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Lagrangian circulation of the North Atlantic Central Water over the abyssal plain and continental slopes of the Bay of Biscay: description of selected mesoscale features

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SUMMARY: Between 1994 and 2001, several experiments (ARCANE, SEFOS, INTERAFOS) were conducted to directly measure the general and mesoscale Lagrangian circulations over the Bay of Biscay abyssal plain and slopes. Two levels (~100 m and ~450 m) were selected to cover the North Atlantic Central Water range. Two types of Lagrangian instruments, drogued surface drifters tracked by satellite (Surdrift) and acoustically tracked subsurface floats (Rafos and Marvor), were used. Overall, more than 36 instrument-years were collected in the Bay of Biscay region (43-49°N, 01-12°W). The weak general circulation in the Bay of Biscay is seen to be highly influenced by the occurrence of several mesoscale coherent features, notably slope currents and eddies, and these affect the exchanges between the abyssal plain and the slopes. The objective of this paper is to depict some specific examples of the observed mesoscale field. Selected float trajectories are shown and used to discuss observations of slope currents and of both anticyclonic and cyclonic eddies. Slope currents exhibit alternation of poleward and equatorward directions, depending on both the period and the geographic area considered. Although the generation process of mesoscale eddies is difficult to observe unambiguously from Lagrangian instruments, eddies are nevertheless ubiquitous over the abyssal plain. Some characteristics of the observed cyclonic and anticyclonic eddies are presented. Smaller anticyclones, localised over the outer shelf and interpreted in terms of ajustment of slope water intrusions, are also depicted.

Keywords: Bay of Biscay, Lagrangian floats and surface drifters, slope current, mesoscale eddies, slope ocean exchanges.

RESUMEN: CIRCULACIÓN LAGRANGIANA DEL AGUA CENTRAL DEL ATLÁNTICO NORTE SOBRE LA PLANICIE ABISAL Y EL TALUD CONTINENTAL DEL GOLFO DE VIZCAYA: DESCRIPCIÓN DE ESTRUCTURAS DE MESO-ESCALA. – Diferentes proyectos (campañas ARCANE, SEFOS, INTERAFOS) han sido llevados a cabo entre 1994 y 2001 para determinar la circulación Lagrangiana, general y de meso-escala, sobre la planicie abisal y del talud del Golfo de Vizcaya. Dos niveles fueron seleccionados para seguir el Agua Central del Atlántico-Norte (100 m y 450 m). Para esto se han usado boyas de deriva en superficie (de tipo Surdrifts de inmersión constante, seguidas por satélite) y flotadores en profundidad localizados por red acústica (Rafos y Marvor). Casi 36 años-flotadores han sido obtenidos por esas experiencias en la región del Golfo de Vizcaya. La circulación general del Golfo se muestra débil, al parecer muy influida por la presencia de procesos de meso-escala, como de corrientes del talud y remolinos que participan en los intercambios entre la planicie abisal y el talud. El objetivo de este trabajo consiste en describir específicamente algunos eventos de meso-escala que han sido observados. Algunas trayectorias de flotadores fueron usadas para describir y discutir las observaciones de las corrientes del talud y de remolinos ciclónicos y anticiclónicos. Las corrientes del talud muestran una estructura alternada, en dirección hacia el polo o el ecuador, según la época del año y la región consideradas. Aunque es difícil observar el proceso de formación de los remolinos de meso-escala con flotadores Lagrangianos, éstas estructuras son muy numerosas sobre la planicie abisal. Diferentes características pueden ser descritas con los datos recogidos de remolinos ciclónicos y anticiclónicos. Además, los remolinos anti-ciclónicos de más pequeña escala son observados en la parte externa de la plataforma, y pueden ser interpretados en términos de ajuste causados por la intrusión del agua proveniente del talud.

Palabras clave: Golfo de Vizcaya, flotadores Lagrangianos y boyas de deriva, corriente de talud, remolinos de meso-escala, intercambios entre el talud y el océano.

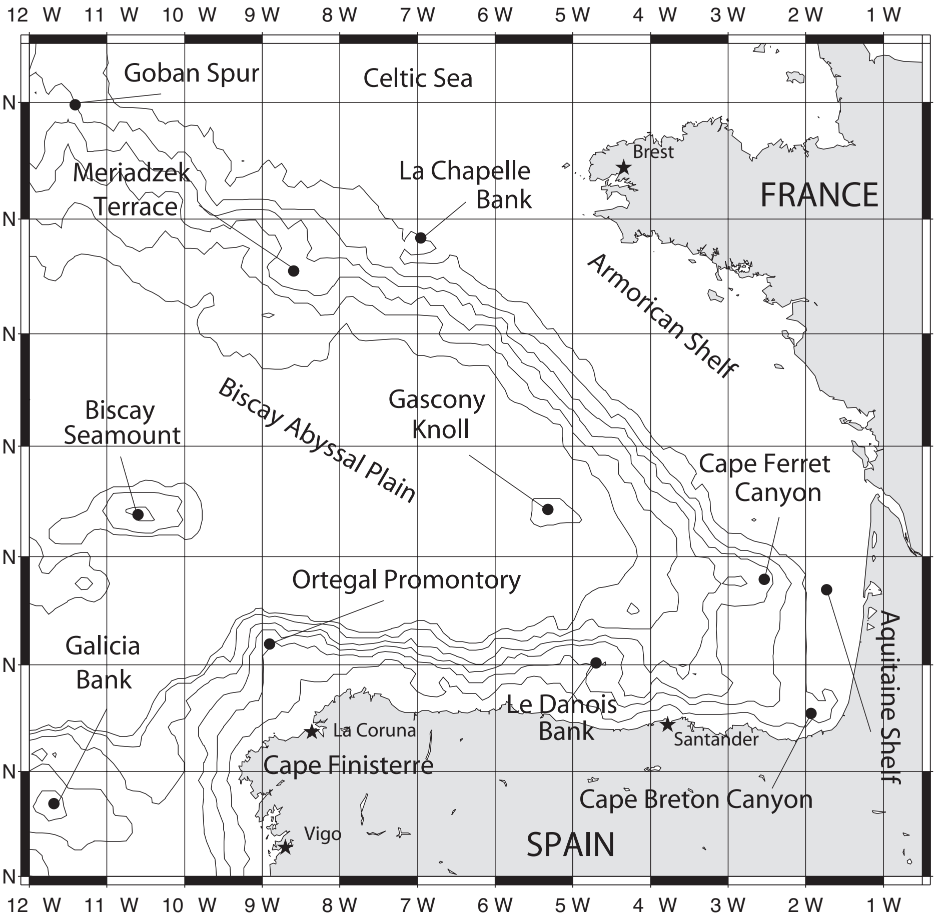

FIG. 1. – General map of the Bay of Biscay, with bathymetric contours and names of principal bathymetric features.

INTRODUCTION

The Bay of Biscay (BB hereafter, defined as the area between ~43 and 49°N, ~01 and 12°W, see Fig. 1) is a region of weak general circulation. From Lagrangian drifter studies, Pingree (1993) showed that North Atlantic Central Waters (NACW) derived from the North Atlantic Current penetrate southeastward into the BB. He depicted an anticyclonic circulation over the BB abyssal plain at 400 m depth. Using an inverse model, Chantry (1995) confirmed this clockwise circulation. Over the same area, surface currents derived from shallow drogued drifters (~15 m) were analysed by Van Aken (2002), who confirmed the southeastward flow tendency, with a seasonal trend, from more eastward in autumn-winter to more southward in spring-summer.

Lagrangian surface drifters may be used in association with sub-surface Lagrangian floats in order to depict the mean Lagrangian circulation and its fluctuations near the eastern boundary of the mid-latitude North Atlantic, as shown by Le Cann *et al.* (in preparation). Their study shows that mean and seasonal circulations in that region could be interpreted in terms of both anticyclonic and cyclonic “regional recirculation cells”.

In this paper, we shall focus on some mesoscale aspects of the Lagrangian circulation of the North Atlantic Central Water (NACW) in the BB. This area has been shown to be a region of various mesoscale currents, such as slope currents and eddies (Dickson and Hughes, 1981; Pingree, 1984; Van Aken, 2002). In the BB, Pingree and Le Cann (1990) depicted the complexity of the structure of the slope currents, showing their spatial and temporal variabilities. They found a consistent poleward slope current, with seasonal variations, phased differently along the slope. Pingree and Le Cann (1992b) also studied the instabilities of the slope currents which generate long-lived anticyclonic Slope Water Oceanic eDDIES (SWODDIES) propagating westward across the BB. These eddies are thought to redistribute a non-negligible part of Central Waters into the Abyssal Plain, and thus contribute to shape the general circulation of the eastern boundary of the North Atlantic Ocean. Some other types of eddies can also be found in the BB: cyclonic eddies have been reported in the literature (Pingree, 1979, 1984; Van Aken, 2002) but have not been thoroughly studied.

