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Ocean Climate Variability on the Flemish Cap in NAFO Subdivision 3M during 2017

by

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ABSTRACT

Oceanographic observations from seasonal surveys in NAFO Division 3M during 2017 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) increased over the previous two years but remained at -0.5°C below normal in 2017. Annual water column temperatures were -1.2°C, -0.3°C, -0.5°C and -0.2°C below normal at depths of 5, 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 a well-defined cold-intermediate layer (CIL) with T<3°C that penetrated to the bottom during the fall (December) survey in 2017. Water column temperatures along the section were predominately above normal in the upper layers during spring (April) and below normal in most areas during the summer and fall when values as low as -2° below normal were observed. Bottom temperatures below 200 m depth were generally near the long term mean. The corresponding salinity cross-sections show near-normal values except for a strong negative anomaly during the summer on the Flemish Pass side of the Cap where values reached >0.5 below normal. The spatial extent of the CIL (<3°C) covered over 80% of the area during the summer 2017 EU survey with average thickness of about 66 m or about 15 m thicker than normal. During the summer of 2017, both the CIL minimum and average observed core temperature was slightly above normal, a significant increase over the record cold values observed in 2015. A composite climate index derived from several metrics based on the EU summer survey show a cooling trend since 2012 that reached a record low in 2015 but has since moderated with 2016 and 2017 returning to near-normal conditions over most of the water column. In general, data from four surveys in NAFO division 3M on the Flemish Cap during the past several years captured a significant event highlighted by an unprecedented cold-fresh water mass over the Flemish Cap that peaked in 2015. Both geostrophic current estimates and direct ADCP measurements showed a very dynamic circulation pattern in 2015 with record high southward flowing LC water over the Cap. In 2017, the circulation pattern was completely different with northward flowing water dominating and temperature and salinity conditions returning to near-normal values over most of the water column except in the near-surface layer where temperature values remained below normal.

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 (Figs. 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.

In the absence of strong wind forcing (mainly summer) the circulation over the Flemish Cap is influenced by a topographically induced anticyclonic gyre over the central portion of the bank (Gil et al. 2004, Colbourne and Foote 2000, Kudlo et al. 1984, Ross 1981). It has been suggested that the stability of this circulation pattern may influence the retention of ichthyoplankton on the Cap 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).

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, 2015, 2016) were produced using data collected on the Flemish Cap fisheries research surveys conducted by the European Union and by Fisheries and Oceans, Canada.

This manuscript presents an updated overview of oceanographic conditions on the Flemish Cap in NAFO subdivision 3M during 2017 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 2017 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 1988-2017 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 2017.

SATELLITE SEA-SURFACE TEMPERATURE CONDITIONS

The 4 km resolution Pathfinder 5.2 sea surface temperature (SST) database (Casey et al., 2010) archived at Bedford Institute of Oceanography (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 2012. Updated values for 2013 to 2017 were available from NOAA satellite data provided by the remote sensing group in the Marine Ecosystem Section at BIO. These updates were adjusted by using a least squares fit of the Pathfinder and NOAA temperatures during the period (2001-2012) given by SST (Pathfinder) = 0.988*SST (NOAA) -0.02 with an r^2=0.98 (Hebert et al. 2018).

The Flemish Cap SST climatology together with the 2017 annual cycle is shown in Fig. 4. On average SST generally range from 2°C - 4°C during winter and early spring then increases to a maximum of about 13°C in August which subsequently decrease to about 5°C in December. In 2017 SSTs were slightly below normal during most months except during June and July when they were near 1-2°C below normal (Figs. 4 and 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 then SST has increased over the low in 2015 reaching -0.5°C below normal in 2017. From 1995-2014, only 6 out of the 19 years had below normal values, however, during the past 4 years SST have been below normal with 2015 showing 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 5, 50, 100 m and near-bottom are shown in Figs. 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 5 m depth the time series of temperature anomalies show a high degree of variability since 1980 unlike the SST values shown in Fig. 6 which show a consistent trend. Since 2012, values have been decreasing reaching a series record low in 2015 but then increasing slightly during the past 2-years but remaining below normal by 1.2°C in 2017. At depths 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 4 years, with the 2015 values reaching the second lowest in the series after 1994. At 50 and 100 m depth temperatures were below normal by -0.3°C and -0.5°C, respectively in 2017.

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 bottom temperatures on the Flemish Cap were either near-normal or above normal reaching a peak of >1°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. In 2016 and 2017 bottom temperatures were slightly below normal at -0.2°C.

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 2017, the Flemish Cap section was sampled by the AZMP during April, July and December. 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 2017 (Figs. 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 adjacent Newfoundland Shelf waters with a sub-surface 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 Figs. 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 >3.5°C. The development of a well-defined cold-intermediate layer (CIL) with T<3.5°C over the Cap was strong during the spring, summer and fall of 2017. In the spring these cold waters extended from near surface to the bottom over the shallower areas of the Cap (Fig. 9).

The corresponding salinity cross-sections show the relatively fresh upper layer shelf water originating from the Newfoundland and Labrador Shelf with values <33.5 extending out over the Cap, contrasting to the saltier Labrador Slope water (34<S<34.8) over the Cap and across the region at depths of 100-400 m. In the deeper water >400 m salinities were >34.8 and are derived mainly from North Atlantic Current water from the south (Fig. 10).

During 2017, temperatures along the section were predominately below normal during all seasons except in the upper layer during the spring when values reached 1°C above normal in some areas. 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 ranged from near-normal to slightly above normal in the deeper layers (>200 m) during the summer and fall surveys (Fig. 9).

Except for a strong negative salinity anomaly during the summer on the Flemish Pass side of the Cap, salinities were generally near normal in most areas to 500 m depth. In general, the seasonal salinity anomalies were much higher in 2017 compared to the fresh anomalies observed in 2015 (Colbourne et al. 2016).

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 1988-2017. The 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 2247 CTD stations available since 1988 were included in this 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 2017 the EU bottom trawl survey in Flemish Cap (Div. 3M) was carried out on board R/V Vizconde de Eza from June 13th to July 19th. The 2017 survey covered depths up to 1430 m with 71 CTD stations sampled (González-Costas et al. 2018) (Fig. 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 2017 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.

Spatial maps of the temperature climatology (1988-2015), the 2017 temperature, the 2017 temperature anomaly as well as the difference from 2016 at 10 m depth over the Flemish Cap are displayed in Fig. 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 2017, conditions were generally colder with cold LSW covering much of the northern half of the Cap where near surface temperatures ranged from 3.5°C - 8°C. NAW dominated the southern areas where temperatures ranged from 8°C – 9.5°C. 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 2016 values by 1°C - 4°C in western and central areas (Fig. 11).

Similarly, temperature conditions at 50 m depth over the Flemish Cap are displayed in Fig. 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 2017, conditions were quite variable with pockets of warmer water over the southern areas where temperatures exceeded 5°C. Temperature anomaly at 50-m depth show values varying about the mean with colder than normal conditions over most of the slope areas. Except for isolated areas these values represent an increase over 2016 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 Figs. 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 NAC water 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 Slope water is dominant with salinities ranging from 34.5-34.7 (Fig. 14).

In 2017, bottom temperatures ranged from 3.6°C to 3.8°C in the shallow area of the centre of the Cap which were close to the long-term average. In deeper waters around the Cap temperatures ranged from 3.8°C to 4°C which were 0.2°C to 0.3°C above normal except for outer periphery where they were about normal (Fig. 13). Salinities during 2017 show relatively low values (<34.5) over the centre part of the Cap compared to 34.8-34.9 in deeper waters. These bottom values were generally close to normal in all areas of the Cap and represent a slight increase over 2016 values in some areas (Fig. 14).

While near-surface temperatures continued to experience colder than normal conditions in 2017 is appears that both temperature and salinity increased over the record cold/fresh conditions observed in 2015 (Colbourne et al. 2016). Even 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 which was 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 and the central shallow areas as low as 2.6°C (Colbourne and Perez-Rodriguez 2015).

COLD INTERMEDIATE LAYER (CIL)

The temperature profiles collected on Flemish Cap from 1988-2017 by the EU bottom trawl surveys were also used to explore the characteristics of the CIL on the Flemish Cap during the June-July period. The water mass 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 sub-surface 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 spatial coverage or presence of CIL water (based on thresholds of <1°C, <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 Cap, 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 Fig. 15 for average conditions, the 2017 conditions and corresponding 2017 anomalies as well as the difference from 2016. On average the CIL thickness range from 30-40 m in the southern areas to 70-80 m in north western areas within the Labrador Current extension. In 2017, the CIL was thicker in the north western areas with values in the range of 100-180 m within the Labrador Current (Fig. 15 top right panel). These values were as much as 120 m thicker than normal but in the eastern and southern regions the CIL was actually thinner than average. Except for isolated areas, the vertical extent of CIL waters <3°C decreased compared to 2016 by over 50 m in some areas (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, 93% reported water <2°C, the 2nd highest in the series after 1993 and 80% reported water <1°C the highest in the 30-year time series (Fig. 16). In 2016 and 2017 while the extent of CIL water over the Cap remained above 80% the extent of water with temperatures <1°C and <2°C decreased significantly to <20%.

In accordance with the expected negative relationship of the CIL spatial coverage with the average surface and bottom water temperature at the three temperature thresholds (1°C, 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 Figs. 7 and 8).

The average thickness of the CIL (<3°) displayed in Fig. 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 is very low but reached over 40 m in 1994 and over 60 m in 2015, the highest in the time series. For CIL water defined by temperatures <1°C the thickness, except for 2015, is very low close to 0 in most years. In 2016 and 2017 the CIL (<3°) decreased significantly from 2014 and

2015 but remained above normal while that for <2° and <1° decreased to below 20 m in 2016 and to near 0 in 2017 (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. In 2017 temperatures conditions within the CIL waters had increased to slightly above normal.

CIRCULATION AND TRANSPORT

The Flemish Cap is located in the confluence zone of sub-polar and sub-tropical western boundary currents of the North Atlantic. 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.

Geostrophic Circulation

In this section we examine the baroclinic component of the circulation around the Flemish Cap from the 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 assumption 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 1988-2017 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, albeit weak, 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 (Fig. 19). The centre of the circulation appears at approximately 47° 15’ N, 45° 15’ W indicated 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. The strongest flow occurs in the northern and eastern regions where the influence of the LC dominates.

Geostrophic current maps for individual years shown in Fig. 20 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. Current speeds ranging from 10-15 cm/s corresponds to maximum re-circulation times ranging from approximately 50-70 days.

Geostrophic current maps for the most recent years of 2014 to 2017 show significant annual variability with 2014 showing a weak circulation pattern dominated by the LC and a weak incoherent flow in 2017. During 2015 the flow was much stronger with speeds ranging from 10-18 cm/s around the periphery of the Cap, with a large area of weak currents towards the central region. The circulation patterns shown in 2009 and 2015 represent the strongest baroclinic flows in the 1988-2017 time series.

In 2015 the circulation of water masses around the Cap also appears in the temperature and salinity fields. In particular, the fall temperature and anomaly patterns shown in Colbourne et al. (2016) showed what appeared to be LC water with temperature anomalies of 2° to 3°C below normal, trapped within the anticyclonic gyro over the Cap. More research is needed 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.

ADCP Measurements

An analysis of data showing the circulation and transport through the Flemish Cap portion of the standard Flemish Cap (47°N) AZMP section (Figure 2) based on direct current measurements using vessel mounted 75 kHz Acoustic Doppler Current Profilers (ADCP) at 8 m resolution with an effective range of about 620 m. All archived ADCP data were used to compute currents and transport along the standard Flemish Cap (47°N) section for the years 2008 to 2017. The ADCP data were collected using Teledyne RDI VmDas and processed using the CODAS3 software suite developed by the University of Hawaii. The data were quality controlled with a percent good threshold of 70 80%. Absolute currents were determined by subtracting ship motion as determined by the ship's 3D DGPS system. Currents were then de-tided using tidal predictions obtained from a high-resolution numerical 2 dimensional tidal model.

The north-south component of the Labrador Current through 47°N for the spring and summer of 2015, 2016 and 2017 are shown in Fig 22. The current field during the spring exhibits considerable variability with generally weak flows over the center of the Cap, a weak northward component on the Flemish Pass side and a stronger component of the Labrador Current to the east of the Cap. In this region peak current speeds range from 20-40 cm/s with 2015 showing extensive Labrador Current flow that decreased during 2016 and weakened even further in 2017. During the spring of 2017 the Grand Bank slope-Flemish Pass component extended further offshore towards the Cap than the previous years.

During the summer current speeds in 2015 were very similar to the spring observations with extensive Labrador Current water over most areas of the Cap. In 2016 the southward flowing Labrador Current was restricted to a narrow jet about 75 km wide with peak currents ranging from 25-30 cm/s. Over the western areas the flow was dominated by northward flowing water possibly contributing to the anti-cyclonic circulation over the Cap during the summer. During the summer of 2017 most of the flow from the Flemish Pass to east of the Cap was dominated by strong northward flow with speeds up to 30 cm/s. The offshore Labrador Current was detected between the last two AZMP stations of the section which possibly extended further offshore (Fig. 22 bottom right panel).

Labrador Current transport values for each survey were computed for offshore branch of the Labrador Current in the shaded area from 650-750 km in the eastern part of the Flemish Cap section shown in the top panel of Fig. 23. Currents in the top 15 m of the water column were extrapolated from the values in the first 8 m data bin (16 24 m). Transport values were then calculated by integrating from the surface to the near bottom bin or to the maximum range of 620 m along the section.

