Surface circulation in the Liguro-Provençal basin as measured by satellite-tracked drifters (2007-2009)

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Abstract

The surface circulation in the Liguro-Provençal basin (Northwestern Mediterranean) is studied using satellite-tracked drifters in 2007-2009. Complex circulation patterns prevailed in the eastern Ligurian Sea, before the drifters eventually joined the Northern Current (NC) in the coastal area off Genoa. Between 5°E and 7°E30’, most drifters 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 Mistral events. 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 Lyons. Fast currents are evident on the shelf break, especially off Imperia (maximum of 90 cm/s) where the bathymetric slope is larger and the NC is closer to shore and narrower. In contrast, 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.

Keywords:

Surface Circulation; Drifters; Coastal Currents; Northwestern Mediterranean

1. Introduction

The Liguro-Provençal basin (LPB) is located in the northwestern Mediterranean Sea (41-45°N, 5-10E°; Fig. 1) off the coasts of Italy and France. The LPB is connected to the east to the Tyrrhenian Sea through the Corsica Channel, whereas to the west, it confines with the Gulf of Lyons. 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. The first, called by Pinardi et al. (2006) the Eastern Corsican Current (ECC), 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 and Gasparini, 1992; Astraldi et al., 1990), as well as by the wind stress curl as shown by Pinardi and Masetti (2000). These authors showed that the Corsica transport weakens dramatically in absence of wind forcing and in particular the transport can reverse in the summer season. 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 Mistral wind regime (Pinardi and Navarra, 1993, 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 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). 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 Gulf of Lyons was qualitatively established by Millot and Wald (1980) using satellite thermal imagery and explained quantitatively by the modeling results. During Mistral wind events the surface flow associated with the NC veers offshore when reaching the Gulf of Lyons, 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 westward along the coast towards the Catalan Basin (Millot and Wald, 1980).

Mesoscale variability is ubiquitous and dominant in most parts of the LPB and in particular in the NC (Taupier-Letage and Millot, 1986, Echevin et al., 2003, Sammari et al., 1995). 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 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. Collocated 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 are noticeable in all the drifter trajectories. After a complex pathway, one drifter eventually joined the NC and moved westward along the French coast. Drifter 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://poseidon.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 the surface circulation in the LPB (and the Gulf of Lyons) using the data of Lagrangian drifters purposefully deployed in the LPB to measure the surface water general circulation and dispersion. 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. After a brief description of the data and methods (section 2), a qualitative description of the LPB based on the drifter trajectories is proposed (section 3). The influence of the Mistral wind forcing is also addressed, and in particular, its role in closing the LPB surface cyclonic circulation southeast of the Gulf of Lyons. The more abundant drifter data in the NC allows 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, 1991; Ursella et al., 2006) and the Gulf of La Spezia (Molcard et al., 2009; Haza et al., 2010).

CODE drifters were developed by Davis (1985) in the early 1980's to measure the currents in the first meter under the sea surface. The CODE drifters used in this study were manufactured by Technocean (model Argodrifter). 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 provide buoyancy (Poulain, 1999). Direct slip measurements (P.-M. Poulain, Personal Communication) with acoustic currentmeters showed that the Technocean CODE drifters follow the surface currents within 2 cm/s. In addition to the standard satellite Argos tracking and telemetry, the drifters were equipped with Global Positioning System (GPS) receivers. The Doppler-based Argos tracking has an accuracy of 300-1000 m and positions are typically available 6-12 times per day. GPS locations have a higher accuracy (~10 m; Barbanti et al., 2005) and are sampled more frequently (every hour). All the drifter data (GPS positions, sea surface temperature, battery voltage) were transmitted to the Argos satellite system.

The 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°E10.2', 43°N47.4'; see

Fig. 1). Deployments were carried out in May 2007 and June 2007 as part of the MREA-07 and LASIE-07 (Ligurian Air-Sea Interaction Experiment) experiments (Teixeira, 2007; Fabbroni, 2009). In 2008, the deployments were repeated three times during the MREA-08 sea trial. Deployment details are listed in Table 1. Some drifters stranded on the Italian and French coasts and were successfully redeployed. Taken into account that some drifters failed transmitting right after deployments and that others were recovered and redeployed, the 26 CODE drifters used provided 34 individual trajectories in total.

Both Argos and GPS data were quality controlled, combined and interpolated at 2-h uniform intervals using a “kriging” optimal interpolation method based on a structure function whose characteristics were calculated from the data themselves (Hansen and Poulain, 1996). They were subsequently low-passed 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 Genoa and the Gulf of Lyons. Some drifters entered the Gulf of Lyons in 2008, before continuing towards the Catalan Sea. Because of stranding and sea hazards, drifters were rather short-lived (mean half life of 20.5 days) and, as a result, the temporal distribution of the data is very intermittent (Fig. 2, top panel). Temporarily, the LPB was sampled by the drifters during 14 May - 19 October 2007 (MREA07-LASIE07) and 1 October 2008 - 23 January 2009 (MREA08). The maximum data density occurred on 23 June

2007 with 12 drifters working simultaneously. If we examine the monthly distribution of the data, independently of the year (Fig. 2, bottom 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 Gulf of Genoa and the Gulf of Lyons, the daily distribution becomes even more intermittent and only the months between June and November have data.

The 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. (2010) 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 northwesterly Mistral winds prevailing in most of the northwestern Mediterranean, and in particular in the Gulf of Lyons, on the surface currents. In order to confirm that the LPB cyclonic surface circulation is short cut with a south-southeastward current in front of the Gulf of Lyons, in other words, that the surface water flowing in the NC is deviated offshore and closes the basin-wide cyclonic loop during Mistral events, the CCMP surface winds at one location southeast of the Gulf of Lyons (41°N52.5' and 5°E52.5') were used. These wind data were sorted in the following categories (winds blowing from the entire northwestern sector with speeds in excess of 5 m/s, considered in this paper as Mistral; all winds with speeds less than 5 m/s or blowing from the other sectors). These wind regimes are used in the next section, along with the drifter trajectories, to qualitatively show the influence of the Mistral when drifters are reaching the vicinity of the Gulf of Lyons.

The CCMP winds were also used to calculate the curl of the pseudo wind stress. Both winds and pseudo wind stresses were averaged over selected periods to produce maps with the mean wind field and the zero wind stress curl lines.

2.3 Pseudo-Eulerian statistics

Pseudo-Eulerian statistics of the surface velocity were computed in the area of the NC extending between the Gulf of Genoa and the Gulf of Lyons 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°N30', 7°E30'. 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 in May 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 southeast towards Corsica and joined the WCC. One of these proceeded northward towards the Gulf of Genoa and closed a basin-wide cyclonic loop in about 35 days. In contrast, the other unit moved eastward north of Corsica and was trapped by a strong 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 is about 3 days.

The drifters deployed in June 2007 (two clusters separated by 5 days, see Table 1), remained in a tight group and moved northward before reaching the Italian coastal areas and joining the NC (Fig. 3b,c). 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 Gulf of Lyons (Fig. 3b). There it was driven offshore again, moved to the south, and then to the east to reach the southwestern 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 eastward north of Corsica (Fig. 3b). The drifters deployed during the second episode (on 22 June 2007), except for some units stranding on the French coast, stayed together as far as the Gulf of Lyons where they were driven offshore (Fig. 3c). One unit eventually came back with the WCC, was caught by a coastal eddy north of Corsica, and then reached the Corsica Channel in the Capraia anticyclone mentioned above.

No basin-wide closed circulation was shown by the drifters released in 2008. Following the first two deployments (Fig. 3d,e), the drifters essentially moved to the northeast, turning anticyclonically into a southward current which extended into the Corsica Channel (Fig. 3d) and then almost reached the NC. Those which arrived in the vicinity of the Gulf of Lyons 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. 3d) but made a U-turn near 6°E30’, 41°N15’, showing northwestward currents in late December 2008 and early January 2009 where all the other drifters (deployed in 2007) have shown southeastward flow. The last drifters deployed in late October 2008 moved to the northwest and one of them sampled the NC as far as the Gulf of Lyons (Fig. 3f).

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 the anticyclone located in the Corsica Channel. The maximum sub-inertial speed of 90 cm/s occurred in the NC off the Italian coast. Speeds are also substantial in the WCC and its extension into the NC, and in the Gulf of Lyons. Slow drifter motions are dominant in the eastern part of the LPB north of the Corsica 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 cyclonic circulation essentially appears between Corsica and France, and in front of the Gulf of Lyons, only if the Mistral winds are blowing. In contrast, the intrusion of two drifters onto the Gulf of Lyons shelf and the northwestward motion of one unit off the Gulf of Lyons (see black arrows in Fig. 5) occurred in 2008 under non-Mistral wind conditions. The surface currents in the eastern Ligurian Sea and in the NC appear less directly influenced by the winds.

