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# Aspects of the surface circulation in the Liguro-Provençal basin and Gulf of Lion as observed by satellite-tracked drifters (2007-2009)

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**Abstract** The surface circulation in the Liguro-Provençal basin and Gulf of Lion (north-western Mediterranean) is studied using satellite-tracked drifters in the period 2007-2009. Complex circulation patterns prevailed in the eastern Ligurian Sea, before the drifters joined the Northern Current (NC) in the coastal area off Genoa. Between 5°E and 7°30'E, most drifters (especially in summer) were advected offshore before heading to the east and eventually closing a basin-wide cyclonic circulation. This offshore turning is related to the wind and wind stress curl during north-westerly wind events. In constrast, most drifters proceeded into the Catalan Sea in the fall. Although the Western Corsican Current was well delineated by the drifters, no signature of the Eastern Corsican Current was shown, indicating limited connectivity between the Tyrrhenian and Ligurian seas in summer 2007. Pseudo-Eulerian velocity statistics were calculated in the coastal region extending between Genoa and the Gulf of Lion. Fast currents are evident on the shelf break, especially off Imperia (maximum of 90 cm/s) where the NC is closer to shore and narrower. A stagnation area inshore of the NC near Fréjus is characterized by little mean flow and low velocity fluctuations. Mean currents are also reduced off Menton-Nice where the variability is maximum. More to the west, the NC broadens and slightly reduces in strength.

**Key words:** surface circulation, drifters, coastal currents, north-western Mediterranean.

## 1. Introduction

The Liguro-Provençal basin (LPB) is located in the north-western Mediterranean Sea (41-45°N, 5-10°E; Fig. 1) off the coasts of Italy and France. It is connected to the east to the Tyrrhenian Sea through the Corsica Channel, whereas to the west, it confines with the Gulf of Lion (GL). The water circulation in the LPB was studied since the 1960s using hydrographic data (profiles of temperature and salinity) and consists of a mean basin-wide cyclonic gyre (Ovchinnikov, 1966; Crépon *et al.*, 1982) which extends over the upper 500 m layer and can spread out to the west into the Catalan Sea. These results were confirmed about 20 years later by direct current measurements (with moored currentmeters) in the Corsica Channel (Astraldi *et al.*, 1990; Astraldi and Gasparini, 1992) and between Corsica and France (Taupier-Letage and Millot, 1986; Millot, 1987; Sammari *et al.*, 1995). The LPB circulation is connected to the Tyrrhenian and Balearic circulations by two northward flowing currents, located on the opposite sides of the Corsica Island (Béthoux *et al.*, 1982). The first, referred to as the Eastern Corsican Current (ECC) by Pinardi *et al.* (2006), brings Tyrrhenian water into the LPB. It is driven by the steric sea level difference between the Tyrrhenian Sea and the LPB, which is maximum in winter and due to the larger heat loss sustained by the LPB during this season (Astraldi *et al.*, 1990; Astraldi and Gasparini, 1992), as well as by the wind stress curl as shown by Pinardi and Masetti (2000) using a numerical model. These authors showed that the Corsica Channel transport weakens dramatically in absence of wind forcing and in particular the transport can reverse in summer. West of Corsica, the other northward current, called Western Corsican Current (WCC) in Pinardi *et al.* (2006), appears to be more constant over the year. The WCC is part of the large cyclonic LPB circulation mainly forced by the geostrophic adjustment to the dense water formation processes occurring in winter in the central LPB (MEDOC Group, 1970; Crépon and Boukthir, 1987) and the dominant wind stress curl due to the northeasterly (Mistral/Tramontane) wind regime [see the numerical simulations of Pinardi and Navarra (1993) and Molcard *et al.* (2002)]. The confluence of the ECC and WCC north of Corsica forms the Northern Current (NC), also called the Liguro-Provençal-Catalan Current, which flows along the Italian (west of Genoa), French and Spanish coasts (Millot, 1991). Molcard *et al.* (2002) showed that the WCC and ECC are part of a basin-wide circulation pattern that is wind-driven and that the confluence of the WCC and ECC produces the NC as a nonlinear intensification at the northern boundary of the domain. The NC transports up to about 2 Sv of sea water between the coast and 33 km offshore (Béthoux *et al.*, 1988; Sammari *et al.*, 1995). Speeds in the NC can be as large as 1 m/s at the surface and about 5 cm/s at depth (400 m), with a decrease in summer (Sammari *et al.*, 1995). Its core is narrow and centered at 20 km or less from the shore in spring-summer, whereas it is broader and more distant from the coast in autumn (Sammari *et al.*, 1995). Béthoux *et al.* (1988) showed that the NC seasonal variability is related to the local river runoffs and to the winter deep water formation processes. Numerical simulations (Pinardi and Navarra, 1993; Herbaut *et al.*, 1997; Pinardi and Masetti, 2000; Mounier *et al.*, 2005) demonstrated that the overall LPB cyclonic circulation is actually thermohaline and wind driven. The cyclonic circulation is reinforced by the wind stress curl acting over the basin. The influence of the wind forcing on the NC in the GL was qualitatively established by Millot and Wald (1980) using satellite thermal imagery and explained quantitatively by modeling results. During Mistral/Tramontane wind events the surface flow associated with the NC veers offshore when reaching the GL, forming the western limb of the LPB cyclonic circulation. Under no or weak wind conditions, and especially during the stratification period (summer), the surface NC continues westwards along the coast towards the Catalan Basin (Millot and Wald, 1980).

Substantial seasonal variations in the LPB circulation were observed, with the winter cyclonic circulation being more extended and coherent and the summer currents being more fragmented

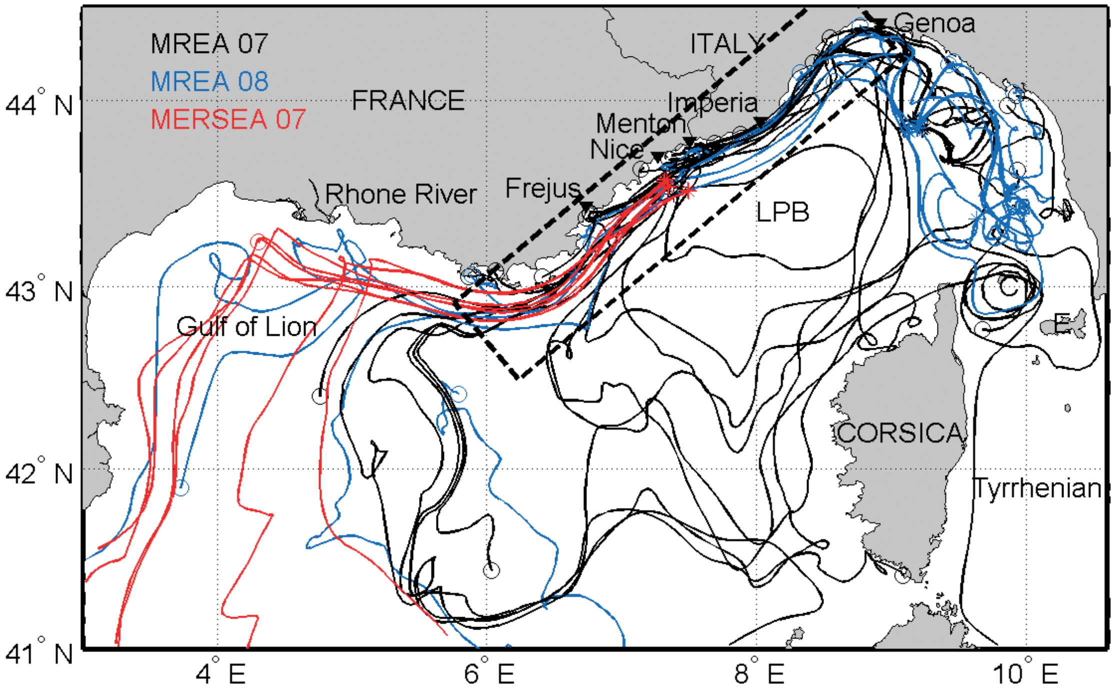

Fig. 1 - Composite diagram with all the drifter trajectories (black: MREA07 and LASIE07; blue: MREA08; red: MERSEA07) in the LPB and GL between May 14, 2007 and January 14, 2009. Star and open circle symbols indicate the deployment and last positions for each drifter, respectively. The area of the NC extending between the Gulf of Genoa and the Gulf of Lion is depicted with a dashed rectangle. The Elba and Capria Islands are indicated by letters "E" and "C", respectively.