Southward transport values for the spring and summer surveys from 2008 to 2017 are shown in Fig 23. No ADCP data were available for 2011-2013. Spring transport values ranged from just over 2 Sv in 2009 to 13 Sv in 2015, a similar pattern was observed during the summer. The spring transport decreased to about 9 Sv in 2016 and to just over 3 Sv in 2017. During the summer the transport peaked at 12 Sv in 2015 and has since decrease to 2 Sv during the summer of 2017. Northward transport values through the western part of the Flemish Cap section during the summer surveys are shown in Fig. 24. The northward transport comprised of NAC water and re-circulated LC water ranged from <1 Sv to near 5 Sv in 2017. The high value in 2017 is reflected in the current field shown in Fig. 22 as northward flow dominated the region. Conversely the low value observed in 2015 resulted from the dominance of the southward flowing LC water (Fig. 22). An examination of the geostrophic currents also 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 (Colbourne et al. 2016).

SUMMARY

A summary of selected temperature and salinity time series and CIL indices for the years 1988-2017 based on the EU data set are displayed in Fig. 25 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 1988–2017. 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. 25). 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 15 time series as the sum (red line) of the standardized anomalies with each series contribution shown as stacked bars (Fig. 26). The composite index may 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. 26). During the past 2-years conditions have moderated considerably with the composite index returning to normal conditions. In general, data from four surveys in NAFO division 3M on the Flemish Cap during the past several years captured a significant event highlighted by an unprecedented cold-fresh water mass over the Flemish Cap that peaked in 2015. Both geostrophic current estimates and direct ADCP measurements showed a very dynamic circulation pattern in 2015 with record high southward flowing LC water over the Cap. In 2017, the circulation pattern was completely different with near-zero geostrophic currents at 47 N and generally northward flowing water dominating the ADCP measurements. In 2017 temperature and salinity conditions returned to near-normal values over most of the water column except in the near-surface layer where temperature values remained below normal.

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REFERENCES

Akenhead, S. 1981. Local sea-surface temperature and salinity on the Flemish Cap. NAFO SCR Doc. 87/66, Ser. No. N426 20 p.

Bailey, W.B. 1982. A time-series of sea-surface temperature on the Flemish Cap, 1962-81. NAFO SCR Doc. 82/4, Ser. No. N489 7 p.

Cabanas, J. M. 2003. Hydrographic conditions on the Flemish Cap in July 2002. NAFO SCR Doc. 03/32, Ser. No. N4848. 9 p.

Casey, K.S., T.B. Brandon, P. Cornillon, and R. Evans. 2010. The past, present and future of the AVHRR Pathfinder SST Program. *In* Oceanography from space: Revisited. Edited by V. Barale, J.F.R. Gower, and L. Alberotanza. Springer, Dordrecht, The Netherlands. 273-287 p. DOI: 10.1007/978-90-481-8681-5_16.

Colbourne, E. B., A. Perez-Rodriguez, A. Cabrero and G. Gonzalez-Nuevo. 2016. Ocean Climate Variability on the Flemish Cap in NAFO Subdivision 3M during 2015. NAFO SCR. Doc. 2016/019. Serial No. N6560.

Colbourne, E. B. and A. Perez-Rodriguez. 2015. Physical Oceanographic Conditions on the Flemish Cap in NAFO Division 3M during 2015. NAFO SCR DOC. 2015/13. Serial No. 6434. 15p.

Colbourne, E. B. 2005. Oceanographic conditions on the Flemish Cap in NAFO Division 3M during the summer 2005. NAFO SCR DOC. 2005/87. Serial No. 5192. 14p.

Colbourne, E., and K. D. Foote. 2000. Variability of the stratification and circulation on the Flemish Cap during the decades of 1950s and 1990s. *J. Northw. Atl. Fish Sci.*, **26**: 103–122.

Gil, J., R. Sanchez, S. Cervino and D. Garabana. 2004. Geostrophic Circulation and Heat Flux accross the Flemish Cap, 1988-2000. J. Northw Atl. Fisf. Sci., Vol. 34: 61-81.

González-Costas, F., G. Ramilo, E. Román, J. Lorenzo, A. Gago, D. González-Troncoso and M. Sacau. 2018. Spanish Research Report for 2017. NAFO SCS Doc. 18/07. Serial No. 6787 50p.

Hays, R. M., D.G. Mountain, and T.C. Wolford. 1978. Physical oceanography and the abiotic influence on cod recruitment in the Flemish Cap region. ICNAF Res. Doc. 77/54, Ser. No. 5107, 33p.

Hebert, D., Pettipas, R., Brickman, D., and Dever, M. 2018. Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/016. v + 53 p.

ICNAF. 1978. List of ICNAF standard oceanographic sections and stations. ICNAF selected papers #3.

Kudlo, B.P., V.A. Borovkov and N.G. Sapronetskaya. 1984. Water circulation patterns on the Flemish Cap from observations in 1977-82. NAFO Sci. Coun. Studies, 7:27-37.

Lopez, Santiago Cervino, 2001. Hydrographic conditions on the Flemish Cap in July 2000. NAFO SCR Doc. 01/24, Ser. No. N4395 10 p.

Petrie, B., R. G. Pettipas and W. M. Petrie. 2007. An overview of meteorological, sea ice and sea surface temperature conditions off eastern Canada during 2006. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/022.

Ross, C.K. 1981. Drift of satellite-tracked buoys on the Flemish Cap, 1970-80. NAFO Sci. Counc. Studies, No. 1: p47-50.

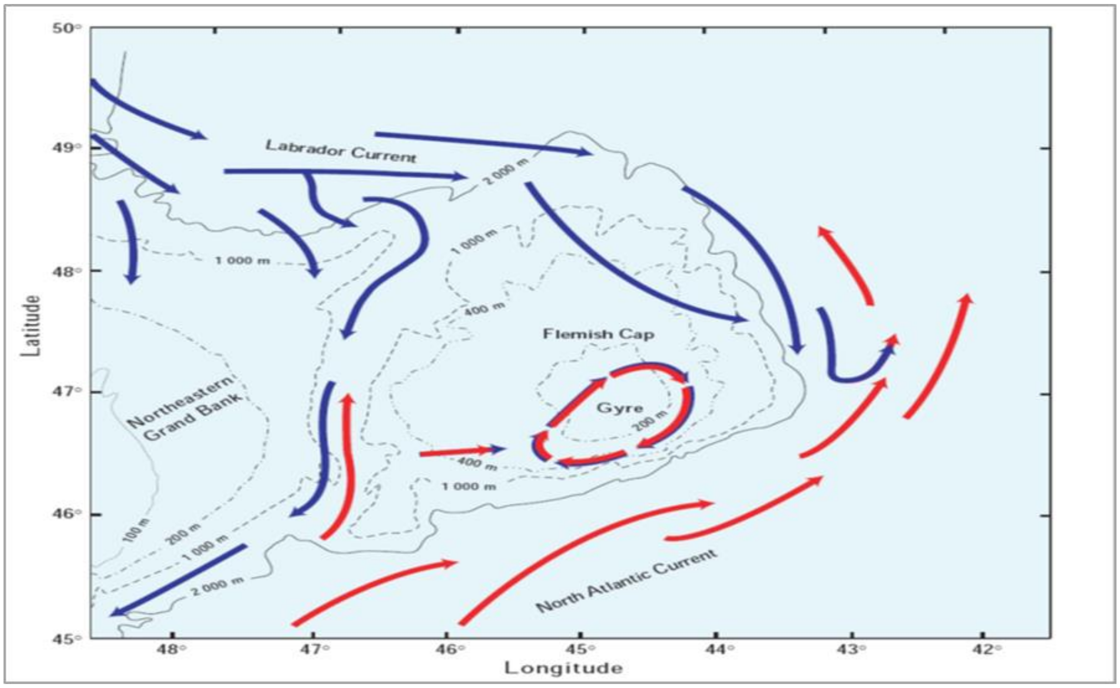

Fig. 1. Areal map showing the local bathymetry and major circulation features around the Flemish Cap area.

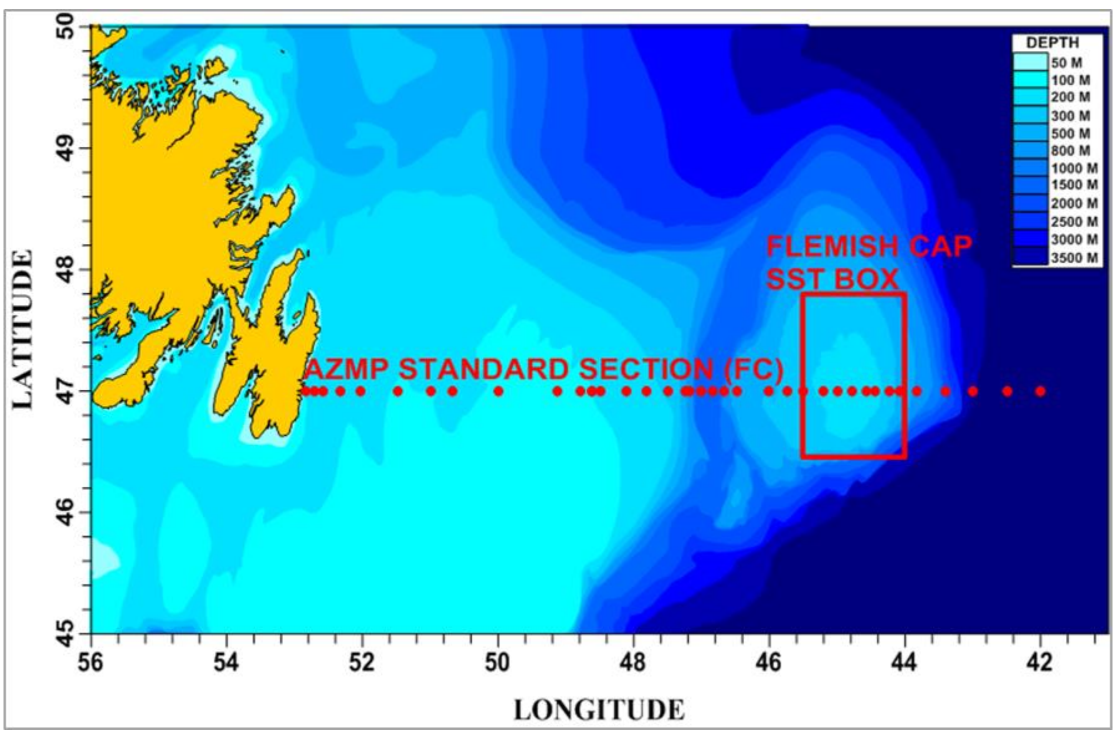

Fig. 2. Areal map showing the standard Flemish Cap (47°N) oceanographic sampling section and the Flemish Cap sub-areas where satellite SST time series were constructed. The red dots show the positions of the stations along the section.

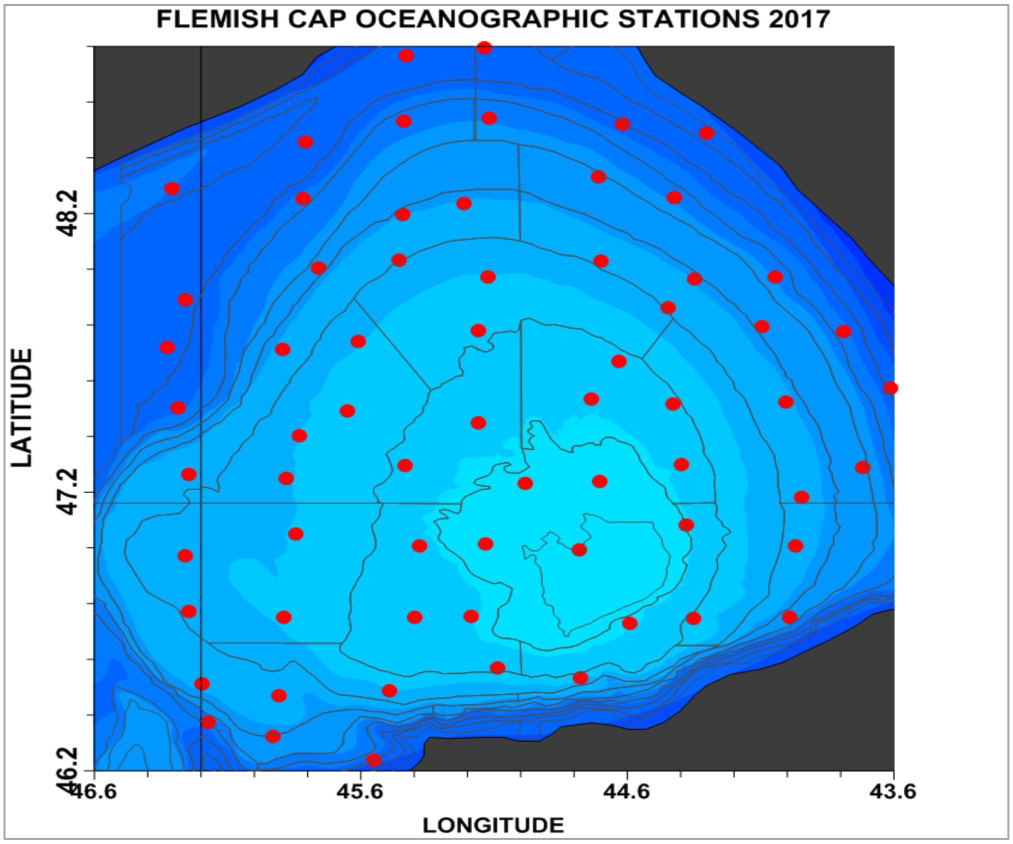

Fig. 3. Map showing the positions of CTD profiles obtained from the summer EU stratified random multispecies survey of the Flemish Cap area during June-July of 2017.

