https://www.degruyter.com/document/doi/10.1515/jag-2020-0012/html

# Vertical land motion in the Iberian Atlantic coast and its implications for sea level change evaluation

V. B. Mendes[a], S. M. Barbosa[b], D. Carinhas[c]

[a]Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749–016, Lisboa, Portugal
[b]INESC-TEC, Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
[c]Divisão de Oceanografia, Instituto Hidrográfico, Lisboa, Portugal

## ABSTRACT

The determination of vertical land motion is essential for a rigorous assessment of sea level changes using tide gauge records. In this study we estimate vertical land motion using GPS time series from with at least eight years of observations, for 35 stations primarily located along the coastline of Portugal and Spain. Based on this set of GPS stations, our results show that vertical land motion along the Iberian coastline is largely dominated by the glacial isostatic adjustment geophysical signal, presenting, in general, a low to moderate subsidence, ranging from -2.2 mm yr$^{-1}$ to 0.4 mm yr$^{-1}$. Geocentric sea level determined from satellite altimetry for the last three decades has a mean of 2.5 ± 0.6 mm yr$^{-1}$, with a significant range, as seen for a subset of grid points located in the vicinity of tide gauge stations, which present trends varying from 1.5 mm yr$^{-1}$ to 3.2 mm yr$^{-1}$. Relative sea level determined from tide gauges for this region shows a high degree of spatial variability, that can be partially explained not only by the difference in length and quality of the time series, but also for possible undocumented datum shifts, turning some trends unreliable. Tide gauge trends for the last three decades not corrected for vertical land motion range from 0.3 mm yr$^{-1}$ to 5.0 mm yr$^{-1}$ with a mean of 2.6 ± 1.4 mm yr$^{-1}$, similar to that obtained from satellite altimetry. When corrected for vertical land motion, we observe a reduction of the mean to ~1.9 ± 1.4 mm yr$^{-1.}$ In general, tide gauges corrected for vertical land motion produce smaller trends than satellite altimetry.

## 1. **INTRODUCTION**

Understanding sea level changes is a societal challenge with implications in coastal management, and major impact for countries with highly populated areas located in the coast [1, 2], such as Portugal and Spain. For these countries, in 2008, the share of population living in coastal regions in comparison to the national population was 83% and 60%, respectively [3]. This study addresses sea level change from tide gauge, Global Positioning System (GPS), and satellite altimetry data along the Iberian Atlantic coast, defined here as extending from the southwest French-Spanish border to the Strait of Gibraltar.

Changes in relative sea level can be obtained from tide gauge measurements available at some locations since the 19th century, being the major source of long-term estimates of sea level variations. However, the network of tide gauges is generally confined to coastal regions, spatially scarce and inhomogeneous. Moreover, as tide gauges are attached to land-based structures (such as wharfs or rock walls) and measure the height of the sea surface relative to land, the determination of the vertical land motion is paramount to estimate long-term sea level changes [ 4], as it may turn out to be a major contributor to relative sea level (RSL) changes 5, 6]. The accurate estimation of vertical land motion allows to correct the tide gauge measurements of signals related to geophysical processes, such as glacial isostatic adjustment, active tectonics and volcanism, and basin evolution, as well as those related to anthropogenic sources (e.g. water impoundment in reservoirs, ground water depletion, changes in land cover, to name a few).

Vertical land motion can be determined using space geodesy techniques, such as Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) [7, 8] or global navigation satellite systems (GNSS). These point-wise techniques that can be complemented with InSAR [9, 10], as it allows the detection local spatial patterns and, when combined with GNSS can be applied to transform geocentric trends from satellite altimetry into relative sea level trends [10]. From this set of techniques, the most widely used is GNSS [11, 12, 13, 14, 15, 16, 17], but this approach to assess vertical land motion has also limitations, as GNSS stations are often not co-located with tide gauges [2], and the assumption that the vertical land motion between the tide gauge and the GNSS station is identical may be flawed [18, 19]. It is also assumed that the GNSS trends obtained using one to two decades of observations are representative of the multi-decade trends obtained from tide gauge records. Even though an accurate determination of vertical land motion remains a challenge, GNSS techniques can provide such valuable information. Vertical land motion can also be obtained by combining satellite altimetry and tide gauge data [11, 20, 21, 22]. The main limitations of this approach are due to the influence of land effects in the radar signal near the coasts and shallow waters [23, 24] and issues in the geophysical corrections at the ocean-land interface, a fact that can be mitigated using improved data processing solutions [25, 26, 27, 28].

Changes in geocentric sea level can be estimated from high-precision multi-mission satellite altimetry measurements, available since the early 1990s. The main advantage of satellite altimetry is to provide global spatial coverage in the open ocean, playing an important role in understanding global climate change for the past ~25 years. However, due to the presence of significant interannual and interdecadal signals in sea level variations [29, 30, 31, 32, 33], the relatively short history of satellite altimetry constitutes a limitation in providing long-term trends of sea level changes.

Exploring the synergy of multiple techniques can lead to enhanced and robust sea level change determination. This work aims to assess sea level change for the Iberian Atlantic coast by using GPS-derived vertical land motions to correct trends obtained from the analysis of tide gauge data and then comparing these trends with those derived from satellite altimetry data.

