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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.

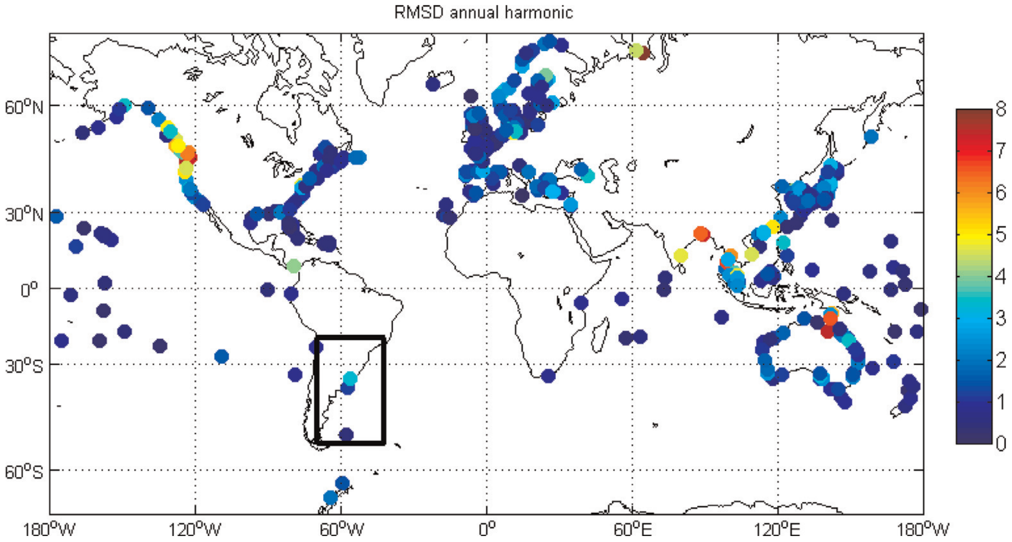

Fig. 1. Location of the 478 tide gauges available at the PSMSL database considered for the validation of the altimetry data. Colours indicate the root mean square difference (cm) between the annual harmonics of SLAtg and SLAsat. The black rectangle indicates the SWACS.

3. Methodology

To compare satellite and TG monthly time series, both datasets were corrected for atmospheric pressure effect using the inverted barometer (IB) approach. The IB is a reasonable assumption at seasonal and longer scales considering a pure isostatic response of the sea level to atmospheric pressure variations (Han et al., 1993). Altimetry data was first de-corrected from atmospheric pressure and wind effects by adding-up the DAC (available at http://www.aviso.oceanobs.com/). Hereafter, we refer to the altimetry and TG time series as SLAsat and SLAtg, respectively.

The IB correction was computed using sea level pressure (SLP) from the National Centers for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996) provided by National Oceanic and Atmospheric Administration (NOAA). The SLP database spatial resolution is 2.5° × 2.5°. To estimate the IB effect, monthly SLP means were extracted at the NCEP grid point closest to each TG location. We selected the NCEP database since it covers the whole TG time period that starts in 1948, in contrast with the ERA-Interim ECMWF database that starts in 1979. Note that we applied the IB correction and not the DAC to both TG and satellite data for two reasons; (i) the high frequencies of the wind are filtered out at time scales longer than a month; (ii) DAC is available since 1992 while subset B defined in the previous section includes TGs not concomitant with the altimeter time period.

The SLAsat and SLAtg annual cycle was extracted from the SLAsat and SLAtg climatologies by harmonic analysis using the least-squares method. Both SLAtg and SLAsat were linearly detrended to avoid biases when computing the respective annual cycles. The harmonic analysis is an estimate of the time series represented by a sum of cosines with different amplitudes and phases:

$$y(t) = \bar{y} + \sum_{q}^{M} C_q \cos(2\pi f_q t - \theta_q) + y_r(t) \tag{1}$$

where C_q, f_q and θ_q are the amplitude, frequency and phase of the qth constituent, respectively. $\bar{y}$ is the mean SLA and y_r is the residual. The aim of the least-squares method is to minimize the squared difference between the original data and the data fitted by Eq. (1).

Root mean squares of the differences (RMSD) between each TG and the closest SLAsat gridded data point were estimated as

$$\mathrm{RMSD} = \sqrt{\frac{\sum (X_1 - X_2)^2}{N}} \tag{2}$$

where X_1 and X_2 are the annual harmonics of the in-situ and satellite data, respectively, and N is the length of the times series. It is important to note that the above formula considers both the amplitude and phase differences between the two dataset.

In order to quantify how well the annual fit adjusts to the climatologies, we defined the goodness of the fit (Gof) as the percentage of the observed variance explained by the annual harmonic. The average of the Gof for all the TGs considered and for the corresponding SLAsat time series are of 84.51% and 87.85%, respectively, suggesting that indeed the annual signal is the dominant signal in the climatologies constructed.

We also considered the vertical crustal motions due to post-glacial rebound as a possible source of error in the comparison between the satellite and in-situ data. To correct the TG data for vertical displacements of land we used the Glacial Isostatic Adjustment (GIA) data from the ICE-5G model (Peltier, 2004). This model provides the present-day rate of change of relative sea level respect to the solid Earth. Results show that the vertical land movement correction has a little impact: the mean of RMSD (defined above) when the isostatic correction is applied is 1.61 cm instead of 1.59 cm. The GIA correction does provide a better consistency between TG and altimetry when the SLA trend is analysed (Valladeau et al., 2012).

4. Results and discussion

4.1. Worldwide comparison

Fig. 2 shows the annual amplitudes of SLAsat and SLAtg. We observed that both data set presented a similar spatial pattern, dominated by values between 4 and 10 cm. Maximum amplitudes were found in the coast of India, west and northeast of Australia, China and Japan, with values within the 12 and 33 cm range. In some of these regions the annual amplitude of SLAsat underestimated the amplitude derived from the TGs.

The spatial distribution of the annual phases of SLAsat and SLAtg (Fig. 3) was also similar, showing the expected difference between hemispheres. In general, the annual cycle peaks between the end of February and early June in the Southern Hemisphere, while SLA peaks between August and November in the Northern Hemisphere.