and including closed recirculation structures (Astraldi *et al.*, 1994). Mesoscale variability is ubiquitous and dominant in most parts of the LPB and in particular in the NC (Taupier-Letage and Millot, 1986; Sammari *et al.*, 1995; Echevin *et al.*, 2003). There are marked seasonal variations in the mesoscale activity with a maximum in winter when the NC is deeper, stronger and narrower, closer to the coast and instability processes generate mesoscale structures.

The circulation in the LPB was recently investigated using satellite altimeter data (Pujol, 2006; Birol *et al.*, 2010). Objectively interpolated and along-track sea level anomalies combined with the mean dynamic topography of Rio *et al.* (2007) show clearly a depression of the order of 10 cm corresponding to the basin-wide cyclonic surface geostrophic circulation in the LPB. The western and southern limbs of this circulation are usually located in the Catalan Sea and just north of the Balearic Islands (forming the Balearic Current), respectively, in good qualitative agreement with the historical maps based on hydrographic data. Monthy-averaged surface geostrophic currents derived from the altimeter data in the NC reach 10 cm/s in winter (Birol *et al.*, 2010). Co-located and contemporaneous in-situ ADCP measurements are comparable with these results (Birol *et al.*, 2010), although being a little more energetic in terms of mean current and variability. The satellite altimeter data reveal substantial interannual variability of the NC during the period 1993-2007.

Lagrangian measurements in the LPB date back to 1982 when three surface drifters where deployed in the WCC during the DYOME experiment (Taupier-Letage and Millot, 1986). Surface speeds of 15-25 cm/s were measured in the WCC. High-frequency (presumably inertial) and mesoscale motions were noticeable in all the drifter trajectories. After a complex pathway, one drifter eventually joined the NC and moved westwards along the French coast. Drifters deployed in the Tyrrhenian Sea occasionally entered into the LPB through the Corsica Channel (see Mediterranean and Tyrrhenian drifter databases at the MedSVP web site: http://nettuno.ogs.trieste.it/sire/medsvp/). In a recent work by Rinaldi *et al.* (2010), Tyrrhenian drifters show complex circulation patterns in the Corsica Channel.

In this study, we describe some aspects of the surface circulation in the LPB and GL using the data of Lagrangian drifters purposefully deployed in the LPB to measure the surface water general circulation and dispersion over the period 2007-2009. Although the drifters were deployed at a unique site in the central Ligurian Sea in order to better describe dispersion properties, during several episodes in 2007 and 2008, they covered the whole LPB and sampled adequately the NC, thus providing an opportunity to describe, for the first time, the LPB surface circulation based on in-situ drifter data. Ancillary wind and satellite altimeter data are used in concert with the drifter observations to study qualitatively the wind-driven and geostrophic velocity components, and to relate them to the drifter-inferred circulation. After a brief description of the data and methods (section 2), a qualitative description of the circulation in the LPB and GL based on the drifter trajectories is proposed (section 3). The influence of the Mistral/Tramontane wind forcing is also addressed, and in particular, its role in closing the basin-wide surface cyclonic circulation southeast of the GL. The more abundant drifter data in the NC allow a description of its surface flow based on pseudo-Eulerian statistics (section 4). Discussions and conclusions are found in section 5.

## 2. Data and methods

### *2.1 Drifter data*

Since the advent of satellite tracking in the late 1970s, the use of drifters has become an effective methodology to measure marine currents and water properties over a large range of spatial and temporal scales. Despite this sampling benefit, surface drifters have the drawback that they can slip with respect to the surface waters due to the direct effect of winds and waves, and they are therefore called quasi-Lagrangian drifters. This slip was reduced and quantified for a few types of drifters such as the Surface Velocity Program (SVP) and Coastal Ocean Dynamics Experiment (CODE) designs (Pazan and Niiler, 2001; Poulain *et al.*, 2009). CODE drifters have been commonly used in coastal regions and marginal seas, such as the Gulf of Mexico (Ohlmann *et al.*, 2001), the Adriatic Sea (Poulain, 2001; Ursella *et al.*, 2006) and the eastern Ligurian Sea (Molcard *et al.*, 2009; Haza *et al.*, 2010). Another type of surface drifter mainly used to track oil spills is the ARGOSPHERE (Goodman *et al.*, 1995).

CODE drifters were developed by Davis (1985) in the early 1980s to measure the currents in the first meter under the sea surface. They consist of a slender, vertical, 1-m long negatively buoyant tube with four drag-producing vanes extending radially from the tube over its entire length and four small spherical surface floats attached to the upper extremities of the vanes to

Table 1 - Details on the drifter deployment episodes carried on off Nice, France (MERSEA07) and in the open Ligurian Sea (from the Italian Navy ships Galatea and Magnaghi and the Italian Consiglio Nazionale delle Ricerche ship Urania during the LASIE07-MREA07 and MREA08 experiments).

| Date | Ship | Experiment | Number of drifters | Number of kriged tracks |
|---|---|---|---|---|
| 14-May-2007 | ITN Galatea | LASIE07-MREA07 | 5 | 8 |
| 17-Jun-2007 | R/V Urania | LASIE07-MREA07 | 5 | 7 |
| 22-Jun-2007 | R/V Urania | LASIE07-MREA07 | 5 | 8 |
| 10-Oct-2007 | _ | MERSEA07 | 7 | 7 |
| 1-Oct-2008 | ITN Magnaghi | MREA08 | 5 | 4 |
| 10-Oct-2008 | ITN Magnaghi | MREA08 | 3 | 3 |
| 21-Oct-2008 | ITN Magnaghi | MREA08 | 3 | 4 |
| Total | | | 33 | 41 |

provide buoyancy (Poulain, 1999). Direct slip measurements made by the first author showed that the CODE drifters follow the surface currents within 2 cm/s.

ARGOSPHERE drifters measure the currents at the surface (first 10-20 cm of water). Since they have been designed to follow the motion of oil slicks under the influence of ocean currents and waves, and surface winds, their wind-induced slippage can be important. However, this slippage has not been quantified yet.

In order to increase the quantity of Lagrangian observations in the study area, and in turn, improve the reliability of the statistical results, we have decided to merge the CODE and ARGOSPHERE drifters in a unique dataset to describe the LPB and GL surface circulation. It has to be kept in mind, however, that the ARGOSPHERE units are worst water-followers compared to CODE drifters.

