On the Quality of Real-Time Altimeter Gridded Fields: Comparison with In Situ Data

ANANDA PASCUAL

Institut Mediterrani d'Estudis Avançats, IMEDEA (CSIC-UIB), Mallorca, Spain

CHRISTINE BOONE AND GILLES LARNICOL

CLS Space Oceanography Division, Toulouse, France

PIERRE-YVES LE TRAON

IFREMER, Brest, France

(Manuscript received 21 February 2007, in final form 29 August 2008)

ABSTRACT

The timeliness of satellite altimeter measurements has a significant effect on their value for operational oceanography. In this paper, an Observing System Experiment (OSE) approach is used to assess the quality of real-time altimeter products, a key issue for robust monitoring and forecasting of the ocean state. In addition, the effect of two improved geophysical corrections and the number of missions that are combined in the altimeter products are also analyzed. The improved tidal and atmospheric corrections have a significant effect in coastal areas (0–100 km from the shore), and a comparison with tide gauge observations shows a slightly better agreement with the gridded delayed-time sea level anomalies (SLAs) with two altimeters [*Jason-1* and *European Remote Sensing Satellite-2 (ERS-2)/Envisat*] using the new geophysical corrections (mean square differences in percent of tide gauge variance of 35.3%) than those with four missions [*Jason-1*, *ERS/Envisat*, Ocean Topography Experiment (TOPEX)/Poseidon_{interlaced}, and *Geosat Follow-On*] but using the old corrections (36.7 %). In the deep ocean, however, the correction improvements have little influence. The performance of fast delivery products versus delayed-time data is compared using independent in situ data (tide gauge and drifter data). It clearly highlights the degradation of real-time SLA maps versus the delayed-time SLA maps: four altimeters are needed in real time to get the similar quality performance as two altimeters in delayed time (sea level error misfit around 36%, and zonal and meridional velocity estimation errors of 27% and 33%, respectively). This study proves that the continuous improvement of geophysical corrections is very important, and that it is essential to stay above a minimum threshold of four available altimetric missions to capture the main space and time oceanic scales in fast delivery products.

1. Introduction

The modern era of operational oceanography depends upon the rapid availability of observations to allow for real-time monitoring and the prediction of oceanic conditions (Smith 2006). Satellite altimetry constitutes a key input dataset for operational applications, since it provides, among other variables, surface topography measurements from which it is possible to obtain surface

geostrophic currents. Furthermore, as surface topography is a vertically integrated variable, it represents a strong constraint to estimate and forecast the three-dimensional ocean state through data assimilation.

Several authors (Ducet et al. 2000; Fu et al. 2003; Le Traon and Dibarboure 2004) have proved that the combination of two altimetric missions gives an improved estimation of the surface ocean circulation compared to the results derived from only one altimeter. However, theoretical studies using simulated altimeter data (e.g., Le Traon and Dibarboure 2002; Leeuwenburgh and Stammer 2002; Chelton and Schlax 2003) have explored the capabilities of different altimeter scenarios and have concluded that two satellite altimeters are still

Corresponding author address: Dr. Ananda Pascual, Institut Mediterrani d'Estudis Avançats, IMEDEA (CSIC-UIB), C/Miquel Marquès 21, Esporles 07190, Mallorca, Spain.
E-mail: ananda.pascual@uib.es

far from an optimal recovery of the main space and temporal scales of the ocean. These scales, ranging from 50 to 500 km and from 10 to 100 days, respectively, correspond to the mesoscale variability that is considered to be the dominant oceanic signal (Le Traon and Morrow 2001). Pascual et al. (2006, hereafter P06) have recently combined the actual data from four satellite altimeters with the aim of improving the representation of the mesoscale variability in the global ocean. P06 have found, through a comparison with surface drifters, that the 4-altimeter scenario improves the recovery of mesoscale structures that were not properly sampled with a classical configuration of two altimeters. Moreover, the merging of four altimeter missions has a significant influence in reducing the errors (by about 25%) in the estimation of the sea level in coastal and shelf areas, which represents a big challenge for satellite altimetry (Vignudelli et al. 2005). More recently, Pascual et al. (2007) have carried out a detailed study evaluating the influence of combining several altimeter missions over the Mediterranean Sea. They have shown that with the combination of three altimeters, the sea level and velocity can be mapped with a relative accuracy of about 6% and 23%, respectively, which is an improvement by a factor of 2.2 compared to the results derived from *Jason-1* alone and an improvement by a factor of about 1.5 from the results obtained from *Jason-1* + *European Remote Sensing Satellite-2* (*ERS-2*). That work demonstrates that at least three—preferably four—altimeter missions are needed to monitor Mediterranean mesoscale circulation.

Note that all of these studies (both using actual and simulated data) have been performed with delayed-time data. However, operational applications require fast delivery products, either to be used alone (e.g., sea level and surface velocity maps) or as an input dataset, which is to be assimilated into numerical prediction models operated by forecasting centers [e.g., Mercator Ocean (available online at <http://www.mercator-ocean.fr/en/>) with the currently operational prototype systems 2 and 3 (PSY2 and PSY3, respectively) or the National Centre for Ocean Forecasting (NCOF; available online at <http://www.ncof.gov.uk/>) using Fast Ocean Atmosphere Model (FOAM) and Proudman Oceanographic Laboratory Coastal Ocean Modeling System (POLCOMS) systems].

Up until now, no study has examined the quality of real-time altimetric data. Real-time altimetric gridded fields differ from delayed-time maps mainly because of three factors: (i) lower quality orbit determination (Dibarboure et al. 2008); (ii) data availability, which is more critical in real time as a result of a potential anomalous delay for a given mission; and (iii) non-centered processing time windows for map production.

