TOWARDS A VALIDATION OF ENVISAT RA-2 HIGH RATE SIGNIFICANT WAVE HEIGHT IN COASTAL SYSTEMS: CASE STUDY OF THE GULF OF CADIZ

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ABSTRACT

Research and development of altimetry in the coastal domain, a key region for the significant impact of changing oceans on society, economy, ecology and climatology, is a challenging target for exploiting and enlarging the number of applications relying on satellite data. In this context, ensuring a thorough validation of the nearshore altimetry information is a key activity. The study presented here addresses the case of the continental shelf of Gulf of Cadiz (SW Iberian Peninsula), a very special environment due to several peculiarities lying in the tourism, fishing, aquaculture and industry strategic importance. We have validated the geophysical parameter of significant wave height derived from ENVISAT RA-2 at high and low rates (20Hz and 1Hz respectively) from the COASTALT processor (20Hz) and Geophysical Data Records (1Hz), covering 8 years of data (2002-2009). We used independent ground truth in-situ measurements to check whether new improvements reducing the uncertainties of the various terms concerning the coastal editing flag, perform as good as standard altimetry in the open ocean. The outcomes demonstrate the potential for accurate geophysical parameter retrieval much closer to the coast than routinely achieved.

INTRODUCTION

Satellite altimetry measurements have been mainly exploited in the open ocean offering high performance. Its use on coastal areas is rapidly evolving because the enormous socio-economic-strategic importance of these crucial regions, even more if it allows establishing long-term trends and climatologies. The coastal domain represents a challenging target for exploiting satellite information, where accuracy is degraded or even not interpretable due to a number of factors including issues of land contamination in the altimeter and radiometer footprints, inaccurate tidal and geophysical (inverted barometer, sea state bias, and wet tropospheric) corrections and incorrect removal of high frequency atmospheric effects at the sea surface. Therefore, altimetry observations collected over the coastal ocean remain largely unexploited in the data archives, simply because these problems have so far resulted in systematic flagging and rejection of the information (1). Some attempts have been made in the past to investigate and retrieve near-shore accurate altimetric data (2,3,4,5,6). Several other studies have dealt with the limitations of, and possible improvements to, coastal altimetry in recent years (7,8,9). The recent advances in waveform processing schemes, optimal retrieval algorithms and improvement in corrections combined with developments in data treatment, lead to a significant percentage of recovered data much closer to the shore-line than is routinely achieved. Moreover, the constant demand of quality altimetry in the vicinity of the coast calls for a generation of optimal products, and recent initiatives were born with the intention of meeting such demand (10).

In this sense, the project COASTALT "*Development of Radar Altimetry Data Processing in the Coastal Zone*" funded by the European Space Agency (ESA), aimed at defining, developing, and testing a prototype software processor to generate new ENVISAT RA-2 products and further enhance its capabilities very close to coasts (11), promoting its uses in a wide range of applications.

Moreover, the PISTACH (Prototype Innovant de Système de Traitement pour les Applications Côtières et l'Hydrologie) project (CNES), as part of Jason-2, developed a dedicated study to improve conventional satellite radar altimetry products over coastal areas and continental waters.

The ENVISAT altimeter provides an immensely valuable source of operational Significant Wave Height (SWH), wind speed (U) and sea level (SLA) data globally available. Focused on wind and wave data, its variability, and possible trends is used for a variety of purposes such as modeling and forecasting of weather, ocean surface conditions, circulation and topography-bathymetry, which have implications for offshore engineering projects, coastal defense design and operation, the protection of coastal areas and ship routing. Furthermore, it greatly enhances the study of storm surges and other coastal phenomena (setup), being also essential for applications such as measuring long term coastal sea level variation, erosion and sediment transport analysis and the mapping and monitoring of sea ice and polar ice sheets. In this context, satellite data validation is a fundamental activity to ensure the accuracy of the products (12). Buoy data are generally assumed to be of high quality and have been used in numerous studies for validation of model data (13,14,15,16) and altimeter data (17,18,19,20,21,22).

In this work we analyzed the accuracy of ENVISAT RA-2 wave measurements in the Gulf of Cadiz, addressing the problem of satellite altimetry data improvement near the shoreline. The Gulf of Cadiz is a wide basin located in the southwestern of the Iberian Peninsula connecting the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar (Figure 1). The continental shelf from the east of Cape Santa Maria to the west of the Bay of Cadiz has a broad width (~ 50km). The coast is predominated by marshes, beaches and estuarine zones, and receives significant fluvial inputs associated with the discharge of major rivers such as the Guadiana and the Guadalquivir (23). This crucial environment has undergone substantial rapid agricultural, fisheries, and anthropogenic development, particularly in recent decades.