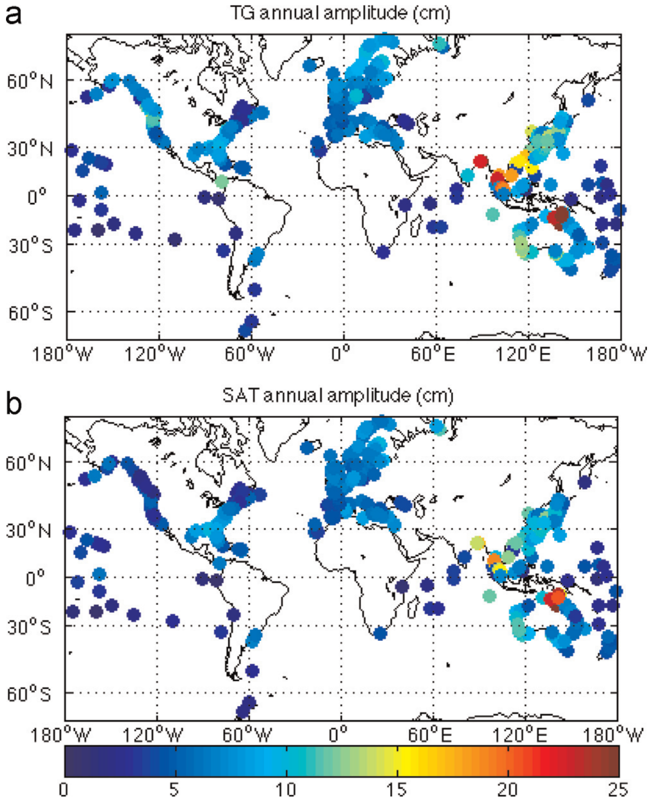

Fig. 2. Annual amplitude distribution (cm) of the a) SLAtg and the b) SLAsat.

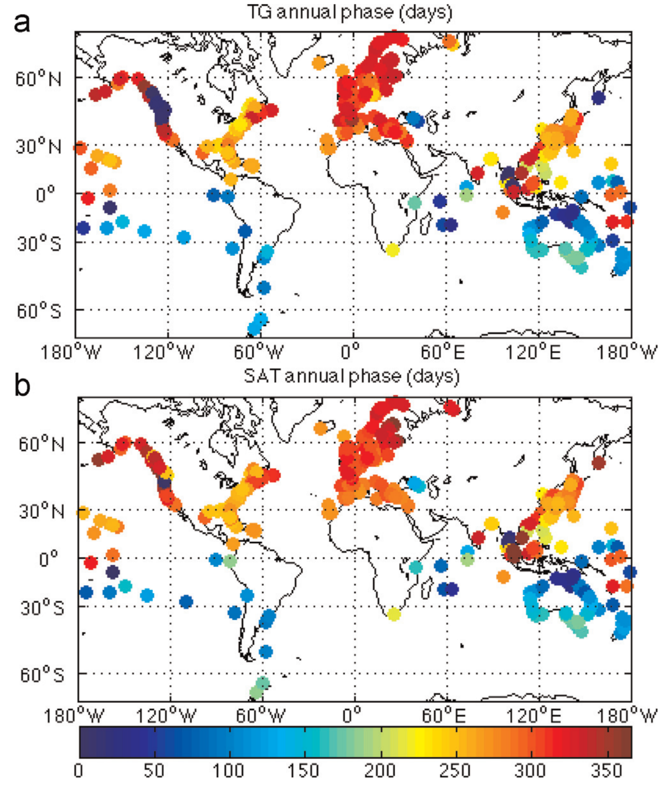

Fig. 3. Annual phase (days) distribution of the (a) SLAtg and (b) SLAsat. The phase indicates the number of days after 1 January when the maximum sea level is observed.

Table 1
Correlation coefficients (*R*), significant at the 95% confident level, and average of the root mean square difference (RMSD) between SLA and TG for different subsets of the PSMSL database.

	All (478)	Islands (73)	Continent (405)
R amplitude	0.88(0.14)	0.99(0.45)	0.85(0.15)
R phase	0.84(0.13)	0.90(0.37)	0.82(0.14)
RMSD (cm)	1.59	0.64	1.76

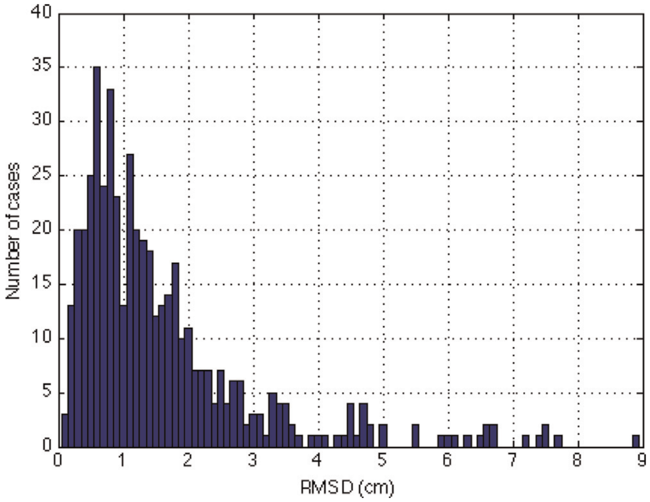

Fig. 4. Histogram of the root mean square difference (RMSD) between the SLA and TG annual harmonics (88.49% RMSD < 3 cm, 76.36% RMSD ≤ 2 cm).

In order to quantify the amplitudes and phases differences, we calculated the RMSD (Eq. (2)). Results showed that the mean of the RMSD computed at 478 worldwide-sites was lower than 1.6 cm (Table 1). 88.5% of the estimated RMSD were lower than 3 cm and 76.4% were equal or lower than 2 cm (Fig. 4). Only 34 TGs presented RMSD higher than 4 cm (Fig. 4). These results clearly indicate that the annual cycle captured by the TGs is well represented by the large majority of the nearby gridded altimetry SLA.

The spatial distribution of the RMSD of the annual cycle reveals the regions where this magnitude is relatively large (Fig. 1). In what follows we consider the regions where RMSD are higher than 4 cm and show that different phenomena make significant and distinct contributions to the SLA climatologies depending on whether TG or altimetry data are used.

