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Recent improvements in mesoscale characterization of the western Mediterranean Sea: synergy between satellite altimetry and other observational approaches

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SUMMARY: Satellite altimetry is a key component of the global observing system and plays a major role in the study of the mesoscale processes that drive most of the ocean circulation variability at middle and high latitudes. However, satellite altimetry alone provides only surface information at a limited spatio-temporal resolution. To address these limitations and to better describe the mesoscale three-dimensional variability, it is necessary to complement altimetry data with additional remote and in situ measurements. This study provides an update of the recent advances in the study of the mesoscale variability using a combination of altimetry and other independent observations, with an emphasis on the results obtained for the western Mediterranean Sea. The circulation in this area is complex because of the presence of multiple interacting scales, including basin-scale, sub-basin–scale and mesoscale structures. Thus, characterizing these processes requires high-resolution observations and multi-sensor approaches. Accordingly, multi-platform experiments and analyses have been designed and undertaken in the different sub-basins of the western Mediterranean Sea. These studies have demonstrated the advantages of synergetic approaches that use a combination of observation techniques and are able to resolve different spatio-temporal scales with the aim of better understanding mesoscale dynamics.

Keywords: satellite altimetry, mesoscale variability, instruments and techniques, Mediterranean Sea.

RESUMEN: AVANCES RECIENTES EN LA CARACTERIZACIÓN DE LA MESOESCALA EN LA CUENCA MEDITERRÁNEA OCCIDENTAL: SINERGIAS ENTRE ALTIMETRÍA Y OTROS SISTEMAS DE OBSERVACIÓN. – La altimetría satelitaria es una componente clave del sistema de observación global y juega un papel importante en el estudio de los procesos de mesoescala que impulsan la mayor parte de la variabilidad de la circulación oceánica en las latitudes medias y altas. Sin embargo, la altimetría por satélite sólo proporciona información superficial y con una resolución espacio- temporal limitada. Para hacer frente a estas limitaciones, es necesario complementar los datos de altimetría con otras medidas. Este estudio proporciona una actualización de los avances recientes en el estudio de la variabilidad de mesoescala utilizando una combinación de observaciones altimétricas con otros datos independientes en el Mediterráneo Occidental. La circulación en esta zona es compleja debido a la presencia de múltiples escalas interactuando entre ellas: cuenca, sub-cuenca y estructuras de mesoescala. Por tanto, la caracterización de estos procesos requiere de alta resolución en las observaciones y de enfoques multi-sensoriales. En este trabajo, presentamos una revisión de diversos experimentos multi-plataforma que se han diseñado y llevado a cabo en los diferentes sub-cuencas del Mediterráneo occidental durante los últimos años. Estos estudios han demostrado las ventajas de los enfoques sinérgicos y métodos innovadores que utilizan una combinación de técnicas de observación, y que son capaces de mejorar nuestra comprensión de la dinámica de mesoescala.

Palabras clave: altimetría, variabilidad de mesoescala, instrumentos y técnicas, mar Mediterráneo.

INTRODUCTION

Satellite altimetry has revolutionized our understanding of surface circulation in the global ocean as a result of the continuous sea surface topography measurements provided by several altimeter missions (TOPEX/Poseidon, ERS-1, ERS-2, Geosat Follow-On, Jason-1, Envisat and OSTM/Jason-2). In two decades of this research, major breakthroughs have been achieved. For example, it is now possible to quantify the kinetic energy of eddies in relation to mesoscale activity, which is the dominant surface signal in mid- and high-latitude areas (Le Traon and Morrow 2001, Pascual *et al.* 2006). Altimetry records can also be exploited to identify and track mesoscale features (Isern-Fontanet *et al.* 2006, Chelton *et al.* 2007, 2011a) and to investigate the potential impacts on biogeochemical processes (Siegel *et al.* 2011, Chelton *et al.* 2011b). A wide range of published studies have used altimetry observations for both global and regional applications, including semi-enclosed seas such as the Mediterranean Sea.

In the context of ocean variability, the Mediterranean Sea is considered a "miniature ocean" (Bethoux and Gentili 1999), a kind of ideal, accessible, reduced-scale ocean laboratory where many phenomena that are present in different regions of the global ocean can be studied at a smaller scale, including deep convection (MEDOC Group 1970, Leaman and Schott 1991, Herrmann *et al.* 2009), shelf-slope exchanges (Bethoux and Gentili 1999), thermohaline circulation and water mass interaction (Wüst 1961), and mesoscale and submesoscale dynamics (Robinson *et al.* 2001). Despite its small size, the thermohaline circulation within the basin is particularly active (Wu and Haines 1996). Robinson *et al*. (2001) give a value of 10-14 km for the internal Rossby radius of deformation, which is one fourth of the typical value in the open ocean. Physical mechanisms are thus more easily monitored and understood in this ocean basin, which contributes to the advancement of knowledge of physical interactions and biogeochemical coupling at near-shore, local, sub-basin and global scales (Tintoré *et al*. 2012).

Altimetric data have provided access to realistic sea surface variability in the Mediterranean Sea. Ayoub *et al*. (1997) and Iudicone *et al*. (1998) highlighted the intricate amalgamation of spatial and temporal scales characterizing the surface circulation variability. Larnicol *et al*. (2002) used a longer study period (1993-1999) to identify the major changes that have occurred in the Mediterranean Sea. Particularly interesting were the detection of strong interannual and seasonal signals in the eastern Mediterranean and the seasonality of the Alborán Gyres in the western Mediterranean. The study underscored the need to continue monitoring the surface circulation to better understand the dynamics of the Mediterranean Sea. Subsequently, Pujol *et al*. (2005) analysed 11 years of eddy kinetic energy (EKE) variability, merging T/P, Jason-1, ERS and Envisat data. Particular efforts to improve the data selection and resolution in the mapping procedure were conducted, showing that mesoscale, seasonal and interannual signals dominate EKE variance.

The contribution of the different temporal scales of variability was quantified in Cipollini *et al*. (2008). By computing the Fast Fourier Transform of the sea-level anomaly (SLA) time series, Cipollini *et al.* (2008) found that the low frequency variability (Fig. 1a) was dominated by the Ionian Sea and the Algerian Basin. The annual signal (Fig. 1b) was almost uniform throughout the basin, with the exception of the Eastern Alborán Gyre and the Ierapetra eddy, which is the most intense peak. The shorter time scales in Figures 1c, 1d and 1e highlighted several areas of known mesoscale activity, most notably in the Alborán and Algerian basins, which peak at 1.5-4.5 months, while the higher frequency signal (periods <1.5 months) was in general of the order of altimetric noise (2-3 cm rms), a fact that proves the need for a better temporal resolution.

Isern-Fontanet *et al*. (2006) showed, for the first time, that a criterion based on the Okubo–Weiss parameter permitted the detection of mesoscale features from altimetric SLA maps. A census of these features revealed statistical properties of the vortices in the Mediterranean Sea, and a tracking algorithm provided the first global picture of eddy preferential paths showing complex but well-defined patterns. More recently, D'Ovidio *et al*. (2009) studied transport and mixing properties of surface currents from altimetric data from both Eulerian and Lagrangian (finite-size Lyapunov exponent diagnostics) perspectives. These two approaches provided similar results for slowly evolving eddies such as the first Alborán Gyre. However, the Lyapunov exponent was able to predict the submesoscale filamentary processes occurring along the Algerian Current.

An important contribution to the study of total mesoscale circulation is the development of a mean dynamic topography (MDT) because, given the present shortcomings of current geoid models, altimetric measurements only provide access to the sea surface signature associated with the variable geostrophic circulation (Cazenave and Royer 2001). Thus, the mean circulation must be analysed from alternative sources. One of these alternative methods uses approximations derived from numerical models as a first guess and subsequently makes local corrections using in situ observations. The first MDT of the Mediterranean Sea was computed by Rio *et al*. (2007) using average data over the period from 1993 to 1999 of dynamic topography outputs from a numerical model output as a first guess. In a second step, drifting buoy and altimetry velocities were combined with a synthetic method to obtain local estimates of the mean geostrophic circulation, which were subsequently used to improve the first guess through an inverse technique to map the synthetic MDT onto a 1/8° grid. The MDT successfully reproduced the primary patterns of the surface circula-

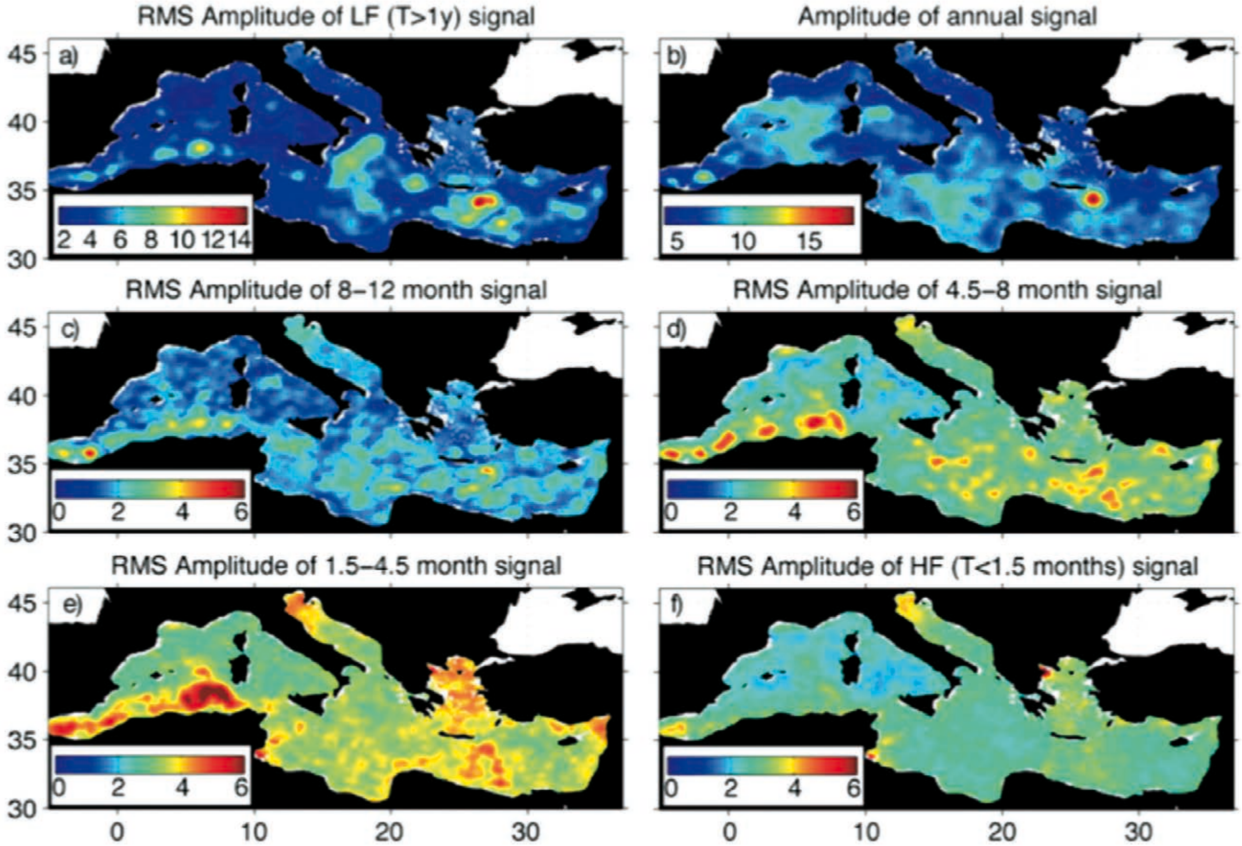

FIG. 1. – Decomposition into spectral bands of SLA variability. RMS amplitude (in cm) of: a) low-frequency signals (with a period >1 year); b) annual component; c) signals between 8 months and 1 year; d) signals between 4.5 and 8 months; e) signals between 1.5 and 4.5 months; f) high-frequency signals (with a period <1.5 months) (from Cipollini *et al.* 2008, Copyright Springer).