Figure 1: Location of the study area showing the descending altimetric track 223 and the AWAC (A) and Gulf of Cadiz (G) coastal buoys. Ground tracks are depicted with yellow dots indicating the position of the 1 Hz measurements (Google Earth copyright).

Here we will assess the performance of new ENVISAT datasets, processed with specialized routines under the frame of the COASTALT project, in order to enhance data accuracy and resolution closer to the coast. The main task is to demonstrate that these derived products at coastal regions perform as good as standard altimetry in the open ocean, aiming to achieve the maximum number of records. We will focus on a diagnostic, testing strategy to ensure a thorough validation of the data. The results can be used to highlight interesting aspects of this coastal zone where altimetric data are often flagged as spurious and consequently, rejected. Thus, another aim is focused on expanding the ongoing most ambitious applications of altimeter data for its use to infer useful oceanographic conclusions in synergy with modelling tools and other data sources.

METHODS

Altimetric Data

Geophysical parameters derived from the dual-frequency Radar Altimeter (RA-2) at full and low rates (20 Hz and 1 Hz, respectively) were assessed in this analysis distributed with the more recent available updates (24,11). The data stream was extracted from the beginning of the mission covering the period of cycles 11 through 84 and spanning eight years (2002-2009). The along-track selected corresponds to the descending pass 223 that crosses the continental shelf of the Gulf of Cadiz in front of the Guadalquivir River mouth (Figure 1), with a 35-day repeating cycle. The dataset consists of the parameters of SWH (Significant Wave Height) at a frequency of 1 Hz (7-7.5 km along track spacing). This data corresponds to the standard Geophysical Data Record (GDR) distributed by ESA. In addition, SWH at high rate: 20 Hz (350 m along-track spacing) from the COASTALT processor was also validated. In a first step, SWH from the COASTALT processor at 20 Hz were converted into 1 Hz resolution data by averaging every twenty points and utilized in the inter-comparison with wave measurements of the GDR data at 1 Hz. For the work presented here, the quality checks applied to the data in order to remove remaining spurious records included testing the land flag, peakiness value, zero or default values in the wave height fields and “Nval” (SWH) > 18 (with “Nval” being the number of 20Hz valid measurements). Flagged data indicating errors in the measurements were eliminated. The time series were further processed with the removal of all the observations for which SWH > 15 m or SWH < 0.15 m. These control procedures were performed to the fully corrected along-track data allowing an increase in the statistical confidence. In a second step, we validated high rate SWH data against ground-truth data available in the study area.

In-situ Measurements

We used several coastal stations deployed in the Gulf of Cadiz for validation. The field data are the significant wave heights. Buoy and moored data were obtained from an array of instruments corresponding to two networks. The first one operated by the Instituto de Ciencias Marinas de Andalucia-Spanish National Research Council, ICMAN - CSIC (25). The second dataset was provided by OPPE (Organismo Publico de Puertos del Estado), which uniformly samples Spanish coasts with high quality (www.puertos.es). *AWAC-AST* (A) coastal buoy belonging to ICMAN-CSIC have been continuously operating in the last years, measuring wave variables (10 km separation from coast). Wave data were also collected by *Gulf of Cadiz* (G) exposed mooring from the independent sets of OPPE network, with a distance of 55 km to coast. With the mentioned data streams, rigorous quality control was undertaken, consisting of the flag or the complete removal of records containing default or null values. The time series were processed further using a filtering process, all the observations for which SWH > 15 m or SWH < 0.15 m were discarded. The station names and positions of the instruments are listed in Table 1, which also shows general information about them, such as the time period coverage and availability, network, measured variables and collection time intervals. Also, other surface meteorological data were retrieved from the buoys as ancillary data. The locations of the in-situ are shown in Figure 1.

Table 1: Specific features of the in-situ datasets used in this study.