4.1.1. *Narrow coastal currents*

Along the west coast of North America, between 42°N and 55°N (Fig. 1) RMSDs were higher than 4.3 cm. Strong and narrow coastal currents are seasonally present in response to coastal wind-forced upwelling/downwelling (e.g. Strub and James, 2000). Those strong, narrow coastal currents are indeed the cause of the difference between the gridded AVISO altimetry product and TGs in this region (Saraceno et al., 2008). Evidently, the gridded altimetry product captures the open ocean conditions and is not able to solve the narrow coastal current that makes a large contribution to the SLA measured by the TGs. Saraceno et al. (2008) show that the correct seasonal SLA fields close to the coast can be reproduced by interpolating the off-shore AVISO data with the coastal TGs.

4.1.2. *Seasonal ice*

Despite the fact that we excluded TGs located north of 72°N, several comparisons were biased due to seasonal ice. Three clear examples of this problem were the Kara Sea, the Gulf of Bothnia and the Gulf of Finland. In the Kara Sea, located at 60°E–70°N, RMSD was higher than 4 cm (Fig. 1). This region presents seasonal sea ice that affects the altimetry signal leading to a poor

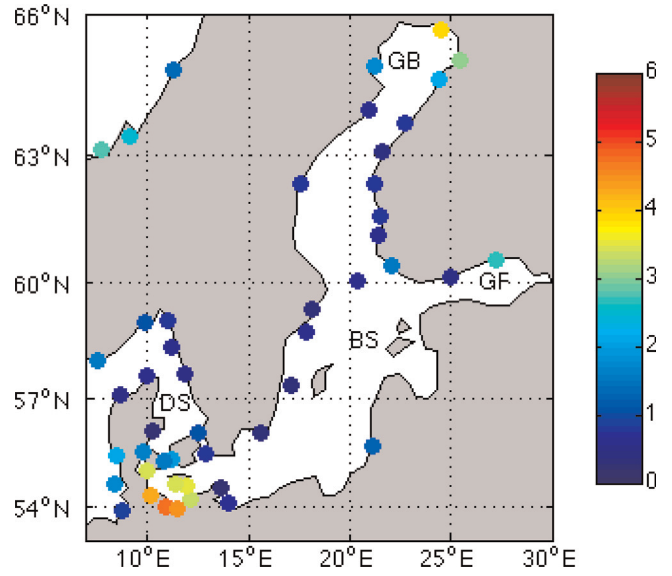

Fig. 5. Location of the tide gauges considered for the validation of the altimetry data on the coast of the Baltic Sea (BS), Gulf of Bothnia (GB), Gulf of Finland (GF) and Danish Straits (DS). Colours indicate the root mean square difference (cm) between the annual harmonics of SLAtg and SLAsat.

comparison with TGs (Volkov and Pujol 2012). In the northern portion of the Gulf of Bothnia (65°N–25°E, Fig. 5) and in the Gulf of Finland (60°N and 25–30°E, Fig. 5) the differences were also due to the sea ice cover. In these regions sea ice forms in late November and melts in late May (Leppäranta, 2012) when the largest differences between SLAtg and SLAsat annual cycles were observed (not shown).

4.1.3. Semiannual cycle and complex coastline geography

RMSDs higher than 4 cm were found in the southern Baltic Sea (near the Danish straits, between 11 and 13°E) (Fig. 5). Several phenomena might cause the observed differences there. The first one could be due to the presence of a semiannual cycle in the SLAtg that was not present in the SLAsat climatologies. Stramska (2013) also describe a semiannual component of the SLA far from the coast in the Baltic Sea. A second phenomenon might be due to the dynamics of inner harbours, fjords and basins where most of the TG in southern Baltic Sea are located (e.g. Kiel, Wismar, Travemunde). At these locations, SLA can behave different from the nearby open ocean where the closest altimeter grid points are located.

4.1.4. River outflows

Large TG annual amplitudes (~25 cm) were observed at two coastal stations located in the northern Bay of Bengal (21.8°N–89.83°W). In contrast, an amplitude of only ~15 cm was estimated from SLAsat at the closest grid point. Hence a RMSD larger than 6 cm was obtained (Fig. 1). Vinogradov and Ponte (2010) arrived at similar results comparing TOPEX/POSEIDON along-track altimetry data with TGs at seasonal time scales. They argued that large monsoonal-driven variability of the Ganges River is responsible for the observed differences. We argue that the altimeter grid point used to compare with the TG data mostly reflects the changes in open ocean circulation and not the coastal circulation affected by the river discharge. This is probably due to the fact that the gridding procedure ignores most of the data close to the coast.

A similar scenario occurs in the Gulf of Carpenteria (14°S–139°E), north of Australia. At annual scale the mean sea level variation is due to monsoon variability, to changes in SLP and to the steric-effect (Forbes and Church, 1983). All these forcings generate a large annual SLA amplitude in the southeast part of the gulf (Forbes and Church, 1983). The annual amplitudes of the SLAtg in the southeast of this region were about 33 cm while the annual amplitudes of the SLAsat were 23 cm. Both time series were in phase and the differences in the amplitudes were reflected in the RMSD (Fig. 1). Since the TGs are located in the Norman River and Embley River, we argue that the altimeter data reflect the open ocean sea level variations while the SLAtg varies mostly in response to river height variability.

At Xiamen TG station (24.54°N–118.07°E) the comparison between SLAtg and SLAsat showed a RMSD of 5 cm. Again, the TG is probably affected by changes in the discharge of the nearby Jiulong River while the monsoon winds might affect the SLAsat offshore (Jan et al., 2002).

4.1.5. Interpolation aliasing

In the Gulf of Thailand (10.58°N–101.17°W) there are 3 TGs (Ko Mattaphon, Ko Sichang and Cendering) where the SLAsat underestimated the annual amplitude observed with SLAtg, giving origin to a RMSD of 6 cm. These large discrepancies could be due to the large distance (> 100 km) existing between the TGs and the TOPEX/Jason along-track data (Trisirisatayawong et al., 2011). ERS/Envisat altimetry tracks pass closer to the TGs, but their lower repeat-orbit periodicity (35 days) compared to the TOPEX/Jason periodicity (10 days) makes the distance to the latter a key factor to explain the large RMSD observed in the region (Trisirisatayawong et al., 2011). As the gridded altimetry product interpolates the two along-track datasets (Ducet et al., 2000), the distance to the region with the largest density of coastal data is most likely a key issue leading to the observed SLA discrepancies. The 4 cm of RMSD observed at Balboa station (8.97°N–79.57°W, Panamá Bay) might also be due to the large distance (> 150 km) between the TG and the geographical region with the densest TOPEX/Jason along-track data.

