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Oceanographic Conditions on the Flemish Cap in NAFO Division 3M during the Summer of 2006

by

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Abstract

Oceanographic data from the summer of 2006 on the Flemish Cap are examined and compared to the long-term (1971-2000) average. The cold near-surface temperatures (0.5° to 2°C below normal) experienced over the Cap from 1993-1996 had warmed to 0.5°-1.5°C above normal by the summer of 1997, which increased further to >2°C above normal by the summer of 1999. Upper layer temperatures over the Flemish Cap during the spring of 2001 and the summer of 2002 generally showed a downward trend with temperatures decreasing to below normal values. During the summer of 2003, temperatures directly over the Cap were highly variable while adjacent areas showed significant positive anomalies and during 2004 and 2006 they increased to above normal values. Near bottom temperatures over the Cap during 2006 were about 4°C, which was near the long term mean. Salinities over most of the water column during the summer of 2002 to 2005 were generally saltier-than-normal but decreased to near-normal values in 2006. In general the colder than normal temperatures experienced over the continental shelf and on the Flemish Cap from the late 1980s up to the mid-1990s moderated by the summer of 1996 and continued to warm until 1999. During the summer of 2000 and into the spring of 2001 the observations indicate a reversal in the recent warm trend in some areas of the water column with temperatures decreasing to near normal values in most areas. During 2003 to 2006 however, upper-layer temperatures continued to increase reaching 3°C above normal in 2006. During 2006 and throughout most of the 1990s and early 2000s summer chlorophyll levels in the upper 100-m of the water column over the Cap were higher compared to the adjacent Grand Bank indicating enhanced productivity over the Flemish Cap. Dissolved oxygen levels were about normal for the region with super-saturated values in the near surface layers reaching 105%. In general oxygen levels observed along this section are similar to that observed during most of the 1990s and are typical of the highly oxygenated water column of this region. Finally, it appears that the circulation pattern around the Cap was dominated by anti-cyclonic gyre circulation with an increase in strength during the summer of 2006 compared to that of 2005.

Introduction

The Flemish Cap is an isolated bank located east of the Grand Bank of Newfoundland centred at about 47°N, 45°W with minimum water depths of 126-m (Fig. 1, top panel). To the west, the Flemish Pass with maximum water depths of about 1 100 m separates the Cap from the Grand Bank. The water mass over the Flemish Cap is a mixture of Labrador Current and North Atlantic Current water, the general circulation of which is shown in Fig. 1 (bottom panel). Since the early 1970s the water masses over the Atlantic continental shelves have been dominated by three anomalously cold periods: early 1970s, mid-1980s and the early 1990s (Colbourne *et al*., 1994) followed by a general warming trend since then. During the cold periods positive winter North Atlantic Oscillation (NAO) index anomalies were mainly responsible for colder than normal air temperatures over the Northwest Atlantic resulting in

increased ice cover and colder and fresher than normal oceanographic conditions over the continental shelf of Atlantic Canada that extended to the Flemish Cap area (Colbourne *et al*., 1994; Drinkwater, 1996). During the mid-1990s however, the ocean climate in this region returned to more normal like conditions and by the late 1990s ocean temperatures in many areas reached record highs (Colbourne 1999, 2000, Colbourne *et al*., 2004).

Keeley (1981) published monthly mean temperature and salinity data from 1910-1980 along the standard Flemish Cap Section (Fig. 1). Drinkwater and Trites (1986) published spatially averaged temperature and salinity from all available bottle data from 1910 to 1982 over the Flemish Cap area. 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 compared 1993 and 1995-2005 observations with the long-term mean and also presented time series of temperature and salinity anomalies at various depths around the Cap (Colbourne, 1993, 1995, 1996, 1997, 1998a, 1998b, 1999, 2000, 2001, 2002, 2003, 2004, 2005). Stein (1996) summarised the most recent studies of oceanographic conditions on the Flemish Cap. Additionally, Cervifio and Prego (1996), Garabana *et al*. (2000), Lopez (2001) and Cabanas (2002, 2003) have presented hydrographic conditions on the Flemish Cap in July from fisheries research surveys conducted by the European Union. This manuscript presents an update to these studies by including data up to the summer of 2006 and represents the 14th such review of oceanographic conditions on and around the Flemish Cap in support of the annual Div. 3M shrimp assessment carried out by NAFO Scientific Council.

This report describes oceanographic variability on the Flemish Cap during the summer of 2006 with a comparison to the long-term mean, based on all available historical data. The normal has been defined as the 30-year period from 1971-2000. The 2006 observations were made by Canada's Department of Fisheries and Oceans oceanographic survey during the summer of 2006. During this survey oceanographic observations were made along the standard NAFO Flemish Cap section at 47°N latitude (Fig. 1, top panel). Physical oceanographic measurements included vertical profiles of temperature, salinity, chlorophyll and dissolved oxygen.