At the deeper level of Mediterranean Water (MW), some other eddy features, called “Northern Meddies”, have recently been discovered and are documented in Paillet *et al.* (1999, 2002). They are anticyclonic lenses generated in the vicinity of Ortegal Promontory and Cape Finisterre, i.e. near the southwestern boundary of the BB. Some of the ARCANE (for “Actions de Recherche sur la Circulation dans l’Atlantique Nord-Est”, Le Cann *et al.*, 1999) floats sampled these structures and their generation process. After being formed, they first drift toward the north or the northwest, and finally westward. They have an indirect influence on the circulation in the BB at the MW level, and possibly at the NACW level.

Here, our intention is to present a non-exhaustive phenomenological description of selected mesoscale features identified in a Lagrangian dataset over the BB, in order to get a better insight of the circulation and its properties at two depth levels of the NACW. Such mesoscale descriptions are also useful for biological implications (fisheries activities for instance) and for regional circulation model validation.

Several drifters and floats will be used in order to illustrate different physical processes occurring in the BB. The Lagrangian data set and its processing are first briefly described. The trajectories depicting selected mesoscale features are then analyzed and separated into categories. These are related to the slope currents and slope-ocean exchanges, and to the anticyclonic and cyclonic eddies. Finally, we summarize the results and discuss their implications in terms of spatial and temporal variability of the slope currents, or characteristic parameters for the mesoscale eddies. We also describe a few properties of newly identified anticyclonic eddies located over the outer shelf (Outer Shelf AntiCyclones (OSACS)).

THE LAGRANGIAN DATA SET

The Lagrangian data set used in this study was collected during the ARCANE programme, a joint project between IFREMER (Institut Français de Recherche pour l’Exploitation de la Mer) and SHOM (Service Hydrographique et Océanographique de la Marine). The major objectives of this project were to quantify the general and mesoscale Lagrangian circulations in the Eastern North Atlantic region, to observe the slope currents and eddies generated near the eastern boundary, and to depict the exchanges between the slopes and the ocean. Drifter data from the previous European SEFOS programme (for “Shelf Edge Fisheries and Oceanographic Studies”, Le Cann *et al.*, 1997) and INTERAFOS programme (a French Navy technological intercomparison test of Rafos type floats and of drifters, Gourmelen, 1996) were combined with this data set. We do not give here a comprehensive description of the instrument preparation, deployment and data processing, of which details can be found in the above mentioned papers.

The surface drifters, which were drogued at 80 m (SEFOS drifters) and 150 m (ARCANE and INTERAFOS drifters), are representative of a water layer located under the seasonal thermocline, beneath the Ekman layer (~80-150 m). The choice of this depth is slightly different from that of the drifters (drogues at ~15 m) intensively used during the WOCE/TOGA programmes (Sybrandy and Niiler, 1990; Otto and Van Aken, 1996, for example). It is then possible to sample the top of the North Atlantic Central Water, outside the direct action of the wind. Brügge (1995) also made this choice to study the near-surface mean circulation of the central North Atlantic, with drifters drogued at 100 m.

Because their drogues are outside the direct influence of the wind, these drifters may be more easily trapped in mesoscale features than the WOCE/TOGA type drifters. This reduces the number of mesoscale features sampled by a single drifter during its life time. On the other side, a longer time spent by a drifter in a mesoscale feature may help to obtain a finer determination of physical characteristics of these features. This led us to choose a ~80-150 m drogue depth, which we shall call the “80-150 m depth level”.

The subsurface acoustically tracked floats, whose target depth was around 450 dbars (~450 m), are representative of the base of the NACW, above the permanent thermocline. The floats were effectively between 350 and 550 m, due to imprecision of ballasting of Rafos floats, (±100 m) or depth tolerance (±50 m) for Marvors. For simplicity, we shall identify this level as the “450 m depth level”.

We may rapidly summarise the major characteristics of our dataset. At the 80-150 m depth level, 14 Argos surface drifters drogued at 80 m were deployed during SEFOS, between 1994 and 1996, 2 drifters drogued at 150 m during INTERAFOS in 1995, and 34 drifters drogued at 150 m during ARCANE, between 1996 and 1998. At the 450 m depth level, subsurface acoustically tracked floats of Rafos (21) and Marvor (11) types were released during ARCANE. Five Rafos were released during INTERAFOS. The sampling period stretched from 1995 to 2002. Instrument tracking was achieved by the Argos system for the surface drifters (typically 10-12 positions per day) and by an acoustic sources network for the subsurface tracked Marvor and Rafos floats (1 to 3 positions per day). Marvor are multicycle floats, whereas Rafos are monocycle floats. A cycle corresponds to the period between successive surfacing of floats. Rafos floats dive to a nominal depth, release a weight at the end of a prescribed duration (nominally 12 months), surface and transmit the stored data through the Argos system, effectively terminating their mission at the end of their first cycle. Marvor floats are actively ballasted and repeat a sequence of cycles (dive – drift at depth – surfacing – transmission) with a typical duration of 3 months.

The data processing consists first in obtaining a validated trajectory (the usual problems encountered, like drogue loss for the buoys or sampling and geometry errors for the acoustic floats, are not developed here), then the trajectories are resampled to obtain a daily position. Finally, the trajectories are interpolated and filtered with cubic smoothing spline functions. The high frequency kinetic energy part (frequency > (2.5 days)$^{-1}$) is then mostly filtered out.

Since we are interested in the mesoscale structures in the BB, we select trajectories, or segments of trajectories, restricted to this region. Finally the available data set for this study is composed of 11.0 drifter-years at the 80-150 m depth level and 25.1 float-years at the 450 m depth level. Table 1 gives the main characteristics of the selected drifters and floats that are presented in this paper. The list is not exhaustive and only the instruments that have revealed mesoscale features depicted here (slope current, eddies) have been reported. Sometimes only part of the total trajectory has been used for clarity of the analysis.

TABLE 1. – Summary and presentation of some drifters and floats deployed during the Arcane (A), Sefos (S), and Interafos (I) experiments. The table lists the drifters and the floats used to describe the mesoscale features (slope currents and eddies) presented here. Average and maximum speeds were computed from the trajectories of the surface drifters.

Exp. code	Drifter number	Drogue depth (m)	Launch date dd/mm/yy	Launch latitude	Launch longitude	End of mission dd/mm/yy	Last good data estimation dd/mm/yy	Average speed (module) (cm s^{-1})	Maximum speed (module) (cm s^{-1})	Comments
S	23074	80	26/09/94	46° 29.5’N	04° 42.5’W	19/11/94	19/11/94	3.7	10.6	Recovered at sea (drogue attached)
S	23076	80	27/09/94	47° 29.9’N	06° 44.8’W	30/09/95	30/09/95	4.5	16.0	Recovered at sea (no drogue attached)
S	23077	80	27/09/94	47° 30.2’N	06° 44.8’W	05/02/95	05/02/95	8.8	20.1	
S	04233	80	09/07/95	46° 46.4’N	05° 14.9’W	23/10/95	23/10/95	3.5	11.1	Recovered at sea (drogue attached)
I	23443	150	18/10/95	46° 44.2’N	08° 30.1’W	22/02/96	22/02/96	5.2	21.3	
I	23449	150	18/10/95	46° 44.2’N	08° 30.1’W	22/02/96	22/02/96	8.0	21.1	Lost during recovery
A	16852	150	29/11/96	44° 11.9’N	08° 57.7’W	01/05/97	07/03/97	9.2	22.0	
A	16850	150	01/12/96	42° 06.6’N	09° 28.1’W	05/03/97	29/12/96	7.8	11.9	
A	16853	150	01/12/96	42° 06.9’N	09° 32.0’W	12/05/97	30/03/97	7.8	34.6	
A	29508	150	23/08/97	45° 01.0’N	04° 42.2’W	18/02/98	05/01/98	9.8	23.1	
A	29517	150	04/12/97	42° 06.8’N	09° 28.2’W	22/01/98	22/01/98	8.9	23.1	

Exp. code	Float number	Nominal pressure (dbar)	Launch date dd/mm/yy	Launch latitude	Launch longitude	Mission duration	Surface date dd/mm/yy	Effective mission length (days)
A	28644	450	23/06/97	42° 06.8’N	09° 31.8’W	1 year	23/06/98	358

Exp. code	Float number	Nominal pressure (dbar)	Launch date dd/mm/yy	Launch latitude	Launch longitude	Cycle duration (days)	Number of cycles performed
A	19956	450	13/11/96	44°50.28’N	11°59.82’W	90	16
A	19954	450	03/11/96	45°30.12’N	09°07.20’W	90	17
A	402	450	04/09/96	49°01.14’N	15°00.72’W	90	18

MESOSCALE FEATURES

Slope currents and slope-ocean exchanges

Maps of the mean and the seasonal Lagrangian circulations obtained from objective analysis methods after Lagrangian statistics applied to the floats will be presented elsewhere (Le Cann *et al.*, in preparation; Colas, 2003).

