On the dynamics in the southeastern Ligurian Sea in summer 2010

Continental Shelf Research

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Sgonico, 13 September 2019

Dear Sir/Madam:

Please find attached a manuscript entitled “On the dynamics in the southeastern Ligurian Sea in summer 2010” that we would like to be considered for publication in the Continental Shelf Research.

Sincerely yours.

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On the dynamics in the southeastern Ligurian Sea in summer 2010

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Highlights

- The surface circulation in the southeastern Ligurian Sea is strongly wind-dependent.
- Anticyclonic circulation around Capraia Island is predominant.
- Currents transport offshore filaments of low-salinity and nutrient-rich waters of riverine origin.

Abstract

Drifters and a glider were operated in the southeastern Ligurian Sea to study the near-surface currents and water mass properties in summer 2010. Additional data were collected by a moored current meter in the Corsica Channel (CC). These in situ data were complemented by surface wind products, satellite images of chlorophyll concentration and a Regional Ocean Modeling System (ROMS) numerical model that was implemented to simulate the local coastal dynamics. Southward currents were prevailing along the continental Italian coast, advecting filaments with a high optical signal coming from the Arno River. North of Elba Island, currents turned westward and northward in the vicinity of the CC. Further to the north they veered eastward, forming an anticyclonic circulation feature centered around Capraia Island. This general circulation picture was disrupted and reversed during events of sustained southerly winds occurring with a period of about a week. The near-surface currents in the CC and the anticyclonic circulation around Capraia Island showed the same weekly variations related to the local wind forcing. The ROMS model simulations agreed satisfactorily with the observations, in particular the strength of the Capraia anticyclonic circulation (quantified with the Capraia index) was confirmed to be strongly wind-dependent.

1. Introduction

Currents and transports of water mass properties in sea areas including islands and channels and in the coastal zone are crucial at the local scale for the dispersion and mixing of pollutants and at the large scale for the interaction between different basins, which in turn can control the whole functioning of entire seas or oceans. Besides, if important river mouths co-exist in the vicinity of islands and channels, the distribution of the water masses and the local ecosystem dynamics can even be more complex and challenging to monitor and study.

The Mediterranean area in the southeastern Ligurian Sea and northern Tyrrhenian Sea (Fig. 1), connected by the Corsica Channel (CC), is such an area, with complex topography and coast morphology, the existence of several islands (Elba, Monte Cristo, Giglio, etc) and also the mouth of an important Italian river (the Arno River). Fluxes across the CC have been measured almost continuously between 1982 and 1998 with moored currentmeters (Manzella, 1984; Astraldi et al., 1990; Astraldi and Gasparini, 1992). The northward flowing current in the CC, also referred to as the Tyrrhenian (Astraldi and Gasparini, 1992) or Eastern Corsica Current (ECC, Pinardi et al. 2006), is maximum in winter and is mainly driven by the steric sea level difference between the Tyrrhenian to the south and the Ligurian Sea to the north. This difference is larger in winter due to the larger heat loss and the local effect of the wind stress curl in the Liguro-Provençal basin (Pinardi and Masetti, 2000). The heat flux associated with the ECC varies seasonally and plays a crucial role for deep water formation processes in the NW Mediterranean (Astraldi and Gasparini, 1992). The ECC is characterized by velocity fluctuations with periods between 2 and 15 days with the occurrence of intermittent reversals (Astraldi et al., 1990).

This ECC seasonal (and also inter-annual) variability was confirmed by satellite altimetry data along selected satellite sub-tracks criss-crossing in the CC vicinity (Vignudelli et al., 1999, 2000, 2005; Bouffard et al., 2008). Vignudelli et al. (1999) have shown that the interannual variations of water transport through the CC, as measured by satellite altimeters, can be related to the North Atlantic Oscillation. More recently, Bouffard et al. (2008) have demonstrated that multi-mission altimetric data agree well with in-situ measurements and therefore represent an accurate long-term mean to monitor the exchange between the Tyrrhenian and Ligurian seas.

Conductivity-temperature-depth (CTD) measurements and numerical simulations (Onken et al., 2005) as well as surface drifters (Poulain et al., 2012) have shown that the ECC can veer in the clockwise sense around Capraia Island and form an anticyclonic eddy centered around the island. We will refer to this circulation feature as the Capraia anticyclone, although it has recently been also named “Ligurian Anticyclone” by Ciuffardi et al. (2016). It appears to be dominant in summer when the ECC is weak. In particular, one drifter in summer 2007 completed 5 full loops around the island with a periodicity of about 3 days (Poulain et al., 2012).

In this paper, simultaneous observations of currents and water mass properties obtained by a glider, surface drifters and moored instruments, along with ancillary satellite data and wind products and numerical model simulations, are used to explore and study the dynamics of the southeastern Ligurian and CC in summer 2010. Most data were collected as part of the LIDEX10 campaign, whose general objective was to improve the understanding of turbulent transport and dispersion in the ocean, more specifically to study the dispersion in a coastal frontal zone due to mixing by meso- and submesoscale structures (Schroeder et al., 2012). The main focus of this paper is on mesoscale (~10 km) and submesoscale (< 10 km) structures, some of them transporting offshore and mixing the fresh and nutrient-rich waters of river origin. The Capraia anticyclone, which has a subbasin scale (40-50 km), is described quantitatively using the drifter data. Some aspects of the near-surface circulation and ECC transport are also investigated, relating them to the local wind forcing.

Details about the instruments used and the collected data are provided in section 2. The surface circulation as measured by the drifters is described in section 3.1, including a qualitative description of their motions and a quantitative study of the Capraia anticyclone. The effect of the local wind forcing is explored in section 3.2, using both observations and numerical simulations obtained with the Regional Ocean Modelling System (ROMS). The surface circulation derived from ocean color satellite images superimposed with drifter tracks is discussed in section 3.3. Section 3.4 includes the results on the 3D spatial structure and temporal evolution of the water mass properties (temperature and salinity) provided by the glider and also detected in ocean color satellite images. Discussion of the most salient results and conclusions are found in section 4.

2. Data and methods

The LIDEX10 experiment took place on-board the R/V Maria Grazia of the Italian National Research Council (CNR) on 3 July 2010 in the southeastern Ligurian Sea off the Tuscany coast (Italy). First, a conductivity-temperature-depth (CTD) survey was carried on, along a zonal transect at latitude 43˚ 35.34' N and between longitudes 9˚ 56.7' E and 10˚ 5.94' E, including 12 casts down to 50 m depth and separated by 1-4 km. The CTD data revealed a near-surface vertical front in the top 7-8 m below the surface, separating lower salinity and higher chlorophyll fluorescence water inshore from saltier and poorer water offshore (Schroeder et al., 2012). The CTD data are not discussed any further in this paper since the glider repeated the same transect shortly after.

2.1 In-situ observations

2.1.1 Drifters

Two groups of 9 drifters were deployed after the CTD transect on 3 July 2010, on each side of the front, approximately 5 km apart. For each group, the drifters were released in three tight triplets separated by 300-500 m, and with 50-100 m distance between the drifters within each triplet (see Fig. 2 of Schroeder et al., 2012). An additional drifter was deployed between the 2 groups on the front. In brief, the 19 drifters were deployed with relative distances ranging from 50 m to 6 km. The deployments were conducted in less than 4 h (from 11:34 to 15:26 GMT). All drifters were CODE designs (Poulain, 1999; Poulain and Gerin, 2019), fitted with GPS receivers and manufactured by Technocean (Cape Coral, Florida). They measure the currents in the top first meter below the surface with an accuracy of 1-2 cm/s. The principal error is a wind-induced slip of about 0.1% of the wind speed (Poulain and Gerin, 2019). Most of the drifters (17 units) transmitted their data to the Argos system on-board polar-orbiting satellites, whereas 2 drifters used the Iridium telemetry system. GPS positions and ancillary data (e.g., sea surface temperature, battery voltage) were transmitted every hour.

The drifter GPS data were quality controlled and interpolated at 0.5 h intervals using a kriging technique (see Menna et al., 2017 and references therein). Velocities were calculated by finite differencing the interpolated positions (central difference scheme with hourly interval). For some applications (see section 3.2) the drifter velocity timeseries were low-pass filtered with a Hamming filter (36 h) to remove high frequency motions.

The mean half-life of the 19 drifters deployed on 3 July 2010 is about 2 weeks (many drifters stopped on 19-21 July after 16-18 days). Unfortunately, the single drifter deployed between the two clusters was rather short lived and stopped functioning on 7 July.

2.1.2 Glider

A shallow water Slocum glider manufactured by Teledyne Webb Research, Falmouth, Massachussetts was deployed at location 43° 35.78’ N, 10° 06.20’ E on 3 July 2010, shortly after the drifter deployments (i.e., at 16:29 GMT). The glider was equipped with an un-pumped Sea-Bird Scientific SBE 41 CT to measure conductivity (0.0003 S/m), temperature (0.002 °C) and pressure (0.5 psi), along with sensors to measure dissolved oxygen, particle backscattering and coloured dissolved organic matter fluorescence. It was programmed to measure vertical properties of the water column as deep as 200 m. All sensors were set to record every 8 seconds. The typical horizontal resolution of the glider data along its route was about 0.5 km. In this paper only temperature, salinity and density observations are considered to describe the local dynamics, with a main focus on the top 40 m of water.

The glider was initially piloted to sample the transect surveyed by the research vessel. Given the southward motion of the drifters, and in order to have the glider and drifters in the same area at about the same time, the glider was subsequently programmed to survey the southeastern Ligurian Sea in a southward zig-zag pattern until it approached the northern coast of Elba Island (Fig. 1). At this point it was piloted to move westward and to sample the CC, until it was recovered on 20 July 2010 (at about 10:00 GMT) at 43° 00.90’ N, 09° 35.82’ E, between the northern tip of Corsica and Capraia Island.

2.1.3 Mooring

A mooring with current meters is maintained by CNR ISMAR in the CC (between the northern tip of Corsica and Capraia Island) since 1985. Its location is 43° 1.5’ N, 9° 41.0’ E. Current profiles are measured with an upward 75 KHz RDI Acoustic Dopler Current Profiler (ADCP), with a bin size of 16 m, between 32 and 384 m at 2 h intervals. The meridional and zonal velocities were extracted from the dataset for the period July-August 2010. Only the meridional (along-channel) component is considered here, since it is more significant for our scopes than the zonal (across-channel) component (the meridional speed is on average 3 times stronger than the zonal one), and gives indication on the water exchange between the Tyrrhenian and the Ligurian Sea. For comparison with the surface drifter data, the mooring data near 32 m depth was considered. In order to remove high frequency fluctuations, a Hamming filter with cut off period of 36 h was applied to the velocity time series.