1. *Average Temperature and Salinity*

Vertical distributions of the July temperature and salinity fields over the Flemish Cap along 47°N based on all available historical data from 1971-2000 are shown in Fig. 2. The average near-surface temperature across the Flemish Cap for this period ranges from 9°-11°C (Fig. 2, upper panel). Below the thermocline (approximately 40-50 m) average temperatures range from 2°- 4°C on the Flemish Pass side of the Cap to <3°- 4°C over the Cap and to the east of the Cap. The areas with temperatures <3^{o} in the Flemish Pass and on the eastern side of the Cap correspond to Labrador Current Water. Water temperatures at depths >200 m in the Flemish Pass, and on the eastern slopes, range from 3.5°- 4°C. Bottom temperatures over the Cap and on the eastern slopes of the Cap also range from 3.5°- 4°C. The corresponding average surface salinities (Fig. 2, bottom panel) range from <33.25 in the Flemish Pass to about 33.5-33.75 over the Cap and eastward of the Cap. Near bottom over the Cap, in water depths of 150 to 300-m, salinities range from 34.5 to 34.75. In general, cold sub-surface and relatively fresh surface water from the Newfoundland Shelf normally influences the water mass characteristics over most of the Flemish Cap.

2. *2006 Temperature and Salinity*

Surface temperatures over the Flemish Cap during the summer of 2006 ranged from about 12°-14°C, which were above normal by 2°-4°C in most areas (Fig. 3). Below the surface layer, temperatures ranged from 3.5° to 4°C which were above normal in eastern areas and slightly below normal on the western side. The edge of the cold intermediate layer (CIL) waters with temperatures <3°C from the Newfoundland Shelf were present as usual in the Flemish Pass during July of 2006. Near-bottom temperatures over the Cap in water depths from 150-500 m were ~4°C, which were about normal. Except for the surface layers, temperatures decrease by about 0.5°C in the intermediate depths during the summer of 2006 compared to 2005 but still remained well above normal in most areas.

Near-surface salinities observed during the summer of 2006 (Fig. 4, top panel) were <33.5 over the Flemish Pass and Flemish Cap. Salinities generally increased with depth from 33.5 to 34.5 at 150 m depth. Salinities near bottom over the Cap in water depths around 150 m were generally >34.5 and >34.8 below 200-300 m depth. In

general these values were close to the long-term mean in mostly areas of the water column except in the Flemish Pass where they were slightly above normal (Fig. 4, bottom panel). These values represent a slight freshening of the waters over the Cap compared to that observed in 2005.

Temperature conditions over the Flemish Cap area during the past 2 years are in sharp contrast to the cold-fresh conditions that prevailed over and around the Flemish Cap during the first half of the 1990s. During 1993 for example temperatures ranged from 1°-3°C over most of the water column which were up to 2°C below normal in some areas. Fresh water from the Newfoundland Shelf with near-surface salinities <33.5 reached offshore to the eastern slopes of the Cap producing fresher-than-normal conditions over all areas of the upper water column (Fig. 5).

3. *Long-Term Trends in Temperature and Salinity*

The time series of annual temperature anomalies in the upper water column on the Flemish Cap (Fig. 6, left panels) show considerable variability with cold periods during most of the 1970s, mid-1980s and the late 1980s to the mid-1990s. During most of the 1960s, late 1970s to early 1980s and again during the late 1990s to early 2000s temperatures were generally warmer-than-normal. The cold period beginning around 1971 continued until about 1977. From 1978 to 1984 temperature anomalies showed a high degree of variability in the upper water column with a tendency towards positive anomalies. By 1985 in the top 100-m of the water column negative temperature anomalies had returned. This cold period moderated briefly in 1987-88 but returned again by 1989 and continued until the mid-1990s. From 1995 to 1998 temperatures moderated and remained above normal during the summer of 1999 in the depth range from 0 to 150-m. During 2000 and 2001 temperatures decreased significantly over 1999 values but remained near normal at 150 m and slightly above normal at shallower depths. Temperatures at all depth increased during 2003 to 2005 to above normal values by >2°C at the surface and >1°C at 150 m depth. In 2006 temperatures continued to increase near the surface to 3°C above normal but decreased slightly at 100 and 150 m depth. In general, temperature trends on the Flemish Cap are very similar to those observed on the Newfoundland Shelf during the same period (Colbourne and Foote, 2000).

The time series of annual salinity anomalies (Fig. 6, right panels) show fresher-than-normal conditions during the mid-1970s and mid-1980s in the upper 100-m of the water column, with peak amplitudes reaching 0.9 below normal. In general, the magnitude of the salinity anomalies decreases with increasing depth. The trend in salinity values during the early 1990s was mostly below normal until 1995 from the surface to about 100-m depth. From 1996 to 1998 salinities were generally above normal. During 1999-2000 salinities were near the long-term average on the Flemish Cap but increased to above normal values during 2001-2002. Upper layer salinities during 2003 increased to some of the highest values observed in the time series. During 2004 and 2006 they decreased but remained above the long term mean for the 6th consecutive year. In general, salinity anomalies are very similar to those at Station 27 and elsewhere on the continental shelf over similar depth ranges (Colbourne, 1998b). It should be noted however, that unlike the time series of anomalies from fixed points (e.g. Station 27 on the inner Newfoundland Shelf), these anomalies, both temperature and salinity, are based on data collected over a larger geographical area and therefore may exhibit variability due to spatial differences in the monthly estimates. In addition, the annual values may be based on only a few monthly estimates for the year. Therefore caution should be used when interpreting short time scale features of these series. The long-term trends however, generally show real features.

