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A comparison of the annual cycle of sea level in coastal areas from gridded satellite altimetry and tide gauges

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ABSTRACT

In this work we compare the annual component of sea level variations derived from 478 worldwide-distributed tide gauges with the annual component computed from a weekly gridded multi-mission altimeter product. Gridded altimetry data products allow for spatio-temporal analyses that are not possible based on along-track altimetry data. However, a precise validation is necessary in the coastal region before the gridded data can be used. Results of the comparisons show that root-mean-square differences (RMSD) between the two datasets are ≤ 2 cm for 76.4% of the sites. RMSD higher than 4 cm are caused by narrow coastal currents, nearby river outflows or other local phenomena. A methodology is proposed to assess the accuracy of the seasonal component of the gridded altimeter product in regions with a low density net of tide gauges. As a case study it is shown that the Southwestern Atlantic coast is a suitable region to study the spatio-temporal variability of the annual cycle of sea level since RMSD between annual altimetry data and in-situ data are lower than 2.1 cm.

1. Introduction

Satellite altimetry is a useful tool to describe the surface circulation of the open ocean and marginal seas. Nowadays more than 20 years of global altimetry observations are available. In contrast with other satellite-based observations, such as those in the infrared or visible part of the spectrum, altimeter data are not affected by cloud coverage. Sea level anomalies retrieved from satellites are essential to describe and understand large scale and mesoscale ocean circulation and climate-related processes as well as operational oceanography applications. However, the use of altimetry data in coastal and shelf areas has been questioned due to instrumental and geophysical limitations. Instrumental limitations include land contamination close to the coast: altimeter footprints may encounter the coastline and corrupt the raw along-track remote-sensed signal (Anzenhofer et al., 1999; Strub, 2001). Geophysical limitations include a non-precise tide (e.g. Lyard et al., 2006) and/or wet tropospheric modelling (Desportes et al., 2007). In fact, both tide and atmospheric models currently used to correct the altimetry data are global and are focused on the open ocean. However, tides and meteorological conditions close to the coast and over continental shelves are often very different from those found in the open ocean. Therefore a significant bias is introduced when applying these corrections to the altimeter data near shore (Vignudelli et al., 2011).

Several approaches are available to address the problems described above. Volkov et al. (2007) showed that using improved corrections of tidal and atmospheric forcing, gridded altimetry data provided by Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) improves the quality of estimates of sea level variability over continental shelves in scales ranging from intra-annual (periods from 20 days) to interannual. Other efforts to correct the altimeter signal near the coast include recomputing the wet tropospheric correction (Manzella et al., 1997; Vignudelli et al., 2005; Madsen et al., 2007; Desportes et al., 2007), the use of customized tidal modelling (Vignudelli et al., 2000; Volkov et al., 2007), higher-rate data (e.g. Lillibridge, 2005), and/or retracking (Deng and Featherstone, 2006). Algorithms to correct these and other effects of contamination of the atmosphere and land in coastal regions is the subject of study of several international initiatives such as ALTICORE (Vignudelli et al., 2008; Bouffard et al., 2008; www.alticore.eu), COASTALT (Cipollini et al., 2008; www.coastalt.eu), eSURGE (http://www.storm-surge.info/) and PISTACH (Lambin et al., 2008), among others.

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The above-mentioned efforts to improve the quality of the altimetry data in coastal regions have encouraged studies at regional and global scale. In particular, satisfactory results have been found at seasonal scales using different altimetry products. Volkov and Pujol (2012) showed that in the Nordic seas gridded altimetry and tide gauge data are in good agreement in terms of amplitudes and phases of the seasonal cycle. Gridded altimetry data were also validated at seasonal and interannual scales in the Gulf of Cadiz by Gómez-Enri et al. (2012). At global scale, Vinogradov and Ponte (2010) compared the annual cycle derived from TOPEX/POSEIDON along-track data with the annual cycle derived from 345 coastal tide gauges. Their results suggest that the altimeter measurements adequately represent the annual cycle in most shallow regions. They also showed that differences between satellite and in-situ data are found in areas adjacent to strong river outflows and narrow coastal currents. The present work follows the study of Vinogradov and Ponte (2010), but is based on the analysis of the gridded altimetry data. Despite gridded altimetry data is an interpolation of along-track data, the former product has a better temporal and spatial resolution, because it is based on more than one satellite. Therefore, the gridded product allows for spatio-temporal analyses that are not possible with along-track data.

Variability of coastal sea level from seasonal to interannual time scales is caused by several processes, such as changes in ocean heat content and circulation, changes in sea level pressure, and changes in river runoff regimes (e.g. Tsimplis and Woodworth, 1994), among others. The influence of the tide is negligible compared with those processes (Pugh, 1987). The main contributions to the seasonal cycle on sea level at global and regional scales have been addressed by several studies (e.g. Laiz et al., 2013; Bell and Goring, 1998; Vivier et al., 1999; Willis et al., 2008). These studies indicate that the annual variation of pressure-adjusted sea level is mainly explained by the expansion and contraction of the water column due to density changes (steric-effect) (e.g. Stammer, 1997; Ivchenko et al., 2007). This effect also contributes significantly to the observed sea level trends. In particular, the main contributor of the sea level rise is the thermal component of the steric effect in the upper 750 m of the ocean, which is related to the global warning (Lombard et al., 2009; Levitus et al., 2012).