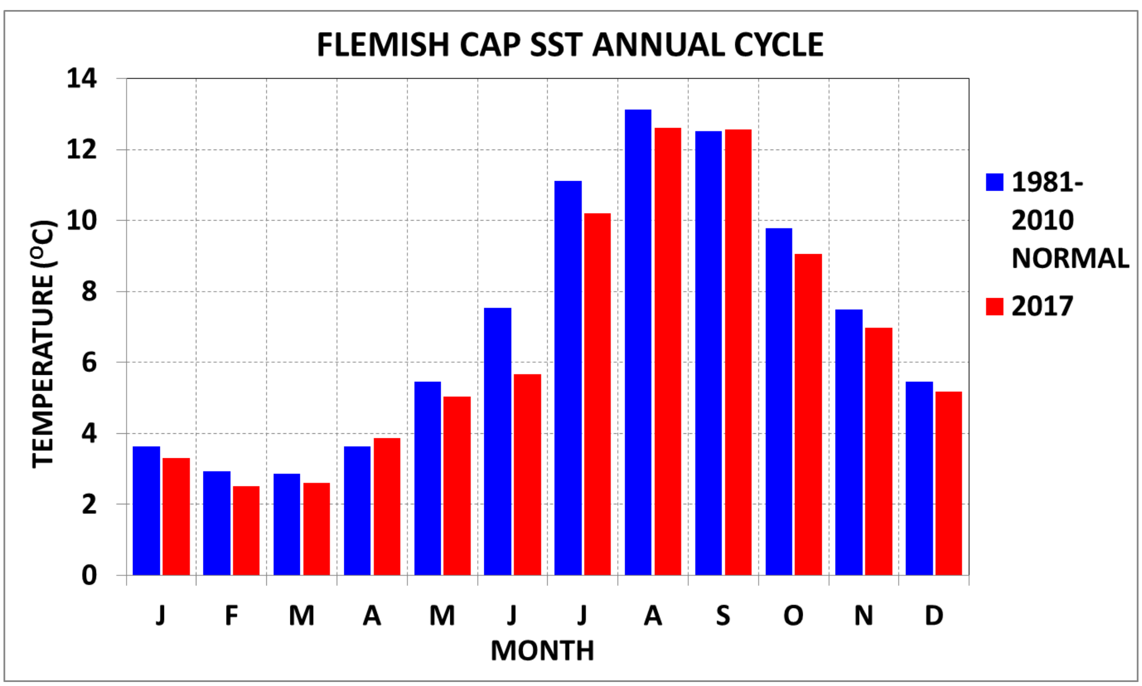

Fig. 4. Sea surface temperatures from the Flemish Cap sub-area (Fig. 2) showing the monthly 1981-2010 normal and the 2017 monthly values.

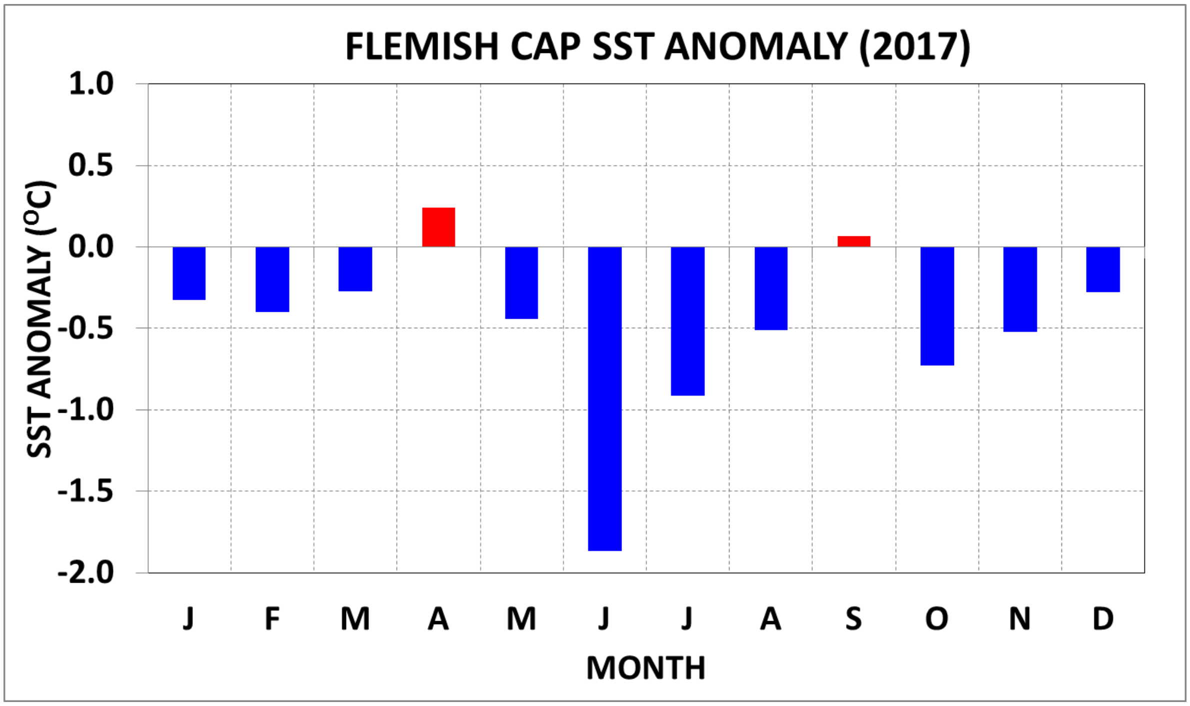

Fig. 5. Monthly sea surface temperature anomalies from the Flemish Cap sub-area (Fig. 2) referenced to the 1981-2010 normal.

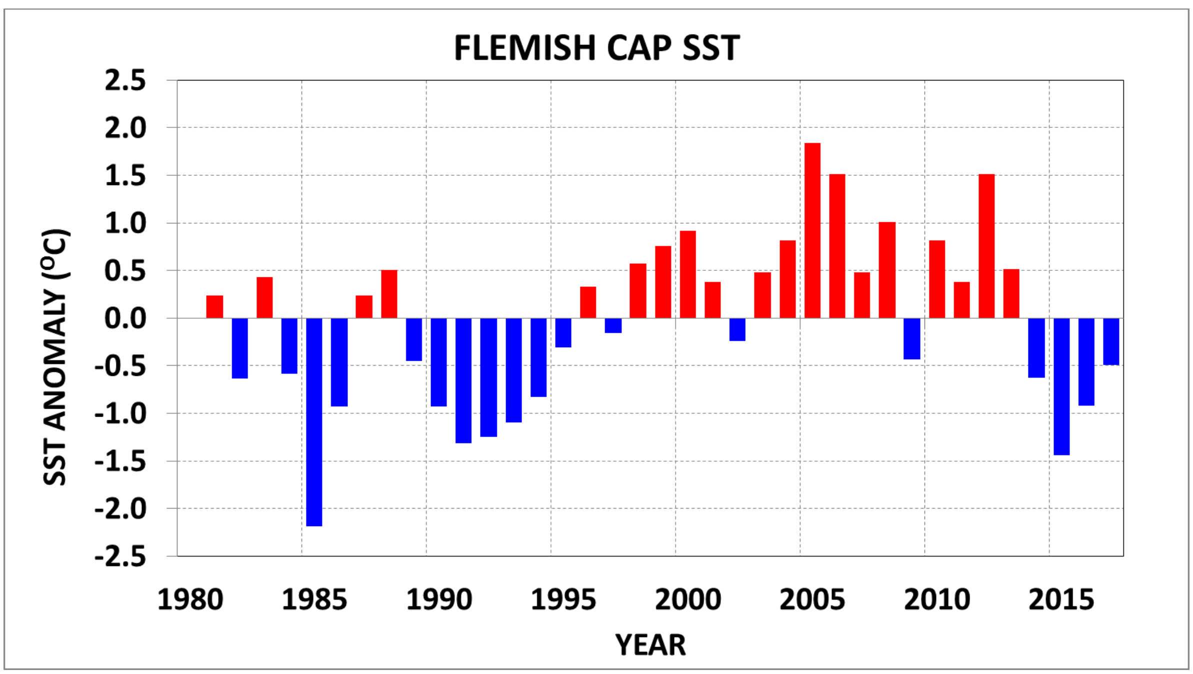

Fig. 6. Annual sea surface temperatures from the Flemish Cap sub-area (Fig. 2) referenced to the 1981-2010 mean.

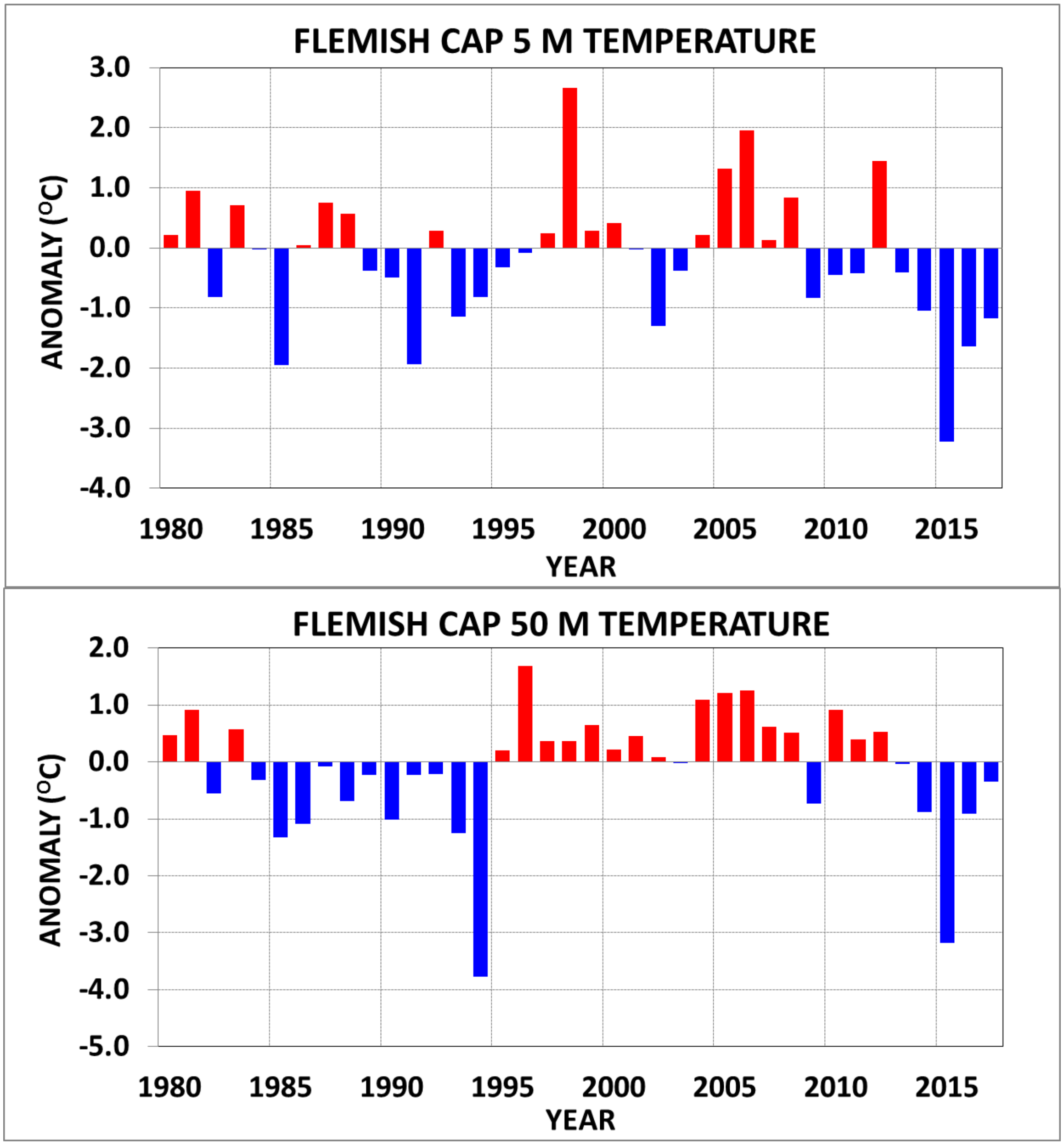

Fig. 7. Annual 5 and 50 m temperature anomalies from the central Flemish Cap referenced to the 1981-2010 mean.