To quantify how much the RMSD is aliased by the number of tracks that pass close to a TG, we computed the seasonal cycle considering data from one, two and three tracks that passed at a distance shorter than 90 km from the TG at Katsuura, Japan (35.13°N–140.25°E). For this test, no interpolation was done between the along-track data. We then computed the RMSD (Eq. (2)) between the three along-track annual cycles and the TG. Results showed that the RMSD decreases from 1.77 cm (one track) to 1.17 cm (three tracks). The interpolation done by AVISO is more effective than our approach to just consider the data along the tracks since RMSD considering gridded data for this particular TG was 0.69 cm.

4.2. Islands vs. continental TGs

The mean RMSD considering only the 73 TGs located over islands was 0.64 cm (Table 1), while the 405 continental TGs leaded to a mean RMSD of 1.76 cm (Table 1). This difference in RMSD may be due to the fact that there are more continental TGs than over islands. To account for this difference we randomly selected 73 TGs among the 405 continental TGs and computed the average of the RMSD. We repeated this procedure 100 times. The median of the 100 means of RMSDs was 1.76 cm, which is larger than that based on the 73 island TGs (0.64 cm). The correlations between the annual amplitudes and annual phases were higher in the island TG subset than in the continental subset (Table 1). These results clearly indicate that the satellite altimeter data provides a more robust representation of the annual cycle in open ocean, where SLAsat estimates are not affected by large continental masses. Satellite altimetry data are affected by the proximity of land at distances shorter than 50 km, since the radiometer footprints encounter the coastline and corrupt the raw along-track signal (e.g. Strub, 2001). Although this can also occur over islands, land contamination and aliasing due to high frequencies is generally smaller around islands than approaching continents (Ponte and Lyard, 2002; Mitchum, 1994). Also, the wet tropospheric correction is probably more homogeneous in the proximity of islands than close to continents.

On the other hand, as shown in Fig. 1, very few TGs are located along large portions of the coasts of Central and South America, Africa and the Arabian Peninsula. Including TGs from the UHSLC (University of Hawaii Sea Level Center, http://uhslc.soest.hawaii.edu) database and applying the data selection criteria described above does not modify the geographical coverage of TGs shown in Fig. 1. A turn-around to provide a better coverage in these regions is presented in the next section.

4.3. Extending the number of TG considered

To improve the spatial coverage of the TGs, we considered all the TGs that have more than 10 years of data but are not necessarily concomitant with the altimetry era. Our assumption is that monthly climatologies do not change over the time of the TG records. To validate this hypothesis we separated the TGs that have data since 1970 from the 478 TGs selected in Section 2.2 and constructed two climatologies using: (i) ten years of data, before the satellite altimetry era (between January 1975 and December 1985) and (ii) ten years of data during the altimetry era (between January 1995 and December 2005). We then extracted the annual harmonic of those climatologies and compared them. We present the results obtained in Japan where there is one of the densest TG networks. RMSD between the annual cycles of the two periods considered were lower than 2 cm in the 63 stations around Japan (Fig. 6), with an average value of 0.61 cm (Table 2). The annual amplitudes of the two periods were well correlated with a correlation coefficient of 0.99 (95% confidence level, CL) (Table 2). The phases were also significantly correlated (Table 2). These results suggest that, at least for the coast of Japan, the annual cycles have not changed in the time periods considered. At global scale, results also showed a good agreement between the two climatologies: 88.45% of the RMSDs were lower than 2 cm. The annual amplitudes and phases were also well correlated (0.92 and 0.87, respectively, 95% CL). In the following section, we assume that the annual cycle in the SWACS does not change in time and therefore we used TG data collected prior to the altimeter era to improve the spatial coverage of TG data.

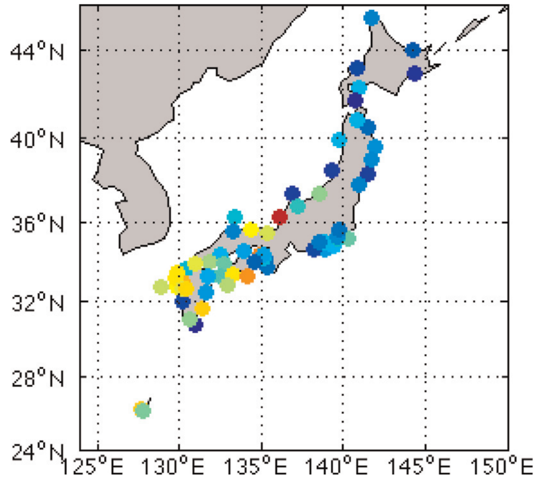

Fig. 6. Location of the tide gauges available at the PSMSL database considered for the validation of the altimetry data on the coast of Japan. Colours indicate the root mean square difference (cm) of SLA between two periods of time (1975–1985 and 1995–2005).

Table 2
Correlation coefficients (*R*), significant at the 95% confident level, and average of the root mean square difference (RMSD) between TG period 1975–1985 and TG period 1995–2005.

	All (63)
R amplitude	0.99
R phase	0.98
RMSD (cm)	0.61

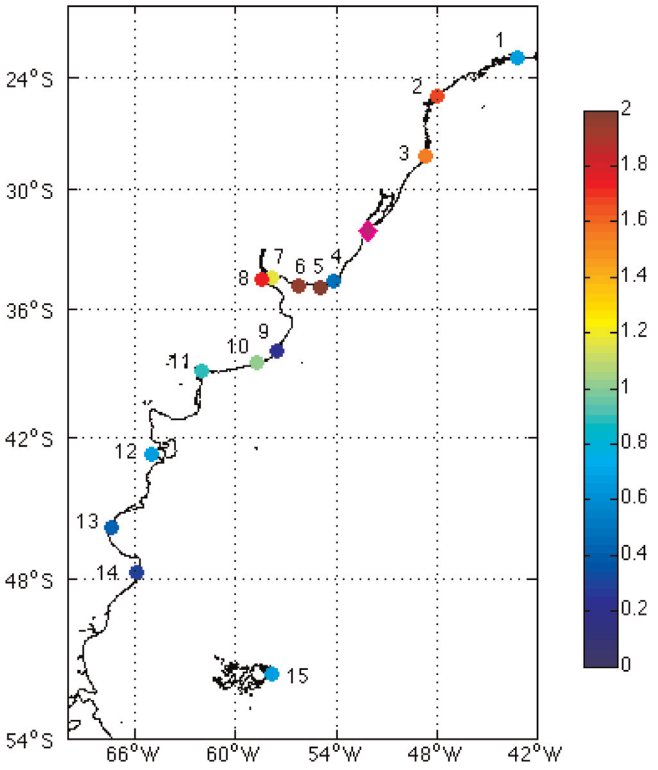

Fig. 7. Location of the tide gauges considered for the validation of the altimetry data in the southwest Atlantic. Name of the TG stations are indicated in Table 3. Colours indicate the root mean square differences (cm) between the annual cycles of the SLA extracted from satellite gridded altimetry and from tide gauge stations. Porto do Rio Grande is indicated with a magenta rhombus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.4. SWACS analysis