Station name	Coordinates (Lat/Lon)	Temporal coverage	Variable	Network	Time record (min)
Gulf of Cadiz Buoy	36°28'37.20"N/6°57'46.80"W	1997-2010	SWH	OPPE	60
AWAC moored	36°48'6.48"N/6°30'56.16"W	2008-2009	SWH	ICMAN-CSIC	60

Relative calibration and satellite/in-situ comparisons

Relative calibration between the GDR and COASTALT 1 Hz SWH data were performed for assessing and monitoring the products, with an evaluation of both datasets. Thereby, because one of the main goals of this activity is to check and determine the quality of satellite data at this coastal region, it is also necessary to make comparisons with reliable and independent observations. Then, we have assessed the altimeter-derived SWH against concurrent field measurements to obtain a set of collocated data. So far, buoy observations are considered the most reliable observations, but they are limited to some locations along this coast. Comparisons between satellite and field data are complicated by the fact that each of them is measuring different aspects of the temporally and spatially varying field, and hence may differ, even in the case that both instruments are making accurate estimates (26). The above-mentioned problem has been aware by the altimetric community for many years (27). Usually, a temporal window and a spatial separation of acceptability are established between the altimeter track and the buoy location. In the space domain, the size of the window ranges from 0 km to 150 km; while in the time domain, it varies from 0 h to 1.5 h. Based on assessments of the spatial and temporal variation of the wave field, Monaldo proposes collocation criteria of observations occurring within 50 km and 30 min of one another, being widely adopted as the standards. Furthermore, for data near the coast, the determination of an optimal size is very often a puzzling task because of the conflicting requirements involved. Usually, to eliminate interference from land, stations were required to be at distances greater than 50 km offshore. This condition is defined because if buoys are too close to the coast, altimeter overpasses will generally occur seaward of the buoy location, thus sampling generally higher wave conditions (28). This will affect the collocation statistics, particularly the bias, so excluding buoys that are too close to the coast mitigates this problem. In order to extent the recovery of this valuable information to the coast, it is therefore necessary to use an expert system configured to successfully deal with the complex echo shapes of the altimeter signals.

For each comparison between sets of collocated wave height measurements from satellite and buoy we adopted the following procedure. Altimeter GDR data are available every 1.1 seconds and at distances of about 7 km apart. Buoy measurements are recorded at hourly intervals, giving a maximum time difference from a satellite overpass of less than 10 min (Table 1). This temporal separation difference should have only a small effect on the comparison. One of objectives of this work is to recognize the influence of land on altimetric data and to strictly define the sufficient distance to avoid coastal contamination at this area, thus limitation on the separation from the shoreline was not applied. The number of total altimeter data points selected was 15, with a maximum distance of 85 Km from the buoy stations (Figure 1). The accuracy specifications for buoy data are typically 5% for SWH, while satellite measurements aim for lesser accuracies of 10% or 0.5 m (29). The differences between altimeter products and observations were also quantified by computing some standard monitoring statistics, generally used to evaluate the results. The most common for specific observations are the bias, root-mean- square (rms) error, and linear correlation coefficient (R). Observations that deviate out of the 95 % confidence intervals of the scatter are identified as outliers and removed from the data. These controls were compiled to ensure the consistency and the relevance of the statistics performed on results once we get closer to coast.

RESULTS

Relative calibration of SWH 1 Hz from GDR and COASTALT based products

SWH values at 1 Hz from the GDR datasets were compared against COASTALT records in order to enhance the performance of both datasets nearshore. A statistical evaluation of the altimetric measurements is presented with nearly eight years of data (2002-2009). Results of regression analysis are showed in Figure 2, with the scatter of the 15 satellite 1Hz control points. Overall, good statistics are founded with a slight positive general bias (0.08 m) in the COASTALT data. The rms difference between the two datasets was founded to be 0.84 m with a large correlation of 0.72 (N=837). The first point of the along-track closer to coast (big black dots in Figure 2) indicated an intense overestimation of SWH in the GDR observations. Moreover, point 2 (squares in Figure 2) had similar behavior but less accentuated. Figure 3 shows the along-track results (rms, bias and R) of each 1Hz point individually with respect to the distance to land. The two closest altimeter points to the land show the lower correlation (R below 0.5) and are quite noisy with high rms, especially the last point declared as “ocean”. The remaining 1Hz points presented the higher correlation, with most regression line slope close to, but slightly more than 1.0, confirming the underestimation of the SWH from GDR data. The degradation of quality data is quite evident at distances to land lower than 18km,where the major disagreements between both datasets are found. The correlation increased as we moved away from coast (R maximum=0.98 for point 13), also with a reduction in noise (rms minimum=0.30 m for point 13). The underestimation of GDR records respect to COASTALT data is almost constant along-track (points 3 to 15) with positive bias of about 0.28 m.