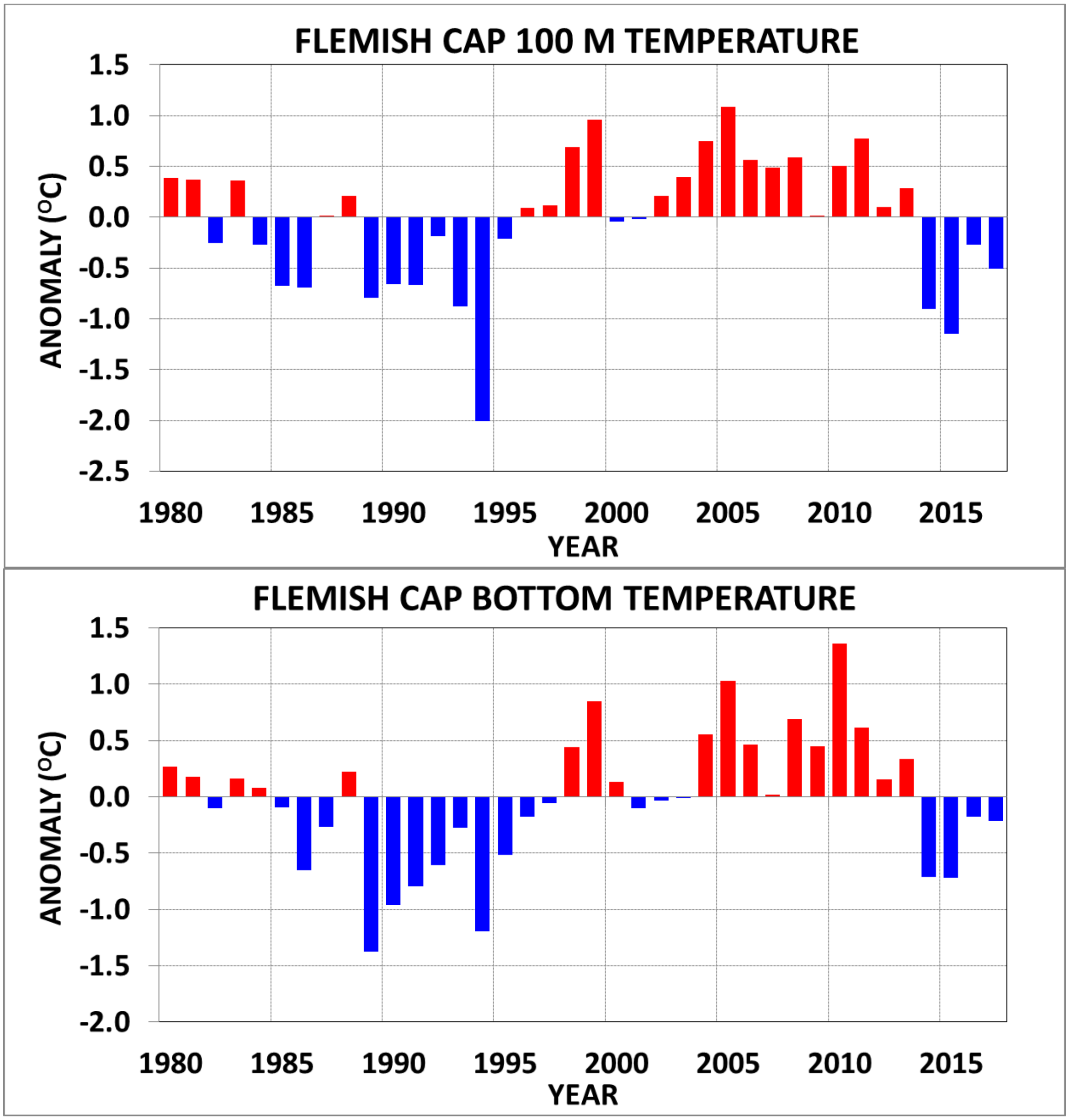

Fig. 8. Annual 100 m and bottom temperature anomalies from the central Flemish Cap referenced to the 1981-2010 mean.

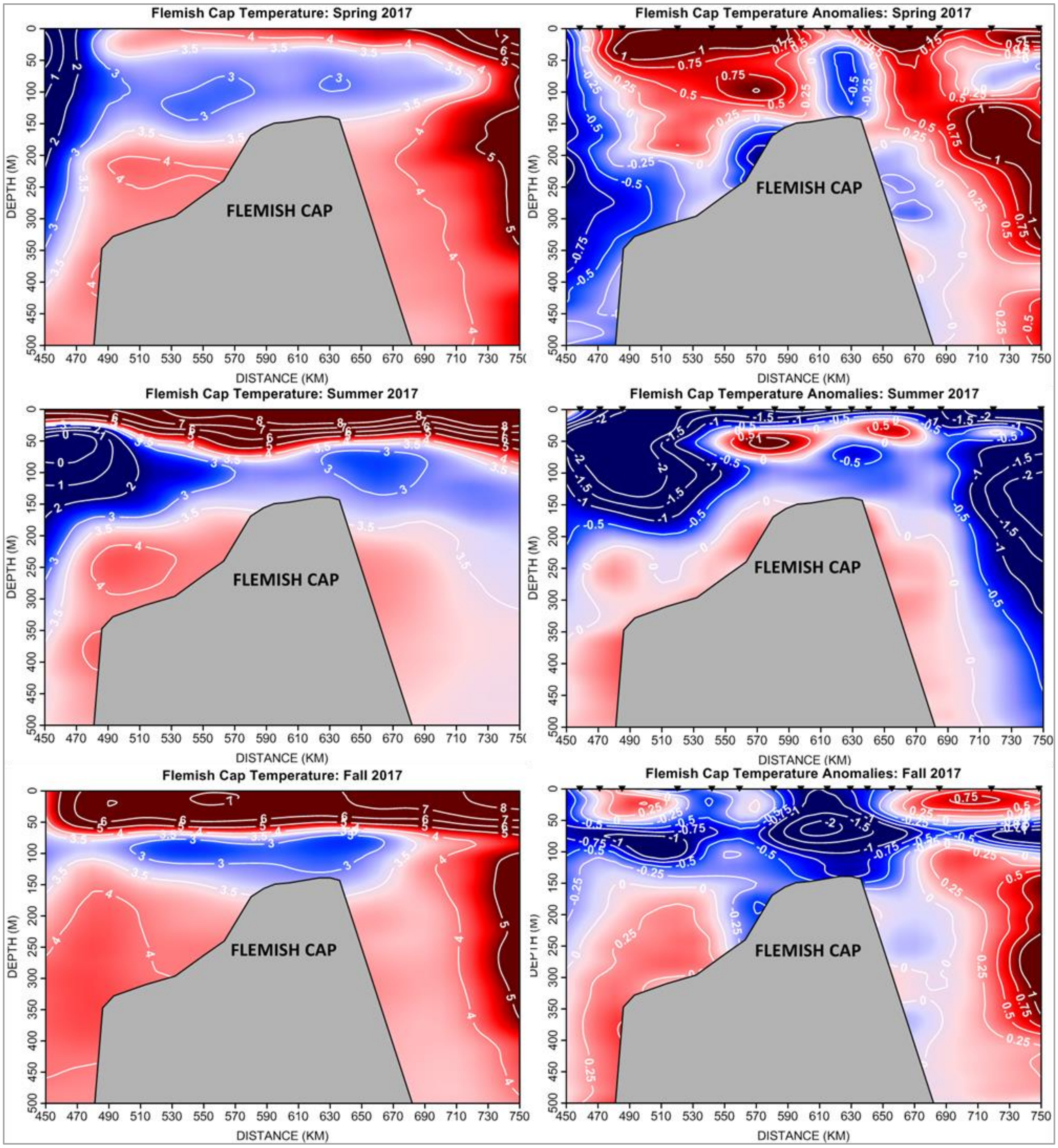

Fig. 9. The vertical distribution of temperature and temperature anomalies (in °C) over the Flemish Cap (along 47°N) for the spring, summer and fall of 2017. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section. The horizontal distance is measured from the start of the 47°N section off eastern Newfoundland.

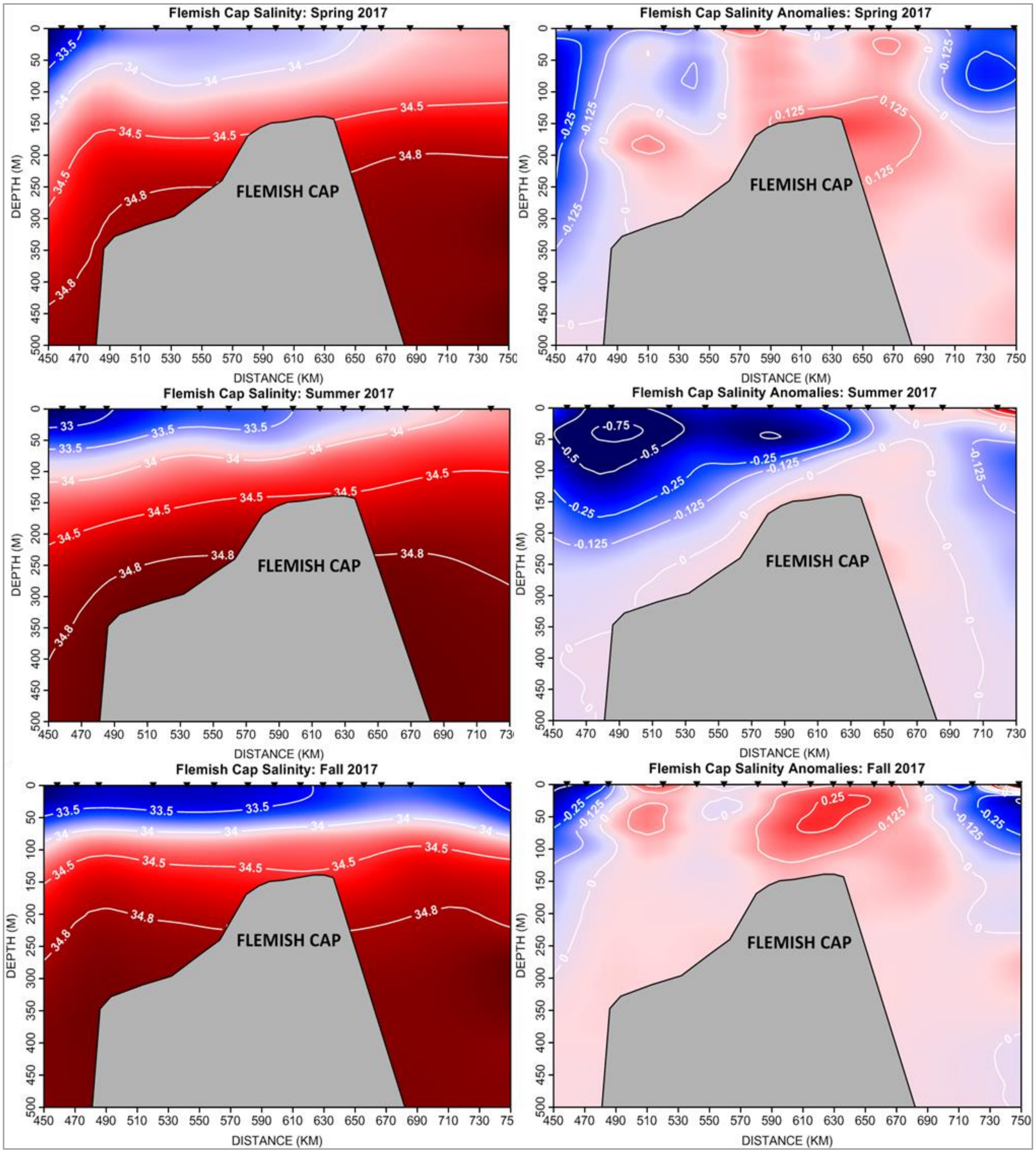

Fig. 10. The vertical distribution of salinity and salinity anomalies over the Flemish Cap (along 47°N) for the spring, summer and fall of 2017. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section. The horizontal distance is measured from the start of the 47°N section off eastern Newfoundland.

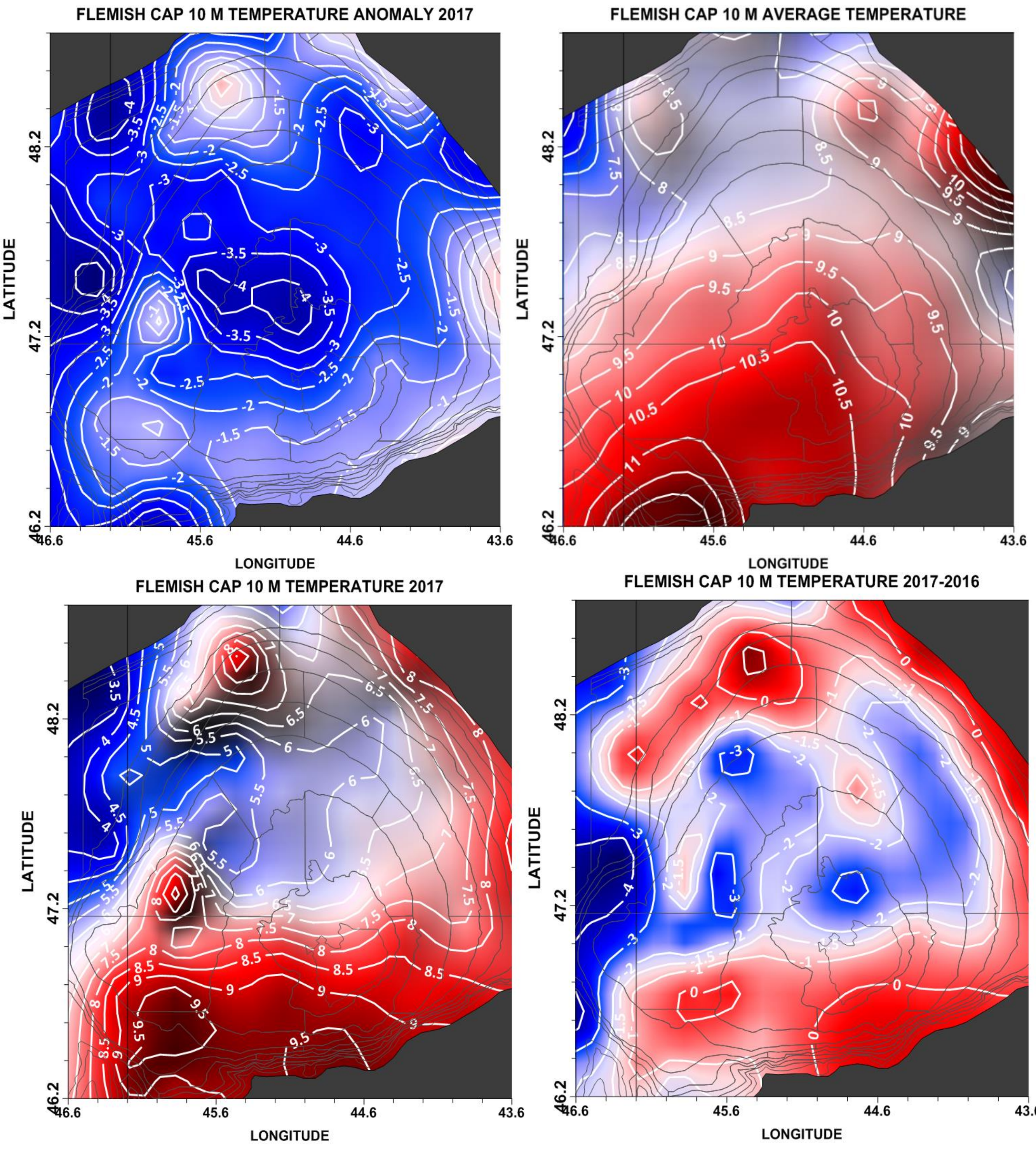

Fig. 11. Spatial maps at 10-m depth of the average temperature (in °C), the 2017 temperature, the 2017 temperature anomalies and the temperature difference from 2016 during the summer (July) based on data collected from 1988-2017 in NAFO Div. 3M.