As a case study to analyse the annual cycle in a region with few TGs, we computed RMSDs between SLAsat and SLAtg constructing TGs climatologies with all TGs that have more than 10 years of data but are not necessarily concomitant with the satellite altimetry era in the SWACS (Fig. 7). Only three of the 15 TGs that have data for more than 10 years since October 1992 (stations 6, 9 and 15, Fig. 7, Table 3) were included in the previous analysis. A monthly and an inter-annual analysis of the annual component of the SLAsat are presented as well for this region.

4.4.1. SWACS: monthly time series

We first compared the SLAsat and SLAtg monthly time series for the period 1993–2010 at Mar del Plata (station 9 in Fig. 7). Both time series displayed a very similar pattern of variation, with a marked seasonal cycle during the entire record length (Fig. 8). The largest differences were observed during the first half of 1994 and during the second half of 2003. Along-shore wind stress could cause upwelling or downwelling close to the coast. However, wind stress time series (not shown) did not explain the observed

Table 3
Goodness of the fit (Gof) applied to the SLAsat and SLAtg climatologies. Number of months used to estimate the climatology is indicated.

	TG			Aviso
	Months	Gof (%)		Gof (%)
Rio de Janeiro(1)	228	94.42		93.13
Cananeia(2)	624	97.22		92.88
Imbituba(3)	240	95.02		94.54
La Paloma(4)	480	82.84		91.50
Punta del Este(5)	204	90.04		95.64
Montevideo(6)	672	92.43		86.55
Colonia(7)	240	51.79		91.34
Palermo(8)	216	81.56		91.34
Mar del Plata(9)	636	95.45		95.56
Quequen(10)	420	94.12		94.41
Rosales(11)	156	85.82		92.81
Pto. Madryn(12)	504	82.23		84.61
Comodoro(13)	264	73.19		94.57
Pto. Deseado(14)	372	84.79		
			82.41	
Stanley II(15)	204	89.76		
			90.32	

differences in those two years. Despite of those two periods with relatively large differences, the two time series were significantly correlated (0.72, 95% CL). The RMSD computed based on eighteen years was 4.95 cm. Note that this RMSD value corresponds to the monthly time series and therefore is not comparable to the values obtained with the annual component. The RMSD of the annual cycle for this station was 0.22 cm. Results from the comparison between SLAsat and SLAtg at monthly scales are in agreement with other regions such as the Northwest European shelf (Volkov et al., 2007). Thus the good agreement at monthly scales encourages us to validate altimetry data at climatological scale in the SWACS.

4.4.2. *SWACS: climatologies*

Fig. 9 shows the SLAtg and SLAsat climatologies from 4 sites: Rio de Janeiro, La Paloma, Mar del Plata and Quequén (stations 1, 4, 9 and 10 in Fig. 7). At each station both climatologies were in good agreement. Error bars, computed as ±1 standard deviation, overlapped in both datasets in the 15 locations, suggesting that the seasonal cycle computed from TGs and altimetry data did not present significant differences. We then computed the annual harmonic of the climatologies for the 15 time series in the SWACS as we did for the global data set (see methodology in Section 3). Gof values, that are the percentage of the variance explained by the annual harmonic, express the level of agreement between the data and the fit independently of the data sources and locations (Table 3). Gof were larger than 84% for the satellite data and larger than 73% for the TG data, except at Colonia, where the Gof in the TG was ~52% (Table 3). The low Gof at Colonia is due to the fact that the semiannual component explains 33% of the variance (Fig. 10). Colonia is located on the northern margin of the Rio de la Plata estuary. The origin of the semiannual component might be associated with variability of the river discharge (Meccia et al., 2009).

In the SWACS the RMSD between the annual harmonics of SLAsat and SLAtg climatologies ranged between 0.22 and 2.09 cm (Table 4, Fig. 7). As discussed in Sections 4.1, 76.4% of the 478 worldwide TG considered presented a RMSD lower than 2 cm. Thus our results suggest a very good agreement between TGs and gridded altimetry data in the SWACS at the annual scale. Correlations between SLAsat and SLAtg annual cycles were higher than 0.89 (95% CL) (Table 4). A closer inspection of the time series showed that the lowest correlation coefficients correspond to differences between SLA phases rather than between amplitudes (Table 4).

Cananeia (25.02°S–47.93°W), Punta del Este (34.97°S–54.95°W), Montevideo (34.90°S–56.25°W) and Palermo (34.57°S–58.40°W) showed phase differences larger than 20 days. There are various possible mechanisms that may lead to the phase differences at these locations. Cananeia is located inside a large bay at five km from a narrow passage that connects with the open ocean and is therefore more affected by the discharges of the rivers Itapangui and Ribeira de Iguape than by the ocean.

At Montevideo and Punta del Este, the main forcing close to the coast is the seasonal variability of upwelling/downwelling favourable winds while offshore is the solar radiative forcing (Saraceno et al., 2014). Therefore, the phase lag is due to the fact that the SLAsat mainly captures the radiative solar forcing and the SLAtg also captures the wind stress forcing.

At Palermo, located on the south margin of the Rio de la Plata, the distance to the nearest TOPEX/Jason along track is 150 km. Thus, as in the Gulf of Thailand, the distance to the region with the largest density of data to construct the SLAsat might affect the comparison with the TG. Furthermore, as noted above, the annual variability of the Rio de la Plata river discharge might cause the semiannual variability in the TG (Fig. 10a), which is not apparent in the SLAsat, leading to the observed phase differences.