For the first source, the orbit error is minor (<2 cm rms) and relatively well corrected through the optimal interpolation procedure (Le Traon et al. 1998). Regarding the second source, the real-time error degradation when altimeter flows cannot be delivered normally (operational delay, platform anomaly, or ground segment issues) can be relevant. C. Boone (2006, personal communication) has assessed that the quality of near-real-time (NRT) maps quickly deteriorates when altimeter data are delayed or missing. After a few days of anomalous data flow, it is not clear that a three-altimeter near-real-time observing system is still able to meet the minimum requirements for observing mesoscale structures. The influence of missing data will be investigated in this paper through the number of altimeter missions used in the processing. The third source of differences is significant and is inherent to the NRT timeliness. In delayed-time mode, both past and future data are available for the mapping, which involves centering the day of the map in a time window for better accuracy. However, for operational purposes, the most recent map needs to be available, which thereby results in using a noncentered processing time window at the cost of losing accuracy. This effect will be analyzed in detail in this study by simulating a real-time dataset from a delayed-time dataset through an observing system experiment (OSE) approach.

The aim of this paper is to evaluate the quality of real-time altimetric products (both sea level and velocity) by comparing them with independent in situ data [tide gauges (TGs) and drifter data] and by assessing the degradation of the fast-delivery gridded fields with respect to the delayed-time gridded fields.

The paper is, therefore, organized as follows. The data and methods are presented in section 2. In section 3, delayed- and real-time altimeter products are intercompared and the differences between merging two and four altimeter missions are analyzed. The influence of the new corrections, the quality of real-time and delayed-time sea level anomaly maps, are validated against independent tide gauges and drifter observations in sections 4 and 5, respectively. Finally, in section 6, the conclusions are outlined.

2. Data and methods

a. The reference delayed-time sea level altimetric maps

To carry out an intercomparison with the results presented in P06, the same 11-month period (2 October 2002–27 August 2003) has been chosen. The altimeter data (both along-track and interpolated maps) from all

the missions used in this study—that is, *Jason-1*, *ERS-2*, *Envisat*, Ocean Topography Experiment (TOPEX)/Poseidon (T/P) interleaved and *Geosat Follow-On* (*GFO*)—are currently delivered by the AVISO Web server (SSALTO/DUACS system; available online at <http://www.aviso.oceanobs.com/>). As in P06, the same two configurations are analyzed: a combination of two altimeters (*Jason-1* + *ERS-2/Envisat*, hereafter C2) and four altimeters (*Jason-1* + *ERS-2/Envisat* + T/P + *GFO*, hereafter C4).

The along-track data processing follows the standard approach. The sea surface height (SSH) is corrected for geophysical effects [wet and dry troposphere, ionosphere, and others; for details see Le Traon and Ogor (1998) and Le Traon et al. (2003)]. Note that since P06, two corrections have been updated. The classical inverted barometer (IB) correction, which formulates the static response of the ocean to atmospheric pressure forcing, ignoring wind effects, is replaced by a dynamic atmospheric correction based on the barotropic model [Modèle d'Onde de Gravité à 2 Dimensions (MOG2D)], developed by Lynch and Gray (1979). This improves the representation of high-frequency atmospheric forcing, as it takes into account wind and pressure effects (Carrère and Lyard 2003). The dynamic atmospheric correction applied to altimetry combines the high frequencies of the barotropic model MOG2D forced by pressure and wind [from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis] with the low frequencies of the IB correction (available online at <http://www.aviso.oceanobs.com/en/data/products/auxiliary-products/atmospheric-corrections/index.html>). The other modification concerns the tide model, since GOT99.2 is replaced by the updated GOT00.2 (Ray 1999). These two changes, as it will be shown, constitute an important step forward with respect to previous altimeter products (e.g., those used in Brachet et al. 2004 and P06). This is particularly relevant close to the coast (defined here as the region over the continental shelf and slope, ranging from 0 to 100 km from the coast), where altimetric observations often are of lower accuracy or not interpretable as a result a number of factors, including inaccurate tidal corrections and the incorrect removal of atmospheric (wind and pressure) effects at the sea (Volkov et al. 2007).

The corrected SSH obtained for each mission is then intercalibrated with a global crossover adjustment of the *ERS-2*, *GFO*, and *Jason-1* orbits using T/P data as a reference (Le Traon and Ogor 1998). Next, the data are resampled every 7 km along the tracks using cubic splines. A mean profile is removed from the individual SSH measurement. The mean profile contains the geoid signal and the mean dynamic topography over the averaging period. For *Jason-1* and *ERS-2*, a mean profile calculated over a 7-yr period (1993–99) is used. In terms

of T/P interleaved and *GFO*, only several months of data are available and for that reason a specific processing is applied to get mean profiles that are consistent with *Jason-1* and ERS mean profiles [refer to Le Traon et al. (2003) for details on the *GFO* mean profile and Le Traon and Dibarboure (2004) for T/P interleaved mean profile].

Finally, the sea level anomalies (SLA) are smoothed using a median and a Lanczos filter to reduce measurement noise before being subsampled to decrease the number of redundant observations for the objective analysis scheme and thus reducing the computing time.

The mapping method to produce gridded SLA fields from along-track data is detailed in Le Traon et al. (1998). It has been applied in many studies (e.g., Ducet et al. 2000) and has been recently improved in Le Traon et al. (2003). This mapping technique consists in a sub-optimal space–time objective analysis that takes into account along-track correlated errors. For each grid point to be estimated with the objective analysis scheme, data are selected in a temporal subdomain with typical radii of 10–50 days (time scale of oceanic signal). In the case of delayed-time maps, this data selection implies considering a centered time window of along-track data, taking into account both past and future measurements.