All the Mistral events concomitant with drifters approaching the Gulf of Lyons were studied in detail. In total, three such events were found for the following periods: 2-6 July 2007, 28-31 July 2007 and 12-25 November 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 northwest-southwest direction and crossing the Gulf of Lyons in its central area, with positive (negative) curl to the east (west) of it. Contemporarily, the drifters move offshore to the south and southeast in the vicinity of the Gulf of Lyons (or more to the east in the Ligurian Sea), hence short-cutting the

LPB basin-wide cyclonic circulation. For two events (28-31 July 2007 and 12-25 November 2008; Fig. 6b,c) the offshore turning is approximately collocated with the zero wind stress curl curve. Whereas during 2-6 July 2007, the turning appears to the east of this curve in an area characterized by positive wind stress curl (Fig. 6a).

4. Pseudo-Eulerian statistics in the NC

The geographical area of the NC between the Gulf of Genoa and the Gulf of Lyons 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. 7). 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. 7 since observations separated by small temporal (e.g., 6 h) and spatial distances can be correlated.

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. 8) is large in the NC west of about x = 100 km, all the way to the Gulf of Lyons. It is maximum (~1800 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. 7). The EKE (Fig. 9) is large in the area off Menton-Nice with values approaching (~700 cm^2/s^2). 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. 10) are towards the coast and then westward, 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 Gulf of Lyons and the other proceeding offshore can be as large as 50 cm/s. Reduced or practically no mean flow characterize the local coastal waters near Menton-Nice and Fréjus, inshore of the NC.

Velocity variance ellipses (Fig. 11) confirms the dominance of the variability near the Italian coast (more or less inshore of the 200 m isobath) and the more extended maximum off Menton and Nice. The large eccentricity of the ellipses indicate 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.

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. 12), the following results are obtained: 1) The NC off Imperia (Fig. 12a) 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 (Fig. 12b,c), 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. 12b) the currents are higly variable between 10 and 20 km from the coast, whereas off Fréjus (Fig. 12c) 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 the surface circulation in the LPB between May 2007 and January 2009. The drifters revealed a complex circulation in the 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 and Gasparini (1992), Astraldi et al. (1990) 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 southwestward coastal current forming in the Gulf of Genoa and extending as far west as the Gulf of Lyons. 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, 10 and 12). 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. 12). 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 Gulf of Lyons, some drifters (those deployed in 2007, see Fig. 3a,b,c) moved offshore to the south-southeast 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 Gulf of Lyons mainly occur during Mistral events (Figs. 5 and 6). In contrast, if the Mistral is not prevailing, the drifters continued moving towards the southwest on the continental slope and eventually entered the Gulf of Lyons before proceeding in the direction of the Catalan Sea (see the drifters deployed in 2008 in Fig. 3d,e,f).

We therefore conclude that the Mistral winds are mainly responsible for the closing of the LPB cyclonic gyre between longitudes 5-6°E and for the formation of smaller sub-gyres such as the Ligurian-wide gyre of Fig. 3b. This recirculation was already noted by Ovchinnikov (1966) using hydrographic data, 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 Gulf of Lyons and the Catalan Sea as shown in the historical (Crépon and al., 1982) and satellite altimeter (Pujol, 2006) maps is therefore not verified by the drifters. It is noticeable that the Mistral wind stress curl has its zero crossing line around 5-6^{o} E (Molcard et al., 2002; Fig. 7b,c) and this might induce the early closing of the LPB wide circulation into a smaller gyre, as mapped in Figs. 3b and 6a. The position of the offshore turning of the sub-gyre is also about at the location of the Rhone Fan, a very important bathymetric structure developed from the centre of the Gulf of Lyons shelf to deep ocean (Madec et al., 1991). This bottom structure helps to form a stable cyclonic circulation eastward of the fan and that could produce the offshore turning of the drifters. This coincidence should be better explored in the future process models of the LPB basin scale circulation.

Pseudo-Eulerian statistics (Figs. 7 to 11) focused on the area coastal area between the Gulf of Genoa and Gulf of Lyons, quantified some of the characteristics of the NC mentioned above. In particular, fast currents and maximal MKE (~1800 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.

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References

Astraldi, M., Gasparini, G.P., Manzella, G. and Hopkins, T.S., 1990. Temporal variability of currents in the Eastern Ligurian Sea. Journal of Geophysical Research, 95 (C2), 1515-1522.

Astraldi, M. and Gasparini, G. P., 1992. The seasonal characteristics of the circulation in the North Mediterranean basin and their relationship with the atmospheric climatic conditions. Journal of Geophysical Research, 97 (C6), 9531-9540.

Atlas, R., Ardizzone, J.V., Hoffman, R., Jusem, J.C. and Leidner, S.M., 2009. Cross-calibrated, multi-platform ocean surface wind velocity product (MEaSUREs Project). Guide Document. Physical Oceanography Distributed Active Archive Center (PO.DAAC). JPL, Pasadena, California, 18 May 2009, Version 1.0., 26p.

Barbanti, R., Iungwirth, R. and Poulain, P.-M., 2005. Stima dell'accuratezza del drifter tipo CODE con GPS nella determinazione della posizione geografica, Rel. 32/2005/OGA/20, OGS, Trieste, Italy.

Béthoux, J.-P., Prieur, L. and Bong, J.-H., 1988. Le courant Ligure au large de Nice. Oceanologica Acta (n°spécial), 59-67.

Birol, F., Cancet, M. and Estournel, C., 2010. Aspects of the seasonal variability of the Northern Current (NW Mediterranean Sea) observed by altimetry. Journal of Marine Systems. Submitted.

Crépon, M., Wald, L. and Monget, J.-M., 1982. Low-frequency waves in the Ligurian Sea during December 1977. Journal of Geophysical Research, 87 (C1), 595-600.

Crépon, M. and Boukthir, M., 1987. Effect of deep water formation on the circulation of the Ligurian Sea. Annales Geophysicae, 5B (1) 43-48.

Davis, R. E., 1985. Drifter observation of coastal currents during CODE. The method and descriptive view. Journal of Geophysical Research, 90, 4741-4655.

Echevin, V., Crépon, M., and Mortier, L., 2003. Simulation and analysis of the mesoscale circulation in the northwestern Mediterranean Sea. Annales Geophysicae, 21: 281-297.

Fabbroni, N. 2009. Numerical simulations of passive tracers dispersion in the Sea. Ph.D. Thesis, University of Bologna. 164p.

Hansen, D.V., and Poulain, P.-M., 1996. Processing of WOCE/TOGA drifter data, Journal of Atmospheric and Oceanic Technology, 13, 900-909.

Haza, A.C., Ozgokmen, T.M., Griffa, A., Molcard, A., Poulain, P.-M. and Peggion, G., 2010. Transport properties in small scale flows: relative dispersion from VHF radar measurements in the Gulf of La Spezia. Ocean Dynamics. Submitted.

Herbaut, C., Mortier, L. and Crépon, M., 1997. A sensitivity study of the general circulation of the western Mediterranean. Part II: the response to atmospheric forcing. Journal of physical Oceanography 27, 2126–2145.

Madec, G., Chartier, M. and Crépon, M., 1991. The effect of thermohaline forcing variability on deep water formation in the western Mediterranean Sea: a high-resolution three-dimensional numerical study. Dynamics of the Atmosphere and Oceans, 301-332.

MEDOC Group, 1970. Observation of formation of deep water in the Mediterranean, Nature, 227, 1037-1040.

Millot, C., 1987. The structure of mesoscale phenomena in the Ligurian Sea inferred from the DYOME esperiment. Annales Geophysicae, 5B (1), 21-30.

Millot, C., 1991. Mesoscale and seasonal variabilities of the circulation in the western Mediterranean. Dynamics of Atmospheres and Oceans, 15 (3-5), 179-214.

Millot, C. and Wald, L., 1980. The effect of Mistral wind on the Ligurian current near Provence. Oceanologica Acta, 3 (4), 399-402.

Molcard, A., Pinardi, N., Iskandarami, M., Haidvogel, D.B., 2002. Wind driven general circulation of the Mediterranean Sea simulated with a Spectral Element Ocean Model. Dynamics of Atmosphere and Oceans, 17, pp. 687-700.

Molcard, A., Poulain, P.-M., Forget, P., Griffa, A., Barbin, Y., Gaggelli, J., De Maistre, J.C., and Rixen, M., 2009. Comparison between VHF radar observations and data from drifter clusters in the Gulf of La Spezia (Mediterranean Sea). Journal of Marine Systems, 78 (Supplement 1), S79-S89.