Finally, we considered the TG at Porto do Rio Grande (Fig. 7). As noted in Section 2.2, this is the only TG available between 28.5 °S and 34.5 °S i.e. along more than 850 km of coast. This TG was not included in the PSMSL dataset analysed in this work because it did not fit our selection criteria. However, using the best subset of those data (monthly average of two years, 1989 and 2003) the RMSD with the closest AVISO data was 1.82 cm. This result suggests that the annual component of the altimetry data is also in good agreement with in-situ data in this region.

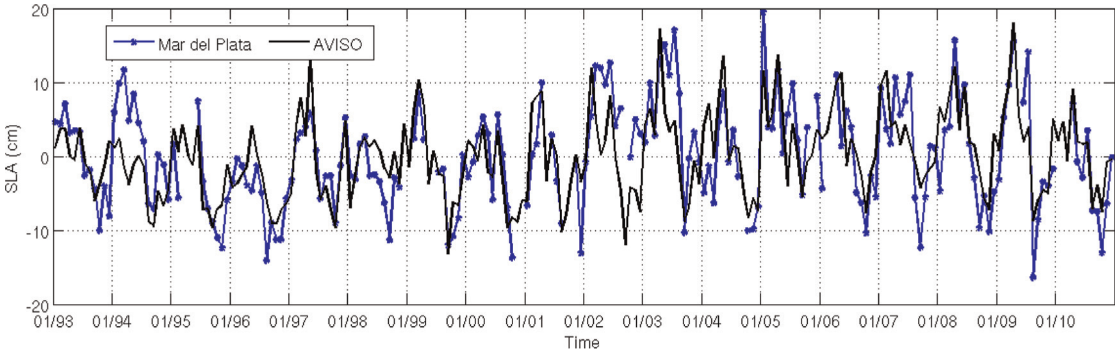

Fig. 8. Time series of in-situ (blue) and altimeter (black) montlhy SLA (cm). The in-situ data correspond to the TG of Mar del Plata (38.033°S–57.517°W, station 9 Fig. 7). The satellite data are extracted at the nearest grid point relative to the TG. Period: January 1993–December 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

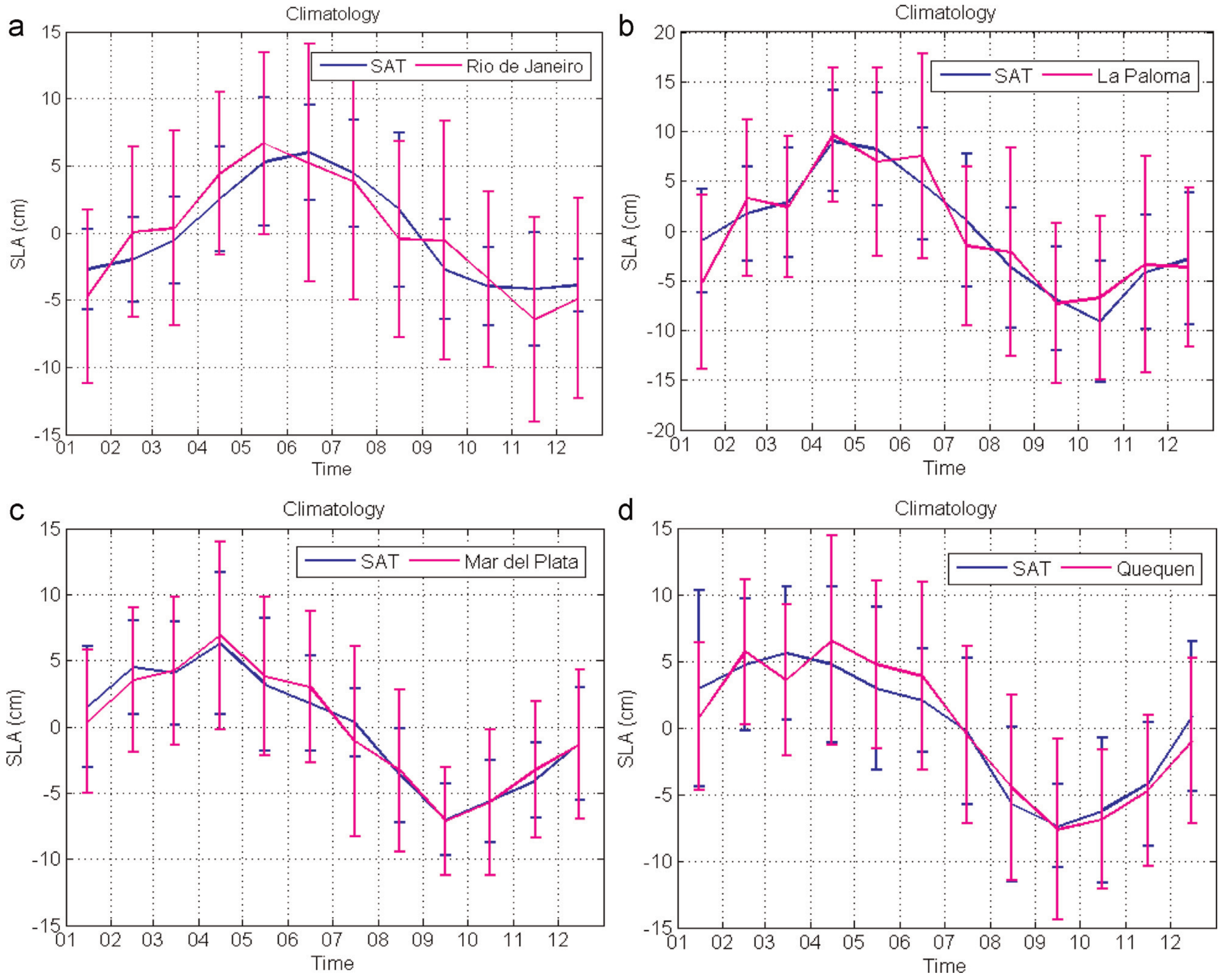

Fig. 9. SLA climatology of the TG (magenta) and satellite (blue) (cm) at four stations. (a) Rio de Janeiro, (b) La Paloma, (c) Mar del Plata and (d) Quequén. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

