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PHYSICAL OCEANOGRAPHIC CONDITIONS ON FLEMISH CAP IN SUMMER 1998

by

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ABSTRACT

In summer 1998 a well-developed anticyclone was found over Flemish Cap. Intense mesoscale activity, in form of cyclonic rings surrounding the Bank's periphery, was observed. This dynamical configuration seems to be relevant on considering the distribution of photic layer fertilization-related parameters.

1. **INTRODUCTION**

Flemish Cap is a ca. 200 km radius plateau situated in NAFO division 3M, centered at 47ºN 45ºW. It is separated from the Grand Bank of Newfoundland by the ca. 1100 m deep Flemish Pass, that relatively isolates the Flemish Cap (Akenhead, 1986; Colbourne, 1997; Gil *et al*., 1998). Bathimetry ranges between 125 m on the central part of the bank and 700 m around its edge. Characteristic slope is very steep at the southern half of the plateau, where depth increases from 200 to 1000 m over a distance of 20 miles, whereas the slope increases gradually northwards before the Flemish Pass is reached.

The general circulation of water masses is associated to the confluence of Labrador and North Atlantic currents (hereafter on referred to as LC and NAC respectively) over the study area of Flemish Cap. LC brings cold and less saline arctic waters (below 2ºC and 34.3 PSU) which interact with the warmer and saltier NAC waters (above 12ºC and 35.5 PSU). Dynamics of the frontal system associated to the confluence of warm and cold waters is postulated as the driving mechanism that condition circulation dynamics in the region. The wall effect and subsequent boundary condition the Grand Bank of Newfoundland exerts on the circulation, and the permanence of the NAC and LC system permits the area to be well understood in terms of average dynamics (Robe, 1974).

At the southern part of the Grand Bank the LC may be merged with the Gulf Stream (hereafter on referred to as GS) to result in the formation of the NAC front. USSR works evidenced that there is strong variability of the NAC behavior (Baranov and Ginkul, 1984; Fofonoff and Hendry, 1985) although on the average it circulates parallel to the 4000 m isobath (Krauss *et al.*, 1987). Heywood *et al.* (1994) evidenced topographic control of the NAC. Such topographically-driven flows may suffer from important baroclinic effects. Near the Newfoundland Rise a quasi-permanent meander forces NAC to maneuver its way some 50-150 miles off the Bank, being a dynamic low formed between the NAC-LC current systems (Robe, 1974), in the middle of which the Flemish Cap Bank is placed. The variability of the current system seems to be closely related to the eddies near the NAC front (Krauss *et al.*, 1987). Meanders and eddies dominate the region and intensive mixing of waters occurs.

Flemish Cap waters are often referred to as *mixed waters of LC and NAC* (Hayes *et al*., 1977; Anderson, 1984; Colbourne, 1997; Cerviño and Prego, 1997; Gil *et al.*, 1998), or more commonly to as Typical Flemish Waters (TFW) although Akenhead (1986) postulates its Labradorian origin. A barotropic model purely based on the LC underestimates the strength of the clockwise circulation over Flemish Cap, and the importance of accounting the influence of both LC and NAC flows was evidenced (Greenberg and Petrie, 1988).

Anticyclonic circulation over Flemish Cap is a quasi-permanent feature, reported in most of previous studies (Kudlo and Borokov, 1975; Robe, 1974; Borokov and Kudlo, 1980; Ross, 1981). From observations in 1977-1982, Kudlo *et al*. (1984) found the occurrence of four types of geostrophic flows, of which the most common situation happened to be given by anticyclonic patterns (67%). Colbourne (MS 1993) ADCP current maps confirm the existence of an anticyclonic circulatory scheme with average current speed of 10 cm/s and a nominal width of 200 km.

The anticyclonic gyre imposes homogeneous water properties of waters over Flemish Cap. Several papers report the existence of subsurface temperature minims below the summer thermocline elsewhere (Karasyev, 1962; Templeman, 1974; Colbourne, 1993, 1995, 1996 and 1997; Cerviño and Prego, 1997; Gil *et al.*, 1998), being associated to seasonal termohaline fronts and emergence of LC.

2. MATERIAL AND METHODS

The 1998 Flemish Cap physical oceanography survey was performed over 111 CTD and water-sampling stations, paired to the majority of the fishing hauls. The probe used was a Sea-bird SBE 25, from Sea-bird electronics USA. It was configured to acquire data records at a rate of 2 data per meter. The maximum depth ranged from 513 m at station E06 to 135 m at station E104. At every station a Niskin bottle was attached to the winch wire in order to take water samples for nutrient analysis at 40 m depth.