Mounier, F., Echevin, V., Mortier, L. and Crépon, M., 2005. Analysis of the mesocale circulation in the occidental Mediterranean Sea during winter 1999-2000 given by a regional circulation model. Progress in Oceanography, 66, 251-269.

Ohlmann, J.C., Niiler, P.P., Fox, C.A. and Leben, R.R. 2001. Eddy energy and shelf interactions in the Gulf of Mexico. Journal of Geophysical Research, 106, 2605-2620.

Ovchinnikov, I. M., 1966. Circulation in the surface and intermediate layers of the Mediterranean, Oceanology, 6, 48-59.

Pazan, S. E. and Niiler, P. P., 2001. Recovery of near-surface velocity from undrogued drifters. Journal of Atmospheric and Oceanic Technology, 18, 476-489.

Pinardi, N. and A. Navarra, 1993. Baroclinic wind adjustment processes in the Mediterranean Sea, Deep Sea Research II, Vol. 40, No. 6, 1299-1326.

Pinardi, N., Masetti, E, 2000. Variability of the large-scale general circulation of the, Mediterranean Sea from observations and modelling: a review. Palaeogeography, Palaeoclimatology, 158, pp. 153-173.

Pinardi, N., E. Arneri, A. Crise, M. Ravaioli and M. Zavatarelli, 2006**.** The physical, sedimentary and ecological structure and variability of shelf areas in the Mediterranean Sea**.** *The Sea* Vol. 14 (A. R. Robinson and K. Brink Eds.), Harvard University Press, Cambridge, USA, 1245-1330

Poulain, P.-M., 1999. Drifter observations of surface circulation in the Adriatic Sea between December 1994 and March 1996. J. Marine Sys., 20, 231–253.

Poulain, P.-M., 2001. Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999, J. Marine Sys., 29, 3-32.

Poulain, P.-M., Gerin, R., Mauri, E., and Pennel, R., 2009. Wind effects on drogued and undrogued drifters in the Eastern Mediterranean. Journal of Atmospheric and Oceanic Technology, 26 (6), 1144–1156.

Pujol, M.-I., 2006. Analyse de la variabilité de surface en Méditerranée à partir des données altimétriques et comparaison aux simulations MERCATOR et MOG2D. Thèse de Doctorat. Université Toulouse III – Paul Sabatier U.F.R. P.C.A., 307p.

Rinaldi, E., Buongiorno Nardelli, B., Zambianchi, E., Santoleri, R. and Poulain, P.-M., 2010. Lagrangian and Eulerian observations of the surface circulation in the Tyrrhenian Sea. Journal of Geophysical Research. Submitted.

Rio, M.H, Poulain, P.M., Pascual, A., Mauri, E., Larnicol, G. and Santoleri, R., 2007. A mean dynamic topography of the Mediterranean Sea computed from altimetric data, in-situ measurements and a general circulation model. J. Marine Syst. 65 (1–4), 484–508.

Sammari, C., Millot, C. and Prieur, L., 1995. Aspects of the seasonal and mesoscale variabilities of the Northern current in the western Mediterranean Sea inferred from the PROLIG-2 and PROS-6 experiments. Deep-Sea Research I, 42(6), 893-917.

Schroeder, K., Griffa, A. and Poulain, P.-M., 2010. Relative dispersion in the Ligurian Sea derived from surface drifters. Submitted.

Taupier-Letage, I. and Millot, C., 1986. General hydrodynamical features in the Ligurian Sea inferred from the DYOME experiment. Oceanologica Acta, 9 (2), 119-131.

Teixeira, J., 2007. LASIE07 Trial Plan. NATO Undersea Research Centre, La Spezia, Italy. 30 pp.

Ursella, L., Poulain, P.-M. and Signell, R. P., 2006. Surface drifter derived circulation in the northern and middle Adriatic Sea: Response to wind regime and season, J. Geophys. Res., 111, C03S04, doi:10.1029/2005JC003177, [printed 112(C3), 2007].

Vandenbulcke, L., Beckers, J.-M., Lenartz, F., Barth, A., Poulain, P.-M., Aidonidis, M., Meyrat, J., Ardhuin, F., Tonani, M., Fratianni, C., Torrisi, L., Pallela, D., Chiggiato, J., Tudor, M., Book, J.W., Martin, P., Peggion, G. and Rixen, M. (2009) Super-ensemble techniques: Application to surface drift prediction. Progress In Oceanography, 82 (3), 149-167.

Figure captions

Fig. 1. Composite diagram with all the drifter trajectories (back: MREA-07 and LASIE-07 and gray : MREA-08) in the LPB between 14 May 2007 and 23 January 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 Lyons is depicted with a dashed rectangle.

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

Fig. 3. Trajectories of the drifters sorted by deployment episodes/clusters listed in Table 1. 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. 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°N52.5’ and 5°E52.5’ and sorting them into two categories (Mistral: winds blowing from the entire northwestern sector with speeds in excess of 5 m/s; Non-Mistral: winds with speeds less than 5 m/s and

blowing from the other sectors. Black arrows indicate northwestward drifter motion into and towards the Gulf of Lyons when Mistral is not blowing.

Fig. 6. CCMP winds averaged over the periods of prevailing Mistral winds: (a) 2-6 July 2007, (b) 28-31 July 2007 and (c) 12-25 November 2008. 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).

Fig. 7. Drifter data density in the NC area extending between the Gulf of Genoa and the Gulf of Lyons: number of 6-hourly observations in bins of 10 x 5 km^2 (gray tones). The 200 m and 2200 m isobaths are shown with thin black and gray curves, respectively. Coordinates are in km.

Fig. 8. Same as in Fig. 7 but for the kinetic energy of the mean flow (MKE) and considering only bins with at least 3 observations.

Fig. 9. Same as in Fig. 8 but for the kinetic energy of the fluctuating velocities (EKE).

Fig. 10. Mean circulation in the NC area extending between the Gulf of Genoa and the Gulf of Lyons (vectors) along with the drifter trajectories (light gray). Drifter velocities were averaged in bins of 10 x 5 km^2 containing at least 3 observations. The 200 m and 2200 m isobaths are drawn with thin black and gray curves, respectively. Coordinates are in km. The location of the maximum speed is indicated by a black dot near Imperia.

Fig. 11. Same as in Fig. 10 but for the velocity variance ellipses.

Fig. 12. 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.

Date	Ship	Experiment	Number of drifters	Number of kriged tracks
14-May-2007	ITN Galatea	MREA-07	5	8
17-Jun-2007	R/V Urania	LASIE-07	5	7
22-Jun-2007	R/V Urania	LASIE-07	5	8
1-Oct-2008	ITN Magnaghi	MREA-08	5	4
10-Oct-2008	ITN Magnaghi	MREA-08	3	3
21-Oct-2008	ITN Magnaghi	MREA-08	3	4
Total			26	34

Table 1. Details on the drifter deployments conducted in the open Ligurian Sea from the Italian Navy ships Galatea and Magnaghi and the Italian Consiglio delle Ricerche (CNR) ship Urania during the MREA-07, LASIE-07 and MREA-08 experiments.

