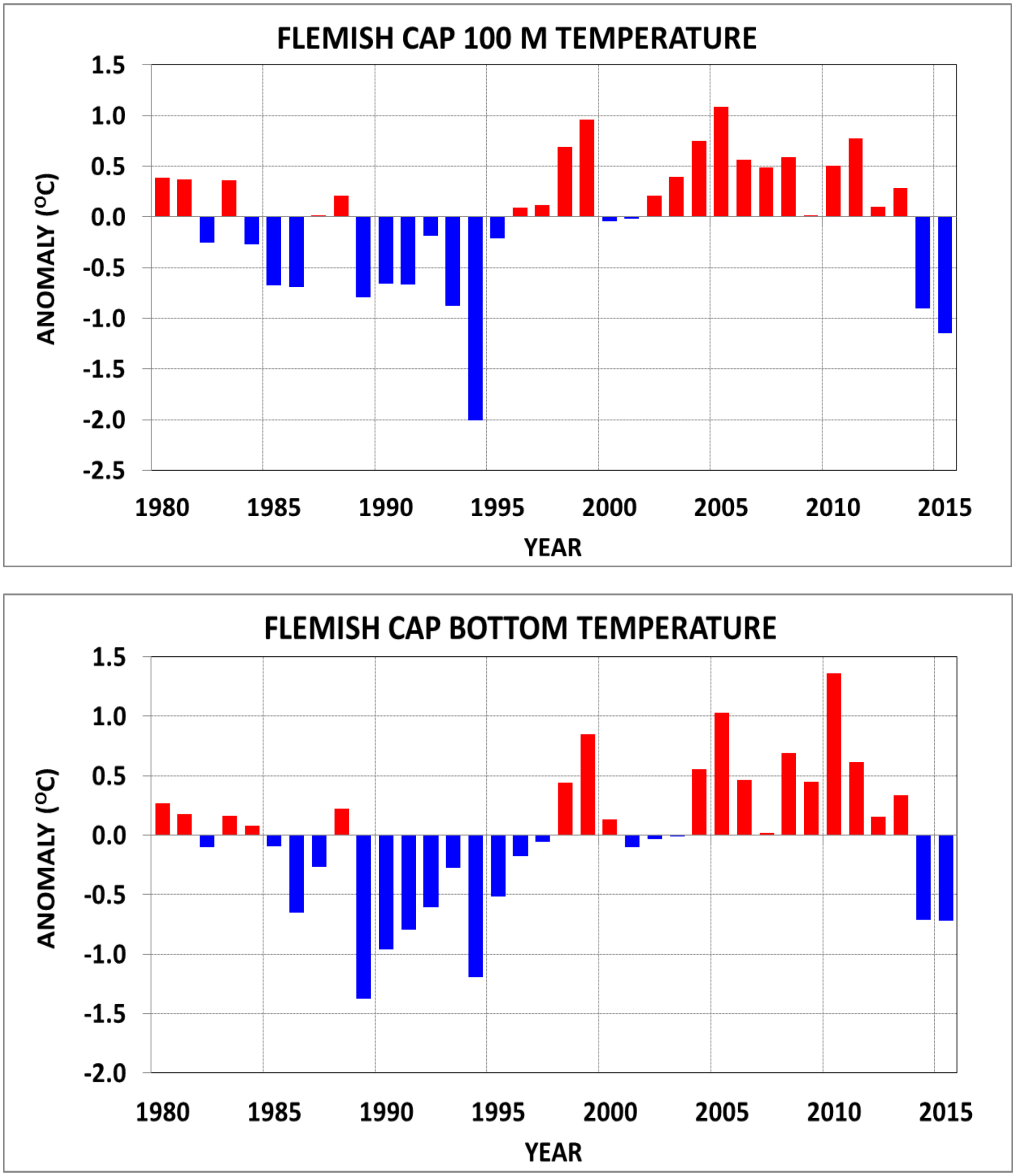

Fig. 8. Annual 100 m and bottom temperature anomalies from the central Flemish Cap referenced to the 1981-2010 mean.

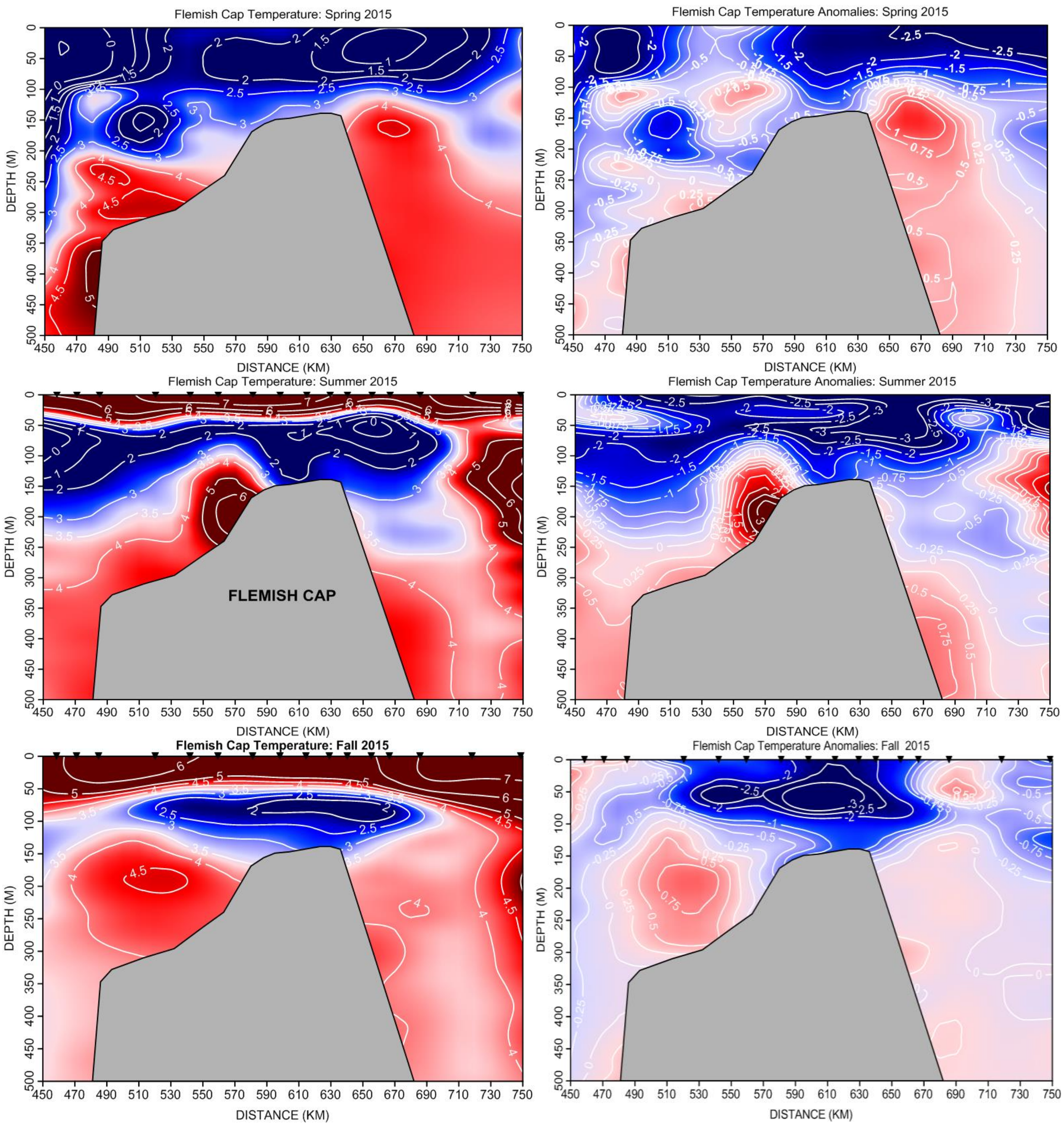

Fig. 9. The vertical distribution of temperature and temperature anomalies (in °C) over the Flemish Cap (along 47°N) for the spring, summer and fall of 2015. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section.