## 2. DATA SOURCES

### 2.1. TIDE GAUGE DATA

For the Atlantic Iberian coast tide gauge (TG) records we used monthly data from the Permanent Service for Mean Sea Level [34, 35], complemented with data provided by other institutions: the University of Hawaii Sea Level Centre [36], the Portuguese Instituto Hidrográfico (IH; http://www.hidrografico.pt), and Direção-Geral do Território (DGT; http://www.dgterritorio.pt). The location of the TGs and their raw time series are presented in Figure 1.

Datasets for the Spanish tide gauges and for the tide gauge in France Boucau (1801) come from the Permanent Service for Mean Sea Level (PSMSL) database and are referred to the Revised Local Reference (RLR) datum. For the Portuguese tide gauges (numbers in parenthesis correspond to the PSMSL codes), namely Viana (1482), Leixões/Leixoes (791), Aveiro (1402), Cascais (52), Lisboa/Lisbon (1336), Setúbal-Troia/Setroia (1425), and Sines (1456), data was compiled from different sources, with different formats, sampling times, and different reference benchmarks (Lisboa), requiring special care in the harmonization process. This compilation process was mandatory to achieve extended time series for all these stations, as the PSMSL database has no data available for the most recent decades (recent data for Leixões and Sines became available in the PSMSL in August 2019).

Cascais tide gauge data is the result of a compilation of monthly data from PSMSL (up to 1994), daily data from UHSLC (comprising Research Quality Data (RQD), for years 1959-2006, hourly data from DGT, for years 2007-2008, and Fast Delivery Data (FDD), for years 2008-2018. The raw data (or “metric data”, term used by the PSMSL to designate data that has not been reduced to a common datum) was converted to the common RLR datum, using the benchmark information provided by the PSMSL.

Time series for the remaining four Portuguese tide gauges result from a compilation of RLR data available at the PSMSL database with (hourly) metric data provided by IH. In the computation of the monthly means for these complementary data sets, we disregarded all days with more than 12 hours of missing records and all months with less than 15 daily records, in close agreement with the recommendations by the PSMSL. Whenever available, we subsequently compared our monthly means against those provided by the PSMSL (“metric data”) to confirm the accuracy of the procedure; in the few cases where disagreement occurred, the (non-significant) differences were at the mm level. Finally, we converted the metric data to the RLR datum.

Cascais has the longest time series, but we consider only data for the last decades (1940 onward), as long-term assessment of trends for these long time series have been addressed in the literature [ 5, 37, 38, 39] and the remaining tide gauges discussed here have no data prior to 1940.

### 2.2. SATELLITE ALTIMETRY DATA

Satellite altimetry data from the Topex, Jason-1, Jason-2, and Jason-3 are considered. The data are extracted from the RADS database [40, 41] for the Iberia region (-12° W to 3.5° E, 34° N to 48° N), for the period 1993-2018, including Topex cycles 11 to 343 (from January 1993 to January 2002 ), Jason-1 cycles 1 to 239 (from January 2002 to July 2008), Jason-2 cycles 1 to 280 (from July 2008 to

February 2016) and Jason-3 cycles 1 to 75 (from February 2016 to February 2018). All standard instrumental and geophysical corrections are applied, including the dry tropospheric correction (based on the ECMWF model), the wet tropospheric correction (from the altimeter radiometer measurements) the (dual-frequency) ionospheric correction, solid earth and pole tide corrections, ocean tide and load tide (from FES2004 model) and sea state bias (from non-parametric CLS model). The mean sea surface DTU15MSS is used as the reference surface. Further details can be found in the RADS Data Manual (*https://github.com/remkos/rads/raw/master/doc/manuals/rads4_data_manual.pdf*). The only standard geophysical corrections that is not applied in this study is the inverse barometer correction, which is not applied for consistency with the tide gauge observations, as these are also not corrected for atmospheric pressure effects. The time series of satellite altimetry data are built by along-track gridding of satellite measurements along each individual satellite pass. Only the grid points with at least 90% of non-missing values are retained, resulting in a total number of 482 available time series of sea level anomalies.

### 2.3. GPS DATA

The GPS data used in this study are part of a much larger data set encompassing several hundreds of globally distributed continuous sites available at the International GNSS Service (IGS) [42], EUREF [43] and data from networks of other institutions operating at regional level. These continuously operating GPS stations have different operation lifetimes.

GPS data was processed using the GAMIT/GLOBK software package [44, 45]. Major guidelines used in data processing can be seen in [14]. In this processing, we used double-differenced, ionosphere-free linear combination of L1 and L2 carrier phases to estimate loosely constrained station coordinates, satellite state vectors, and other parameters, along with the associated variance-covariance matrices. At this stage, we used precise orbits from ESA/ESOC, absolute antenna phase center models from IGS, ocean tide loading corrections from the FES2004 ocean tide model [46], and solid earth tide corrections according to the IERS Conventions [47]; to model the neutral atmospheric refraction, we used a priori zenith delays from GPT2 model [48], mapped with the VMF mapping functions [49], complemented with station zenith delays corrections estimated at each station at 1 hr interval, and station gradients parameters in north–south and east–west directions at 24 hr interval. In a second stage, these solutions were used to obtain a consistent set of daily station position time series for all sites, expressed in the ITRF2008 reference frame [50].

