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Physical Oceanographic Conditions on the Flemish Cap in NAFO Subdivision 3M during 2014

by

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ABSTRACT

Oceanographic observations from seasonal surveys in NAFO Division 3M during 2014 are presented referenced to their long-term (1981-2010) means. An analysis of infrared satellite imagery around the Flemish Cap indicates that annual sea-surface temperatures (SST) decreased to about -0.6°C below normal in 2014, while water column temperatures decreased to-0.8°C, -0.4°C and -0.7°C below normal at 10, 50 and 100 m depth, respectively. The results from seasonal surveys along the standard Flemish Cap section show the development of a well-defined cold-intermediate layer (CIL) with T<3°C over the Cap during the summer and fall of 2014. Temperatures along the section were predominately below normal during spring, summer and fall but particularly during the spring survey when upper layer values reached between 1°C -2°C below normal. The cold water penetrated to the bottom directly over the Cap with a cold anomaly persisting at depth over the Cap during the fall survey. 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 and average thickness of the CIL observed in 2014 was close to that observed during the cold period of early-mid 1990s. In 2014, bottom temperatures ranged from 2.7°C -3°C over the centre of the Cap which was up to -0.6°C below the long-term average. However, it appears that the below normal temperatures only impacted the bottom area over the shallow portions of the Cap during the summer but expanded deeper into the water column by late fall. In general, there was a significant decrease in bottom temperatures in 2014 compared to the previous year (by >1°C) thus reversing the decade long warm trend in the waters of 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 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 Figure 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 (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 2014 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 2014 is derived from two main sources: (1) measurements made along the standard NAFO cross-shelf section from seasonal oceanographic surveys (Figure 2); and, (2) oceanographic observations made during an annual summer multi-species resource assessment bottom-trawl surveys carried out on Flemish Cap from 1988-2014 by the EU (Figure 3). Data from other research surveys and ships of opportunity if available were also used to help define the long-term means and the conditions during 2014.

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 two defined subareas, the Flemish Pass and Flemish Cap (Figure 2). This dataset runs from 1981 to 2010. Updated values for 2011 to 2014 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 common period (2001-2010) given by SST (Pathfinder) = 0.989*SST (NOAA) -0.02 with an r^2=0.98 (Hebert et al. 2012).

Annual SST anomalies for the Flemish Pass (Figure 2) are presented in Figure 4a. Since the cold period of the early 1990s SST have been generally increasing (exception of 2009) reaching a peak in 2006. A fitted linear trend to the data indicates an increase in SST in the Flemish Pass of about +1.2 °C over the past 34 years. In 2012 SST was 1°C above normal decreasing to slightly above normal in 2013 and to -0.5°C below normal in 2014.

A similar trend was apparent on the Flemish Cap (Figure 4b) with a generally increasing trend since the early 1990s, 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. Since 1995, only 5 out of the past 20 years had below normal values, however, 2014 had the lowest value since 1994. A fitted linear trend to the data indicates an increase in SST on the Flemish Cap of about +1.5 °C over the past 34 years.

LONG-TERM TEMPERAUTE TRENDS

Time series of annual temperature anomalies on the Flemish Cap at depths of 10, 50, 100 and near-bottom constructed from the historical data are shown in Figure 5. 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 with no significant trend unlike the SST values shown in Figure 4. At a depth of 50 m to the bottom there are clear trends with a cold period from about 1985 to the mid-1990s. During the early 1990s bottom temperature anomalies exceeded -1°C below normal. During the past decade and a half temperatures on the Flemish Cap were mostly above normal reaching 2.3°C and 1.4°C above normal at 50 and 100 m depth, respectively. Near bottom temperatures reached a peak of 1.4°C above normal in 2010, the highest in the series. A fitted linear trend to the data indicates an increase in bottom temperatures on the Flemish Cap of about +1°C since 1980.

Since the peak in 2010 bottom temperatures on the Flemish Cap have been decreasing with 2014 showing the lowest value since 1995 at -0.5°C below normal. At 10, 50 and 100 m depth temperatures were below normal by -0.8°C, -0.4°C and -0.7°C, respectively in 2014.

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 2014, the Flemish Cap section was sampled 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 2014.

The water masses characteristics of the Flemish Cap area are derived from a mixture of Labrador Current Slope Water and North Atlantic Current Water. The resulting water mass is generally warmer and saltier than the sub-polar Newfoundland Shelf waters with a temperature range of 3-4°C and salinities in the range of 34-34.9.

The Labrador Current which flows southeastward along the slopes of the Newfoundland and Labrador Shelf undergoes a bifurcation in the vicinity of the northeast Grand Bank. The major portion of this current then flows southward through the Flemish Pass following the bathymetry southward to the tail of the Grand Bank. A smaller portion of the current flows eastward north of the Cap and then southward on the eastern side of the Cap. To the south, the Gulf Stream flows to the northeast mixing with remnants of the Labrador Current to form the North Atlantic Current which influences the waters around the southern areas of the Cap. In the absence of strong wind forcing the circulation over the central Flemish Cap is dominated by a topographically induced anti-cyclonic (clockwise) gyre (Figure 1).

In general, the water mass characteristics along the standard Flemish Cap section (Figure 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 6 and 7 along the Flemish Cap portion of the section with the colder Newfoundland Shelf and Labrador Slope waters ($T < 3$°C) as the dominate thermal feature. The development of a well-defined cold-intermediate layer (CIL) with $T<3$°C over the Cap was evident in the summer and fall of 2014. The corresponding salinity cross-sections show the relatively fresh upper layer shelf water originating from the Labrador Shelf with values <33.5 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 (Figure 7).

During 2014 temperatures along the section were predominately below normal during all seasons but particularly during the spring survey when upper layer values reached between 1°C -2°C below normal. These cold anomalies penetrated to the bottom directly over the Cap with a striking cold anomaly persisting at depth over the Cap during the fall survey. There were some exceptions where temperatures were above normal, for example in the near-surface layer during the summer directly over the Cap and at deeper depths during all three surveys (Figure 6).

Spring salinities were lower than normal (>0.5) in the upper layer on the Flemish Pass side of the Cap and slightly above normal (0.2) over the outer portion of the Cap, otherwise near-normal. During the summer salinities were slightly lower than normal at depth and lower than normal by 0.5 in the upper water column. During the fall salinities continued below normal by 0.2-0.4 from the surface to the bottom over the central portions of the Cap.

