**Lagrangian analysis of satellite-derived currents:
Application to the North Western Mediterranean coastal dynamics**

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Abstract

Optimal interpolation methods for improving the description of coastal dynamics from satellite altimetry measurements have been recently developed over the North Western Mediterranean Sea. Maps of satellite-derived geostrophic current anomaly are generated using these methods, and added to different mean circulation fields in order to retrieve absolute geostrophic currents. The resulting fields are then compared to standard AVISO products, and their accuracy is assessed through the development of Lagrangian diagnostics. These are obtained by first simulating the trajectories of virtual particle clusters with a Lagrangian code. These are then compared to 16 drifter trajectories to evaluate the performance of the different velocity fields. The systematic comparisons with the available drifter trajectories show that the *new* velocity fields allow for a better agreement with respect to *standard ones* from AVISO. The improvement is higher over the shallow water area of the Gulf of Lion (20%) than in deeper zones (15%). However, despite the use of innovative strategies, some altimetry limitations still persist in the coastal domain, where, small scale and partially ageostrophic processes remain sub-sampled by conventional altimetry coverage.

Key words: Lagrangian diagnostics, satellite altimetry, mean dynamic topography, coastal dynamics

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1. Introduction

Coastal regions are characterized by a complex dynamics, often dominated by small, rapidly evolving structures at the mesoscale. In the open ocean, mesoscale dynamics plays a key role in modulating large-scale circulation, heat fluxes and primary production enhancement (McGillicuddy et al., 2007; Lehahn et al., 2007; Levy et al., 2001). Such hydrodynamic processes are also crucial at coastal scales, where the associated currents are known to significantly influence water-mass mixing and exchanges between the continental shelf and the open ocean (Hutchinson, 1995). The high spatial/temporal variability and complexity associated with coastal mesoscale processes make them difficult to be studied with sparse *in situ* observations. Alternative options rely on exploiting satellite data specifically adapted to the coastal domain. Satellite altimeters are well adapted to observe open-ocean mesoscale structures (Fu et al., 2010) and represent an invaluable source of data that provides repetitive views of phenomena unachievable by other means (Fu and Chelton, 2001). Characterizing the influence of mesoscale dynamics on water-mass stirring, mixing and tracer transport based on satellite observations is still a challenging issue, and requires the development of diagnostics that combine synoptic 2D current fields coupled with Lagrangian tools.

Optimal interpolation of along-track altimetry Sea Level Anomaly (SLA) into 2D fields was originally based on the combination of two altimeter missions, which did not fully resolve dynamical features of 10-100 km (Le Traon and Dibarboure, 1999; 2004). Nowadays, despite using 4 altimetry missions, the resulting AVISO regional maps (Pascual et al., 2006; Ssalto/Duacs, 2006) may still smooth a large part of mesoscale signals, especially in the coastal domain where the spatial horizontal scales are known to be smaller and more anisotropic than in the open ocean. This has been confirmed by recent studies which evidenced that Map of Sea Level Anomaly (hereafter (M)SLA) still lack enough of temporal and spatial resolution and/or accuracy for the detection of small mesoscale features (less than 50 km of horizontal scale; Bouffard et al., 2012; Dussurget et al., 2011). Furthermore, Nencioli et al (2011) have identified inconsistencies between surface transport patterns derived from altimetry in the western Gulf of Lion and the *in situ* structures detected through an adaptive sampling strategy, which combined ship-based ADCP velocities and Lagrangian drifter trajectories. Finally, using glider measurements, Pascual et al., (2010) as well as Bouffard et al. (2010) also highlighted limitations of standard AVISO gridded fields in characterizing coastal mesoscale dynamics.

In order to improve altimetry gridded fields, a series of alternative methods have been recently developed. For example Gaultier et al (2012) exploit the information from oceanic submesoscale structures retrieved from tracer observations of sea surface temperature, in order to improve the characterization of mesoscale dynamics from altimetric (M)SLA. Dussurget et al. (2011) successfully applied another technique consisting of a two steps Optimal Interpolation (OI) methods. In the first step, the large scale signals (~100 km) are removed by subtracting the standard AVISO (M)SLA from along track data. In the second step, the residuals are mapped with an OI scheme with regionally adjusted correlation scales.

Another critical aspect for satellite-derived Lagrangian transport analysis may concern the inaccuracies of the Mean Dynamic Topography (hereafter MDT). A MDT has to be added to altimetric (M)SLA in order to derive absolute geostrophic currents. Since the marine geoid component dominates the altimetry signal and is not known well enough to be removed independently, a temporal mean altimeter height is usually constructed from several year-long time series and subtracted to eliminate the geoid component. This procedure removes not only the geoid component but also any current component with a non-zero mean. What is left are height anomalies, thus geostrophic current anomalies are the only component that can be

computed from purely altimetric measurements. In order to restore absolute velocities, a MDT, i.e. the non static component of the stationary sea surface height, is generally added to the (M)SLA. The AVISO products in the Mediterranean Sea typically use the MDT from Rio et al., (2007).