Due to the lack of data in some parts of the BB, mainly in the vicinity of the northern slope of Spain, the presence of the so-called "Navidad" event (Pingree and Le Cann, 1992a) was not clearly revealed. The averaging process over space and time may also obscure meso-scale features that are found in the drifter tracks. However, some of the floats exhibited trajectories which were coherent with an initiation of Navidad interpretation. The Navidad is characterised by a winter increase in the temperature of the surface layers along the Cantabrian slope. These increases in temperature are observed on AVHRR satellite images (not shown) and are related to the presence of a slope current around Cape Finisterre and along the Cantabrian slope (Pingree and Le Cann, 1989, 1990, 1992a; Frouin *et al.*, 1990; Pingree, 1994; Garcia-Soto *et al.*, 2002). Drifters 16850 and 16853 (Fig. 2a) are two examples showing the presence of the slope current in the vicinity of Ortegal Promontory. They were launched over the slope west of Vigo on 2 December 1996. After a brief southward motion, the two drifters reversed back northward (10 December) until 28 December. Drifter 16853 made a cyclonic loop off Cape Finisterre, then drifted back to the north and

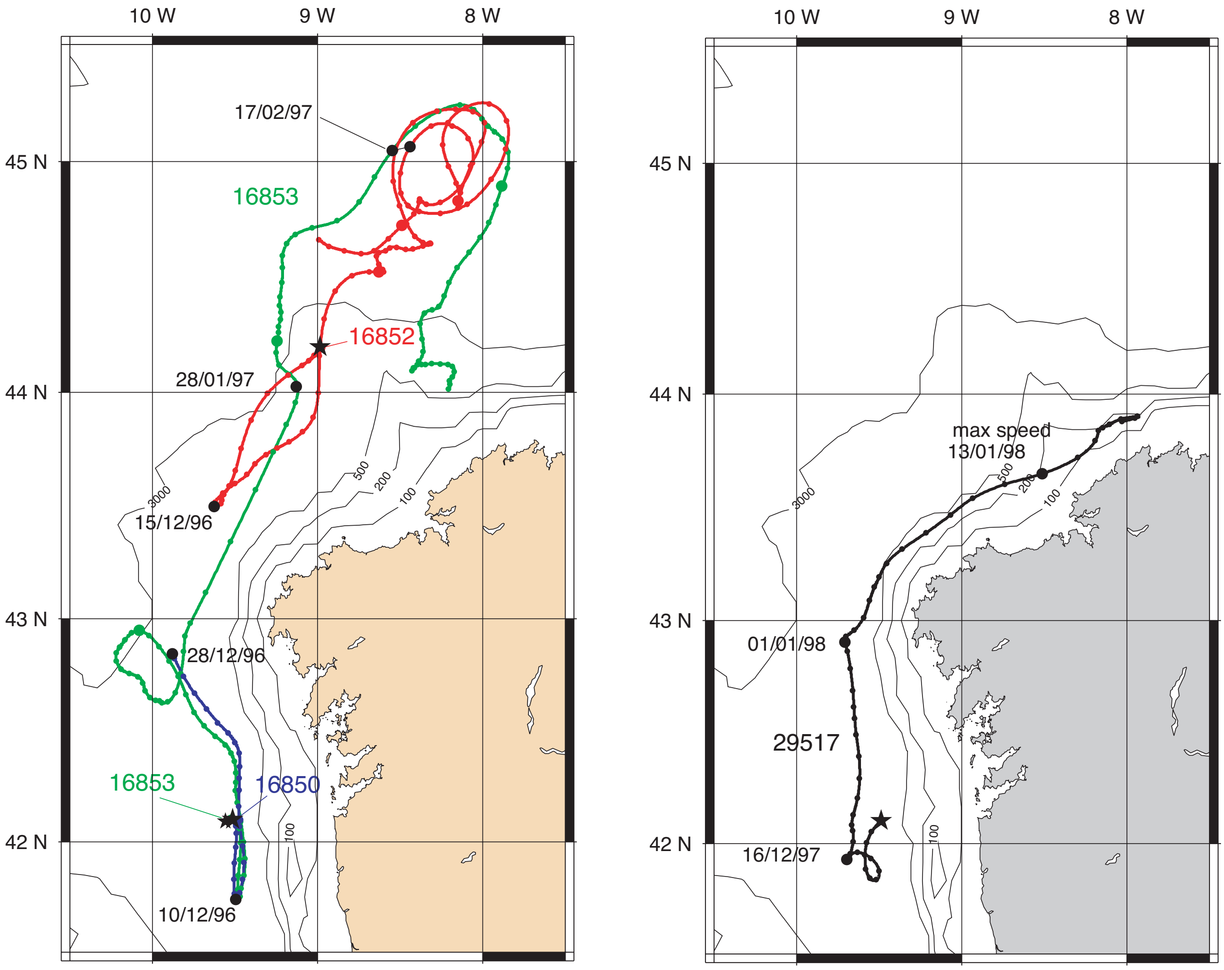

FIG. 2. – A: Low-pass filtered trajectories of Surdrifts 16850 (blue), 16853 (green) and 16852 (red), drogued at 150 m. Deployment positions are indicated by a star. Surdrifts 16850 and 16853 were released on 2 December 1996 and Surdrift 16852 on 30 November 1996. Along the trajectories, small coloured dots indicate days and unlabeled bigger coloured dots indicate the first day of each month. Black labeled bigger dots indicate selected dates. B: Low-pass filtered trajectory of Surdrift 29517 drogued at 150 m. The deployment took place on 5 December 1997 (indicated by a star). The trajectory ended on 22 January 1998 in the vicinity of Ortegal Promontory. Small black dots indicate days and black labeled bigger dots indicate selected dates.

penetrated into the BB after a large anticyclonic loop. This loop corresponds to the trapping of the float by an anticyclonic mesoscale eddy, well sampled by drifter 16852 (see the anticyclonic eddies section). Timing difference between reversals at different locations along the slope (10 December for drifters 16850 and 16853 and 15 December for drifter 16852, separated by a distance of ~200 km) give an order of magnitude of propagation of ~0.5 m s^{-1} for the reversal event. As an example of estimated slope current values, drifter 16853 moved northward from 11 December to 28 January with a mean velocity of ~9 cm s^{-1} and a maximum value of ~35 cm s^{-1} on 23 January (this high value is obtained along a surprisingly rectilinear portion of the trajectory, which has been validated).

Drifter 29517 is one example of the possible initiation of the Navidad event (Fig. 2b). The drifter was launched at the same location and time as drifters 16850 and 16853, but one year after, on 5 December 1997 over a water depth of around 1000 meters: the track extended until 22 January 1998, when the drifter was in the vicinity of Ortegal Promontory. The drifter, which was drogued at 150 m depth, began to loop cyclonically before drifting northward after 16 December to turn around Cape Finisterre over water depths of between 200 and 500 metres. The mean velocity of the drifter during the northward drifting period was ~10 cm s^{-1}, with a maximum value of ~23 cm s^{-1} in mid-January. Frouin *et al.* (1990) reported slope current geostrophic values of about 20 to 35 cm s^{-1}, coherent with our drifter data. Similar experiments with surface drifters were conducted by Haynes and Barton (1990, 1991) in the same region with similar results.

The two sets of drifters were launched at one-year intervals. As can be seen from AVHRR satellite images (not shown here), 1997 and 1998 were different in term of Sea Surface Temperature (SST). At the beginning of 1998, SST around Cape Finisterre and Ortegal Promontory was higher than SST in the same area at the beginning of 1997. This could indicate the possibility of the slope current being more extended or more intense in winter 1997-98 than in winter 1996-97. However, the mean velocities of the 1996-97 floats and 1997-98 float 29517 were approximately the same. It therefore appears difficult, without complementary data, to directly link the 1997-98 winter surface warming to a possible intensification of the slope current in that region. Nevertheless, Garcia-Soto *et al.* (2002) also reported a marked Navidad at the beginning of 1998, from AVHRR imagery and high SST values obtained in the vicinity of the Cantabrian slopes, which agrees with the presence of a significant slope current in early 1998 in this region. Although the mechanisms of formation of the poleward slope current have not yet been thoroughly investigated, the wind is expected to be important in the generation and modulation process. Garcia-Soto *et al.* (2002) showed a relationship between a negative NAO (North Atlantic Oscillation) index in November-December and SST over the northern Spanish slopes in January of the following year during Navidad years. They speculate that during negative NAO index years, the northerly component of the wind relaxes or reverses, driving slope water poleward. The analysis of the meteorological conditions (not presented here) is indeed markedly different in terms of surface winds. In December 1996 – January 1997 (no Navidad) winds were weak and southerly west of Iberia and significantly easterly over the BB, thus blocking penetration of surface waters there. In December 1997 – January 1998 the prevailing winds were markedly southwesterly over the whole region and could thus induce a strong Navidad event in the BB.