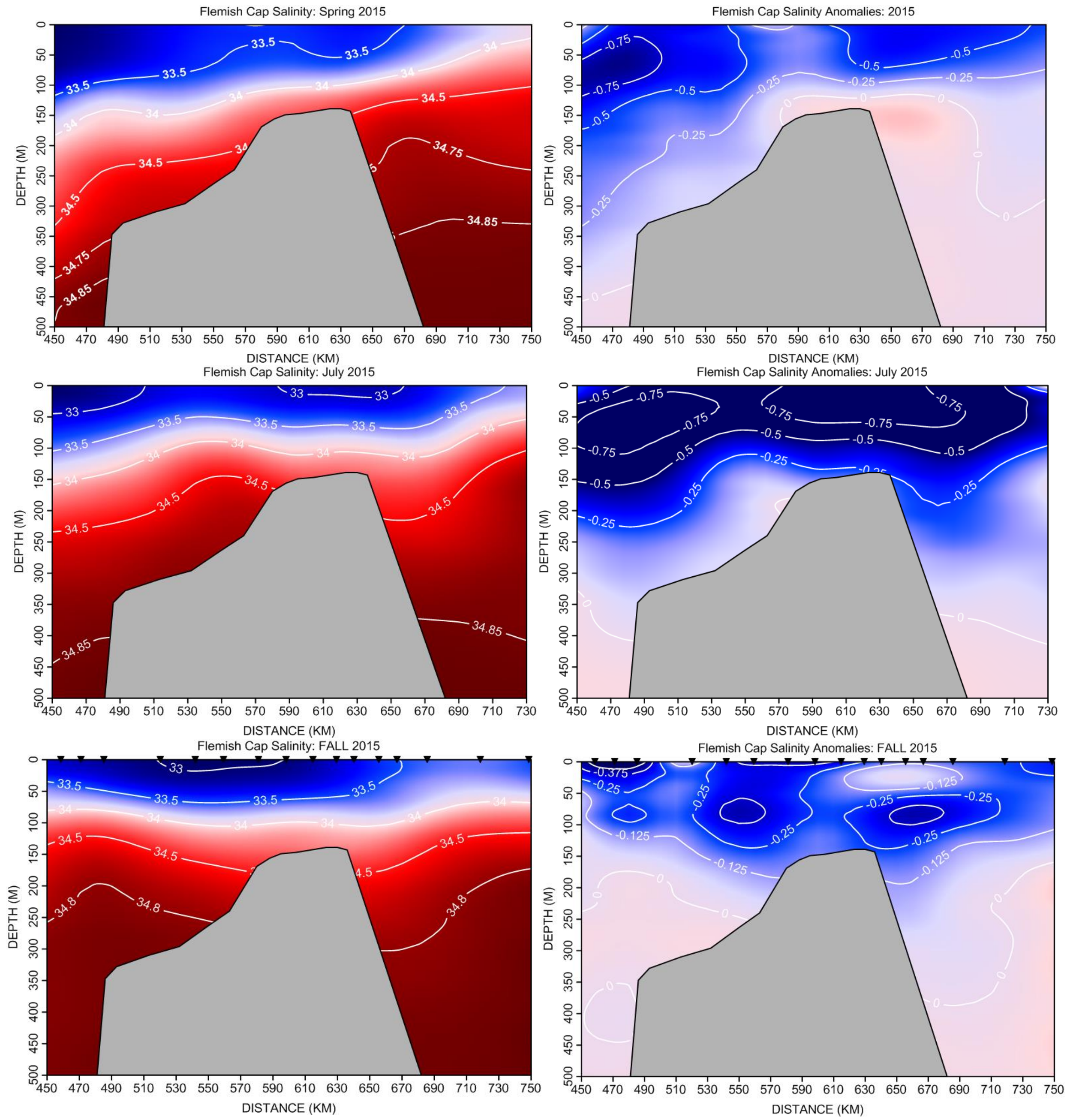

Fig. 10. The vertical distribution of salinity and salinity anomalies over the Flemish Cap (along 47oN) for the spring, summer and fall of 2015. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section.