Maps are produced every week on a 1/3° Mercator projection grid combining either two or four altimeter missions, using the same parameters as given in Le Traon et al. (2003) and Dibarboure et al. (2008) with the exception of the long-wavelength error variances that have been adjusted according to the new geophysical corrections (L. Carrère 2006, personal communication).

b. Real-time altimetric sea level maps

As stated in the introduction, the quality of real-time maps is assessed by focusing on the third—and most important—factor regarding the differences between real-time and delayed-time products, that is, the fact that in real-time, future information is not available and, therefore, the amount of data that can be included in the objective analysis is reduced by a factor of 2. In this sense, the differences that are analyzed here between real-time and delayed-time products represent the lower boundary of the errors, as there are other sources of error that are not included in the construction of the real-time maps, as mentioned earlier.

An alternative way of proceeding is to directly compare the delayed-time maps described in the previous section with the real-time maps that are routinely delivered by AVISO, which are produced using the fast-delivery along-track data with a preliminary medium orbit ephemeris (MOE) orbit (Dibarboure et al. 2008). However, in this case, the different factors (orbit

correction, data availability, and others) are all mixed and, therefore, they cannot be distinguished.

As a consequence, the real-time maps used herein are constructed following an OSE approach. The same along-track delayed-time data described in the previous section are used, but the time window for data selection in the objective analysis is chosen to be asymmetric. Namely, to compute a map on day t , all of the along-track data from $t - 50$ days to t are used. The 50-day time lag selection corresponds to the largest time correlation scale in the global ocean (Dibarboure et al. 2008).

c. Computation of absolute velocities

Absolute velocities derived from the altimetric data are obtained as follows. First, the geostrophic velocity anomalies are computed from the SLA (η') gridded maps using the geostrophic equation

$$\begin{aligned} \mathbf{U}'_g &= -\frac{g}{f} \frac{\partial \eta'}{\partial y} \\ \mathbf{V}'_g &= \frac{g}{f} \frac{\partial \eta'}{\partial x}, \end{aligned} \quad (1)$$

where $\mathbf{U}'_g$ and $\mathbf{V}'_g$ denote the zonal and meridional geostrophic velocity anomalies (relative to the 7-yr mean), respectively; f is the Coriolis parameter; g is the acceleration of gravity; and the derivatives $\partial \eta' / \partial y$ and $\partial \eta' / \partial x$ are computed using finite differences, where x and y are the distances in longitude and latitude, respectively.

An approximation to absolute velocities is made by adding the geostrophic anomaly velocities ($\mathbf{U}'_g$ and $\mathbf{V}'_g$) and an Ekman component to the mean geostrophic currents ($\mathbf{U}_g$ and $\mathbf{V}_g$)

$$\begin{aligned} \mathbf{U} &= \mathbf{U}'_g + \bar{\mathbf{U}}_g + \mathbf{U}_{\text{Ek}} \\ \mathbf{V} &= \mathbf{V}'_g + \bar{\mathbf{V}}_g + \mathbf{V}_{\text{Ek}}. \end{aligned} \quad (2)$$

In this study, the mean geostrophic velocities are obtained from the Rio and Hernandez (2004) mean dynamic topography (MDT), which is computed using a synthetic approach, briefly described next. A large-scale MDT is calculated by subtracting a geoid model (EIGEN-2) from the mean sea surface height CLS01, determined from 7 yr of altimetric data (the same years as those considered in the extraction of SLA; refer to section 2a). The shorter scales are provided by merging the resulting MDT with the Levitus climatology (Levitus et al. 1998) and combining in situ measurements and altimetric data with an inverse technique. This yields a synthetic MDT, which gives estimates of the mean geostrophic currents. Rio and Hernandez (2004) compared their MDT to other mean dynamic fields [U.K. Ocean Circulation and Advanced Modeling

Project (OCCAM); Fox and Haines 2003; Le Grand et al. 2003; Levitus et al. 1998], and a validation using independent in situ measurements showed improvement in most areas, especially in zones of intense variability (Gulf Stream, Agulhas, among others). However, residual small-scale noisy structures were found to slightly deteriorate the comparison to observations in areas characterized by low oceanic variability.

The estimation of the Ekman component is provided by a two-parameter (angle and amplitude) model fitted to wind stress fields and high-frequency ageostrophic currents derived from drifting buoys [the same methodology as in Rio and Hernandez (2003)]. In this study, about 40 000 drifter observations have been used for the parameter determination. The daily wind stress fields are produced by Center for Satellite Exploitation and Research (CERSAT) using an objective analysis scheme that combines data from several satellites (QuikSCAT, among others; available online at <ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-quikscat/>). The resulting parameters are latitudinally dependent and, in particular, the angle ranges between -60° and $+60^\circ$. Once the parameters of the model have been determined, the daily Ekman currents are generated from the daily wind stress fields.

To summarize, an estimation of daily absolute currents is obtained by linearly interpolating the original weekly geostrophic velocity anomalies into daily fields and then adding them and the daily Ekman currents to the mean velocities.