Acquired data were processed in order to: discard warm-up data and average values per depth unit. Selected variables were: pressure (dbars), salinity (PSU), temperature (deg. C), sigma theta (kg/m^3), oxygen content (% saturation) and fluorescence (arbitrary units). A water column stabilization program was applied to the data in order to smooth anomalous density distributions due to analytical errors.

CTD stations are homogeneously distributed over the studied area, yielding a mean distance of 12 nautical between stations (Fig. 1). This regular distribution allows us to apply an objective technique for detection of mesoscale structures similar to the one described by Tintoré *et. al.* (1991.), Gil and Gomís (1994), Gil (1995) and Viúdez *et al.* (1996)

Dynamic calculations were based upon the dynamic topography field, which was calculated upon the 135 meters reference level; this level was the most adequate to include all sampling data and so to obtain the maximum resolution grid. The field of related parameters was subsequently constructed.

3. INCOMING FLUXES OVER FLEMISH CAP

Over Flemish Cap converge LC and NAC waters which configure the starting mass field. Posterior modification within the bank's topography and associated dynamics give a resulting mass field formed by four water types: LW (Labrador Waters), NAW (North Atlantic Waters), TFW (Typical Flemish Cap Waters) y AGW (Anticyclonic Gyre Waters).

The influence in the vicinity of Flemish Cap of the low salinity and cold LC water (LCW), defined as Canadian Arctic Water (CAW) by Lee (1968) with –1.75ºC and 33.2 psu, has been reported by Krauss *et al*. (1987). This author found strong mixing between the LW and NAC by interleaving. The strong and vigorous eddy field and the associated branching of the NAC have been reported as time-dependent intermittent phenomena, although their detached eddies may have a lifetime of several months.

Labradorian waters do not appear as persistent flows, at least by the sampling time. Consequently they will be referred to as LW better than LCW. A similar statement stands for NACW and NAW. Vertical salinity and temperature profiles evidence an interleaved superposition of cold and less saline LW and warm and saline NAW onto a mean field defined by AGW and TFW with homogenous temperature and salinity profiles. On getting at Flemish Cap both LW and NAW are distributed in the 3D field, horizontally constrained by the gyre's wall effect, resulting in a horizontal front, and vertically constrained by density stratification.

The trace of LW track is evidenced by means of the topography of 34.0 psu iso-surface (Fig.1). The regular W-E tilting of this surface and the strong gradient found over a distance of less than 10 miles (where the 34.0 psu surface deepens from 30 m down to 90 m) let us ascertain their presence as a surface flow on the westernmost area. Elsewhere, including the anticyclonic region, salinities reach 34.0 psu well above 30 m depth.

Temperature distribution at 25 m (Fig. 2) clarifies the presence of the LW, AGW and TFW, since LW are colder and less saline than the rest of types. The strongest LW influence is, according to Fig. 2, restricted to the north-western region of the study area, where cold nuclei (between 3.5-6 ºC, in dark) place and border the central region. These low temperatures indicate the recently coming waters from northern fluxes and have not been modified by summer heating. Conversely the AGW, that occupy the bank's central region, are older LW strongly modified by the solar heating during the summer season. Therefore in this region the highest surface temperatures are found, reaching values from 9-12 ºC at 25 m.

From Figs. 3 and 4, we can observe how the density of the different water masses conditions their situation in the Bank. The temperature distribution at 135 m (Fig. 3) shows how a central region, where the gyre is placed, with minor temperature gradients, is observed, bearing values below 4-3.5 ºC. This reveals the strong degree of vertical mixing within the anticyclonic gyre and its vertical homogenization mechanism. The general tendency of AGW is to converge towards TFW typical temperature values (see Fig. 3, temperature at 135 m). Below this 100-m layer TFW shows homogeneous subsurface temperatures near to 3.5 ºC that evidence their former belonging to the gyre.

Warm mesoscale nuclei (over 4 ºC) presented in dark tones at Fig. 3 are disposed around the Bank's topography and bordering the anticyclonic gyre. These nuclei are linked to NAW. Their absence in surface layers is due to their high relative salinity, what gives them a density higher than waters occupying surface strata.

Associated to the gyre's vertical homogenization mechanism, relatively less saline waters are brought towards subsurface layers, being a good core defined below 34.5 psu at 135 m (Fig. 4).

Conversely, saline nuclei (over 34.7 psu) presented in dark tones at Fig. 4 are linked to NAW. They do not break the gyre but are allowed to module the dynamic frontal system as will be presented in next section.