D'Ovidio et al. (2011) have developed a Lagrangian approach to show the effect of this MDT on the shape and intensity of fronts of Sea Surface Temperature (SST). However, the major limitation of their method is the implicit assumption that the main driver behind the spatial patterns of SST (used in their study as a tracer) is the horizontal stirring. The mechanisms controlling SST patterns are indeed more complex, since SST gradients depend on the effect of transport integrated over several days as well as on heat fluxes and vertical mixing. Moreover, applying the proposed method requires cloud-free conditions, thus it is likely to provide patchy results on both the spatial and temporal domains.

The analysis of horizontal mixing and transport properties in the coastal domain requires not only the use of new satellite-derived fields but also relevant diagnostics in order to evaluate them. None of the previous studies have focused on the quantification of the impact of different OI methods and MDT products on altimetry-based approaches. This paper addresses this issue by applying an improved Lagrangian diagnostics to several satellite-derived velocity fields, regionally adapted to North Western Mediterranean basin.

The major dynamical feature of the North Western Mediterranean (hereafter NWMed) is the so-called “Northern Current” (hereafter NC). As shown on Figure 1, this density current arises from the junction of the Eastern and Western Corsica Current (respectively ECC and WCC on Figure 1) and flows westward along the coast from the Ligurian Sea until the Balearic Sea (Millot, 1991). The NC is marked by a strong seasonal variability (Gostan, 1967). Over the Gulf of Lion (hereafter GoL), NC intrusions can bring open Mediterranean water onto the continental shelf depending on the stratification and wind conditions (Millot, 1990; Gatti, 2008; Petrenko et al. 2008; Poulain et al., 2012b). Another key aspect related to NC dynamics concerns the development of baroclinic and barotropic instabilities (Pedlosky, 1979). The generated coastal mesoscale structures such as meanders and eddies arise along the NC external and internal border, forced by strong wind events and/or bottom topography irregularities (Millot, 1991).

Figure 1

The NC mean position is within 50 km off the coast, where radiometer and altimeter footprints may encounter the coastline and corrupt the raw along-track remote-sensed signals (Anzenhofer et al., 1999; Strub, 2001). However, recent advances in coastal altimetry data processing can be used to characterize small scale signals in coastal regions, specifically over the NWMed (Vignudelli et al., 2003; 2005; Bouffard et al., 2008a,b; 2010; 2011, 2012). Birol et al. (2010) analyzed ADCP current measurements and satellite across-track current anomalies at different locations on the NWMed shelf edge. The results indicated good altimeter performances at seasonal time scales, confirming that improved coastal along-track altimetry is reliable to observe low frequency variations of the NC dynamics. Along-track data have also allowed to observe the NC intrusions over the GoL continental shelf for the first time (Bouffard et al., 2011) and to characterize the inter-annual (Bouffard, 2007; Birol 2010) and intra seasonal (Bouffard et al., 2008b) variability of coastal currents.

Despite such major advances in coastal altimetry (in the NWMed and in many other areas; refer to Vignudelli et al., 2011 for an exhaustive review), most of the studies were based on eulerian analysis of along-track altimetric measurements from which it is impossible

to precisely identify and monitor in space and time coherent mesoscale features. The main objective of this study is therefore to evaluate improvements in new coastal gridded currents by analyzing the resulting Lagrangian trajectories. In particular, this work aims at assessing, for the first time, the impact of different OI methods combined with different mean currents. This is achieved by comparing the real trajectories of drifters launched in the summers 2008, 2009 and 2010 with clusters of virtual particles advected by the different velocity fields. The paper is organized as follow: First, we present the different datasets used (altimetry and drifters) and the metrics used to integrate the Lagrangian trajectories of the altimetry products. Secondly, we present statistics and Lagrangian analysis of altimetry-derived currents over the NWMed basins scale with a specific focus over the GoL continental shelf. In particular, we discuss the ability of optimized altimetric gridded fields to reproduce specific mesoscale features identified by *in situ* observations and model results (Hu et al., 2009; 2011; Nencioli et al., 2011; Kersalé et al., 2012) but not by AVISO velocity fields.

2. Material and methods

2.1 Remote-sensed geostrophic current anomaly

In this paper, two kinds of (M)SLA products derived from different OI methods, are used and evaluated :

- The AVISO (M)SLA from Pujol and Larnicol (2005); hereafter AVISO;
- The High Resolution (M)SLA with bathymetric constraint described in Escudier et al. (2012) ; hereafter HR+Bathy;

The AVISO fields are a specific product for the Mediterranean Sea, obtained by merging delayed-time "Updated" along track altimetry (SSALTO-DUACS, 2006). They are computed weekly on a $1/8^\circ \times 1/8^\circ$ Mercator grid. The spatial and temporal correlation scales used to obtain this altimetry fields are, respectively, 100 km and 10 days. The more recent fields described in Escudier et al. (2012) are computed by interpolating the same along-track altimetry data but by adding smaller spatial correlation scales in the OI scheme (30 km and 3 days). For the AVISO field the spatial correlation is assumed to be isotropic. However, dynamical structures in the coastal zone are known to be anisotropic due to the strong bathymetry constraint (Liu and Weisberg, 2005).. The HR+Bathy fields are thus computed modifying the correlation scales of OI in order to better take into account the shape and propagation of coastal features. The reader specifically interested in the details of the 2D mapping procedures has to refer to each of the associated references.