It should be noted that Eq. (2) is only an approximation to absolute velocities because some ageostrophic signals, such as the centrifugal force for eddies and meanders, as well as other high-frequency motions, such as inertial oscillations, are disregarded. For instance, the neglect of the centrifugal force from the momentum balance yields an underestimation (overestimation) of the actual velocity field for an anticyclone (cyclone). Gomis et al. (2001) estimated the importance of cyclostrophic acceleration relative to the Coriolis acceleration in the western Alboran gyre (western Mediterranean) and obtained a ratio of about 0.17.

d. Tide gauge data

TG records represent a reference for evaluating the influence of the new geophysical corrections as well as the quality of the real-time products in coastal areas. We use here the same TG dataset as in P06. The TG time series come from the Global Sea Level Observing System (GLOSS)/Climate Variability and Predictability (CLIVAR) near-real-time hourly network delivered by the University of Hawaii Sea Level Center (available online at <http://ilikai.soest.hawaii.edu/uhscl/>). Only the

FIG. 1. Rms (cm) of C4 SLA differences between old (IB, GOT99.2) and new (MOG2D, GOT00.2) corrections.

complete time series without gaps are selected, leading to a total of 86 TG stations. The processing of the TG data consists of the application of the combined MOG2D correction and filtering of the short wavelengths (semi-diurnal and diurnal) with a Demerliac filter, as in Mourre et al. (2006) and Crosnier and Le Provost (2007). The altimeter maps are interpolated onto the position of the TG stations and both time series are filtered with a 20-day low-pass filter to remove the high frequencies that cannot be resolved by the altimetric data.

Notice that some errors may be introduced by the bilinear interpolation of the altimetry field onto the TG position. These errors mainly depend on the grid resolution and on the spatial scales resolved by the fields. In our case, these scales are sufficiently large (correlation scales of 150–250 km; Ducet et al. 2000) compared to the grid size ($1/3^\circ$ Mercator grid, that is, about 37 km at the equator and 18.5 km at 60°N/S). In any case, these errors will affect equally all the different datasets that are evaluated in this study (delayed and real time), so that the relative differences between the results with those datasets will remain the same. Another option for providing error estimates would be to determine the sea level at the TG location by using objective analysis, but this is very expensive computationally and it is not the aim of our study. Furthermore, bilinear interpolation is the most extended method when dealing with similar problems of irregularly sampled data (Emery and Thomson 2001). This comment also holds for the interpolation of altimeter data onto the drifters' positions presented in the next section.

e. Drifter data

Drifter measurements are a valuable tool for validating altimetry velocities in the open sea. The drifter dataset is provided by the Atlantic Oceanographic and Meteorological Laboratory 9 (available online at <http://www.aoml.noaa.gov/phod/dac/>). It contains 673 000 measurements of Argos-tracked drifters, with a drogue located at a 15-m depth. The Argos location data is used to compute a velocity following the path of the drifters by time differencing the processed 6-hourly positions.

Drifter velocities are compared with the previously mentioned absolute current fields derived from altimetry by interpolating the altimeter velocity maps onto the position and time of the drifter data. Other ageostrophic phenomena occurring mainly at high frequencies (inertial oscillations, tidal currents, internal waves, coastal upwelling, cyclostrophic waves, and so on) are reduced by applying a 3-day low-pass filter, as proposed by Rio and Hernandez (2004).

3. Comparison of altimetry products

Figure 1 shows the rms of the SLA differences between the processing with the old geophysical corrections (IB + GOT99.2) and the new corrections (MOG2D + GOT00.2) for the four-altimeter scenario. In the open sea at low and midlatitudes, the SLA rms differences are lower than 1 cm, which falls in the range of typical satellite altimetry errors and thus are not significant.

FIG. 2. Rms differences (cm) between delayed-time and real-time C4 SLA.

Over the major western boundary currents, which are characterized by intense mesoscale variability (e.g., Gulf Stream, Kuroshio, Brazil–Malvinas confluence region, among others), the SLA rms differences are about 2–3 cm larger than in the rest of the open sea but still almost negligible compared to the intrinsic variability of these areas. The largest influence of the new dataset, most affected by an improvement of the aliased high-frequency and tidal signal, is located in the continental shelf waters and at high latitudes. Maximum values can reach about 5 cm rms.

The rms of the SLA differences between delayed-time and real-time C4 maps are shown in Fig. 2 (note that the scale is different from that in Fig. 1). The greatest values are found in areas of intense mesoscale variability (those mentioned above) and can reach more than 10 cm rms, which represents an important fraction of the signal variance. In coastal high-latitude areas (e.g., northwestern U.S. coast in the Pacific and northern European Atlantic shelves), some nonnegligible rms values are likely a result of the reduction of available data in the real-time maps, which increase the aliasing of the high-frequency signals, resulting in poorer SLA estimation. The same influence applies in regions characterized by intense tides, such as around Australia. It is worth mentioning that the SLA rms differences found there between delayed-time and real-time C4 maps are larger than the differences between C2 and C4 delayed-time maps, as presented in P06.

Errors in the estimated fields can be obtained as outputs of the objective analysis. The mapping errors averaged over the period of study and for different

configurations are shown in Fig. 3. In all the panels, the highest errors are found at very high latitudes (greater than 66°N/S), where only *ERS-2/Envisat* missions provide data. Significant errors are also found in low-variability areas (e.g., North Pacific). Note that the errors are expressed in percent of the signal variance. The difference between the left and right panels of Fig. 3 clearly reveals the error reduction as a result of an increase in the amount of observations processed in the objective analysis (either because two or four missions are taken into account). As expected, the highest errors are obtained with the real-time C2 (average error of 36.13%), which is a factor of 2.3 larger than the error given by the delayed-time C4 (15.7%). The other two configurations, delayed-time C2 and real-time C4, present intermediate errors (20.61% and 26.73%, respectively).

This theoretical error is, however, strongly dependent on the chosen correlation scales. Thus, unless the actual covariance structure of the estimated field is well known, estimates of the formal mapping errors usually underestimate the actual errors (Leeuwenburgh and Stammer 2002). Consequently, external methods are used in the next sections to quantify the error in both sea level and current estimates.