Summarizing, in summer 1998 there were two incoming fluxes over Flemish Cap. On the one hand the entrance of cold and low salinity LW nuclei through the NW region. These are low density waters and spread mainly through at surface strata. On the other hand warm and saline NAW nuclei that surround the bank's topography and find their equilibrium stratum at subsurface layers.

4. GEOSTROPHIC BALANCE OF WATER MASSES

The various mass and energy fluxes converging onto Flemish Cap result in the subsequent formation of the geostrophic balance, whose dynamic topography at 10 dbars (upon a 135 dbars reference level) is shown at Fig. 5. It is possible to observe a number of mesoscale structures surrounding a larger and well developed clockwise gyre centered over the bank, labeled by **A**. The quasi-permanent anticyclonic vortex appears as a topographically generated Taylor column over the bank and raised to values above 15 dynamic centimeters.

The formation of Taylor columns was theoretically shown by some authors (Huppert, 1975; Huppert and Bryan, 1976) and experimentally by others (Taylor, 1923; Davis, 1972). Conditions for its formation are high fluid stratification, conspicuous height of the topographical feature and weak flow (Huppert and Bryan, 1976). Advection of LCW against the Bank's topography causes the flow to be induced to acquire negative vorticity, in order the potential vorticity to be balanced. A geostrophically isolated Taylor column is formed.

In spring-summer, water retention within the gyre cause waters confined to become warmed up, being the surface temperatures raised up within this structure more than elsewhere. LW are brought to lighter densities by solar warming, whereas salinity values do not raise at the same rate. The warming of low saline LW yields a feeding mechanism that reinforces the gyre's structure.

The 13-14.5 dyn cm dashed lines in Fig. 5 mark a dynamical front that draws the main gradients and defines zones along Flemish Cap. Below the 13 dyn cm line a number of mesoscale structures are placed, each of different sign. There we have labeled **cc** for **c**old **c**yclone, **ca** for **c**old **a**nticyclone and **wc** for **w**arm **c**yclone. The warm anticyclones appear on the western part of the study area as dynamic adjustment of warm but saline NAW intrusions embedded in cold LW.

The LW are recently arrived onto the Bank and, in spite of their low temperatures, they bear such low salinity values that are light enough as to result in cold anticyclones. Cold cyclones come after the adjustment of cold and saline TFW bulks and are located around the northern and north-eastern periphery. At the south-eastern corner a strong front (labeled at Fig. 5) is developed after the confluence of a cold cyclone and a NAW nucleus. On that spot the strongest gradients are observed.

NAW entrances are located around the south-western periphery of Flemish Cap. These formations were visible as saline and warm inputs at 135 dbars (see Figs. 3 and 4) but they are persistent at deeper regions, evidencing that they belong to a macroscale confluence event rather than to discrete entrances.

The coupling of NAW bulks over the gyre and associated circulatory system play a determinant role in the Bank's dynamic equilibrium. The main flow (properly defined by the dashed lines at Fig. 5) circulates between the cyclonic mesoscale structures and the larger anticyclonic gyre. It presents a series of meanders, eddy-driven intensification and horizontal shears that are the cause of intense vorticity advections. The vorticity field (not presented here) is therefore moduled by the NAW entrances, and may have implications upon the evaluation of vertical forcing upon the basis of the quasi-geostrophic (QG) dynamics (Gil *et al*., 1998).

5. FERTILIZATION OF PHOTIC LAYERS

In summer conditions in temperate latitudes, after the Spring Bloom and when the seasonal thermocline is well developed, nutrient depletion within surface layers occurs. The pycnocline deepens below the photic level, falling the nutricline as well. Upon these conditions deep fluorescence maxims (DFM) develop (Rodríguez *et al.*, 1998). Vertical forcing associated to horizontal velocity shears and strong meanders are of paramount importance concerning photic layer fertilization. According to this, nitrate and phosphate distributions at 40 m level are presented in Figs. 6 and 7. In order to draft the main flow, the dynamical front has also been depicted. One may see how distributions of both nutrients are almost identical, being strongly correlated either to sharp direction shifts along meanders or to strong shears at the south-eastern NAW-TFW front. This front is ascertained as one of the mechanisms of fertilization. Vertical forcing (not presented here) associated to vorticity advections, as QG vorticity equation puts forward (Gil *et al.*, 1998), seems to be responsible.

There is no relation among LW nuclei and presence of high nutrient concentrations. However warm NAW cyclones seem to be associated with sharp elevations of nutrient content, maybe due to raising of both pycno- and nutricline onto the photic layer (see Figs. 3 and 4, and Figs. 6 and 7).