2.2 Remotely sensed data

Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images of chlorophyll concentration of the study area were used to describe the spatial structure and temporal evolution of the surface circulation assuming that chlorophyll is a passive tracer advected by the surface horizontal currents. Images of chlorophyll concentration were preferred on sea surface temperature images as they delineate better the circulation features at meso- and submesoscales (better contrast). Being in a coastal area where a river outflows nutrient-rich water, there is a sharp contrast between coastal and offshore waters, the former being richer (higher chlorophyll) and slightly colder (by about 1 ˚C, in our case). The daily images have a horizontal resolution of 1 km.

2.3 Wind products

Consortium for Small-scale Modeling (COSMO, http://www.cosmo-model.org) wind products run by the Italian Air Force National Meteorological Center were obtained for the study area in July and August 2010. In particular, the COSMO-ME gridded 10-m vector winds with 7 km grid spacing were used to force the ROMS model and to relate the wind forcing to the currents measured by the drifters and at the CC mooring. For some applications (see section 3.2) the COSMO-ME wind velocity timeseries were also low-pass filtered with a

Hamming filter (36 h) to remove high frequency fluctuations. Wind data at 10-m were also obtained from the ODAS buoy (also called W1-M3A) located in the central Ligurian Sea (43° 48’ N, 9° 9.6’ E).

2.4 Numerical simulations

The ocean model employed in this application is the ROMS (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005). As part of LIDEX10, the model was set up in operational forecast mode on a domain covering the entire Ligurian Sea. The horizontal resolution is 2 km, with 32 vertical sigma-levels non-linearly stretched to resolve the surface boundary layer. The ocean model was forced by the COSMO-ME 10-m winds. Open boundary conditions were applied to tracers and baroclinic velocity with radiation and nudging (Marchesiello et al. 2001) from daily averages of the large-scale Mediterranean Forecasting System (MFS) forecasts (Oddo et al., 2009). Three major rivers were included: the Arno (daily discharges), Serchio and Magra (monthly climatologies). The operational ROMS-based system was initialized on 1 May 2010 using an analysis field from the Mediterranean Forecasting System (MFS) model. Since then, ROMS was run in forecast mode once a day (00:00 UTC) with output data every 3 h and forecast range of 72 h. Data assimilative analysis fields from the forecast system are available in Mourre and Chiggiato (2014), but just for a short period. Thus, for this work only the free run (i.e., without data assimilation) is considered. Additional details on the physics and numerical details implemented in this application and performance can be found in Alvarez et al. (2012), Schroeder et al. (2012), Mourre et al. (2011) and Mourre and Chiggiato (2014).

3. Results

3.1 Surface circulation

After deployment, all drifters moved southward, with the coastal group (red tracks in Fig. 2) going faster and reaching 43˚N latitude after 4 days, on 7 July. The other group (blue tracks in Fig. 2) followed with about 1-day delay. Between 7 and 10 July the coastal group proceeded westward towards the CC, and veered southward upon approaching Corsica. In contrast, the other drifters slowed down and stagnated just north of Elba Island for about 2 days (11-12 July). Most of these drifters then moved northward (in the ECC and also near the Italian continental coast) on 13-14 July, before turning back and moving south and west starting on 15 July. On 15-19 July, the drifters in the southern part of the CC showed slow and rather chaotic currents, except for 2 drifters which moved swiftly northward between the northern tip of Corsica and Capraia Island on 14 and 19 July. Four drifters (blue tracks) moved to the southwest rapidly on 19 July and joined the area of the CC.

After the recovery of the glider on 20 July, some drifters continued to provide data on the surface circulation in the study area for about another month (not shown). The most striking characteristics of the currents during that period are: 1) on 22 July, fast northward currents in the CC; 2) on 23-25 July, reversal of this current with drifter moving south in the CC; and 3) a prevailing anticyclonic circulation around Capraia Island mostly during the period 20 July - 17 August. No drifter moved north of 43˚ 30’ N and only 3 drifters moved eventually to the Tyrrhenian Sea south of 42˚ 30’ N after some time. The composite plot of all the drifter trajectories between 3 July and 27 August 2010 is shown in Fig. 3, with speed color-coded along the trajectories. Fastest unfiltered currents reaching 90 cm/s occur north of the CC in the ECC (near 43˚ 15’ N). Southward currents sampled during the first few days after deployment range in 30-40 cm/s. Currents in the anticyclonic circulation around Capraia Island are mostly in the 30-60 cm/s range. In the “stagnant” areas north of Elba Island and in the CC, the speed is bounded by 20 cm/s. Note that high frequency motions, shown as loops in the tracks, are ubiquitous in most of the drifter data. These motions have speeds of 10-20 cm/s. Spectral analysis revealed that they correspond to near-inertial oscillations, tidal motions and currents driven by sea breeze. These high frequency motions are not considered in the rest of the paper since the main focus is on dynamics at meso- and submesoscales.

Pseudo-Eulerian statistics were calculated from the drifter data for the period 3 July to 27 August 2010 using bins of 0.05˚ latitude x 0.05˚ longitude. The number of hourly drifter observations in the bins is maximum (in excess of 500) north of Elba Island and in the southern part of the CC (not shown). Mean currents are shown in Fig. 4. for bins with more than 5 hourly observations. The strong anticyclonic circulation around Capraia Island is striking with mean speeds reaching 30 cm/s. This feature is about 60-70 km in diameter and is bounded by 9˚ 30' E and 10˚ 20' E in longitude and 42˚ 50' N and 43˚ 30' N in latitude. Its center is just to the northeast of Capraia Island. The period of rotation is 5-10 days. In total, eight drifters executed 13 loops in this structure between 19 July and 19 August (one month). Two drifters executed 4 loops each.

Fig. 5 shows the geographical distribution of the variability of the surface currents with respect to the mean pattern shown in Fig. 4. The eddy kinetic energy (see definition in Poulain, 2001) is low in the eastern part of the study area and in the southern CC. It increases near the northern tip of Corsica and the northern extension of the CC (in the ECC) and the northern limb of the anticyclonic circulation around Capraia Island.

3.2 Wind forcing, near-surface currents and numerical simulations

The COSMO-ME wind products at the grid point nearest the CNR mooring in the CC (43˚ 7.5' N, 9˚ 37.5' E, see Fig. 1) were considered to study the variability of the near-surface currents related to the wind forcing. As shown in Fig. 6, in addition to daily variations corresponding to sea breeze (see thin curve in middle panel), the wind is alternating between northerly and southerly regimes with a periodicity of about a week. More specifically, major northerly wind events occurred on 19, 24 and 30 July and on 6 and 21 August. On 14, 22 and 29 July and 15-16 and 27 August, winds were primarily southerly. Fig. 6 shows that the low-pass filtered currents at 32 m depth measured by the mooring in the CC respond to the local wind forcing, i.e., major events of southerly (northerly) winds correspond to increased northward (southward) velocity. The correlation with zero-time lag between the meridional winds and currents is about 0.69, but it increases to 0.71 for a lag of 5 h. This means that the currents are barely delayed with respect to the wind.

If we plot the low-pass filtered drifter meridional velocities versus time along with the low-pass filtered near-surface meridional flow in the Corsica Channel (Fig. 6, bottom panel), it is striking that most drifter speeds co-vary with the mooring data. In particular, during the events of strong northward flow (and southerly winds) of 13-14, 22-23 and 28-29 July, most drifters are moving northward with speeds up to about 50 cm/s (after low-pass filtering). On 18-19, 23-24 and 29-30 July under northerly wind forcing the majority of drifters are moving southward and the upper current in the CC is reversed (southward). Note that the variance of the drifter meridional velocity is much higher than the mooring data mostly due to the spatial variability sampled by the drifters.

Fig.7 shows the average surface circulation in the Ligurian Sea in July - August 2010 produced by ROMS. The two–month average clearly suppresses all short-term variability and the emerging picture is controlled by the permanent features in the area. The overall circulation of the western Ligurian Sea is cyclonic. Surface Atlantic Water (AW) enters the Ligurian Sea from the south, mostly from the Algerian basin through the Western Corsica Current (WCC). As expected in summer, the ECC in the CC is weak, in good agreement with the drifter data (Fig. 4). The resulting current proceeds northward as a geostrophic frontal system becoming the so-called Northern Current (NC) in the northern Ligurian Sea. In the eastern Ligurian Sea, the Capraia anticyclone, identifiable in Fig. 7 by the relative maximum in sea surface elevation, was a robust permanent feature of summer 2010.

In order to test the relationship with wind impulses, a Capraia Index was defined as the difference in sea surface elevation between points A and B (see location in Fig. 7, top panel); thus, a value close to zero corresponds to a wide shelf current whereas a large positive value is suggestive of a strong anticyclone. The choice of an index that included point C (see Fig. 7) was discarded, as the difference in sea surface elevation with respect to A may be due to a structured boundary current (i.e., the WCC) disregarding the existence of the anticyclone. From the time-series of the Capraia index (Fig. 7, middle panel) it can be seen that (a) the anticyclone grows in intensity from early July to the end of August and (b) significant wind events have the ability to partially or totally suppress the feature, with the noticeable example of the (southwesterly) storm on 14-15 August (see wind speed in Fig. 7 bottom panel). As the wind impulse weakens however, the index is suggestive of a re-emergence of the feature. The southerly wind event around 13-14 July is in good agreement with the reversal of the coastal current revealed by the drifters (Fig. 2).

3.3 Surface circulation and satellite images

During the period of glider operation (3-20 July) only 8 MODIS images were partially cloud free and provided a useful description of chlorophyll concentration and the associated near-surface circulation. On the day of the drifter and glider deployments (3 July), there was a rather well-developed area of water with high chlorophyll concentration off the continental Italian coast from the Arno River mouth to about 43˚N 15’ (Fig. 8a). This increased optical signal is related to the higher nutrients discharged by the river. The significant Arno plume was probably the result of an event on high discharge rate (reaching nearly 200 m^3/s) around 21 June 2010 (data courtesy of Regione Toscana). The image confirms that the two groups of 9 drifters were deployed in and outside the coastal layer. The next two days (4 and 5 July, Fig. 8b,c), while all drifters were moving southward, the coastal layer developed two instabilities forming offshore-flowing (and also southward flowing) filaments near 43˚ 25' N and 43˚ 10' N. On 8 July (Fig. 8d), these instabilities were well separated in latitude and showed cyclonic veering, that is offshore and southward circulation. The rich water of the southern instability was advected towards Elba Island and then westward towards Corsica. There is a particularly good agreement between the chlorophyll structures and the drifter tracks.