4. Comparison with tide gauge measurements

The consistency between TG data and altimetry from C4 is shown in Fig. 4. This figure is equivalent to Fig. 4 of P06 but with the new geophysical corrections. The mean square differences (in terms of percentage of the TG

FIG. 3. Statistical errors obtained from the optimal interpolation analysis. Delayed-time (top left) C2 and (top right) C4 SLA errors. (bottom) Same as top, but for the real-time fields. The errors are expressed in percent of signal variance and are averaged over the study period (October 2002–August 2003).

variance) are lower than 20% just off islands and in areas representing the open ocean, whereas for continental stations the misfit is larger (between 20% and 30%). The most striking difference in relation to P06 is the error reduction in areas of intense tides and at high latitudes. This is due to the application of the MOG2D correction, which represents a better estimation of the

wind and pressure effects compared to the classical inverted barometer correction and to the implementation of the updated GOT00.2 tide model. On average, the error variance averaged over all of the TG stations is 29.7% in terms of the new geophysical corrections compared to the 36.7% obtained with the old geophysical corrections. Regarding the influence on the

FIG. 4. Mean square differences between TG and delayed-time C4 SLA [$\text{variation}(\text{TG} - \text{altimeter}) / \text{variation}(\text{TG})$]. The new geophysical corrections (MOG2D, GOT00.2) are applied. Units are percent of the tide gauge variance.

TABLE 1. Rms differences between C4 altimetry and TG sea level derived [variance (var), altimeter (alti)] with (left) new (i.e., GOT00 and MOG2D) and (middle) old (i.e., GOT99 and IB) corrections. (right) The ratio of the variance reduction at TGs $[\text{Var}(\text{TG} - \text{alti})_{\text{old}} - \text{Var}(\text{TG} - \text{alti})_{\text{new}}] / \text{Var}(\text{TG} - \text{alti})_{\text{old}}$.

	Rms(TG – alti _{C4}) _{new} (cm)	Rms(TG – alti _{C4}) _{old} (cm)	Variance reduction (%)
Total	3.94	4.27	14.79
High latitude	5.00	5.75	24.40
Low latitude	3.28	3.46	10.17
Atlantic Ocean	4.43	5.04	23.00
Pacific Ocean	4.05	4.35	13.28
Indian Ocean	2.82	2.89	4.74
Continental	5.05	5.65	20.04
Islands	2.89	2.96	4.82

number of missions that are merged, the error misfit for C2 with the new corrections is 35.3%, whereas it was 46.7% with the old dataset. A summary of the error reduction, which depends on the geophysical corrections and the number of missions used (C2 or C4), is given in Tables 1 and 2 for different areas. On average, the effect of the new geophysical corrections is more critical for C2 than for C4. This is because the multi-satellite configuration contributes to the reduction of high-frequency aliasing errors that are not accurately corrected by the geophysical models. The contribution of the new models is considerably larger at high latitudes than at low latitudes, since the high latitudes are very energetic areas where the ocean response to atmospheric forcing is farther from a classical IB response (Carrère and Lyard 2003). Finally, the influence is also larger for continental TG rather than island gauges, which reveals the efficiency of MOG2D in shallow water, as a result of the smaller finite element spacing.

TABLE 2. Same as in Table 1, but for the two satellite configurations.

	Rms(TG – alti _{C2}) _{new} (cm)	Rms(TG – alti _{C2}) _{old} (cm)	Variance reduction (%)
Total	4.26	4.72	18.71
High latitude	5.15	6.20	30.97
Low latitude	3.66	3.93	13.23
Atlantic Ocean	4.60	5.32	25.38
Pacific Ocean	4.43	4.90	18.39
Indian Ocean	3.27	3.37	5.91
Continental	5.44	6.24	24.14
Islands	3.20	3.34	8.60

In summary, the comparison between altimetry and TG made by applying different models demonstrates that slightly better results are obtained with two altimeters with the new geophysical corrections (35.3% and 4.26 cm) than those obtained with four missions but with the old corrections (36.7% and 4.27 cm). This increases the evidence of the importance of a continuous improving of the altimetric data processing, which can be as critical as the number of altimeters that are merged in the analysis. However, with the new geophysical corrections, the combination of four altimeters still plays an important role in reducing errors (Tables 1 and 2).

Figures 5–7 present several examples of altimetry and TG records at different stations, characterized with clearly different dynamics. At the Townsville site (Fig. 5), where strong tides take place, altimeter records with old corrections are contaminated and aliased by tidal signals that are not properly corrected by the GOT-99 model. This translates into a large misfit between altimetry and TG observations (rms differences of 8.74 cm and mean square differences relative to tide gauge variance of 99.78%). With the new corrections, the signals are less noisy, and the agreement is slightly

FIG. 5. Comparison between C4 delayed-time SLA (red) and TG sea level (blue) time series at Townsville site (South Pacific Ocean; 19.25°S, 146.83°E). The dotted (continuous) lines are the unfiltered (filtered) time series. SLA time series are interpolated onto the position of the TGs. (left) SLA with the old corrections (IB, GOT99.2) and (right) SLA with new corrections (MOG2D, GOT00.2). Note that the same atmospheric correction (IB or MOG2D) is applied to the TG data.

FIG. 6. Same as in Fig. 5, but for the Andenes site (North Atlantic Ocean; 69.32°N, 16.15°E).

improved (6.64 cm and 63.53%). The Andenes example is characteristic of a high-latitude station, where the new corrections have a significant contribution: while the rms differences with the old corrections were 5.42 cm (74.84%), the differences with the new corrections are 3.56 cm (33.77%). For low-latitude islands, Fig. 7 reveals that altimeter and TG observations match almost perfectly (1.31 cm and 2.91% for Point La, and 1.81 cm rms and 2.71% error for Guam Island). At these locations, the influence of the geophysical corrections is almost negligible (not shown).