## 3. DATA ANALYSIS

### 3.1. TIDE GAUGE

The tide gauge datasets used in this study were collected from different sources and, in some cases, the new time series are the result of compilation of data, as previously mentioned. Moreover, some tide gauges suffered changes of equipment and/or location, leading to structural changes in the time series. Structural changes are potential unexpected changes in the series temporal structure such as in the level, variance, autocorrelation, or a mixture of these [51, , 53]. In order to assess potential variations in datum, change point analysis methods were applied to test for changes in the level of the tide gauge time series. For most of the tide gauge records (e.g. Leixões, Boucau, Setroia, Sines), the detected change points are often associated with existing gaps in the time series, thus reflecting a significant difference in the sea level heights before and after the gap that could be related to eventual changes in the monitoring set-up during the period with no data. Other cases are the change points detected for Tarifa, which will be discussed in section 4, and a clear change point identified for Lisboa (Figure 2).

The dataset for Lisboa (1336) consists of data collected at different locations: I) 1972-1987; II) 1998-2009; III) 2010-2017. The tide gauge was removed from location III during February 2017 and setup in a new location by the end of 2017 (data for this new location is not included). Hardware changes occurred in 2004 and 2010.

Figure 2 shows the result of the analysis of Lisboa time series for structural changes.

The break point identified in 2006 cannot be related to either changes in hardware or location, which occur at different dates. After documentary analysis, we suspect that the jump in the data coincides with the time when an accident occurred in the place where the tide gauge was. A passenger ship struck the wharf during the docking operation, leading to its collapse. Due to the provisional location of the tide gauge, no corrections were applied to the data by the operating institution. The combined effect of location changes for the TG, lack of continuity of the data (namely connecting the periods corresponding to locations I and II), and the existence of the break point in 2006 constitute a major source of uncertainty and lack of reliability in trend estimation. For those reasons, we present no trend for Lisboa.

For TG Leixoes (PSMSL 791), as also mentioned in the PSMSL database, data prior to 1965 looks suspicious; consequently, we opted to disregard data prior to 1965 for Leixoes. A close-by TG, Leixões II/Leixoes II (PSMSL 2163), also exists. Leixões II has only "metric" data and is the result of a work developed by [56], who concluded that the mean rate of sea level change for the period 1906-2008 was -0.70 ± 0.27 mmyr $^{-1}$, a negative trend that is not in agreement with those from other TG gauges in the region. As the records for this TG are influenced by the construction work at the harbor and do not include the last decade, we do not consider this time series in this study.

Even though we include TG Boucau (1801) in this study, the results presented require a careful interpretation. Tide gauge records reflect not only sea level variations associated with oceanic processes but also variations in sea level associated with local changes in water temperature/and or salinity [57, 58]. Changes in sea-level driven by local density fluctuations are particularly obvious in the case of tide gauges located in sheltered areas and near a river outflow, as is the case of Boucau [59], Lisboa (already withdraw) or even Cascais [60].

Trends for the tide gauge time series were obtained using the Hector software [61], taking into consideration the seasonal annual and semi-annual contribution of the seasonal cycle and using the generalized Gauss-Markov (GGM) model as noise model in the estimation of the uncertainties (for details on noise model analysis see [12, 62, 63, 64, 65, 66, 67]). The results are listed in Table 1. Trends were computed for 3 different time spans, starting in years 1940, 1960, and 1990, and designated, for discussion purposes, as trends A, B and C, respectively; the choice of these periods is related with the extent of operation of the tide gauges. The period beginning at 1990 includes all tide gauges in this study and coincides roughly with the period covered by satellite altimetry time series ("satellite altimetry era"). Figure 3 shows the comparison of the our estimates for the full length of the series against those determined by the PSMSL and NOAA's Center for Operational Oceanographic Products and Services (https://tidesandcurrents.noaa.gov). The trends for Santander I, La Coruna I, and Vigo also agree with those published in the literature (e.g. [38, 68, 69]); the level of agreement is slightly worse for Vigo. The small (non-significant) discrepancies can be explained by differences in the size of the time series and methodologies of analysis. Trends for Boucau are also presented by [70].

Figure 4 shows the comparison of trends for periods A, B, and C. It is noteworthy that, in general, trends estimated for period C are much higher than those estimated for the two periods A and B, except for Vigo I and Cadiz III. To determine whether there is any significant difference in the trends for the three periods analyzed, a statistical test [71] using a 5% significance level was applied.

No statistically significant differences exist between the trends relative to periods A and B. As regards the comparison concerning periods A and C, significant differences in trends exist for Santander I and Tarifa; a similar conclusion is obtained in testing those trends for periods B and C, a fact also observed for Aveiro. A question that may arise is whether these differences are the result of a true change in sea level variation or due to undocumented problems with the time series, such as a datum shift. Taking the advantage of having a few tide gauges separated by very short distances for period C, we repeated the test for three pairs of “co-located” TGs: Santander I – Santander III, Vigo I – Vigo II, and La Coruna I – La Coruna III (the cases of Tarifa and Aveiro are analyzed in section 4). The results show that the null hypothesis of equal trends is only rejected for the pair Santander I – Santander III. The reason for this difference can be realized from the analysis of Figure 5.