The biggest DFM values appear to be linked to the highest nutrient concentrations, as observed in Fig. 8. For both nutrients and DFM the gyre appears as an oligotrophic region where the strong vertical mixing and homogenization allows only residual values to be found.

Surface oxygen distribution is well correlated with temperature (Fig. 9). Surface temperatures are mainly conditioned by both the gyre's formation and the entrance of LW. According to this we observe in the oxygen (% saturation) at 20 m how the anticyclonic gyre defines a large-scaled central region where oxygen saturation values are below 94%. A NW-SE front is formed between this anticyclonic region and the colder water masses of LW and TFW, where typical values range 98-102%.

It is interesting to remark the existence of two important mesoscale anomalies, each of different sign. On the central part a conspicuous nucleus above 106% shows the surface trace of an upwelling event situated at 47.5ºN 44.6ºW, and present also on the nutrient (Figs. 6 and 7) and the DCM charts (Fig. 8). On the south-eastern part a spot bearing less than 90% oxygen saturation coincides with the southernmost extension of the NAW inputs. It is therefore more than possible that where NAW inputs are very strong, its properties upwell and be not only subsurface phenomena, but have also surface implications.

ACKNOWLEDGMENTS

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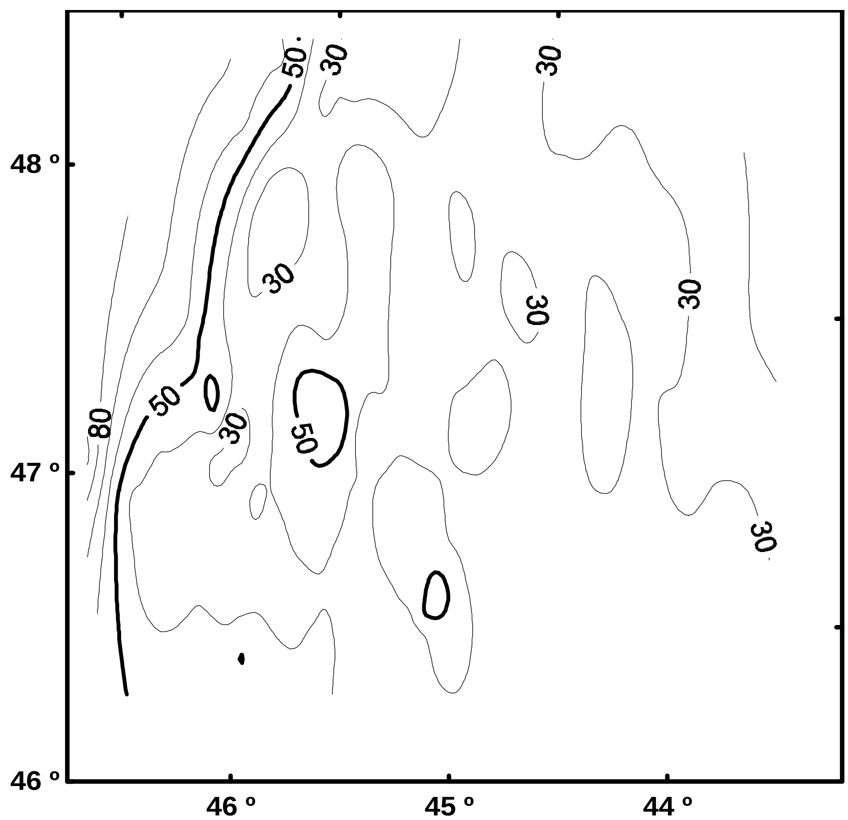

Figure 1. Depht of 34.0 psu (in meters)