COLD INTERMEDIATE LAYER (CIL)

The temperature profiles collected on Flemish Cap from 1988-2014 by the EU bottom trawl surveys were used to explore the spatial coverage and average thickness of the CIL on the Flemish Cap 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 and North Atlantic Current Water, which produce waters with average temperatures in the range of 3-4°C. During cold years however, a well-defined CIL develops over the Cap (Figure 6) with T<3°C and indeed as low as 1°C. Hence, by analyzing the vertical temperature profile of each CTD cast, it can be determined if the CIL was registered at a given CTD station by checking if the temperature was lower than 3°C at some point of the vertical profile. Once this analysis has been developed for all CTD stations, the percentage of CTD cast where the CIL was found can be estimated for each survey year. As CTD cast are well distributed over the bank, it could be assumed that this percentage is comparable to the Flemish Cap surface area covered by the CIL water mass. It is however important to highlight that there is no objective temperature value that define the limits of the CIL. For this reason we explored other temperature values (<1°C, <2°C) when estimating the percentage of the Flemish Cap surface covered by the CIL. Temperature profiles were also used to determine the vertical thickness of the CIL in each CTD cast, and an average value for the whole Flemish Cap was estimated for each year.

In concordance with the expected negative relationship of the CIL spatial coverage with the average surface and bottom water temperature, at all the three temperature levels (1°, 2° and 3°C), the higher spatial coverage was usually found during those years with negative temperature anomalies, with the exception of 2000 and 2008 (Figure 8). 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 Figure 8 and Figures 4a and 5). The CIL coverage defined by temperature <1°C is comparable in 1993 and 2014. However, the CIL coverage when the 2°C limit is used is lower in 2014 (60%) than 1993 (100%). These observations are both in agreement with conclusions above when comparing bottom temperature in years 1993 and 2014, i.e. that water temperature in the shallowest areas of the cap were comparable (equal CIL coverage bellow 1°C), but temperatures in the ring around the cap were higher in 2014 (lower CIL coverage bellow 2°C).

The average thickness of the CIL shown in Figure 9 show large vertical thickness during the cold years of the early 1990s, below normal to near-normal values from 1996 to 2013 but a significant increase during the summer of 2014. The value observed in 2014 was close to those observed in the cold period of early-mid 1990s (Figure 9).

BOTTOM TEMPERATURE STRUCTURE

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 1988-2014. Surveys are typically 4-5 weeks duration during which CTD stations were conducted within selected stratum following the randomly stratified survey or 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 2046 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 2014 the EU bottom trawl survey in Flemish Cap (Div. 3M) was carried out on board R/V Vizconde de Eza from June 25th to July 23rd. The survey covered depths up to 1460 m with 67 CTD stations conducted (González-Costas et al. 2015) (Figure 3).

Temperature and salinity grids of the survey area were computed using standard geostatistical techniques by extracting T/S values corresponding to the bottom of the CTD profiles. Contour maps of bottom temperatures and salinity and their anomalies and difference from the previous year were derived for selected surveys and for the average conditions. Anomaly maps were produced by subtracting the average grid from the individual yearly grids.

The average bottom temperature and salinity conditions on the Flemish Cap are displayed in Figure 10. On average bottom temperatures range from 3.5°C -3.7°C along the periphery and central portions of the Cap. An area of warmer 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 North Atlantic Current water. Over the central portions of the Cap Labrador Shelf water is dominate with salinities ranging from 34.5-34.7.

Bottom temperature and temperature anomalies for 1993 (one of the coldest years on record) and for 2013 (one of the warmest years on record) are shown in Figure 11 to highlight the maximum annual variation in bottom temperatures on the Flemish Cap. In 1993 the entire bottom area of the Flemish Cap was covered by Labrador Slope and Shelf water with T<3.7°C over most areas but <3°C on the central Cap with water depths <200 m. These values were below the long-term average over almost the entire region with anomalies near -1°C below normal in the shallowest waters of the Cap. In contrast, 2013 bottom temperature were generally >4°C over most regions with anomalies ranging from 0.2°C-0.7°C above normal.

In 2014, bottom temperatures ranged from 2.7°C -3°C over the centre of the Cap which was up to -0.6°C below the long-term average. In deeper waters around the Cap temperatures ranged from 3.8°C -4°C which were 0.2°C -0.4°C above normal (Figure 12). Thus it appears that while most of the water column experienced below normal temperatures (Figure 6) the cold water anomaly only impacted the bottom area over the shallow portions (<200 m) of the Cap during the summer but appears to have expanded deeper into the water column by late fall (Figure 6). Nevertheless, a significant decrease in bottom temperatures occurred in 2014 compared to the previous year with values decreasing by over 1.2°C in some areas (Figure 13).

SUMMARY

An analysis of oceanographic data collected around the Flemish Cap indicate that annual sea-surface temperatures (SST) based on infrared satellite imagery decreased to about -0.5°C below normal in 2014, while water column temperatures decreased to-0.8°C, -0.4°C and -0.7°C below normal at 10, 50 and 100 m depth, respectively. The results from seasonal surveys along the standard Flemish Cap section show the development of a well-defined cold-intermediate layer (CIL) with T<3°C over the Cap during the summer and fall of 2014. Temperatures along the section were predominately below normal during spring, summer and fall but particularly during the spring survey when upper layer values reached between 1°C -2°C below normal. The cold anomalies penetrated to the bottom directly over the Cap with a cold anomaly persisting at depth over the Cap during the fall survey. The corresponding salinity cross-sections show the 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 and average thickness of the CIL observed in 2014 was close to that observed during the cold period of early-mid 1990s. In 2014, bottom temperatures ranged from 2.7°C -3°C over the centre of the Cap which was up to -0.6°C below the long-term average. However it appears that the below normal temperatures only impacted the bottom area over the shallow portions of the Cap during the summer but appears to have expanded deeper into the water column by late fall. In general there was a significant decrease in bottom temperatures in 2014 compared to the previous year (by >1°C) thus reversing the decade long warm trend in the waters of the Flemish Cap.

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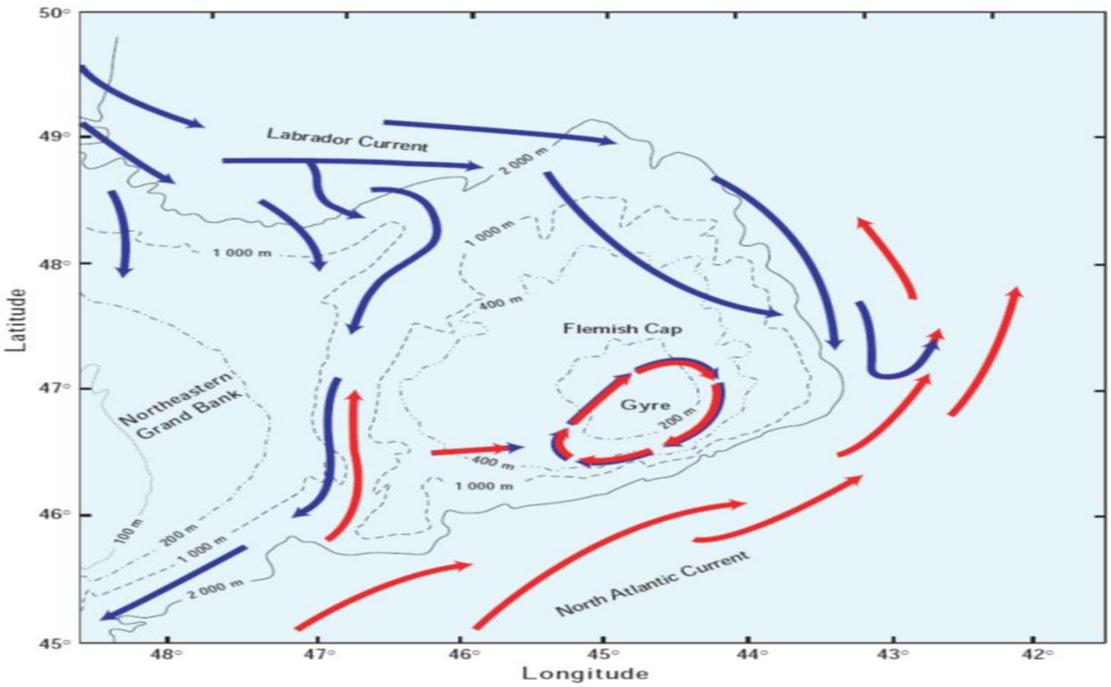