All the drifters used the Argos Data Collection and Location System (DCLS) for data telemetry and positioning. The Argos tracking has an accuracy of 300-1000 m and positions are typically available 6-12 times per day. Global Positioning System (GPS) locations were also available for the CODE drifters with higher accuracy [~10 m; Barbanti *et al.* (2005)] and higher frequency (every hour).

The CODE drifters were deployed as part of Marine Rapid Environmental Assessment (MREA) exercises in small scale clusters (~1 km) of 3-5 units at a single location in the open Ligurian Sea in the vicinity of the ODAS buoy (9°10.2’E, 43°47.4’N; see Fig. 1). Deployments were carried out in May 2007 and June 2007 as part of the MREA07 and LASIE07 (Ligurian Air-Sea Interaction Experiment) experiments (Teixeira, 2007; Fabbroni, 2009). In 2008, the deployments were repeated three times during the MREA08 sea trial. Deployment details are listed in Table 1. Some drifters stranded on the Italian and French coasts and were successfully recovered and re-deployed. Taken into account that some drifters failed transmitting right after deployments and that others re-used, the 26 CODE drifters provided 34 individual trajectories in total.

The ARGOSPHERE drifters were deployed in the NC in front of Nice on October 10, 2007. In total, 7 units were deployed during an oil spill drift forecast demonstration, referred to as

MERSEA07 hereafter, carried out as part of the FP6 EC MERSEA project (*www.mersea.eu.org*). They were deployed by CEDRE (*www.cedre.fr*).

Both Argos and GPS position data were quality controlled. For the CODE drifters they were combined. The positions were then interpolated at 2-h uniform intervals using a "kriging" optimal interpolation method (Hansen and Poulain, 1996). They were subsequently low-pass filtered with a hamming filter with cut-off period at 36 hours, in order to eliminate tidal and inertial variability, and then subsampled every 6 hours. Velocities were then calculated as finite differences of the subsampled positions.

The drifters covered a relatively large area of the LPB (Fig. 1), and some units even escaped into the Tyrrhenian, Catalan and Algerian basins. Spatial coverage is maximal in the eastern Ligurian Sea north of Corsica, and in the NC between the Gulf of Genoa (GG) and the GL. Some drifters of MERSEA07 and MREA08 entered the GL, before continuing towards the Catalan Sea. Because of stranding and sea hazards, drifters were rather short-lived (mean half life of ~23 days) and, as a result, the temporal distribution of the data is very intermittent (Fig. 2, left panel). Temporarily, the LPB was sampled by the drifters during May 14 – October 30, 2007 (MREA07-LASIE07 and MERSEA07) and October 1, 2008 - January 14, 2009 (MREA08), amounting to a total of 3.5 drifter-years. The maximum data density occurred on June 23, 2007 with 12 drifters working simultaneously. If we examine the monthly distribution of the data, independently of the year (Fig. 2, right panel), it appears that no (few) data are available from February to April (in January and September), and that essentially the summer and fall conditions were sampled. Restricting the dataset to the NC area between the GG and GL, the daily distribution becomes even more intermittent and only the months between June and November have data.

The CODE drifter data used in this study were also used by Fabbroni (2009) to validate numerical simulations of the dispersion of surface tracers using relocatable nested models, by Vandenbulcke *et al.* (2009) to predict surface drifter with super-ensemble techniques and by Schroeder *et al.* (2011) to study relative dispersion in the LPB.

### *2.2 Wind products*

Cross-Calibrated, Multi-Platform (CCMP) ocean surface wind velocity products were downloaded from the NASA Physical Oceanography DAAC for the period of study (Atlas *et al.*, 2009). These products were created using a variational analysis method to combine wind measurements derived from several satellite scatterometers and micro-wave radiometers. Six-hourly gridded analyses with 25 km resolution were used (level 3.0, first-look version 1.1).

These wind products were utilized to assess the effect of the north-westerly winds prevailing (Mistral and Tramontane) in the LPB, and in particular in the GL, on the surface currents. The CCMP surface winds at one location (area of 25 km x 25 km, centred at 41°52.5'N and 5°52.5'E), representative of the open sea conditions southeast of the GL, were used to show that the LPB cyclonic surface circulation is short cut with a S-SEward current in front of the GL, in other words, that the surface water flowing in the NC is deviated offshore and closes the basin-wide cyclonic loop, during Mistral/Tramontane events. These wind data were sorted in the following categories (winds blowing from the entire north-western sector with speeds in excess of 5 m/s, considered in this paper as Mistral/Tramontane winds and referred to as "Mistral regime"; all winds with speeds less than 5 m/s or blowing from the other sectors, "Non-Mistral

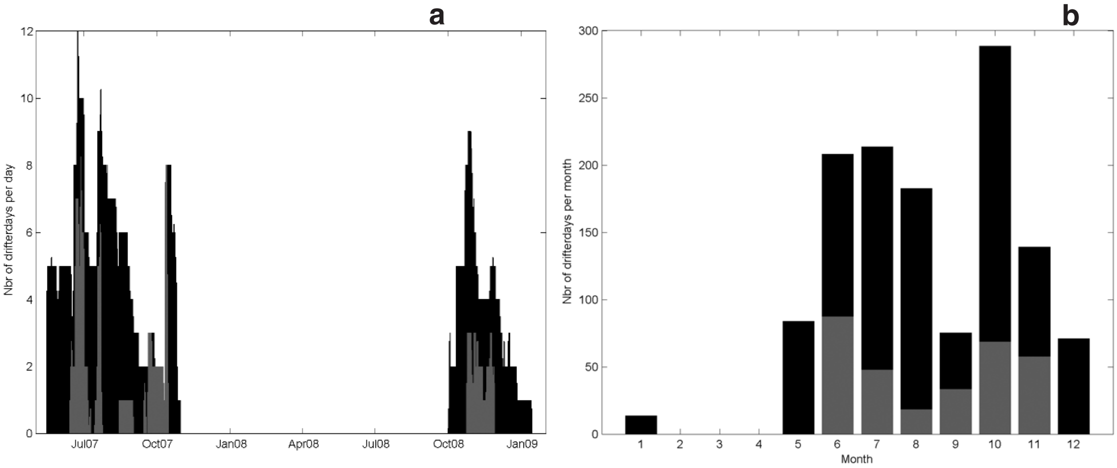

Fig. 2 - Temporal distribution of the drifter data in the LPB and GL: number of drifter-days per day (left panel) and per month (independently of the year; right panel). The embedded gray bars correspond to the area of the NC extending between the GG and GL (see dashed rectangle in Fig. 1).

regime”). These wind regimes are used in the next section, along with the drifter trajectories, to qualitatively show the influence of the Mistral or Tramontane when drifters are reaching the vicinity of the GL. The CCMP winds were also used to calculate the curl of the wind stress. Both winds and wind stresses were averaged over selected periods to produce maps with the mean wind field and the zero wind stress curl lines.

### *2.3 Satellite altimeter data*

Maps of the Mediterranean Absolute Dynamic Topography (MADT) produced by SSALTO/DUACS were obtained from the AVISO web site (*http://www.aviso.oceanobs.com*). They are updated gridded products (regular 1/8° grid on a weekly basis) merging the data of up to four satellites at a given time (Jason-2 / Jason-1 / Envisat from 2009 or between October 2002 and September 2005, the association Jason-1 / Topex/Poseidon / Envisat / GFO). The MADT was computed by adding a mean dynamic topography (MDT) to the sea level anomalies (SLA). The method applied to calculate the MDT was developed and described by Rio and Hernandez (2004) and has been specifically applied to the Mediterranean data by Rio *et al.* (2007).