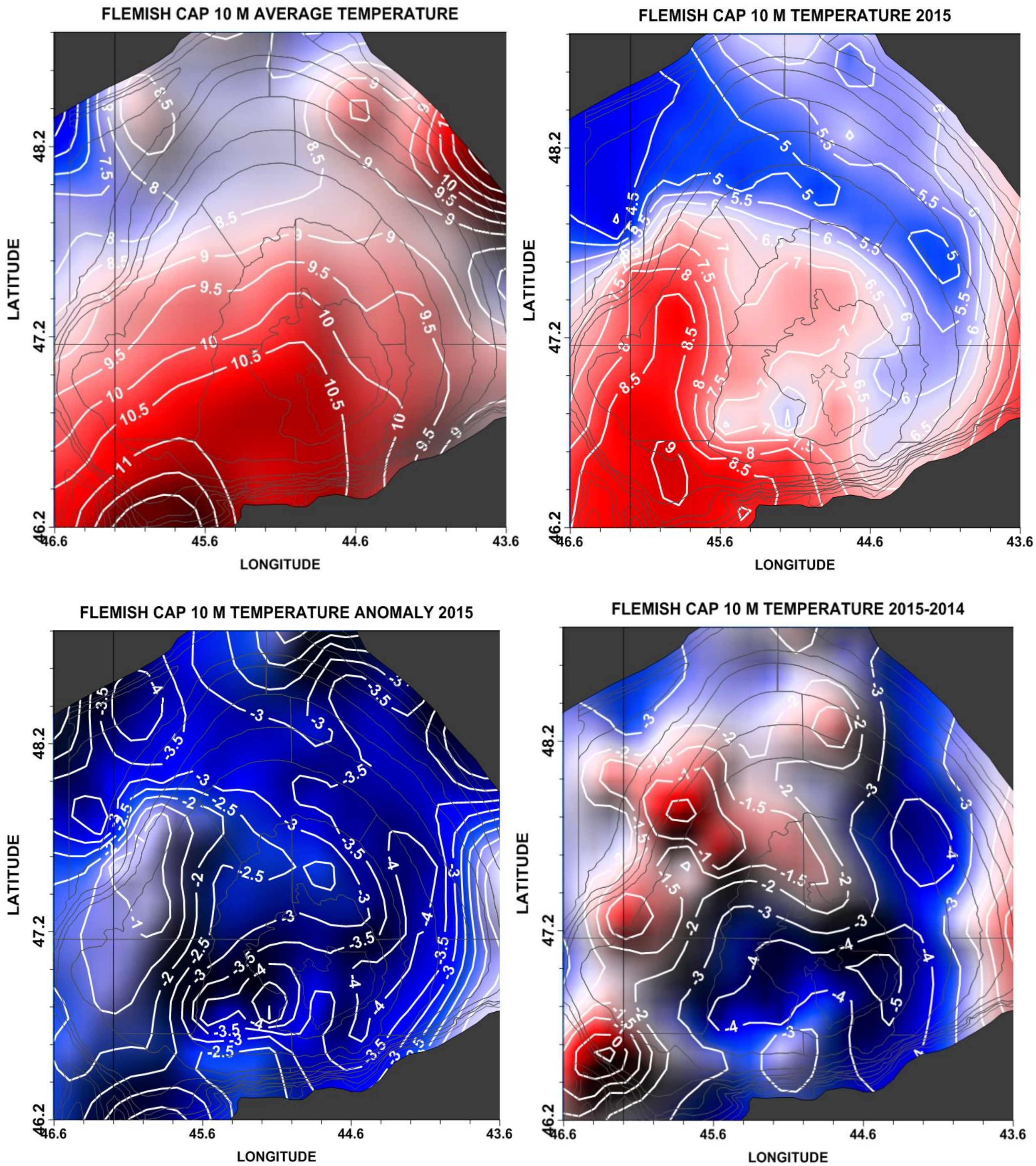

Fig. 11. Maps of the average 10-m temperature (in °C), the 2015 10-m temperature, the 2015 10-m temperature anomalies and 10-m temperature difference from 2014 during the summer (July) based on data collected from 1988-2015 in NAFO Div. 3M.

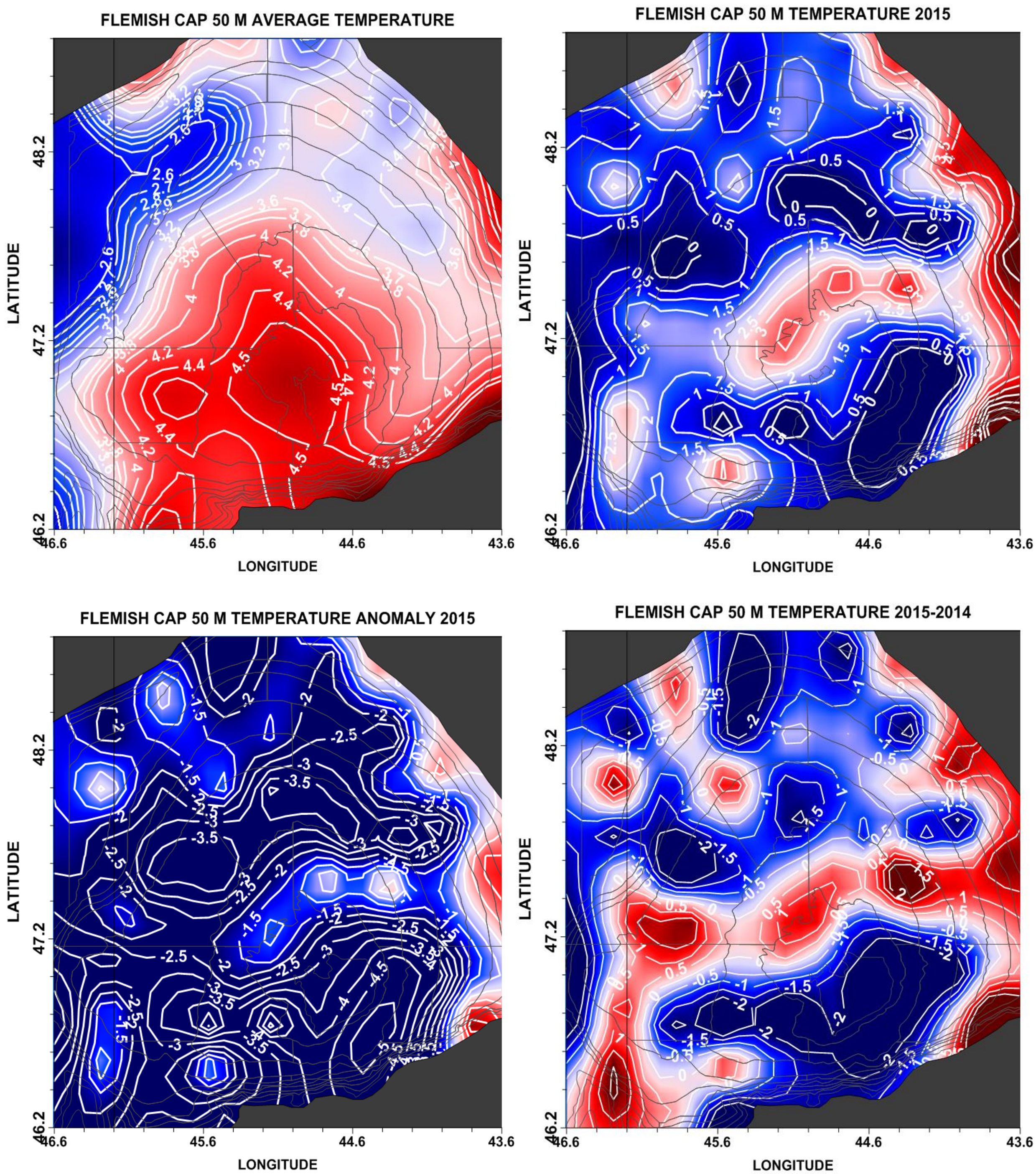

Fig. 12. Maps of the average 50-m temperature (in °C), the 2015 50-m temperature, the 2015 50-m temperature anomalies and 50-m temperature difference from 2014 during the summer (July) based on data collected from 1988-2015 in NAFO Div. 3M.