Figure 1. Areal map showing the local bathymetry and major circulation features around the Flemish Cap area

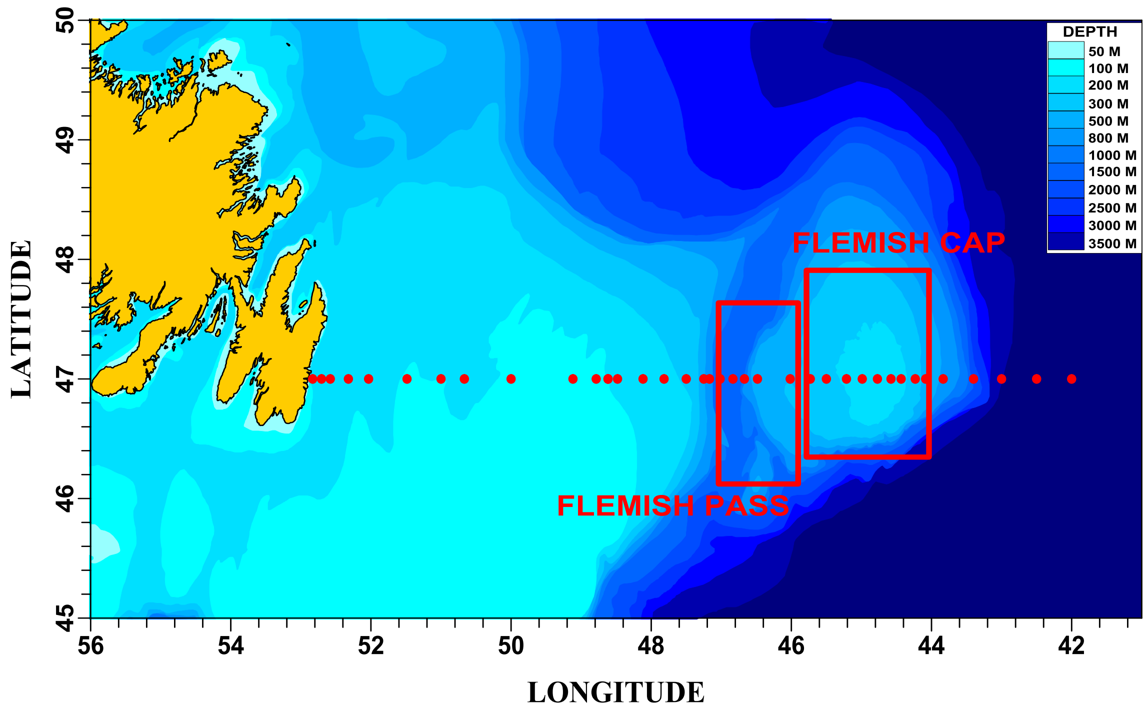

Figure 2. Areal map showing the standard Flemish Cap (47°N) section and the Flemish Cap sub-areas where satellite SST time series were constructed. The red dots show the positions of the stations along the section.

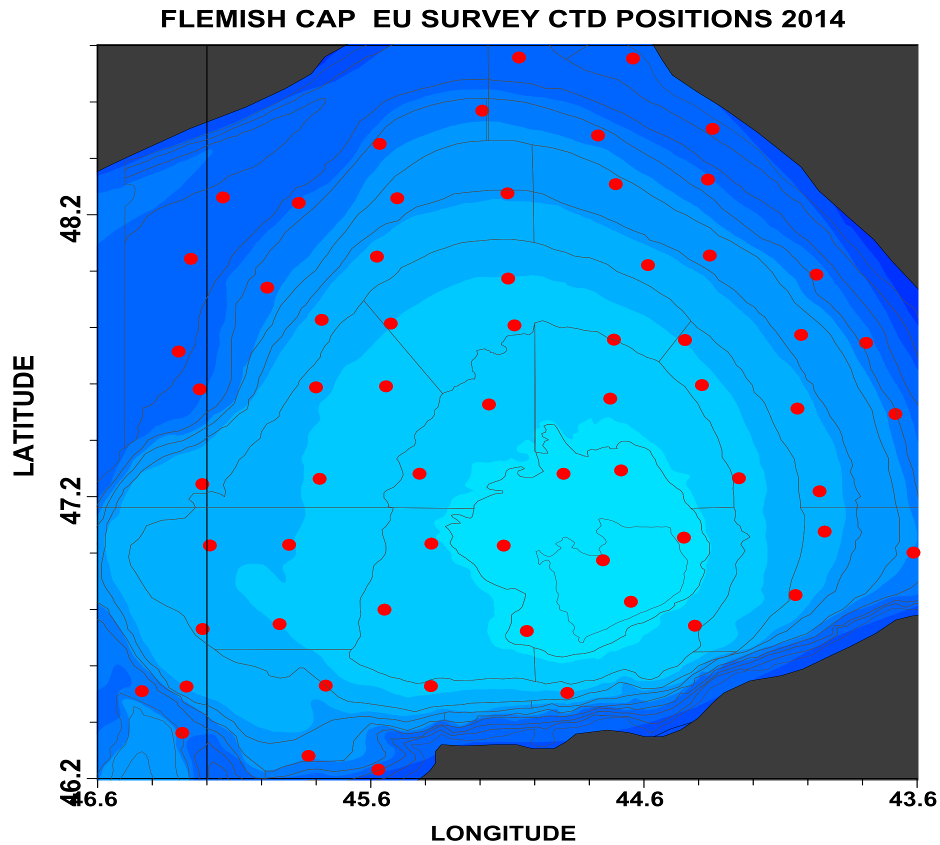

Figure 3. Map showing the positions of CTD profiles obtained from the summer EU stratified random multispecies survey of the Flemish Cap area during June-July of 2014.