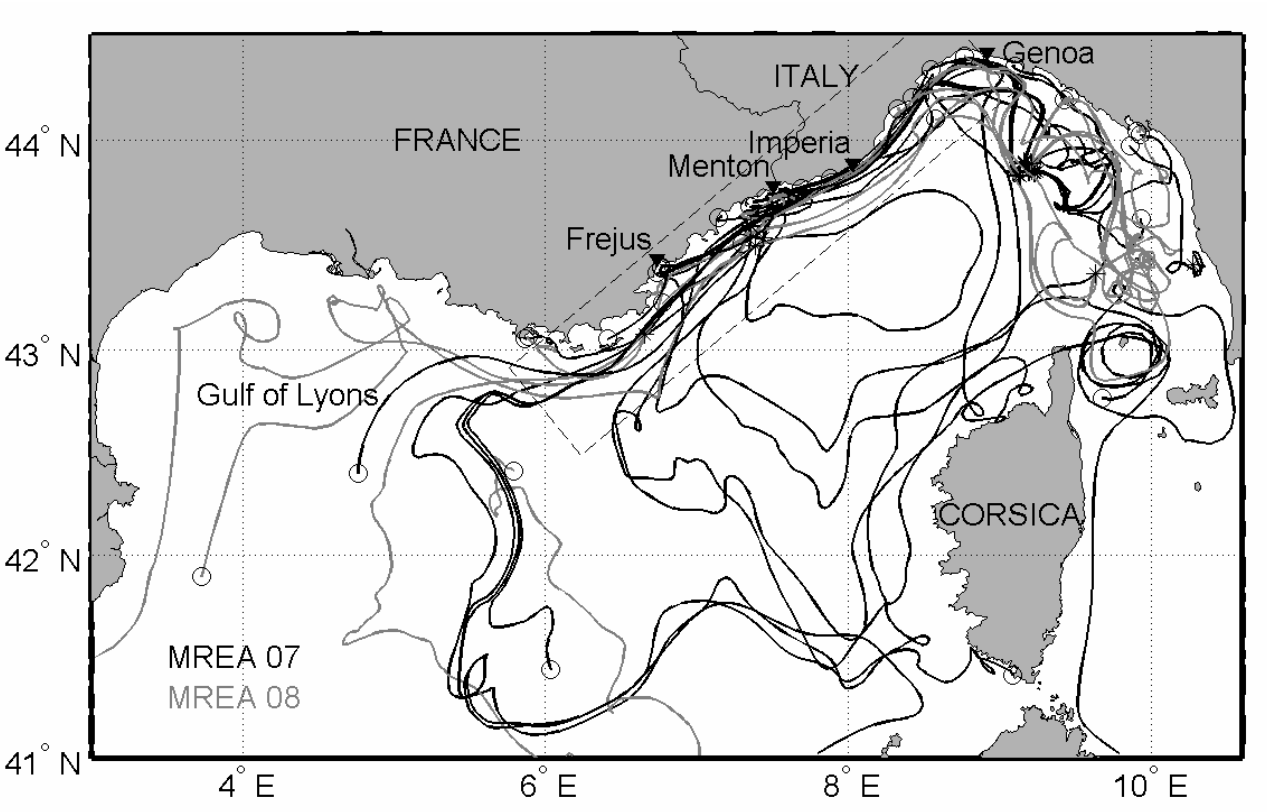

Genoa
ITALY
FRANCE
Imperia
Menton
Frejus
Gulf of Lyons
CORSICA
MREA 07
MREA 08
44° N
43° N
42° N
41° N
4° E
6° E
8° E
10° E

Fig. 1.

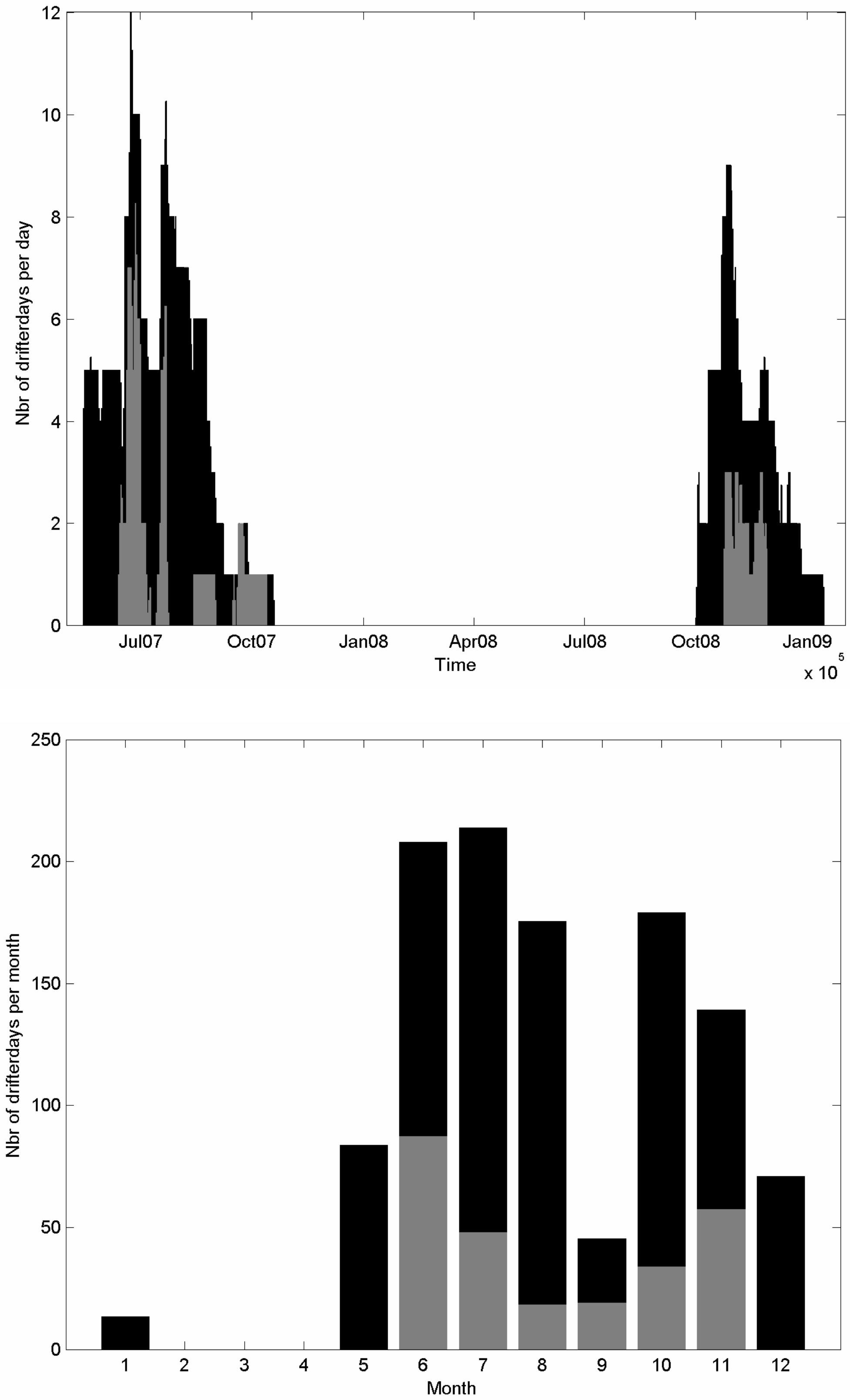

Nbr of drifterdays per day
0
2
4
6
8
10
12
Jul07
Oct07
Jan08
Apr08
Jul08
Oct08
Jan09
Time
x 10
5
Nbr of drifterdays per month
0
50
100
150
200
250
1
2
3
4
5
6
7
8
9
10
11
12
Month

Fig. 2.

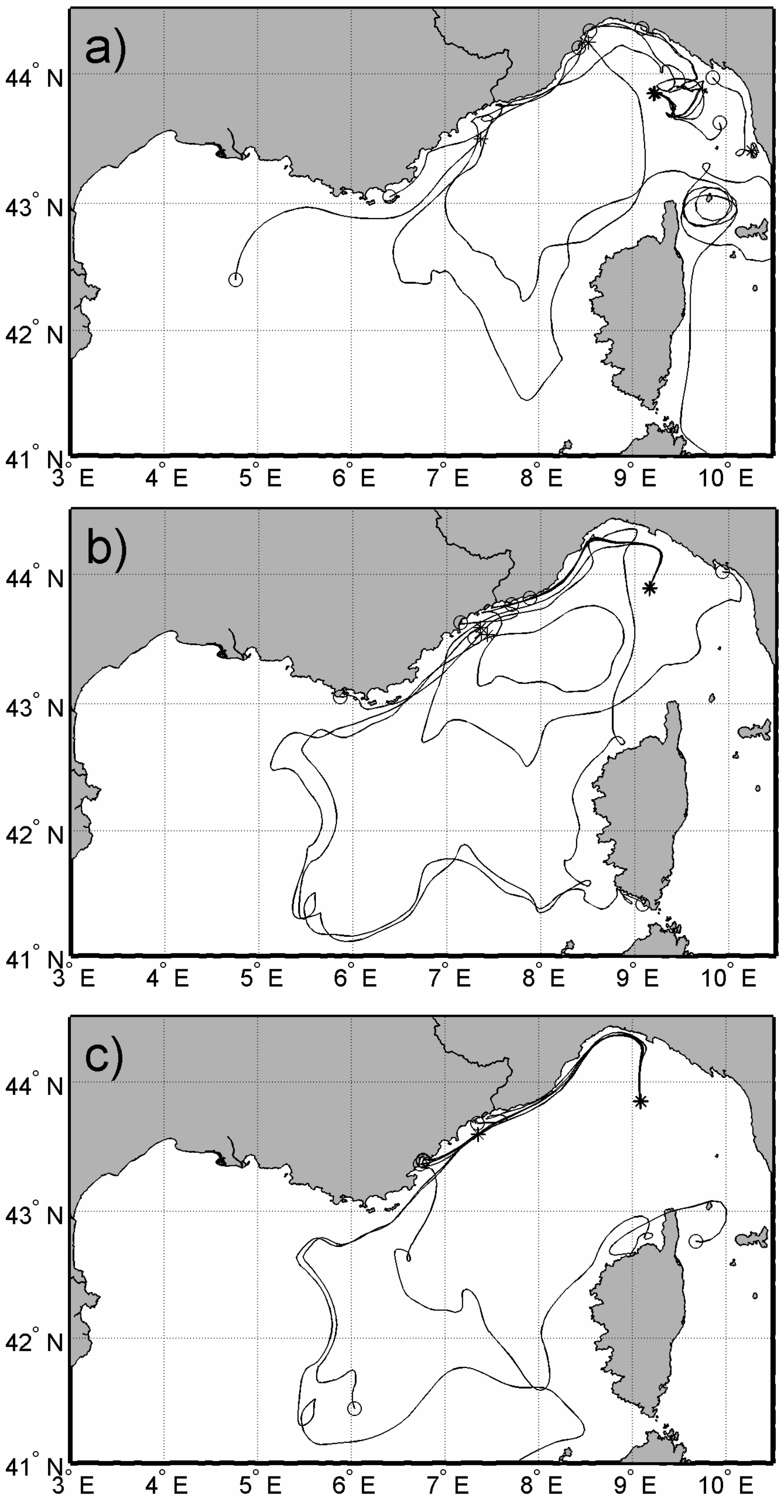


Fig. 3.