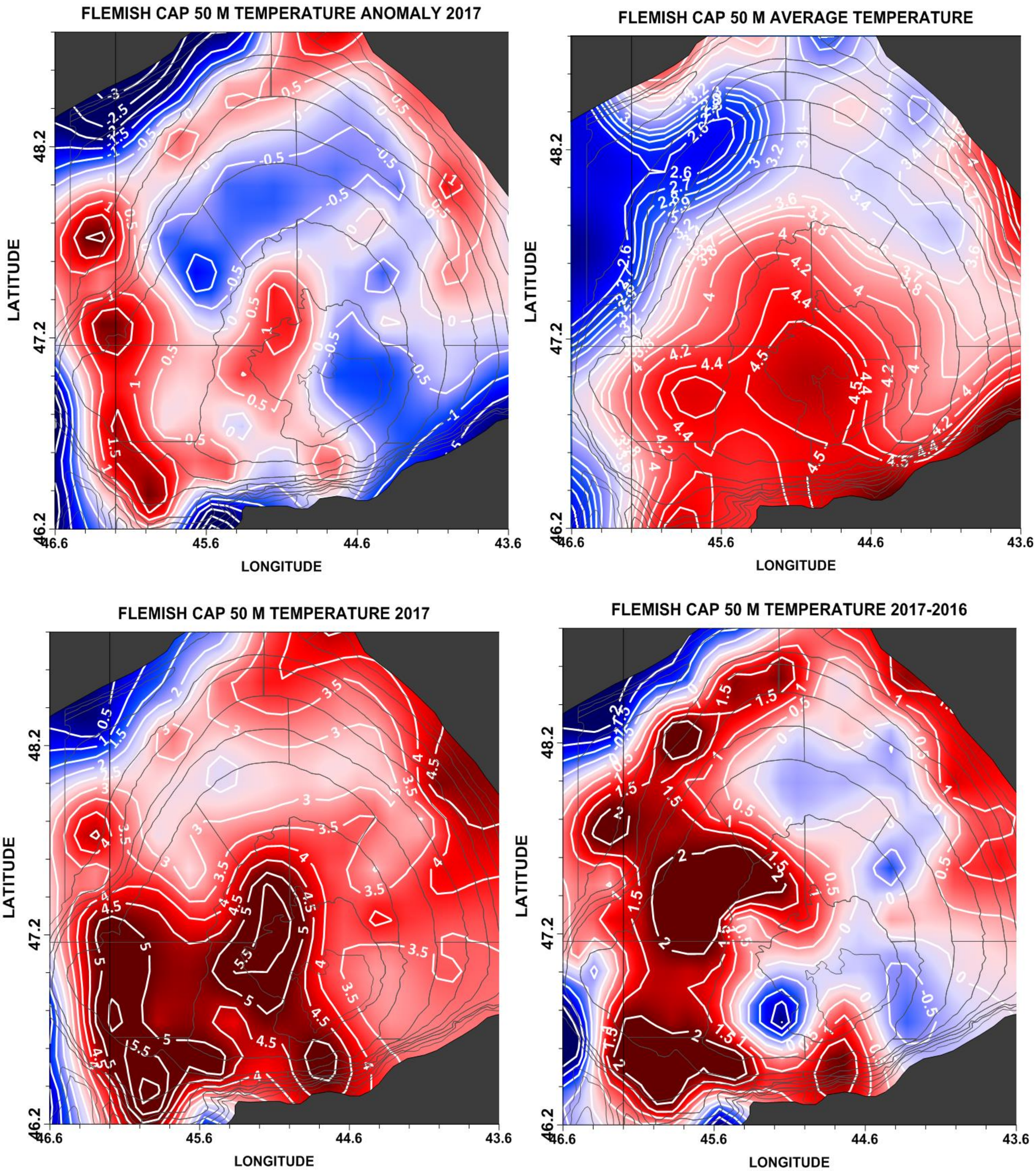

Fig. 12. Spatial maps at 50-m depth of the average temperature (in °C), the 2017 temperature, the 2017 temperature anomalies and the temperature difference from 2016 during the summer (July) based on data collected from 1988-2017 in NAFO Div. 3M.

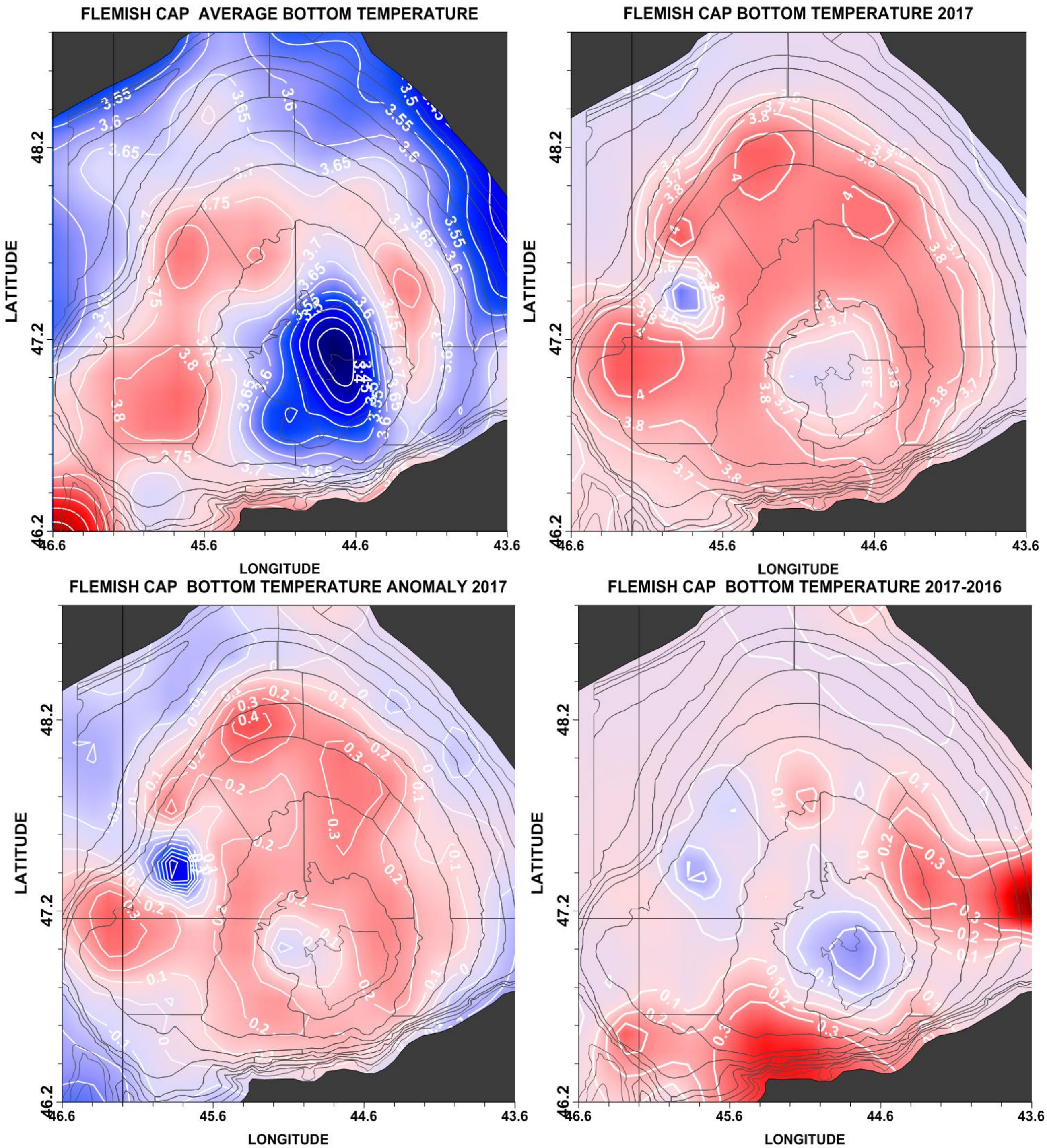

Fig. 13. Maps of the average bottom temperature (in °C), the 2017 bottom temperature, the 2017 bottom temperature anomalies and bottom temperature difference from 2016 during the summer (July) based on data collected from 1988-2017 in NAFO Div. 3M.

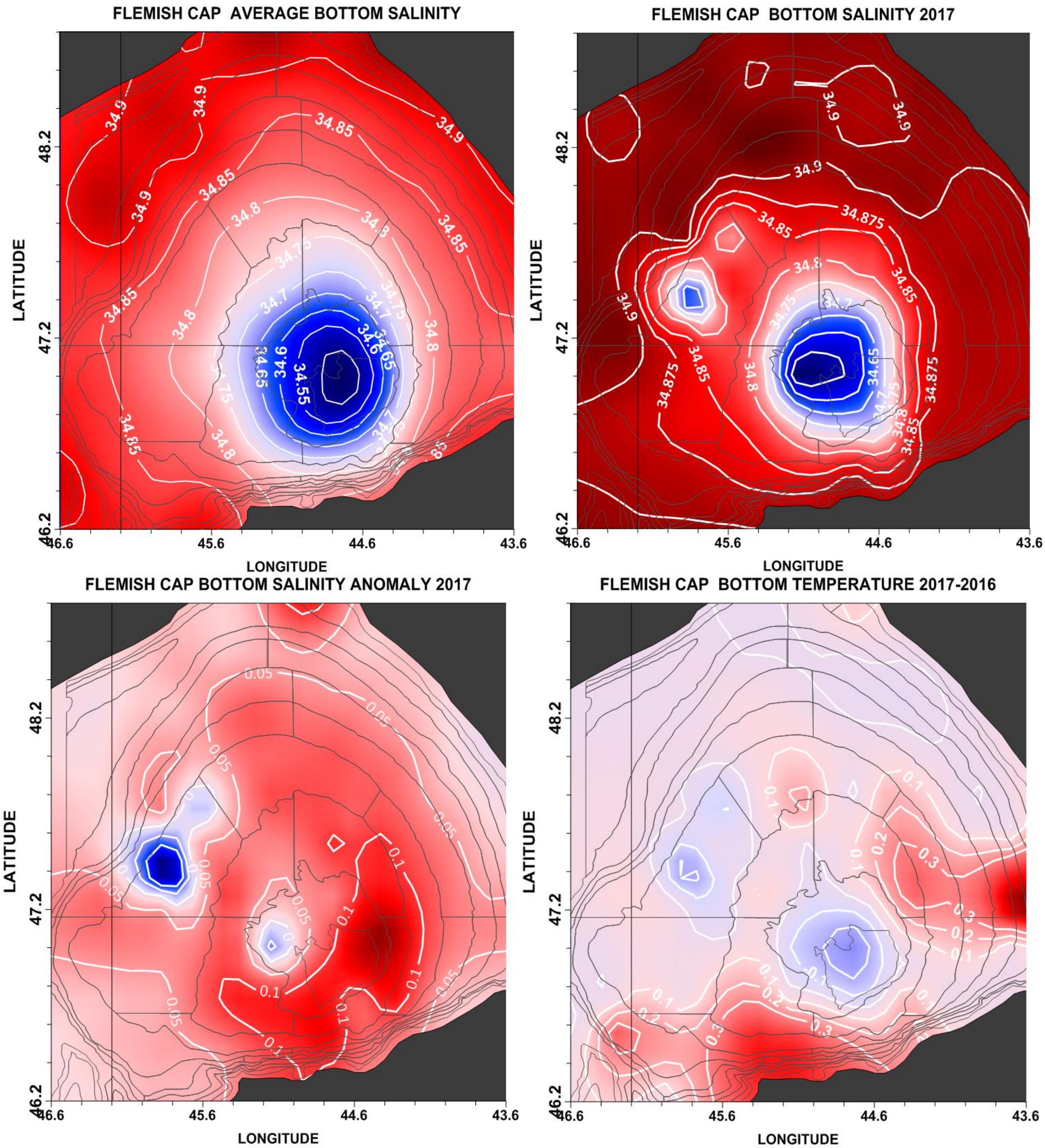

Fig. 14. Maps of the average bottom salinity, the 2017 bottom salinity, the 2017 bottom salinity anomalies and bottom salinity difference from 2016 during the summer (July) based on data collected from 1988-2017 in NAFO Div. 3M.