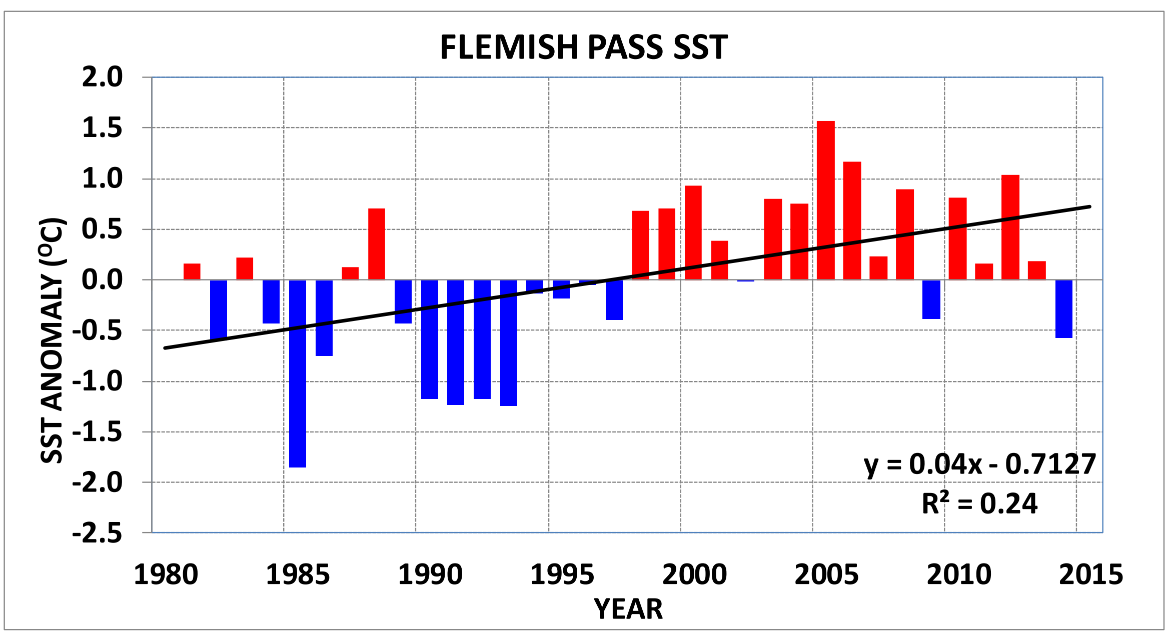

Figure 4a. Annual SST from the Flemish Pass sub-area (Figure 2) referenced to the 1981-2010 mean. The black line shows a linear trend over the length of the time series.

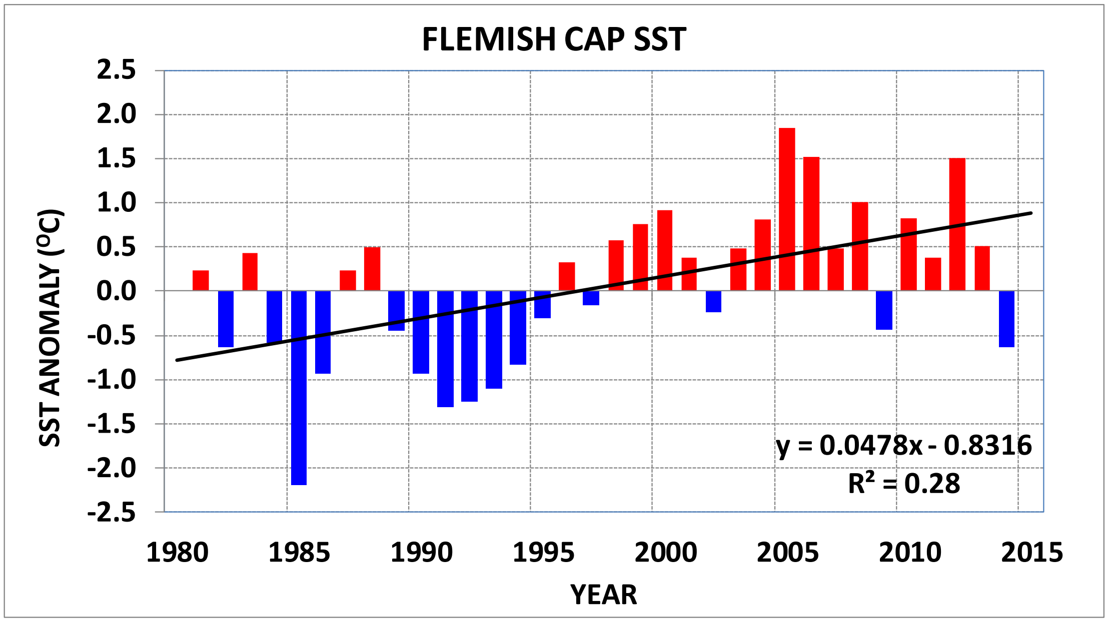

Figure 4b. Annual SST from the Flemish Cap sub-area (Figure 2) referenced to the 1981-2010 mean. The black line shows a linear trend over the length of the time series.