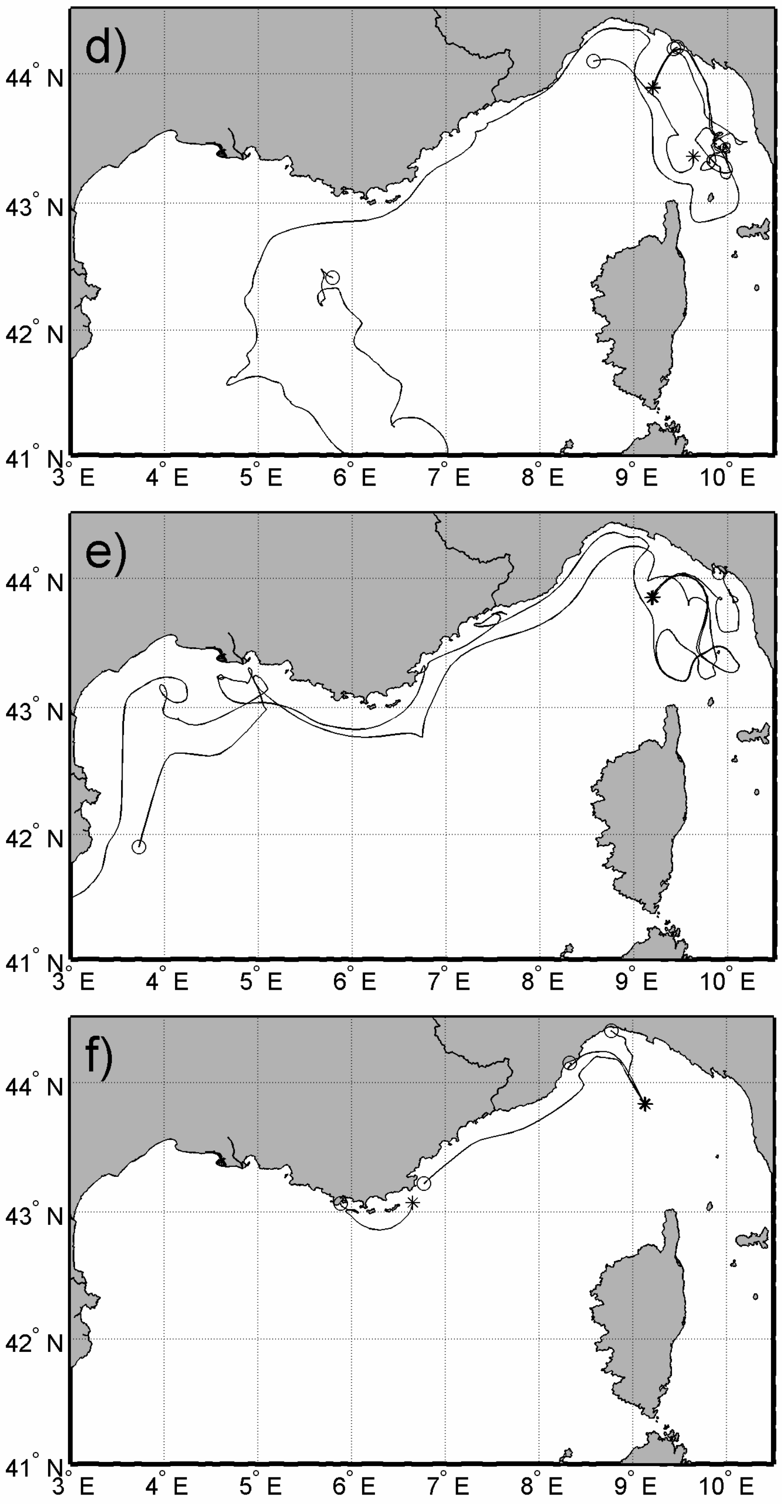


Fig. 3.

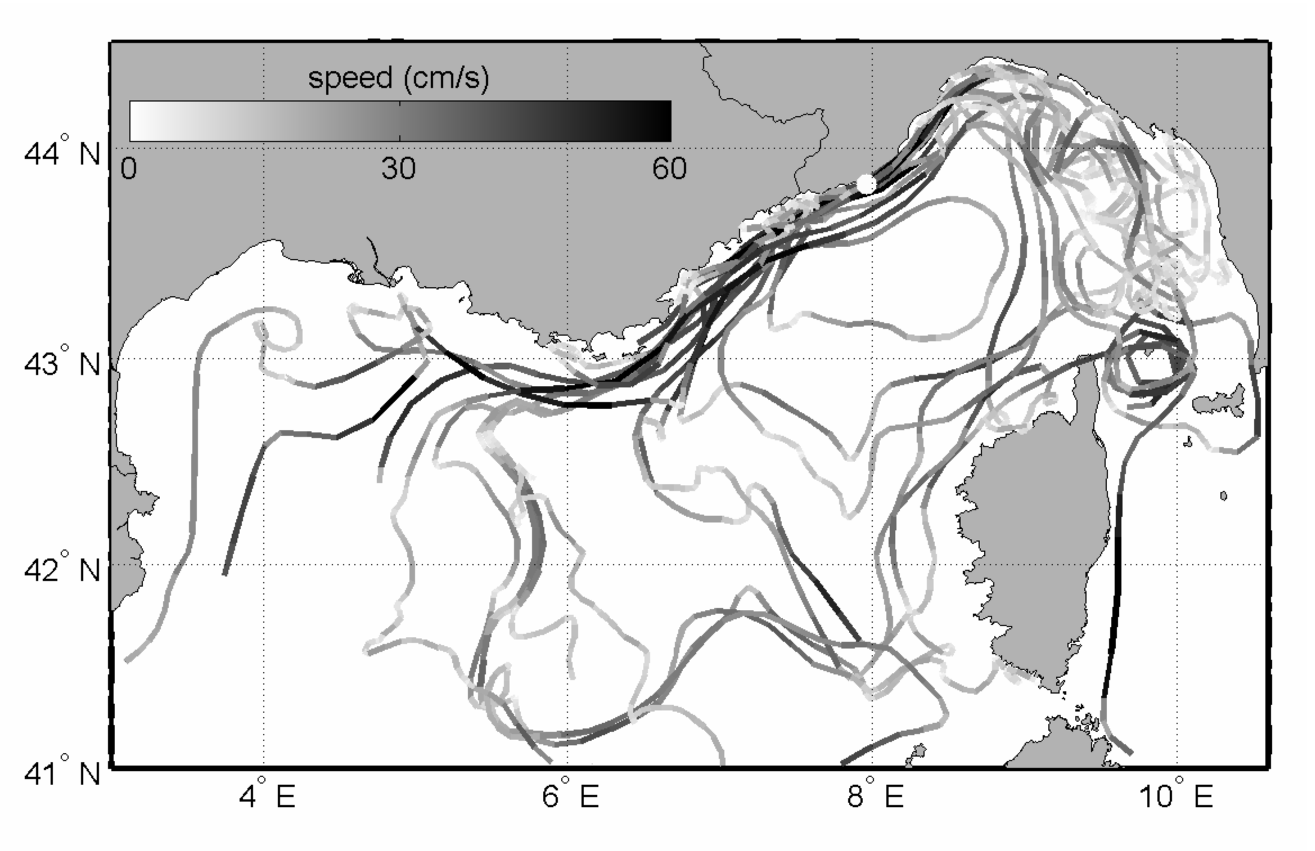

speed (cm/s)
0
30
60
44° N
43° N
42° N
41° N
4° E
6° E
8° E
10° E

Fig. 4.