The offshore-flowing instabilities rooted on the Italian continental coast were still present between 10 and 19 July (Fig. 9) with various shapes and offshore extensions. The northern one extended as far as the Gorgona Island. Others developed near and south of Elba Island, but were away from the areas sampled by the drifters and glider. To the west, off Corsica, an instability plume was evident on 12, 17 and 19 July (Fig. 9b,c,d). On 12 July (Fig. 9b) drifters were even trapped in it as it developed more offshore (as far as east as 9˚ 45' E).

During its entire mission, the glider protruded in and out of the chlorophyll-rich waters. For instance, on 8 July (Fig. 8d) it encountered richer waters near the surface at both extremities of this southwestward transect.

3.4 Water mass properties and geostrophic currents in the water column

The distribution of temperature, salinity and density along the glider track is discussed here below, with main focus on the top 40 m of water where most of the variability occurs. Selected transect (1, 8 and 15, see location in Fig. 1) are considered for the sake of brevity.

During its entire operation, the glider revealed a near-surface mixed layer extending down to 5-10 m (Figs. 10-12) on top of a thermocline spreading between approximately 10 and 40 m. Along the northernmost transect 1 (Fig. 10) the isotherms and isopycnals are inclined (deepening going offshore to the W) and the corresponding geostrophic currents are directed southward. Further to the south, along transect 8 (Fig. 11), the above-mentioned iso-curves are characterized by a concave upward structure. Qualitatively, the geostrophic currents are to the SW in the eastern portion, where the drifters also move to the S and SW (see Fig. 8d). More offshore (to the W) the currents are reversed, thus representing a mesoscale anticyclonic circulation feature. In the southern part of the CC, along the zonal transect 15 (Fig. 12), the isotherms and isopycnals correspond to concave downward. Again this is compatible with the southward motion of the drifters near Corsica, and the usual northward direction of the ECC, which is rather weak in summer.

Low-salinity water of Arno River origin (as demonstrated before in satellite images) extends almost across the entire section but most importantly for distances larger than 2 km from the westernmost point (Fig. 10). Water with salinity less than 37.6 prevails in the top 5-m layer. Below it, the salinity is gradually increasing and reaching values in excess of 38.0 around 40 m depth. This is a signature of the upper core of the Levantine Intermediate Water which can reach salinity of 38.6-38.7 at depths of 300-500 m in the Ligurian Sea (Bosse et al., 2015). Besides the above-described features, the high horizontal resolution of the glider allowed to sample a vein of relatively low salinity (~37.6) expanding offshore along transect 1 (Fig. 10) between 10 and 25 m depth. The inclination of the vein is compatible with the slope of the isopycnals and indicates the subduction of coastal water.

Along transect 8 the near surface salinity above 10 m has two minima (near 37.0) at the extremities, corresponding to the Arno River plume extending offshore (to the east), and presumably to the Atlantic Water coming from the CC (to the west). This low-salinity water is also seen in transect 15 across the CC, although a little bit deeper (5-10 m) and capped partially by saltier water.

In the CC (eastern part of transect 15), the glider data show consistent northward currents in the entire depth range (0-200 m) whereas the mooring currents (Fig. 13) show mostly northward currents above 80 m, with intensification on 13-14, 22 and 29 July and 14-15 August. Below, there are 1-2 weeks long periods of flow reversal, the most prominent one lasting from 14 to 25 July and involving the water column up to 60 m depth. The surface northward velocities average was 11.2±7.4 cm/s, while the southward ones were much weaker (-2.8±2.6 cm/s).

4. Discussion and conclusions

During summer 2010, surface drifters and a glider were operated simultaneously to explore the dynamics of the southeastern Ligurian Sea where the wind forcing, the local geography/bathymetry and the outflow of the Arno River are supposed to affect significantly the circulation and the distribution of the water mass properties. The glider was piloted in order to obtain information in the water column in the area sampled by most of the drifters. Ancillary data were obtained from a permanent mooring in the CC and from satellites (MODIS images of chlorophyll concentration). In addition, a ROMS numerical model was used to simulate the local dynamics and to help with the interpretation of the collected data.

The drifters revealed a surface circulation strongly affected by the local winds. Southward currents dominated off the Italian continental coast. These currents reversed on 13-14 July due to a change in wind direction, changing to southerly. The fluctuation of surface currents between the southward and northward directions is seen in the drifter tracks over the entire study area (in particular in the vicinity of Capraia Island) and in the near-surface records of the mooring in the CC (see Fig. 6) during July and August 2010. The typical period of these oscillations is one week.

Some drifters eventually depicted a strong anticyclonic circulation pattern centered on Capraia Island (the Capraia anticyclone) starting on 20 July. The rotation period of these drifters is 5-10 days, that is, slightly longer than the value (3 days) reported by Poulain et al. (2012). Both drifters (Fig. 2) and the simulated sea surface height (Capraia index in Fig. 7) showed an enhancement of the Capraia anticyclone in late July and August, only interrupted by a storm on 14-15 August. This trend is related to the increase of negative vorticity of the winds from July to August (not shown). On 14-15 August, strong winds from the SW disrupted this trend and the anticyclone essentially vanished. In conclusion, ROMS numerical model successfully simulated the occurrence of the Capraia anticyclone as a semi-permanent and strengthening feature during July-August 2010, corroborating the hypothesis of the significant role played by wind-storms in perturbing this eddy as well as the surface circulation in the area.

The southward coastal currents advected the plume of the Arno River and associated filaments of nutrient-rich waters towards the south, forming a layer of high chlorophyll concentration along most of the Italian continental coast. This layer became unstable and offshore-flowing filaments were generated typically at two locations between the Arno mouth and Elba Island (see for instance Fig. 8d.). The northernmost filament reached almost the area near Gorgona Island (Fig. 9d) and the southern one was advected near the northern coast of Elba Island, into the CC and around Capraia Island (Fig. 8c,d).

The temperature, salinity and density data provided by the glider between 3 and 20 July 2010 show stratified conditions typical of summer with a surface mixed layer down to 10-20 m, a thermocline expanding down to a maximum depth of 40 m. In terms of salinity, horizontal variability (fronts) associated with the Arno plume and/or the AW occur along most transects. For the Arno plume and its extension into offshore-flowing filaments, there is a good agreement between the satellite chlorophyll images and the glider data. In the thermocline, an inclined intrusion of fresher water (probably of Argo River origin) observed in transect 1 (Fig. 10) corresponds to subduction along isopycnals. Below 40 m, the increase of salinity with depth represents the upper part of the LIW.

Currents measured at the CNR mooring in the CC corroborated the fluctuations of the near-surface circulations with events of northward flow on 13-14, 22 and 29 July and 14-15 August also experienced by the drifters (Fig. 13). Deeper in the water column, southward reversing flow was observed for longer period (1-2 weeks) and rather independently from the surface variability. These flow reversal events have already been reported by Astraldi et al. (1990). They are not forced by the local winds but are probably related to the sea level difference between the Tyrrhenian and Ligurian Sea.

The combined use of data provided by mobile and fixed autonomous instruments (drifters, glider, mooring), by environmental satellites and numerical simulations in the southeastern Ligurian Sea exemplifies an efficient way of collecting oceanographic data in this complex sea area at relatively low costs. Obviously, a better sampling approach could have involved data collection with more than one glider, the deployment of fixed moorings at key locations, and an extensive survey of the entire study area with a research vessel. The study of coastal dynamics as described in this paper, nevertheless, is a good example of multi-platform and multi-parameter approach, which is the future paradigm in observational oceanography.

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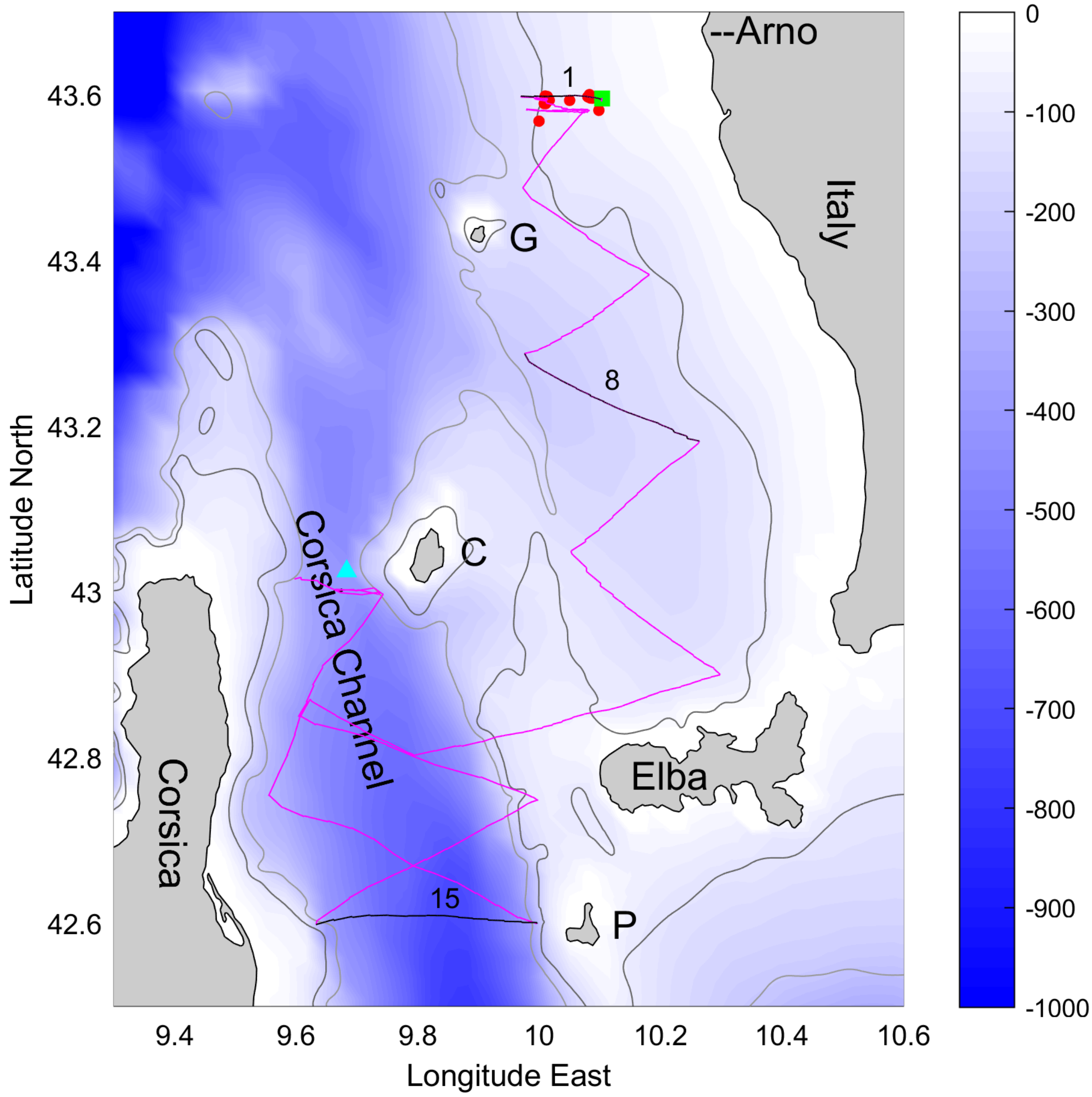


Figure 1. Geography and bathymetry of the study area in the southeastern Ligurian and Corsica Channel. The Gorgona (G), Capraia (C) and Pianosa (P) islands are shown in addition to the Elba Island. The location of the CNR mooring is shown with a cyan triangle. The deployment locations of the drifters (red dots) and glider (green square) are also indicated. The glider track is shown in magenta, including the 3 transects (1, 8 and 15) described in the paper. Bathymetry is contoured (100 and 200 m) and shown with blue shades (m).