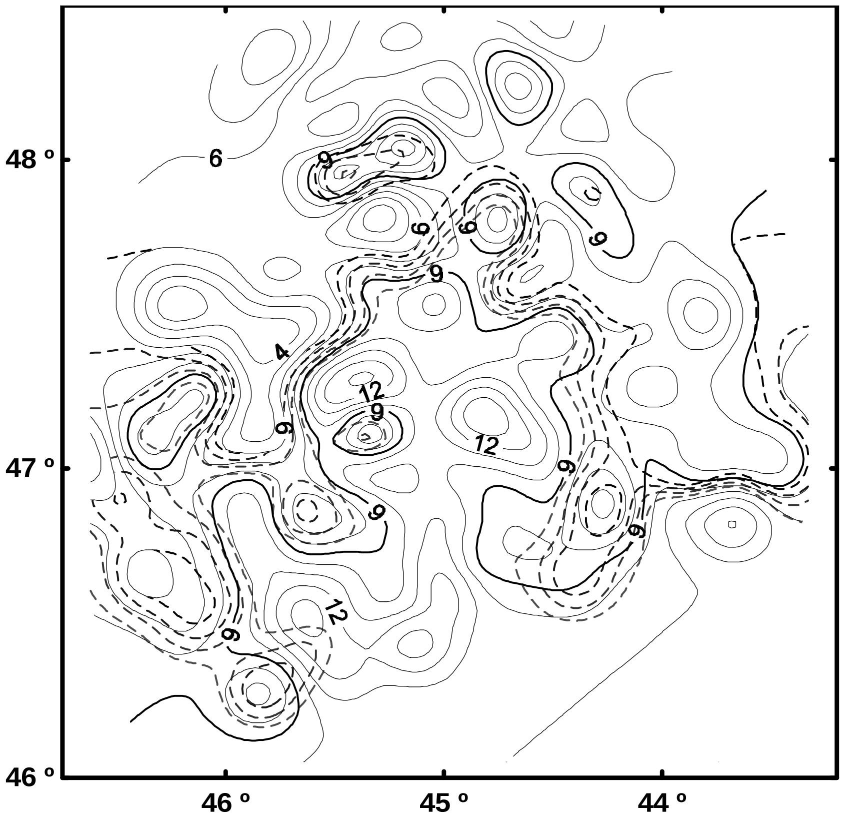

Figure 2. Temperature at 25m and dynamical front

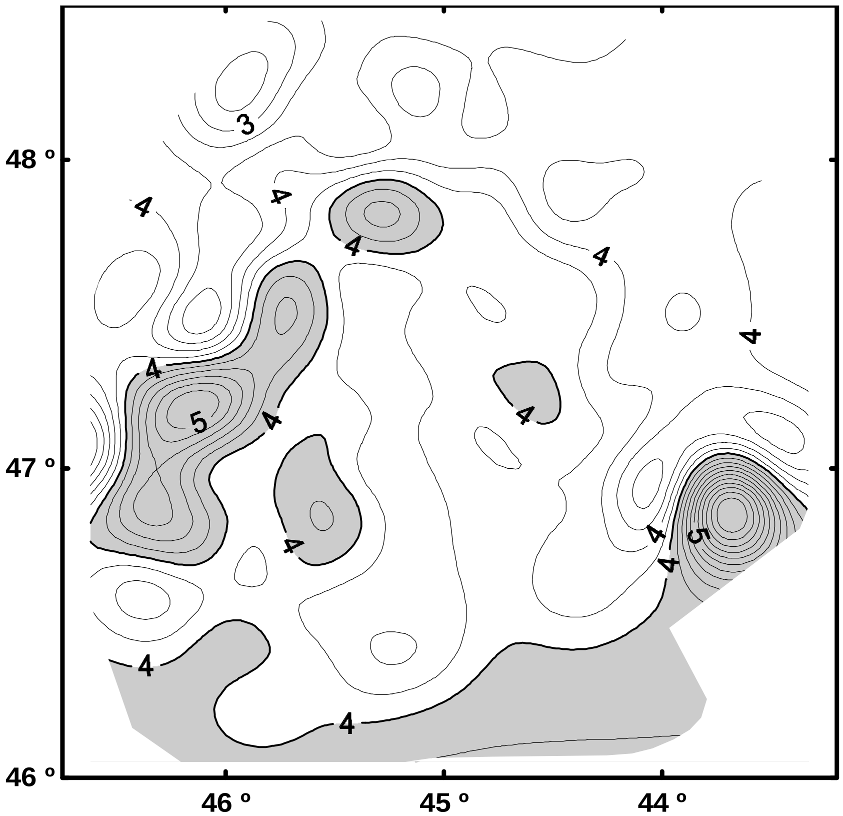

Figure 3. Temperature at 135m