### *2.4 Pseudo-Eulerian statistics*

Pseudo-Eulerian statistics of the surface velocity were computed in the area of the NC extending between the GG and GL where the data are more abundant (dashed rectangle in Fig. 1). First, the coordinate system was rotated around, and distances were computed from, a point located at 43°30’N, 7°30’E. The rotation is 40° anti-clockwise from the zonal direction in order to align the x-axis approximately parallel to the coast. Second, the low-pass filtered 6-hourly drifter velocities were averaged in non-overlapping bins of 5 km (y-axis or cross-shore direction) by 10 km (x-axis or along-shore direction). This anisotropy was adopted because cross-shore variations are expected to be more pronounced than those in the along-shore direction. The following quantities were computed within the bins: number of 6-hourly observations, mean flow, velocity variance ellipses, kinetic energies of the mean flow (MKE) and of the fluctuating currents (EKE). Definitions can be found in Poulain (2001). The statistics are only considered (and plotted) for the bins with at least 3 observations.

In selected coastal areas, such as the area of Imperia, Menton-Nice and Fréjus, the drifter velocities were averaged in 4 km by 30 km rectangles oriented in the along-shore direction (rotated anti-clockwise by 40° with respect to the zonal direction and with 50% overlapping in the cross-shore direction) to study the structure of the NC and its relation to bathymetry.

## 3. Qualitative description and wind effects

The first group of drifters deployed on May 14, 2007 (Fig. 3a) moved coherently to the SE for about 10 days and then spread apart with some units eventually approaching the Italian coast and joining the NC. Two drifters were advected offshore near longitude 7°E, veered to the SE towards Corsica and joined the WCC. One of these proceeded northward towards the GG and closed a basin-wide cyclonic loop in about 35 days. In contrast, the other unit moved eastwards north of Corsica and was trapped by an anticyclonic eddy located in the Corsica Channel. After completing a total of five loops, four around the Capraia Island and an extended one encircling the Elba Island as well, between late July and mid August 2007, this drifter finally escaped to the south in the Tyrrhenian Sea. The period of rotation in the anticyclone centered on Capraia Island is about 3 days.

The drifters deployed in June 2007 (two clusters released on June 17 and 22, 2007), see Table 1), remained in a tight group and moved northwards before reaching the Italian coastal areas and joining the NC (Figs. 3b and 3c). As a result, all 10 units sampled the NC. One drifter travelled in a first cyclonic loop located between 7° and 9°E (size of about 100 km and rotation period of 16 days) and then continued with the NC towards the GL (Fig. 3b). There it was driven offshore again, moved to the south, and then to the east to reach the south-western Corsican coast and joined the WCC. It continued with northward heading towards Genoa and entered the NC for the third time. This external loop in the LPB took about 2 months. A second drifter travelled approximately along the same path but stranded near the southern tip of Corsica. Another drifter re-circulated cyclonically from the NC to WCC but moved eastwards north of Corsica (Fig. 3b). The drifters deployed during the second episode (on June 22, 2007), except for some units stranding on the French coast, stayed together as far as the GL where they were driven offshore (Fig. 3c). Two drifters eventually came back with the WCC, one was caught by a coastal eddy north of Corsica, and then reached the Corsica Channel in the Capraia anticyclone mentioned above, the other moved northwards into the GG and joined the NC.

All the MERSEA07 drifters deployed on October 10, 2007 in the NC off Nice (Fig. 3d) were advected towards the west and into the GL. Two units subsequently escaped to the south in the open sea, whereas 4 drifters continued drifting in the NC and reached the Catalan Sea.

No basin-wide closed circulation was shown by the drifters released in 2008. Following the first two deployments (on October 1 and 10, 2008; Figs. 3e and 3f), the drifters essentially moved to the NE, turning anticyclonically into a southward current which extended into the Corsica Channel (Fig. 3e) and then some of them reached the NC. Those which arrived in the vicinity of

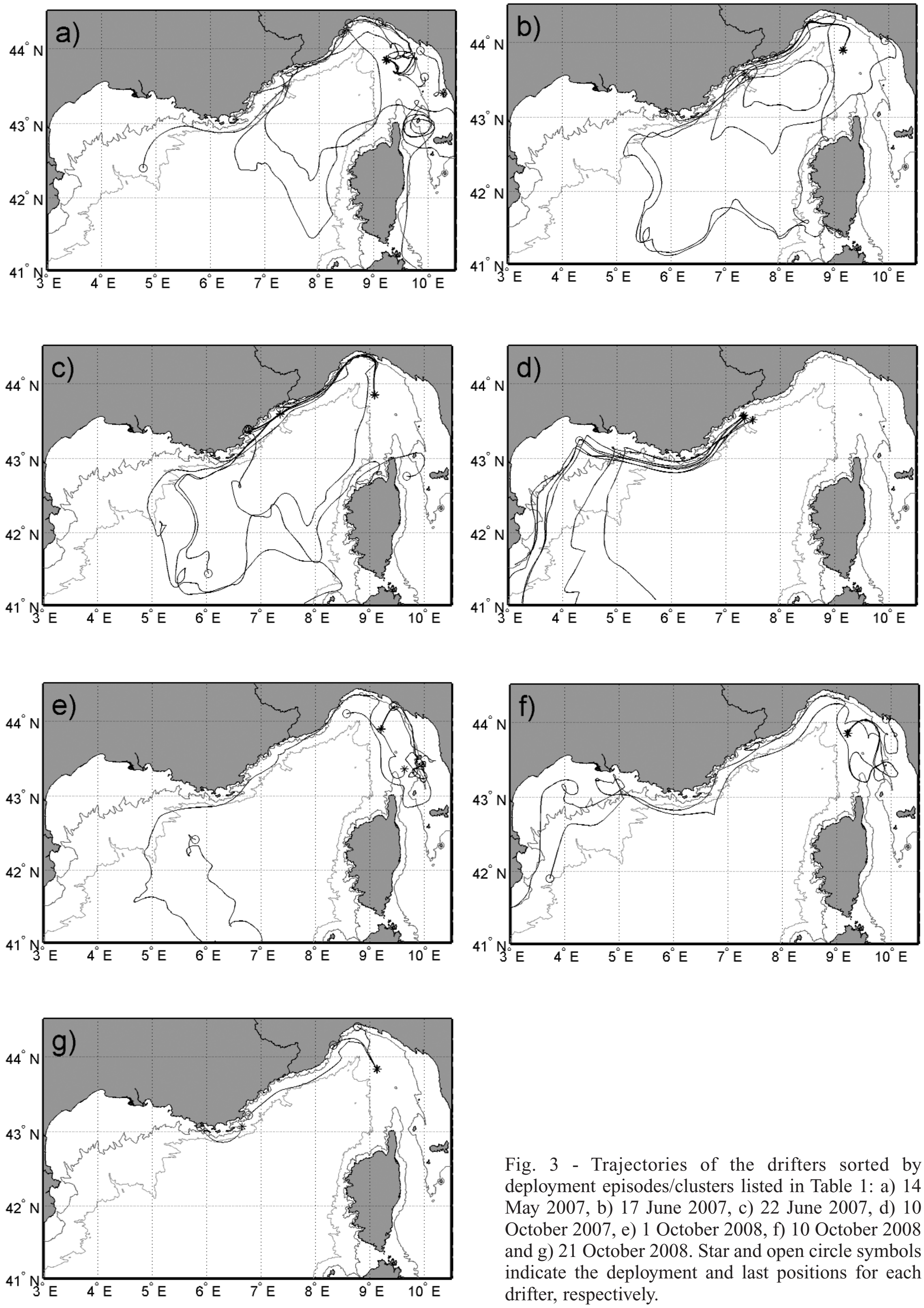

Fig. 3 - Trajectories of the drifters sorted by deployment episodes/clusters listed in Table 1: a) 14 May 2007, b) 17 June 2007, c) 22 June 2007, d) 10 October 2007, e) 1 October 2008, f) 10 October 2008 and g) 21 October 2008. Star and open circle symbols indicate the deployment and last positions for each drifter, respectively.