tion in the Mediterranean Sea (more details are provided in Section 2). However, several limitations were also identified, and some improvements were achieved in Dobricic *et al*. (2005).

All of these studies were based on the combination of two altimeter missions, which do not fully resolve mesoscale structures of 10-100 km (Le Traon and Dibarboure 2004, Tai 1998), the typical scale for the Mediterranean Sea. In this respect, Pascual *et al.* (2007) intercalibrated and merged four altimeter missions [Jason-1, ERS-2, TOPEX/Poseidon (T/P) interleaved and Geosat Follow-On (GFO)] to improve the description of surface mesoscale activity in the Mediterranean Sea. Mean EKE was estimated from different altimeter configurations, providing evidence that the classical combination of two missions (Jason-1 + ERS-2) failed to reproduce several intense signals, as was revealed through a comparison with other independent data. Conversely, when T/P interleaved was included in the analysis, these features were retrieved, and the primary current systems in the Mediterranean Sea did not show discontinuities related to sampling artifacts. The fourth mission (GFO) was more moderately effective but increased the accuracy of detection of certain structures. The study concluded that at least three, but preferably four, altimeter missions are required to effectively monitor the Mediterranean surface mesoscale variability.

However, it is necessary to complement altimetry data with alternative remote and in situ sensors to fully characterize the three-dimensional circulation covering the full spectrum of spatio-temporal scales. Moreover, multi-source data also help in distinguishing noise from small dynamical structures as a result of cross-calibrations and validations between the different sensors. This assemblage of multi-source alternative data paves the way to a complete exploitation of the available observation systems, which is likely to lead to improved capabilities for mesoscale studies.

In this study, we review recent advances in mesoscale variability as seen through the merging of altimetry and independent observations in the western Mediterranean, one of the two sub-basins of the Mediterranean Sea, where the circulation is complex due to the presence of multiple interacting scales, including basin scale, sub-basin scale and mesoscale dynamics. These processes require high-resolution observations and multi-sensor approaches. Accordingly, multi-platform experiments have been designed and conducted in the different sub-basins of the western Mediterranean Sea, highlighting the need for synergetic approaches through the combined use of observation systems at several spatio-temporal scales.

The article is organized as follows. We first briefly review the surface circulation in the study area as de-

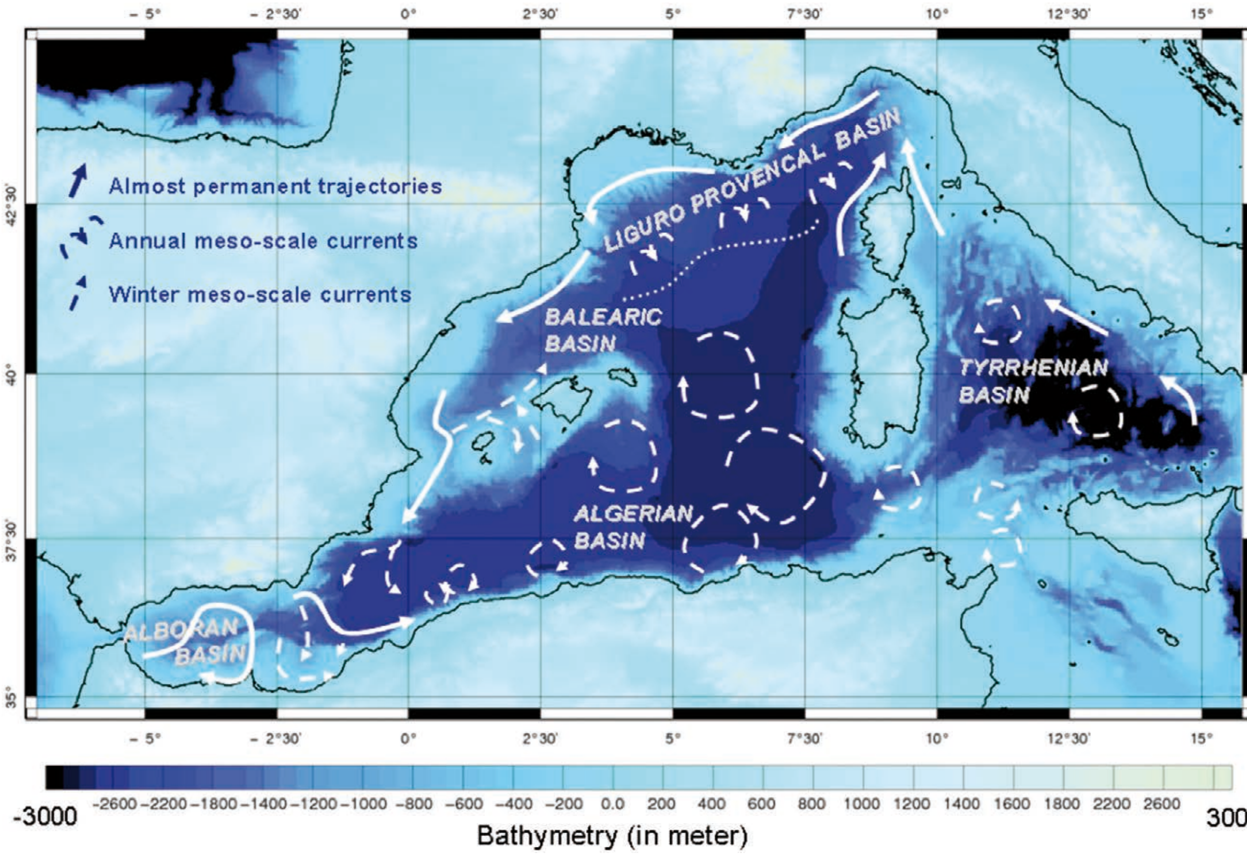

FIG. 2. – The western Mediterranean Sea and the basins considered in this study. The colour contours represent the bathymetry and the primary surface circulation patterns are indicated with continuous and discontinuous lines (adapted from Millot and Taupier Letage 2004).

scribed by previous studies. Then we focus on the major findings in each sub-basin of the western Mediterranean Sea with the goal of better understanding mesoscale variability by combining, comparing, validating and contrasting altimetric data with alternative sensors. Finally, a summary is presented and the challenges for the near future are addressed.

STUDY AREA

The western Mediterranean is one of the two basins of the Mediterranean Sea, a mid-latitude, semi-enclosed sea linked to the Atlantic Ocean through the Strait of Gibraltar. The western (WMED) and eastern (EMED) Mediterranean basins are connected by the Sicily Strait and are composed of several sub-basins, that are characterized by different oceanographic features (topography, water masses and atmospheric forcing) and separated by straits and channels (Astraldi *et al.* 1999). Figure 2 shows the sub-basins of the WMED with the primary surface currents as described in Millot and Taupier-Letage (2004). In the Alborán Basin, an exchange of water between the Atlantic and the Mediterranean through the Strait of Gibraltar occurs. Therefore, the basin is characterized by an intense inflow/outflow regime and complex circulation patterns. Atlantic waters enter through the Gibraltar Strait at the surface and form a powerful inflow current called the Atlantic Jet. This jet meanders and forms a quasi-permanent gyre in the western portion of the Alborán Basin called the Western Alborán Gyre (WAG) (Viúdez *et al.* 1998, Baldacci *et al.* 2001), in addition to an intermittent Eastern Alborán Gyre (EAG) (Vargas-Yanez *et al.* 2002, Macias *et al.* 2008). The eastern boundary of the EAG typically forms the Almería-Orán front (Tintoré *et al.* 1988) that marks the start of the Algerian Current (Astraldi *et al.* 1999, Millot 1999). At its start, near 0° longitude, the Algerian Current is fairly narrow (30-50 km), flowing close to the coast. As the current progresses eastward, its width and separation from the coast vary and, due to baroclinic instabilities in its flow, meanders are regularly formed and can eventually detach from the current and become both cyclonic and anticyclonic coastal eddies (Olita *et al.* 2011). Some of the stronger eddies, which are predominantly anticyclonic, may become "open sea eddies" and reach the southern Balearic Islands (Millot 1999).

The traditional concept (Millot 1987 and 1999) of the circulation in the Tyrrhenian Basin is based on a cyclonic circulation in the entire water column. However, as noted by Rinaldi *et al.* (2010), the circulation appears to be much more complex, with a combination of mesoscale, seasonal and interannual variability. The northwest Tyrrhenian is characterized by the presence of North Tyrrhenian cyclones (Marullo *et al.* 1994), which are driven by northwesterly winds. In the central-western part of the Tyrrhenian Sea, an anticyclonic gyre is coupled with a North Tyrrhenian cyclone. In the northern part of the Tyrrhenian, where the interannual variability is likely related to teleconnection mechanisms (Vignudelli *et al.* 1999), the seasonal variability is primarily conditioned by steric effects and modulates the exchange between the Tyrrhenian and Ligurian Seas (Marullo *et al.* 1994, Vignudelli *et al.* 1999; 2000). In the southern Tyrrhenian Basin, the dynamics are dominated by the water exchanges through the Sicily and Sardinia Straits.