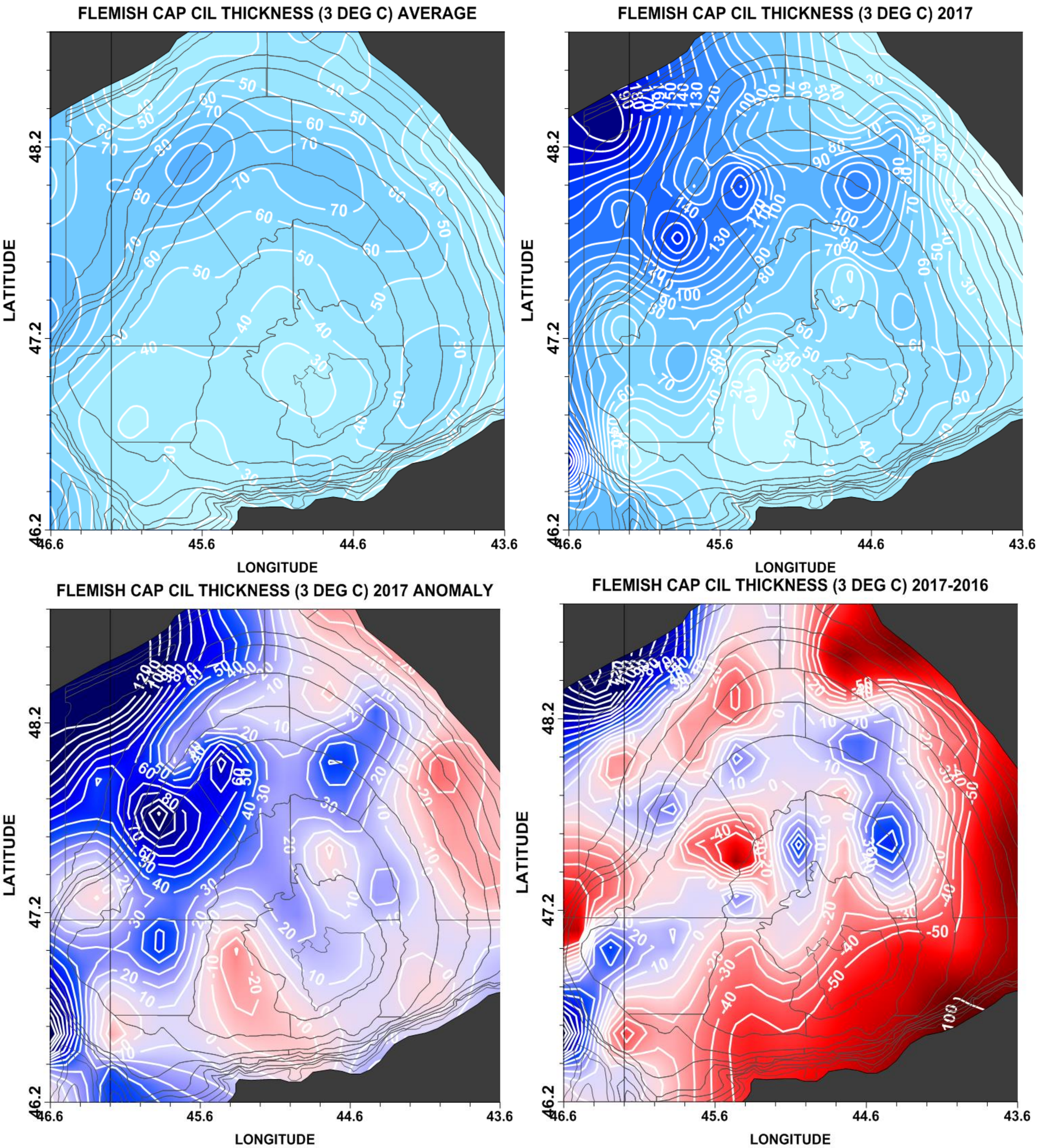

Fig. 15. Maps of the average CIL thickness (in-m) defined by water with temperatures <3°C, the 2017 CIL thickness, the 2017 CIL thickness anomalies and the CIL thickness difference from 2016 during the summer (July) based on data collected from 1988-2017 in NAFO Div. 3M.

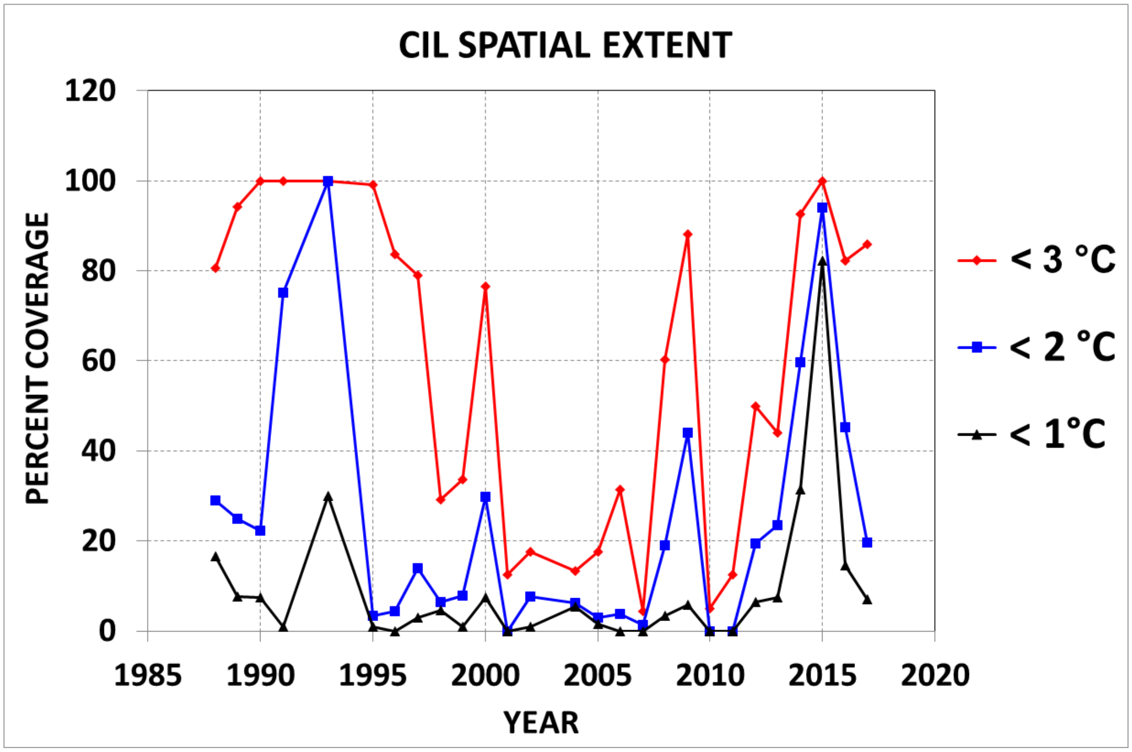

Fig. 16. Percentage by year of the CTD profiles from the Flemish Cap survey where temperature values <1°C, <2°C and <3°C were encountered.

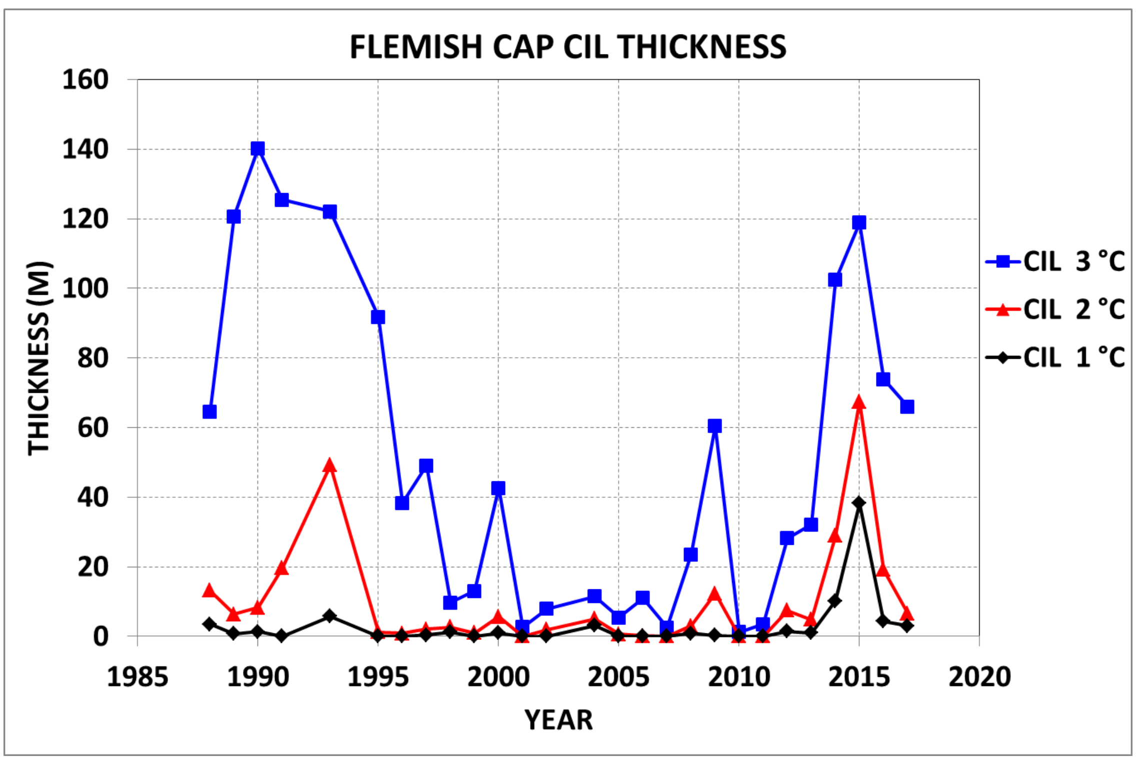

Fig. 17. Thickness anomaly (in-m)of the Cold-Intermediate-Layer (CIL) water mass on the Flemish Cap defined by temperatures <1°C, <2°C and <3°C.

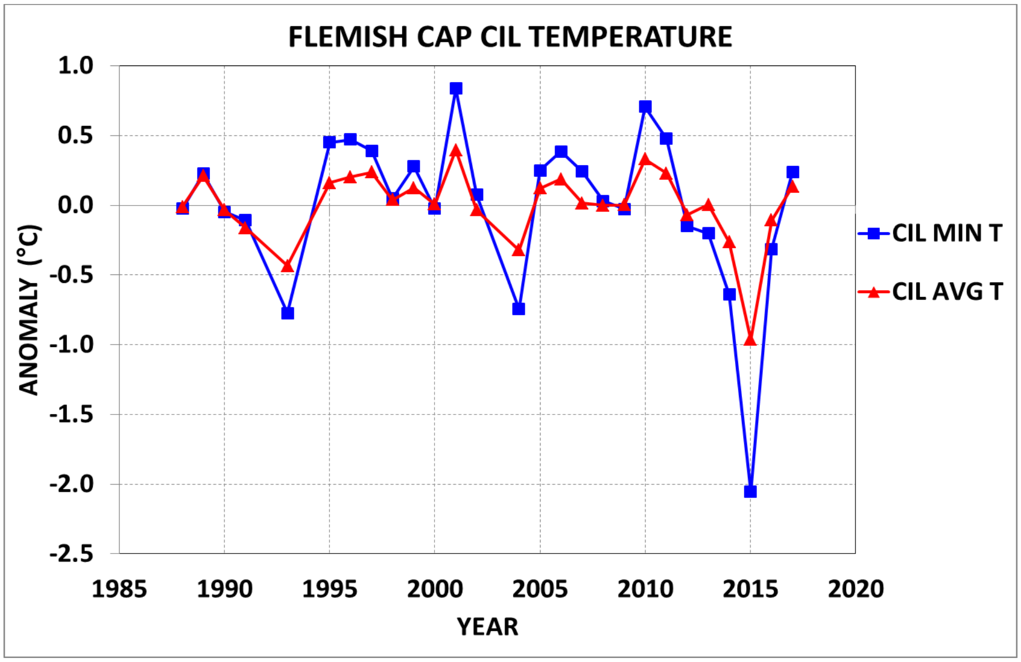

Fig. 18. The Flemish Cap cold-intermediate-layer (CIL) water mass minimum and average temperature.

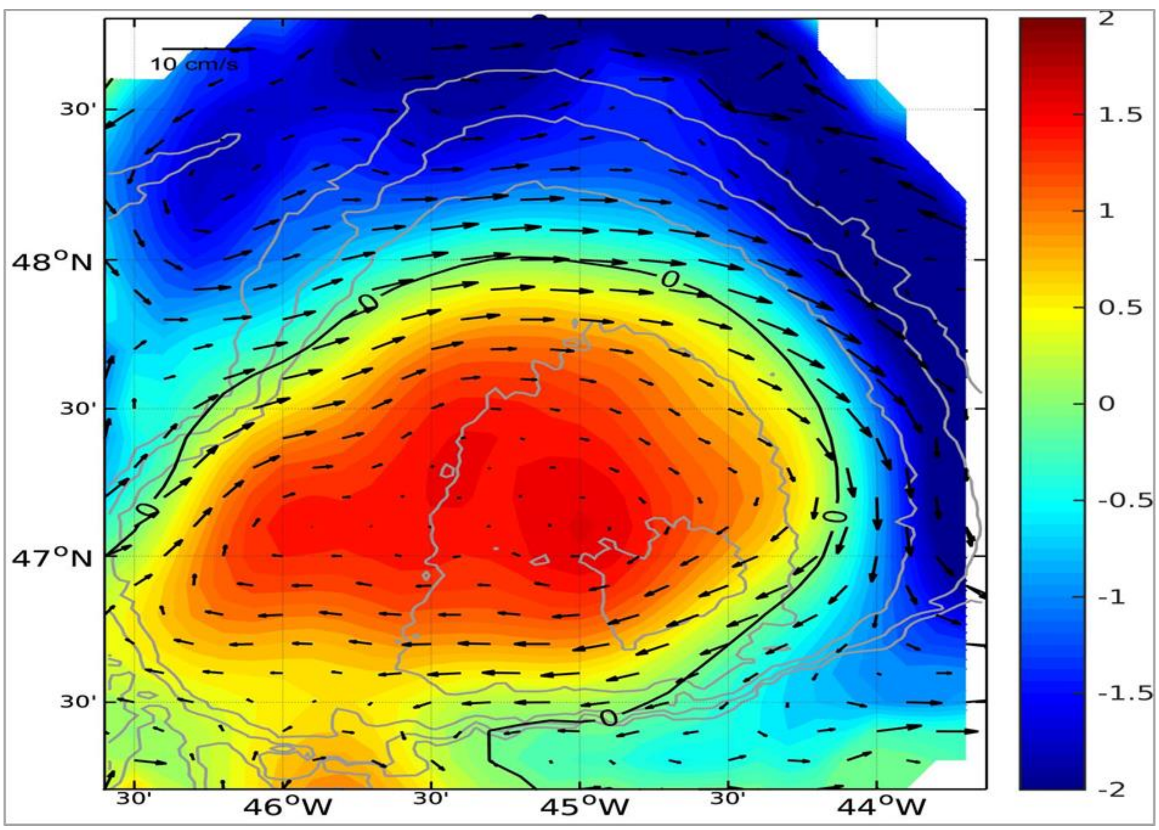

Fig. 19. The mean geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period from 1988 to 2017. The color contours represent the dynamic height field.