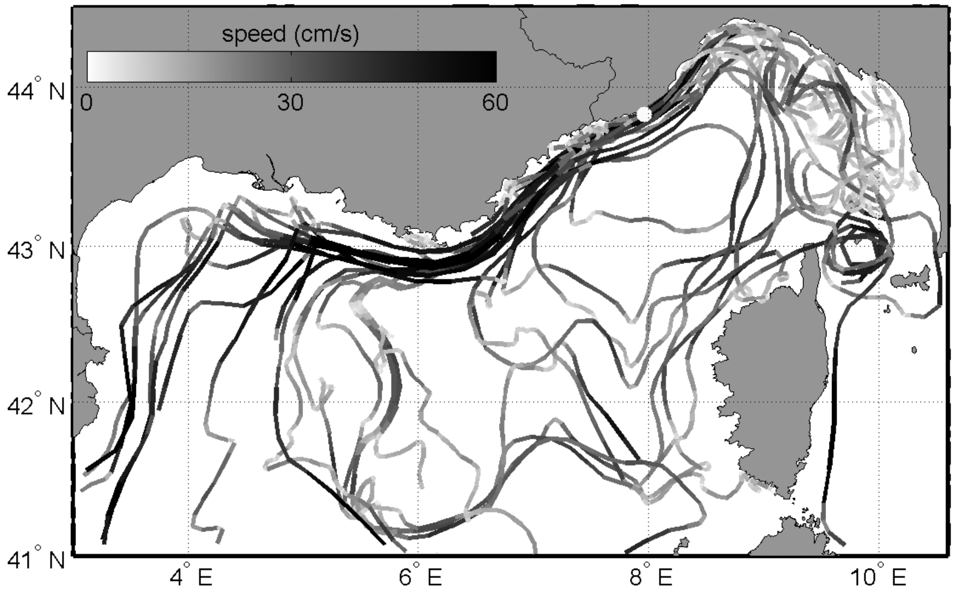

Fig. 4 - Segments of drifter trajectories sorted by drifter speed in the LPB and GL. The maximum sub-inertial speed of 90 cm/s occurred in the NC off the Italian coast (marked by a white dot).

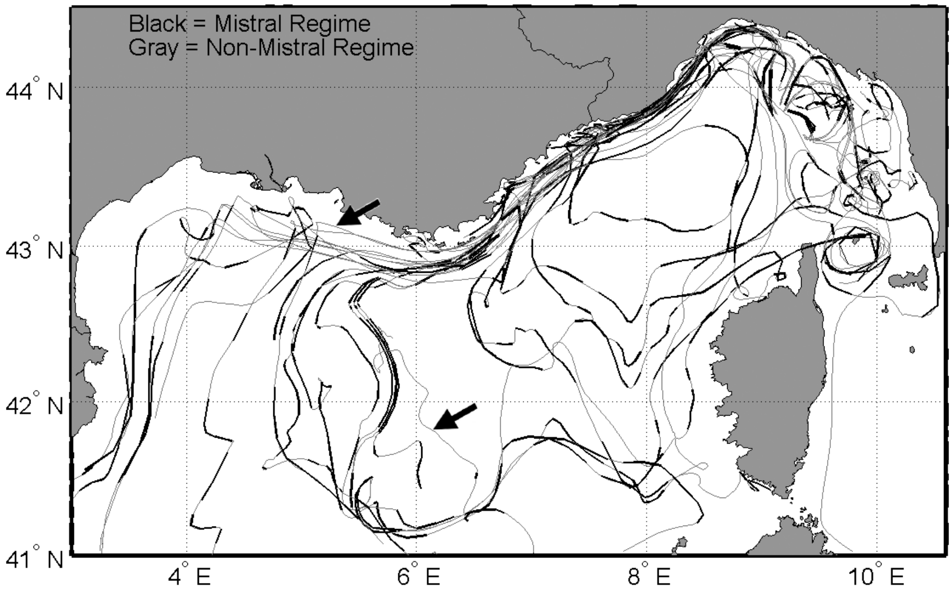

Fig. 5 - Segments of drifter trajectories sorted by wind regimes. Wind regimes are defined considering the CCMP winds at 41°52.5'N and 5°52.5'E and sorting them into two categories (Mistral regime: winds blowing from the entire north-western sector with speeds in excess of 5 m/s; non-Mistral regime: winds with speeds less than 5 m/s and blowing from the other sectors. Black arrows indicate north-westward drifter motion into and towards the GL when Mistral is not blowing.

the GL continued their westward motion, with some meandering and looping into the gulf, towards the Catalan Sea. One unit was advected again offshore in front of the gulf (near longitude 5°E, Fig. 3e) but made a U-turn near 6°30'E, 41°15'N, showing north-westward currents in late December 2008 and early January 2009 where all the other drifters (deployed in 2007) have shown south-eastward flow. The last drifters deployed on October 21, 2008 moved to the NW and one of them sampled the NC as far as the GL (Fig. 3g).

The surface speeds measured by the drifters are represented along the tracks in Fig. 4. Fast currents with speeds in excess of 50 cm/s are concentrated in the NC and in the anticyclone located in the Corsica Channel. The maximum sub-inertial speed of 90 cm/s occurred in the NC off the Italian coast (see white dot in Fig. 4). Speeds are also substantial in the WCC and in its extension into the NC, and in the GL. Slow drifter motions are dominant in the eastern part of the LPB north of the Corsica