We shall focus now on some drifters deployed over or near the Armorican slope of the BB (Fig. 3). The drifters were launched in pairs in early autumn 1994 and 1995. They were drogued respectively at 80 and 150 m depth and drifted northwestward following the slope. It is not our purpose here to discuss the separation rates of the pairs of drifters. For the sake of the discussion, we shall loosely distinguish between two regimes: the first one is when the displacements of the two drifters were mostly correlated, the second when they were mostly uncorrelated. In 1995, the two drifters were deployed over the abyssal plain offshore of the continental rise and entered the slope in the Meriadzek Terrace area, branching poleward. First, the pairs drifted roughly together for half a month in 1994 and one month and a half in 1995. They separated after these periods, and three of them continued to follow the slope, typically north of 48°N. The estimated mean velocities of the 4 drifters when they moved together before their separation were very similar (~9 cm s^{-1} in 1994, ~7 cm s^{-1} in 1995). Drifters 23076, 23443 and 23449 continued to follow the slope with mean velocities of around 7-8 cm s^{-1} between their separation and the moment when they left the slope to drift onto the

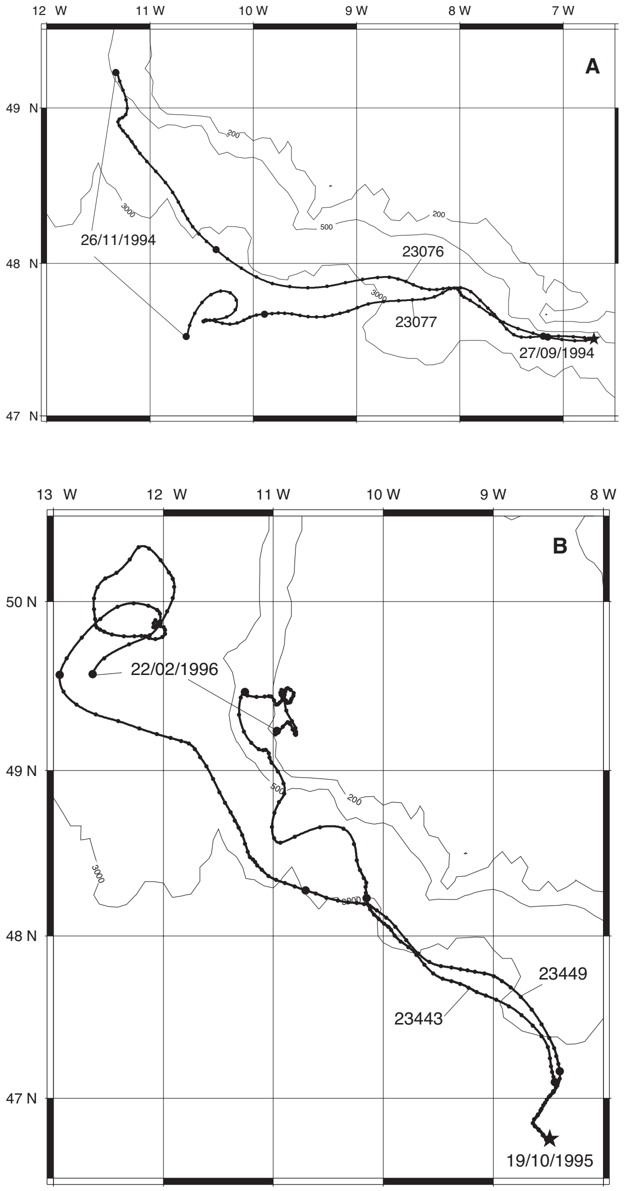

FIG. 3. – Low-pass filtered trajectories of Surdrifts 23076 and 23077, drogued at 80 m, and launched on 27 September 1994 (A) and Surdrifts 23443 and 23449, drogued at 150 m, and launched on 19 October 1995 (B) at the same location (indicated by a star). Small black dots indicate days and unlabeled bigger black dots indicate beginning of months.

continental shelf (drifters 23076 and 23443) or to be trapped in an anticyclonic eddy (drifter 23449) off Goban Spur. Drifter 23077 left the slope prematurely and penetrated into the abyssal plain of the BB.

These floats give evidences of poleward surface slope currents. Nevertheless, some other floats, notably several of the 450 m level Marvor floats, show evidences of equatorward slope currents. In Figure 4, we present selected trajectories over the slope at the 450 m depth level which confirm this tendency: most float trajectories indicate an equatorward flow over the northern Spanish slope, but also over the Armorican slopes to the north. Examination of the trajectories shows that these equatorward slope currents tend to occur during the winter period over the Armorican slopes, and in winter-spring over the northern Spanish slopes. The winter maximum of equatorward Armorican slope currents may be put together with the winter minimum of poleward slope currents found by Pingree and Le Cann (1990) over the Celtic slopes. Typical equatorward drift velocities are around 5-6 cm s^{-1} over the Armorican slopes and ~6 cm s^{-1} over the northern Spanish slopes, reaching higher values (~11 cm s^{-1}) in the vicinity of Cape Ortegal. Poleward drift velocities on the slope west of the Ortegal Promontory are around 4-5 cm s^{-1}, and no penetration into the BB is observed from the floats at this depth level.

Anticyclonic eddies

The area north of Ortegal Promontory has been depicted as a location of important mesoscale eddy activity (Pingree and Le Cann, 1992a,b; Pingree, 1994; Paillet *et al.*, 1997). SWODDIES (Slope Water Oceanic Eddies) were first mentioned in Pingree and Le Cann (1992b), when these authors observed large anticyclonic eddies along the continental slope of the BB, mainly from Ortegal Promontory to Cape Ferret canyon. Their observations originated from AVHRR satellite images, and were confirmed by a series of in situ observations in the case of one important structure which drifted across the BB for about a year. Swoddy generation is linked to instabilities of the slope current when it flows over topography. Instabilities tend to be generated where pronounced changes in topography occur, notably near promontories. Several floats deployed during the ARCANE project have been trapped in swoddy-like structures.

Drifter 16852 (Fig. 2a) illustrates the trapping of a drifter by an anticyclonic eddy in the area of Cape Ortegal. This drifter, drogued at 150 m, was launched at the end of November 1996. After moving southward for 15 days, it suddenly reversed its direction to drift northward, and then started to follow a clockwise cycloidal trajectory after 15 January 1997. After completing several revolutions, the drifter lost its drogue after 7 March. This anticyclonic eddy exhibits a swoddy-like structure. The eddy azimuthal

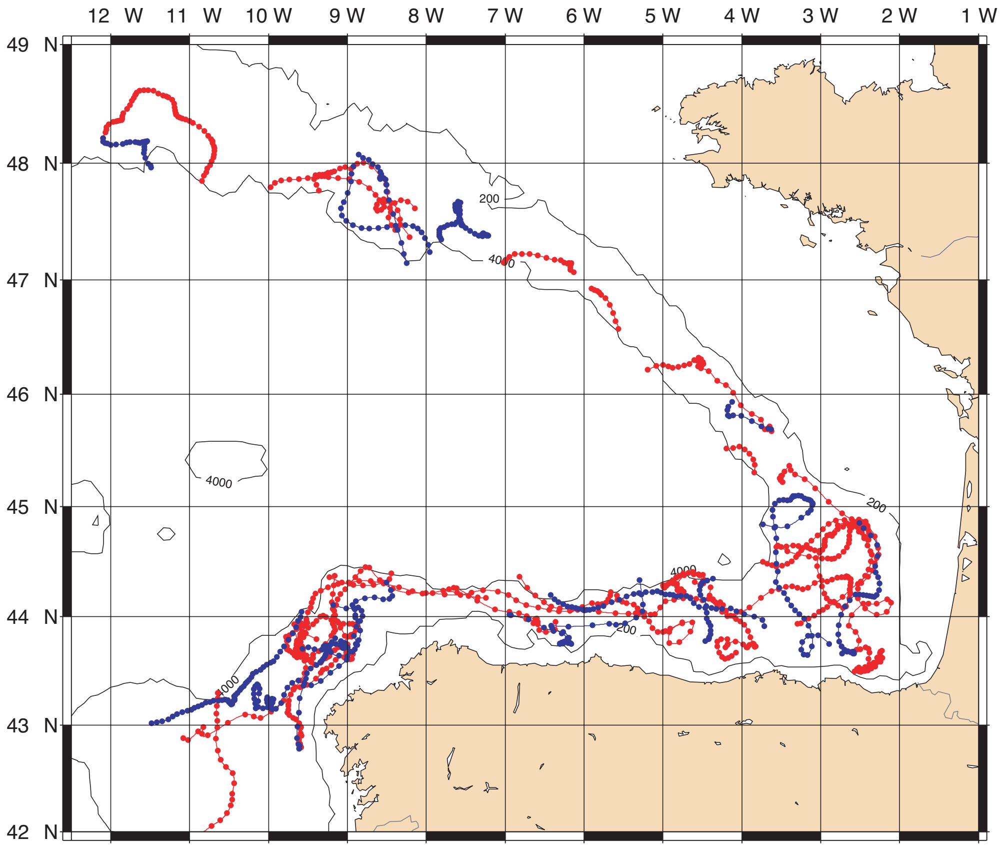

FIG. 4. – Selected low-pass filtered trajectory portions of Marvor and Rafos floats at the 450 m depth level over the continental slope. Poleward flows are in blue and equatorward flows in red. Small coloured dots indicate days.