4. *2006 Chlorophyll and Dissolved Oxygen*

The vertical distribution of dissolved oxygen saturation during the summer of 2006 along the standard NAFO section across the Grand Bank and the Flemish Cap is shown in Fig. 7. These data were collected in conjunction with the temperature and salinity data using a SBE-43 type polarographic element dissolved oxygen sensor interfaced to a Seabird-911 CTD system. The oxygen sensor was factory calibrated at zero and air-saturated water oxygen levels and also field calibrated by taking water samples at standard depths. The oxygen levels of the samples were determined by semi-automated analytical chemistry using a modified Winkler titration technique. The sensor readings were then corrected by using least-squares fit of the titration measurements to the electronic sensor measurements. Over the Flemish Cap dissolved oxygen saturation levels during the summer of 2006 ranged from 100-105% from the surface to about 75-m depth (Fig. 7). From 75-100 m depth, saturation values decreased from 100% to 90% and near bottom

values were generally around 85-90% saturation. In general oxygen levels observed along this section are similar to that observed during most of the 1990s and are typical of the highly oxygenated water column of this region.

The vertical distribution of relative chlorophyll concentrations for the summer of 2006 across the Grand Bank and the Flemish Cap is shown in Fig. 8. These data were also collected in conjunction with the temperature and salinity data using a fluorometer interfaced to a Seabird-911 CTD system. No field calibrations were applied to the chlorophyll values presented here. The chlorophyll concentrations were very low over the Grand Bank but higher in the slope branch of the Labrador Current and over the Flemish Cap. Maximum chlorophyll values over the Cap were confined to the surface layer of about 80-m thick (Fig. 8). The higher chlorophyll values over the Flemish Cap are similar to previous years and appear to extend into mid-summer and indicate an extended offshore plankton bloom relative to the Newfoundland Shelf areas (Colbourne, 2000).

5. *Circulation*

The general circulation in the vicinity of the Flemish Cap consists of the offshore branch of the Labrador Current which flows through the Flemish Pass on the Grand Bank side of the continental slope and a jet that flows to the east, north of the Cap, which then flows southward. To the south, the Gulf Stream flows to the northeast merging with the Labrador Current to form the North Atlantic Current (Fig. 1, bottom panel). 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).

The anticyclonic motion of the water mass around the Flemish Cap was first described by Kudlo and Burmakin (1972), Kudlo and Borovkov (1975) and Kudlo *et al*. (1984) using geostrophic currents estimated from density measurements. Gil et al. (2002) and Colbourne and Foote (2000) provided additional analysis based on more recent data. The geostrophic currents perpendicular to the 47^{o} N section calculated from the density data collected during the summer of 2005 and 2006 are shown in Fig. 9. These estimates, which are referenced to 300-m, or the bottom, in water depths <300-m, show some of the well-known features of the circulation. The strong baroclinic component of the offshore branch of the Labrador Current west of the Flemish Pass and the northward flowing water of the North Atlantic Current east of the Cap are evident in the 2006 cross-section. The current estimates over the Cap itself show evidence of a weak anticyclonic circulation with northward flowing water to the west and southward flow on eastern side of the Cap. The northward component of the gyre on the western side of the Cap during 2004 was similar to that observed in 2002, much weaker than that observed during the summers of 1999, 2000 and 2003 (Colbourne, 2000, 2003). During 2005 and 2006, there appeared to be an increase in the northward component compared to the previous year, indicating a slight strengthening of the gyre circulation. During most oceanographic surveys of the 1990s and up to 2004 ocean currents around the Flemish Cap area were also measured with hull-mounted acoustic Doppler current profilers (ADCPs). In general, the details of the circulation patterns measured with ADCPs differ significantly from the geostrophic estimates, thus showing the potential importance of wind driven and tidal currents, however, they both show similar features in the overall circulation pattern.

6. *Summary*

The cold near-surface temperatures (0.5° to 2°C below normal) experienced over the Cap from 1993-1996 had warmed to 0.5°-1.5°C above normal by the summer of 1997, which increased further to >2°C above normal by the summer of 1999. Upper layer temperatures over the Flemish Cap during the spring of 2001 and the summer of 2002 generally showed a downward trend with temperatures decreasing to below normal values. During the summer of 2003, temperatures directly over the Cap were highly variable while adjacent areas showed significant positive anomalies and during 2004 to 2006 they increased to above normal values. Near bottom temperatures over the Cap during 2006 were about 4°C, which was near the long term mean. Salinities over most of the water column during the summer of 2002 to 2005 were generally saltier-than-normal but decreased to near-normal values in 2006. In general the colder than normal temperatures experienced over the continental shelf and on the Flemish Cap from the late 1980s

up to the mid-1990s moderated by the summer of 1996 and continued to warm until 1999. During the summer of 2000 and into the spring of 2001 the observations indicate a reversal in the recent warm trend in some areas of the water column with temperatures decreasing to near normal values in most areas. During 2003 to 2006 however, upper-layer temperatures continued to increase reaching 3°C above normal in 2006. During 2006 and throughout most of the 1990s and early 2000s summer chlorophyll levels in the upper 100-m of the water column over the Cap were higher compared to the adjacent Grand Bank. Dissolved oxygen levels were about normal for the region with super-saturated values in the near surface layers reaching 105%. In general oxygen levels observed along this section are similar to that observed during most of the 1990s and are typical of the highly oxygenated water column of this region. Finally, during the summer of 2006, it appears that the circulation pattern around the Cap was dominated by anti-cyclonic gyre circulation with an increase in strength compared to that of 2005.