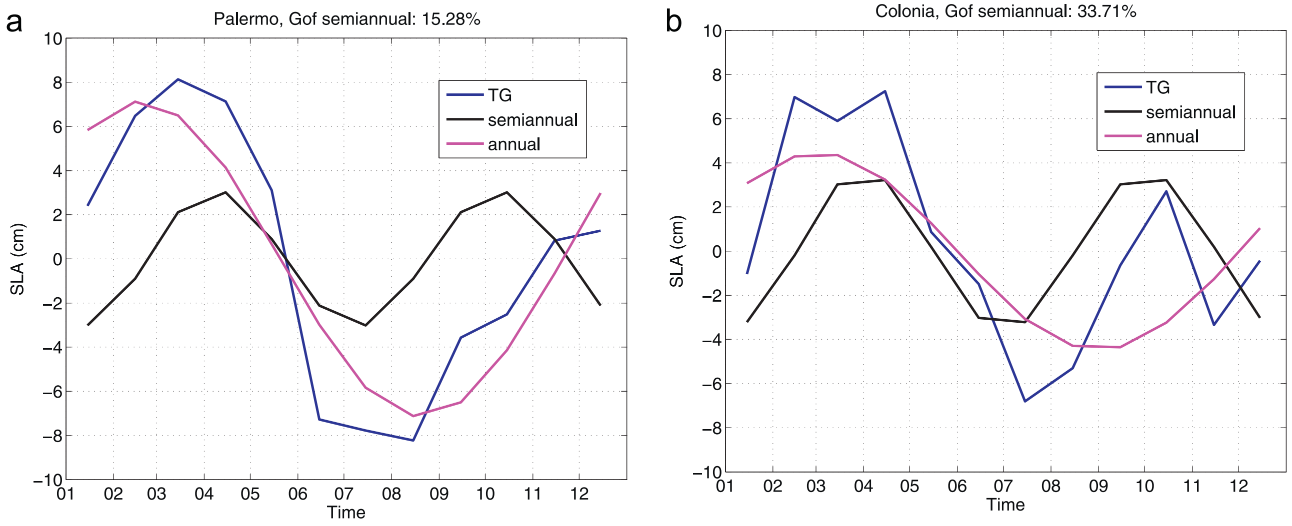

Fig. 10. SLA climatology (blue), semiannual harmonic (black) and annual harmonic (magenta) for a) Palermo and b) Colonia. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Extensive coastal regions without TGs in the SWACS are also present south of 48°S (Fig. 7). Unfortunately, even considering time series that do not match our selection criteria, the length of those time series is too short to extract the annual component.

4.4.3. *SWACS: interannual variability of the seasonal cycle*

A possible source of the RMSD observed can be the presence of interannual variability in either the satellite or the in-situ data. We therefore computed the annual mean RMSD between the annual

Table 4
Amplitude and phase of the annual harmonic of the SLAsat and SLAtg for the 15 sites. Root mean square difference (RMSD) between annual harmonics SLAsat and SLAtg, and the correlation coefficient (*R*), significant at the 95% confident level, is also included.

	TG vs Aviso		TG		Aviso	
	RMSD (cm)	*R*	Ampl (cm)	Phase (day)	Ampl	Phase (day)
Rio de Janeiro	0.67	0.99	5.69	149.47	4.98	156.32
Cananeia	1.67	0.93	6.30	139.59	6.40	161.33
Imbituba	1.56	0.98	7.43	146.27	5.51	156.05
La Paloma	0.48	0.99	7.15	118.74	7.34	113.50
Punta del Este	2.09	0.93	8.06	126.18	7.51	104.38
Montevideo	1.96	0.89	5.76	130.46	6.03	103.00
Colonia	1.18	0.99	4.47	62.53	5.99	70.57
Palermo	1.74	0.94	7.16	51.23	5.99	70.57
Mar del Plata	0.22	0.99	5.77	96.93	5.70	93.81
Quequén	1.01	0.98	6.58	96.45	6.18	83.88
Rosales	0.88	0.96	4.69	61.34	4.59	76.85
Pto. Madryn	0.68	0.99	5.15	88.47	4.45	80.58
Comodoro	0.43	0.98	3.87	83.87	3.97	92.62
Pto. Deseado	0.31	0.99	4.07	79.76	3.72	83.72
Stanley II	0.68	0.98	3.49	90.22	2.72	101.44

harmonic of the altimetry and in-situ data. The computation was carried out for two TG stations that have more than ten years of data concomitant with the satellite altimetry era: Mar del Plata and Port Stanley (Fig. 11). It is worth noting that the interannual RMSD obtained for the two stations analysed were slightly higher than 2 cm, which is the standard RMS error accepted for a high-quality TG (Hannah, 2004). Nevertheless, we observed a larger variability of RMSD values in Mar del Plata than in Port Stanley, reaching a maximum in 2003 (3.24 cm). In Port Stanley the RMSD was low, varying between 0.33 cm and 2.38 cm; and 58.8% of the values were lower than 1 cm. These discrepancies between Port Stanley and Mar del Plata could be due to the fact that Port Stanley TG is located in an island. As mentioned above (Section 4.2), the altimeter measurements are less contaminated by land on islands than on major continental masses. On the other hand, some large RMSD values, either at Mar del Plata (e.g. 2003, 2008) or Port Stanley (e.g. 1994, 2005, 2008) (Fig. 11), might be related with wind variability. However, further study must be carried out to confirm this hypothesis. We also observed that in other cases, large RMSD values is associated with years when there are missing monthly estimates of SLAtg. For instance, in 1995 and 2001 at Mar del Plata 3 out of 12 monthly averages are missing and at Port Stanley 7 out of 12 monthly averages are missing in 2000. Depending on the temporal distribution of the missing values in the year, the fitted annual harmonic may poorly represent the annual cycle, leading to increased RMSD. This issue is compensated when climatologies are constructed with several years.

To test the impact of missing monthly observations of SLAtg and to determine how many years of data are required to overcome this impact, we constructed two synthetic time series of monthly data. In one of these time series, we randomly eliminated 20% of data. We then calculated the RMSD between both data sets. The length of the time series was increased from 1 to 12 years. After adding one year all the above computations were estimated. The process was repeated one hundred times for each year being added. After that, the mean of the 100 RMSDs was calculated, obtaining twelve values, one for each additional year. The distribution of the normalized mean RMSD versus the number of years being analysed clearly reveals that after 6 years the RMSD decreases to about 40% of its initial value (Fig. 12).