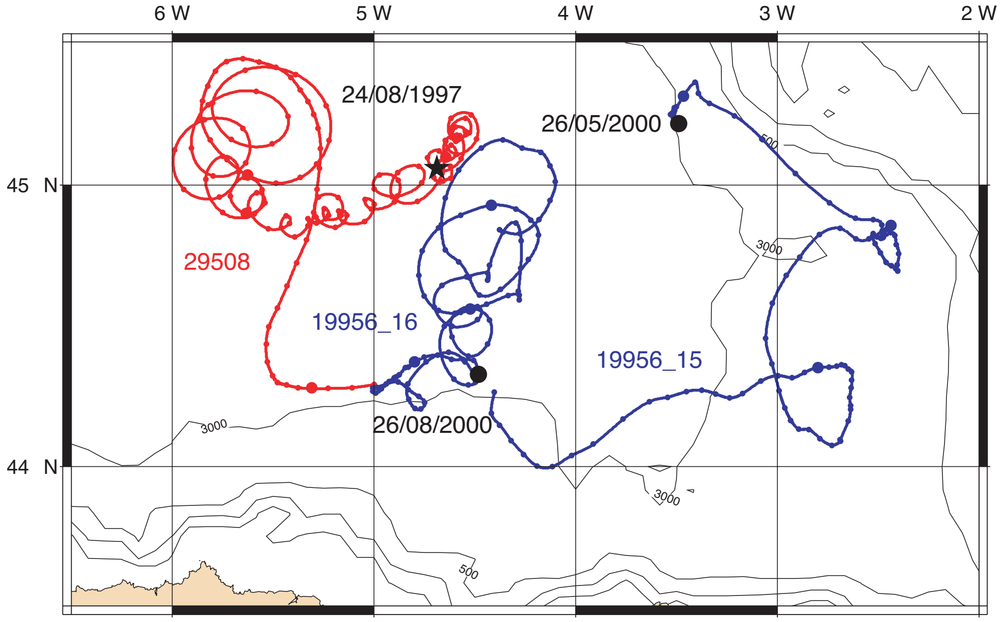

FIG. 5. – Low-pass trajectories of Surdrift 29508 (red), drogued at 150 m and Marvor float 19956 (blue, cycles 15 and 16), ballasted at ~450 m depth. The Surdrift was launched on 24 August 1997 (indicated by a star). The Marvor float cycles 15 and 16 started on 26 May 2000 and on 26 August 2000 (indicated by black dots). Small coloured dots indicate days and unlabeled bigger coloured dots indicate beginning of months. Near the middle of the eddy trajectory, some inconsistencies seem to appear, but are probably linked to uncertainties in acoustic positioning rather than a real physical event.

velocity was of the order of 15 cm s^{-1} at a radius of about 20 km. A second drifter was launched in the same period (drifter 16853, which has already been depicted in the previous section), and after a global northward trajectory it was also trapped by the eddy at its periphery when drifter 16852 began its second main loop. Drifter 16853 left the swoddy before the end of its first revolution, before losing its drogue a few days later.

Another area which is favourable to the presence or the formation of swoddy-like structures in the BB is the Cape Ferret Canyon region, as reported in previous works (Pingree and Le Cann, 1992a,b). This can be illustrated by two examples of drifters which have moved in the vicinity of this area (Fig. 5). Drifter 29508, drogued at 150 m depth, was launched at the estimated centre position of a swoddy-like eddy detected during a hydrology survey. The drifter was trapped in the swoddy for almost 4 months, and covered about 23 complete revolutions. A rough estimation of the path length of the swoddy indicates a translation distance of ~46 km in ~120 days, leading to a mean drift velocity vector of ~0.5 cm s^{-1}, which is coherent with previous observations of swoddies (Pingree and Le Cann, 1992b: Pingree, 1994), with theoretical estimates for the β-induced westward propagation speed of anticyclonic eddies, and finally with the distribution obtained by Van Aken (2002). The azimuthal velocity was again ~0.15 m s^{-1} at a radius of ~20 km. Hydrology XBT measurements (not shown here) made across the eddy indicated a depression of the isotherms down to about 800 meters, which can be considered as the influence of the swoddy on the water column. Swoddies may therefore be observed from deeper floats. As an example, we show cycle 16 of Marvor 19956 (Fig. 5) at 450 m depth, which first followed a westward current with a mean velocity of around 7 cm s^{-1}, offshore of the 3000 m isobath. Then the float started a small anticyclonic loop, and drifted back. Several complete revolutions were made while the float was translated northward, trapped in a swoddy-like structure. The float continued to turn clockwise until the end of its subsurface mission. It was trapped for about 2 months and a half. These two examples showed how rich the southern region of the BB situated between 4 and 6°W is in terms of swoddy generation or presence.

Another type of anticyclonic eddies has been found in the dataset: when penetrating the Armorican Shelf from the slope area, some drifters experience small anticyclonic motions. Figure 6

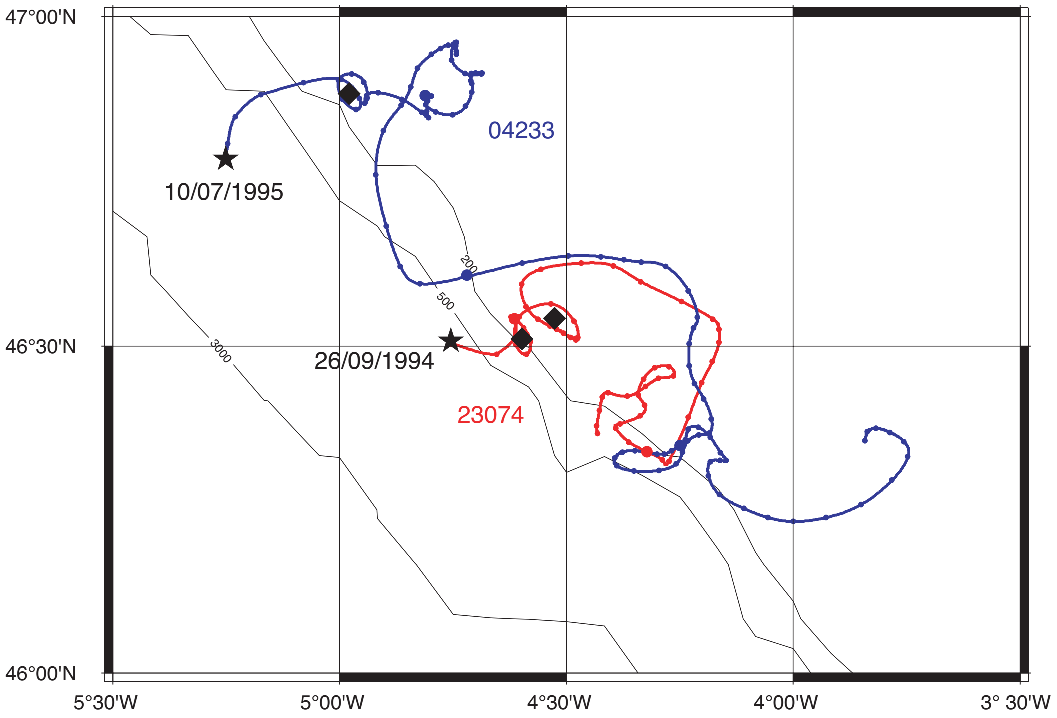

FIG. 6. – Low-pass filtered trajectories of surdrifts 04233 (deployed on September 1994, blue) and 23074 (deployed on July 1995, red), drogued at 80 m. Deployment positions and dates are indicated on the figure (black stars). Small coloured dots indicate days and unlabeled bigger coloured dots indicate beginning of months. Diamonds (♦) indicate the positions of the Outer Shelf AntiCyclones (OSAC_S).