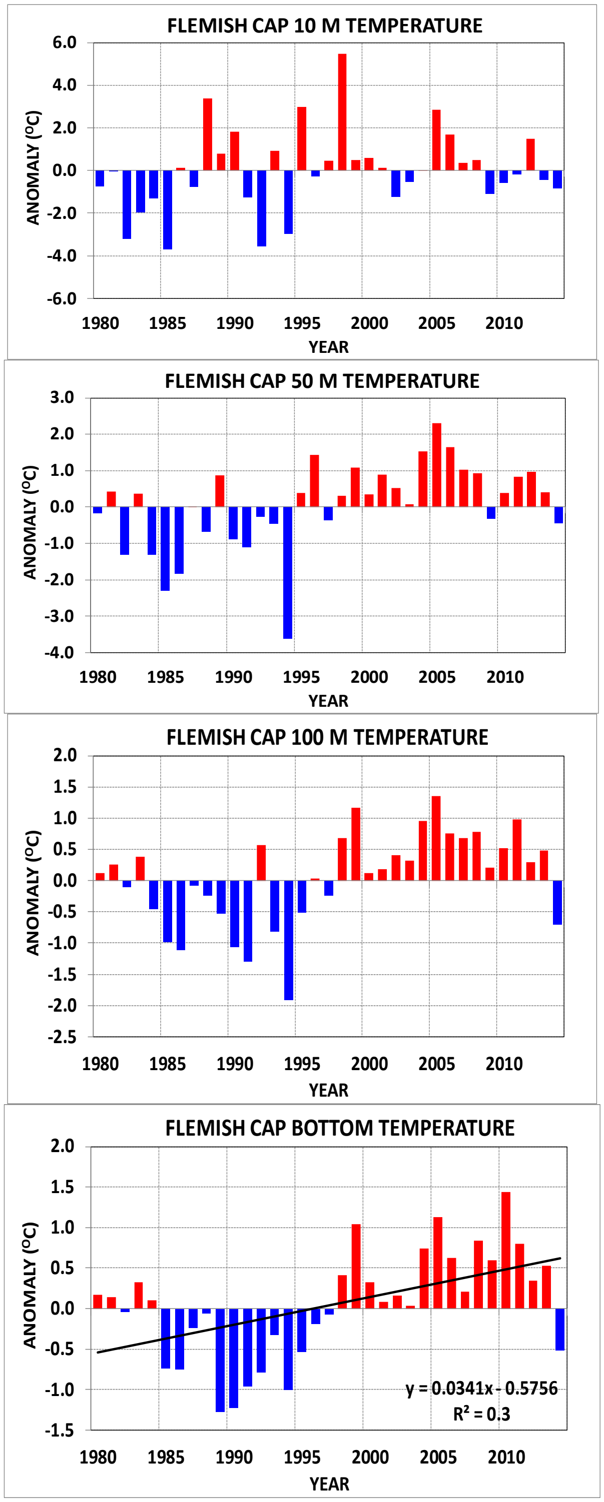

Figure 5. Annual 10, 50,100 m and bottom temperature anomalies from the central Flemish Cap referenced to the 1981-2010 mean. The black line shows a linear trend over the length of the time series.

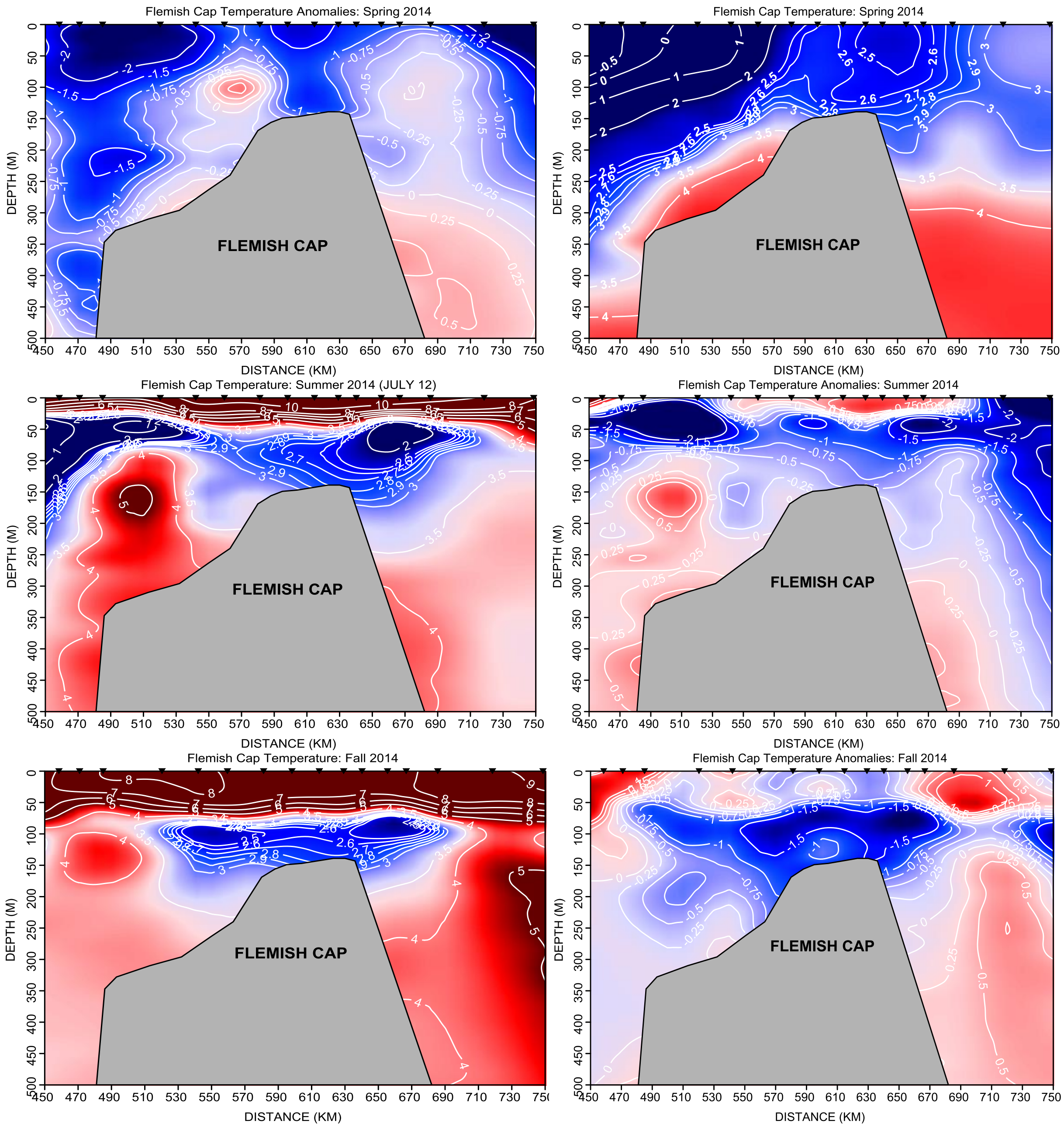

Figure 6. The vertical distribution of temperature and temperature anomalies (in °C) over the Flemish Cap (along 47°N) during the spring, summer and fall of 2014. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section.