In this study, the AVISO and HR+Bathy (M)SLA are spatially interpolated on a common horizontal grid of $1/8^\circ \times 1/8^\circ$. Since the AVISO maps are available only on a weekly basis, whereas the HR+Bathy maps are computed each day, a daily (M)SLA is created for each product by linear interpolation in time. The daily geostrophic current anomaly fields are then derived by applying the geostrophic balance equation.

2.2 Mean currents

As previously reminded, the long term mean (1993-1999) of the altimeter Sea Surface Height ($\overline{SSH} = \overline{(M)SLA + MDT + Geoid} = \overline{MDT + Geoid}$) is subtracted from the SSH observations to remove the geoid contribution. However, this procedure also removes the contribution due to the MDT. Therefore, mean currents has to be estimated from an

independent source and added to the the (M)SLA-derived anomaly currents in order to obtain the absolute geostrophic currents. In this paper, two kinds of mean currents specifically computed for the Mediterranean Sea (see Figure 2) are used and evaluated:

- The mean geostrophic current derived from the MDT of Rio et al. (2007); hereafter Rio07
- The mean geostrophic current derived from the MDT of Dobricic (2005); hereafter Dobricic05

Figure 2

The standard MDT from Rio et al. (2007) is built from the results of the $1/8^\circ \times 1/8^\circ$ Mediterranean Forecasting System model (MFS, Pinardi et al., 2003) for the period 1993–1999 (see Figure 2a). The MFS does not directly apply data assimilation. However, this standard MDT includes corrections from drifter velocities and altimetric SLA. These data are combined together to obtain local estimates of the mean geostrophic circulation. These estimates are then used in an inverse technique to improve the MTD computed from the model (which is used as a first guess).

The MDT from Dobricic (2005) (see Figure 2b) is also estimated from the MFS model for the 1993–1999 periods, but with the assimilation of temperature from XBT observations and altimetric SLA. The MDT computation is mainly based on the assumption that the error in the MDT field appears in the assimilation system as a temporally constant and spatially variable observational bias. This error can thus be reduced by subtracting the long term average of the dynamic topography departures from the MDT first guess.

From Figure 2, it follows that the two mean current fields show maximum intensity along the NC, confirming that this structure is the dominant dynamical feature of the NWMed (refer to section 1). Depending on the considered field, regional differences in terms of current magnitude and direction can be observed: In the Gulf of Genoa, the mean current Dobricic05 (Figure 2b) shows relative strong magnitude along the coast (> 15 cm/s) whereas it is not the case for the mean current Rio07 (Figure 2a).. In the GoL - from Marseille to the Cap Creux - the two mean current fields have similar values and direction. However, major differences can be observed also in the Catalan and Balearic Sea: although the mean current Dobricic05 clearly shows a NC return loop north of Mallorca Island, the mean current Rio07 evidences the NC reaching the south of the Balearic Sea.. These differences may induce strong modifications in terms of Lagrangian particle transport. This will be quantified and discussed in the sections 3 and 4. The comparisons with 16 independent drifter trajectories, launched over the GoL in the summers 2008, 2009 and 2010 will provide robust insights about their relative performance over the NWMed coastal zone (see Section 2.2).

2.3 *In situ* data

The 16 drifter trajectories for validation (see table 1) were launched within the framework of the Lagrangian Transport Experiments (LATEX) conducted in summer 2008, 2009 and 2010 by the Mediterranean Institute of Oceanography (M.I.O.) in order to study the influence of mesoscale structures on both physics and biochemistry in the western GoL. Each drifter used in this study was tethered to holey-sock drogue centred at 15 m. In 2008 and 2010, the drifters trajectories are exploited for our analysis for a maximum duration of 60 days, during which the drifters did not strand ashore and remained inside our study area (see

Figure 3). In 2009, trajectories were exploited (Figure 3b) for only 20 days, the maximum period of common available data, before two of the three drifter launched were lost.

Table 1

Until the present study, altimetry data have been not yet analyzed within the framework of Latex08 and Latex09 campaigns. On the other hand, the near real time AVISO data showed inconsistencies with respect to the drifter trajectories of Latex10, especially close to the GoL coast (Nencioli et al., 2011). The comparisons between altimetry and drifters trajectories from Latex08, Latex09 and Latex10 give a unique opportunity to evaluate the relative performances of new altimetry products in the NWMed. This is especially true for the coastal regions of the GoL, since numerous drifter positions are available (see Figure 3) and its dynamics have been intensively studied (see introduction).

Figure 3

2.4 Methods of validation

A method, principally inspired by Liu and Weisberg (2011), has been specifically developed for diagnosing the relative performances of the different combinations of OI scheme (section 2.1.1) and mean current (section 2.1.2) for computing absolute geostrophic currents. This improved method, which aims at computing a Lagrangian skill score, consists of three steps:

1) For each drifter, each day a clusters of 600 virtual particles are launched in a square centered on the drifter initial positions (grey squares on Figure 4a, 4b). The initial particle square is set to a width of 30 km, corresponding to the spatial correlation scale from Escudier et al. (2012).