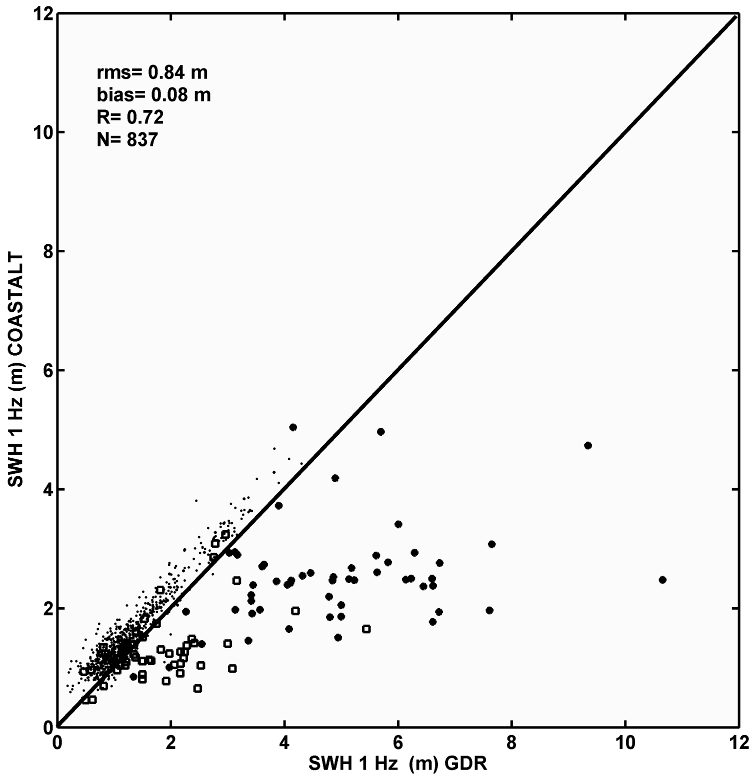

Figure 2: Comparison of significant wave height values at 1 Hz frequency measured by the ENVISAT RA-2 altimeter from the Geophysical Data Records (GDRs) and from the COASTALT project. Large dots indicated 1Hz track point 1, squares the 1Hz track point 2 and small dots the rest of the 1Hz points from 3 to 15. Regression results are included in the figure.

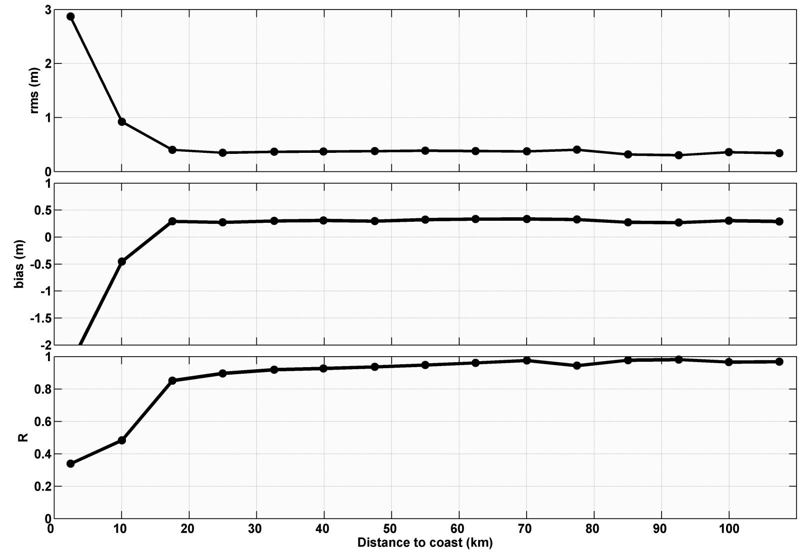

Figure 3: Statistics (rms, bias and R) of the comparison of GDR and COASTALT significant wave height 1 Hz products with respect to the distance to coast. Track points are indicated with dots.

The comparative statistics of both datasets are very similar and a good agreement is inferred with the exception of the two closest points to coast (less than 18 km) presenting a severe overestimation of GDR data. This interference is a common feature in altimeter measurements nearshore and is associated to land contamination, sampling generally higher wave conditions (28). Moreover, the proximity of land is affecting in a very different way the retrieval of SWH, when using the ESA standard retracking processing, respect to the processing developed in COASTALT. For distances to land higher than 18km, the COASTALT processor performs as well as the standard processor used by ESA.