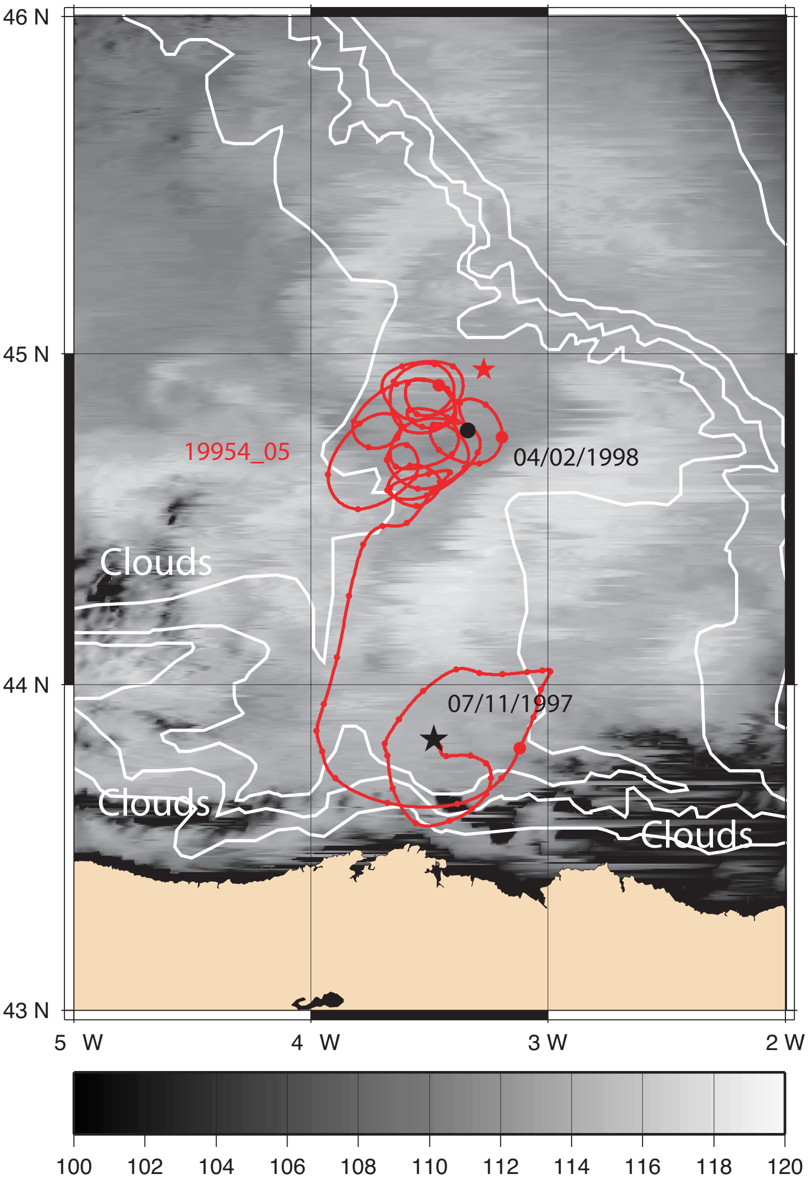

FIG. 7. – Low-pass filtered trajectory of Marvor 19554 (red, cycle 5) superimposed on AVHRR satellite image (IR Channel 4) of 6 February 1998 03:44 UTC. Image is coded in radiance counts (dark shades are cold and light shades warm). Float deployment location is indicated by a star and end of the trajectory by a big black dot. Small coloured dots indicate days and unlabeled bigger coloured dots indicate beginning of months. The colder structure probably associated with the cyclone is indicated by a red star (*). Thermal contrast (AVHRR SST) can be estimated to be about 1 to 2°C between warmer structures and colder adjacent waters. White bathymetric contours (100 m, 200 m, 1000 m, 2000 m, 4000 m) are plotted and probable cloudy areas are indicated.

shows anticyclonic loops near 46°50’N, 05°00’W (drifter 04233) and near 46°30’N, 04°30’W (drifter 23074). These events occurred in summer (drifter 04233) and early autumn (drifter 23074). The drifters have performed loops with a typical diameter of 5-10 km and their rotation period is around 5 days, which gives an azimuthal speed of around 5 cm s^{-1}. They are located just inshore of the shelf break. Drifters 04233 and 23074 only made two loops before leaving the eddies and then slowly drifted to the southeast. The fact that trajectories from two different years closely following each other (near 46°30’N, 4°30’W) may be coincidence, or may reflect some link with topography: many canyons indent the slope in this area and may funnel cross-slope exchanges.

Cyclonic eddies

Other types of eddy structures may be observed over the BB abyssal plain with the help of the floats. These are cyclonic eddies (Pingree, 1984; Van Aken, 2002), which have been much less studied in the BB. Pingree and Le Cann (1992b) report the occurrence of cyclonic eddies (around 30 km in diameter) during the early stages of swoddy formation. These give the eddy structure a tripole appearance which quickly fades away, in less than two weeks. Cyclonic eddies appear on several ARCANE float recordings, mainly at the 450 m depth level. Figure 7 shows 12 complete cyclonic revolutions made by Marvor float 19954 during its fifth cycle (overall 51 days trapped in the eddy). The characteristics of this eddy were slightly less intense than those of the anticyclonic eddies found in the region, with an azimuthal velocity of ~10 cm s^{-1} at a radius of ~20 km. The area where the float began to loop is a known major swoddy generation site (Pingree and Le Cann, 1992b). It is located in the neighbourhood of Cape Ferret canyon, where swoddy-like structures have been reported. Other data types available at the time of the float drift, and representing a two-dimensional distribution of sea level or sea surface temperature, are the TOPEX/POSEIDON altimetric data and the AVHRR satellite images. The altimetric image from 15 December (not shown here) revealed a lowering of the sea surface height of the order of 5 cm, with maximum values of about 10 cm, at the location where the float drifted cyclonically. This surface deepening confirms the cyclonic movement of the water column observed from the float at 450 m level and shows that the eddy extends from the surface to at least this depth level. Nevertheless, the altimetric data are not sufficiently precise to describe correctly the detection and subsequent evolution of such mesoscale events, because of satellite track resolution. Although AVHRR images are often affected by important cloud coverage, their finer resolution allows better interpretations. The image of 6 February 1998 (Fig. 7) shows a structure which can be related to a cyclone, located near the area where float 19954 evolved cyclonically. A warmer structure is detected southeast of the float trajectory, but it is difficult to attribute this warming to the presence of an anticyclone in the vicinity of the cyclonic eddy. This image may nevertheless points out the good correlation which could exist between different types of information, namely float drift and AVHRR data, subsurface and surface informations which are probably linked to the same mesoscale phenomenon.

A second typical cyclonic structure may be seen on Figure 8, for float 19956. It seems to correspond

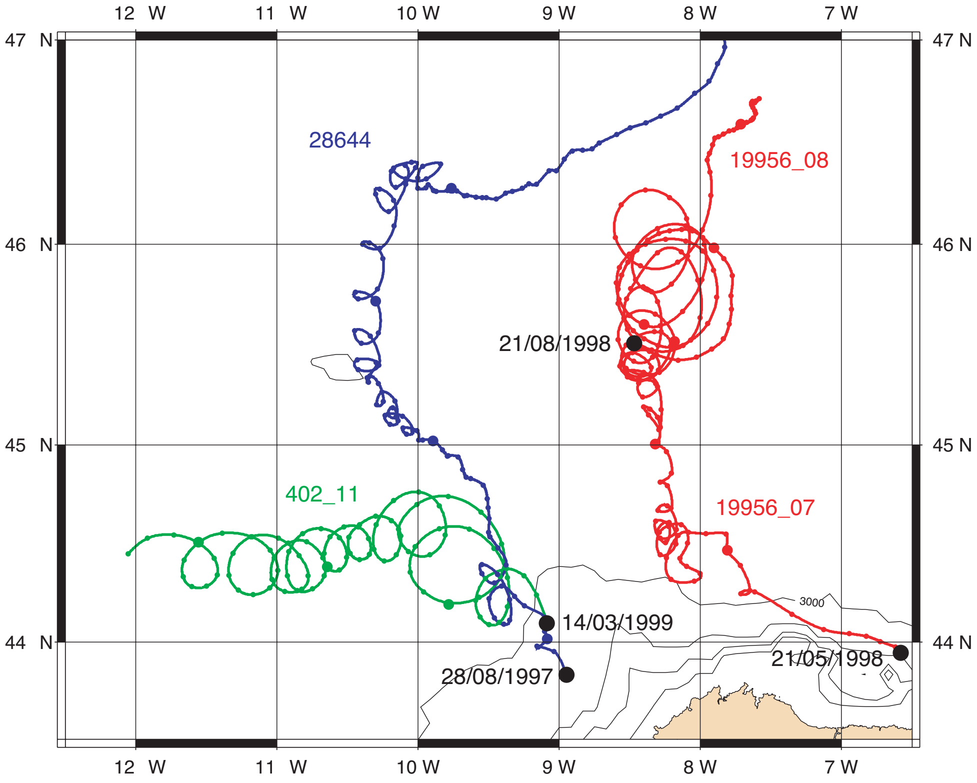

FIG. 8. – Low-pass filtered trajectories of Rafos 28644 (blue) at the 450 m depth level, Marvor 402 (green, cycle 11), and Marvor 19956, cycles 7 and 8 (red) for different years (1997, 1998, 1999). Black dots indicate the beginning of trajectories. Coloured small dots indicate days and coloured bigger dots indicate beginning of months.

to the generation of a cyclonic eddy following an overshoot of the westward slope current in the vicinity of the Ortegal Promontory. The westward direction of the slope current is coherent with the mean currents obtained during this period (Le Cann *et al.*, in preparation). The cyclonic pattern of circulation appears on cycles 7 and 8 of Marvor 19956, which was drifting at the 450 m depth level. The float completed 16 revolutions during cycle 7, then 4 revolutions during cycle 8 before escaping from the eddy to flow northward (overall 142 days trapped in the eddy). The looping trajectory was also different from one cycle to another, being more elliptic and smaller (~less than 40 km diameter) during cycle 7, and becoming quasi circular and growing (~70 km diameter) during cycle 8. The altimetric data could not confirm the link between the birth of the eddy and the overshoot of the slope current; nor were they able to confirm the elliptical shape or the path of the eddy until the ejection of the float off the eddy six months later.