Table 1 - List and location of the tide gauges used in this study and respective trends considering three different perio (trend B) and 1990 (trend C). Gap denotes the percentage of missing observations for the complete time series.

| PSMSL | Name | j<br>(°) | l<br>(°) | Gap<br>(%) | Time Span<br>(# years, total) | Trend A<br>(mm/yr) | Tre<br>(mm |
|---|---|---|---|---|---|---|---|
| 1801 | Boucau | 43.527 | -1.515 | 12.1 | 1967.5 – 2018.2 (50.7) | - | 1.66 |
| 1806 | Bilbao | 43.352 | -3.045 | 0.3 | 1992.5 – 2018.0 (25.5) | - | |
| 485 | Santander I | 43.461 | -3.791 | 3.2 | 1943.4 – 2019.0 (75.6) | 2.27 ± 0.32 | 2.10 |
| 1807 | Santander III | 43.461 | -3.791 | 0.7 | 1992.5 – 2018.0 (25.5) | - | |
| 1871 | Gijon II | 43.558 | -5.698 | 3 | 1996.0 – 2018.0 (22.0) | - | |
| 484 | La Coruna I | 43.369 | -8.398 | 4 | 1943.2 – 2019.0 (74.8) | 2.44 ± 0.25 | 2.36 |
| 1808 | La Coruna III | 43.357 | -8.389 | 2.9 | 1992.5 – 2018.0 (24.5) | - | |
| 483 | Vigo I | 42.238 | -8.731 | 1.7 | 1943.2 – 2019.0 (75.8) | 2.05 ± 0.31 | 1.31 |
| 1898 | Vigo II | 42.243 | -8.726 | 2 | 1993.1 – 2018.0 (24.9) | - | |
| 1482 | Viana | 41.683 | -8.833 | 16.3 | 1978.0 – 2015.3 (37.3) | - | 1.46 |
| 791 | Leixões | 41.183 | -8.7 | 30.3 | 1965.0 – 2019.0 (54.0) | - | 1.05 |
| 1402 | Aveiro | 40.65 | -8.75 | 13.1 | 1975.9 – 2017.7 (41.8) | - | 2.32 |
| 52 | Cascais | 38.683 | -9.417 | 12.2 | 1940.0 – 2018.0 (78.0) | 1.04 ± 0.16 | 0.76 |
| 1425 | Setroia | 38.5 | -8.9 | 19.3 | 1976.3 – 2016.4 (40.1) | - | 1.11 |
| 1456 | Sines | 37.95 | -8.883 | 19.6 | 1977.4 – 2019.0 (41.6) | - | 3.26 |
| 1883 | Huelva | 37.132 | -6.834 | 0.8 | 1997.0 – 2018.0 (21.0) | - | |
| 1809 | Bonanza | 36.802 | -6.338 | 4.9 | 1992.5 – 2018.0 (25.5) | - | |
| 985 | Cadiz III | 36.54 | -6.286 | 3.4 | 1961.0 – 2019.0 (58.0) | - | 3.57 |
| 488 | Tarifa | 36.009 | -5.603 | 1.8 | 1943.7 – 2019.0 (75.3) | 1.39 ± 0.36 | 2.05 |
| 498 | Ceuta | 35.892 | -5.316 | 2.7 | 1944.2 – 2019.0 (74.8) | 0.72 ± 0.20 | 0.85 |

†Differences in trends for periods A and C are statistically significant; ‡Differences in trends for periods B and C are statistically significant.

Figure 5 shows the differences in relative mean sea level for both tide gauges and it reveals not only a reduction in the scatter of these differences starting 2002.5 (change of sensor in Santander I – see [72]), but more importantly, a shift in time series of the differences circa 2009. This is reflected in the standard deviation of the differences for the periods pre-2002.5 and 2002.5-2009.4, that changes from 9.7 cm to 2.8 cm, and an offset estimated at 2009.4 of 3.4 cm. The analysis of the records of the individual tide gauges per se does not allow to clearly identify which TG suffered a datum shift, but the inconsistency of the trends for Santander I for the different periods and changes in sensors [72] raises some doubts on the reliability of this time series.

### 3.2. **SATELLITE ALTIMETRY**

Figure 6 shows the linear slopes computed from the satellite altimetry time series using the same methodology applied to the TG time series. The linear trends show some spatial coherency with higher trends in the south part of Iberia and lower values to the north, but with considerable spatial variability. The uncertainties in the slope estimates are largest in the Mediterranean area.

A linear trend can be a poor representation of the long-term variability of a time series in case of significant interannual variability, particularly if the length of the series is comparatively short, as in satellite altimetry records. An alternative is to adopt a more flexible description of trend by replacing a straight line by a smooth non-linear signal. Wavelet methods are particularly appealing to derive robust descriptions of the long-term variability of a time series. Here the discrete wavelet transform is used to perform a scale-by-scale decomposition of each time series of sea level anomalies and the signal corresponding to scales larger than ~5 years (64 months) is taken as the trend signal, as illustrated in Figure 7 for two individual time series of sea level anomalies.

Principal component analysis (PCA) [73] allows the extraction from a multivariate dataset of the dominant modes of variability (in terms of maximal variance), expressed by the product of a spatial pattern (the PCA loadings) and a time-varying amplitude (the PCA scores). The trend components obtained from the wavelet decomposition for the whole satellite altimetry dataset are summarized by (PCA) in order to extract the dominant long-term variability features for the study area [74].