Validation with in-situ data

We have collected, assessed, and compared the SWH data from the altimeter-derived products (GDR and COASTALT) with two in-situ stations separately (AWAC-A and Gulf of Cadiz-G). The results of regression analysis of the buoy in exposed location (G) showed very high correlation for both datasets GDR (N=797) and COASTALT (N=787), and were statistically significant at the 95% level, with most regression line slope close to, but slightly more than 1.0. The closest 1Hz track point to the buoy (20 km) offered the best fit in both data streams: 0.17 m rms, 0.006 m bias and R=0.97 (GDR) and 0.15 m rms, 0.007 m bias and R=0.96 (COASTALT), presenting consistent altimeter products typical of more offshore locations.

The outcomes of the sheltered water moored AWAC located in the estuarine zone of the Guadalquivir River (10 km from coast), a very dynamic area, are presented in Figure 4. The regression analysis gives large correlation for both datasets and good agreement is inferred for the track points located 10-15 km away from the shore-line. The rms (m), bias (m) and R values along-track for each altimeter point and for the two data streams are displayed with respect to distance to coast and the separation to the in-situ station. Due to nearshore ground-truth data availability the number of observation is lower than offshore station, with N=161. The comparison against GDR dataset shows that the bias obtained indicates that the altimeter overestimates SWH respect to the buoy measurements over the entire segment of along-track analyzed, especially in the first two points. The bias slightly increases as the along-track 1Hz points are far from the buoy. Figure 4 also indicates that rms in the present comparison are reduced monotonically when satellite/buoy distances are restricted. The best fit corresponds to the minimum along-track point's distance to the buoy (~11 km in point 4). Figure 5 presents the scatter of SWH from ground-based observations against altimeter GDR retrieval of this track point number 4 (dots), showing that the total collocations are situated above the 1:1 line with a positive bias in the satellite data. Average scatter about the regression line amounts to 0.36 m rms, 0.28 m bias, and 0.78 R. It is known that in coastal systems the background energy may significantly vary within the region and affect the wave spectra differently (30). Firstly, the effects associated with the remaining dispersion are interpreted due to local variations in wave climate because the proximity to land. Secondly, the low correlation of the last two track points 1 and 2 (1.5 and 9 km distance from coast, respectively) demonstrated that, in addition to the coastal processes, the effects of land contamination in the altimeter footprint might distort the retrieval of SWH.

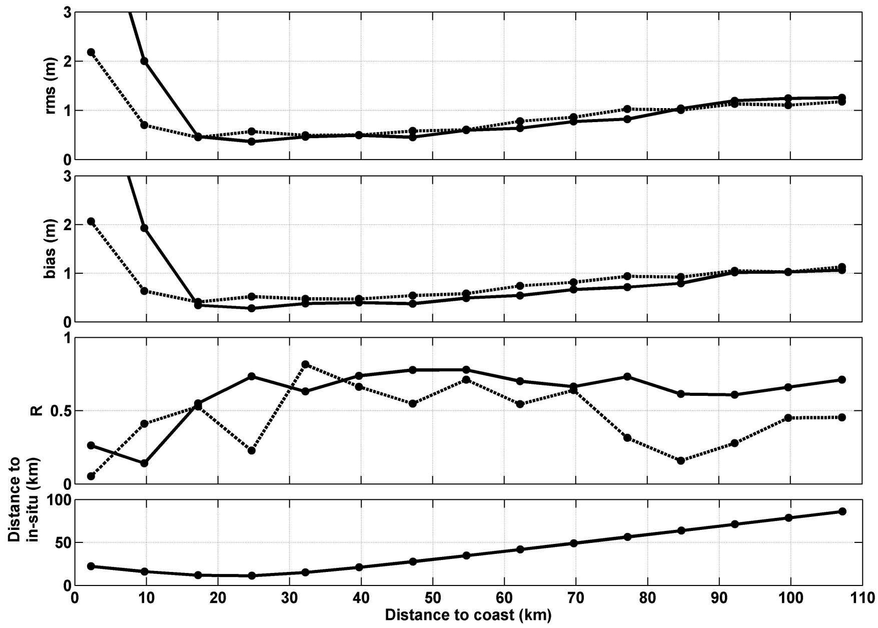

Figure 4: Statistics (rms, bias and R) resulting of the validation of significant wave height from the altimeter products against in-situ observations from the AWAC coastal buoy with respect to the distance to coast. Continues lines correspond to GDR datasets and dashed lines to COASTAL records. The distance to in-situ emplacement of each track point in the bottom of the plot.