2) The virtual particles are then advected for a given time interval (see trajectories in red on Figure 4a, 4b) using each of the 4 altimetry-derived currents (2 OI methods multiply 2 mean currents). The advection scheme is a *fourth-order Runge-Kutta* integrator (see d'Ovidio et al 2004), with velocities interpolated bi-linearly in space and linearly in time. The chosen time interval for advection is 10 days, which corresponds to the temporal correlation scale of the AVISO OI scheme. An illustration is provided on Figure 4 and shows the virtual particle dispersion after 10-day advection from their daily initial position (sub sampled every 5 days for clarity). Several sensitivity tests have been performed in order to check the robustness of our methods in particular with 3-day advection, corresponding to the temporal correlation scale from Escudier et al.(2012) Several tests with 1000 particles in 50 km squares and 30 days advection have also been done (not shown).

Figure 4

3) For each particle p and drifter D , we then compute the normalized cumulative separation distance $s_{D,p}$ defined in Liu and Weisberg, (2011) as:

$$s_{D,p}(t,x) = \frac{\sum_{i=dt}^T d_i}{\sum_{i=dt}^T l_i} \quad (\text{Eq. 1})$$

For each drifter D , $s_{D,p}$ is the ratio between the cumulative separation distance d - between virtual particle p and *in situ* drifter positions - normalized by the length of the drifter trajectory l after $T*dt$ days of advection (10 or 3 days in our case) from the drifter initial position (dt is the advection time step - here every 3 hours - and i is the time index). $s_{D,p}$

scores are then computed every day t and position x (X,Y) (with X longitude and Y latitude of the drifter daily position)

The procedure to compute $s_{D,p}$ is repeated each day for all the virtual particles launched around a given drifter D . Thus, the values $s_{D,p}$ can be equivalently thought as being associated either to a given day t or daily drifter position x . For each drifter D , the daily values of $s_{D,p}$ can be averaged together to obtain the mean score $S_D(t,x)$ defined as:

$$S_D(t,x) = \frac{1}{N} \sum_{p=1}^N s_{D,p}(t,x) \quad (\text{Eq. 2})$$

Among the virtual particles released, only the N ones still in the water are used in the computation (Eq. 2). Virtual particles stranded ashore are not included. The use of particle clusters, rather than single particles, allows to increase the statistical robustness of the score. Based on its definition, the smaller the value of S_D , the more accurate the altimetry absolute velocity field (see Figure 5). By averaging together the $S_D(t,x)$ values for each drifter D , it is possible to compute the temporal mean score $\bar{S}_D$ for the period T_0 (60 days mean for LATEX 2008 and 2010, 20 days mean for LATEX 2009) for each of the 4 altimetric products (when the average is done with every drifters we note $\bar{S}$).

$$\bar{S}_D = \frac{1}{T_0} \sum_{t=1}^{T_0} S_D(t,x) \quad (\text{Eq. 7})$$

Figure 5 shows the temporal evolution of S_D for drifter 1 and drifter 9 between September and November 2010 (see Figure 4 for their respective trajectories). These curves are used as examples to illustrate the variation of the score S_D with respect to the chosen combination of (M)SLA and mean currents as well as to the time of advection. A detailed analysis of S_D will be presented in the result section (section 3). Here we briefly present some sensitivity results. The curves computed with 3-day and 10-day advection show similar patterns. The main difference between the curves is the amplitude of the signals, with S_D scores roughly 50 % higher for 10-day advection ($1.5 < S_D < 10$) than for the 3-day ($0.7 < S_D < 5$). This has been already observed in Liu and Weisberg, (2011), who evidenced that oceanic advection tends, indeed, to increase the separation distance between virtual particles and *in situ* drifters with time. Experiments with 30-day advection (not shown) confirm this effect, with mean $\bar{S}_D$ scores of about 7 for drifter 1 and drifter 9. These are much higher than what obtained with 3-day and 10-day advection. The differences in S_D between different velocity fields also become larger for longer time of advection. In general it is less than 1 for 3-day advection (Figure 5a, 5c), whereas significant differences (higher than 2) can be observed for 10-day advection (Figure 5b, 5d).

In the following section we focus on the 2 altimetric current products (section 3.1) which show the most statistically different results. In a second step, statistics are presented aiming at discriminating the relative influence of mean currents and OI methods (section 3.2).

Figure 5

3. Results

3.1 Comparisons of current fields

3.1.1. Statistics at the basin scale

In this section we focus on the comparison between 2 of the products presented in section 2.1: The first one (hereafter called *standard*) is the standard regional AVISO gridded field combining standard AVISO (M)SLA with geostrophic mean current derived from Rio07. The second one (hereafter called *New*) is an alternative current field which consists of the combination of geostrophic currents derived from HR+Bathy (M)SLA (Escudier et al., 2012) with the MDT Dobricic05. The main statistical results at the surface are summarized in table 2, table 3 and table 4 for respectively Latex08, Latex09 and Latex10 Results at 50 m for Latex10 are also provided in table 5. The statistics are obtained from 180 daily points of comparisons for Latex08 (60 days by 3 drifters); 60 for Latex09 (20 days by 3 drifters) and 780 for Latex10 (60 days by 10 drifters at the surface, and 60 days by 3 drifters at 50 m depth). It is important to note we only present here statistics in terms of mean and not standard deviation (STD) because the STD for each product have very close values (done but not shown). This implies that the particle dispersions around the mean trajectories are equivalent, independently of the considered product, implying STD does not discriminate current field performances.