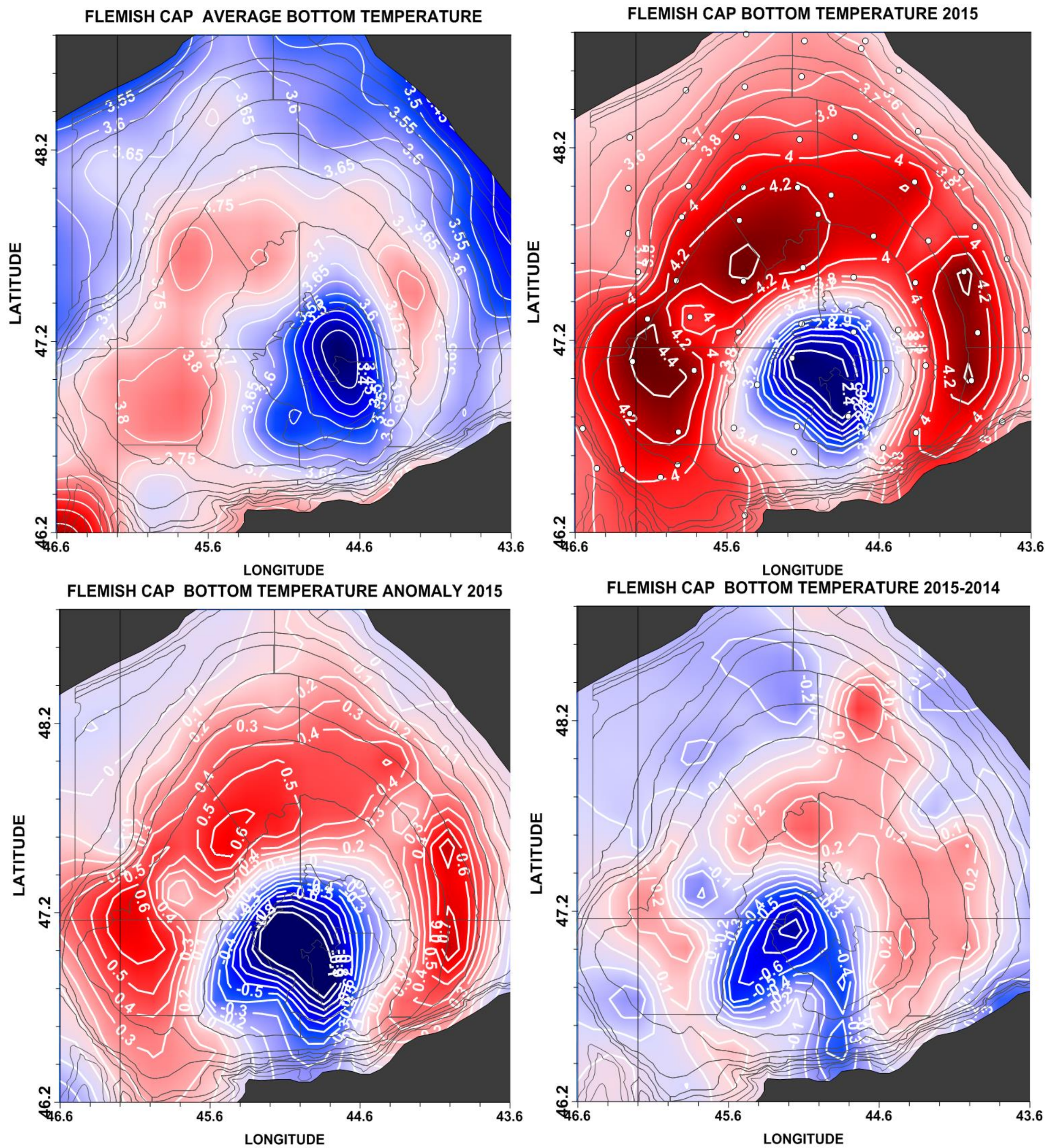

Fig. 13. Maps of the average bottom temperature (in °C), the 2015 bottom temperature, the 2015 bottom temperature anomalies and bottom temperature difference from 2014 during the summer (July) based on data collected from 1988-2015 in NAFO Div. 3M.

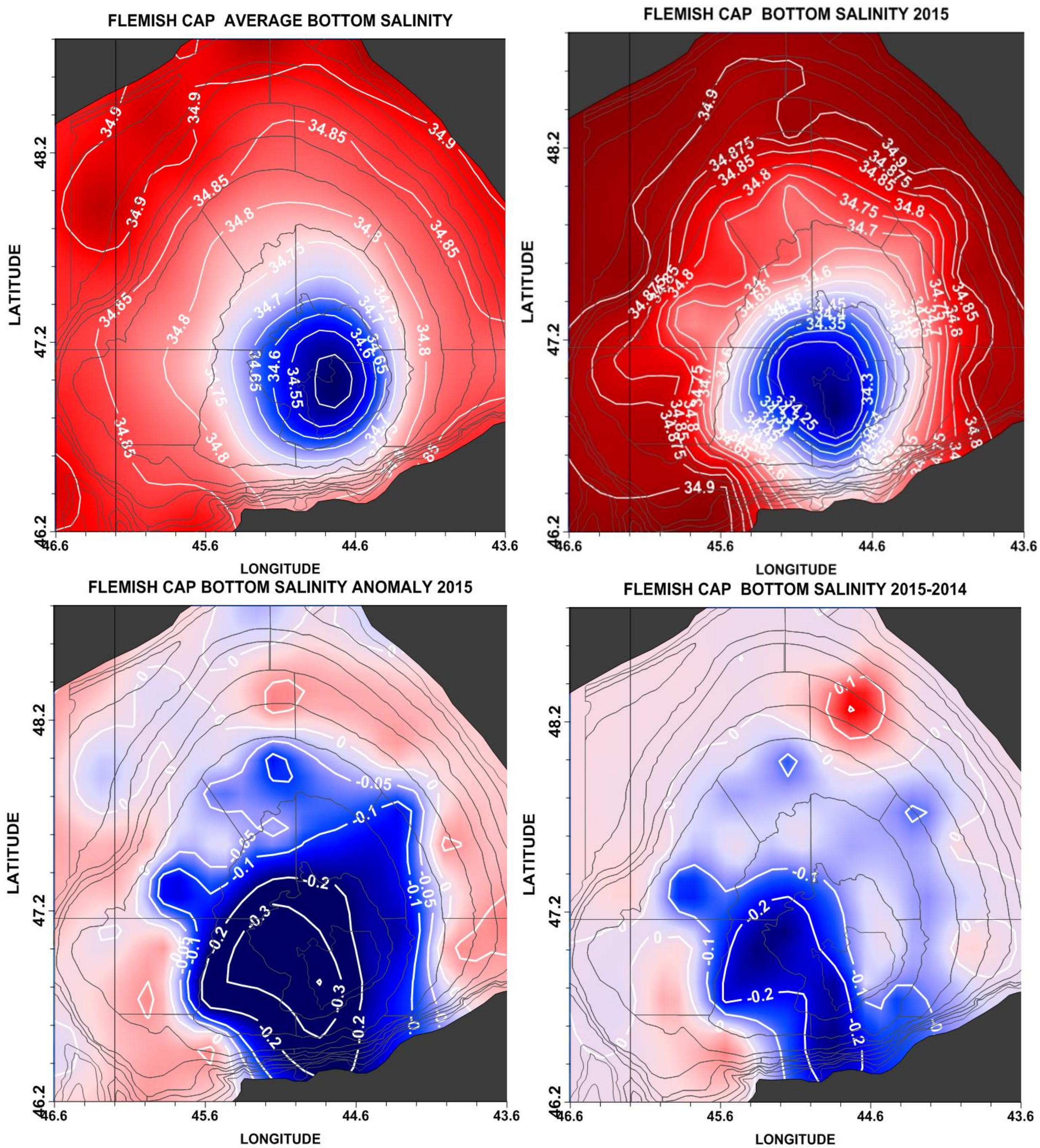

Fig. 14. Maps of the average bottom salinity, the 2015 bottom salinity, the 2015 bottom salinity anomalies and bottom salinity difference from 2014 during the summer (July) based on data collected from 1988-2015 in NAFO Div. 3M.