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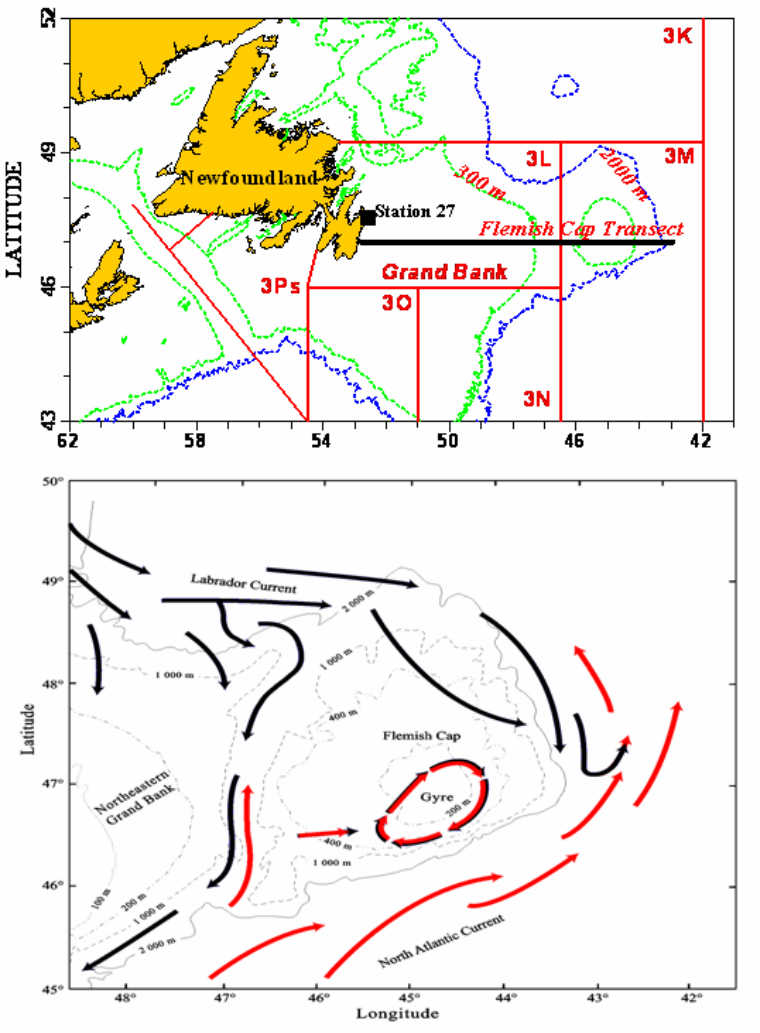

Fig. 1. Areal map showing the standard Flemish Cap section in NAFO Sub-area 3 (top panel) and the major circulation features around the Flemish Cap area (bottom panel).

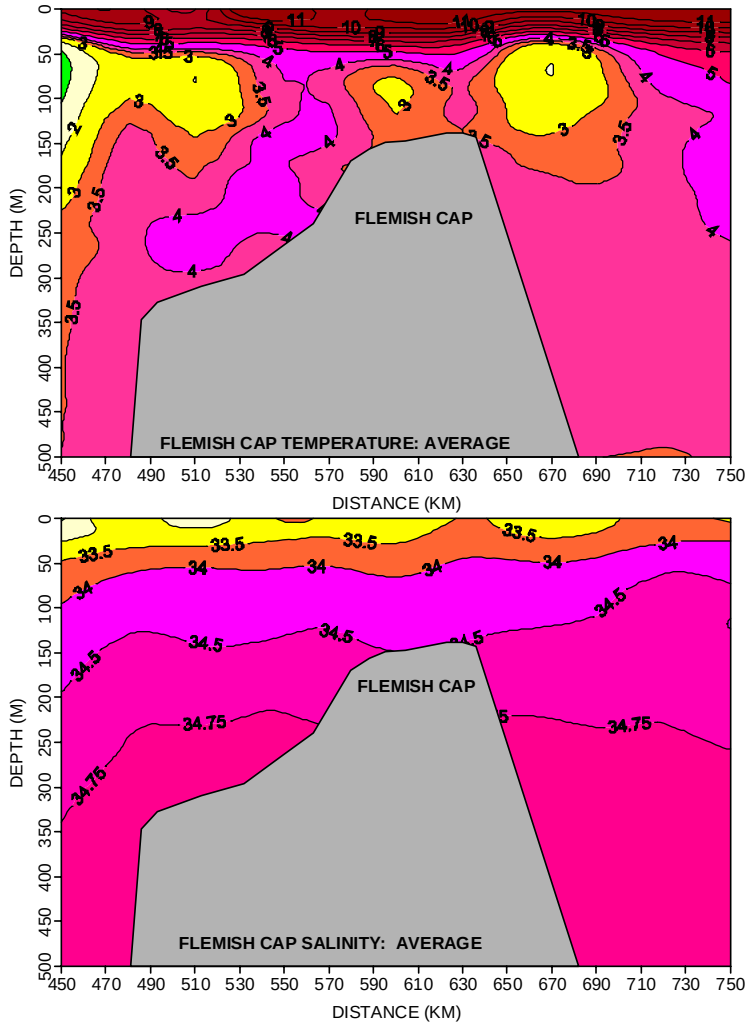

Fig. 2. Average temperature (in °C) and salinity on the Flemish Cap based on all data collected during July for the years 1971-2000.