From tables 2, 3 and 4 it follows that the *new* surface gridded field gives better mean statistical results both with 10- and 3-day advection (less pronounced with 3 days). The average $\bar{S}_D$ scores with 10-day advection for all the surface drifters and the three years (which represents about 840 points of comparisons) is of 4.3 and 3.7 for respectively the *standard* and *new* gridded geostrophic currents. This represents a significant mean improvement of about 15% for the *new* products with respect to the standard one. Below are detailed the differences per year:

For Latex08 (Table 2), the mean improvement is of 5 % (both with 3- and 10-day advection). Only for drifter 2 the results are significantly different with $\bar{S}_D$ score 14% better for the *new* product.

Table 2

For latex09 (Table 3), the $\bar{S}$ score with 10-day (3-day) advection is 21% (5%) less for the *new* fields (3.7 vs. 4.7 with 10-day advection). However, depending on the considered drifter, the statistics are significantly different. *New* fields give smaller, and therefore better, $\bar{S}_D$ values of about 35 % and 24 % for, respectively, drifter 1 and 2, whereas 50% higher for drifter 3. Results with 3-day advection show less pronounced differences despite a slight improvement for the *new* fields.

Table 3

Statistics for Latex10 (Table 4), confirm the results obtained for Latex08 and Latex09 with a mean improvement higher than 13 % with the *new* fields, both with 3- (2.1 vs. 2.5) and 10-day advection (3.9 vs. 4.5). With 10-day advection, seven drifters, from the ten available, give better scores for the *new* fields whereas only three drifters (drifter 1, 3 and 9) have better results with the *standard* ones. Moreover, in that case the differences are weaker than 0.2. On the other hand, major differences are observed for drifter 4 (17% of improvement with the *new* field), 6 (32% of improvement with the *new* field) and 7 (28% of improvement with the *new* field). We therefore analyze with more attention their trajectories and the associated S_D

temporal variability and spatial repartition in order to better understand when and where the velocity fields can be improved (see Figure 6)

Table 4

3.1.2. Regional differences

Both for drifter 4 and drifter 6, the worst S_D scores (> 5) are obtained between the last week of September and the first week of October. This period corresponds to a northward drifter migration not well reproduced by altimetric currents (for all altimetric products, despite better results with the *new* fields). Indeed, as observed in Nencioli et al (2011) and confirmed later (section 3.1.3), these two drifters - launched at the same time - are first advected in a shallow coastal area north of the GoL where the circulation dynamics might be strongly ageostrophic because of intense wind and/or bathymetric effects. For drifter 4 (drifter 7), major differences can also be observed along the Mallorca northern coast (in the middle part of the NWMed). Other than over these particular zones, drifters 4, 6 and 7 show relative low S_D scores (< 4 for 10 days advection), especially for the *new* fields along the coastal corridor (see Figure 1) characterized by Nencioli et al., (2011) in the south-western part of the GoL.

Figure 6

The previous averaged Lagrangian statistics highlight significant differences between the *standard* and alternative satellite-derived velocity fields. Moreover, the detailed analysis of the S_D scores along three drifter trajectories of Latex10 shows a strong regional dependency on current field performances. Now, we therefore analyze in more detail the daily S_D scores along all drifter trajectories from the LATEX experiments, focusing in particular on its spatial distribution. For clarity we only discuss the S_D scores with 10-day advection for Latex10 and Latex08, since they are characterized by longer drifter trajectories (conclusions for LATEX 2009 and with 3 days advection are however similar).

As previously observed, the worst scores are located in the northern GoL with S_D higher than 6 for Latex10, north of the 150 m isobaths (see Figure 7). There are three possible reasons (or a combination): the dynamical structures are maybe too small or close to the coast to be captured by the conventional along-track measurements (instrument limitation) or the OI methods smooth a large part of signals even with smaller and bathymetry-constrained correlation scales (methodology limitation) or else ageostrophic dynamics may dominate the surface signals (see introduction and associated references). Indeed, high S_D scores are not observed for all the drifters reaching this region. This suggests the presence of episodic, small scale dynamics in the region. Therefore, depending on the time a drifter reached the northern GoL, it could be advected by currents associated with high frequency dynamics not reproduced in the altimetry derived velocity field.

On the contrary, the southern and western part of the GoL show relative good statistics with relative small S_D scores (< 3 for LATEX 2008 and 2010) for both *new* (Figure 7c,d) and *standard* (Figure 7a, 7b) fields (for all drifters/times). This is true even very close to the coast, along the coastal corridor (Figure 1; Figure 7) described in Nencioli et al (2011) suggesting the dynamics over this area is quite stable and geostrophic. Over the whole domain, S_D is generally less than 4 except in the area close to an external border of the NC (4°E -5°E , 40°N -42°N) which may be potentially affected by mesoscale instabilities not perfectly reproduced by altimetry. This is also the case for the *standard* product along the Catalan coast which corresponds to NC internal borders.

Figure 7

Figures 8a and 8b show the S_D difference between *standard* and *new* surface gridded currents respectively for 2008 and 2010. Except in the South-Eastern and South-Western parts of the NWMed domain, the *new* fields are characterized by better statistics. The major differences are however observed close to the coast and over the GoL continental shelf where S_D from the *new* velocity field is lower (S_D difference > 2).