The Ligurian Provençal Basin, located in the northern part of the WMED, is dominated by the Northern Current, which flows cyclonically along the coasts of Italy, France and Spain, following the bathymetry. The flux is maximum during long winter periods (December-May), with significant mesoscale variability, and it weakens during the summer (Millot 1999). The Gulf of Lions is a site of intense mesoscale activity and winter deep-water formation (Herrmann *et al.* 2008). The Northern Current flows southward along the Spanish coast, enters the Balearic Basin and splits into two branches; one recirculating into the Balearic Current (Ruiz *et al.* 2009a), and one continuing south through the Ibiza Channel (Pinot *et al.* 2002).

The general surface circulation described agrees closely with the synthetic MDT derived by Rio *et al.* (2007), which was obtained by combining numerical modeling outputs, altimeter observations and drifting buoy velocities. In Figure 3, the primary features of the WMED can be identified: WAG and EAG in the Alborán Basin, the Algerian Current meandering along the African Coast and the Northern Current and Balearic Current in the northwestern Mediterranean.

MULTI-SENSOR APPROACHES

The Alborán Basin

As described in the previous section, the Alborán Basin is the transition zone between the Mediterranean Sea and the Atlantic Ocean. The Atlantic water flows into the Alborán Basin at the surface through the Strait of Gibraltar and generally forces two anticyclonic gyres: the WAG and the EAG (La Violette 1984, Allen *et al.* 2001).

The combination of satellite altimetry with independent in situ data has been shown to improve our knowledge of mesoscale dynamics in this area. Flexas *et al.* (2006) provided evidence of a migrated stage of the WAG for the first time using altimetry and syn-

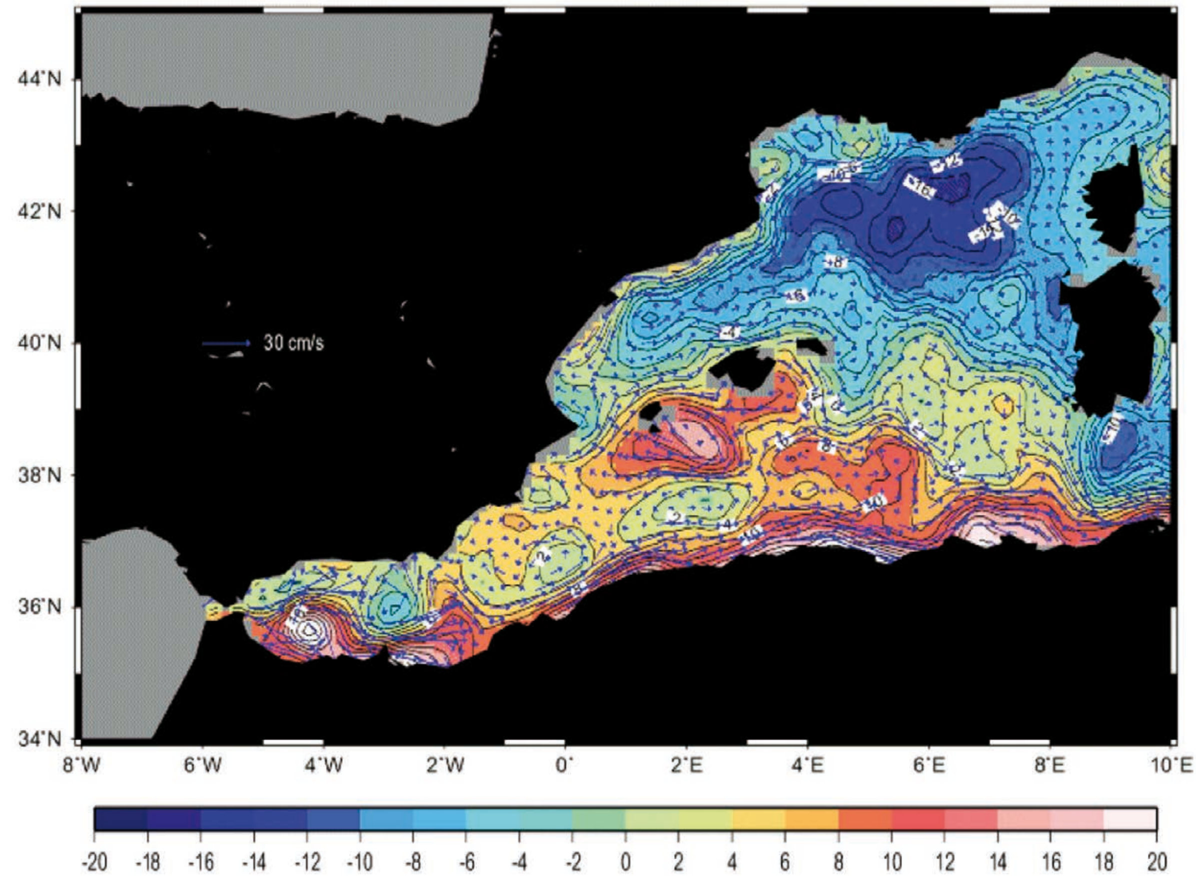

FIG. 3. – The synthetic mean dynamic topography. The units are cm. The associated geostrophic currents are superimposed as blue arrows (from Rio *et al.* 2007, Copyright Elsevier).

optic in situ data. The displaced and deformed WAG was apparent in the weekly averaged SLA maps and sea surface temperature (SST) images. The propagation speed of the gyre was estimated from altimetry as approximately 3.5 km/day. The in situ data collected during an intensive survey (high-resolution CTD with regular sampling) confirmed the anomalous situation of the WAG and permitted the characterization of its 3D structure and the study of the causes of migration (Flexas *et al*. 2006).

Ruiz *et al*. (2009b) reported a pioneering attempt to combine high-resolution (approximately 0.5 km) hydrographic observations from new glider technology with altimetry measurements to quantify vertical exchanges in areas with intense horizontal density gradients. Gliders are autonomous underwater vehicles that provide high-resolution observations in three dimensions, contributing to the characterization of mesoscale processes and multidisciplinary interactions (e.g. Hodges and Fratantoni 2009). The experiment described by Ruiz *et al*. (2009b) was performed in July 2008, and the glider sampling was designed to coincide with an OSTM/Jason-2 passage across track number 172 in the eastern Alborán Basin (western Mediterranean). The mission occurred during the calibration phase of the OSTM/Jason-2 altimeter, just two weeks after the satellite launch. The dynamic height estimated by the glider data revealed a sharp gradient (approximately 15 cm in approximately 100 km) that was consistent with the absolute dynamic topography derived from the Jason-1 and Jason-2 missions (rms differences < 1.6 cm and r > 0.97). As part of the study, Ruiz *et al*. (2009b) proposed a method for estimating vertical motion by (1) merging glider vertical profiles and altimetry gridded products to obtain a full 3D field and (2) using the quasi-geostrophic omega equation (Hoskins *et al*. 1978). The authors reported vertical velocities of approximately 1 m day^{-1}, which are associated with the observed mesoscale circulation (approximately 100 km diameter; Fig. 4).

More recently, Navarro *et al*. (2011) analysed 12 years (1998-2009) of absolute dynamic topography from altimetry and surface chlorophyll to determine coupled patterns of variability in the Alborán Basin. Using a singular value decomposition analysis, the authors demonstrated that the pelagic ecosystem in the Alborán Basin is partially controlled by the inverse barometer effect (first mode). The authors also showed that the distribution of rich and poor areas of chlorophyll could be explained by the second mode.

The Algerian Basin

The Algerian Basin, located in the south of the WMED, is open to the effects of the fairly fresh surface waters coming from the Atlantic and the more saline waters from the northwestern Mediterranean. This area is dominated by the presence and evolution of intense mesoscale eddies (Font *et al.* 2004, Salas *et al*. 2002), which have been studied primarily through remote sensing (altimetry and SST) and scarce in situ data. Ruiz *et al*. (2002) presented a clear example of how to combine altimetry and hydrographic data to characterize the surface and deep structure of an open sea eddy

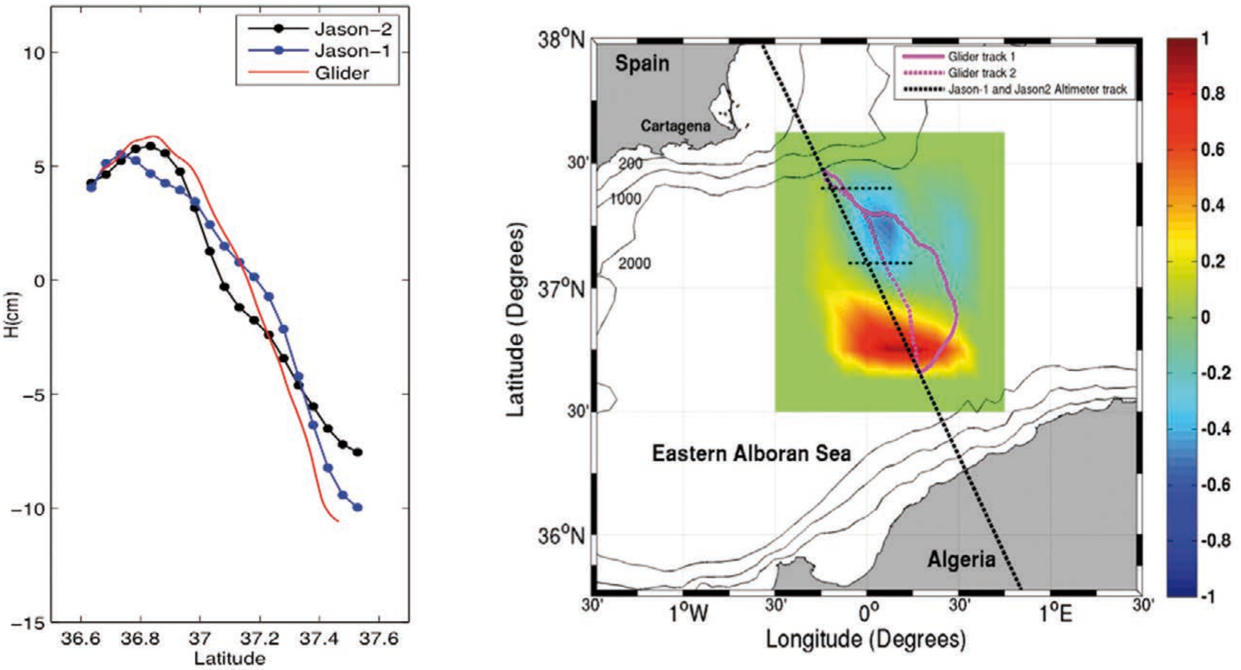

FIG. 4. – (Left) The dynamic height computed along a glider track and the absolute dynamic topography along Jason-1 and Jason-2 altimeter track 172 (dotted line). The units are cm. (Right) The quasi-geostrophic vertical velocity at 75 m. The units are m day^{-1}, with positive/negative values indicating upward/downward motion, respectively (from Ruiz *et al.* 2009; copyright American Geophysical Union).