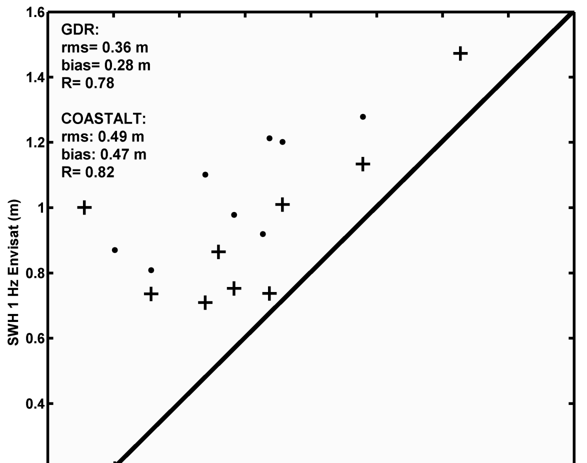

Figure 5: Comparison of significant wave height records from the AWAC coastal buoy versus altimeter 1Hz of the track point 4 from the GDR data streams (dots) and of the track point 5 from COASTAL measurements (crosses).

The COASTALT records show quite a good correspondence with the in-situ data, similar to the GDR data, with a total of 120 collocations (Figure 4). Overall, there is a positive bias in the altimeter data (higher nearshore). This agrees well with previous work and with the GDR comparisons, suggesting that altimeter systematically overestimates SWH respect to ground-truth observations. We observe an improvement in statistics as we get closer to the ground-based emplacement (same as GDR data). Accordingly, the best fit appeared in the track point number 5, at 20 km from the buoy, with a correlation factor of 0.82, 0.49 m rms and 0.47 m bias. The scatter of this point 5 can be observed in figure 5 (crosses), presenting an overestimation of the satellite data observed in the regression line slope, more than 1.0.

In general, the rms between the two respective data streams was found to be similar, with the exception of the two closest points to coast, presenting lower errors in COASTALT data. In fact, the second 1Hz point (COASTALT) presents rms and bias values of the same order of magnitude than offshore points. For Geosat/buoy validations, Monaldo defined scatter of about 0.4 m rms. While this is close to that displayed for most comparisons in the SWH studies, results using smaller comparison distances show the buoys to be more precise than this. This characteristic is founded in the present analysis; as we move away from buoy, rms values increase. Indeed, the closest the tracks are to the buoy, the better the estimate of the bias between altimetric and in-situ data is. Apart from the discrepancy in the two points nearshore, the comparative statistics of both analysis in terms of significant wave height are very similar. Both the COASTALT and GDR records persistently overestimate the wave conditions in the control region with respect to the in-situ observations. In general, the results stated extremely in good agreement between the buoy and the altimeter GDR and COASTALT measurements, roughly consistent with the accuracies planned for each system. RA-2 estimates of SWH is characterized by stable and precise performance, indicating that the spatial and temporal variability of the wave field is well reproduced in this coastal region. The current outcomes of the SWH validation synthesized accuracy data at the boundary of 10-20 km from coast. The effect of slight spatial variations in wave climate over the 10 to 100 km distances used in the comparisons can explain different statistics values, and appears typically in nearshore regions due to the differences in swell and wind wave properties. This could reflect, at least in part, the noisier radar returns from a generally rougher sea surface condition than usually found in deep oceans. Some of the systematic error could be due to buoy imprecision in measuring waves, and some may be due to the indirect nature of the satellite measurement. In addition, the results of the two points closest to shore clearly manifested the influence of land contamination in the retrieval of the SWH in both GDR (more intensely) and COASTALT retrackers. However, the retracker used in COASTALT seems to retrieve less noisy SWH.