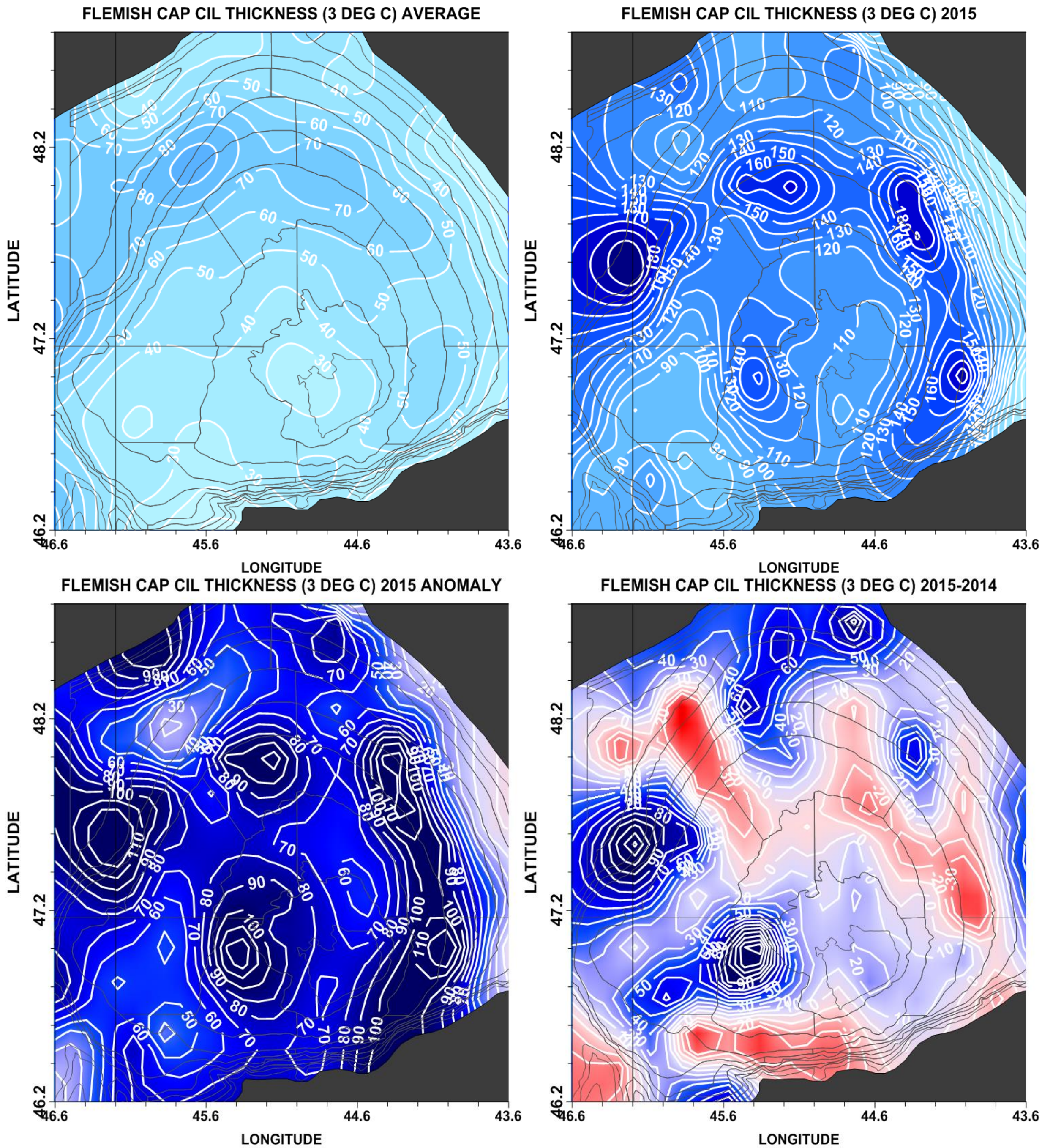

Fig. 15. Maps of the average CIL thickness (in m) defined by water with temperatures <3°C, the 2015 CIL thickness, the 2015 CIL thickness anomalies and the CIL thickness difference from 2014 during the summer (July) based on data collected from 1988-2015 in NAFO Div. 3M.

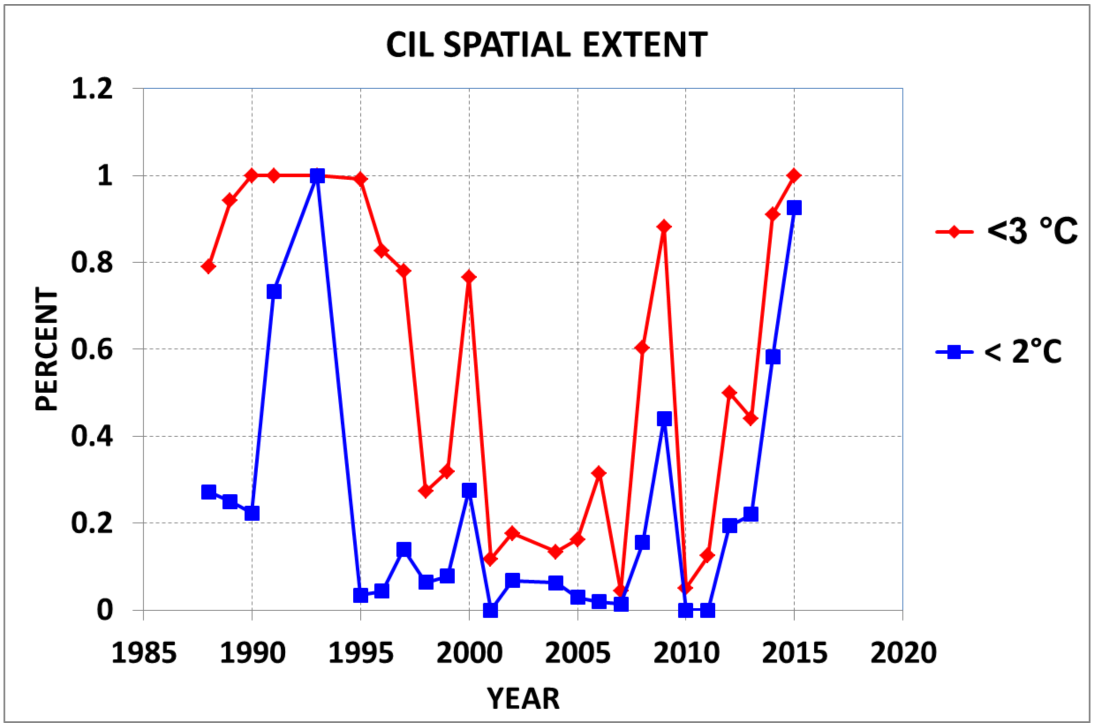

Fig. 16. Percentage by year of the CTD profiles from the Flemish Cap survey where temperature values were lower than <1°C, <2°C and <3°C.