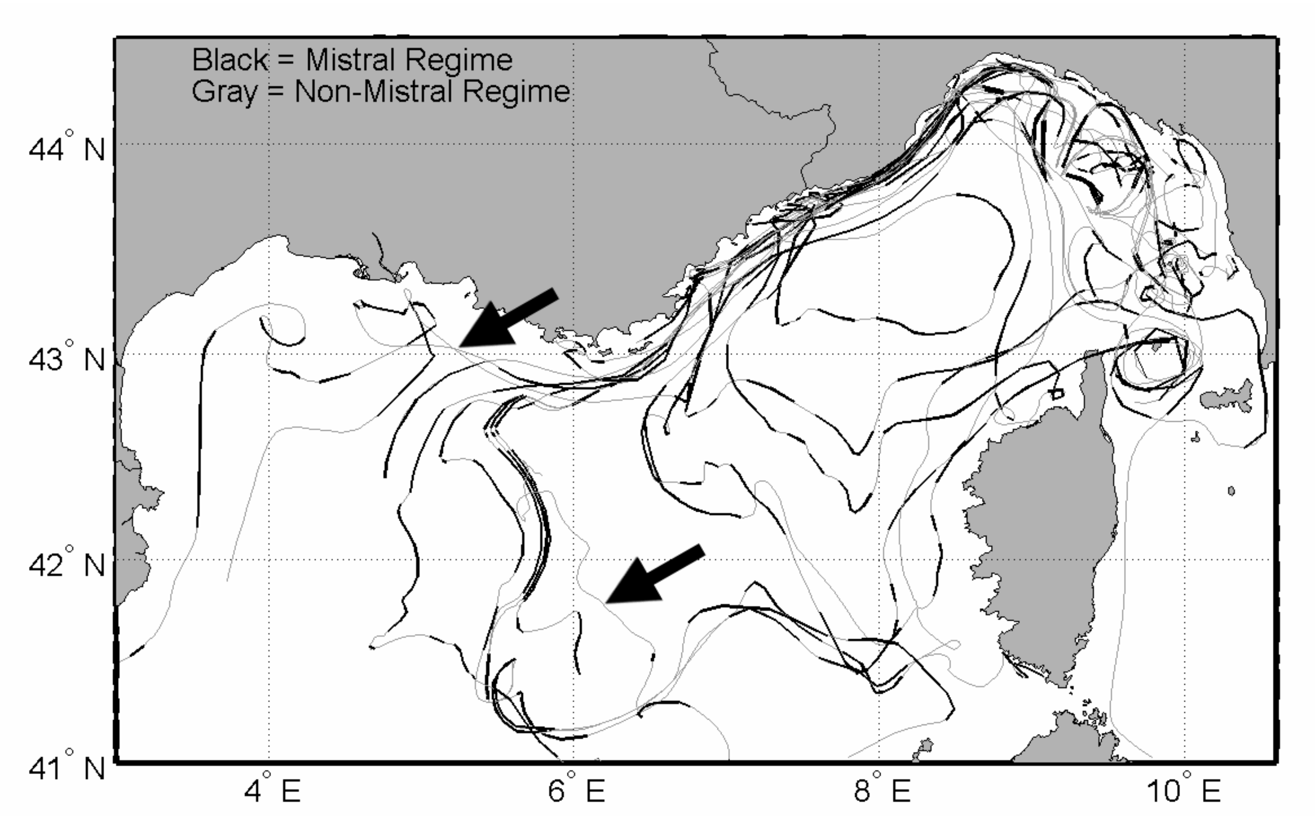

Black = Mistral Regime
Gray = Non-Mistral Regime
44° N
43° N
42° N
41° N
4° E
6° E
8° E
10° E

Fig. 5.

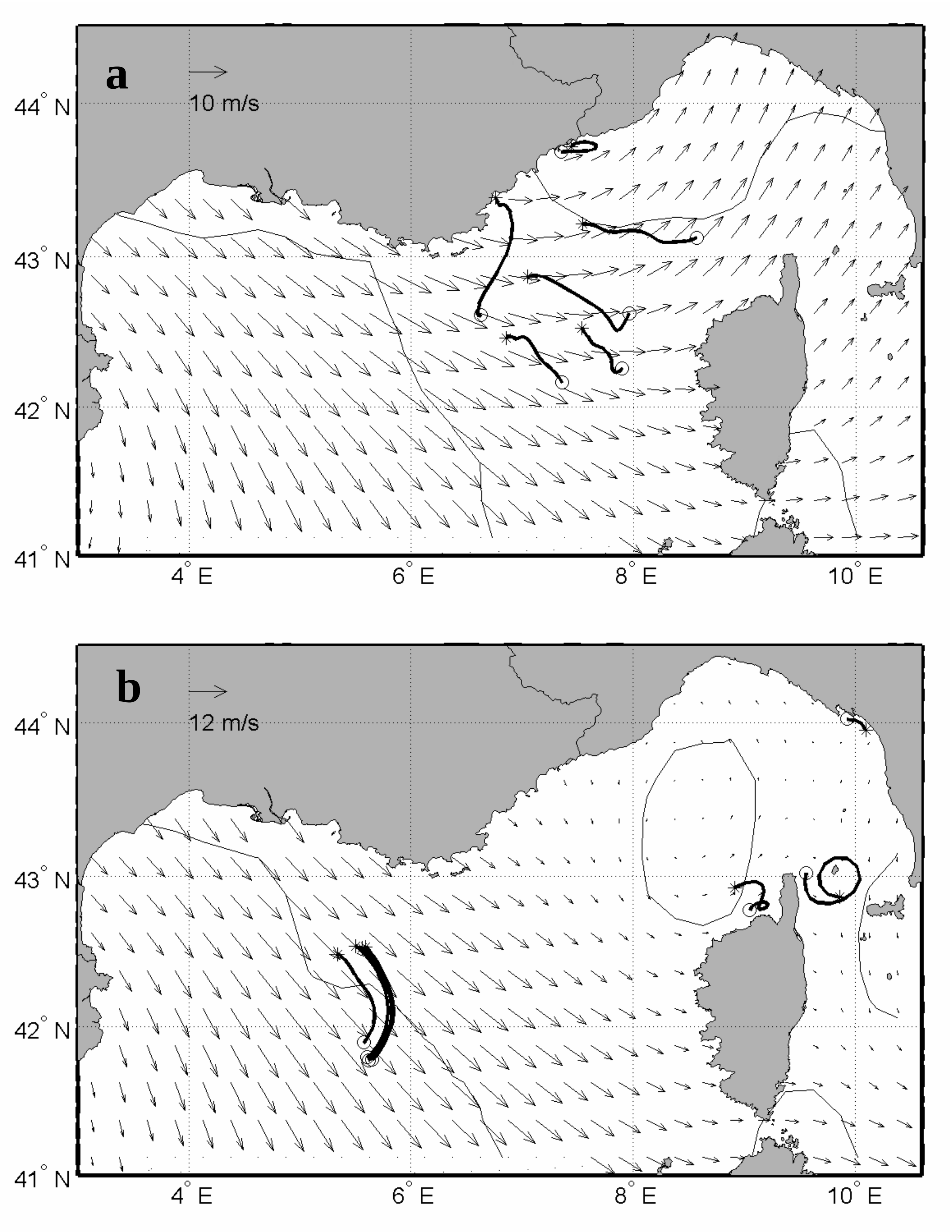


Fig. 6.