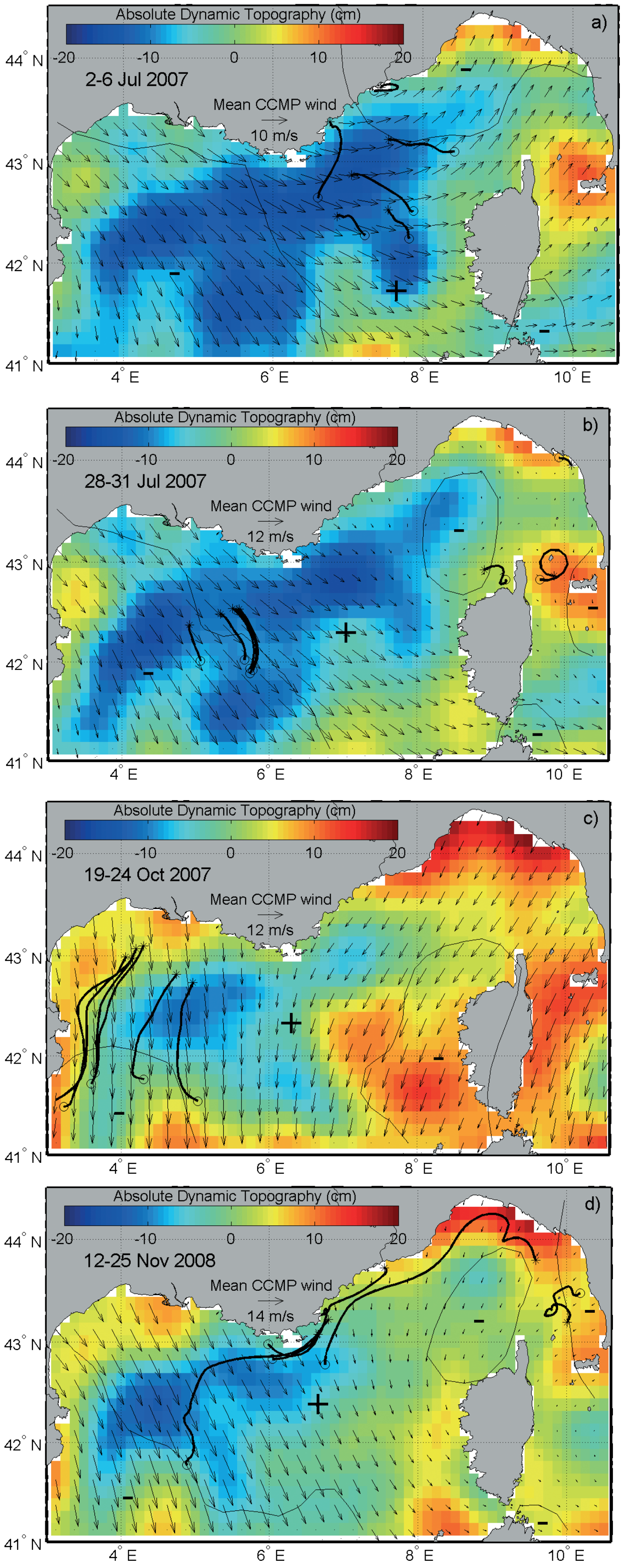

Fig. 6 - CCMP winds averaged over the periods of prevailing Mistral winds (arrows): a) 2-6 July 2007, b) 28-31 July 2007, c) 19-23 October 2007 and d) 12-25 November 2008, and 7-day mean absolute dynamic topography (cm) corresponding approximately to the same periods (color shading). The zero wind stress curl lines are also depicted, as well as segments of drifter trajectories corresponding to the time periods (star and open circle symbols indicate the first and last positions for each drifter, respectively). Plus and minus sign symbols correspond to areas of positive and negative wind stress curl, respectively.

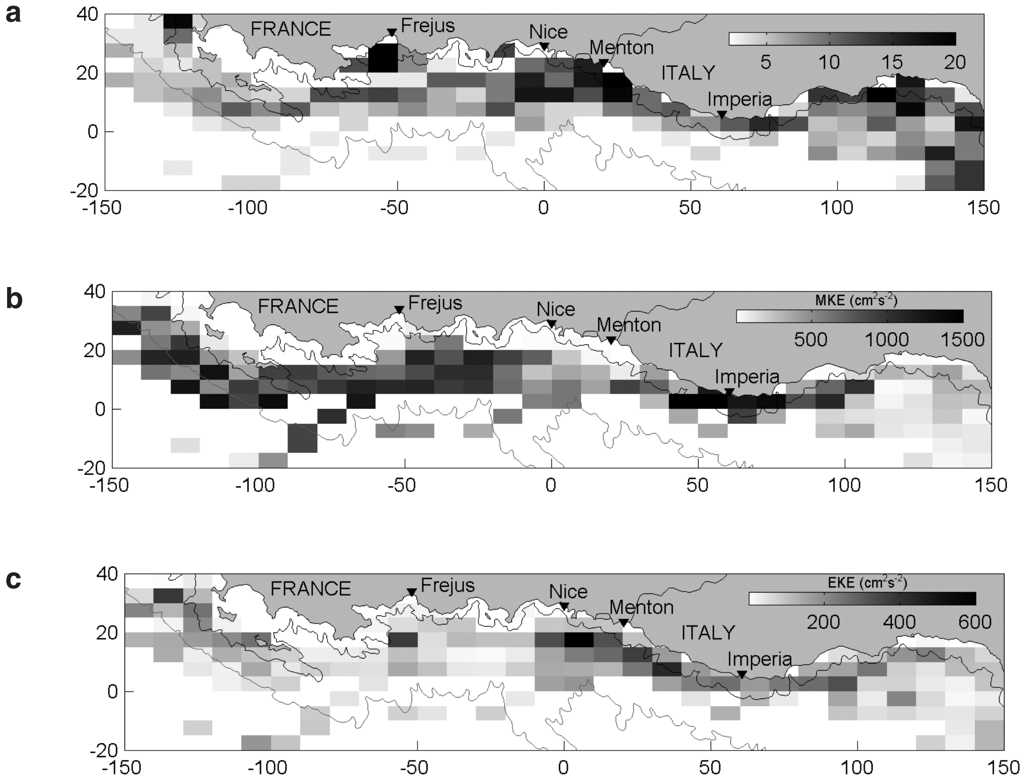

Fig. 7 - Pseudo-Eulerian statistics in the NC area extending between the GG and GL: a) number of 6-hourly observations in bins of 10 x 5 $km^2$ (gray tones); b) kinetic energy of the mean flow (MKE, $cm^2/s^2$) and c) kinetic energy of the fluctuating velocities (EKE, $cm^2/s^2$). Results in panels (b) and (c) are only shown for bins with at least 3 observations. The 200 m and 2200 m isobaths are shown with thin black and gray curves, respectively. Coordinates are in km.

Channel and in some very coastal areas off France and Corsica.

The surface drifter motions sorted into Mistral and non-Mistral wind regimes are depicted in Fig. 5. It can be seen that the re-circulation or short-cutting of the basin-wide surface cyclonic circulation essentially appears between Corsica and France, and in front of the GL, only if the Mistral/Tramontane winds are blowing. In contrast, the intrusion of drifters onto the GL shelf and the north-westward motion of one unit off the GL (see areas indicated by black arrows in Fig. 5) occurred under non-Mistral wind regime. The surface currents in the eastern Ligurian Sea and in the NC appear less directly influenced by the winds.

All the Mistral/Tramontane events concomitant with drifters approaching the GL were studied in detail. In total, four such events were found during the following periods: July 2-6, 2007, July 28-31, 2007, October 19-23, 2007 and November 12-25, 2008 (Fig. 6). In all cases, the mean Mistral wind exceeds 10 m/s and the mean wind stress curl changes sign along a line approximately oriented in the NW-SW direction and crossing the GL in its central area, with positive (negative) curl to the east (west) of it. Contemporarily, the drifters move offshore to the south and SE in the vicinity of the GL