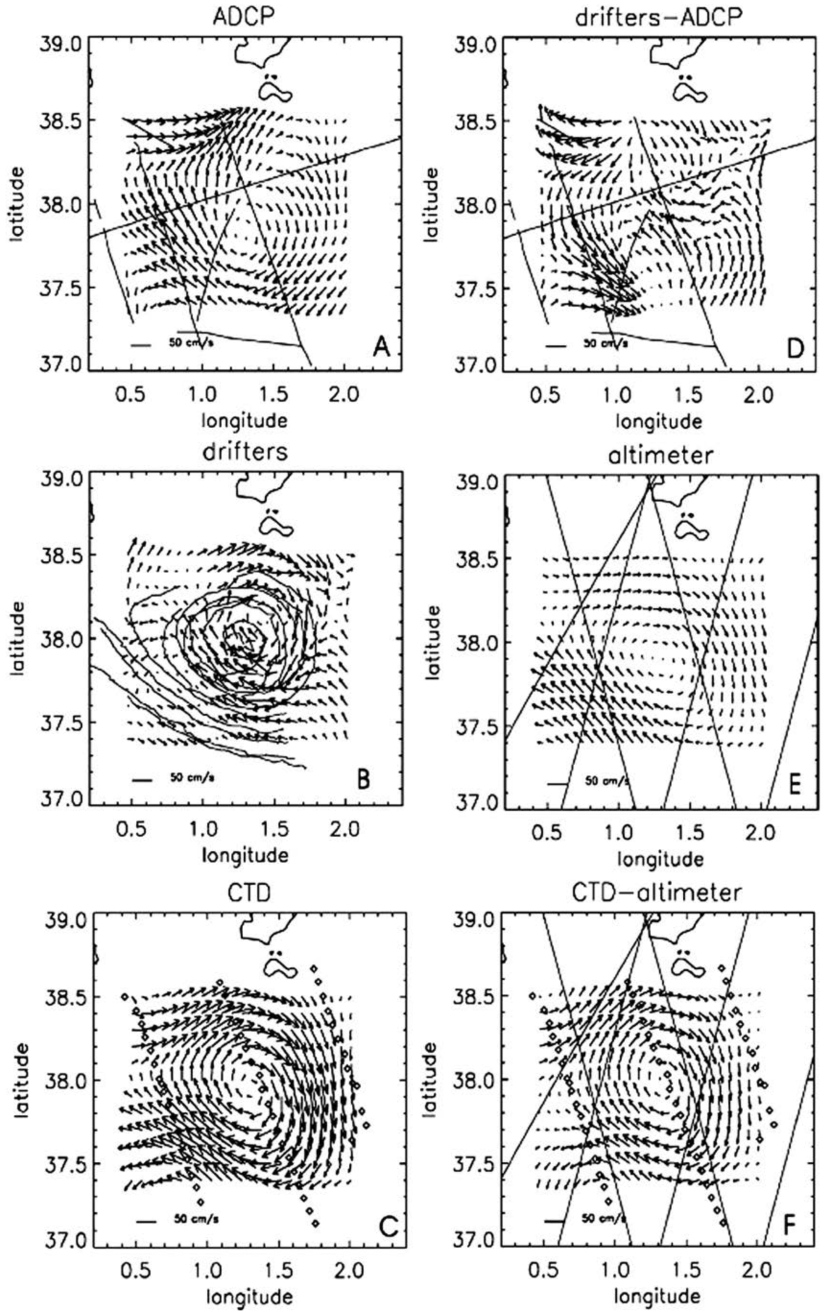

FIG. 5. – The surface velocity field (10 m) generated from ADCP measurements (A), drifters (B) and geostrophic computations using a reference level of 1000 m (C). The difference between (B) and (A) is shown in (D), SLA maps (altimeter) are shown in (E) and the difference between (C) and (E) is shown in (F) (from Ruiz *et al.* 2002; copyright Elsevier).

(150 km diameter and 2800 m depth) of the Algerian Basin. The experiment (AE 98-1) was conducted in May 1998 in a region south of the Balearic Islands. The authors showed that the pattern of the geostrophic velocity field derived from altimetry (Fig. 5) was consistent with independent in situ observations (drifters, ADCP and geostrophic estimations from CTD casts). However, the magnitude was slightly weaker due to the low resolution of the altimetry product (an effect of the correlation scale and smoothing filter). Font *et al.* (2004), using 15 Lagrangian buoys that were launched during the same AE-98-1 experiment and the SLA maps, studied the drift of this large anticyclonic eddy. The authors found remarkable agreement between the identification and characterization of the eddy with the two independent data sets, reporting reasonable average translation speeds (slightly lower from the drifters) and similar diameter sizes (96.5%). Additionally, using the drifter positions, the authors validated the location of the eddy center that was derived from SLA maps.

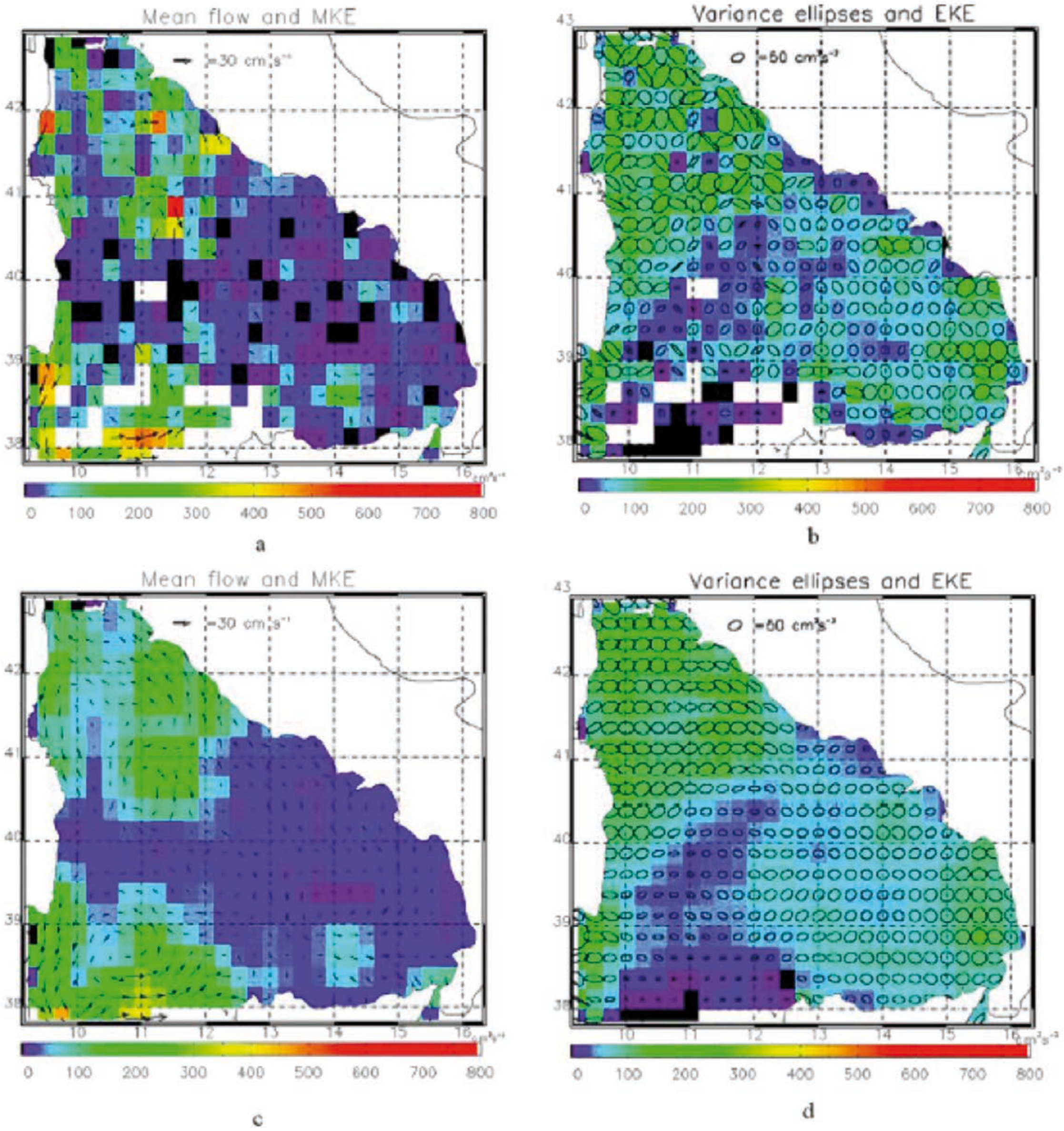

FIG. 6. – Pseudo-Eulerian statistics from drifter data. (a) The mean kinetic energy with superimposed mean flow vectors; (b) The eddy kinetic energy with superimposed variance ellipses; (c) the MKE and mean flow vectors obtained by smoothing the fields shown in panel (a); (d) the EKE and variances ellipses obtained by smoothing the fields shown in panel (b) (from Rinaldi *et al.* 2010; copyright American Geophysical Union).

The Tyrrhenian Basin

Our understanding of the dynamics governing the Tyrrhenian Basin remains incomplete. In particular, little is known about the variability of the primary patterns controlling the large-scale circulation and mesoscale processes of this basin. Some progress has been recently made by Rinaldi *et al*. (2010) through the complementary nature of altimeter measurements and drifter trajectory data. Satellite altimeters provide Eulerian records and Eulerian diagnostics that are generally calculated to analyse the sea level and kinetic energy (KE) variability obtained from the interpolation of along-track altimeter data. Conversely, drifter measurements are typically analysed using a Lagrangian approach, providing a different view of the surface circulation. Furthermore, the space-time variability of drifter trajectories is determined by the full dynamical evolution of the system, whereas altimeters only provide a measure of the geostrophic components of the flow. Even if drifter data generally display large gaps in space and time, a pseudo-Eulerian approach can be used to estimate statistical properties from drifter measurements.