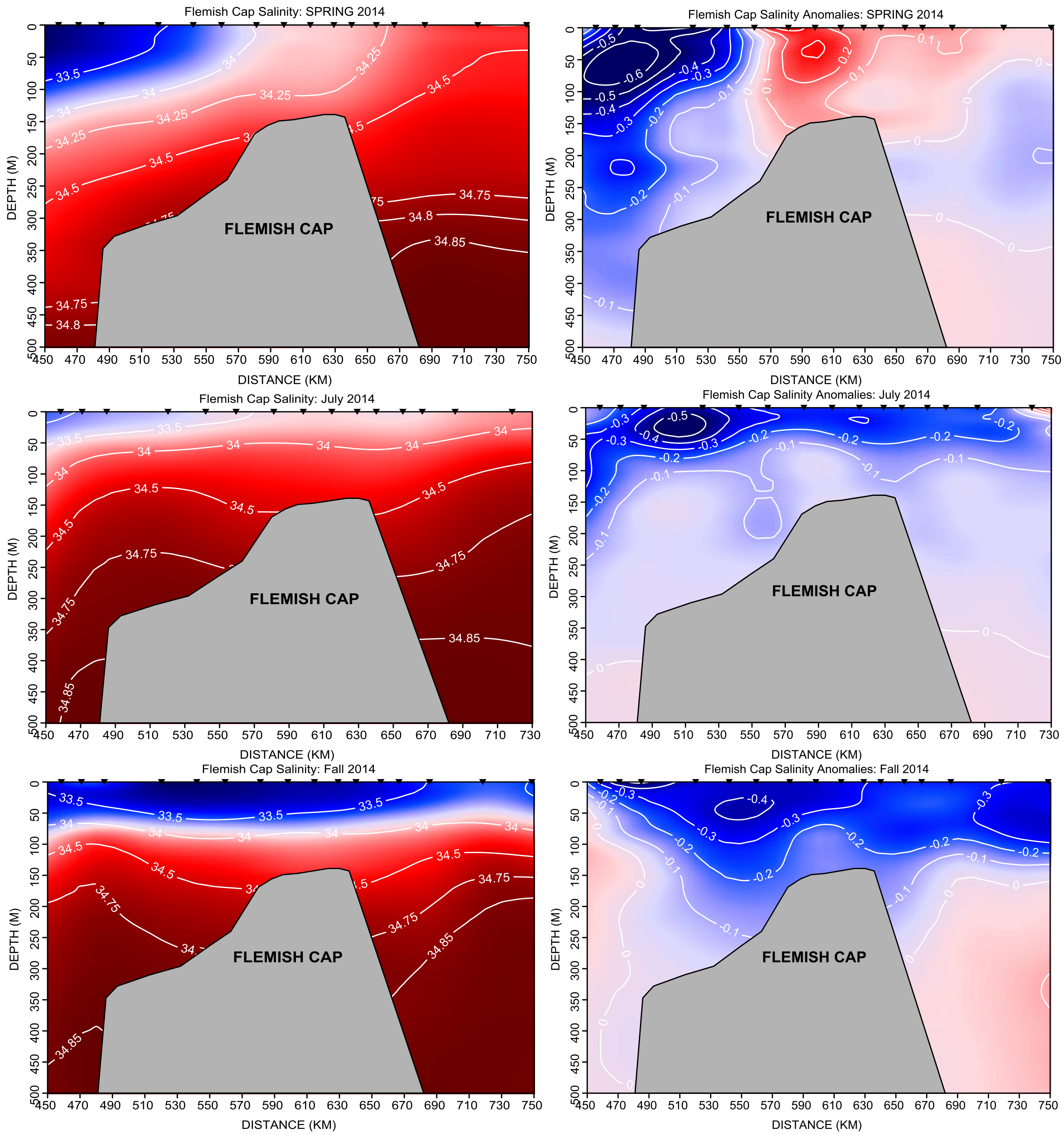

Figure 7. The vertical distribution of salinity and salinity anomalies over the Flemish Cap (along 47°N) during the spring, summer and fall of 2014. Anomalies are referenced to the 1981-2010 mean. The black triangles at the top of each panel indicate the vertical CTD profile locations along the section.

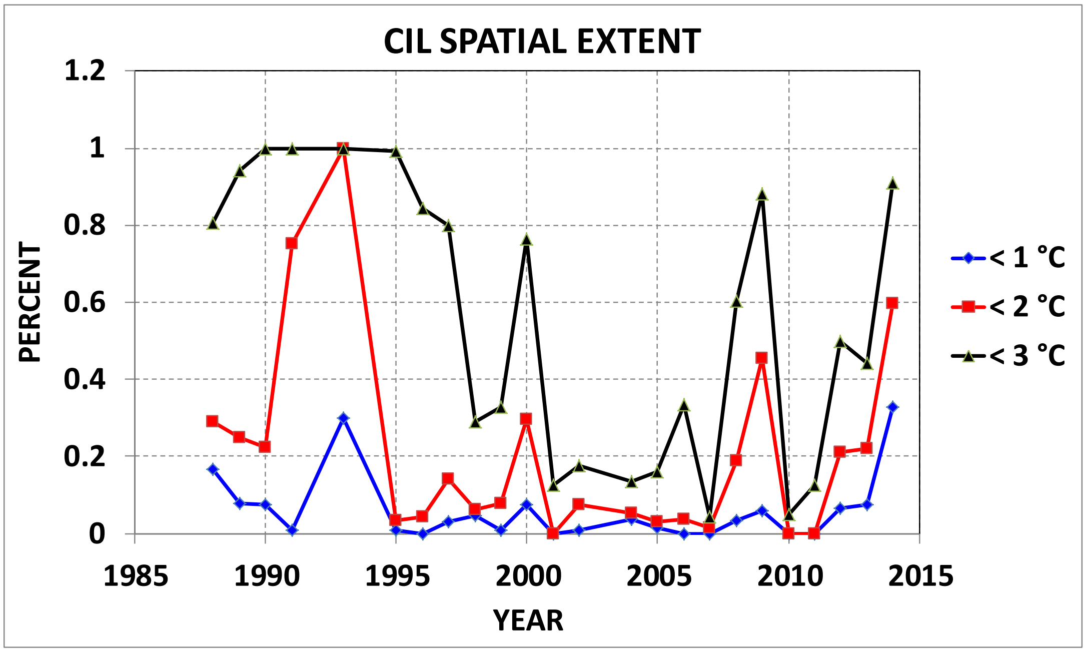

Figure 8. Percentage by year of the CTD profiles from the Flemish Cap survey where temperature values were lower than <1 ºC, <2 ºC and <3 ºC.

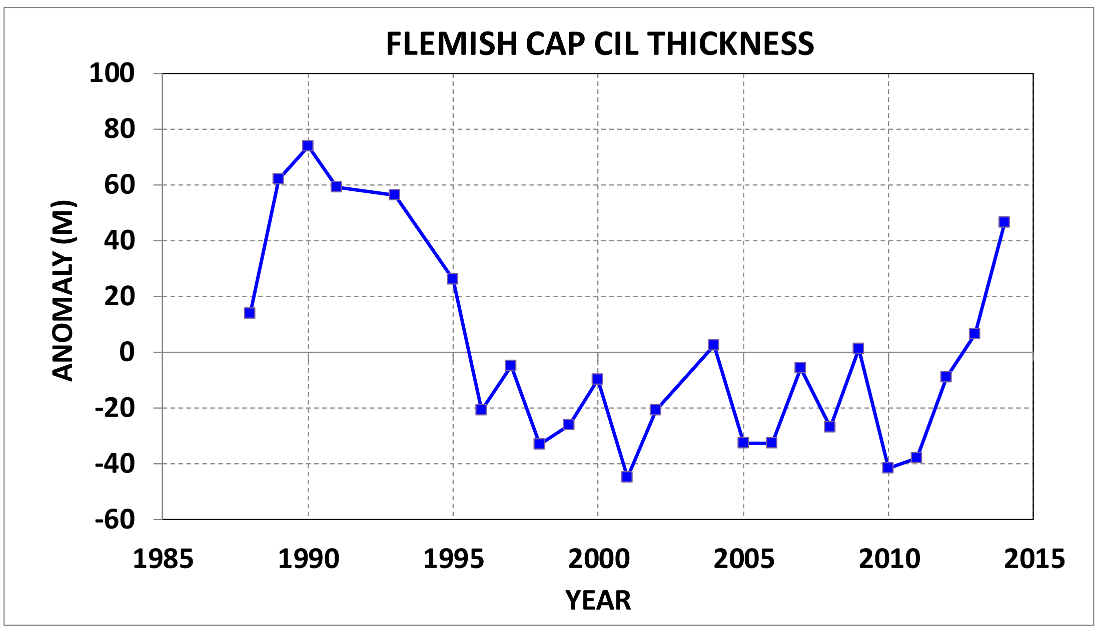

Figure 9. Thickness of the Cold-Intermediate-Layer (CIL) (M) water mass on the Flemish Cap defined by temperatures <3 ºC.