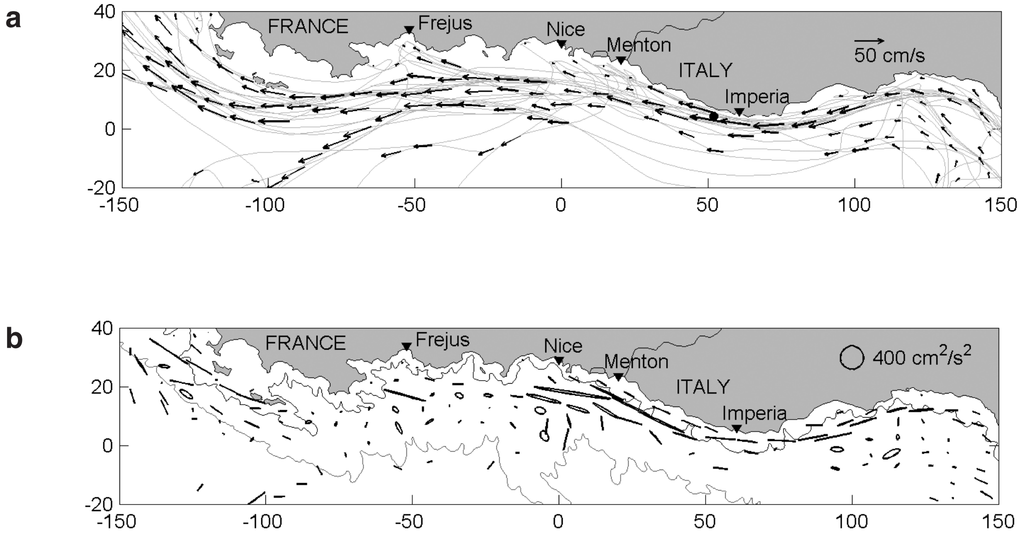

Fig. 8 - Mean circulation (a) and velocity variance ellipses (b) in the NC area extending between the GG and GL. Drifter velocities were averaged in bins of 10 x 5 $km^2$ containing at least 3 observations. The drifter trajectories are overlaid in light gray on the mean circulation map, whereas the 200 m and 2200 m isobaths are drawn with thin black and gray curves, respectively, in the variance map. Coordinates are in km. The location of the maximum speed is indicated by a black dot near Imperia in the circulation map.

(or more to the east in the Ligurian Sea), hence short-cutting the LPB basin-wide cyclonic circulation. For three events (July 28-31, 2007, October 19-23, 2007 and November 12-25, 2008; Figs. 6b to 6d) the offshore turning is approximately co-located with the zero wind stress curl curve. Whereas during July 2-6, 2007, the turning appears to the east of this curve in an area characterized by positive wind stress curl (Fig. 6a). In all cases, most drifter motions disagree substantially with the surface geostrophic currents obtained from the absolute dynamic surface topography measured by satellite altimeters. Indeed, they cross the basin-wide topographic depression (as strong as -20 cm) corresponding to the LPB cyclonic geostrophic circulation.

## 4. Pseudo-Eulerian statistics in the NC

The geographical area of the NC between the GG and GL was sampled by several drifters in June-October 2007 and October-November 2008 (see Fig. 2). If the drifter data are considered in bins of 10 km (along-shore direction) by 5 km (across-shore direction), the data density, i.e., the number of drifter 6-hourly observations, can be as large as 20-30 in local coastal areas such as near Menton-Nice and Fréjus (Fig. 7a). In contrast, the density remains low in areas where the currents are swift and the drifters move fast in and out of the bins. As a practical rule, we consider only the bins with at least 3 drifter observations to compute the velocity statistics. Note that the number of independent drifter observations might be less than the values depicted in Fig. 7a since observations separated by small temporal (e.g., 6 hours) and spatial distances can be correlated. Given the general small number of drifter observations in the bins, some of the statistical results presented below should be interpreted with caution.

The averaging in bins allows to separate the kinetic energy of the surface currents into two components, the energy of the mean flow (MKE) and the energy of the fluctuations (EKE). The MKE (Fig. 7b) is large in the NC west of about x = 100 km, all the way to the GL. It is maximum (~1600 $cm^2/s^2$) close to the coast near Imperia. Off France, the large MKE appears a little more offshore, more or less centered on the continental slope. Small values of MKE occur in the eastern area (near Genoa, x > 100 km) and in the coastal areas off Menton-Nice and Fréjus, all these areas being characterized by more abundant data (Fig. 7a). The EKE (Fig. 7c) is large in the area off Menton-Nice with values approaching (~700 $cm^2/s^2$) where it can even exceed the MKE (mostly inshore of the main NC core where recirculation can occur). It is also significant east of Menton in a narrow coastal (~10 km wide) band extending almost to Genoa.

In the eastern region of the domain where the NC originates, mean currents (Fig. 8a) are towards the coast and then westwards, and have amplitude varying in 7-21 cm/s. Following the flow towards the west, the NC is seen to strengthen in a coastal strip (< 10-20 km from shore) in water depth less than 200 m. The bin-averaged speed is maximal (~60 cm/s) in front of Imperia, that is in the same area where the maximum 6-hourly speed was found (Fig. 4). Upon reaching France off Menton-Nice, the NC decelerates and widens, in correspondence with the general broadening of the continental shelf and slope. Further downstream, the mean currents of the two branches, one entering the GL and the other proceeding offshore can be as large as 50 cm/s. Reduced or practically no mean flow characterizes the local coastal waters near Menton-Nice and Fréjus, inshore of the NC.

Velocity variance ellipses (Fig. 8b) confirm the dominance of the variability near the Italian coast (more or less inshore of the 200 m isobath) and the more extended EKE maximum off Menton and Nice. The large eccentricity of the ellipses indicates that the fluctuating currents are essentially polarized and oriented parallel to the coast. There is a slight trace of cross-shore variability off Menton-Nice where the ellipses are less elongated and which might correspond to the meandering of the NC.

If the along-shore velocities are considered and averaged in elongated bins parallel to the coast (size of 4 km by 30 km and overlapping by 50%) in selected areas such as 30 km-wide regions off Imperia, Menton-Nice and Fréjus (Fig. 9), the following results are obtained. 1) The NC off Imperia (Fig. 9a) is limited within 20-30 km from shore above the continental slope. Its core with maximal (individual near 90 cm/s and averaged near 50 cm/s) and highly variable speeds is located between the coast and about 10 km offshore, in water depths less than 200 m. 2) Further to the west (Figs. 9b and 9c), the continental slope is less abrupt and the NC widens, weakens (average speeds less than 50 cm/s) and moves offshore between 15 and 35 km from the coast. In front of Menton-Nice (Fig. 9b), the currents are highly variable between 10 and 20 km from the coast, whereas off Fréjus (Fig. 9c) the currents are weak (averaged speed less than 10 cm/s) from the coast to about 10 km offshore.

## 5. Discussion and conclusions

Satellite-tracked drifters were used to study some aspects of the surface circulation in the LPB and GL between May 2007 and January 2009. The drifters revealed a complex circulation in the