Marvor float 402 was also trapped in a cyclonic eddy during its 11th cycle (Fig. 8) at the 450 m depth level. The loops described by the float have a mean diameter of around 30 km (after analyses of the trajectory by the method described in Paillet *et al.* (2002)), and the mean drift velocity of the eddy was high compared with the drift velocity obtained previously for the anticyclone depicted by drifter 29508 (Fig. 5). We can estimate the mean westward drift velocity to be close to ~3 cm s^{-1}, which is significantly higher than the estimates in the previous section, but coherent with some other previously observed eddying structures, such as swoddy F90a studied in Pingree and Le Cann (1992b) (~2 cm s^{-1}). Moreover, the eddy is located exactly where a strong westward current is depicted at the 450 m depth level in Le Cann *et al.* (in preparation), so we can consider an advection effect to be superimposed on the proper dynamics of the eddy.

Another cyclonic eddy was also found in the same area (Fig. 8), in the vicinity of the Ortegal Promontory at the 450 m depth level, but its characteristics and behaviour were completely different from the structure identified by float 402. The size of this cyclone appears much smaller and the drift is markedly northward for around 3 months before the float left the eddy. The loops performed by this float have a diameter of ~15 km, and the northward translation velocity during the 3 months is ~4 cm s^{-1}. The azimuthal velocity is typically ~13 cm s^{-1} at a radius of 8 km, and this value decreases to about 4 cm s^{-1} at a radius of 2 km. The estimation of the Rossby number at the centre of the cyclone gives a value of ~0.4, indicating a relatively intense eddy.

DISCUSSION AND SUMMARY

Slope currents

Poleward slope currents have long been known to exist in the Eastern North Atlantic Ocean (Swallow *et al.*, 1977: Pingree and Le Cann, 1990). Our dataset evidences these flows, with additional information: notably the widespread evidence for equatorward flows over the BB slopes. Such return flows have been hinted at by Pingree and Le Cann (1990), who described a mean westward (i.e equatorward) flow at 500 m depth from currentmeter measurements on the northern Spanish slope near 7°W. The NACW equatorward flow over the Armorican and northern Spanish slopes seems to be linked to the eastward penetration of waters over the abyssal plain near 46°N (Pingree, 1993; Chantry, 1995; Van Aken, 2002; Le Cann *et al.*, in preparation). This eastward flow diverges over the slope near 47°N, 08°W, in the Meriadzek Terrace area. Part of this flow branches to the North as a poleward current, but a fraction of it enters the slope region to flow equatorward. This poleward induction of slope currents was described in Pingree and Le Cann (1990) from Eulerian measurements, but is more easily depicted by Lagrangian data and is intensified in spring-summer. The westward flow over the northern Spanish slopes was postulated by Schopp (1993) and attributed to (negative) windstress curl forcing (Isemer and Hasse, 1985), which drives a southward Sverdrup flow component over the BB abyssal plain, which collects over the Spanish slopes as a westward flow. This mechanism cannot explain the Armorican equatorward flow. Another possible mechanism could be the collective effects of anticyclonic eddies (swoddies). These are thought to be mostly generated near the slopes (Pingree and Le Cann, 1992a,b) and the most persistent ones seem to be located in the southern part of the BB. When in the vicinity of the slopes, they could drive the observed equatorward flow. This alternation of poleward and equatorward flows has important implications: it shows that the poleward slope current is not continuous along the slope, and this will promote

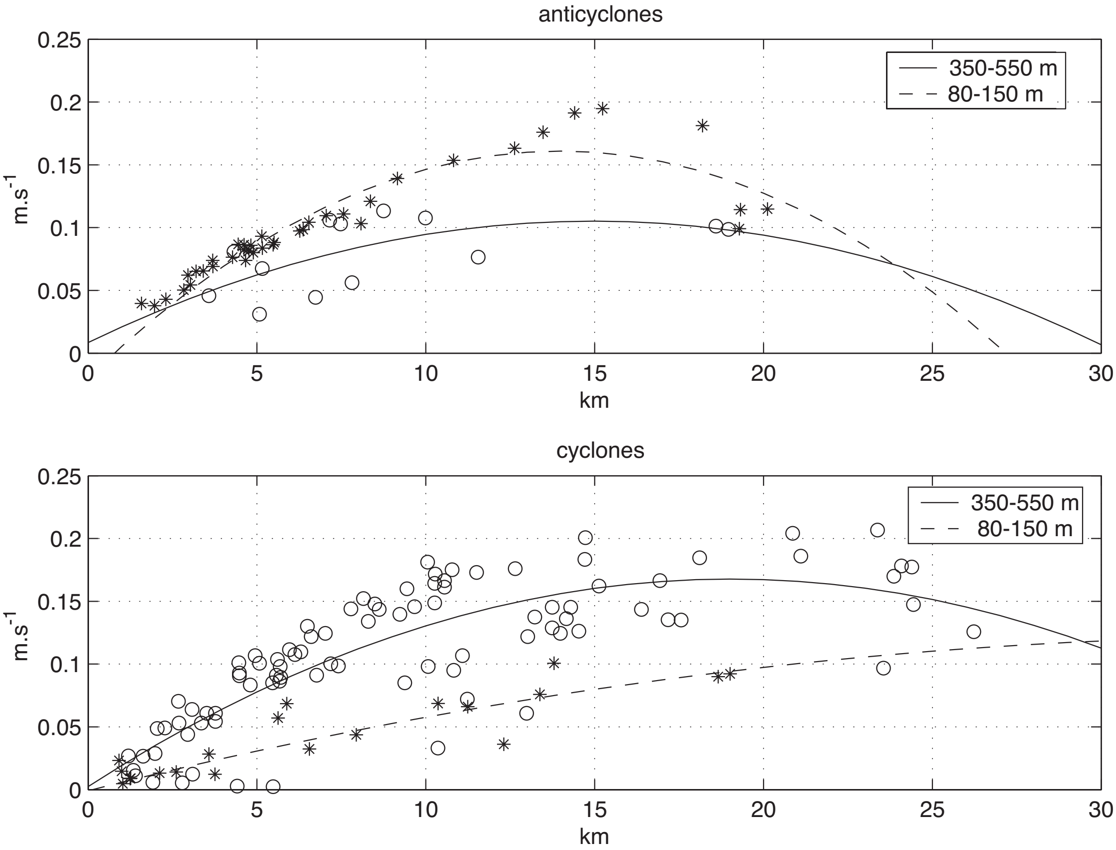

FIG. 9. – Azimuthal velocity (m/s) against distance from the eddy centre (km), for anticyclones (upper panel) and cyclones (lower panel) sampled in this study. Circles (o) stand for data from floats at the 450 m level and star (*) for data from Surdrifts at the 80-150 m depth level. A second-order polynomial fit is shown for the 80-150 m depth level (dashed-line) and the 450 m depth level (solid line) data.

slope-ocean exchanges, a key parameter for biogeochemical studies (Huthnance *et al.*, 2002).

These slope currents are unstable, particularly in the vicinity of topographic features, like the Ortegal Promontory area. These instabilities are seen to deflect a significant part of the slope current over the abyssal plain and can even retroact on the slope current, making penetration of slope waters into the BB more difficult, particularly near the Ortegal Promontory region. In our dataset, none of the floats deployed over the western Iberia slope entered the BB through this route.

Mesoscale eddies over the slope and abyssal plain

Azimuthal velocity structure

Figure 9 depicts the radial distribution of azimuthal velocities for the eddies sampled by the floats. We used the method described in Paillet *et al.* (2002) to derive the velocities. We used trajectories with more than 3 loops. A different parabolic fit is given for the ~80-150 m and ~450 m depth level drifters/floats. The radial velocity structure is seen to be quite similar for the both cyclonic and anticyclonic eddies. There are some exceptions: a weaker cyclone in the central BB (trajectory not shown) sampled by a drifting buoy drogued at ~80 m, and a weaker anticyclone sampled by a float at the 450 m level (depicted in Fig. 5). In our dataset, anticyclones' azimuthal velocities tend to be intensified at the 80-150 m level, and decrease at depths (450 m level), whereas the reverse is true for cyclones. For the other eddies, maximum velocities are found at a radius of ~15-20 km, which is smaller than the swoddy studied by Pingree and Le Cann (1992b), and than that found in the distribution given by Van Aken (2002). It is noted that we lack points to describe the outer edges of the eddies. This tendency for smaller eddies may be due to the fact that we impose a minimum number of loops to define an eddy, and thus probably bias the sampling toward the inner core of the structures. A rough fit for the inner solid body rotation core gives an estimated central normalized relative vorticity ζ/f ~0.3-0.4, where ζ is the relative vorticity and f the Coriolis parameter (~10^{-4} s^{-1}). Again, this is smaller than the ~0.5 value reported by Pingree and Le Cann (1992b).