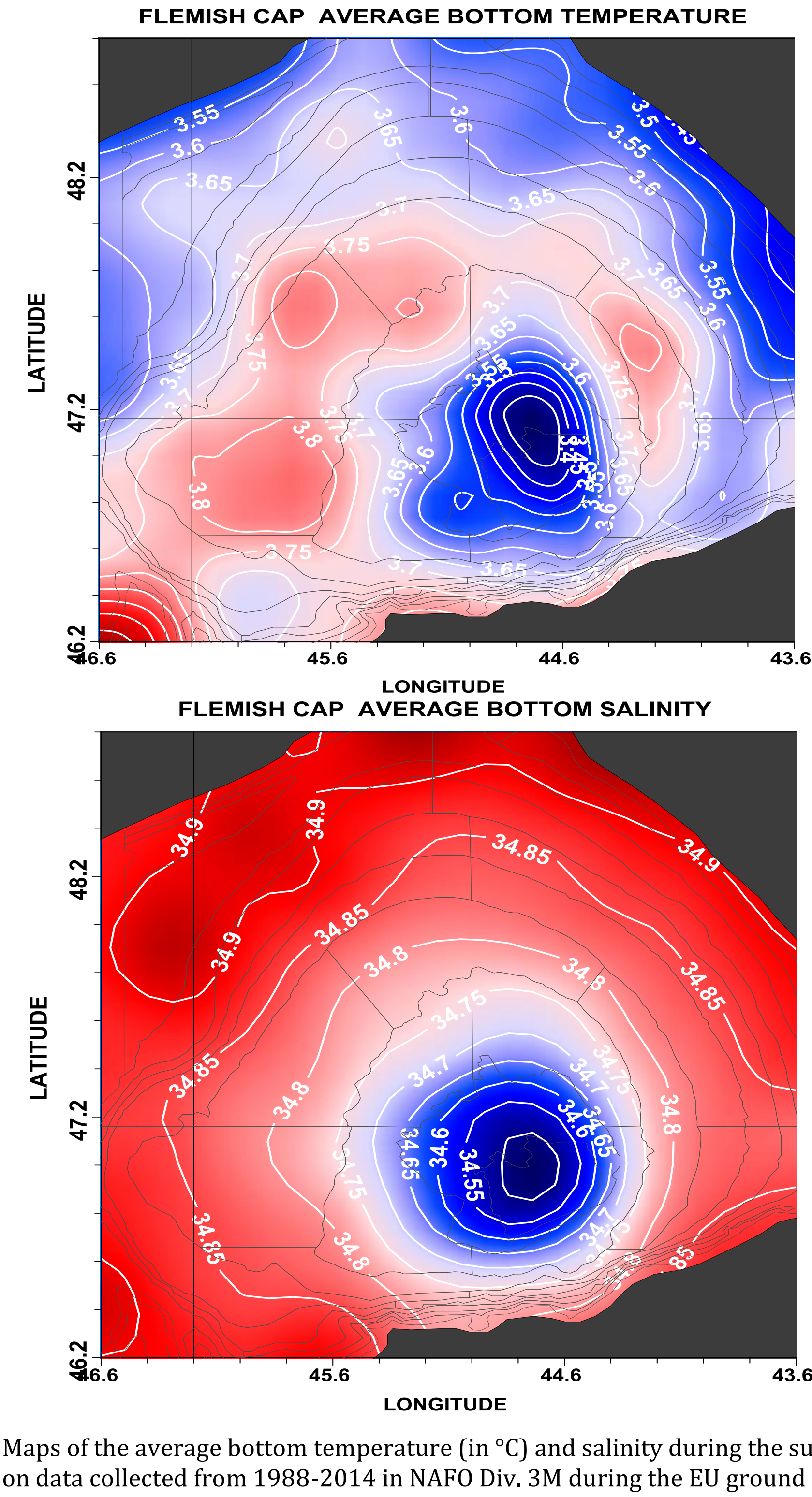

Figure 10. Maps of the average bottom temperature (in °C) and salinity during the summer (July) based on data collected from 1988-2014 in NAFO Div. 3M during the EU ground fish survey.