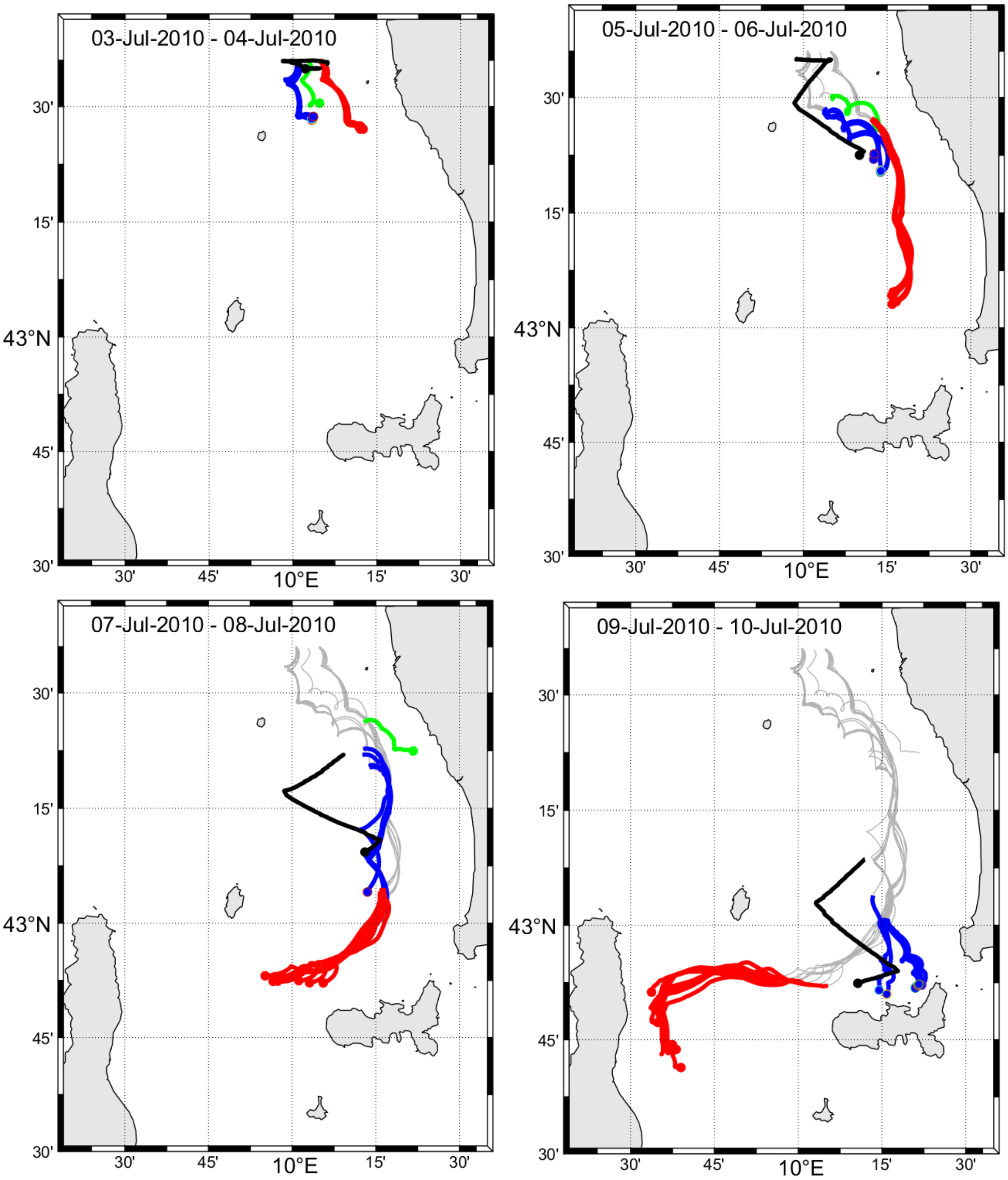


Figure 2. Two-day long drifter (red: coastal group; blue: outer group; green: intermediate drifter) and glider (black) track segments, with dot corresponding to the end of the second day, between 3 and 20 July. Cumulative tracks are shown in light grey shade.

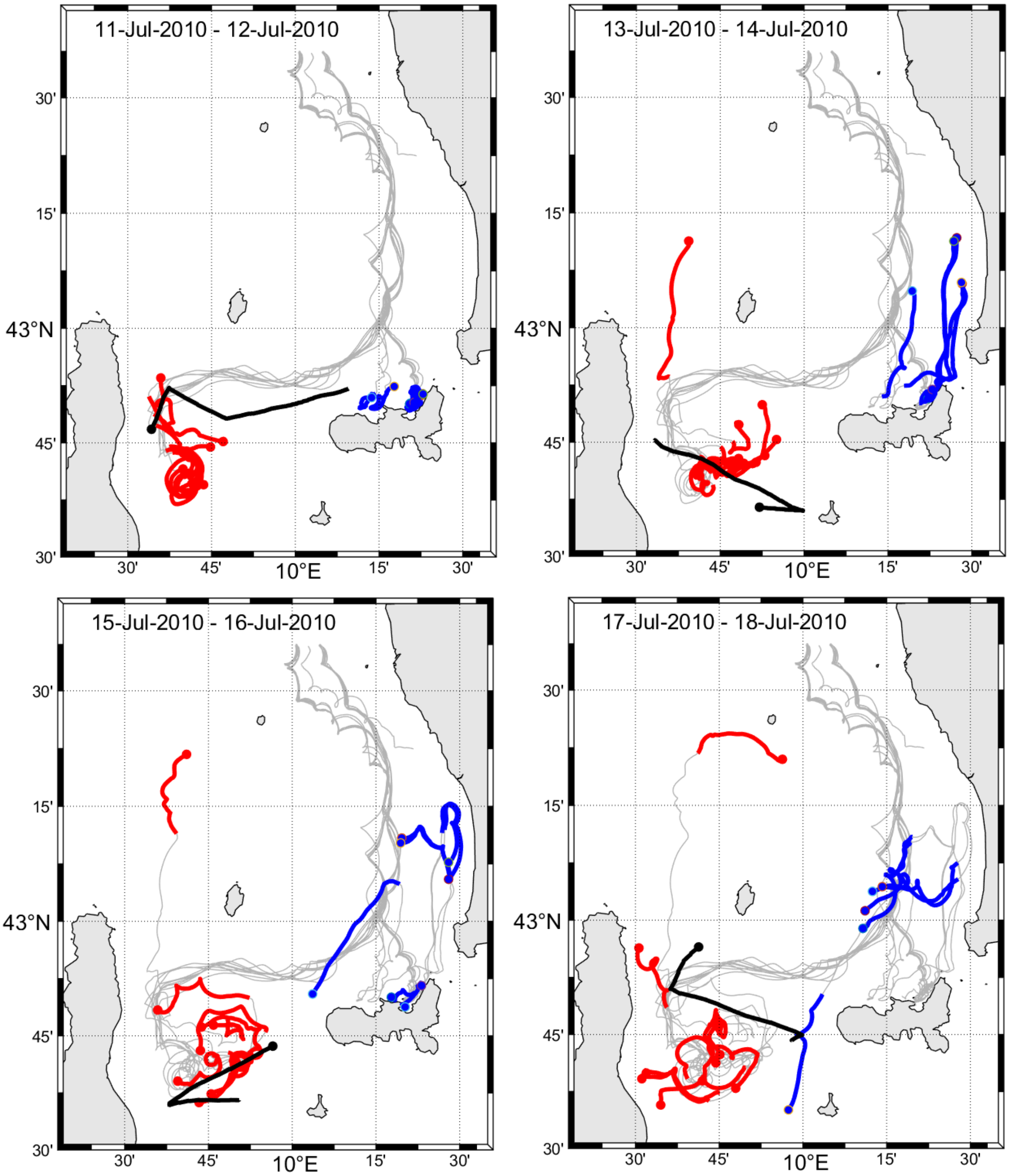
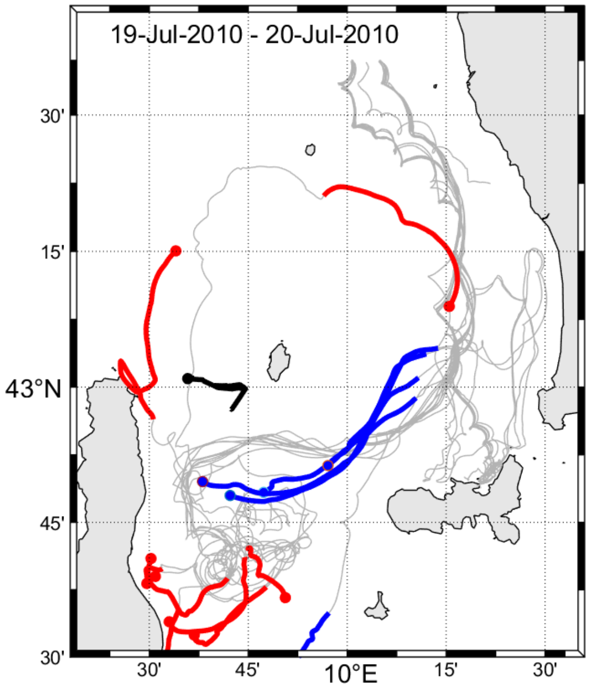


Figure 2. Continued.