Figure 8 shows the first two time series of PCA scores, explaining respectively 67% and 8% of the overall variance of the total 482 time series of trend components. Figure 9 displays the corresponding PCA loadings for each trend component (loadings are the weights (coefficients) of the linear combination of components, thus reflecting the relevance of the mode at each point). The spatial distribution of the loadings for the first mode (Figure 9 left) is spatially consistent with the map of linear slopes (Figure 6), in the sense that areas with high positive slopes (e.g. Biscay Gulf, South-western part of the study area) are also areas of large positive loadings. Although the two maps are not quantitatively comparable, since they represent different aspects - the map of slopes gives the linear trend at each point while the map of loadings reflects the "strength" of the non-linear trend component represented in Figure 8a at each point - since this non-linear trend component is dominated by a positive increase the points in which it is more representative coincide with points of large positive slopes. The first mode reflects a positive trend over the satellite altimetry period, while the second mode displays oscillations over a mainly stable level with a large peak in 2010/2011. The first mode, as an inherently increasing trend mode, is spatially consistent with the map of linear slopes (Figure 6). The second mode contrasts the north western Iberia and Bay of Biscay area, and a decrease in geocentric sea-level in 2010/11, with the southern Iberia and Mediterranean region, with an increase in sea-level in 2010/11. This mode reflects the influence of the North Atlantic Oscillation (NAO) on sea level long-term variability. The NAO affects sea level directly through the hydrostatic response to changes in the pressure field and indirectly through wind forcing effects [75, 76, 77]. The year of 2010, corresponding to the most prominent peak in the second PCA mode of the altimetry trend components, was one of the most negative annual values of the NAO annual index (Figure 10), with significant effects on the northern hemisphere atmospheric and oceanographic variability [78, 79, 80].

### 3.3. GPS

The daily GPS time series are first screened for outliers and discontinuities. Subsequently we used these cleaned time series to derive the vertical trend, after removing the seasonal component (annual and semi-annual components), using the Hector software [61]. We accounted for the time-correlated noise by applying a combination of white noise and a generalized Gauss-Markov model, in line with the conclusions withdraw in [14].

The results from the analysis of GPS data are listed in Table 2. Apart from the stations that are used for correction of tide gauge trends, we also list velocities for other stations located in the coast. These additional GPS velocities can provide useful information regarding the spatial coherency of coastal vertical land motions.

In order to assess our estimates of vertical movement, we compared our GPS trends against those estimated by other analysis centers and, in addition, against the predictions of ICE-6G_C model [82, 83], which are represented in Figure 11. As the analysis centers use different noise models to express the uncertainties of their estimates, those are not plotted for the sake of clarity. The analysis of the figure allows to withdraw some conclusions:

- In general, there is a good agreement between all GPS-based solutions, with a notorious exception for station SCOA, where the range of trends reaches almost 3 mmyr $^{-1}$. Differences among solutions can be explained by multiple factors, such as the different length of the time series, the different options to introduce discontinuities in the series (namely those that are more subjective), and the different reference frames used to express the velocities. Apart from PASA, our solution shows a very good agreement with that produced by EUREF (standard deviation of the differences of 0.3 mm yr$^{-1}$, if we exclude PASA). The larger difference for PASA can be explained by the small time series used by EUREF. It should also be noted that EUREF's solution (EPN solution C2055) is expressed in the ITRF2014 reference frame [84]. NGL presents velocities for most stations listed in Table 2 (sometimes with different name, previously checked). There were no solutions for 5 stations (BAIO, CAMI, CARI, COR1, GROV, and RIB1) and some of them have much shorter time series (ALCO, ARRA, CERC, PACO, PVAR, and SJAC). For the remaining stations, the standard deviation of the differences between the two solutions is 0.5 mm yr$^{-1}$, with a maximum difference for SCOA (1.5 mm yr$^{-1}$ – see also Figure 11).
- It also worth mentioning that the ICE-6G_C (hereinafter designated simply ICE6G) predictions are in good agreement with GPS-based results for many of these common stations. If we compare the ICE6G predictions for the full set of GPS stations listed in Table 2, the absolute differences with respect to the GPS-derived rates fall below 0.5 mm yr$^{-1}$ for 66% of GPS stations and below 1.0 mm yr$^{-1}$ for 86% of those stations. Both ICE6G and GPS rates point for a generalized subsidence rate along the Atlantic Iberian coastline. ICE6G gives an average subsidence rate of ~0.3 mm yr$^{-1}$, about half of the rate observed by GPS (0.6 mm yr$^{-1}$) suggesting that GIA has only a moderate contribution in explaining the observed subsidence along the Iberian coastline. Despite some agreement between the GPS and ICE6G rates, cases like ACOR, for which the largest discrepancy is noted, reveal the limitation of using GIA models predictions for areas where local effects are dominant over long-time scale effects, with implications in evaluating sea-level change scenarios for coastal regions.

- The discrepancies between solutions for some stations reveal that the determination of vertical land motion with GPS remains a challenge (see also [85]); furthermore, the use of GPS trends derived from stations too far away from the tide gauges can lead to errors [18], particularly in areas where local tectonic or anthropogenic phenomena occur, hence the need of co-located GPS stations at the tide gauges for a correct evaluation of the mean sea level at tide gauges.
- The good agreement between solutions for most stations near tide gauges, gives confidence in establishing GPS-corrected tide gauge trends.

## 4. **TREND ANALYSIS**

In order to compare the sea level trends computed from tide gauge time series corrected for vertical land motions against the trends derived from satellite altimetry, adequate satellite grid points need to be selected. The criterion adopted here consisted in selecting the grid point leading to the highest correlation between SA and TG time series for a search region of approximately 1° x 1° centered at each TG location; in the cases where this search region contained no grid points, the search region was enlarged (up to 1.5° x 1.5°). These correlations were computed after detrending and deseasonalizing both time series.