To analyze the contribution of each new correction separately, we have also generated a “mixed” SLA altimetric dataset corrected by IB and the new GOT00.2. The averaged mean square differences, in percent of signal variance, between this mixed altimetric dataset and TG data are 40.8% for C2 and 32.7% for C4. Thus, as follows from these values and from Table 3, the reduction of rms differences as a result of the MOG2D correction is comparable to the reduction as a result of the application of the GOT00.2 tidal model. This is in agreement with Volkov et al. (2007), who analyzed the influence of the new corrections on the northwest European shelf.

The error misfit between TG and real-time altimeter maps are 45.2% (4.82 cm) and 37.1% (4.42 cm) for C2 and C4, respectively (Table 4). These values can be compared with those obtained for the delayed-time products, that is, 35.3% (4.26 cm) for C2 and 29.7% (3.94 cm) for C4. This puts in evidence that in real-time, four altimeters are needed to obtain the same scores as in the delayed-time mode with only two altimeters and, also, that the improvement from C2 to C4 is slightly more critical in real time (18% relative correction) than in delayed time (16% relative correction).

5. Comparison with drifter measurements

The spatial distribution of the available drifter measurements is rather inhomogeneous (Fig. 8). While the Atlantic, tropical Pacific, and Indian Oceans have relatively good coverage, the North and South Pacific Oceans are very poorly sampled as well as the very high latitudes for all of the oceans. Note that since geostrophic altimeter velocities are based on Eq. (1), whose validity fails close to the equator, data from drifting buoys in the 10°S–10°N latitude band are excluded.

FIG. 7. Same as in Fig. 5, but for (left) Point La Island (equatorial Indian Ocean; 4.67°S, 55.53°E) and Guam Island (tropical Pacific Ocean; 13.43°N, 144.65°E). In this figure, only the results with the new corrections are shown.

TABLE 3. Rms differences between altimetry and TG sea level derived with IB and GOT00 corrections: (left) C2 and (right) C4 satellite configuration. Low latitudes are defined as less than 30°N/S and high latitudes as greater than 50°N/S.

	Rms(TG – alti _{C2}) (cm)	Rms(TG – alti _{C4}) (cm)
Total	4.54	4.10
High latitude	5.66	5.20
Low latitude	3.75	3.36
Atlantic Ocean	5.39	5.00
Pacific Ocean	4.52	4.10
Indian Ocean	3.51	2.92
Continental	5.76	5.28
Islands	3.38	2.99

Rms differences between drifter velocity and altimeter observations with new corrections and for C4 are shown in Figs. 9 and 10. The pattern is quite robust, and the rms velocity values range between 8 and 12 cm s⁻¹ in areas of low variability for both zonal and meridional components and up to 35 cm s⁻¹ in areas of intense variability.

On average, focusing on energetic zones (with rms velocities higher than 20 cm s⁻¹) deeper than 1000 m and outside of the equatorial band, the misfits are 24.2% and 28.1% of the drifter variance for the *U* and *V* components, respectively (Table 5). These values are almost the same as the values obtained with the old corrections (24.3% and 28.4%, respectively), which confirms that the effect of the new corrections is not significant in the deep ocean.

TABLE 4. Rms differences between real-time altimetry and TG sea level. (left) C2 and (right) C4 satellite configuration.

	Rms(TG – alti _{C2}) (cm)	Rms(TG – alti _{C4}) (cm)
Total	4.82	4.42
High latitude	5.83	5.70
Low latitude	4.05	3.59
Atlantic Ocean	5.60	5.36
Pacific Ocean	4.78	4.38
Indian Ocean	3.91	3.37
Continental	6.03	5.62
Islands	3.65	3.28

The agreement between real-time products and drifter data is estimated following the same methodology. The results (Table 5) are consistent with those obtained in the comparison with TG measurements. In real time, C4 has the same error misfit as C2 in delayed time (zonal and meridional velocity estimations errors of about 27% and 33% respectively). Furthermore, the merging of four missions has a larger influence on the real-time products (the relative correction from C2 to C4 is 13% for *U* and 19% for *V*) compared to the delayed-time products (relative correction from C2 to C4 is 9% for *U* and 15% for *V*). However, it is worth mentioning that the figures given above also contain the errors from the in situ data (TG and drifter data), including both interpolation errors and residual signals as a result of the direct effect of wind forcing on the surface drifter and nonlinear wave phenomena.

FIG. 8. Number of 6-hourly drifter observations into 2° × 2° boxes for the period October 2002–September 2003.

FIG. 9. Rms differences (cm s^{-1}) between altimetry and drifter zonal velocities averaged over $2^\circ \times 2^\circ$ boxes. The altimeter data correspond to the interpolation of the C4 delayed-time absolute velocity fields onto the position and time of the drifter observations.

Finally, Figs. 11 and 12 present two examples illustrating the degradation of the real-time products. They correspond to a buoy that was entrained in a cyclonic eddy in the Brazil–Malvinas confluence region. The

trajectory followed by the drifter is in good agreement with the velocity vectors and the map of the absolute dynamic topography of 9 July 2003 obtained from the delayed-time C2 maps (Fig. 11a), which presents, in

FIG. 10. Same as in Fig. 9, but for meridional velocity.

TABLE 5. Rms differences (cm s^{-1}) between drifter and altimeter velocities in areas of intense variability ($\text{rms} > 20 \text{ cm s}^{-1}$) and outside the equatorial zone (defined here as between -10°S and 10°N). The mean square differences between drifter and altimeter velocities expressed in percent of the drifter variance are in brackets.