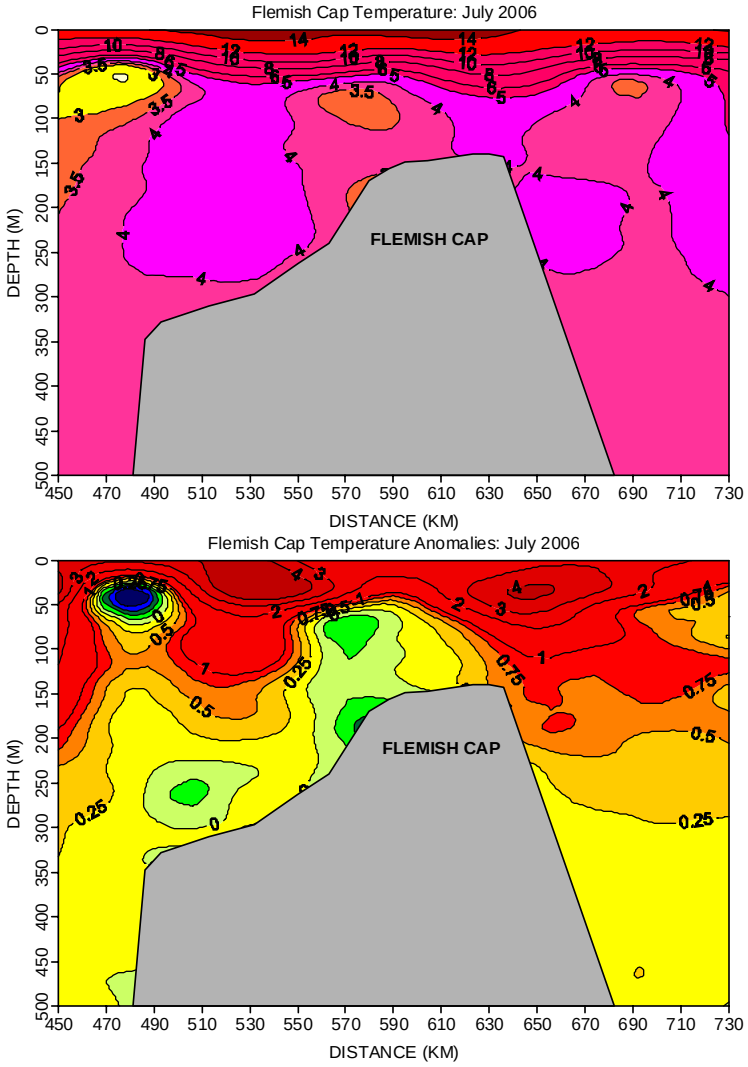

Fig. 3. The vertical distribution of temperature and temperature anomalies (in °C) over the Flemish Cap (along 47°N) for the summer of 2006.