Table 2 List of the GPS stations located in the vicinity of the Iberian Atlantic coast, along with the respective vertical component trend and uncertainty (at the one-sigma level), expressed in mm/yr. Stations underlined have been decommissioned. Data for these stations were provided by different sources (RAP:http:// http://www.ideandalucia.es/portal/web/portal-posicionamiento/rap ; RGAPA:http://rgapa.cartografia.asturias.es/; RGP: http://rgp.ign.fr; Galnet: http://cartogalicia.com/galnet2; EUREF: http://www.epncb.oma.be; IGS: http://www.igs.org, CiGeoE: https://www.igeoe.pt/index.php?id=45; DGT: http://renep.dgterritorio.gov.pt,; ROA - Real Instituto y Observatorio de la Armada,U. Cadiz: Universidad de Cádiz).

| STATION |  |  | Time Span (# years) | CI (%) | trend | S | Source |
|---|---|---|---|---|---|---|---|
|  | (°) | (°) |  |  | (mm/yr) |  |  |
| BIAZ | 43.4720 | -1.5369 | 2009.0–2019.7 (10.7) | 94.2 | -0.95 | 0.20 | RGP |
| SCOA | 43.3952 | -1.6817 | 2009.7–2019.7 (10.0) | 97.8 | -1.73 | 0.41 | RGP |
| CARI | 43.7378 | -7.8664 | 2009.1–2019.7 (10.6) | 72.7 | -0.46 | 0.19 | Galnet |
| AVLS | 43.5661 | -5.9058 | 2010.1–2019.3 (9.2) | 95.9 | -0.34 | 0.24 | RGAPA |
| LUAR | 43.5473 | -6.5281 | 2011.5 –2019.7 (8.2) | 95.1 | 0.43 | 0.23 | RGAPA |
| RIB1 | 43.5366 | -7.0357 | 2009.1–2019.7 (10.4) | 80.2 | -1.47 | 0.18 | Galnet |
| RIBE | 43.4645 | -5.0670 | 2010.1–2019.7 (9.6) | 96.3 | 0.36 | 0.20 | RGAPA |
| CANT | 43.4720 | -3.7981 | 2001.0–2019.7 (18.7) | 97.6 | -1.01 | 0.16 | EUREF |
| ACOR | 43.3644 | -8.3989 | 2000.0–2019.7 (19.7) | 90.5 | -2.23 | 0.08 | EUREF |
| PANE | 43.3250 | -4.5833 | 2010.1–2019.1 (9.0) | 92.3 | -0.41 | 0.19 | RGAPA |
| PASA | 43.3218 | -1.9315 | 2009.0–2019.7 (10.7) | 99.1 | 0.25 | 0.43 | EUREF |
| IGEL$^{\dagger}$ | 43.3064 | -2.0410 | 2009.0–2019.7 (10.7) | 97.9 | -0.64 | 0.24 | EUREF |
| COR1$^{\dagger}$ | 42.9447 | -9.1904 | 2009.1–2019.7 (10.6) | 79.4 | -1.61 | 0.12 | Galnet |
| GROV | 42.4980 | -8.8645 | 2009.1–2019.7 (10.6) | 71.2 | -1.04 | 0.15 | Galnet |
| BAIO$^{\dagger}$ | 42.1194 | -8.8463 | 2009.1–2019.7 (10.6) | 81.5 | -0.27 | 0.19 | Galnet |
| VIGO | 42.1840 | -8.8131 | 2005.8–2019.7 (13.9) | 97.6 | -0.73 | 0.06 | Galnet |
| CAMI | 41.8785 | -8.8377 | 2013.4–2019.7 (6.3) | 97.5 | -0.60 | 0.22 | CiGEOE |
| PVAR | 41.3904 | -8.7382 | 2007.0–2019.7 (12.7) | 94.1 | -0.81 | 0.08 | CIGeoE |
| GAIA | 41.1060 | -8.5891 | 2000.8–2019.7 (18.9) | 94.8 | -0.44 | 0.13 | ReNEP |
| SJAC$^{\dagger}$ | 40.6602 | -8.7348 | 2008.9–2019.7 (10.8) | 93.4 | -0.39 | 0.15 | CIGeoE |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ALCO | 38.7853 | -8.8729 | 2006.2–2019.7 (13.5) | 88.1 | -0.57 | 0.18 | CIGeoE |
| ODEM | 37.5987 | -8.6313 | 2008.2–2019.7 (11.5) | 95.7 | -0.77 | 0.16 | ReNEP |
| ARRA | 38.4928 | -8.9611 | 2006.2–2019.7 (13.5) | 90.7 | -0.28 | 0.09 | CIGeoE |
| SCAC | 38.0188 | -8.6926 | 2008.9–2019.7 (10.8) | 97.2 | -0.97 | 0.21 | ReNEP |
| CERC | 37.7898 | -8.7132 | 2008.9–2019.7 (10.8) | 90.2 | -1.66 | 0.12 | CIGeoE |
| PACO | 38.6943 | -9.2949 | 2007.3–2019.7 (12.4) | 93.5 | -0.23 | 0.10 | CIGeoE |
| CASC | 38.6934 | -9.4185 | 1997.3–2019.7 (22.4) | 93.9 | -0.40 | 0.08 | ReNEP |
| HULV† | 37.2803 | -6.9135 | 2011.0 – 2019.7 (8.7) | 98.5 | 0.04 | 0.24 | RAP |
| HUEL† | 37.2000 | -6.9203 | 2007.7–2019.7 (12.0) | 98 | -0.20 | 0.20 | EUREF |
| LEBR† | 36.9224 | -6.0819 | 2011.0 – 2019.7 (8.7) | 88.2 | -0.01 | 0.25 | RAP |
| ROAP | 36.4643 | -6.2063 | 2008.0 2018.2 (10.2) | 97.1 | -0.48 | 0.22 | ROA |
| SFER† | 36.4643 | -6.2056 | 1996.2–2019.7 (23.5) | 92.9 | -0.03 | 0.25 | IGS |
| ALGC | 36.1110 | -6.4442 | 2011.0 – 2019.7 (8.7) | 87 | 0.21 | 0.34 | RAP |
| TARI | 36.0085 | -5.6026 | 2010.8 – 2019.4 (8.6) | 97.3 | -0.43 | 0.34 | EUREF |
| CEU1 | 35.8920 | -5.3064 | 2008.1–2019.7 (11.6) | 97.3 | -0.64 | 0.25 | EUREF |