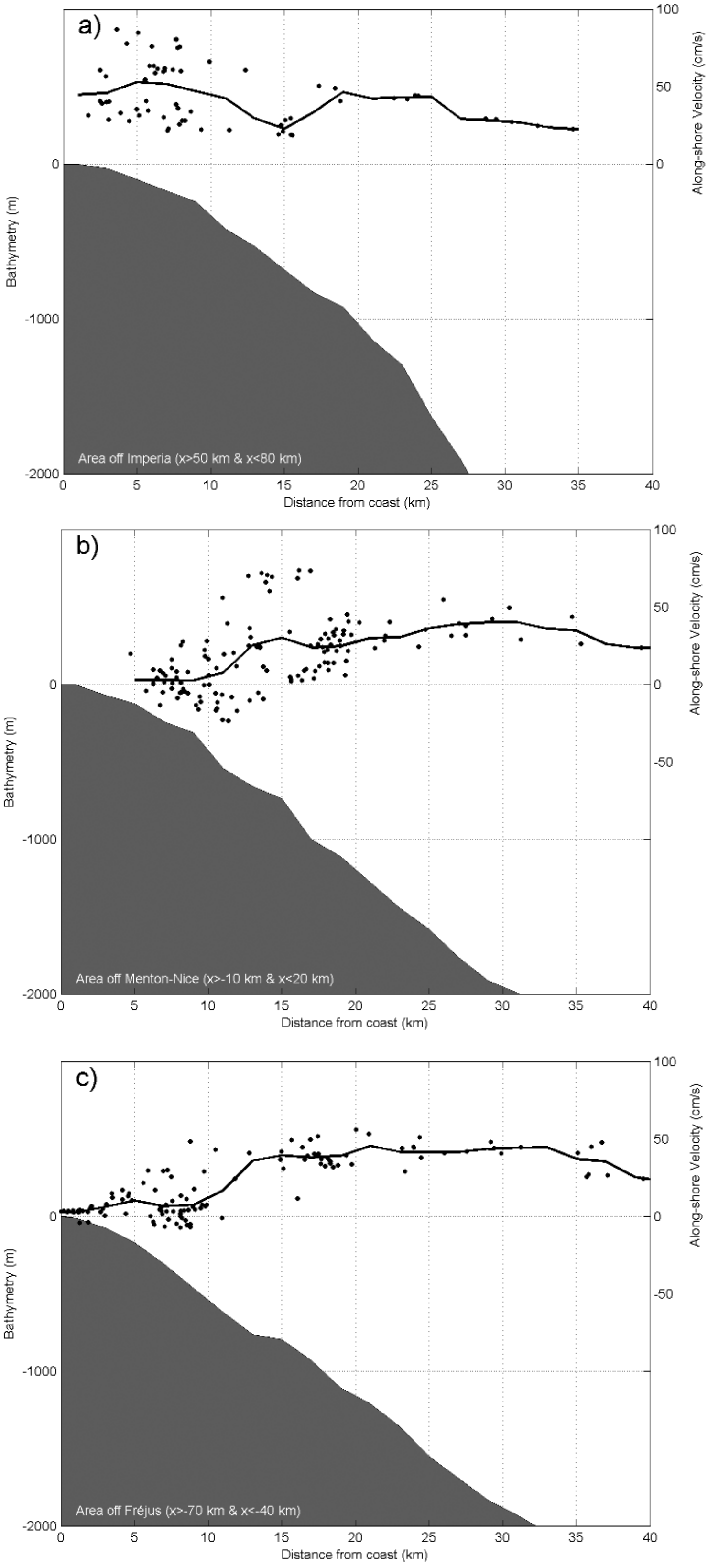

Fig. 9 - Along-shore velocities off Imperia (a), Menton-Nice (b) and Fréjus (c) as a function of distance from the coast. Individual velocities in a 30-km wide band are shown by dots, whereas the bin-averaged (in 30 km by 4 km) are depicted with a solid curve. Bathymetry is shown with gray shading.

eastern Ligurian Sea north of Corsica and a very weak signature of the ECC (Fig. 4). Instead, the transport through the Corsica Channel appears to be limited due to the prevalence of an anticyclonic eddy in summer 2007. The reduced connection between the Tyrrhenian and Ligurian seas in summer is in agreement with the results of Astraldi *et al.* (1990), Astraldi and Gasparini (1992), and the simulations of Pinardi and Masetti (2000). In contrast, the WCC is well delineated by the drifters with northward surface currents reaching 50 cm/s (Fig. 4). Most of the drifters deployed in the Ligurian Sea eventually ended up in the NC, a strong SW-ward coastal current forming in the GG and extending as far west as the GL. Surface speeds in the NC can be as large as 90 cm/s, especially off Imperia where the NC core is narrow and located less than 10 km from the coast (Figs. 4, 8a and 9). Further to the west, in front of Menton-Nice, the NC is slightly weaker (speeds ≤ 50 cm/s) and broader (extending between 15 and 35 km from the coast; Fig. 9). The currents inshore of the NC are highly variable. These results are compatible with those of Béthoux *et al.* (1988) and Sammari *et al.* (1995). Off Fréjus, the NC is still mainly located between 15 and 35 km from shore, but the inshore area is characterized by sluggish currents (resulting in a stagnation area where some drifters ultimately stranded or were picked up).

Upon reaching the GL, some drifters (the LASIE07-MREA07 units, see Figs. 3a, 3b and 3c) moved offshore to the south-SE and proceeded towards Corsica. They joined the WCC and closed a basin-wide cyclonic gyre in the LPB. It was shown that the recirculation or the offshore currents at the level of the GL mainly occured during Mistral/Tramontane events (Figs. 5 and 6). In contrast, if these winds are not prevailing, the drifters continued moving towards the SW on the continental slope and eventually entered the GL before proceeding in the direction of the Catalan Sea (see the MERSEA07 and MREA08 drifters in Figs. 3d and 3f).

We therefore conclude that the Mistral/Tramontane winds are mainly responsible for the closing of the LPB surface cyclonic gyre between longitudes 5-6°E and for the formation of smaller sub-gyres such as the Ligurian-wide gyre of Figs. 3a, 3b and 3c. This recirculation was already noted by Ovchinnikov (1966) using hydrographic data and by Pinardi and Navarra (1993) and Molcard *et al.* (2002) in wind driven numerical simulations of the Mediterranean Sea. The existence of a large-scale cyclonic circulation encompassing all the LPB, the area off the GL and the Catalan Sea as shown in the historical (Crépon *et al.*, 1982) and satellite altimeter (Pujol, 2006) maps is therefore not verified by the drifters. It is noticeable that the Mistral/Tramontane wind stress curl has its zero crossing line in (or in the vicinity of) the GL (Molcard *et al.*, 2002; Fig. 7) and this might induce the early closing of the LPB wide circulation into a smaller gyre. The position of the offshore turning of the sub-gyre often corresponds to the location of the Rhone Fan (Figs. 3a, 3b and 3c), a very important bathymetric structure developed from the centre of the GL shelf to the deep sea (Madec *et al.,* 1991). This bottom structure helps to form a stable cyclonic circulation eastwards of the fan that could produce the offshore turning of the drifters, in addition to the wind forcing. This coincidence should be better explored in the future process models of the LPB basin scale circulation.

Despite the fact that the drifters provided mostly observations in summer/fall 2007 and fall 2008, seasonal variations can be seen in their trajectories in good agreement with the results of Astraldi *et al.* (1994). Indeed, in summer (Fig. 3a, 3b and 3c), the circulation is more fragmented and often shows closed recirculation structures in the LPB. In contrast during fall (Figs. 3d, 3e, 3f and 3g), the drifters showed a more coherent and extended cyclonic circulation, eventually expanding into the Catalan Sea. This is somehow contradicting the conclusions of Millot and Wald (1980) favouring extension in the Catalan Sea in summer.

Pseudo-Eulerian statistics (Figs. 7 and 8) focused on the coastal area between the GG and GL, quantified some of the characteristics of the NC mentioned above. In particular, fast currents and maximal MKE (~1600 $cm^2/s^2$) occur off Imperia, whereas small mean currents prevail off Menton-Nice and Fréjus. The latter areas are also characterized by a high density of observations, and high probability of stranding and pick up near Fréjus, indicating that drifters deployed offshore do enter them. The EKE and velocity variance ellipses are large along the coast between Imperia and Nice (maximum ~700 $cm^2/s^2$). The ellipses are mainly oriented along the coast. They correspond to variations at temporal scales ranging between a few days to a few months and exclude seasonal variability.

The aspects of the surface circulation in the LPB and GL described in this paper will be addressed more quantitatively in a subsequent work including all the historical drifter dataset available in the north-western Mediterranean Sea. In particular, the components of the surface circulation directly driven by the winds will be analyzed in detail and compared to the geostrophic surface currents estimated from satellite altimeters and the drifters themselves.

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