In Rinaldi *et al*. (2010), the advantages and limitations of altimetry and drifter datasets in terms of their physical contents and sampling characteristics are discussed. The work was based on 53 CODE drifter trajectories and 4 years of altimetric maps, which were obtained by merging and interpolating the measurements obtained by four sensors. The approach consisted of splitting the area into sub-regions (bins) and calculating the mean field and associated standard deviation by averaging all of the velocity measurements within each bin (see also Swenson and Niiler 1996, Poulain and Zambianchi 2007). The bin size must include a sufficient number of observations to guarantee the reliability of the estimated statistical variables, but it cannot be too large without resulting in excessive smoothing and resolution that is too low to provide useful information. The resulting circulation pattern was markedly different from the classical schematic view previously described in the literature (e.g. Millot 1987 and 1999). Unexpectedly, the mean flow described a relatively weak and poorly defined general cyclonic circulation combined with sub-basin/mesoscale signals of both a quasi-permanent and a transient nature. The energy associated with these features sustained the mean cyclonic flow, particularly in the southern portion of the Tyrrhenian Basin. Rinaldi *et al*. (2010) also showed that even if the overall circulation pattern revealed in the mean EKE from altimeter and drifter data was comparable, the energy levels were fairly different (Fig. 6a-d). The EKE maps displayed even more marked differences, in terms of both patterns and energy values, even when the different sampling/filtering in the two datasets was accounted for (Fig. 7a-d). In brief, the study revealed that a large part of the drifter EKE could be linked with ageostrophic motions and suggested that interpolated altimeter data underestimate the energy levels associated with variable mesoscale processes.

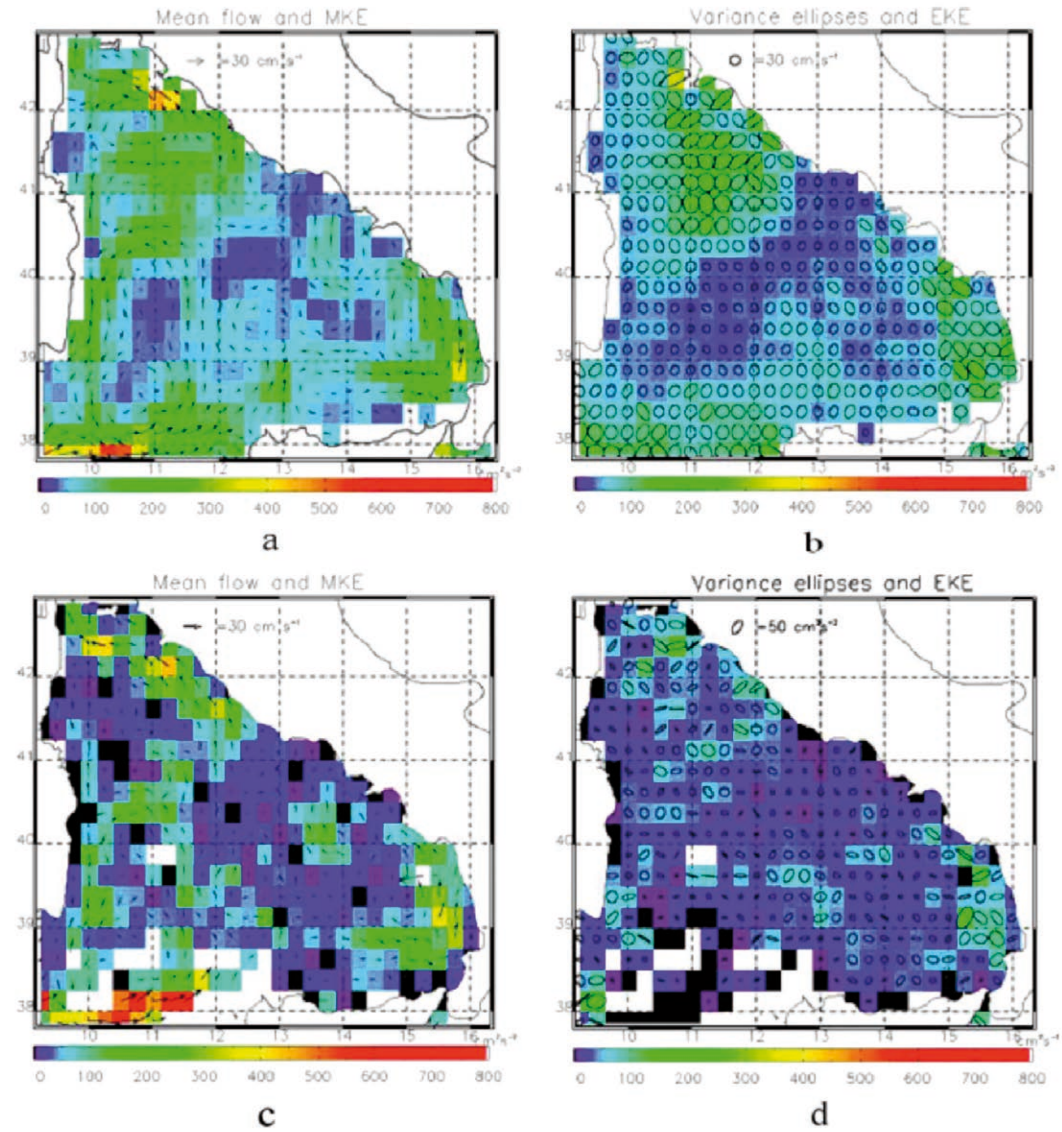

Fig. 7. – Pseudo-Eulerian statistics from altimeter data. (a) The mean kinetic energy with the mean flow vectors superimposed; (b) the eddy kinetic energy with the variance ellipses superimposed; (c) the MKE and mean flow vectors computed using altimeter data sampled in conjunction with the drifter measurements; (d) the EKE and variances ellipses computed using altimeter data sampled in conjunction with the drifter measurements (from Rinaldi *et al.* 2010; copyright American Geophysical Union).

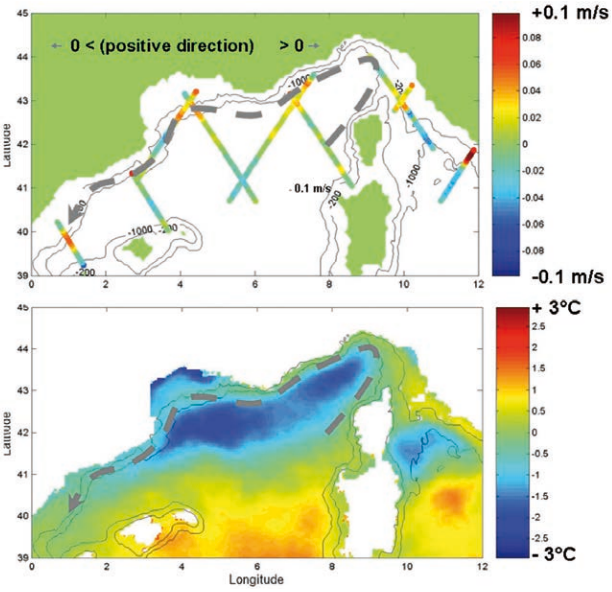

FIG. 8. – (top) The mean across-track geostrophic current anomaly in December from X-TRACK data along the TOPEX/Poseidon and Jason-1 tracks; (bottom) The mean SST anomaly in December obtained from satellite measurements (AVHRR).

The Liguro-Provençal Basin

The major dynamical feature of the Liguro-Provençal Basin is the cyclonic Northern Current, which flows along the Italian, French and Spanish coast, as described in the Study Area section. Observing the complex dynamics of this current with satellite altimetry raises challenging issues given its mean position at a maximum distance of 50 km offshore (where radiometer/altimeter footprints may encounter the coastline) and the wide range of small interacting spatial and temporal scales of variability. This coastal current also shows a strong signature in terms of its SST, with a temperature front that is almost perfectly co-localized with the across-track currents, separating relatively cold offshore water from the coastal area of the Ligurian Sea (Fig. 8).

Birol *et al.* (2010) used in situ ADCP current observations on the Liguro-Provençal slope and compared the measurements with surface geostrophic velocity anomalies derived from satellite altimetry. The analysis indicated close agreement at seasonal scales, showing that the flow is weaker in summer (Fig. 9), as already noted in the literature (e.g. Millot 1990).