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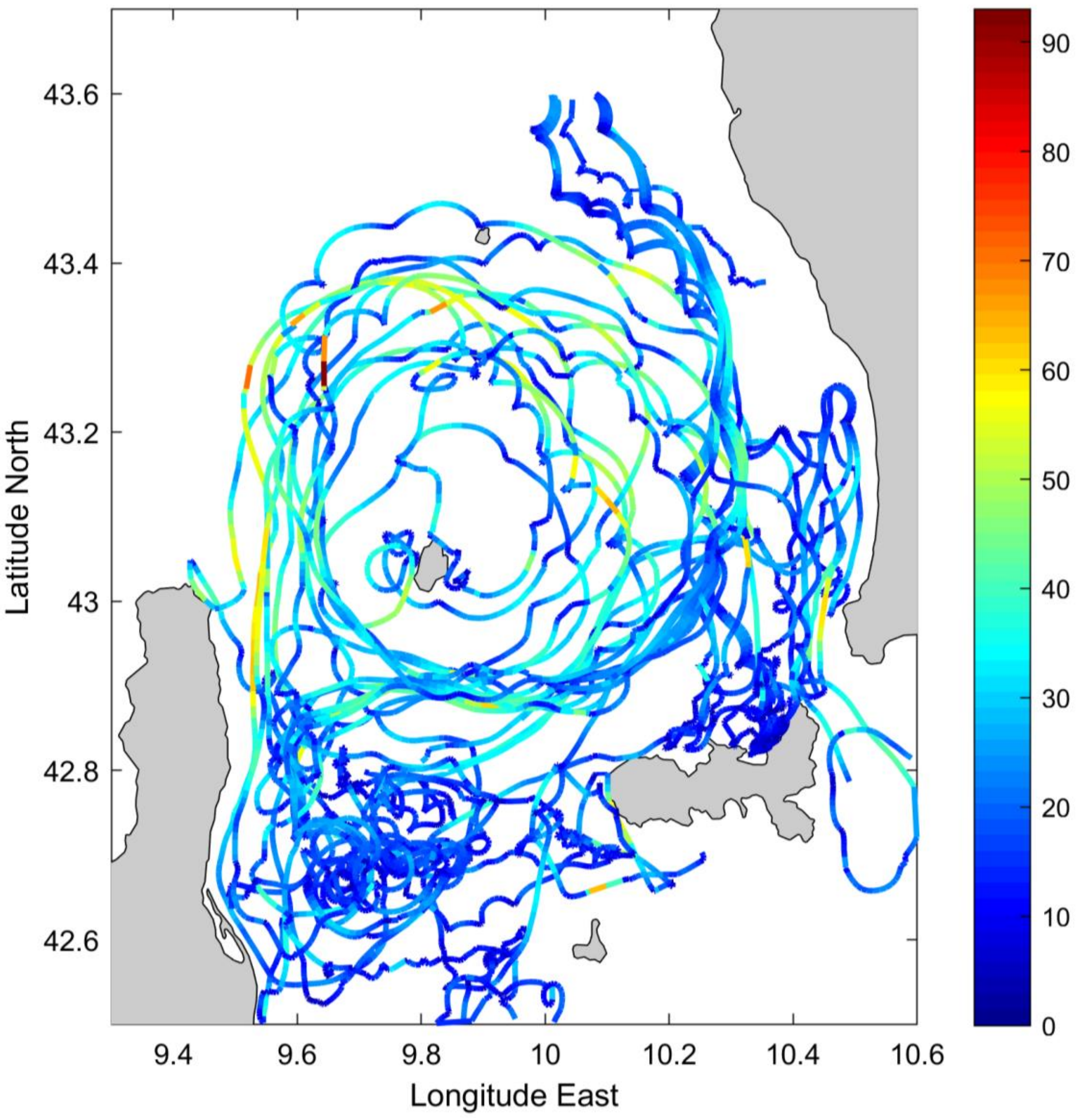

Figure 3. Drifter trajectories for the period 3 July – 27 August 2010 color-coded as a function of drifter speed (cm/s).

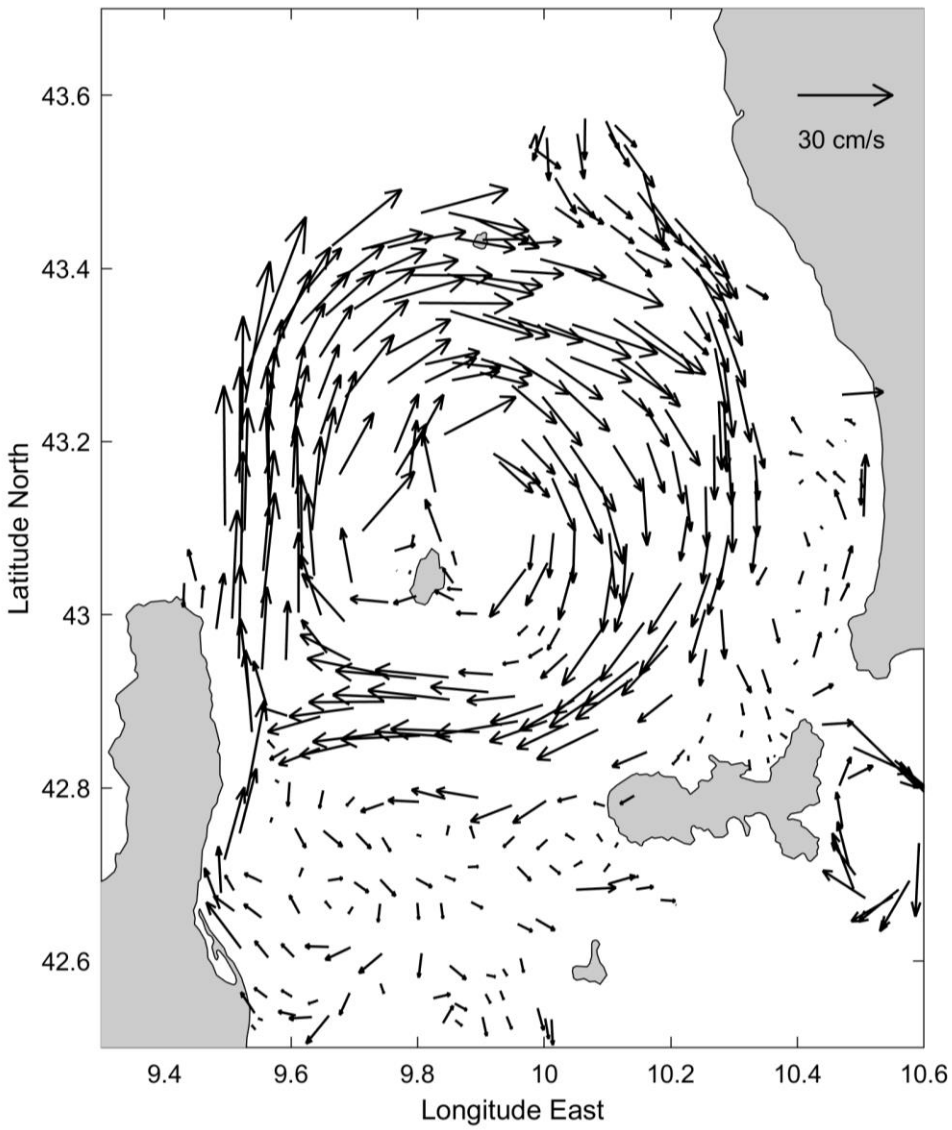

Figure 4. Mean surface circulation (arrows) and mean kinetic energy (colors, cm^2/s^2) in study area for the period 3 July – 27 August 2010 using bins of 0.05º x 0.05º. Bins with less than 5 hourly observations were omitted.

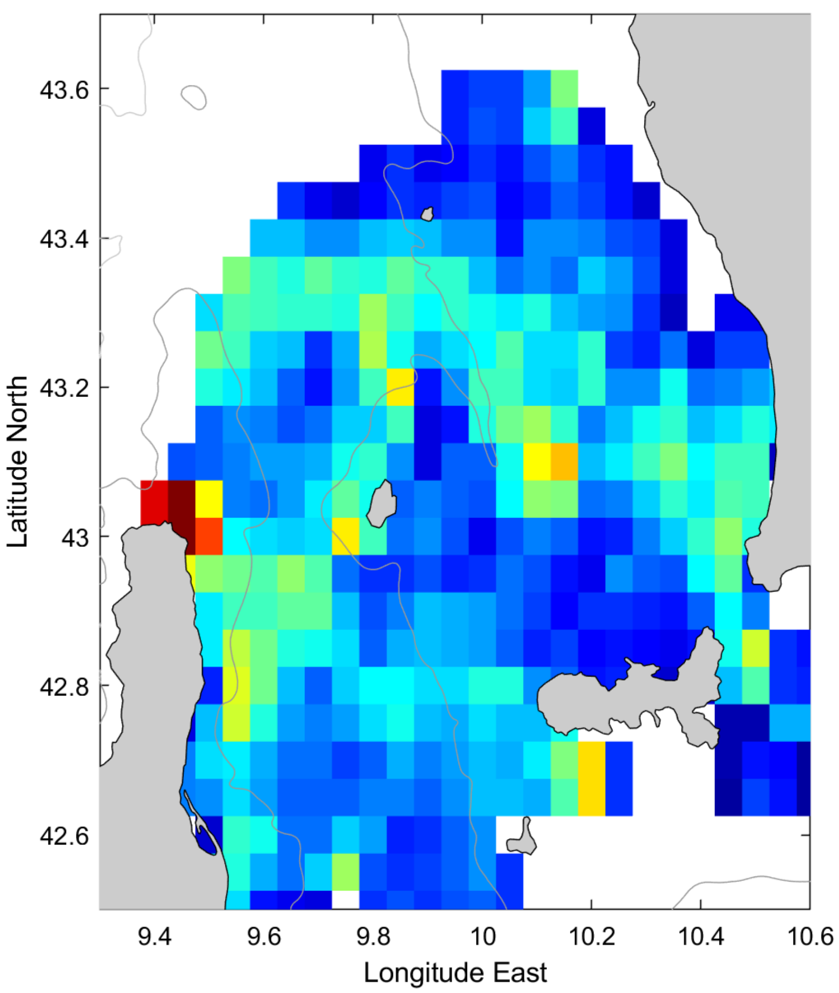

Figure 5. Kinetic energy per unit mass of the velocity residuals or eddy kinetic energy (EKE, $cm^2\ s^{-2}$) in study area for the period 3 July – 27 August 2010 using bins of 0.05º x 0.05º. Bins with less than 5 hourly observations were omitted.