	Delayed time (old)		Delayed time (new)		Real time	
	C2	C4	C2	C4	C2	C4
U	11.24 (26.7)	10.72 (24.3)	11.23 (26.6)	10.72 (24.2)	12.06 (31.0)	11.30 (26.9)
V	10.68 (33.0)	9.99 (28.4)	10.70 (33.1)	9.97 (28.1)	11.63 (41.2)	10.69 (33.4)

the same location, a cyclonic eddy of very similar shape and size. Conversely, the real-time C2 products (Fig. 11b) fail to reproduce this structure. In fact, according to this map, the buoy would have gone undercurrent during the last days (near B). One week later (Fig. 12), the drifter continued circling the eddy on the western and northern edge. The delayed-time figure reveals a small displacement of the eddy toward the west and a shape deformation, which are in good agreement with the path followed by the drifter. On the contrary, the real-time product was unable to detect this displacement.

6. Summary and conclusions

Two aspects concerning the quality of altimetric gridded fields have been addressed in this study. The first aspect quantified the influence of applying improved geophysical corrections. In particular, a new tide model is included (GOT00.2) and the classical IB cor-

rection has been replaced by a dynamic atmospheric correction based on the MOG2D barotropic model. These two new corrections have produced a significant influence in coastal areas, as revealed by a comparison with TGs. It has been shown that slightly better results are achieved with the new geophysical corrections with two missions than those obtained with the old corrections but with four missions. On the contrary, the improved geophysical corrections have little effect in the deep ocean, as demonstrated in the comparison with drifter data. This was an expected result, since the new corrections play a major role over the shelf areas. However, while the influence of MOG2D and GOT00.2 is mainly located in near-shore areas (Fig. 1), the effect of the combination of four altimeters influences both coastal regions and the open ocean.

The second aspect involved performing a quality assessment of real-time altimetric maps through an OSE approach. The evaluation with TG and drifter observations demonstrates a clear degradation of real-time

FIG. 11. Comparison of C2 altimetry and drifter data in a cyclonic eddy in the Brazil–Malvinas confluence region. The white line represents the trajectory followed by a buoy between A (4 Jul 2003) and B (13 Jul 2003). The vectors correspond to the absolute velocity field (geostrophy + Ekman), and the background color field is the SLA + MDT (cm) on 9 Jul 2003. (a) Delayed-time and (b) real-time products.

FIG. 12. Same as in Fig. 4, but one week later. The vectors and the background color field correspond to 16 Jul 2003. The white line represents the trajectory followed by the surface float between A (11 Jul 2003) and B (21 Jul 2003).

products in relation to delayed-time data. Namely, in real-time, four altimeters are needed to get the same scores as two altimeters in delayed time. This is due to the amount of data available to compute the sea level maps, which are reduced by a factor of 2 in real time with respect to delayed time, since only past data are accessible.

In summary, in this paper we have highlighted (i) the importance of a continuous improvement of the altimetric data processing; (ii) the degradation of real-time products in contrast with the delayed mode; and (iii) the influence of the number of merged altimeters (two versus four missions).

These results have important practical implications for operational oceanography and satellite altimetry requirements. Altimeter requirements have generally been analyzed in terms of space/time sampling capabilities, in particular, for climate and mesoscale signals (e.g., Koblinsky et al. 1992; Greenslade et al. 1997; Le Traon and Dibarboure 1999). The general requirement is that at least two missions (with one reference high-quality mission) are needed (Koblinsky et al. 1992). Recent studies have pointed out the need for higher resolution (e.g., up to four altimeters and/or in the longer run swath altimetry) to provide a good representation of mesoscale signals and associated surface currents (e.g., P06; Pascual et al. 2007). All these studies did not consider, however, real-time issues and constraints. Our paper shows that in a real-time context, requirements for high-resolution altimetry are, therefore, even higher. This is a very important result for the design of future altimeter missions.

The next step will involve the development of key indicators for the monitoring of the performance and the state of the altimeter observing system. The objective is to provide to the operational users, such as forecasting centers, useful and synthetic information about the quality of the products.

Acknowledgments. The altimeter products were produced by SSALTO/DUACS and distributed by AVISO with support from CNES. Useful discussions with G. Dibarboure are greatly acknowledged. Thanks are extended to Aaron Boone for helping with the revisions of this paper.

REFERENCES

- Brachet, S., P.-Y. Le Traon, and C. Le Provost, 2004: Mesoscale variability from a high-resolution model and from altimeter data in the North Atlantic Ocean. *J. Geophys. Res.*, **109**, C12025, doi:10.1029/2004JC002360.
- Carrère, L., and F. Lyard, 2003: Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing—Comparisons with observations. *Geophys. Res. Lett.*, **30**, 1275, doi:10.1029/2002GL016473.
- Chelton, D. B., and M. G. Schlax, 2003: The accuracies of smoothed sea surface height fields constructed from tandem satellite altimeter datasets. *J. Atmos. Oceanic Technol.*, **20**, 1276–1302.
- Crosnier, L., and C. Le. Provost, 2007: Inter-comparing five forecast operational systems in the North Atlantic and Mediterranean basins: The MERSEA-strand1 methodology. *J. Mar. Syst.*, **65**, 354–375.
- Dibarboure, G., O. Lauret, F. Mertz, and V. Rosmorduc, 2008: SSALTO/DUACS user handbook: (M) SLA and (M) ADT