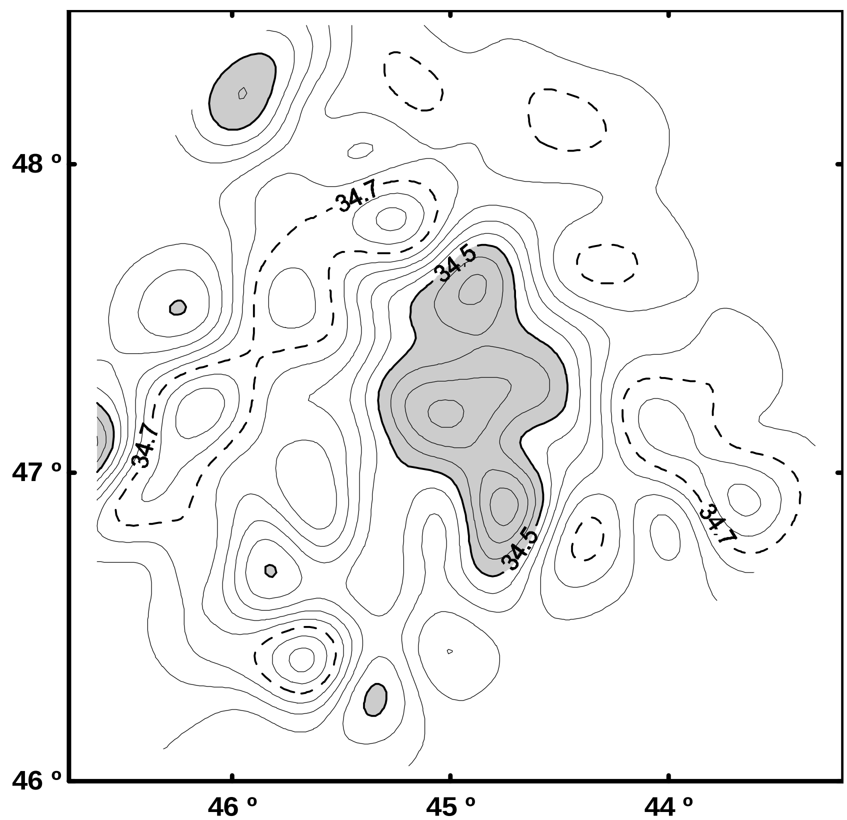

Figure 4. Salinity at 135m

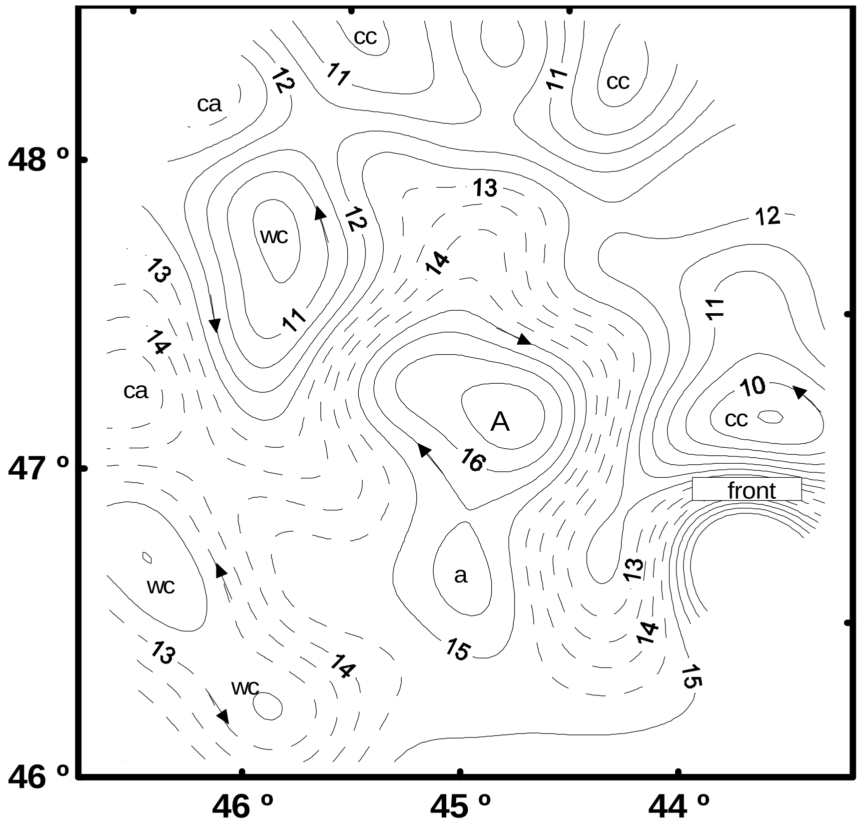

Figure 5. Dynamic heigh at 10db (ref level 135db)