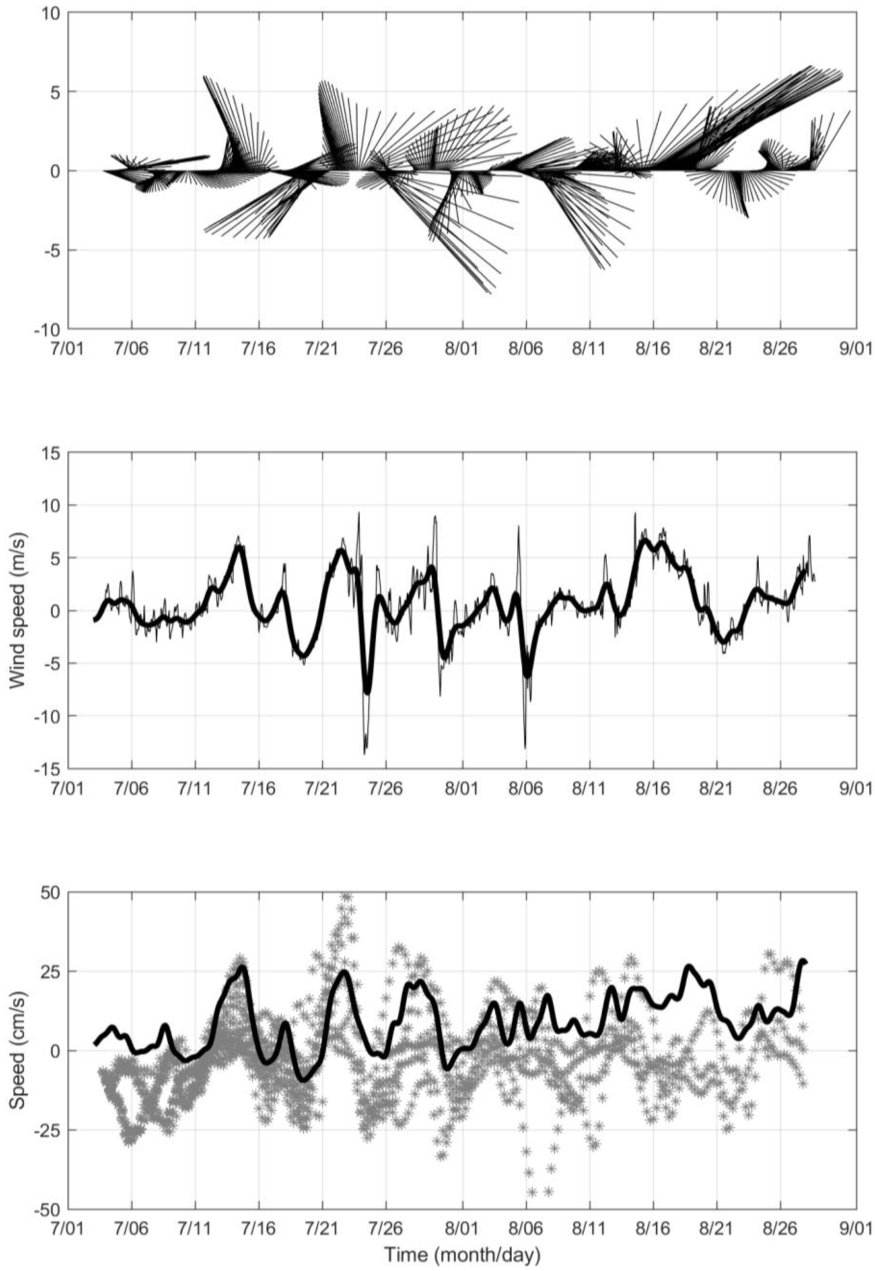

Figure 6. Stick diagram of the low-pass filtered COSMO-ME 10-m winds at grid point 43˚ 7.5’ N, 9˚ 37.5’ E in the CC between 3 July and 27 August 2010 (top panel). Full (thin curve) and low-pass filtered (tick curve) COSMO-ME 10-m wind meridional component at the same location (middle panel). Low-pass filtered near-surface velocities at 32 m in the CC from mooring data (thick curve) and low-pass filtered velocities (light grey stars) of all the drifters in the study area (bottom panel).

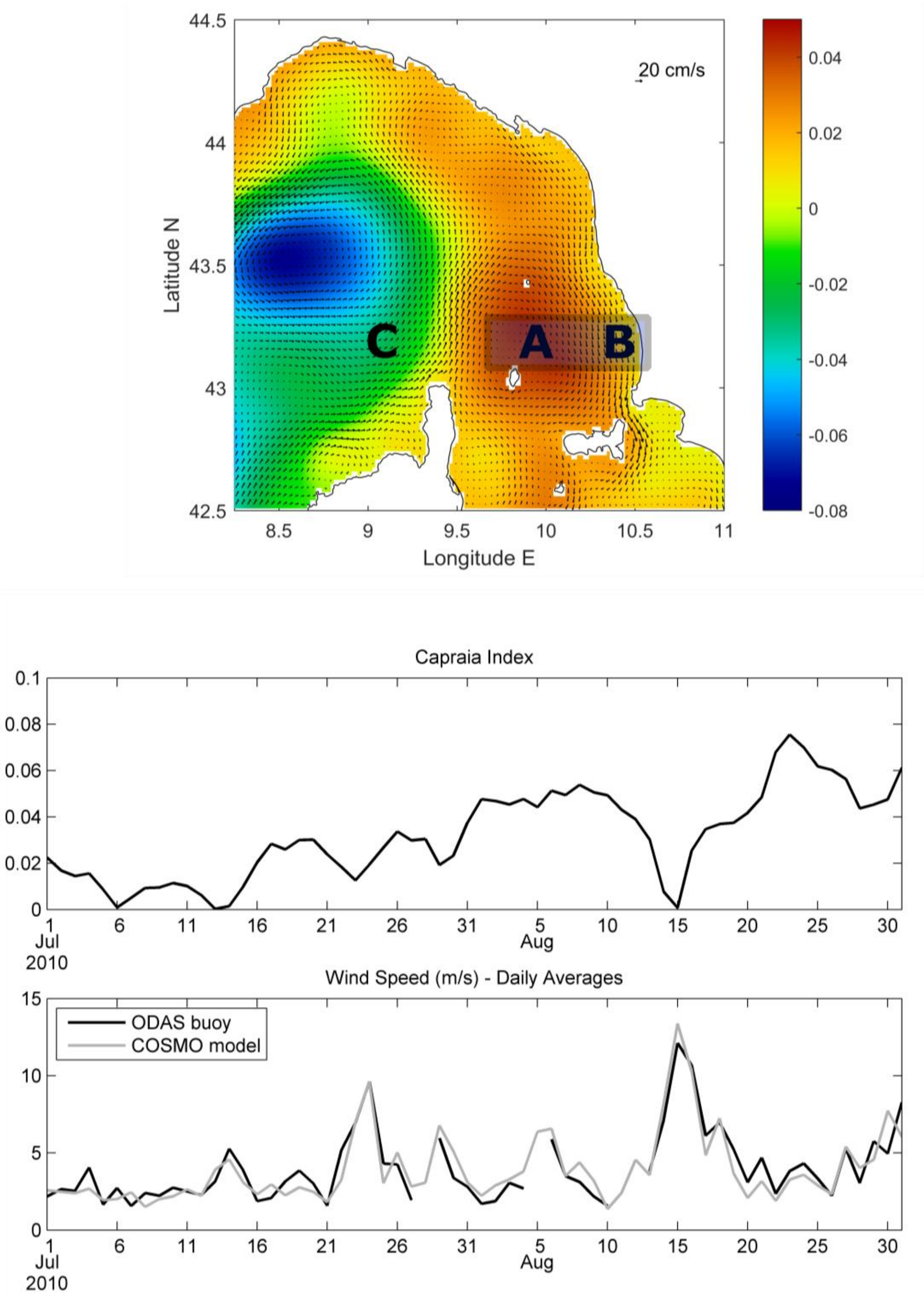

Figure 7. Ligurian Sea average circulation in July-August 2010 as simulated by ROMS (top panel). Colour is sea surface height (m) and arrows surface currents. Evolution of the daily average of the Capraia Index (m; middle panel) confronted to the daily average of COSMO-ME 10-m wind speed (m/s) at the ODAS buoy location and the measured ODAS 10-m wind speed (bottom panel).