Figure 8

Considering all the drifters and the all the periods, the mean $\bar{S}$ scores over the GoL is 3.6 against 4.5 for respectively the *new* and *standard* velocity fields. This represents a stronger regional improvement of the *new* product ($> 20\%$) with respect to result obtained over the entire NWMed domain ($\sim 15\%$, see section 3.1.1). S_D along the continental shelf slope is relatively good (< 3), especially for LATEX 2008. There, stable dynamical features may be influenced by bathymetry and altimetry appears to be well adapted to resolve the associated geostrophic dynamics. This seems to be not always the case in shallower regions in the north-western part of the GoL, as observed during the Latex10 experiment. In order to address this issue, we now focus on a specific event occurring at the beginning of Latex08.

3.1.3. Focus on a dynamical event

We have previously evaluated the accuracy of two satellite-derived products and highlighted significant quantitative differences function of the considered area. In particular, bad S_D scores have been found in the Western GoL requiring a closer Lagrangian-based analysis of dynamical events occurring during the Latex experiments. Numerous numerical simulations and analysis of multi-source data from Latex08 and Latex09 have already identified the recurrent presence in summer of intense anticyclonic eddies of about 20 km radius in the western side of the GoL (Hu et al, 2009; Kersalé et al., 2012). These are clearly depicted in drifter trajectories of Figure 3a and Figure 3b. In 2001 one of such eddies was also modeled (Hu et al., 2011) and observed with *chlorophyll a* satellite data (Campbell et al., 2012). The issue addressed here is to check if altimetry gridded fields are able to reproduce or not this coastal mesoscale feature

For this, a cluster of 600 virtual particles is launched in the 15 km neighborhood of the initial positions of the 2 drifters trapped by the eddy of Latex08. Then, the particles are advected for 10 days both with the *standard* and the *new* absolute geostrophic velocities and compared qualitatively to real drifters trajectories. From Figure 9 it turns out that most of the particles advected by the *new* field (Figure 9b) closely follow the drifter positions, whereas all the particles advected by the *standard* AVISO currents (figure 9a) go directly southward, without following the observed eddy loop. Indeed, the *new* field shows northward flow close to the GoL coast, which is in agreement with the two drifters. Analysis of this event evidence that the *new* field using a bathymetric constraint and the Dobricic 05 mean current better represent well developed, stable, coastal geostrophic mesoscale features as the one observed during Latex08. A similar conclusion is found by Escudier et al., 2012 by comparing drifter trajectories, glider and altimetry north of Mallorca. However, for Latex09 (not shown) neither the *new* nor the *standard* velocity field are able to reproduce such an eddy-like structure. This structure is too small and/or too close to the coast to be captured with conventional altimetry or reproduced by the 2D fields, even by the use of innovative OI techniques and alternative MDT (see section 2.1).

Figure 9

3.2 Influence of mean currents and optimal interpolation methods

The previous results have pointed out significant differences between *new* and *standard* gridded fields both qualitatively and quantitatively. However, they did not inform on the respective influence of OI methods (see section 2.1) and mean currents (see section 2.2) on the Lagrangian metrics. We therefore computed in the following section the 3 average $\bar{S}$ scores per OI methods and the 3 average $\bar{S}$ scores per mean current. In order to do this and to isolate the relative influence of OIs with respect to mean currents, we compute, for each OI (respectively mean currents), the average of the three $\bar{S}$ scores using the three available mean currents (respectively OIs).

3.2.1 Statistics at the basin scale

Table 5 shows the average $\bar{S}$ score for the different OI methods. Both with 10-day and 3-day advection, the mean $\bar{S}$ score are very close (between 3.8 and 4.5 for surface 10-day advection). Hence, this does not allow to conclude whether one OI approach is better than another. However, even if the statistics are similar at the NWMed basin scale, this does not imply that there are no temporal and regional differences.

Table 5

From table 5, it turns out that the Rio07 mean currents have close results whereas the Dobricic05 exhibits better statistics. Indeed, the mean $\bar{S}$ score with 10-day advection shows improvements of about 12 % when comparing the Dobricic05 mean current with, respectively the Rio07. We do not propose here detailed explanations on the origins of such differences. However, we hypothesize that the main cause most likely lies in the availability of data used. The mean computation can indeed be biased due to the non uniform sampling in space and time of the *in situ* data used to constraint the MDT computation..

From the previous analysis it appears that mean currents have a stronger influence than the OI methods on our Lagrangian diagnostics. However, even if this is true for the regional average at the NWMed Basin scale, alternative OI methods might still have significant regional impacts, especially in shallow areas where the smaller correlation scale and bathymetric constraints described by Escudier et al. (2012) may have stronger impacts.