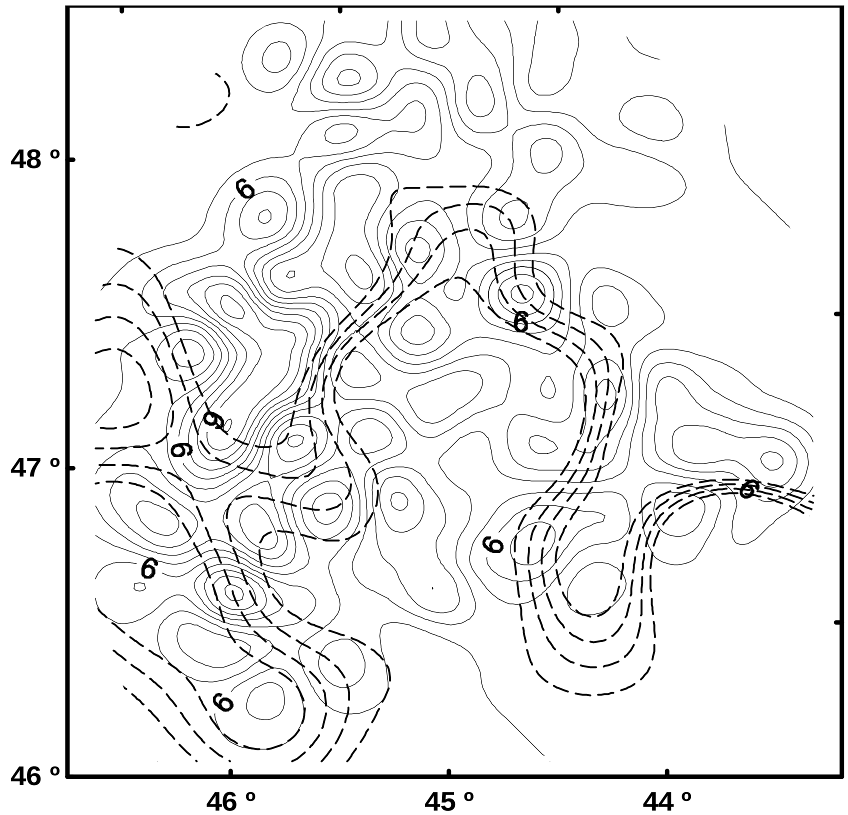

Figure 6. Nitrates at 40m (µg/l) and dynamical front

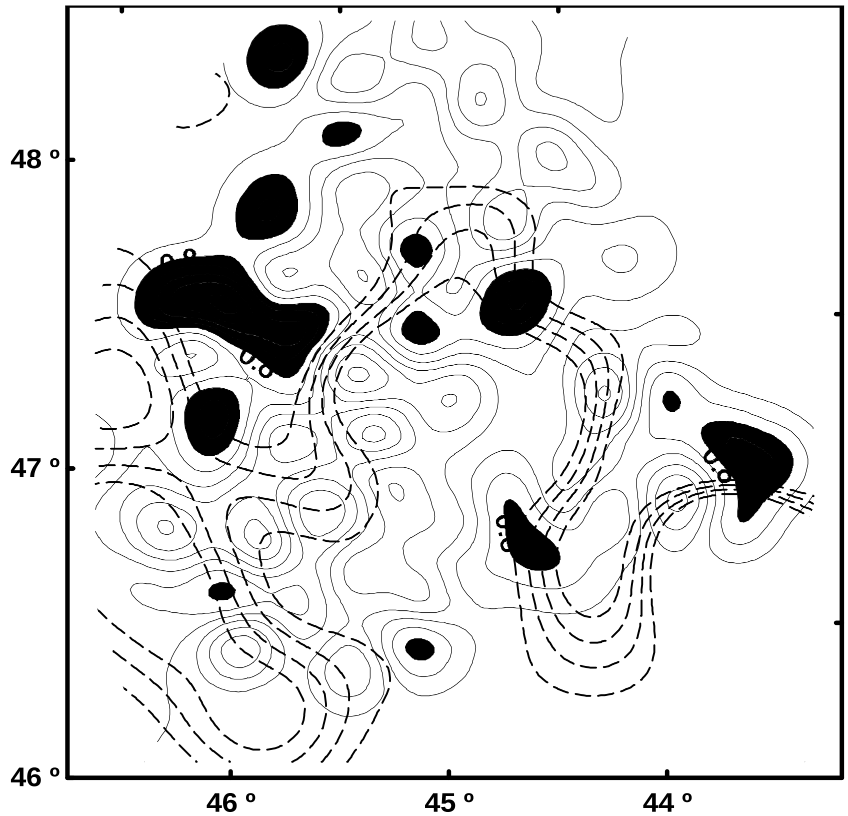

Figure 7. Phosphates at 40m (μg/l) and dynamical front