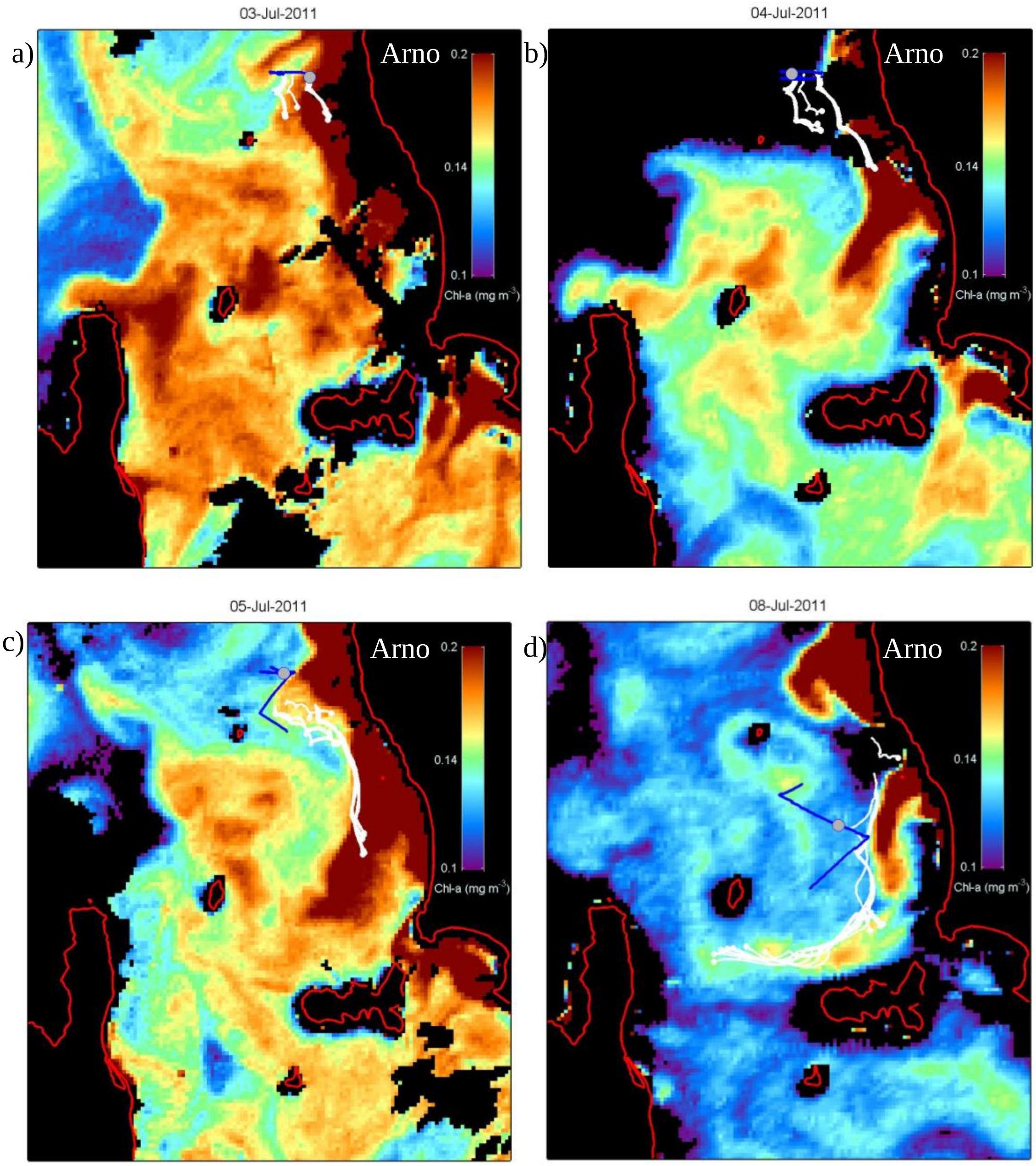

Figure 8. MODIS images of chlorophyll concentration on 3, 4, 5 and 8 July 2010, superimposed with centered 2-day long trajectories of drifters (white) and glider (blue). The gray dot represents the location of the glider at 12 GMT, contemporaneous with the satellite images.

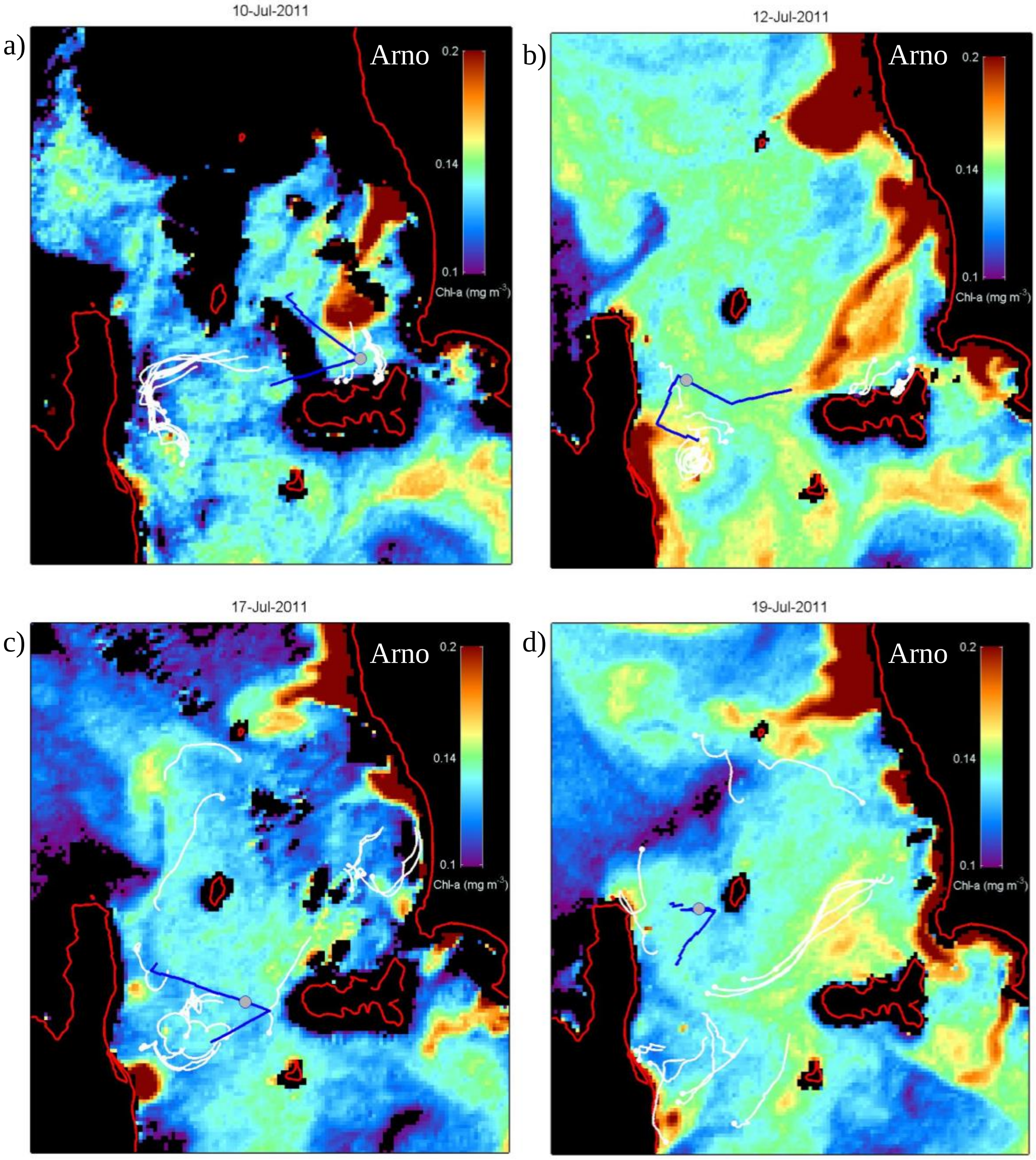

Figure 9. Same as Figure 8 but for 10, 12, 17 and 19 July 2010.

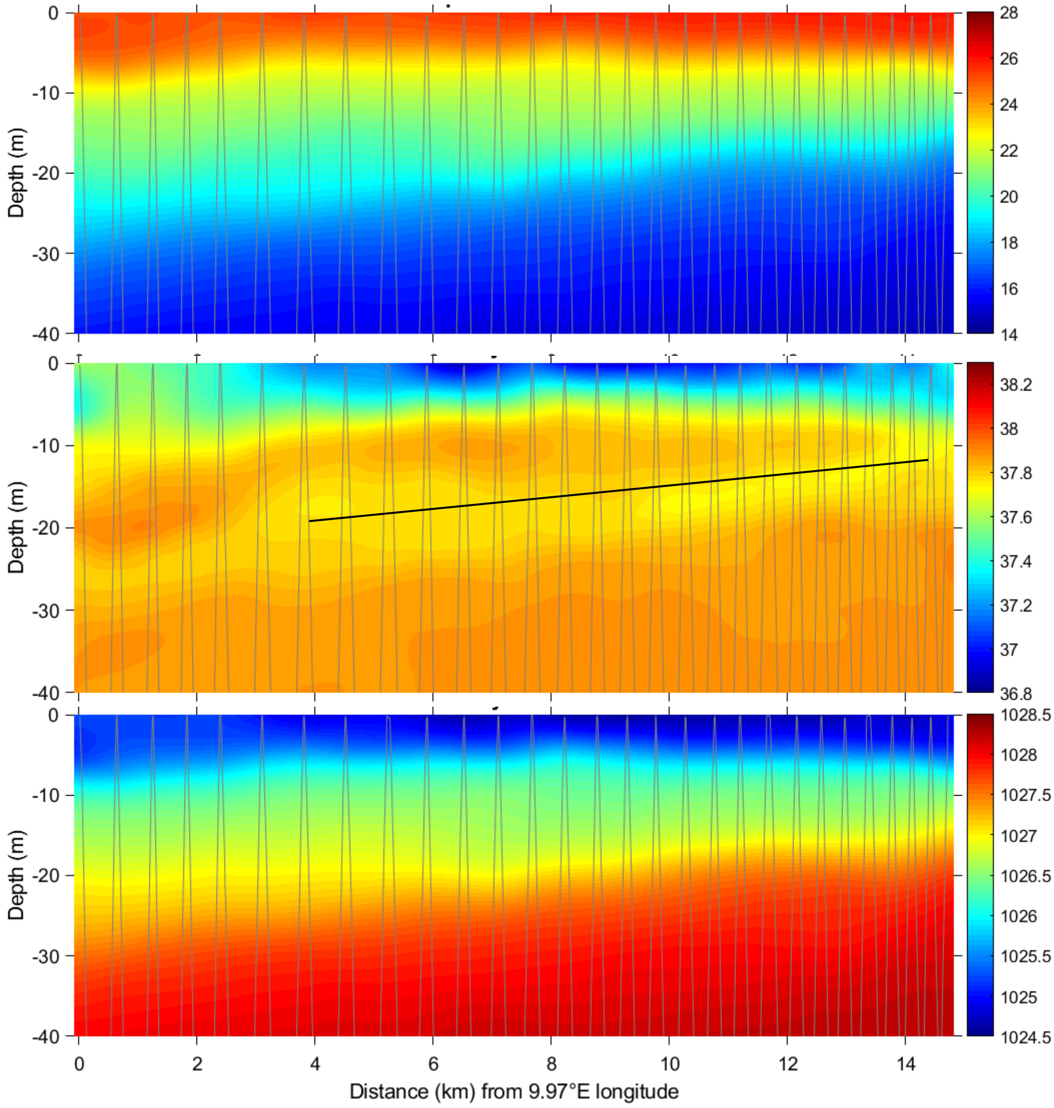

Figure 10. Contour plots of temperature (°C, top), salinity (middle) and density (kg/m^3, bottom) versus depth and horizontal distance along glider transect 1. The origin is the westernmost location and the glider yo-yo track is shown with light grey lines. In the middle panel, a black line indicate subduction of less saline water along the isopycnals.