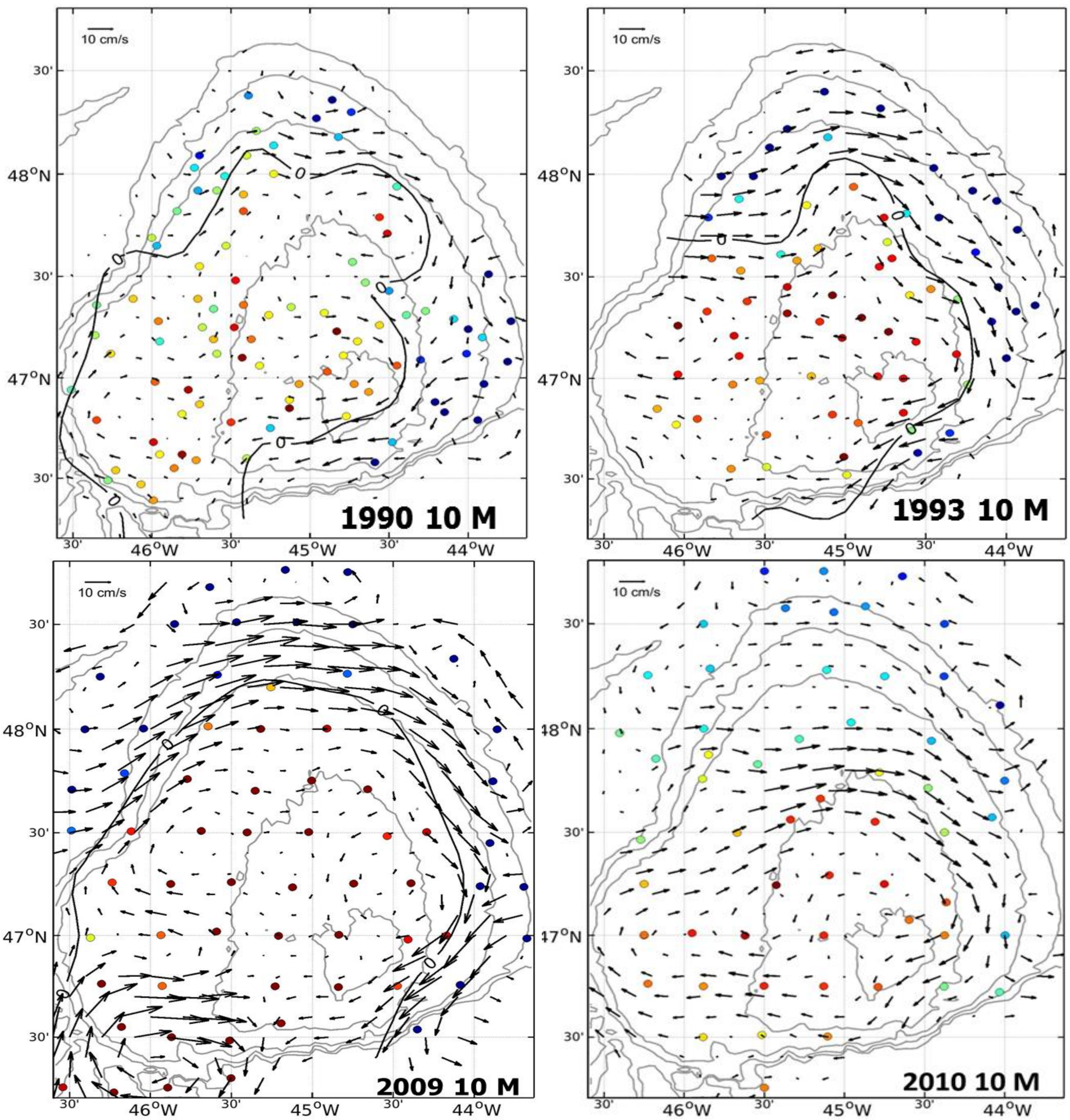

Fig. 20. The geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period for 1990, 1993, 2009 and 2010. The color dots are the CTD locations with the color representing either high (red) or low (blue) dynamic height values.

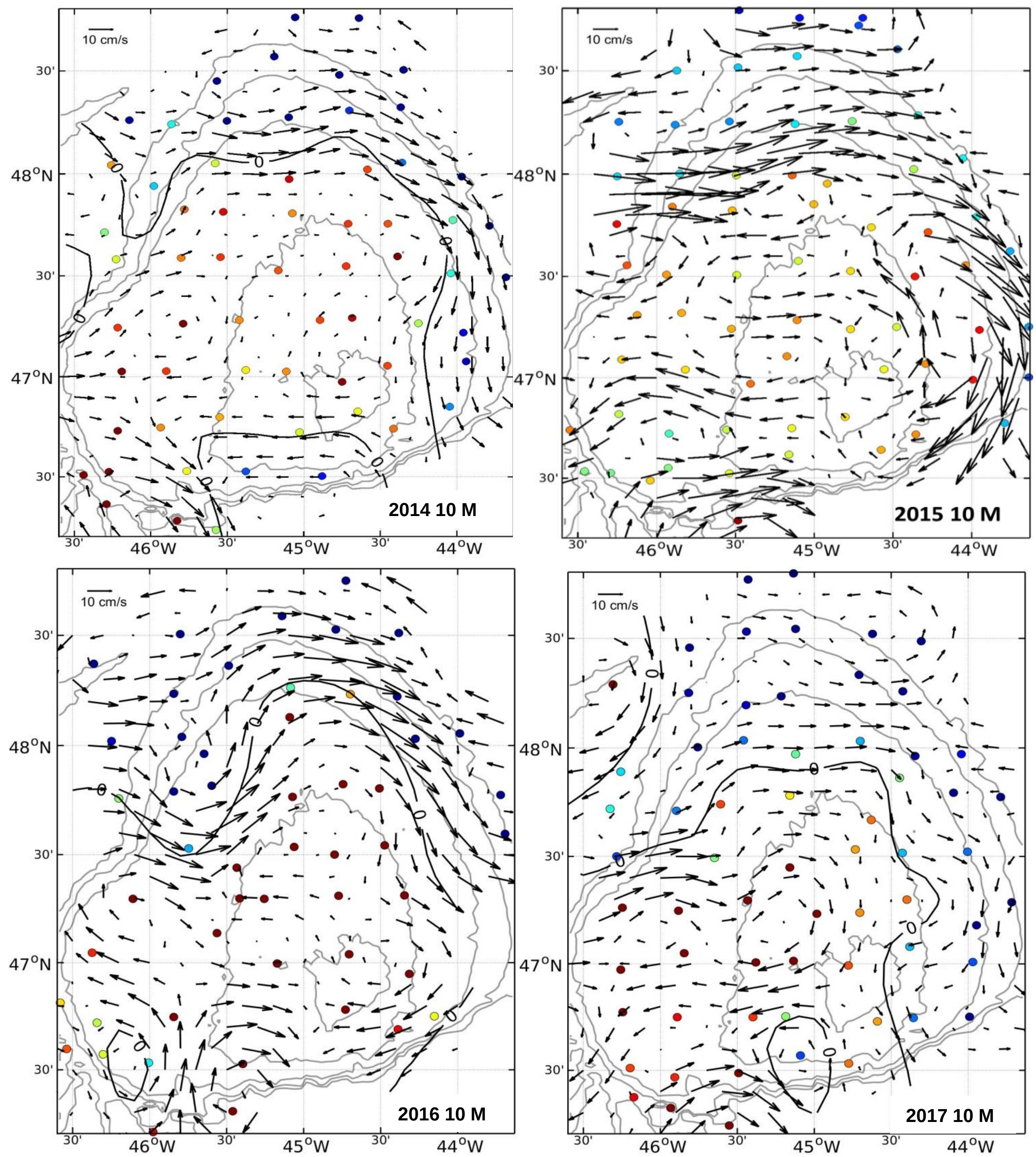

Fig. 21. The geostrophic currents over the Flemish Cap based on all CTD data collected by the EU assessments surveys during the June-July period for 2014 to and 2017. The color dots are the CTD locations with the color representing either high (red) or low (blue) dynamic height values.

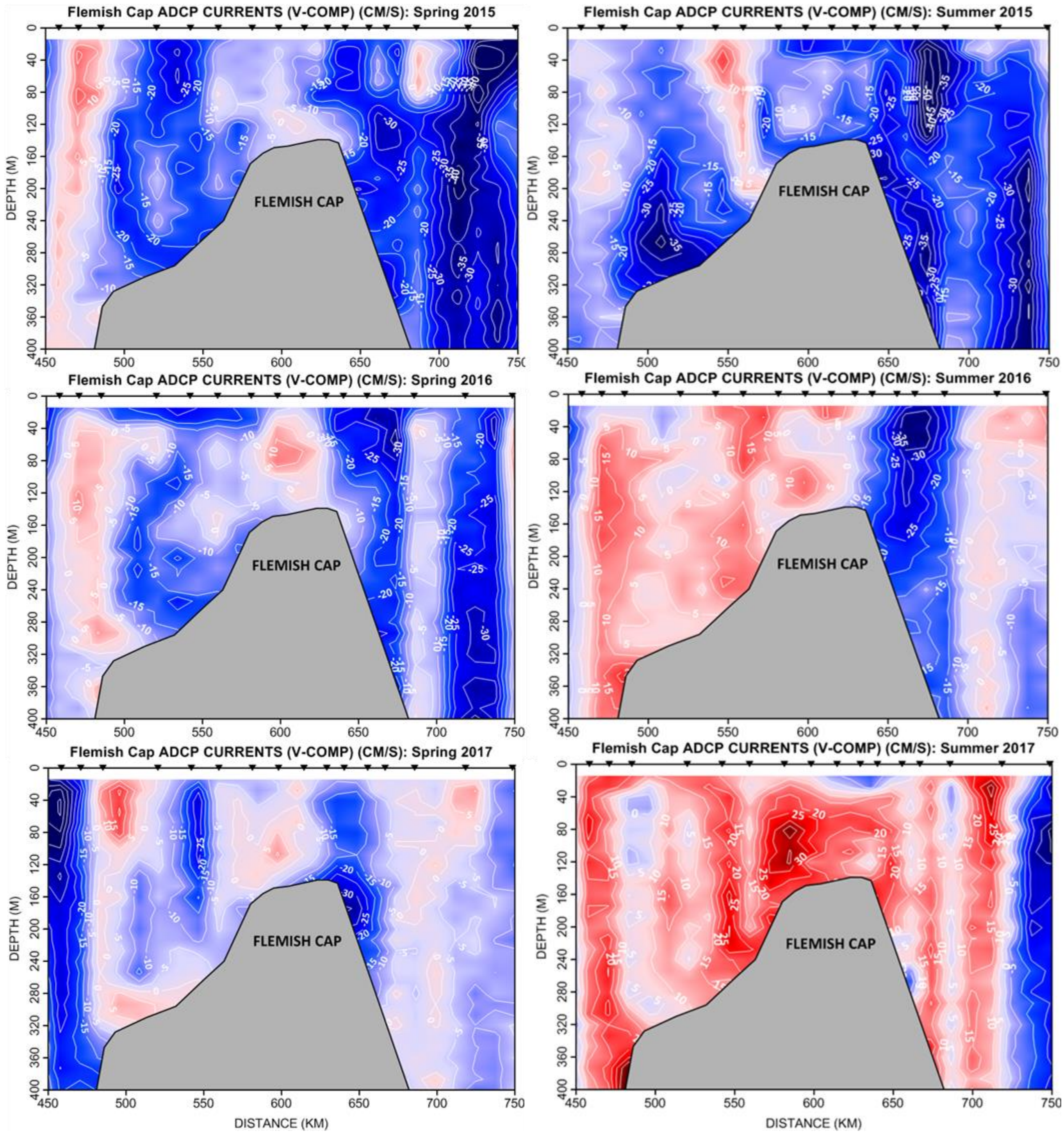

Fig. 22. Average current speeds (cm/s) along the Flemish Cap section (Figure 2) during the spring of 2015, 2016 and 2017 (left panels) and summer of 2015, 2016 and 2017 (right panels). Southward flowing water is colored blue and northward red. The symbols along the top of the panels are the standard AZMP stations.