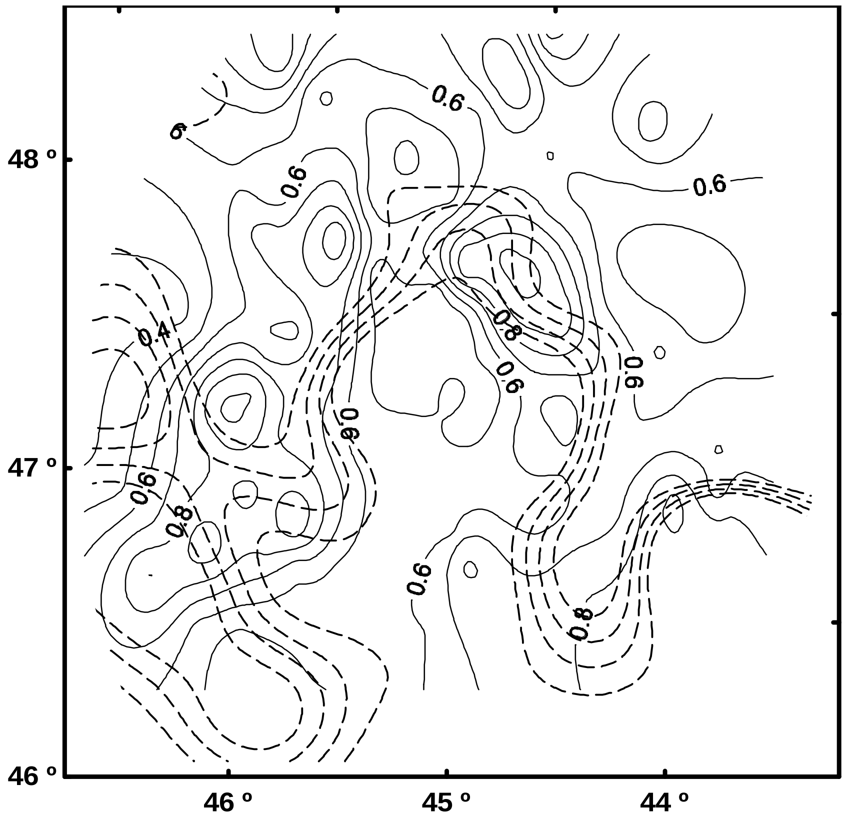

Figure 8. Deep Fluorescence Maximum (Arbitrary units) and dynamical front

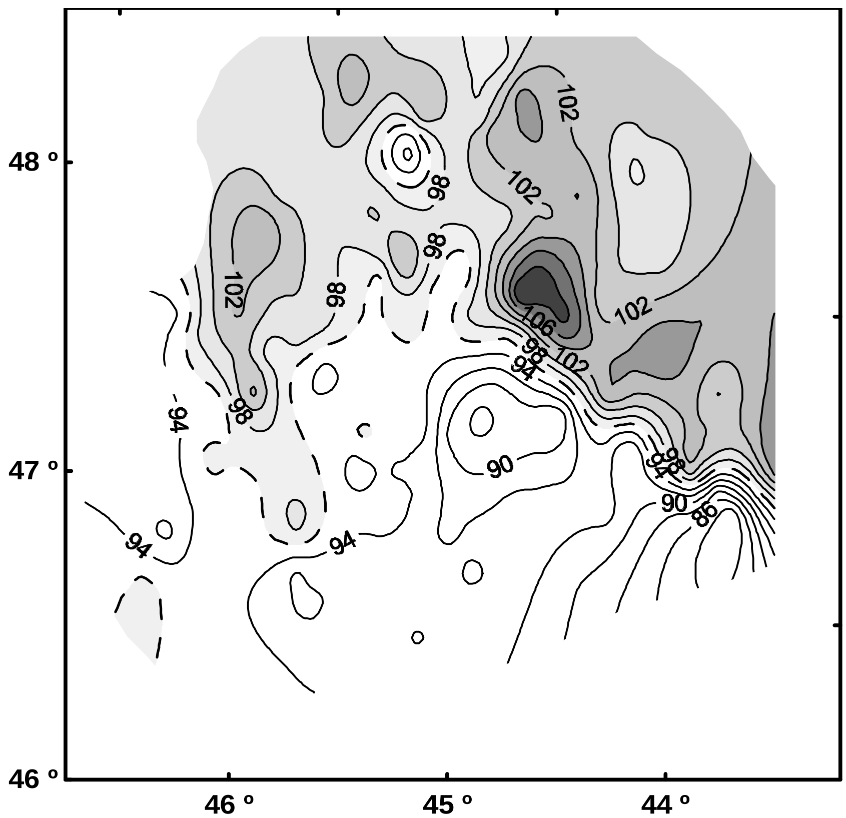

Figure 9. Oxygen at 20 m (% saturation)