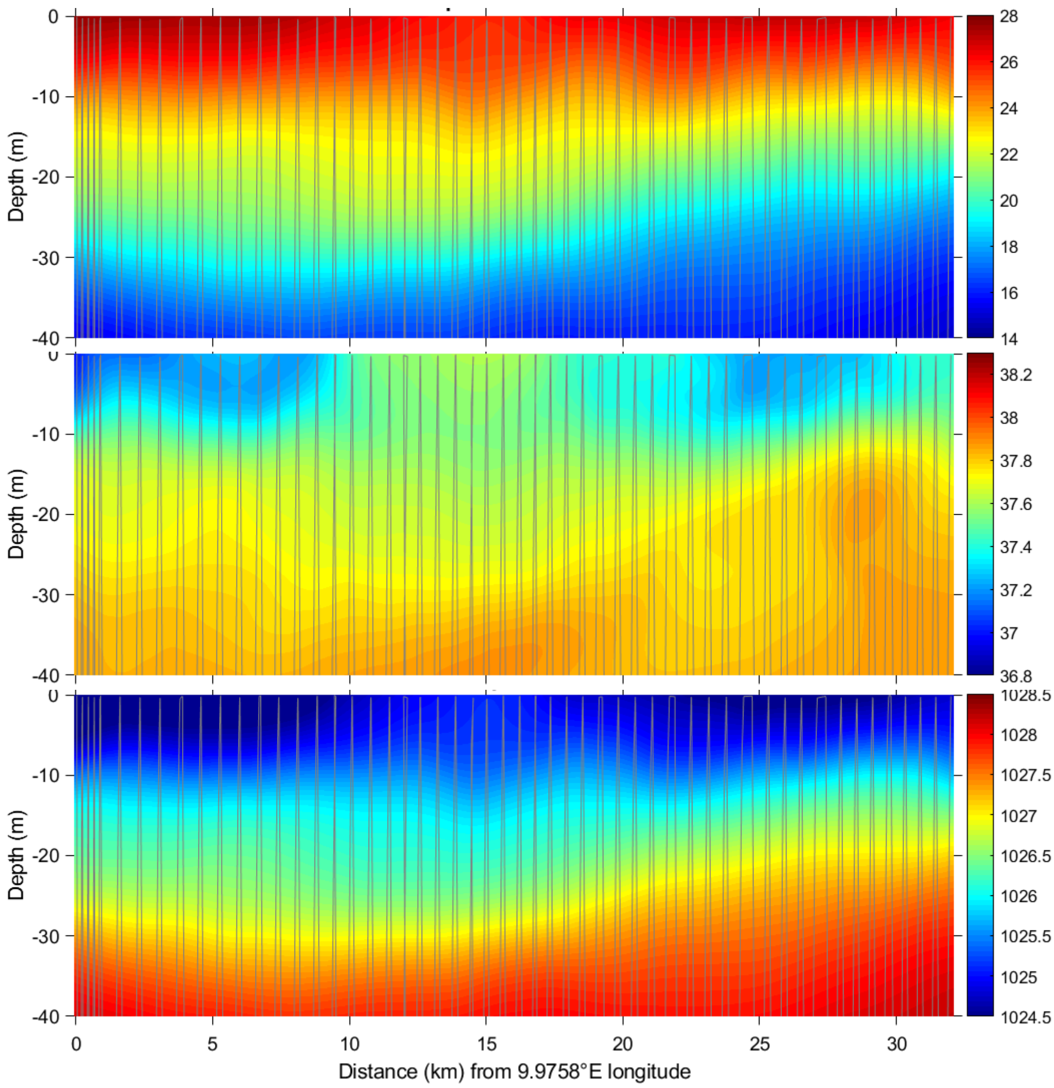

Figure 11. Same as in Figure 10 but for glider transect 8.

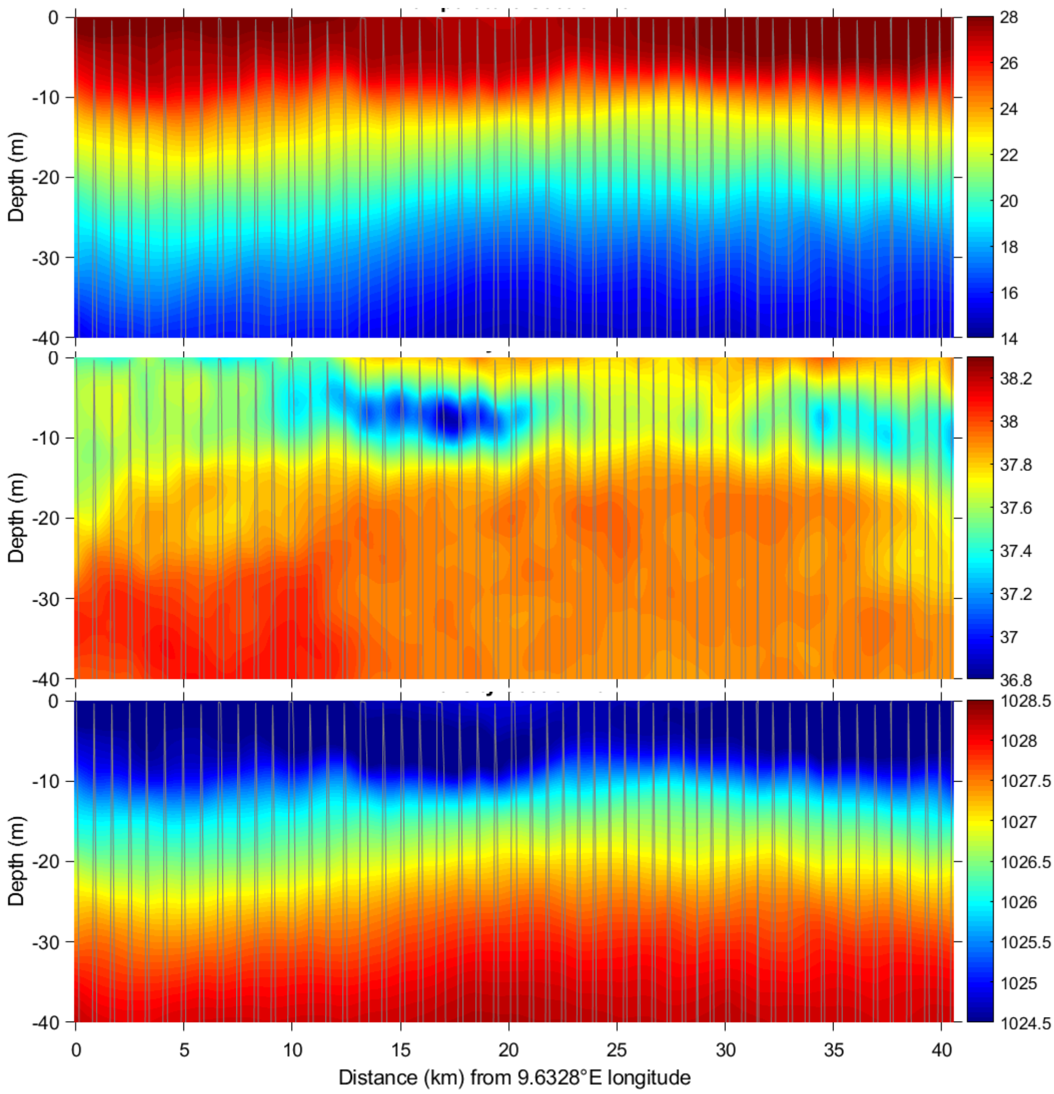

Figure 12. Same as in Figure 10 but for glider transect 15.

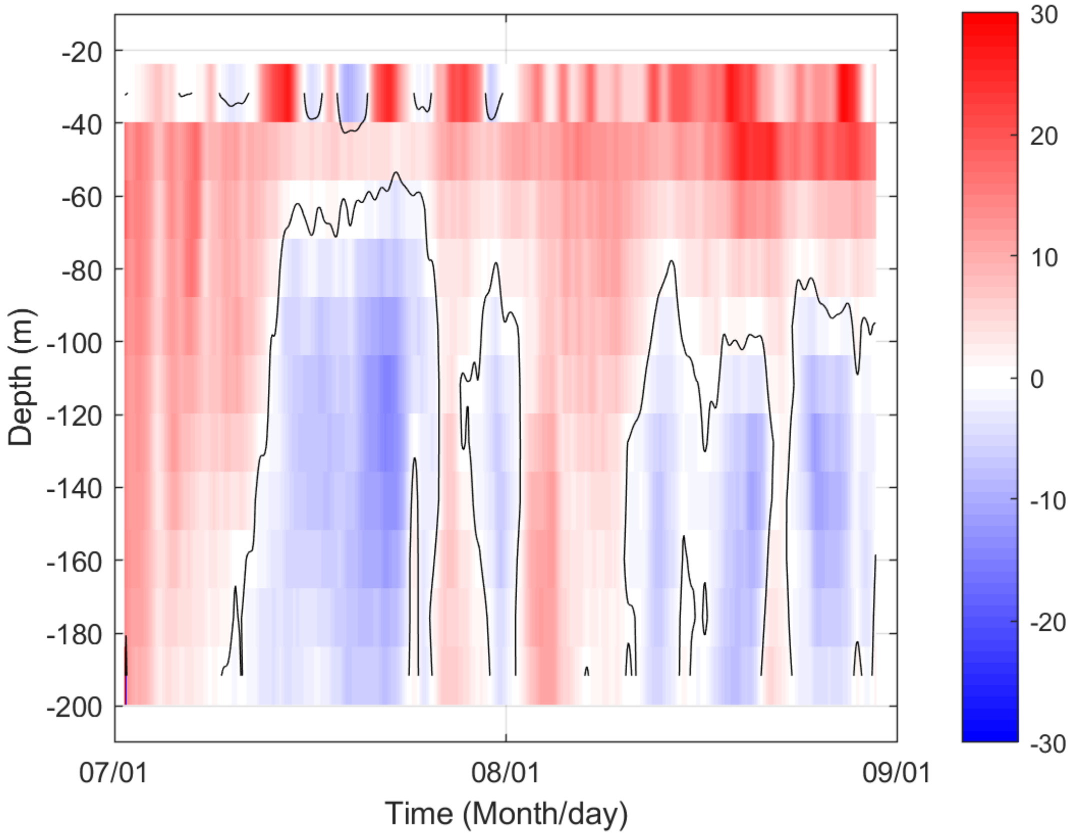

Figure 13. Meridional velocity (cm/s) measured by the moored ADCP in the CC (positive northward) as a function of time and depth above 200 m depth. The uppermost ADCP cell was excluded. The null value is contoured with black curves.