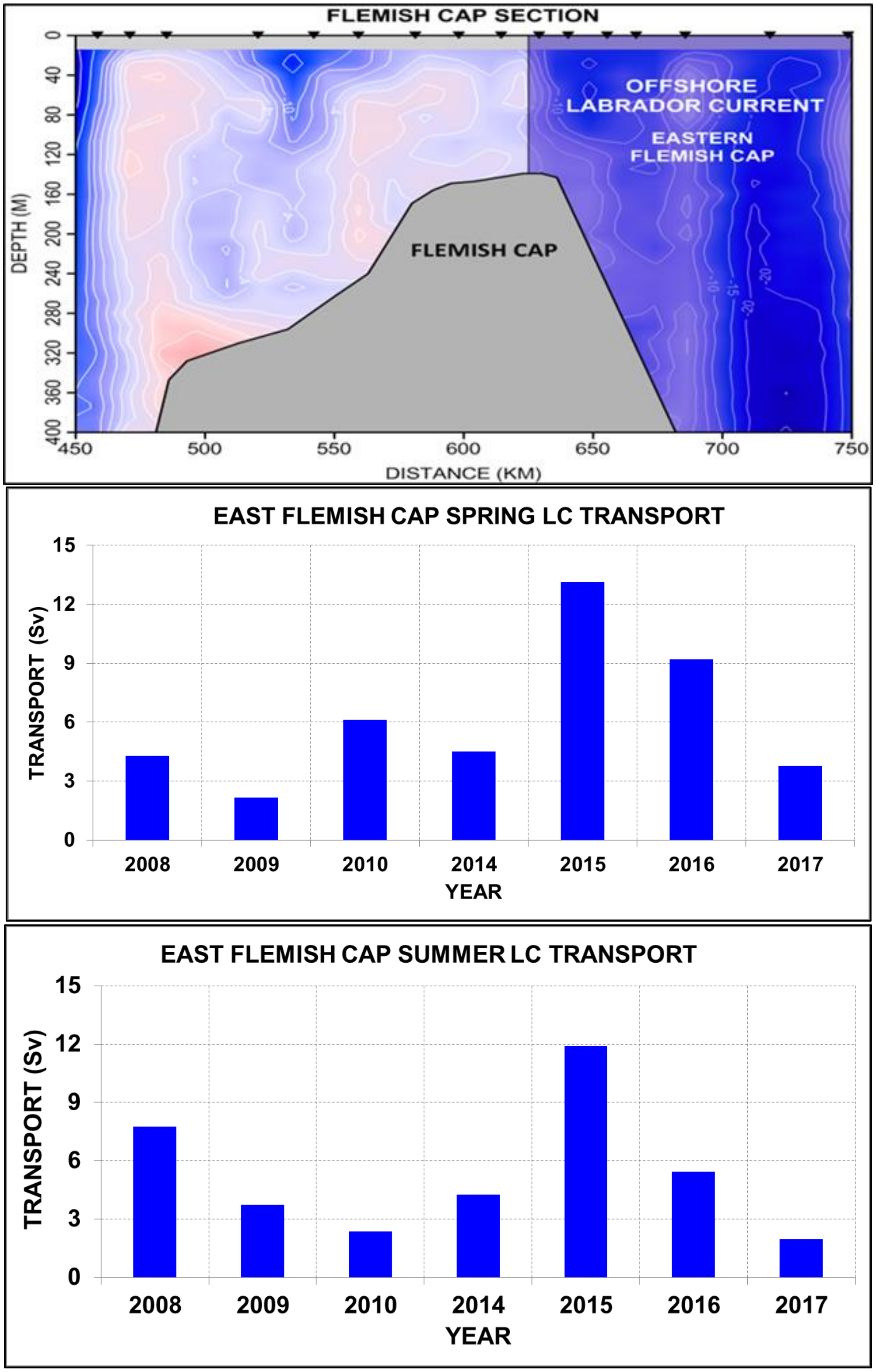

Fig. 23. Labrador Current transport values (Sv, 10^6 m^3/s), through the shaded portion (top panel, 625-750 km) of the Flemish Cap section for spring (middle panel) and summer (bottom panel) based on vessel mounted ADCP data.

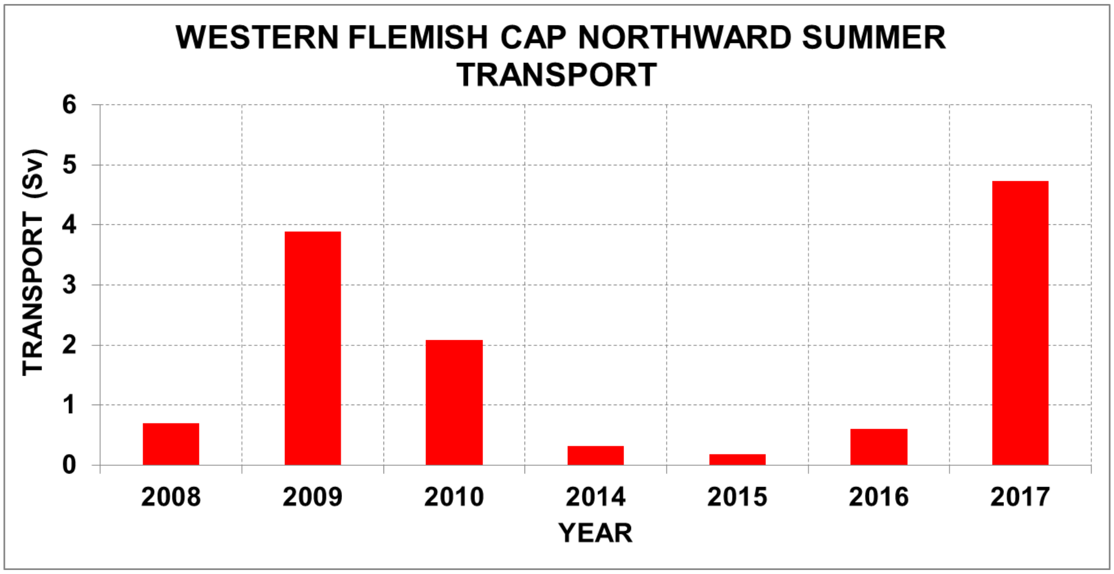

Fig. 24. Northward transport values (Sv, 10^6 m^3/s), through the western Flemish Cap section (top panel, 475-625 km) for and summer surveys based on vessel mounted ADCP data.

YEAR	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
SURFACE T	0.89	-0.08	-0.33	-1.82		-1.88		-0.15	-0.47	0.42	1.98	0.79	1.23	0.30	-0.79		-0.31	1.17	1.24	-0.18	0.73	-0.06	-0.58	0.43	1.41	-0.21	-0.13	-1.69	-0.63	-1.30
10 M T	0.79	-0.13	-0.24	-1.74		-1.81		-0.17	-0.42	0.50	2.05	0.86	1.26	0.33	-0.91		-0.70	1.13	1.30	-0.19	0.68	-0.01	-0.57	0.44	1.46	-0.30	-0.25	-1.56	-0.56	-1.24
50 M T	-0.23	-0.30	-0.53	-0.69		-1.38		0.70	1.51	-0.26	0.12	0.98	-0.53	0.66	0.38		0.83	1.20	0.96	1.26	-0.51	-0.73	1.26	0.53	0.39	-0.14	-1.95	-2.54	-0.89	-0.09
100 M T	0.09	-0.38	-1.13	-1.36		-1.95		-0.81	-0.31	-0.20	0.86	1.49	-0.05	0.35	0.56		1.08	1.08	0.61	0.96	0.78	0.13	0.84	1.08	0.22	0.17	-0.74	-2.75	-0.01	-0.63
BOTTOM T	-0.17	-1.32	-2.27	-1.89		-1.19		-1.49	-1.23	-0.72	-0.26	1.16	0.77	-0.07	0.04		0.17	0.58	0.29	0.63	0.85	1.34	0.73	0.91	1.05	1.24	0.29	0.16	0.53	-0.12
SURFACE S	-1.19	0.11	-0.80	0.34		-0.05		0.88	0.23			-0.79	-2.36	1.21	0.92		1.02	0.23	0.01	1.89	-1.06	0.83	1.15	0.56	-0.29	-1.24	-0.94	-1.14	-0.22	0.71
10 M S	-0.83	0.03	-0.62	0.33		-0.22		0.93	0.41			-0.54	-1.94	1.22	1.18		1.28	0.18	-0.25	1.88	-0.67	-1.39	1.12	0.77	0.11	-0.84	-0.48	-1.77	-0.72	0.82
50 M SAL	-0.05	0.05	-0.23	-0.64		-0.71		-0.12	-0.66	0.08	-0.03	-0.31	-0.71	0.18	0.38		0.42	0.06	0.02	0.43	0.01	-0.63	0.06	0.90	4.29	-0.29	-0.36	-1.78	-0.61	0.24
100 M S	0.09	0.44	-0.29	-0.95		-1.31		0.11	-0.44	0.65	0.63	0.00	-0.83	-0.18	0.70		1.31	1.06	0.67	1.06	0.51	-0.53	0.87	1.68	-0.90	-0.24	-0.38	-3.32	-0.52	0.08
BOTTOM S	-0.71	-1.01	-1.43	-1.39		-0.67		-0.17	-0.32	-0.01	-0.13	-0.43	-0.51	-0.43	-0.33		0.02	0.55	0.47	0.25	0.04	0.40	0.67	0.67	4.08	0.39	-0.07	-0.43	-0.18	0.68
CIL 1°C	-0.08	0.24	0.18	0.00		-0.34		0.33	0.00	0.29	0.19	0.32	0.22	0.00	0.33		-0.04	0.33	0.00	0.00	0.23	0.31	0.00	0.00	0.16	0.21	-0.87	-4.18	-0.18	-0.02
CIL 2°C	-0.20	0.21	0.10	-0.59		-2.39		0.53	0.55	0.48	0.44	0.54	0.26	0.00	0.48		0.29	0.56	0.59	0.60	0.42	-0.14	0.00	0.00	0.15	0.31	-1.16	-3.50	-0.56	0.20
CIL 3°C	-0.30	-1.52	-1.95	-1.63		-1.55		-0.89	0.27	0.04	0.89	0.82	0.18	1.05	0.93		0.85	0.99	0.86	1.05	0.59	-0.21	1.08	1.03	0.49	0.40	-1.13	-1.48	-0.51	-0.33
CIL MIN T	-0.05	0.40	-0.08	-0.19		-1.36		0.79	0.83	0.69	0.09	0.49	-0.04	1.47	0.13		-1.31	0.44	0.68	0.42	0.05	-0.05	1.24	0.84	-0.26	-0.35	-1.13	-3.61	-0.55	0.42
CIL AVG T	-0.04	0.78	-0.13	-0.60		-1.60		0.60	0.75	0.87	0.14	0.46	0.03	1.46	-0.12		-1.19	0.45	0.69	0.06	0.00	0.00	1.22	0.84	-0.25	0.02	-0.98	-3.56	-0.40	0.50

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. 25. Standardized anomalies of oceanographic indices based on data collected from 1988-2017 during the June-July EU multi-species survey of the Flemish Cap in NAFO Div. 3M. Grey cells indicate no data.

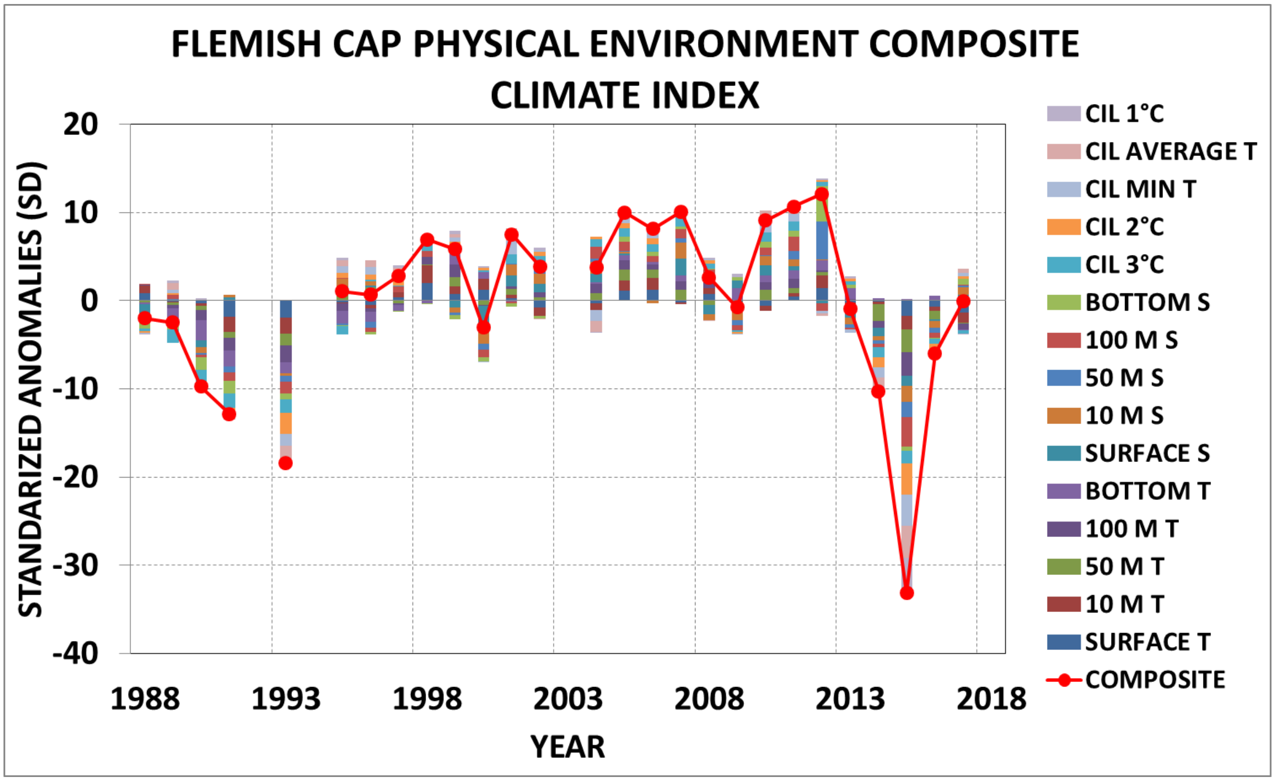

Fig. 26. Composite climate index (red line) derived by summing the standardized anomalies from Fig. 25 together with their individual components.