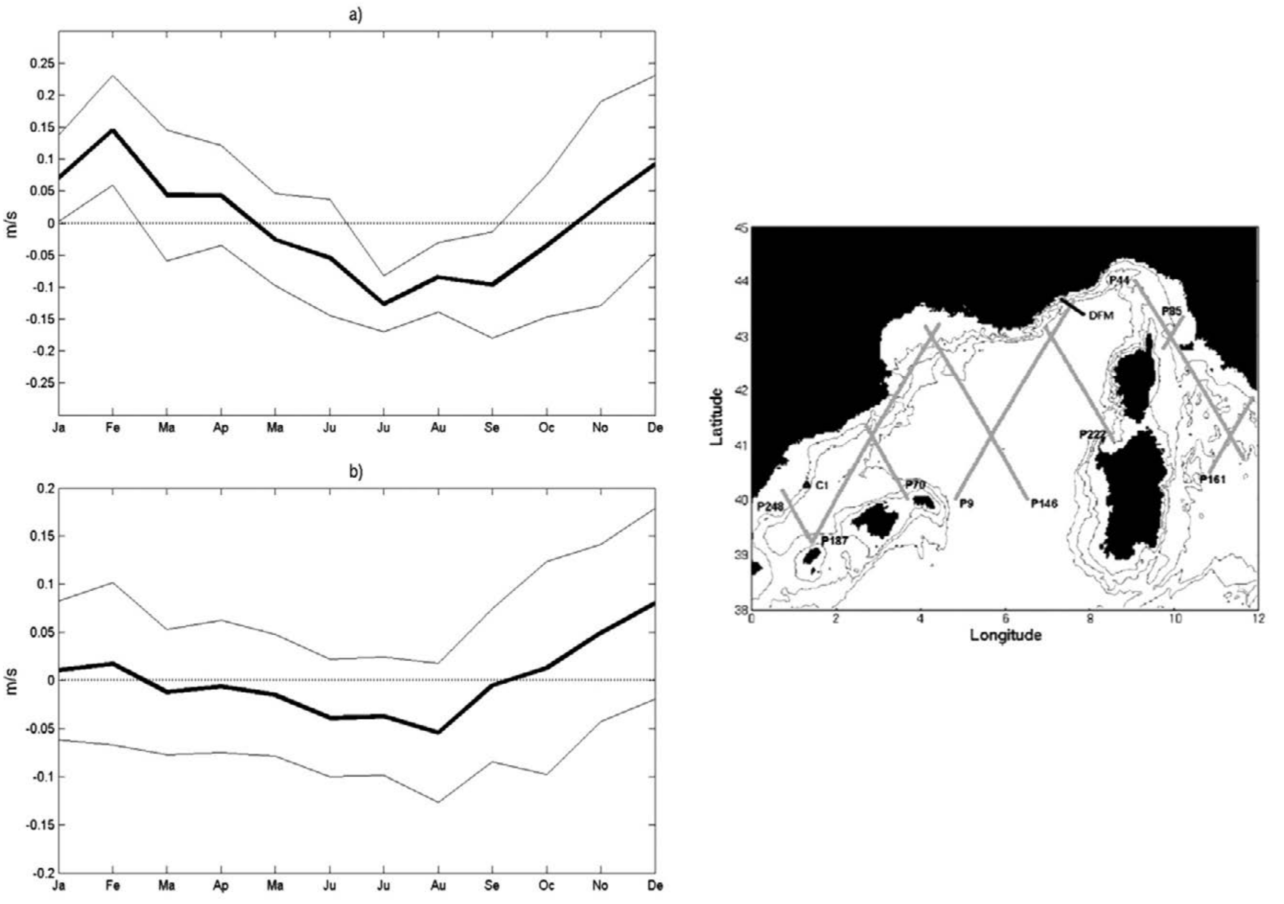

FIG. 9. – (a) Seasonal variations in the maximum current amplitude (bold line) measured by ADCP data along the DFM transect (shown on the right figure); (b) Seasonal variations in the maximum cross-track current anomalies derived from track 222 (shown in bottom figure) near the northern end of the track. Standard deviations are also shown for both datasets (thin line) (from Birol *et al.* 2010; copyright Elsevier).

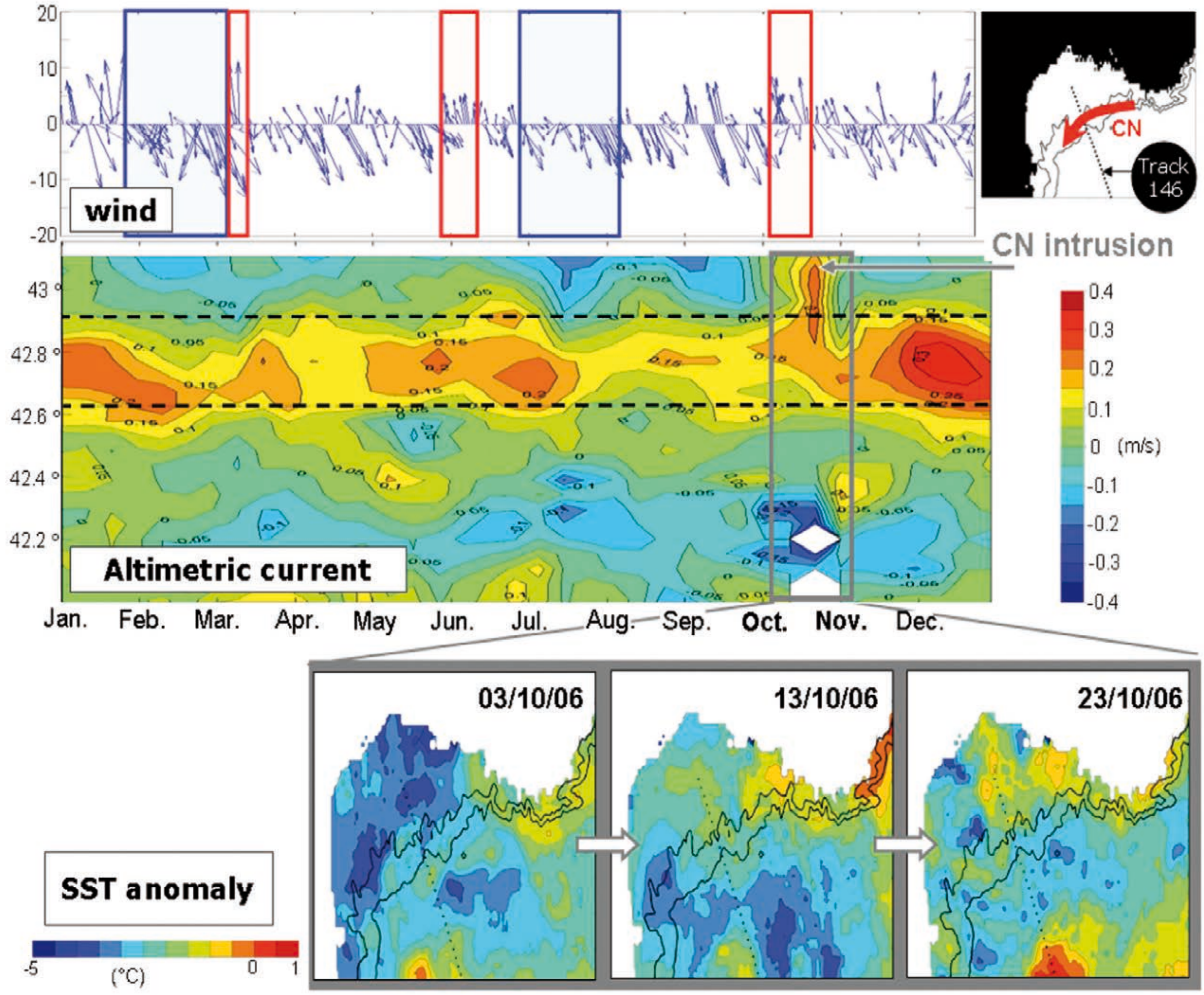

FIG. 10. – (Top) The wind direction and magnitude over the Gulf of Lion (in m/s, courtesy of MeteoFrance) as a function of time from January 2006 to December 2006 (left); T/P track 146 and the location of the 200 and 1000 m isobaths (right). The blue (red) rectangles indicate northern (southern) wind events. Middle: A Hovmöller diagram of the across-track geostrophic velocity (in m/s) of T/P track 146. The dashed lines indicate the positions of the 200 and 1,000 m isobaths. (Bottom) Sea surface temperature (SST) anomalies in degrees Celsius (from the Medspiration database).

These findings corroborate the idea that altimetric data specifically processed with a coastal-oriented strategy can be used to monitor the seasonal variability of the Northern Current.

Over the Gulf of Lion, intrusions of the Northern Current are responsible for shelf/slope exchanges between open waters and the shelf (Petrenko *et al*. 2005). As shown in Millot and Wald (1980), southeasterly winds can induce an oceanic response in terms of surface currents flowing to the north-northeast and penetrating onto the shelf. In this respect, an improved coastal altimetric dataset with a high-frequency (10-20 Hz) along-track sampling has been retrieved from raw geophysical data records (Bouffard *et al.* 2011, Roblou *et al.* 2011). Whereas the standard altimetric products are often poorly sampled as a result of systematic data-elimination procedures, these improved altimetric data (X-TRACK, hereinafter) have, for the first time, enabled the observation of the Northern Current intrusions on the shelf of the Gulf of Lion. For example, such intrusions were observed with X-TRACK data in October 2006 (Fig. 10). SST images are clearly consistent with X-TRACK records, which indicate that the surface current gradually advects warm waters from the Ligurian Sea to the Gulf of Lion shelf.

In the Corsica Channel, the combination of several long-time-series tide gauges operated by national hydrographical services, three absolute calibration sites exploited by CNES, current-meter moorings maintained by CNR, and an XCTD transect in conjunction with along-track altimetry and multi-satellite cross-over points, has enabled the quantification of the geostrophic signal associated with the seasonal and sub-seasonal currents crossing the channel (Vignudelli *et al.* 2005, Bouffard *et al.* 2008b). This combination of data sources has also made it possible to estimate the error budget in monitoring the transport through the Corsica Channel with the X-TRACK coastal-oriented