†No GGM solution

The correlations between the detrended and deseasonalized series were moderate, ranging from 0.45 (Boucau) to 0.75 (Ceuta), in agreement with studies carried out for other regions [27, 88, 89, 91]. Table 3 lists the selected grid points. Figure 12 shows some examples (selected for TGs closer to GPS stations) of the relation between SA, TG and TG+GPS signals.

Table 3 displays the TG-corrected (TG+GPS) and SA trends for the period C. For this period, SA trends are lower than the trends for combination of TG+GPS for six TGs: Santander I, Viana, Sines, Aveiro, Bonanza, and Tarifa, but within the corresponding uncertainties (which were derived using the same method and taking autocorrelation into account). Ceuta is the tide gauge displaying the largest difference between tide gauge and satellite altimetry trends. Although using different periods of TG operations in the analysis, Marcos & Tsimplis [38] had previously identified discrepancies in trends for the TGs located in the Strait of Gibraltar. Our results corroborate their conclusions, namely the inconsistency in both uncorrected and GPS-corrected trends for Tarifa and Ceuta for the altimetry period, for which a difference of ~3 mmyr$^{-1}$ between GPS-corrected trends is observed. Furthermore, we had already mentioned in section 3.1 that a significant change point was identified for Tarifa. To contribute for a better perception of this problem, we performed a comprehensive analysis of these two tide gauges. Figure 13 shows both the raw TG records (A) and the smoothed non-linear signal corresponding to scales larger than ~5 years (C), resulting from the multi-resolution analysis. We can see that the long-term variations for both time series do not match. More importantly, there is a clear increase in the trend for Tarifa, starting circa 1990, which is not visible for Ceuta. For the period 1940-1990, we estimate a negative trend for Tarifa (-0.3±0.6 mmyr $^{-1}$) and a positive trend for Ceuta (0.6±0.5 mmyr $^{-1}$); for the period starting 1990, we see a sharp increase in the trend for Tarifa (4.2±0.6 mmyr$^{-1}$), whereas the trend for Ceuta remains much closer to the previous period (1.1±0.6 mmyr$^{-1}$). A possible explanation for these differences could be the fact that the TGs suffer different vertical land motion, but GPS trends for the two stations do not differ significantly (see Table 2 and Figure 14), therefore they cannot compensate the differences in the TG trends. The large increase in the trend for Tarifa confirms the results of structural change analysis, that indicates a break point in the series.

Other TGs in the region could likely contribute for solving this inconsistency. The closest TGs in the region are Tarifa 2 (PSMSL 2054), and three stations located in Algeciras: Algeciras (PSMSL 490), Algeciras B (PSMSL 2117) and Algeciras 2 (PSMSL 2055). None of these TGs cover the same time span of Ceuta and Tarifa and two of them (Tarifa 2 and Algeciras 2) have very short records. Algeciras has a much longer time series but has no data available for the last ~15 years. The time series for these stations are also represented in Figure 13 (MRA decomposition is not shown for the short time series) that shows that the differences between Ceuta and Tarifa and between Ceuta and Algeciras are in fair agreement until the beginning of the 1990s, despite the large noise. There is a considerable reduction in noise which is likely related with the transition to the tide gauge operation with digital output started in 1991 in Tarifa. From this date onwards, a clear bias for the differences between Ceuta and Tarifa exists (the mean difference between Ceuta and Tarifa is -3±75 mm for the period 1944-1989 and -35±29 mm for period 1991-2019), but such high bias is not present for other TGs, even for those located much further away (Algeciras B and Algericas 2). The most plausible explanation may be an undetected change datum. The documentation for Tarifa available at the PSMSL reveals previous problems with the definition of a precise datum, that should have been corrected in 2013, but these results raise some concerns on the reliability of the adopted solution. For Algeciras, the trend for the period 1940-1990 is 0.5±0.3 mmyr $^{-1}$, very close to the one for Ceuta, despite being further away than Tarifa.