Generation sites

In this study, known eddy generation sites like the Ortegal Promontory region were sampled (Figs. 2a and 8). In this area, both anticyclones and cyclones are generated (Pingree and Le Cann, 1992b). We postulate that the generation of some of these NACW cyclones may be linked to the birth of the "Northern Meddies" (Paillet *et al*., 2002), in a manner similar to the one described by Pingree and Le Cann (1993) for Meddy generation near Tagus Plateau to the south. One occurrence of anticyclone presence was found near Le Danois Bank (Fig. 5). It is possible to link an overshoot of the slope current in this region to the generation of this anticyclonic swoddy-like eddy. Although Cape Ferret Canyon is a privileged site for the swoddy formations, no generation was sampled near this region in our dataset. This is due to the deployment of our floats in the western part of the BB. Nevertheless the presence of the swoddy reported in Figure 5 effectively denotes eddy activity in this area.

Eddy motions and lifetimes

Eddy motions are seen to be quite erratic, but there are some tendencies. When away from the slopes, the anticyclones exhibit mostly westward motions, at typical speeds of around 0.5 cm s^{-1} (see Fig. 5), which is coherent with Pingree and Le Cann (1992b) and Van Aken (2002). Cyclones may display the same behaviour (see Fig. 8). Another type of behaviour exists for both anticyclones and cyclones, namely northward displacements away from the northern Spanish slopes at speeds of around 2-3 cm s^{-1}. These motions are apparently linked to the generation process. Once formed, swoddies in the BB have been estimated to last for up to at least a year (Pingree and Le Cann, 1992b). From our dataset, we can only estimate lower bounds for eddy lifetimes, as we detect only the trapping period. The longest looping trajectory found for anticyclones is ~4 months, and that found for cyclones is ~4.5 months. From the dataset presented here, restricted to the data collected in the BB, we have detected 3 anticyclones and 6 cyclones. This ratio of cyclones to anticyclones is at odds with Paillet (1999) and Van Aken (2002), but may be due to the small number of detected features.

Outer shelf anticyclonic eddies

The "Outer Shelf AntiCyclones" (OSACS) depicted in Section 3-2 may be thought to be generated from conservation of potential vorticity. When water depth decreases, squashing of the water column will generate anticyclonic relative vorticity. Assuming a baroclinic adjustment, scales would be derived from the first internal Rossby radius, which may be estimated using a two-layer system: $R_1 = C_1/f = (g\ \Delta\rho\ h)^{1/2}\ /f$, where C_1 is the phase speed of the first Rossby mode, g the acceleration due to gravity, $\Delta\rho$ the density difference between the two layers, h the thickness of the upper layer with typical values for summer-early autumn ($\Delta\rho \sim \alpha\Delta T \sim 0.2\ 10^{-3} \times 5 \sim 10^{-3}$ kg m^{-3}, h ~25 m, where α is the volume coefficient of thermal expansion and ΔT is the temperature difference). One obtains R_1 ~5 km, compatible with the observed scales. These eddies appear to be of opposite sign to the cyclonic eddies found near the shelfbreak region of the Celtic Sea by Pingree (1979). Assuming that dissipation of these eddies is due to bottom friction, one can estimate a typical decay scale $T = H/(C_D|U|)$, where H is the total depth (~150 m), C_D a drag coefficient (~2. 10^{-3}) and U a typical first order velocity (due to tides and wind, ~0.2 m s^{-1}). This gives T ~4-5 days, which is again consistent with observed values. Further studies are clearly needed in order to investigate these small and short-lived features.

CONCLUSIONS

We have described selected examples of two categories of mesoscale features in the BB region, slope currents and eddies, at two levels of the North Atlantic Central Water (~80-150 m and ~450 m depth). Slope currents exhibit alternation of poleward and equatorward directions: at the base of the NACW, the current is poleward over the northern slopes and tends to be equatorward over the Armorican and northern Spanish slopes. Eddies are ubiquitous over the abyssal plain, and generation processes, initiated in slope areas, are difficult to sample. We found a number of persistent cyclones, some of them probably generated over the northern Spanish slopes, near the Ortegal Promontory and Le Danois Bank. Typical eddy core diameters (as

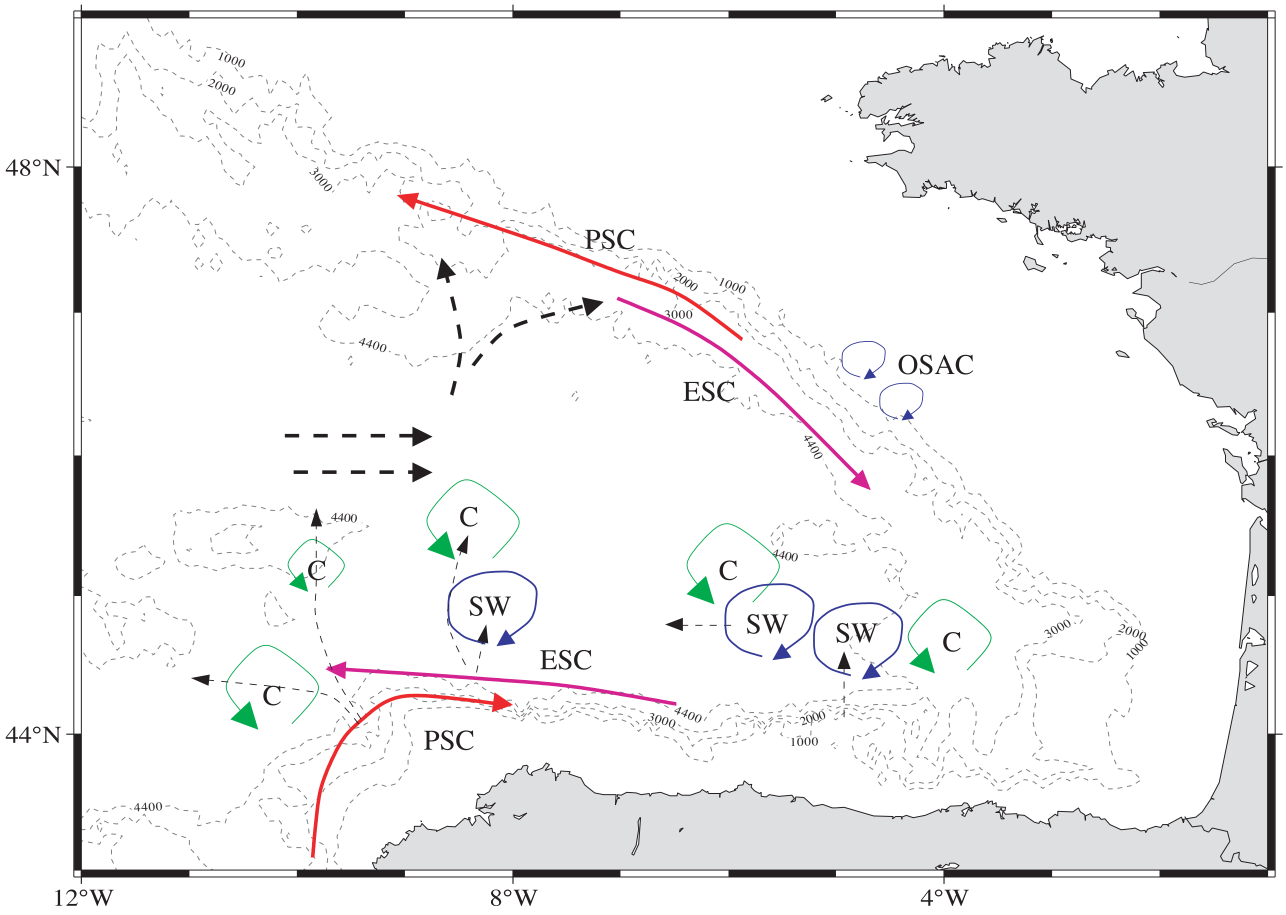

FIG. 10. – Summary sketch of the observed mesoscale features. Abbreviations are: PSC (Poleward Slope Current), ESC (Equatorward Slope Current), C (Cyclone), SW (Slope Water anticyclonic eddy) and OSAC (Outer Shelf AntiCyclone). Thin dashed arrows indicate the mean drift of the eddies (if observed). Thick dashed arrows indicate some observed NACW pathways.

defined by the trapping region of the floats) are around 50 km, but the eddy dynamical influence extends beyond. Relative vorticity reaches 0.3-0.4 f in the centre of both anticyclones and cyclones. There are occurrences of weaker eddies. We have detected small anticyclones near the shelfbreak of the Armorican slope, which may result from adjustment of intrusions from the slopes. A brief sketch of the features observed in this study is presented in Figure 10. The observed alternation of poleward and equatorward slope currents and the generation of eddies in slope areas promote slope-ocean exchanges, are important for biogeochemical processes, and therefore deserve further study.

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