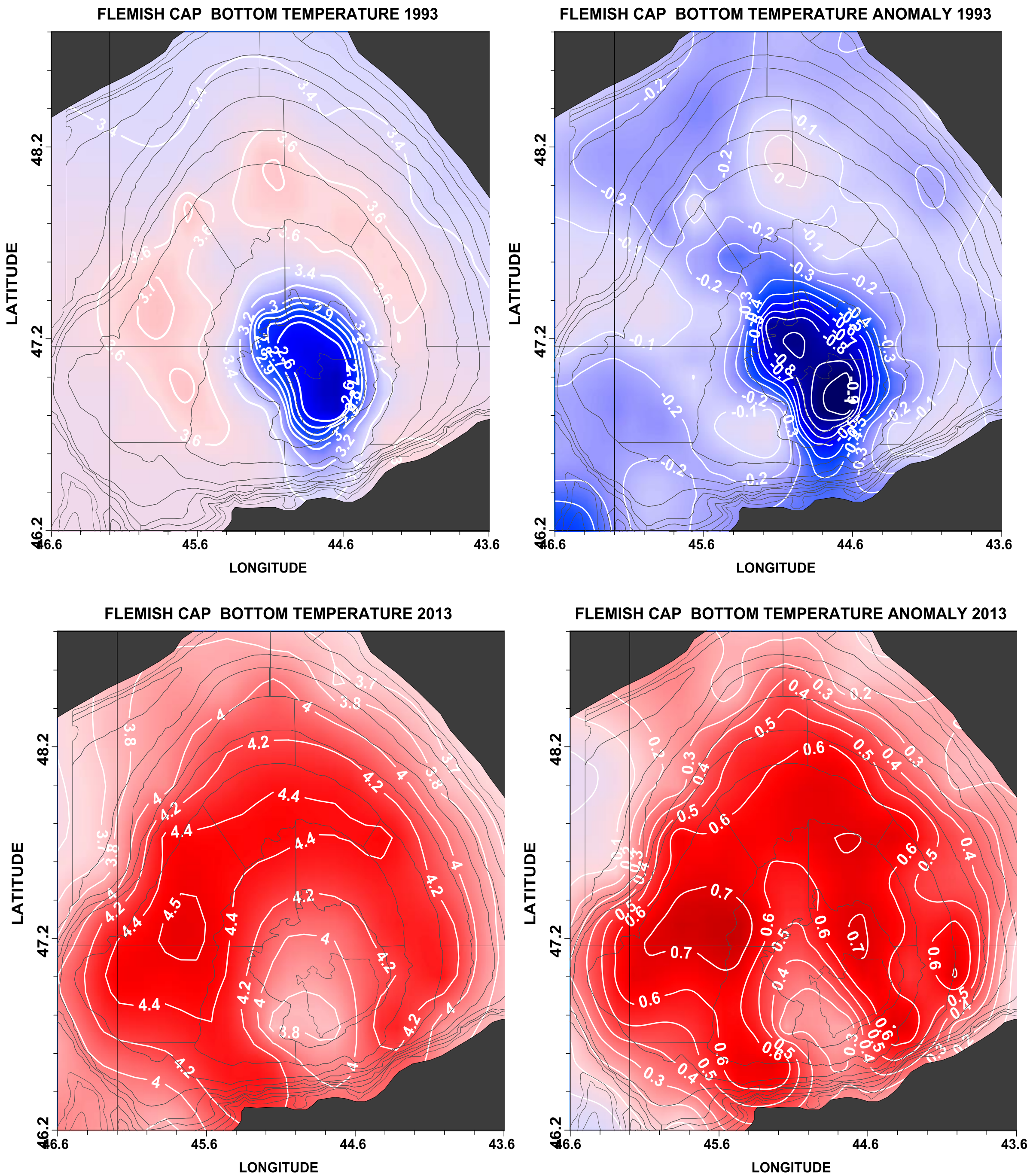

Figure 11. Maps of the bottom temperature and bottom temperature anomalies during the summer of 1993 and 2013 (in °C) in NAFO Divs. 3M based on data collected during the EU ground fish survey.

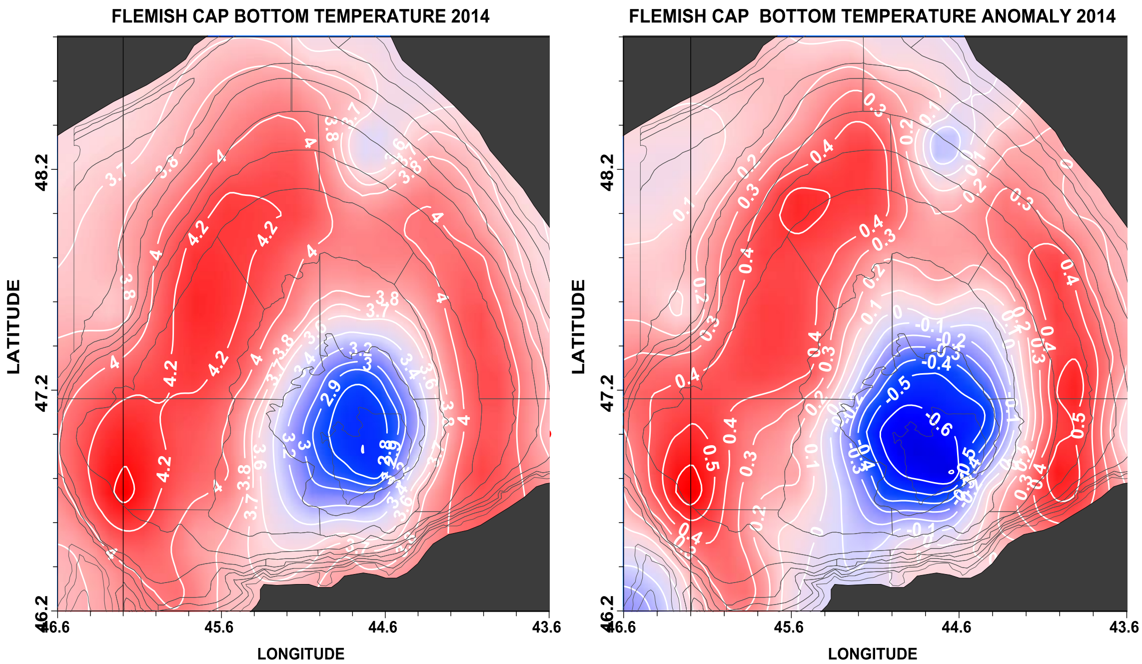

Figure 12. Maps of the bottom temperature and bottom temperature anomalies during the summer of 2014 (in °C) in NAFO Divs. 3M.

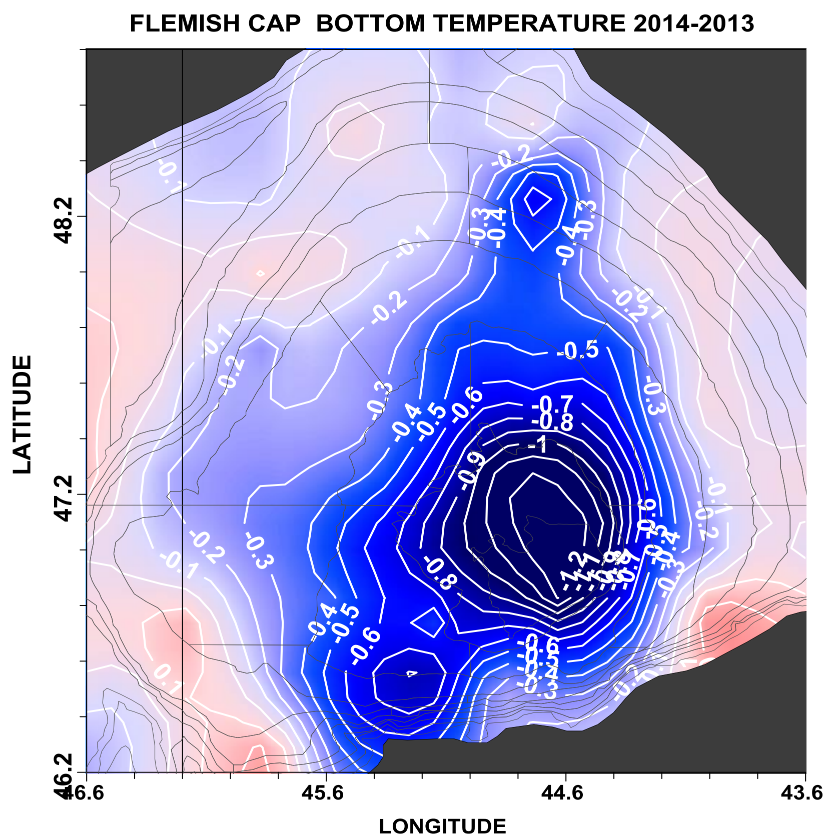

Figure 13. Maps of the bottom temperature difference between the summer of 2014 and 2013 (in °C) in NAFO Divs. 3M.