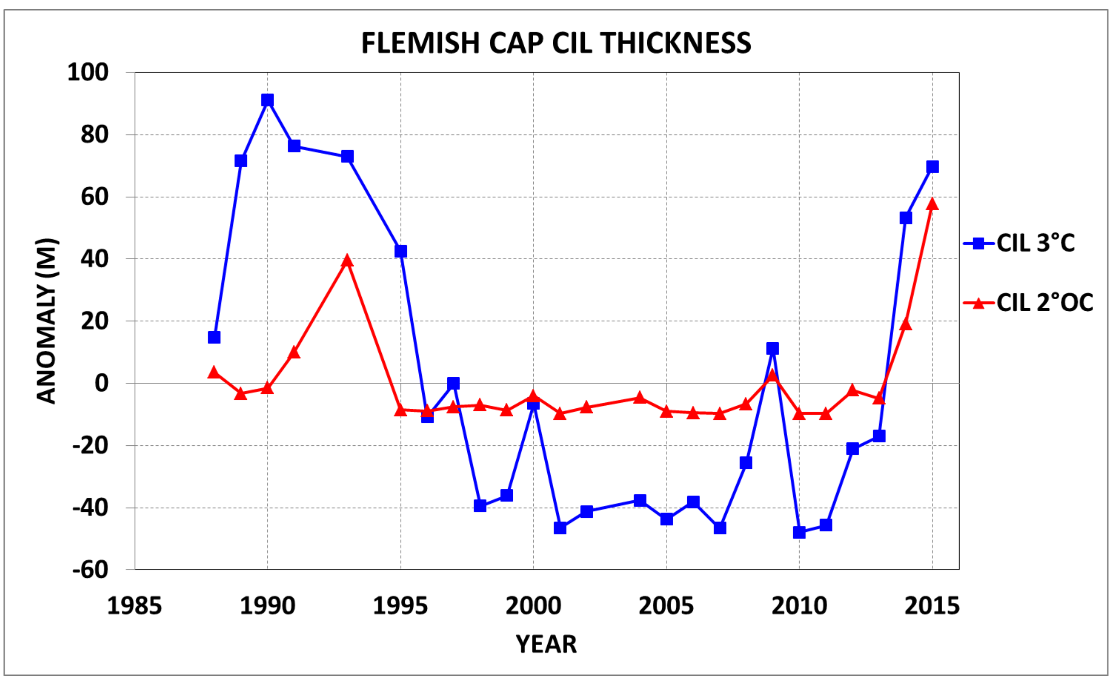

Fig. 17. Thickness of the Cold-Intermediate-Layer (CIL) (M) water mass on the Flemish Cap defined by temperatures <2°C and <3°C.

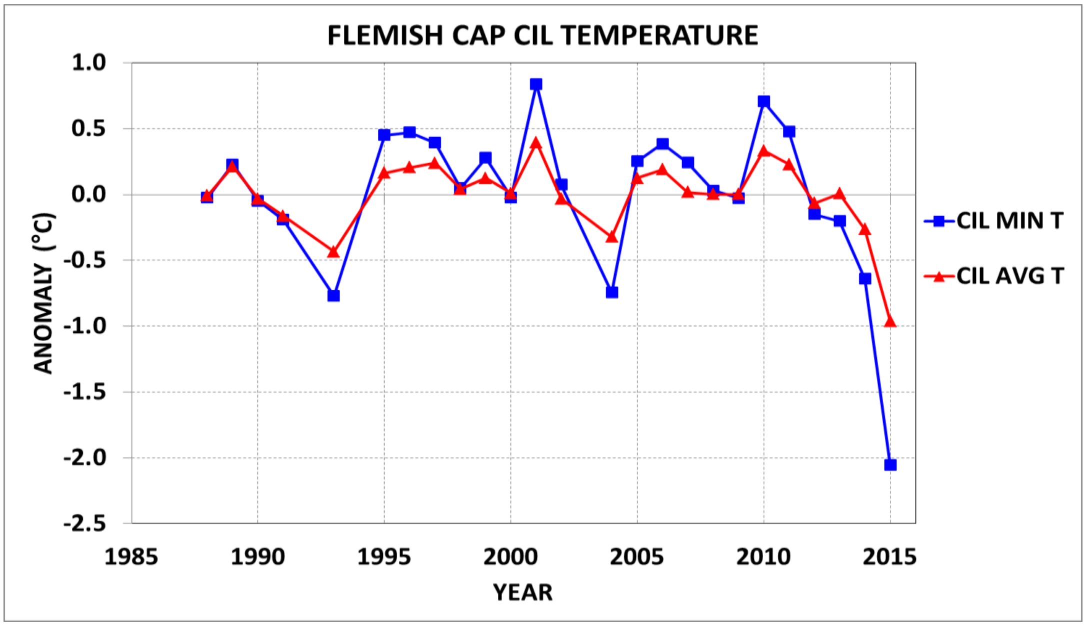

Fig. 18. The Flemish Cap cold-intermediate-layer (CIL) water mass minimum and average temperature.

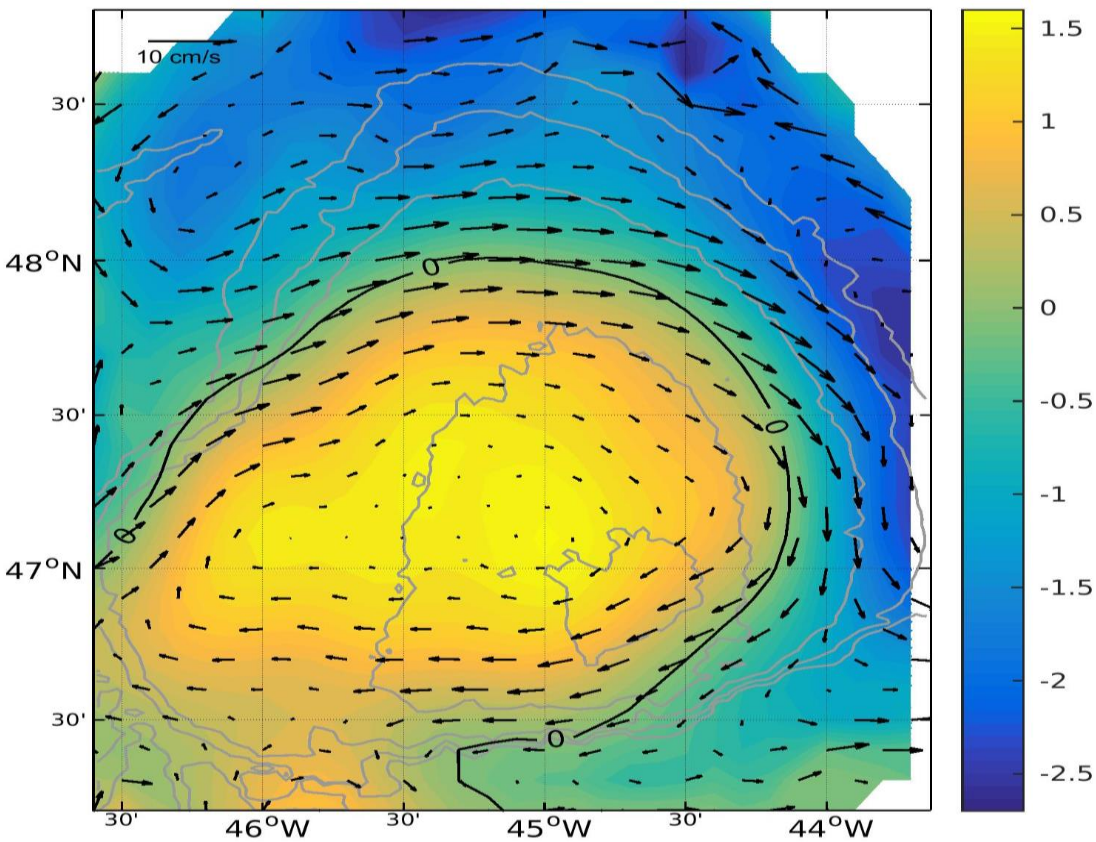

Fig. 19. The mean geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period from 1988 to 2015. The color contours represent the dynamic height field.