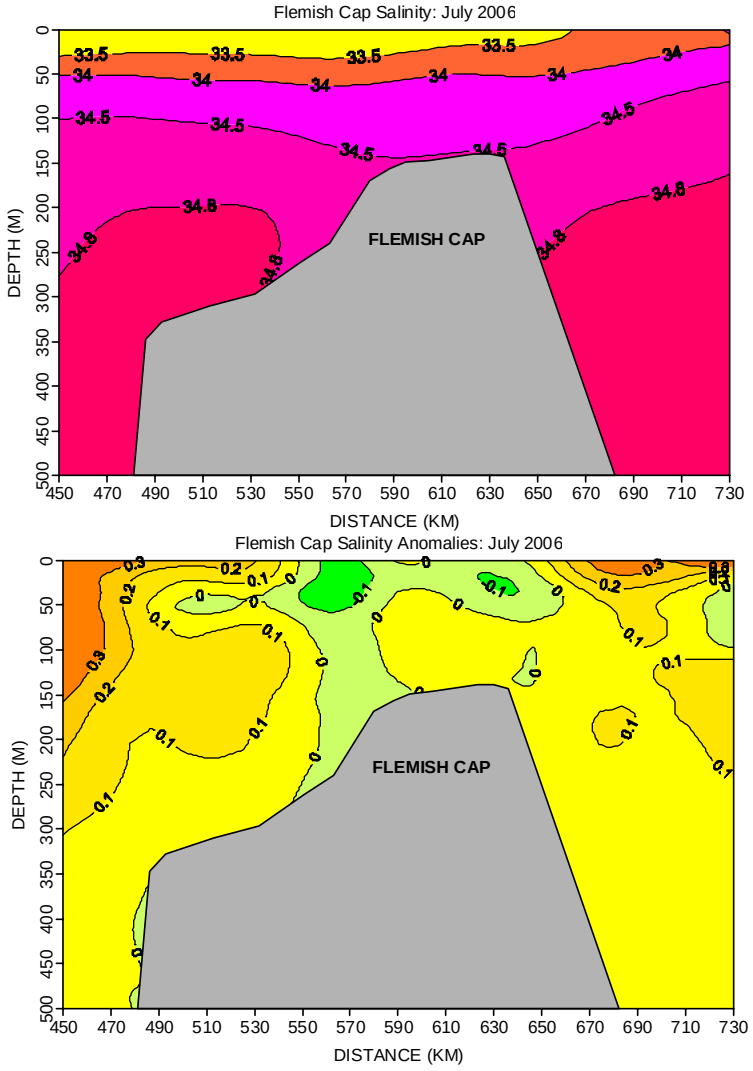

Fig. 4. The vertical distribution of salinity and salinity anomalies over the Flemish Cap (along 47°N) for the summer of 2006.

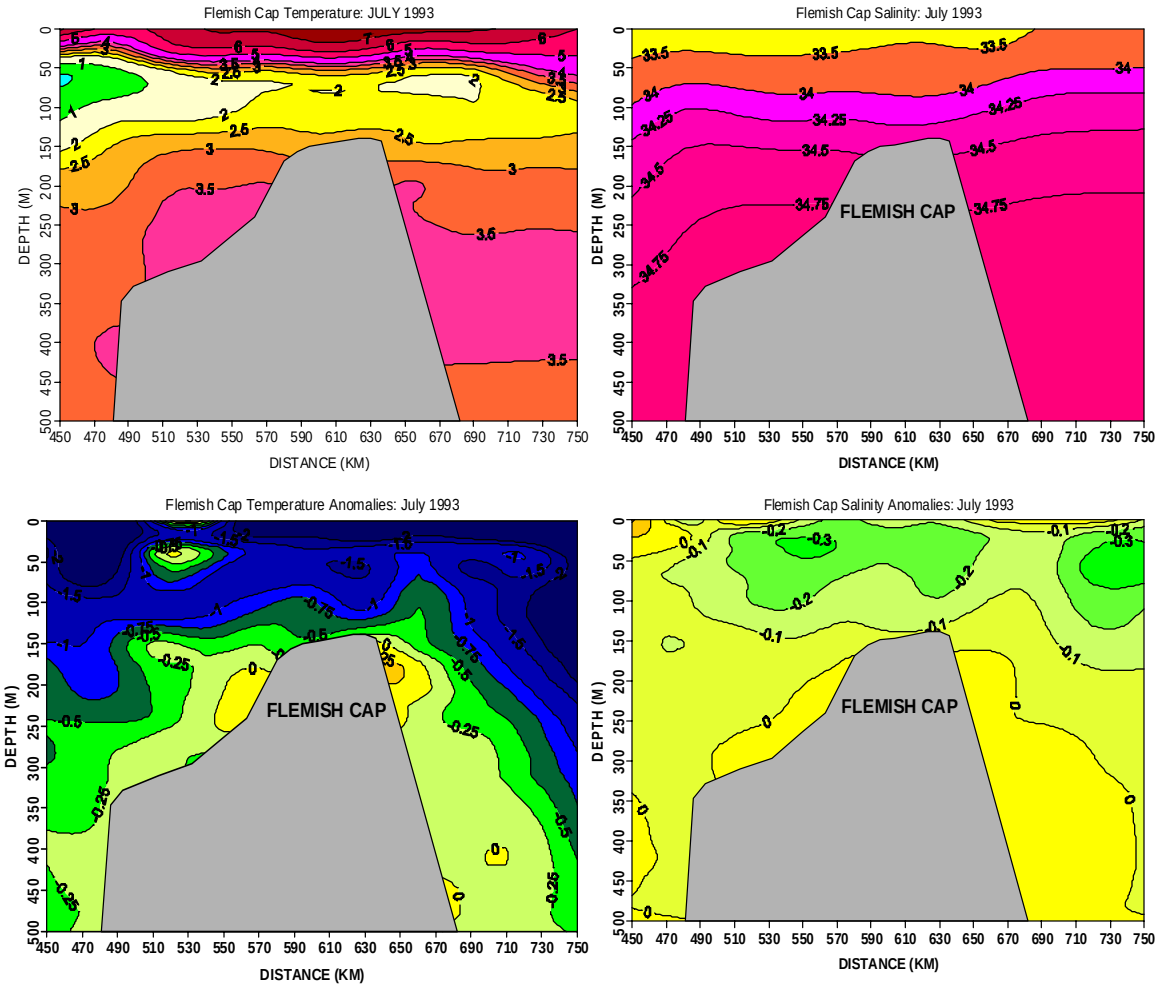

Fig. 5. The vertical distribution of temperature (in °C) and temperature anomalies (left panels) and salinity and salinity anomalies (right panels) over the Flemish Cap (along 47°N) during the summer of 1993.