3.2.2 Focus on the Gulf of Lion

We now focus on the GoL area where major differences, both quantitative and qualitative, between the *new* and *standard* product were previously observed. In order to assess the influence of the bathymetry constraint in the Lagrangian statistics, we compute the $\bar{S}$ score for three bathymetric classes (Figure 10). The first class corresponds to shallow water area, north of the GoL, with depth less 150 m (pink points on Figure 10). The second class is between 150 m and 2000 m depth (cyan points on Figure 10) which roughly corresponds to the NC internal border position whereas the last one (> 2000 m) includes the

open sea (green points on Figure 10). The $\bar{S}$ score is only computed if at least 10 drifter positions are available for a given bathymetric class. Except for 2009, the number of positions is between 20 and 100, depending on the time of advection and of the LATEX mission.

Figure 10

Figure 11

For Latex08 (Figure 11a) and Latex09 (11b), the three OI methods show equivalent statistics for any of the considered bathymetric classes, despite the qualitative differences evidenced in section 3.1.3. Concerning the mean current, the scores are quite similar for depth <150 m ($S \sim 3.0$ for 10-day advection) but for the other bathymetric classes Dobricic05 exhibits better score than Rio07. It is also somehow surprising to note the score in 2008 and 2009 are generally better in shallow water area of the GoL ($S \sim 3$ for depth < 150 m) than in deeper zone ($S \sim 4$ for depth >150 m) where potential small scale and partially ageostrophic instabilities may arise close to the NC external borders. This may suggest that circulation over the GoL during these two cruises is in good geostrophic balance and is relatively well resolved by altimetry gridded fields. But this could also be due to the fact that the satellite-derived transport patterns are quite well reproduced despite errors in the circulation features.

For Latex10 (Figure 11 c, f) the conclusions are quite different. In that case the different OI methods exhibit significant differences for depth less than 150 m (located North West of the GoL). By comparison with the AVISO $\bar{S}$ score with 10-day (3-day) advection, HR+BATHY $\bar{S}$ scores show improvements of respectively 9% (21 %) and 13 % (23%) whereas less pronounced differences are observed depending on the considered mean currents (Figure 11 f). Indeed, in the North Western GoL, (see Figure 13), the dynamics in the *new* fields seems more impacted by the OI methods than by the mean currents. Such differences are not observed for other bathymetric classes. This indicates the new OI methods can have significant impact for some specific events in shallow-water regions. In our case, this corresponds to smaller scale dynamics influenced by the bathymetry that trapped and retained drifters close to the coast. Concerning the mean currents, Dobricic05 have again smaller $\bar{S}$ for the whole bathymetric classes confirming the conclusion obtained for Latex08 and Latex09. Their impact are however stronger for the 2nd bathymetric class (see Figure 11 d, e, f) corresponding to the south-western GoL corridor (see Figure 1 and Figure 10) where significant differences in the S_D scores were previously observed.

4. Discussions and conclusions

Cross-shelf exchanges are of crucial importance to study the impact of anthropogenic discharged pollutants, oil spill as well as the transport of natural biogeochemical elements and biological organisms (e.g. nutrients, larvae, jellyfishes). A quantitative understanding of coastal physical processes is therefore necessary to determine how the ocean dynamics' advection will affect the biological and ecological conditions of coastal environments.

In this paper, new absolute geostrophic currents, derived from satellite altimetry observations in combination with alternative sensors and models, are processed and evaluated using a improved Lagrangian diagnostic based on particle clusters' advection. These methods show a mean improvement of about 15 % in terms of surface transport when using alternative gridded currents during the three LATEX experiments done in the North-Western Mediterranean Sea (an improvement of 20 % is obtained over the Gulf of Lion). The Lagrangian approaches demonstrate the use of HR+BATHY (M)SLA from Escudier et al

(2012) generally gives a better representation of transport patterns over the continental shelf (despite disagreements in current direction). We have also demonstrated that the use of an alternative mean current (ie from Dobricic 2005) rather than the standard one (ie Rio et al., 2007) significantly improves the comparison with drifter trajectories, especially along the corridor located at the South West Gulf of Lion.

Even if the statistical interpretations are relatively robust given the large numbers of drifters used (19 trajectories), it would be interesting to adopt a similar approach with all the available drifters in the Mediterranean Sea since 1992 (> 500 trajectories, Poulain et al., 2012a). This should allow generating a more complete altimetric error map over the Mediterranean Sea than the ones obtained during the single experiments analyzed in this study (Latex 2008, 2009 and 2010). In a second step, the whole drifter database could also be exploited in synergy with altimetry and modelling (with assimilation scheme or statistic constraints) in order to generate a new regional Mean Dynamic Topography more accurate for regional applications. Indeed, in agreement with the finding from d'Ovidio et al. 2011, one of the main conclusions of our study is that the mean circulation of the Mediterranean Sea has a critical influence on Lagrangian transports.

Concerning the Optimal Interpolation methods, the use of shorter and bathymetric constrained correlation scales is not always sufficient to significantly improve the statistics over the whole North Western Mediterranean. However, we pointed out that in some specific cases and areas, such as the continental shelf in the western part of the Gulf of Lion, improvements can be obtained (as also observed in the Balearic Sea by Escudier et al., 2012). However, as shown with the FSLE diagnostics during Latex10, the relative sparse space/time coverage of existing along track altimetric missions is a clear limitation to the long-term tracking of small-scale dynamics even by developing coastal-oriented Optimal Interpolation methods. Coastal altimetry will undoubtedly benefit, in the near future, of a denser satellite constellation and new altimetry sensors. Waiting for SWOT satellite (Fu and Ferrari, 2012), the Lagrangian studies of coastal mesoscale will thus require to integrate data from the SARAK/AltiKa and Cryosat-2 missions in the Optimal Interpolation.