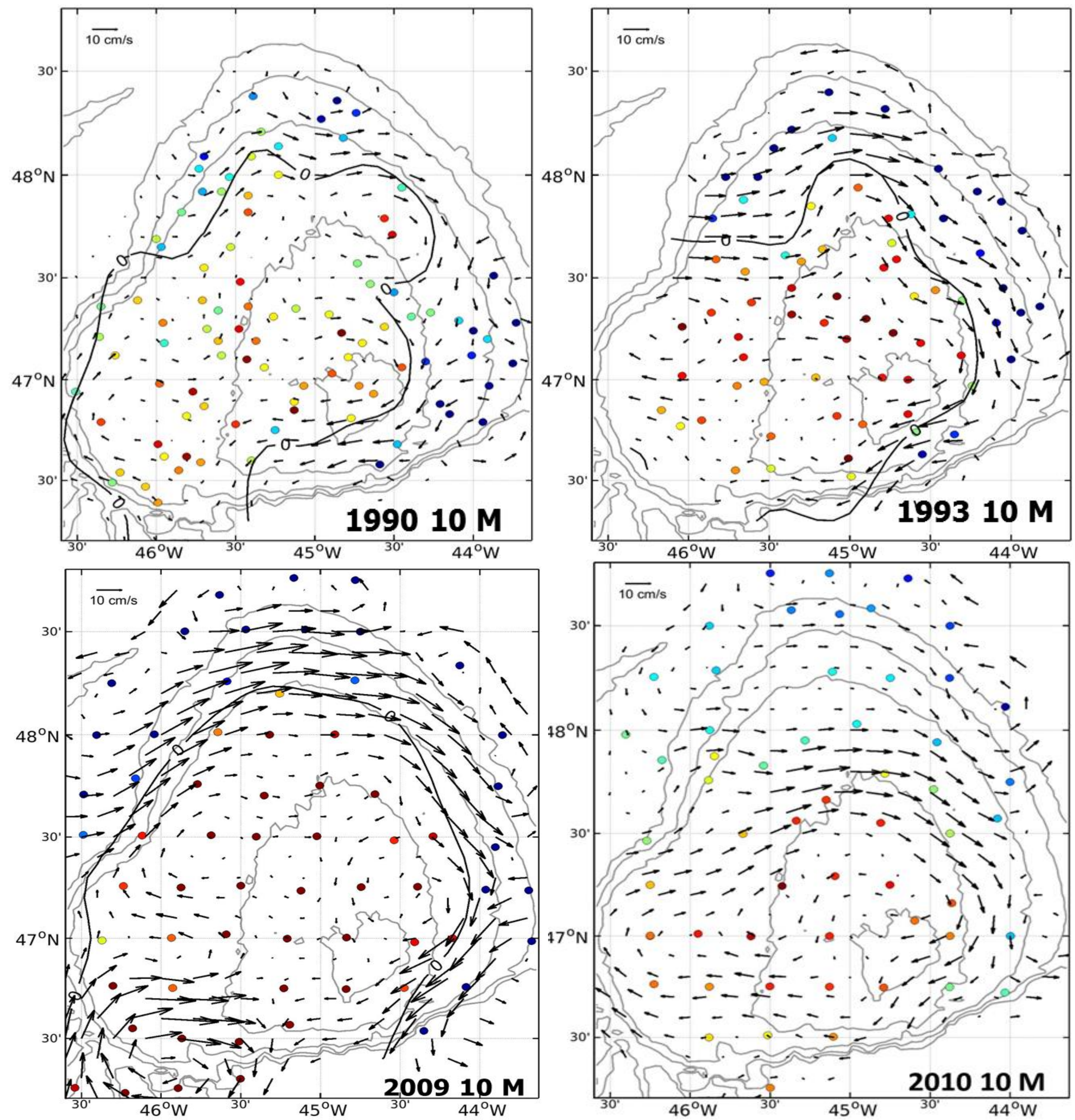

Fig. 20. The geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period for 1990, 1993, 2009 and 2010. The color dots are the CTD locations with the color representing either high (red) or low (blue) dynamic height values.

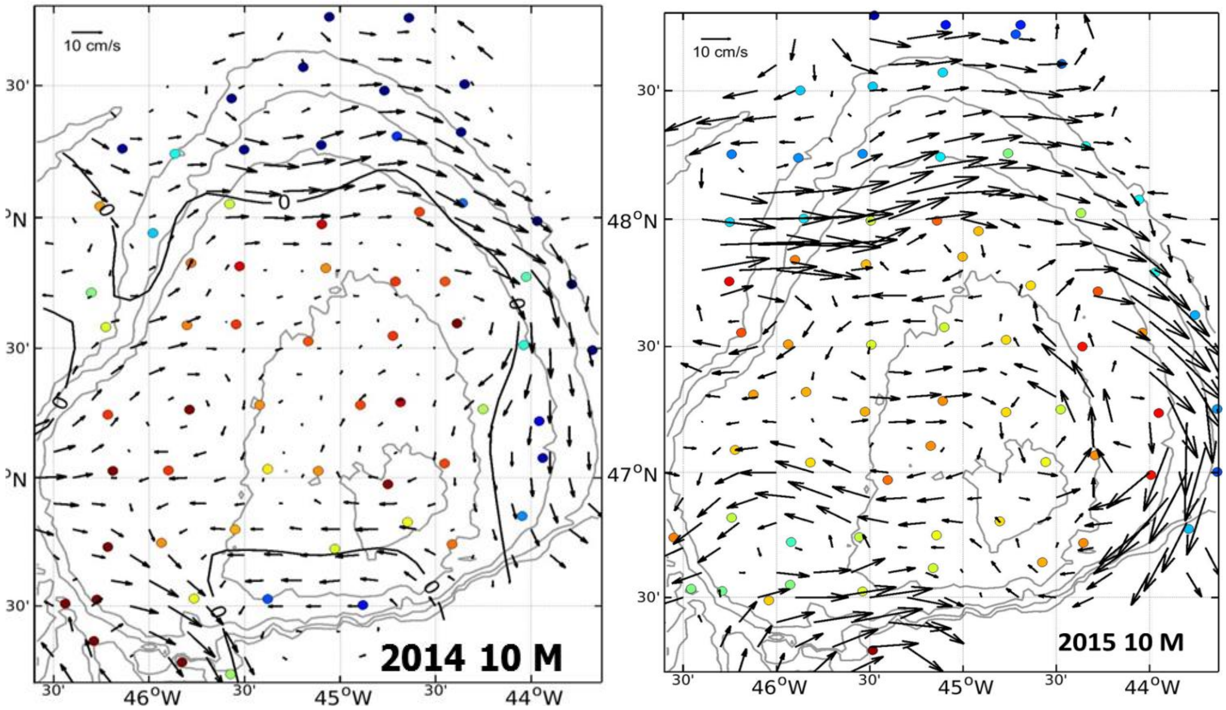

Fig. 21. The geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period for 2014 and 2015. The color dots are the CTD locations with the color representing either high (red) or low (blue) dynamic height values.