CONCLUSIONS

This paper presents the main results in terms of the assessment of RA-2 ENVISAT performances and the quality evaluation of the products. A strategy to process altimeter geophysical parameters shows that the data reprocessing could significantly improve accuracy in a coastal system. Consistent agreement between satellite and corroborative ground-based SWH values are precise enough to suggest that both systems are obtaining their design specifications. The additional difference between the mean altimeter/buoy relationship for the coastal stations reduces when comparison are limited to distances less than a restricted maximum. The above conclusion exposed the importance of using only the smallest possible distances when validating sensors performances. The appeared dispersion in the data may be ascribed to spatial variability in wave climate, with clear local effects in a complex area such as Guadalquivir estuary, or attributed to atmospheric stability effects and phenomena at different temporal-spatial scales, where the continental shelf extension may have significant local impacts with significantly varying background energy within the area not characteristic of offshore regions. The current validation of COASTALT SWH offered good quality altimeter data much closer to the coast than routinely achieved. Even though the maximum correlation position of the data are all less than 50 km of the coast (between 10 and 35 km), we still cannot provide optimized SWH right up to the coastline since the altimeter waveforms and radiometer signals remain contaminated by land reflections. Hence, ongoing research directed to enhance the new generation of products may better fulfill the requirements of a coastal-oriented processing. Over the Gulf of Cadiz area, we expose that it is possible to build an accurate data set yielding more rigorous records closer to the shoreline than previous studies with the typical 50 km coastal-band (80% closer). To conclude, achievable goals during this exercise were encouraging, allowing to infer useful oceanographic conclusions looking for trends (seasonal and longer time scales) in ocean conditions extending to satellite's life period. Accordingly, altimetry may also be used to appropriately monitor the coast for a variety of regional studies, and would benefit and optimize the conditions of models over the Gulf of Cadiz area, a key region of complicated dynamics and with relevant social, economic and ecological strategic importance. The questions raised in this work may be generalized to altimeter-derived wind speed, sea level, or even to other geophysical parameters derived from space-borne radiometers, scatterometers and synthetic aperture radars. In this sense, the outcomes obtained here may serve as a guideline in this coastal region becoming an irreplaceable tool for multiple coastal applications.

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REFERENCES

1 Cipollini P, J Benveniste, J Bouffard, W Emery, L Fenoglio-Marc, C Gommenginger, D Griffin, J Høyer, A Kurapov, K Madsen, F Mercier, L Miller, A Pascual, M Ravichandran, F Shillington, H Snaith, P Strub, D Vandemark, S Vignudelli, J Wilkin, P Woodworth & J Zavala-Garay, 2010. The Role of Altimetry in Coastal Observing Systems. In: Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), edited by J Hall, DE Harrison & D Stammer (ESA, Venice, 21-25 September 2009).

2 Manzella G, G L Borzelli, P Cipollini, T H Guymer, H M Snaith, S Vignudelli, 1997. Potential use of satellite data to infer the circulation dynamics in a marginal area of the Mediterranean Sea. In: Proceedings of 3rd ERS Symposium-Space at the Service of our Environment, (ESA SP-414, Florence, 17-21 March 1997), 3: 1461-1466.

3 Crout R L, 1998. Coastal currents from satellite altimetry. Sea Technology, 8: 33-37.

4 S Vignudelli, P Cipollini, M Astraldi, G P Gasparini & G Manzella, 2000. Integrated use of altimeter and in-situ data for understanding the water exchanges between the Tyrrhenian and Ligurian seas. Journal of Geophysics Research, 105: 649-663.

5 Vignudelli S, P Cipollini, L Roblou, F Lyard, G P Gasparini, G Manzella & M Astraldi, 2005. Improved satellite altimetry in coastal systems: Case study of the Corsica Channel (Mediterranean Sea). Geophysical Research Letters, 32.

6 Bouffard J, S Vignudelli, P Cipollini & Y Menard, 2008. Exploiting the potential of an improved multimission altimetric data set over the coastal ocean. Geophysical Research Letters, 35.

7 Fernandes M J, L Bastos & M Antunes, 2002. Coastal Satellite Altimetry – Methods for Data Recovery and Validation. In: 3rd Meeting of the International Gravity and Geoid Commission, (Thessaloniki, 26-30 August 2002).

8 Deng X, W E Featherstone, C Hwang & P A M Berry, 2002. Estimation of contamination of ERS-2 and POSEIDON satellite radar altimetry close to the coasts of Australia. Marine Geodesy, 25(4): 249-271.

9 Dong X, P Moore & R Bingley, 2002. Absolute calibration of the TOPEX/POSEIDON altimeter using UK tide gauges, GPS, and precise local geoid-differences. Marine Geodesy, 25: 189-204.