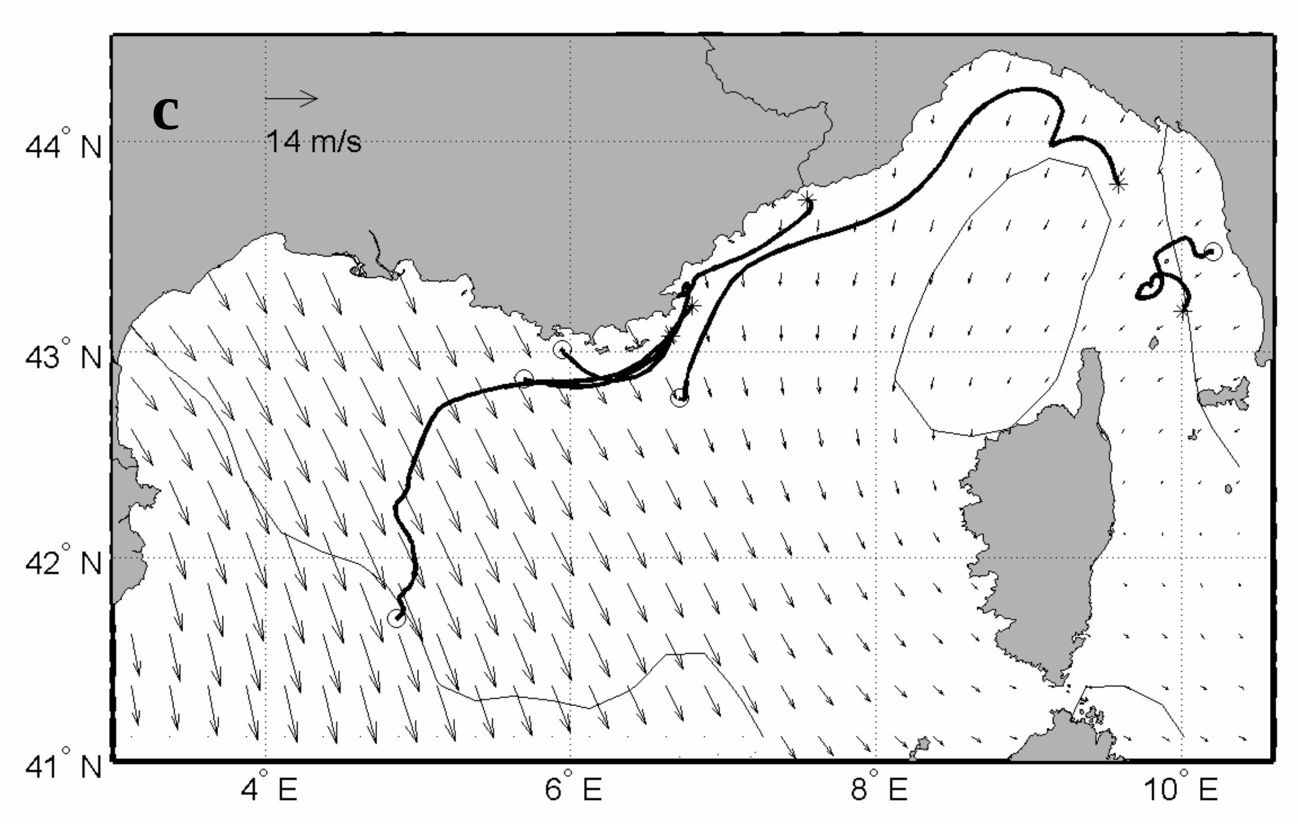


Fig. 6.

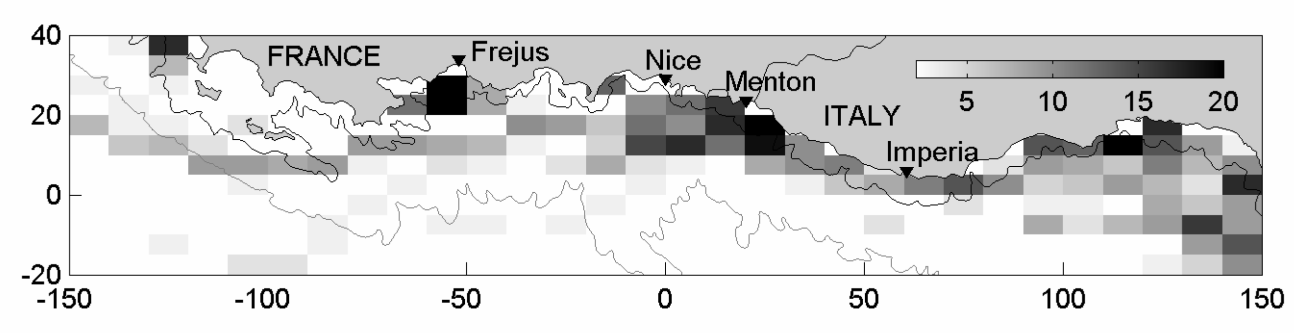


Fig. 7.

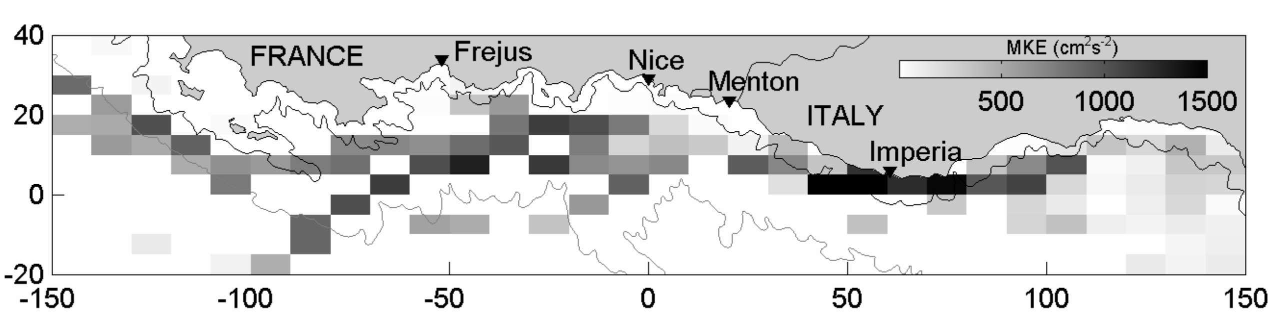


Fig. 8.

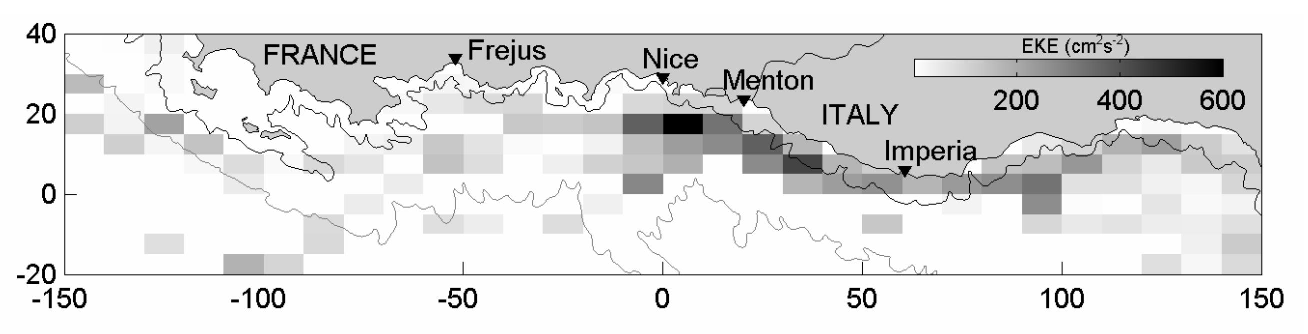


Fig. 9.

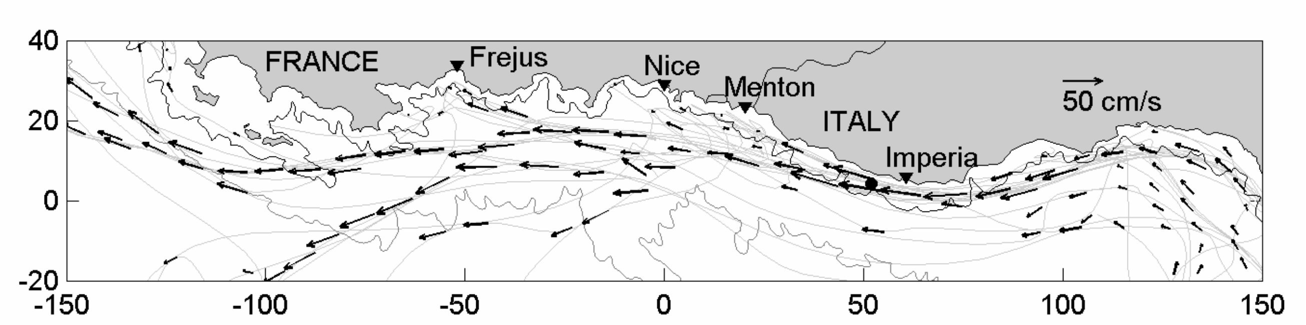

40
20
0
-20
-150
-100
-50
0
50
100
150
FRANCE
Frejus
Nice
Menton
ITALY
Imperia
50 cm/s

Fig. 10.