YEAR	SURFACE T	10 M T	50 M T	100 M T	BOTTOM T	SURFACE S	10 M S	50 M SAL	100 M S	BOTTOM S	CIL 3°C	CIL 2°C	CIL MIN T	CIL AVG T
1985														
1986														
1987														
1988	0.82	0.72	-0.26	0.07	-0.11	-1.13	-0.81	0.22	0.04	-0.91	-0.31	-0.21	-0.04	-0.03
1989	-0.15	-0.20	-0.33	-0.39	-1.22	0.13	0.03	0.41	0.37	-1.44	-1.51	0.20	0.39	0.76
1990	-0.40	-0.31	-0.55	-1.12	-2.15	-0.75	-0.60	-0.12	-0.34	-2.17	-1.92	0.09	-0.08	-0.12
1991	-1.90	-1.81	-0.71	-1.34	-1.81	0.35	0.33	-0.89	-0.97	-1.83	-1.61	-0.61	-0.32	-0.58
1992														
1993	-1.98	-1.88	-1.38	-1.91	-1.12	-0.04	-0.21	-1.03	-1.32	-0.84	-1.54	-2.41	-1.31	-1.55
1994														
1995	-0.23	-0.23	0.61	-0.81	-1.47	0.87	0.92	0.08	0.06	0.02	-0.90	0.52	0.76	0.58
1996	-0.57	-0.53	1.45	-0.32	-1.18	0.24	0.40	-0.94	-0.47	-0.23	0.23	0.54	0.80	0.73
1997	0.35	0.44	-0.29	-0.26	-0.74			0.46	0.58	0.30	0.00	0.46	0.67	0.85
1998	1.87	1.98	0.09	0.81	-0.28			0.24	0.55	0.10	0.83	0.43	0.08	0.14
1999	0.72	0.79	0.89	1.42	1.07	-0.75	-0.53	-0.28	-0.05	-0.43	0.76	0.53	0.47	0.45
2000	1.14	1.19	-0.55	-0.07	0.64	-2.27	-1.90	-1.03	-0.85	-0.56	0.14	0.24	-0.04	0.03
2001	0.20	0.21	0.53	0.32	-0.12	1.19	1.21	0.64	-0.22	-0.43	0.98	0.59	1.43	1.42
2002	-0.86	-0.98	0.34	0.52	0.06	0.92	1.16	1.02	0.62	-0.26	0.87	0.47	0.13	-0.12
2003														
2004	-0.38	-0.77	0.79	1.02	0.22	1.01	1.26	1.10	1.21	0.36	0.79	0.28	-1.27	-1.15
2005	1.11	1.07	1.14	1.03	0.55	0.24	0.18	0.42	0.96	1.28	0.92	0.55	0.43	0.44
2006	1.18	1.23	0.91	0.57	0.34	0.03	-0.24	0.35	0.59	1.14	0.80	0.58	0.66	0.67
2007	-0.26	-0.26	1.20	0.91	0.66	1.85	1.85	1.11	0.97	0.76	0.98	0.59	0.41	0.06
2008	0.67	0.61	-0.53	0.73	0.84	-1.01	-0.65	0.33	0.43	0.39	0.54	0.41	0.05	0.00
2009	-0.13	-0.08	-0.75	0.10	1.35	0.83	-1.36	-0.87	-0.56	1.01	-0.24	-0.16	-0.05	0.01
2010	-0.66	-0.64	1.20	0.79	0.74	1.13	1.11	0.42	0.79	1.49	1.01	0.59	1.20	1.19
2011	0.36	0.37	0.49	1.02	0.94	0.56	0.76	2.01	1.56	1.49	0.96	0.59	0.81	0.82
2012	1.36	1.39	0.35	0.19	1.02	-0.26	0.11				0.44	0.13	-0.25	-0.24
2013	-0.28	-0.36	-0.17	0.14	1.26	-1.18	-0.82	-0.24	-0.29	0.99	0.36	0.30	-0.34	0.02
2014	-0.20	-0.32	-1.94	-0.74	0.31	-0.89	-0.46	-0.37	-0.42	0.20	-1.12	-1.17	-1.09	-0.94
2015	-1.77	-1.63	-2.53	-2.69	0.19	-1.08	-1.73	-3.03	-3.25	-0.43	-1.47	-3.52	-3.49	-3.44

COLD FRESH						WARM SALTY					
<-2.5	-2.5 to -2.0	-2 to -1.5	-1.5 to -1.0	-1.0 to -0.5	-0.5 to 0.0	0.0 to 0.5	0.5 to 1.0	1.0 to 1.5	1.5 to 2	2.0 to 2.5	>2.5

Fig. 22. Standardized anomalies of oceanographic indices based on data collected from 1988-2015 during the June-July EU multi-species survey of the Flemish Cap in NAFO Div. 3M. Grey cells indicate no data.

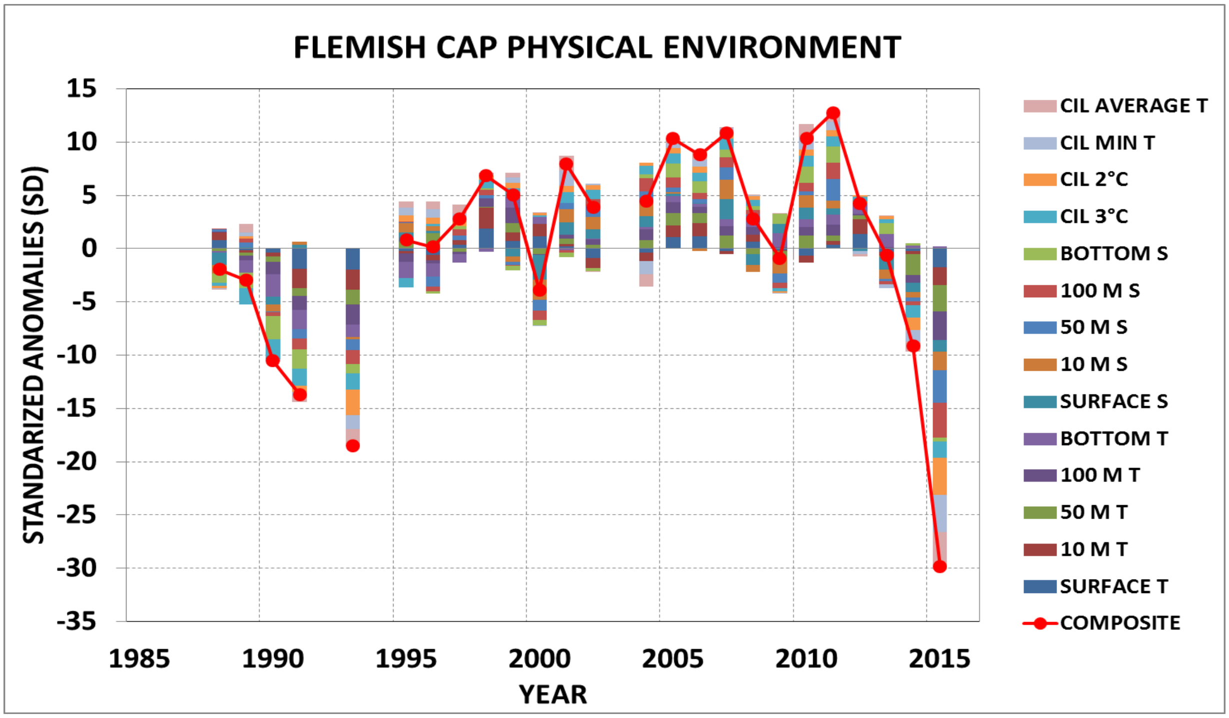

Fig. 23. Composite climate index (red line) derived by summing the standardized anomalies from Figure 22 together with their individual components.