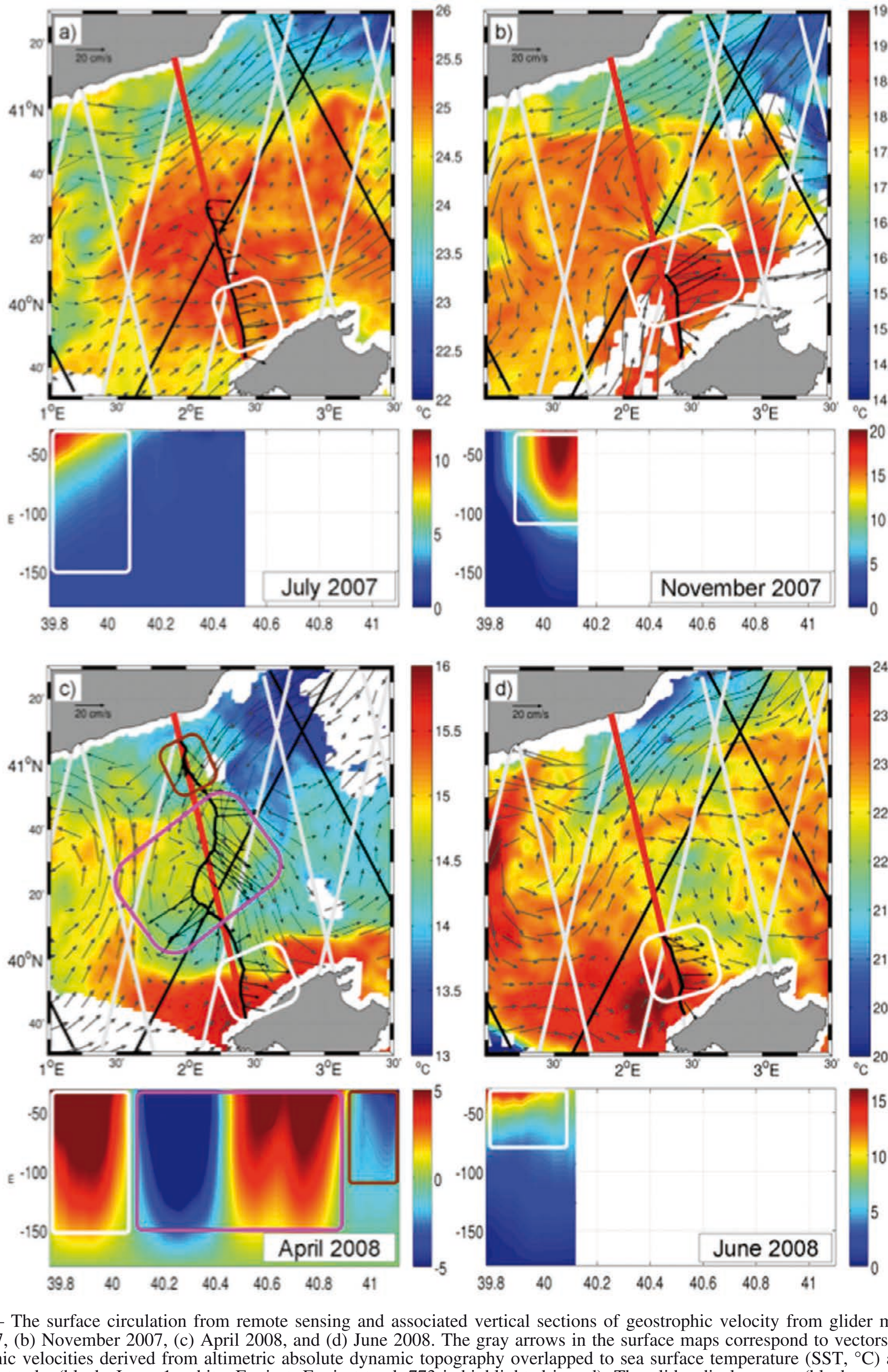

Fig. 11. – The surface circulation from remote sensing and associated vertical sections of geostrophic velocity from glider missions: (a) July 2007, (b) November 2007, (c) April 2008, and (d) June 2008. The gray arrows in the surface maps correspond to vectors of absolute geostrophic velocities derived from altimetric absolute dynamic topography overlapped to sea surface temperature (SST, °C) and satellite altimetric tracks (black, Jason-1; white, Envisat; Envisat track 773 is highlighted in red). The glider displacement (black curve) is shown with raw glider currents (black arrows). The bottom images in Figures 10a–10d show the projected across-track glider CTD velocity (cm/s). Positive values indicate a flow toward the northeast (from Bouffard *et al.* 2010; copyright American Geophysical Union).

data by comparing the estimates deduced with in situ measurements. Similar methods could be applied to several sections of the WMED in comparing transport computed with multi-source remote-sensing data and in situ measurements.

The Balearic Basin

The Balearic Basin is a key sub-basin of the western Mediterranean Sea due to its strategic location separating the Gulf of Lions to the north and the Algerian Basin to the south, and played a major role in the north-south exchanges that have not yet been thoroughly studied. The general circulation of the Balearic Basin is cyclonic and is characterized by the presence of the Northern Current flowing southwestward along the Spanish mainland shelf/slope, with one branch typically exiting the basin through the Ibiza Channel (Pinot *et al.* 2002) and a second branch feeding the Balearic Current (Pascual and Gomis 2003), which flows northeastward, following the slope of the Balearic Islands. In addition to the general current systems, the Balearic Basin is controlled by seasonal and mesoscale variability (Font *et al.* 1988). In particular, mesoscale eddies detected by satellite altimetry modulate the basin circulation at interannual timescales (e.g. Pascual *et al.* 2002) and notably impact the phytoplankton response (Jordi *et al.* 2009).

The compatibility between altimetry and glider observations in the Balearic Basin was initially explored by Ruiz *et al.* (2009a), who provided the first improved description of coastal mesoscale features. Bouffard *et al.* (2010) developed innovative strategies to characterize horizontal ocean currents, specifically in terms of current velocity associated with flow modifications close to the coast. These methodologies were applied to a series of glider missions that were conducted almost simultaneously and were co-localized along the Envisat, Jason-1 and OSTM/Jason-2 satellite tracks (during both the calibration and interleaved phases) as part of an intensive observational programme led by IMEDEA (CSIC-UIB). The goal of these experiments was to validate, intercalibrate and improve observational data dedicated to coastal studies. The new methodologies pointed out the present limitations and possible future improvements for both datasets. The high-resolution hydrographic fields from the gliders, combined with coastal altimetry, revealed the occurrence of stable and transient structures, such as fairly intense eddies. Moreover, the almost synoptic view from altimetry and SST images collected during the glider transects enabled a comprehensive description of regional small-scale features (Bouffard *et al.* 2010, Fig. 11).

A more complete multi-sensor experiment combining two gliders with conventional technologies (CTD from ships, drifters and satellites) was conducted by Pascual *et al.* (2010). The analysis of in situ and remote sensing revealed the presence of an anomalous anticyclonic eddy approximately 20-30 km in diameter near the northwest coast of Mallorca Island (Fig. 12). This structure blocked the typical path of the Balearic Current along the coast, deflecting the main northeastward flow to the north. Based on drifter data analysis, horizontal velocities associated with the eddy were estimated to be approximately 20 cm/s. Comparisons of drifter, glider and altimetry data revealed that altimeter

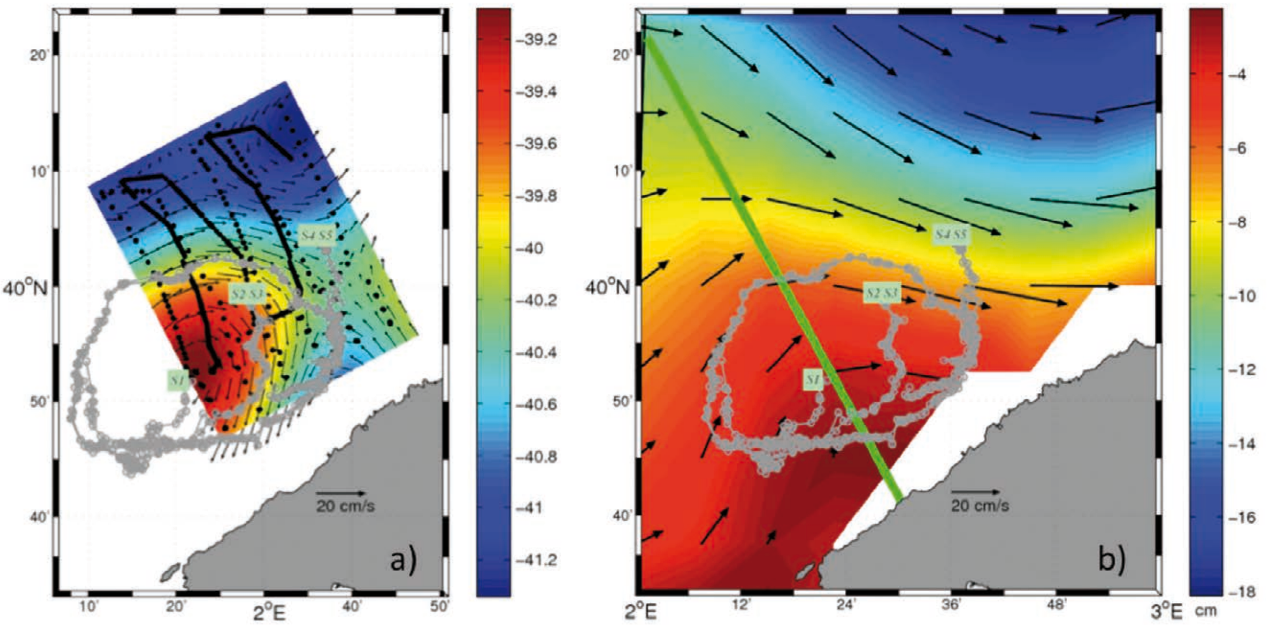

FIG. 12. – The surface circulation obtained with a multi-sensor approach (May 2009, northeast of the Mallorca Coast, Balearic Sea). a) The surface dynamic height and geostrophic velocity computed from an objective analysis scheme combining CTD and glider data (casts are indicated as black dots). The trajectory followed by five surface SVP drifters (S1-5) is superimposed (gray lines). b) The absolute dynamic topography and geostrophic currents from satellite altimetry (SLA + MDT) with the trajectory of drifters superimposed. The green line indicates Jason-1 track 70 (in interleaved orbit).

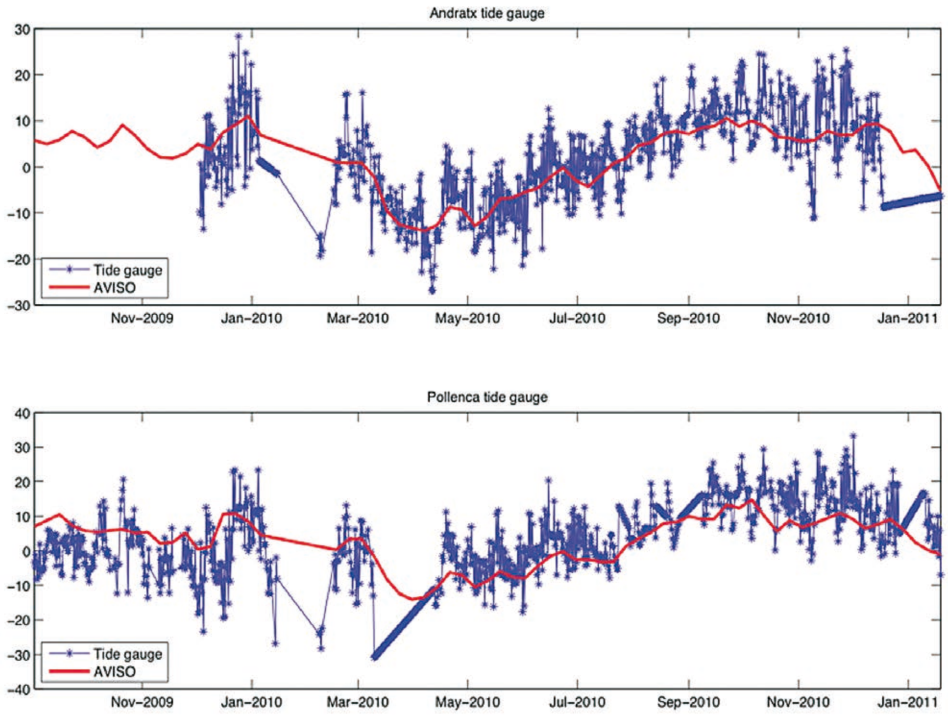

Fig. 13. – A comparison of altimetry and tide gauge sea level time series at the Andratx (west of Mallorca, top) and Pollensa (north of Mallorca, bottom) tide gauges.

geostrophic currents derived from gridded products still lack a high enough resolution to correctly sample regional and coastal features.