In coastal areas the spatial and temporal variability of the sea level at seasonal scales is useful to characterize the circulation, monitor shorelines, detect extremes and trends in sea level, and better understand dynamics of estuaries. In addition, most of these processes may have a significant impact on marine life. In this work we compare the annual variability of sea level anomaly (SLA) computed from the AVISO weekly gridded multi-mission altimeter data and from tide gauges. Because the use of satellite altimetry is particularly useful in regions that lack long-term, high-quality records, such as most of the coasts of Asia, South America and Africa, we propose to use monthly climatologies constructed with ancillary data. As a case study we focus only in one of those regions, the Southwestern Atlantic continental shelf (SWACS) and we show that the annual component of the AVISO data correspond to the in-situ annual signal with a RMSD lower than 2.1 cm.

The paper is organized as follows: in Sections 2 and 3 we describe the datasets used and the methodology, respectively. Then in Section 4 results and discussion are presented in three sections: Section 4.1 deals with the worldwide comparisons; Section 4.2 compares results obtained at the TGs located over islands with those obtained over continents; Section 4.3 improves the spatial coverage of TGs by incorporating stations that are not concomitant with the altimetry data while Section 4.4 presents the results from the Southwestern Atlantic. Finally, Section 5 presents a summary of conclusions.

2. Data

2.1. Satellite altimetry data

To compute the seasonal cycle of sea level from satellite altimetry data we used the delayed-time, reference (DT Ref.) gridded SLA weekly data produced by Ssalto/Duacs and distributed by AVISO (www.aviso.oceanobs.com) for the 18-year period 1993–2010. The DT Ref. product is used because it is more precise than the near-real time (NRT) product and has a stable sampling throughout the record length compared to the update product (AVISO, 2012). Sea surface height (SSH) altimetry data are corrected by AVISO for instrumental noise, orbit error, atmospheric attenuation, tidal effects and the dynamic atmospheric correction (DAC). This atmospheric correction combines high frequencies modelled by MOG2D (2D Gravity Waves model) (Carrère and Lyard, 2003) and low frequencies of the inverted barometer correction. MOG2D is a barotropic model forced by the ERA-Interim pressure and wind reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The SLA is estimated by subtracting the 1993–1999 mean from the corrected SSH.

To generate the DT Ref. grid data, two sets of satellite missions are used (TOPEX/POSEIDON and ERS followed by Jason-1 and Envisat) obtaining a homogeneous time series (AVISO, 2012). An optimal interpolation with realistic correlation functions is applied to produce SLA maps of 1/3° resolution (Ducet et al., 2000). In some cases the interpolation produces values located over land. Land values are often noisy since they are derived from the interpolation of few data. To avoid this problem we built a continental mask as the union between the AVISO gridded data continental mask and all pixels with positive bathymetry (version 8.2, Smith and Sandwell, 1997).

2.2. Tide gauges

Tide gauges data are used to validate the seasonal cycle derived from altimetry data. We downloaded and extracted monthly SSH time series for the locations indicated in Fig. 1 from the Permanent Service for Mean Sea Level (PSMSL) (Holgate et al., 2013; PSMSL, 2013). Wherever possible, PSMSL used available datum information to tie different records at a location to produce Revised Local Reference (RLR) tide gauge (TG) records.

We selected all TGs located south of 72°N and not being flagged as suspicious (http://www.psmsl.org/data/obtaining/notes.php). The northern limit is chosen to avoid contamination by seasonal sea-ice. We then separated the database into two subsets, named A and B. Subset A includes all data from the TGs stations having at least 10 years of data concomitant with the AVISO period (1993–2010), a distance up to 30 km between TG and the nearest grid points, and that presented less than 20% of missing data. With the selection criteria mentioned above, we selected 478 TG stations of 1291 initially available (Fig. 1). The 478 TG stations were then classified as "continental" and "island" based on their geographical location. Subset B includes all TGs with more than 10 years of data located between 20–54°S and 70–42°W in the SWACS (Fig. 1). In this subset only 4 TGs out of 15 have more than 10 years of data concomitant with the altimeter time period. Furthermore, in a large portion of the coast, between 28.5°S and 34.5°S, there is only one TG (Porto do Rio Grande) that is catalogued as Metric data in the PSMSL database (i.e. no datum control, low quality compared with RLR). This TG includes 23 years of data between 1981 and 2003. However, despite of the extended record length, this TG record contains 79% of missing values. In order to improve the spatial coverage of TGs in this region we included the analysis of two years of data with no gaps at the Porto do Rio Grande.