Another critical aspect concerns ageostrophic motions which could influence the transport of tracers in the surface layer but that are not included in altimetry. Their impacts - not addressed in this study - may be more important in coastal zones and could be therefore at the base of significant observed discrepancies between drifter and altimetric trajectories. For example, one of well known ageostrophic motion is the Ekman current. We therefore performed several tests by adding Ekman components to the altimetric current fields but the obtained results did not point-out large differences in terms of S_D score. This is maybe due to the fact that drifters have drogues at 15 m and are less wind sensitive than at the surface. Moreover, it could also be due to the fact that the classical Ekman theory is not always a correct assumption over the coastal domain and may add more noise in signals than relevant dynamical information (as seen in Bouffard et al., 2010)..

The relation between surface and sub-surface mesoscale is also a challenging issue requiring both the continuous development of theoretical models (eg. Lapeyre et Klein, 2006), and high resolution 2D gridded current (Dussurget et al., 2011, Gaultier et al., 2012; Escudier et al., 2012). Our lagrangian diagnostics applied to sub-surface drifters could also be then used to compare results obtained from different reconstructions methods. The use of observation-based currents with Lagrangian tools is indeed promising and might pave the way to new ecological applications for coastal altimetry such as the influence of 3D cross-shelf exchanges on fish larvae, plankton or transport and landing over the north western Mediterranean coastal domain

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Figure Captions

Figure 1 – Bathymetry (in m) and main surface circulation patterns of the study area. The dashed black arrows correspond to mesoscale currents throughout the year whereas the blue arrows correspond to average well known flow patterns. The coastal corridor is the one characterized by Nencioli et al (2011)

Figure 2 – Mean geostrophic current (module in cm/s) derived from the Mean Dynamic Topography of (a) Rio07 and of (b) Dobricic05. (c) Drifter trajectories from 1989 to 2012 (330 trajectories) and (d) derived mean current Poulain12 (the current intensity is in cm/s)

Figure 3 - Trajectories of surface drifters of (a) Latex08, (b) Latex09, (c) Latex10 and (d) sub-surface (50 m depth) drifter trajectories of Latex10. The color corresponds to the time of advection since the positions of origin (in day). The white square corresponds to the drifter initial positions.

Figure 4 – Two examples ((a) Drifter 1 and (b) Drifter 9) of Latex10 drifter trajectories (in blue) versus virtual particle advected during 10 days by gridded currents using HR+Bathy (MSLA) and Dobricic (2005) mean current (in red). For more visibility, the daily particle initial positions (in grey squares) are sub-sampled every 5 days along the drifter trajectories.

Figure 5 - Time evolution of S_D scores for the 9 velocity fields along the Latex10 drifter 1 and drifter 9 with 3 days ((a); (c)) and 10 days advection ((b); (d))

Figure 6 - Trajectories of drifters (a) 4, (b) 6 and (c) 7 and corresponding S_D time series (respectively (d);(e);(f)) for the *new* - black and blue curves for respectively 10 and 3 days advection - and *standard* -pink and red curves for respectively 10 and 3 days advection-altimetric products. In grey are highlighted areas (left) and corresponding periods (right) of bad S_D score.

Figure 7 - Spatial distribution of S_D scores at the surface (10 days advection) along drifter daily positions for the *standard* ((a) and (c)) and *new* product ((b) and (d)) during Latex08 and Latex10. By convention we choose each initial days of advection as drifter daily positions.

Figure 8 - Spatial distribution of S_D difference at surface (10 days advection) between *standard* and *new* products for (a) Latex08 and (b) Latex10.

Figure 9 - Spatial distribution of (a) S_D score for the new product and (b) S_D difference between *standard* and *new* products along the sub-surface drifter (50m) of Latex10

Figure 10 – Latex08 drifter trajectories (cyan, green and blue). Two drifters are trapped by the Latex eddy (in green and blue). In red are the virtual particles initially launched at drifters' trapped initial positions and 10 days advected by (a) the *standard* and (b) new altimetric current field. In grey are the particles trajectories for the last day of advection.

Figure 11 – Geostrophic current (vectors) and corresponding FSLE with *standard* (bottom) and *new* (top) field. (a, d) 5 days FSLE centred September 19; (b, e) 5 days FSLE centred September 23; (c, f) 5 days FSLE centred September 26. In green (in red) are the drifter trajectories over the FLSE period of drifters launched 17 September (19 September). The circles correspond to the drifter last positions of each considered 5-day period.

Figure 12 - Daily drifter positions used in the bathymetric classes computation for (a) LATEX 2008; (b) LATEX 2009 and LATEX 2010. In pink are the points located at depths less than 150 m, in cyan the points between 150 m and 2000 m and in green the points at depths higher than 2000 m.

Figure 13 – Diagram of mean $\bar{S}$ scores with respect to Latex drifters (left; a, b, c) for each OI methods and (right, d, e, f) for each mean currents function of bathymetric classes. The large (respectively thin) diagrams correspond to $\bar{S}$ score with 10 days (respectively 3 days) advection.