- near-real time and delayed time products. SALP-MU-PEA-21065-CLS, 1.9 ed., 39 pages. [Available online at http://www.avisio.oceanobs.com/fileadmin/documents/data/tools/hdbk_duacs.pdf.]
- Ducet, N., P.-Y. Le Traon, and G. Reverdin, 2000: Global high resolution mapping of ocean circulation from the combination of TOPEX/POSEIDON and ERS-1/2. *J. Geophys. Res.*, **105** (C8), 19 477–19 498.
- Emery, W. J., and R. E. Thomson, 2001: *Data Analysis and Methods in Oceanography*. 2nd and rev. ed. Elsevier, 638 pp.
- Fox, A. D., and K. Haines, 2003: Interpretation of water mass transformations diagnosed from data assimilation. *J. Phys. Oceanogr.*, **33**, 485–498.
- Fu, L.-L., D. Stammer, B. B. Leben, and D. B. Chelton, 2003: Improved spatial resolution of ocean surface topography from the T/P-Jason-1 altimeter mission. *Eos, Trans. Amer. Geophys. Union*, **84**, 241, doi:10.1029/2003EO260002.
- Gomis, D., S. Ruiz, and M. A. Pedder, 2001: Diagnostic analysis of the 3D ageostrophic circulation from a multivariate spatial interpolation of CTD and ADCP data. *Deep-Sea Res. I*, **48**, 269–295.
- Greenslade, D. J. M., D. B. Chelton, and M. G. Schlax, 1997: The midlatitude resolution capability of sea level fields constructed from single and multiple satellite altimeter datasets. *J. Atmos. Oceanic Technol.*, **14**, 849–870.
- Koblinsky, C. J., P. Gaspar, and G. Lagerloef, 1992: The future of spaceborne altimetry: Oceans and climate change. NOAA Rep., 75 pp.
- Leeuwenburgh, O., and D. Stammer, 2002: Uncertainties in altimetry-based velocity estimates. *J. Geophys. Res.*, **107**, 3175, doi:10.1029/2001JC000937.
- LeGrand, P., E. J. O. Schrama, and J. Tournadre, 2003: An inverse estimate of the dynamic topography of the ocean. *Geophys. Res. Lett.*, **30**, 1062, doi:10.1029/2002GL014917.
- Le Traon, P.-Y., and F. Ogor, 1998: ERS-1/2 orbit improvement using TOPEX/POSEIDON: The 2 cm challenge. *J. Geophys. Res.*, **103**, 8045–8057.
- , and G. Dibarboure, 1999: Mesoscale mapping capabilities of multiple-satellite altimeter missions. *J. Atmos. Oceanic Technol.*, **169**, 1208–1223.
- , and R. Morrow, 2001: Ocean currents and eddies. *Satellite Altimetry and Earth Sciences*, L.-L. Fu and A. Cazenave, Eds., Academic, 171–215.
- , and G. Dibarboure, 2002: Velocity mapping capabilities of present and future altimeter missions: The role of high-frequency signals. *J. Atmos. Oceanic Technol.*, **19**, 2077–2087.
- , and —, 2004: An illustration of the unique contribution of the TOPEX/Poseidon – Jason-1 tandem mission to mesoscale variability studies. *Mar. Geod.*, **27**, 3–13.
- , F. Nadal, and N. Ducet, 1998: An improved mapping method of multisatellite altimeter data. *J. Atmos. Oceanic Technol.*, **15**, 522–534.
- , Y. Faugère, F. Hernandez, J. Dorandeu, F. Mertz, and M. Ablain, 2003: Can we merge *GEOSAT Follow-On* with TOPEX/POSEIDON and *ERS-2* for an improved description of the ocean circulation? *J. Atmos. Oceanic Technol.*, **20**, 889–895.
- Levitus, S., T. P. Boyer, M. E. Conkright, T. O'Brien, J. Antonov, and C. Stephens, 1998: *Introduction*. Vol. 1, *World Ocean Database 1998*. NOAA Atlas NESDIS 18, 346 pp.
- Lynch, D. R., and W. G. Gray, 1979: A wave equation model for finite element tidal computations. *Comput. Fluids*, **7**, 207–228.
- Mourre, B., L. Crosnier, and C. L. Provost, 2006: Real-time sea-level gauge observations and operational oceanography. *Philos. Trans. Roy. Soc. London*, **A364**, 867–884.
- Pascual, A., Y. Faugère, G. Larnicol, and P.-Y. Le Traon, 2006: Improved description of the ocean mesoscale variability by combining four satellite altimeters. *Geophys. Res. Lett.*, **33**, L02611, doi:10.1029/2005GL024633.
- , M. I. Pujol, G. Larnicol, and P.-Y. Le Traon, 2007: Mesoscale mapping capabilities of multisatellite altimeter missions: First results with real data in the Mediterranean Sea. *J. Mar. Syst.*, **65**, 190–211.
- Ray, R., 1999: A global ocean tide model from TOPEX/Poseidon altimetry: GOT99.2. NASA Tech. Memo. 1999-209478, Goddard Space Flight Center, NASA, Greenbelt, MD, 66 pp.
- Rio, M.-H., and F. Hernandez, 2003: High-frequency response of wind-driven currents measured by drifting buoys and altimetry over the world ocean. *J. Geophys. Res.*, **108**, 3283, doi:10.1029/2002JC001655.
- , and —, 2004: A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model. *J. Geophys. Res.*, **109**, C12032, doi:10.1029/2003JC002226.
- Smith, N., 2006: Perspectives from the Global Ocean Data Assimilation Experiment. *Ocean Weather Forecasting: An Integrated View of Oceanography*, E. P. Chassignet and J. Verron, Eds., Springer, 1–19.
- Vignudelli, S., P. Cipollini, L. Roblou, F. Lyard, G. P. Gasparini, G. Manzella, and M. Astraldi, 2005: Improved satellite altimetry in coastal systems: Case study of the Corsica Channel (Mediterranean Sea). *Geophys. Res. Lett.*, **32**, L07608, doi:10.1029/2005GL022602.
- Volkov, D. L., G. Larnicol, and J. Dorandeu, 2007: Improving the quality of satellite altimetry data over continental shelves. *J. Geophys. Res.*, **112**, C06020, doi:10.1029/2006JC003765.