10 Vignudelli S, A Kostianoy, P Cipollini & J Benveniste, 2010. Coastal Altimetry (Springer) 680 pp.

11 Gómez-Enri J, P Cipollini, C Gommenginger, C Martin-Puig, S Vignudelli, P Woodworth, J Beneviste & P Villares, 2008. COASTALT: Improving radar altimetry products in the oceanic coastal area. In: Proceedings of SPIE, 7104, doi: 10.1117/12.802456. 2008.

12 Strub T, 2001. High-Resolution Ocean Topography Science Requirements for Coastal Studies. In: High-resolution Ocean Topography Science Working Group meeting, edited by D B Chelton (College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon), 224 pp.

13 Janssen P, B Hansen & J R Bidlot, 1997. Verification of the ECMWF wave forecasting system against buoy and altimeter data. Weather Forecasting, 12: 763-784.

14 Caires S & A Sterl, 2003. Validation of ocean wind and wave data using triple collocation. Journal of Geophysical Research, 108.

15 Caires S, A Sterl, J R Bidlot, N Graham & V Swail, 2004. Intercomparison of different wind wave reanalyses. Journal of Climate, 17 (10): 1893-1913.

16 Abdalla S, J Bidlot & P Janssen, 2004. Assimilation of ERS and ENVISAT wave data at ECMWF. In: Proceedings of the ENVISAT-ERS Symposium, edited by ESA (Salzburg, September 6-10 2004).

17 Ebuchi N & H Kawamura, 1994. Validation of wind speeds and significant wave heights observed by the TOPEX altimeter around Japan. Journal of Oceanography, 50 (4): 479-487.

18 Gower J, 1996. Intercalibration of wave and wind data from TOPEX/POSEIDON and moored buoys of the west coast of Canada. Journal of Geophysical Research, 101: 3817-3829.

19 Bauer E & C Staabs, 1998. Statistical properties of global significant wave heights and their use for validation. Journal of Geophysical Research, 103(C1): 1153-1166.

20 Queffeulou P, 2004. Long-term validation of wave height measurements from altimeters. Marine Geodesy, 27: 495-510.

21 Cotton P D, P G Challenor & J M Lefevre, 2004. Calibration of ENVISAT and ERS2 wind and wave data through comparison with in situ data and wave model analysis fields. In: ENVISAT ERS Symposium, edited by European Space Agency (Salzburg).

22 Faugere Y, J Dorandeu, F Lefevre, N Picot & P Femenias, 2006. ENVISAT Ocean Altimetry Performance Assessment and Cross-calibration. In: Special Issue on "Satellite Altimetry: New Sensors and New Application", edited by G Chen & G D Quartly, Sensors, 6 (3): 100-130.

23 García Lafuente J & J Ruiz, 2007. The Gulf of Cádiz pelagic ecosystem: A review. Progress in Oceanography, 74 (2-3): 228-251.

24 ENVISAT RA2/MWR ocean data validation and cross-calibration activities. Yearly report 2009, CLS.DOS/NT/10.018.

25 Navarro G, F J Gutiérrez, M Díez-Minguito, M A Losada & J Ruiz, 2011. Temporal and spatial variability in the Guadalquivir estuary: a challenge for real-time telemetry. Ocean Dynamics, DOI 10.1007/s10236-011-0379-6.

26 Monaldo F, 1988. Expected differences between buoy and radar altimeter estimates of wind speed and significant wave height and their implications on buoy-altimeter comparisons. Journal of Geophysical Research, 93: 2285-2302.

27 Chen G, 2000. Impacts of the collocation window on the accuracy of altimeter/buoy wind speed comparison- A simulation study. International Archives of Photogrammetry and remote sensing, 33 (B2), Amsterdam.

28 Greenslade D J M & I R Young, 2004. A validation of ERS-2 Fast Delivery Significant Wave Height. Bureau of Meteorology Research Centre, BMRC Research Report, 97: 35 pp.

29 Callagan P S, C S Morris & S V Hsiao, 1994. Comparison of TOPEX/POSEIDON σ_0 and significant wave height distributions to Geosat. Journal of Geophysical Research 99, 15-24.

30 Gille S T & C W Hughes, 2001. Aliasing of high-frequency variability by altimetry: Evaluation from bottom pressure recorders. Geophysical Research Letters, 28 (9): 1755-1758.