Accordingly, alternative methods for generating high-resolution altimeter maps must be developed and tested. Dussurget *et al*. (2011) successfully applied a novel technique in the Gulf of Biscay that can be splitted in two steps. In the first step, the large-scale mesoscale signals (approximately 100 km) were removed by subtracting the standard gridded SLA maps (updated delayed time AVISO product; Pujol and Larnicol 2005, Pascual *et al*. 2007) from along-track data (unfiltered and unsubsampled). In the second step, the residuals were submitted to an objective analysis scheme with correlation scales adjusted to smaller local mesoscale dynamics. Escudier *et al*. (2013) have applied a similar methodology in the northwestern Mediterranean. The novelty of the methods used by Escudier *et al*. (2013) consists in an additional bathymetric constraint that has been included in the analysis to provide a pseudo-dynamical boundary condition and to increase reliability in the coastal region. Finally, tide gauge data are also integrated in the objective analysis as an additional observation to gain temporal resolution and to include more information near the coast.

The new fields displayed smaller features that were not present in the standard AVISO product, with higher levels of EKE close to the tracks (not shown, from Escudier *et al.* 2013). The mean power spectra (averaging all tracks and passes) also confirmed an increase in energy for wavelengths smaller than 150 km. Several tests were performed by changing the correlation scales and altimeter, and the results were not very sensitive for small changes in the parameters. A correlation scale of 3 days in time with 30 km in space and a measurement noise variance of 3 cm^2 were finally selected. The dataset was subsequently compared with independent data, such as that from drifters launched in the area from several campaigns with in situ data and glider information, revealing a significant enhancement in resolving some small-scale features (Escudier *et al*. 2013).

Figure 13 presents a comparison of altimetry and tide gauge sea level observations at the Andratx and Pollensa tide gauges (Mallorca) located along the Mallorca coast. The close agreement between the two data sets allows for a combined OI analysis. The potential for combining altimeter data with tide gauges to improve coastal features is explored in Figure 14. The eddy revealed by SST northwest of Mallorca, even if not exactly co-localized, is better reproduced by the two-step optimal interpolation scheme, adding fine-scale features (using a small correlation scale), and is further improved by including tide gauge information compared with standard AVISO products.

Notably, however, these promising results, which have revealed several improvements in comparison with standard AVISO products, are only obtained near altimeter tracks, at the time of the altimetric pass and/or in the close vicinity of tide gauge observations. At points located far from those observations, the impact of the new methods is almost negligible.

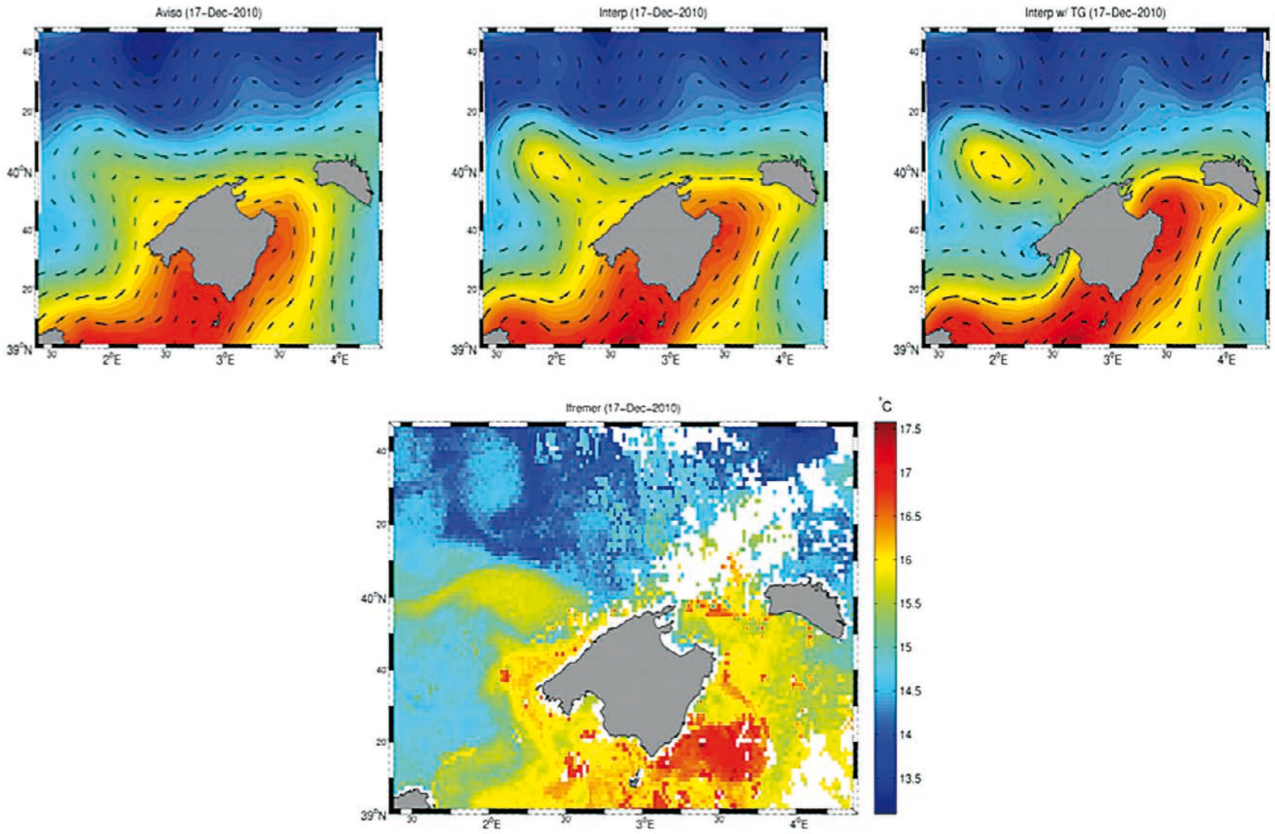

FIG. 14. – Top: The surface circulation (absolute dynamic topography + vectors of geostrophic velocity) on 17 December 2010 near the Balearic Islands, obtained from standard altimetric AVISO product (left); the two-step optimal interpolation including smaller scales and combining Jason-1, Jason-2 (interleaved orbit) and Envisat (centre) and the two-step process including tide gauge information. Bottom: An SST image from IFREMER revealing the presence of a marked warm and elongated eddy northwest of Mallorca Island, which is only correctly visible in the tailored altimeter products.

DISCUSSION AND OUTLOOK

This paper has focused on the mesoscale variability as documented by the combination of altimetry and independent observations in the western Mediterranean, where the circulation is complex due to the presence of multiple interacting scales, including basin-scale, sub-basin–scale and mesoscale structures (Robinson and Golnaraghi 1994, Vidal-Vijande *et al*. 2011). This complexity arises from multiple driving forces, including topographic effects, variable atmospheric forcing and internal dynamical processes leading to strong coastal boundary currents, unstable jets that shed vortices, permanent and recurrent sub-basin gyres and energetic mesoscale eddies. All of these structures interact and give rise to significant variability in a wide range of temporal scales (sub-mesoscale, mesoscale, seasonal and interannual), making it necessary to combine multiple sources of information in order to correctly sample and monitor all of the processes.

Altimetry data are an exceptionally valuable source of near-real-time information due to their frequent sampling rates and large spatial and temporal coverage. However, in this study it has been shown that merging several remote-sensing and in situ sources is key to improving our ability to monitor and understand regional mesoscale dynamics, such as shelf-slope currents, eddies and meanders.

Unfortunately, although satellite altimetry can be used to accurately describe the open ocean mesoscale, results have shown that the detection of these structures in coastal areas is not completely reliable (Vignudelli *et al.* 2005). The primary limitations are represented by the low resolution of standard gridded products (Dussurget *et al.* 2011) in addition to the inaccuracies of along-track altimeter-derived coastal velocity fields (Anzenhofer *et al.* 1999). Furthermore, at the shorter scales, the ageostrophic components of the circulation become more important, and altimetry, as stated above, fails to capture these components. Consequently, corrections to coastal altimetry measurements and the combination with other measurements (e.g. current-meters and HF radars) will be required to improve its ability to capture signatures associated with mesoscale and coastal dynamics

Several past (e.g. ALBICOCCA, ALTICORE, COASTALT) and ongoing (e.g. X-TRACK, PISTACH, eSurge) efforts have been made to increase the reliability and accessibility of coastal altimetry data, with improvements ranging from the definition of specific geophysical corrections to the overall improvement of the data processing chains. Tide gauges and current meters can be used to precisely evaluate the improvements and to calibrate new processing approaches, but these evaluations can be made only at single locations, which precludes the characterization of shape gradients along wavelengths associated with mesoscale currents.

The use of coastal altimetry with other complementary sensors (such as remotely sensed SST and ocean color data, in situ observations from autonomous underwater vehicles and drifter measurements) enables the cross-calibration of observational data to assess and better understand the three-dimensional dynamics by increasing the spatio-temporal sampling of the mesoscale processes (Cipollini *et al.* 2010). An integrated approach combining numerical models and observations is also important to better understand the role of mesoscale processes in coastal- and regional-scale dynamics.

In this context, the establishment of ocean observing networks has been recognized as an important component of defining and implementing strategies for the sustainable management of the marine environment by the countries that are most advanced in terms of marine science research and that have significant economic interests in coastal areas. These facilities, such as IMOS in Australia, OOI and IOOS in the USA, and VENUS and NEPTUNE in Canada, are already providing new insights into coastal and open ocean variability and deepening our understanding of ocean and coastal processes. In the western Mediterranean, the Mediterranean Ocean Observing Site for the Environment (MOOSE) and the Balearic Islands Coastal Observing and Forecasting System (SOCIB) are two examples of such ocean observing networks. The information provided by these systems (to be used in synergy with satellite observations and numerical simulations) will be particularly helpful in addressing the scientific challenges of better understanding 3D biogeochemical (Lévy *et al.* 2009) and energy (Klein *et al*. 2009, Ruiz *et al*. 2012) transfers occurring at meso- and sub-mesoscales. Ocean observing systems will also be important in preparing for forthcoming altimeter concepts that are designed to be better suited for coastal, mesoscale and sub-mesoscale monitoring, such as the wide-swath radar interferometer SWOT (Fu and Ferrari 2008), the Ka-band altimeter SARAL/AltiKa (Verron *et al.* 2001) and the Sentinel-3 mission (Drinkwater and Rebhan 2007).

However, the short-term future of mesoscale studies using satellite altimeters has to face a new period given the recent and sudden interruption of the ENVISAT satellite and changes to the Jason-1 mission orbit. In this context, although Cryosat-2 is designed for cryosphere studies, it is already showing promising results to contribute to mesoscale observation in combination with other radar altimeters (Dibarboure *et al.* 2012).

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