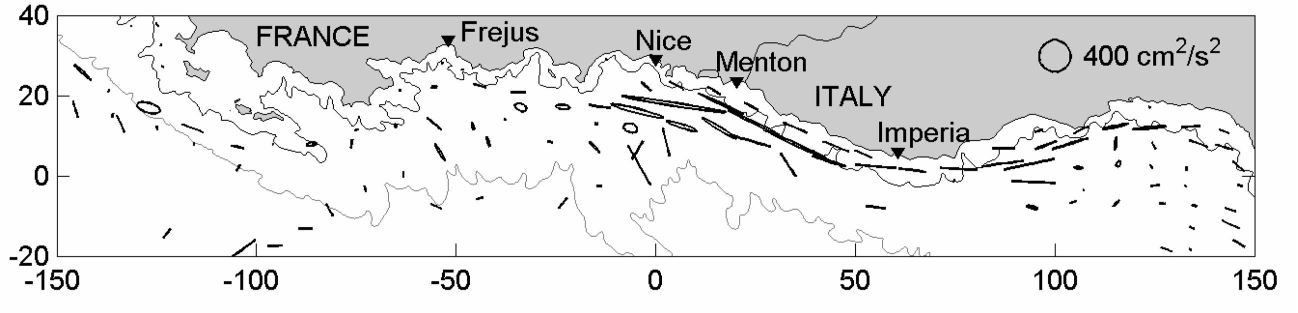
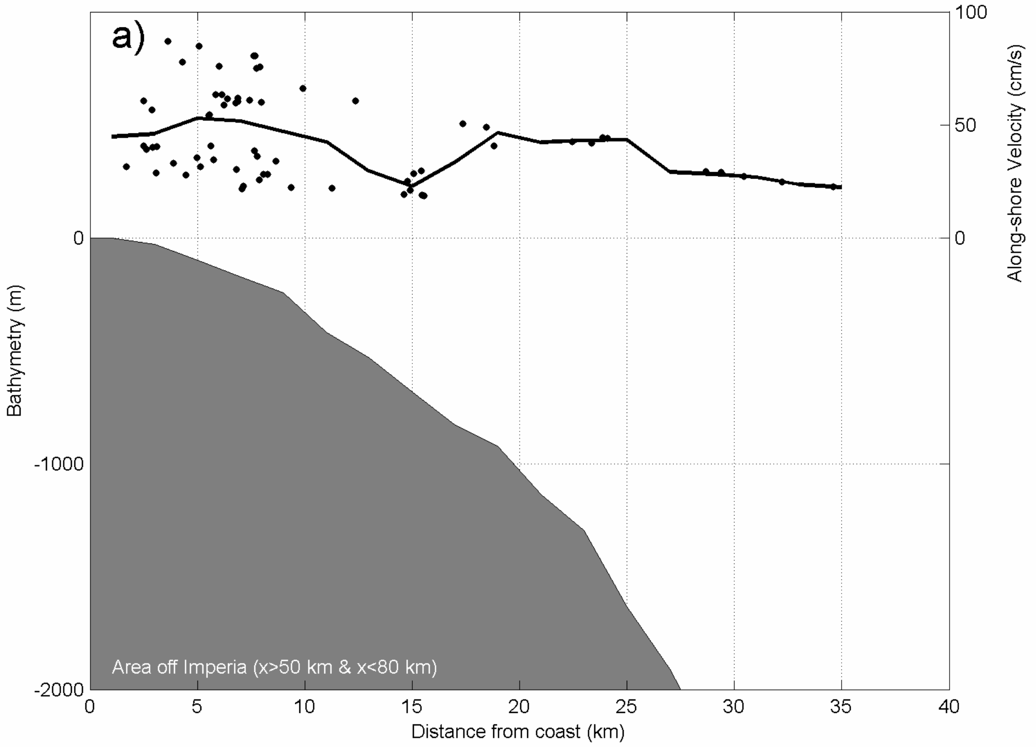
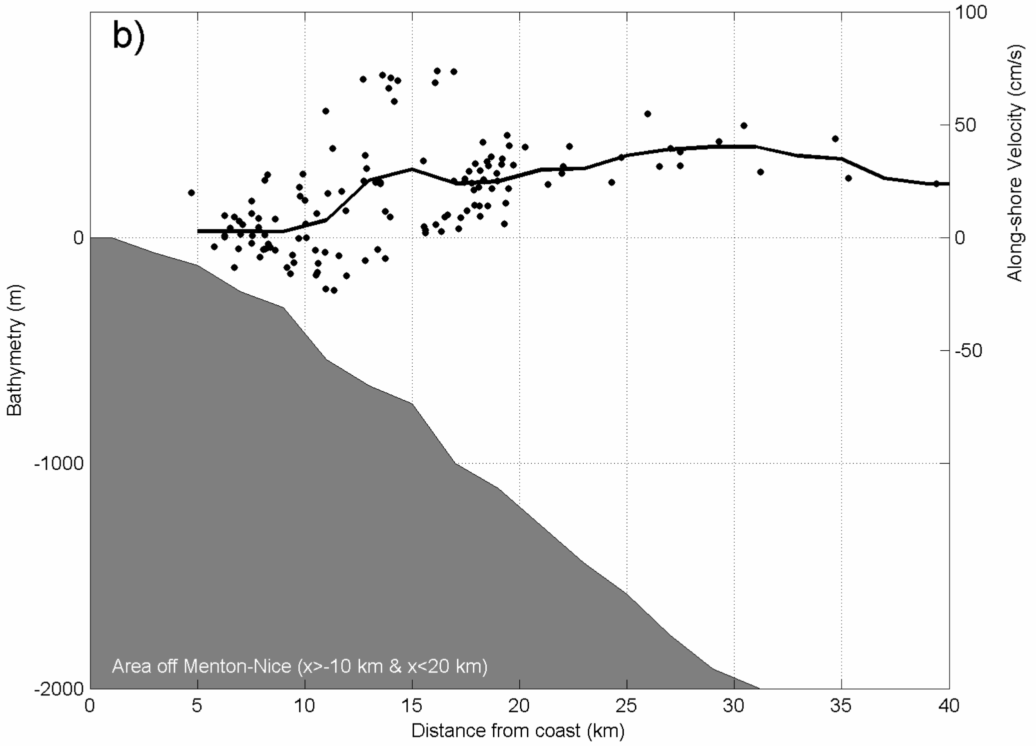

40
20
0
-20
-150
-100
-50
0
50
100
150
FRANCE
Frejus
Nice
Menton
ITALY
Imperia
400 cm^2/s^2

Fig. 11.


a)
Area off Imperia (x>50 km & x<80 km)
Bathymetry (m)
0
-1000
-2000
Along-shore Velocity (cm/s)
100
50
0
0
5
10
15
20
25
30
35
40
Distance from coast (km)


b)
Area off Menton-Nice (x>-10 km & x<20 km)
Bathymetry (m)
0
-1000
-2000
Along-shore Velocity (cm/s)
100
50
0
-50
0
5
10
15
20
25
30
35
40
Distance from coast (km)

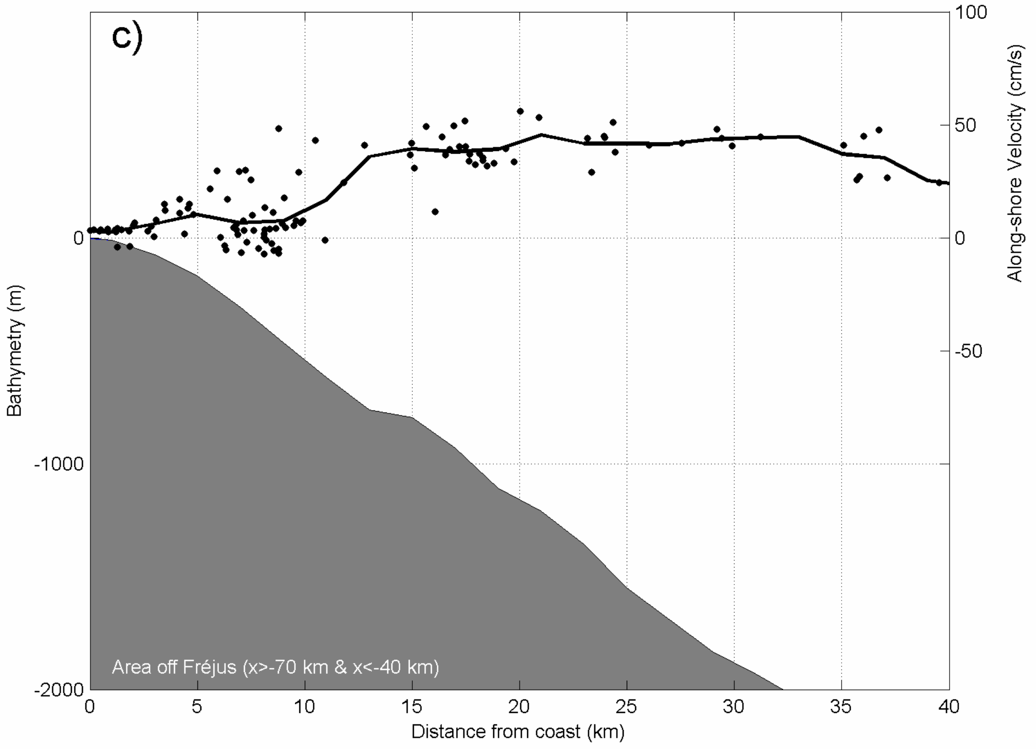

c)
Bathymetry (m)
0
-1000
-2000
Along-shore Velocity (cm/s)
100
50
0
-50
Area off Fréjus (x>-70 km & x<-40 km)
0
5
10
15
20
25
30
35
40
Distance from coast (km)

Fig. 12.