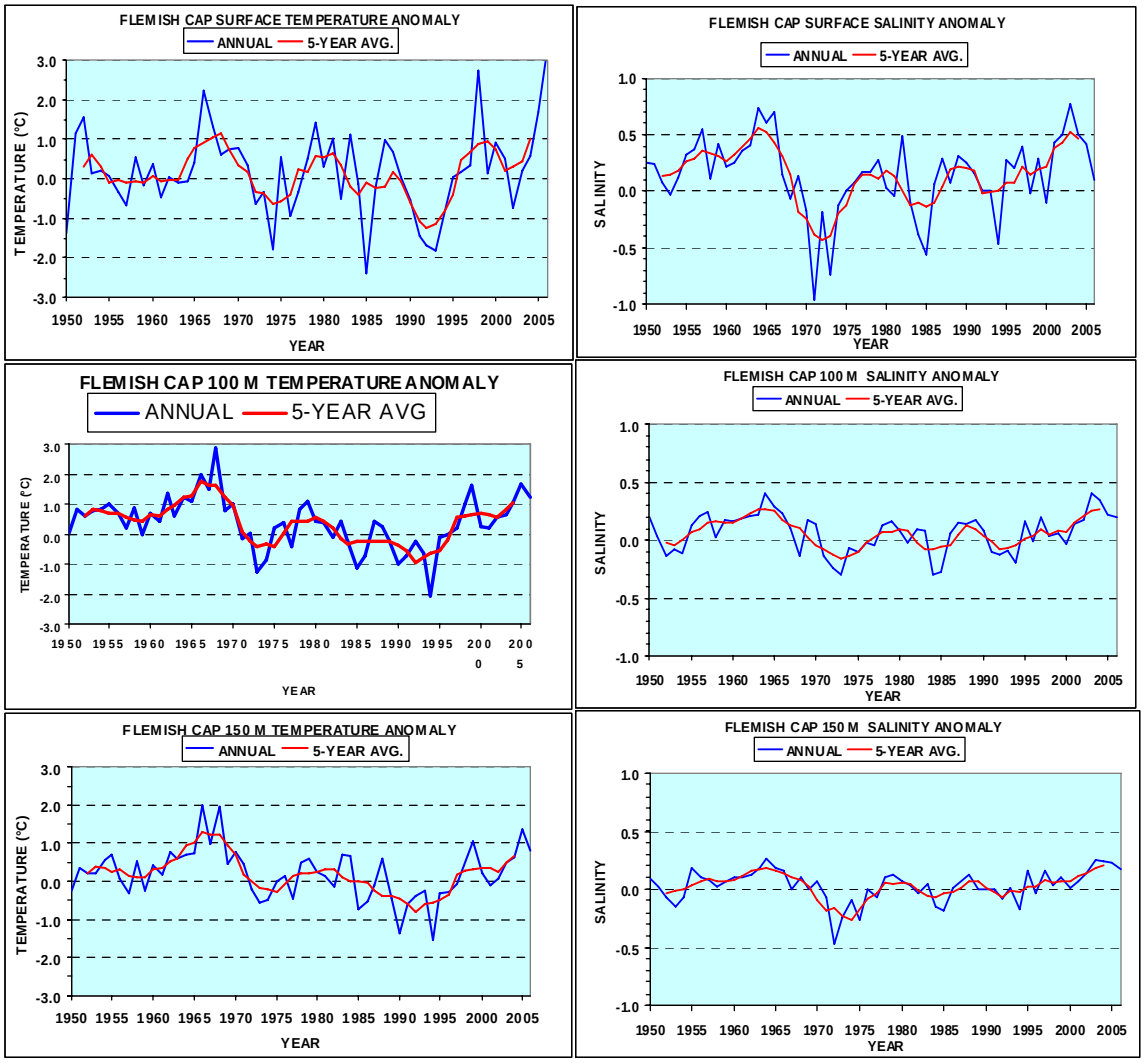

Fig. 6. Annual temperature and salinity anomalies at standard depths on the Flemish Cap in NAFO Div. 3M. The solid line represents a 5-year running mean.

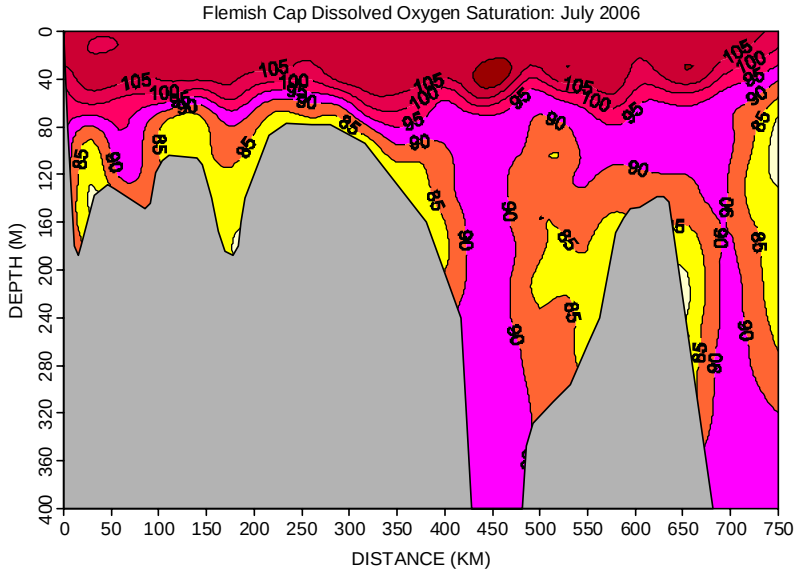

Fig. 7. The vertical distribution of dissolved oxygen percent saturation along 47°N for the summer of 2006.