5. Summary and conclusions

The aim of this work was to compare the annual component of SLA as retrieved from gridded altimetry data with that retrieved from 478 tide gauges distributed worldwide. The comparison was performed through the analysis of the annual harmonic of the seasonal cycle fitted to climatologies of both data sets. Results obtained at global scale show RMSDs lower than 2 cm, which is the nominal accuracy of open ocean satellite altimetry (Fu et al., 1994; Le Traon et al., 1998), for 76.4% of the cases.

The largest RMSD values are associated with near-coastal process such as narrow currents (e.g. California Current), nearby river discharges (e.g. Ganges River, Jiulong River) and seasonal sea ice (e.g. Kara Sea, the Gulf of Bothnia and the Gulf of Finland, Gulf of Carpentaria). Our results are consistent with studies based on along track data instead of gridded altimetry data (Vinogradov and Ponte, 2010). In other cases, RMSD higher than 4 cm are associated with the presence of a semiannual signal and complex coastline (e.g. southern Baltic Sea). Moreover, at other locations the large RMSD might also be partly due to the larger distance between the TG and the closest region with the

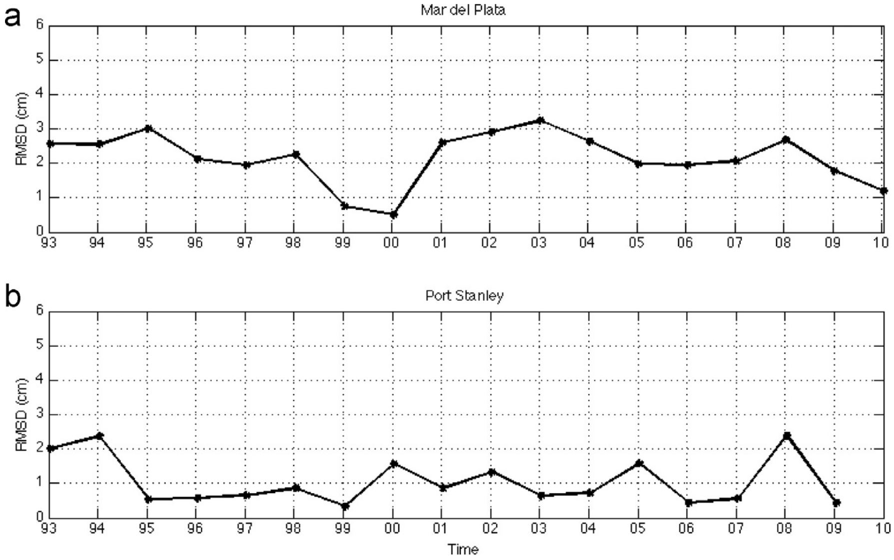

Fig. 11. Yearly variability of the root mean square difference (RMSD) between the annual harmonics of SLAsat and SLAtg for Mar del Plata (a) and Port Stanley (b).

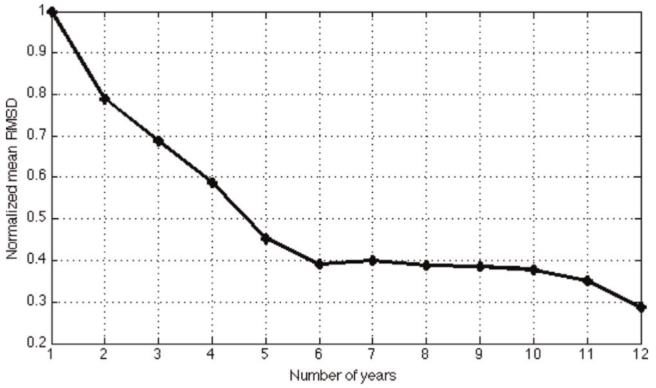

Fig. 12. The mean of the 100 RMSDs of SLA estimated between a complete time series and one with 20% randomly distributed missing values normalized by its maximum value as a function of the number of years considered to compute the climatologies.

dense TOPEX/Jason along-track data, such as the Gulf of Thailand and Panamá bay.

As shown by our results, the annual cycle constructed from 10-year of in-situ data before altimetry era is consistent with the annual cycle constructed during the altimetry era. The high coherence between both data sets (RMSD lower than 2 cm) suggests that the annual cycle of SLA is stationary during several decades. This allows us to include a larger number of TGs in the analysis, which is a critical issue in several areas along the coasts of South America, Africa and Asia, where TG stations are sparse.

A detailed analysis of the annual cycle in the Southwestern Atlantic shows that the RMSD between TG data (considering also data non-coincident with the altimetry era) and satellite data is lower than 2.1 cm. Similar results for comparisons at scales larger than 30 days were also obtained in other regions such as the Gulf of Cadiz and the Mediterranean Sea (Gómez-Enri et al., 2012; Fenoglio-Marc et al., 2005), the northwest European shelf (Volkov et al., 2007), and the Nordic, Barents and Kara seas (Volkov and Pujol, 2012).

It is worth noting that despite the large amplitude of the tides observed in southern Patagonia (e.g. Glorioso and Flather, 1997), the seasonal SLA is well captured by the altimeters, since RMSD are lower than 1 cm south of 42°S (Fig. 7 and Table 4). Results obtained in Port Stanley are in agreement with those of Woodworth et al. (2010).

The yearly variability of the annual harmonic was also investigated in Mar del Plata and Port Stanley. Results show that the altimetry data represent better the annual variability at Port Stanley than at Mar del Plata. The observed differences are due to the fact that Port Stanley is located in an island while Mar del Plata is a continental station. Land contamination and aliasing due to high frequencies is generally smaller in islands than in continents (Ponte and Lyard, 2002; Mitchum, 1994).

Our results suggest that merged gridded altimeter data are, in general, useful to study the annual cycle over continental shelves and coastal areas. A more careful analysis should be done before further exploiting the satellite altimetry data in regions where the RMSD between altimeter and TG data is higher than 4 cm. Custom corrections to along-track altimetry data are probably necessary in those areas. Ultimately, interpolation of those improved along-track altimetry data will improve the accuracy of SLA close to the coast and over continental shelves, better resolving shorter time scales than those analysed in this study. In this sense data provided by the future SWOT (Surface Water Ocean Topography) mission will make a great contribution since it will incorporate two SAR antennae providing a 120 km wide ground track (http://smsc.cnes.fr/SWOT/).

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