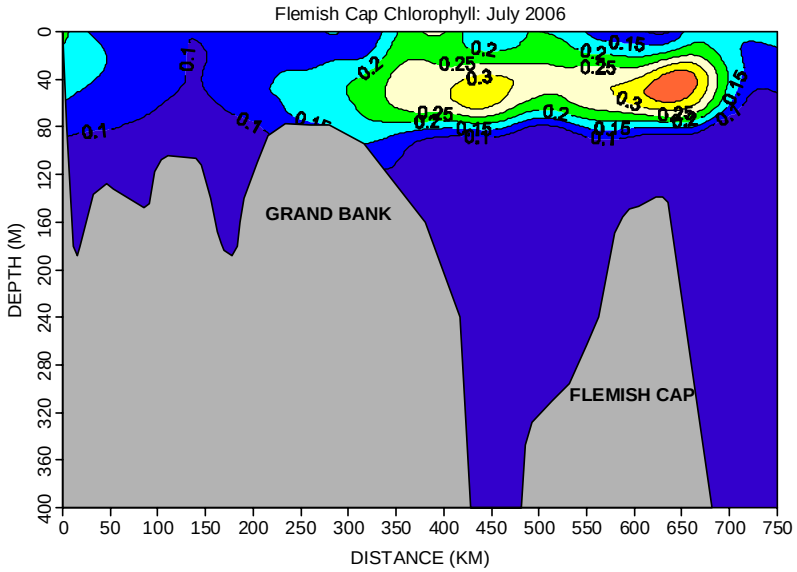

Fig. 8. The vertical distribution of chlorophyll concentrations (mg/l) along the 47°N section for the summer of 2006.

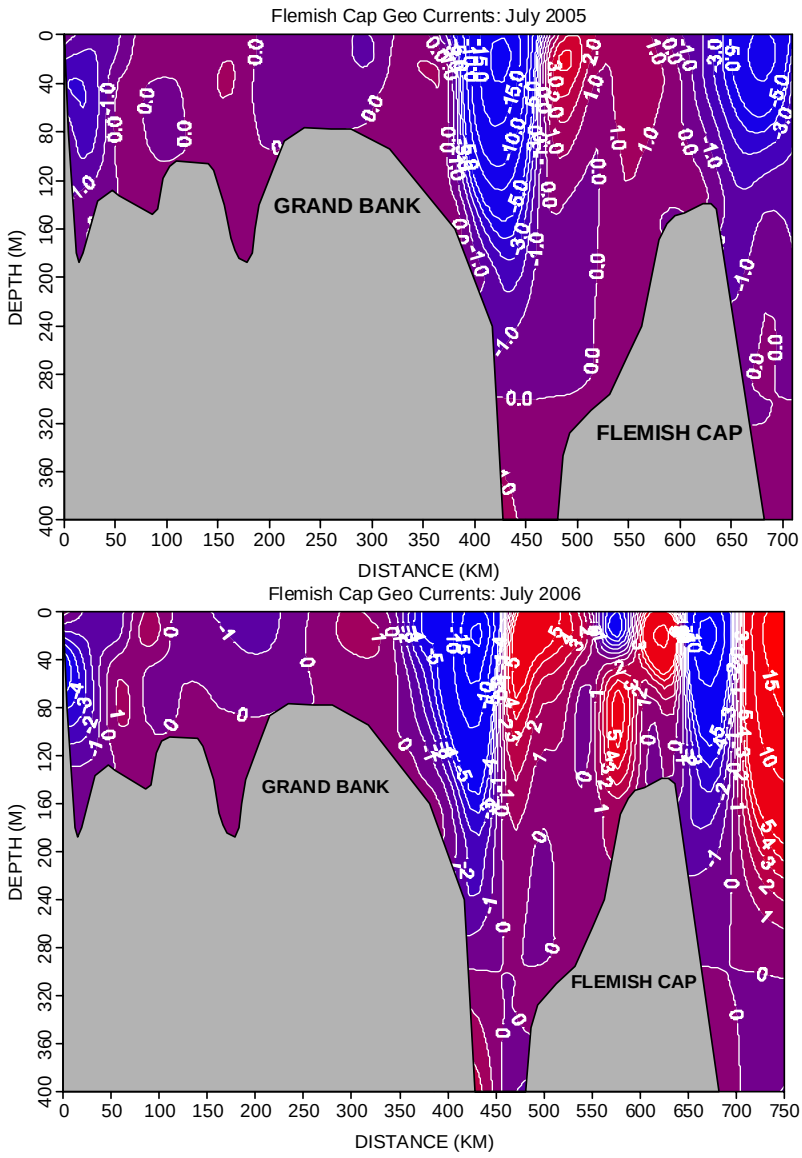

Fig. 9. The vertical distribution of the N-S geostrophic current field (in cm/s) along the Flemish Cap Section during the summer of 2005 (top panel) and 2006 (bottom panel) estimated from the density data. Negative currents (blue) are southward and positive currents (red) are northward.