Table 3 - List of satellite altimetry grid points (GP) and respective location, GPS station used to correct the tide gauge gauges (TG), approximate distance between GPS and TG (s), correlation coefficient between satellite altimetry (SA) ar trend (VSA) along with its uncertainty ( $_{VSA}$), combined TG+GPS trend and uncertainty for period C (VCC,  $_{VCC}$), differe ( C). (Note: For the computation of the distance between GPS and TG at Cascais, we ignored the coordinates the Cas are incorrect; approximate coordinates used: j = 38°.694; l = -9°.418.)

| GP | j<br>(°) | l<br>(°) | GPS | TG<br>(PSMSL) | s<br>(km) |  | VSA | s $_{VSA}$<br>(mm yr$^{-1}$) | VCC |  $_{VCC}$<br>(mm yr$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 44 | -2.3 | BIAZ | 1801 | 7.6 | 0.45 | 3.2 | 0.65 | 3 | 1.31 |
| 1 | 44 | -2.3 | CANT | 1806 | 62.3 | 0.63 | 3.2 | 0.65 | 1.49 | 0.89 |
| 2 | 44 | -5.1 | CANT | 485 | 1.4 | 0.67 | 1.91 | 0.59 | 3.22 | 0.85 |
| 2 | 44 | -5.1 | CANT | 1807 | 1.4 | 0.71 | 1.91 | 0.59 | 0.32 | 0.85 |
| 2 | 44 | -5.1 | AVLS | 1871 | 16.8 | 0.67 | 1.91 | 0.59 | -0.05 | 1.03 |
| 3 | 43.5 | -9.5 | ACOR | 484 | 0.5 | 0.63 | 1.61 | 0.55 | 1.49 | 1.19 |
| 4 | 44.2 | -8.1 | ACOR | 1808 | 1.2 | 0.64 | 1.51 | 0.71 | 0.92 | 1.18 |
| 5 | 43 | -9.9 | VIGO | 483 | 9 | 0.62 | 1.96 | 0.5 | -0.02 | 1.26 |
| 5 | 43 | -9.9 | VIGO | 1898 | 9.7 | 0.66 | 1.96 | 0.5 | 0.94 | 1.06 |
| 5 | 43 | -9.9 | CAMI | 1482 | 21.7 | 0.65 | 1.96 | 0.5 | 2.26 | 1.02 |
| 6 | 39.3 | -10 | GAIA | 791 | 12.6 | 0.66 | 3.06 | 0.58 | 1.84 | 1.4 |
| 6 | 39.3 | -10 | SCAC | 1456 | 18.4 | 0.72 | 3.06 | 0.58 | 3.7 | 0.92 |
| 7 | 39.1 | -10 | SJAC | 1402 | 1.7 | 0.63 | 2.86 | 0.55 | 4.56 | 0.84 |
| 7 | 39.1 | -10 | ARRA | 1425 | 5.4 | 0.74 | 2.86 | 0.55 | 0.9 | 1.3 |
| 7 | 39.1 | -10 | CASC | 52 | 0.1 | 0.71 | 2.86 | 0.55 | 1.04 | 1.01 |
| 8 | 35.6 | -6.6 | HUEL | 1883 | 10.8 | 0.46 | 2.99 | 0.33 | 1.58 | 1.07 |
| 9 | 35.8 | -6.5 | SFER | 1809 | 39.4 | 0.67 | 2.97 | 0.33 | 3.56 | 0.99 |
| 9 | 35.8 | -6.5 | SFER | 985 | 11.1 | 0.66 | 2.97 | 0.33 | 1.76 | 1.03 |
| 9 | 35.8 | -6.5 | TARI | 488 | 0.1 | 0.75 | 2.97 | 0.33 | 3.79 | 0.64 |
| **9** | **35.8** | **-6.5** | **CEU1** | **498** | **0.9** | **0.72** | **2.97** | **0.33** | **0.72** | **0.6** |

†Difference in trends is significant, at the 5% significance level.

Notwithstanding the auxiliary information provided by other TGs, and the recognition that regional variations in mean sea level exist, the inconsistency between the trends for Ceuta and Tarifa remains not completely understood.

The other case in which the comparison of tide gauge and satellite altimetry trends raises some apprehension is Aveiro. Figure 15 shows the raw time series for Aveiro, Viana (~115 km North of Aveiro), and Leixões (~60 km North of Aveiro). The smoothed time series (scales larger than ~5 years from MRA decomposition) show an increased trend for Aveiro starting circa 2011, that is not observed for the other TGs (Figure 15-C). This fact is highlighted in the plot of the differences of records with respect to Aveiro (Figure 15-B), clearly showing a sudden increase of these differences at that date, followed by a steady pattern of differences for both TGs. There are no co-located GNSS stations at those TGs, but all the closest GNSS stations located in the vicinity show similar trends (subsidence of 0.4-0.5 mmyr $^{-1}$ – see Table 2), hence they do not contribute for a differential trend among these TGs. Even though our subjective analysis points to a change in 2011, we cannot exclude the turning point to be related with the change of equipment (which were operated in 2006 and in 2012). In any case, caution is required in the interpretation of the trend for this tide gauge.

The analysis of the trend results for period C reveals regional variability in sea level change. In the case of satellite altimetry (for selected grid points), trends range between 1.5±0.7 mmyr $^{-1}$ to 3.2±0.7 mmyr$^{-1}$; for the tide gauges, the variability is much larger, varying between 0.3±0.8 mmyr $^{-1}$ (Gijon II) to 5.0±0.6 mmyr$^{-1}$ (Aveiro). The use of GPS to correct the TG trends has only a small reduction in the range of the estimated trends (a minimum of -0.02±0.8 mmyr$^{-1}$, for Vigo I, and a maximum of 4.6±0.8 mmyr$^{-1}$, for Aveiro). The benefits of using the GPS-derived vertical motion is more evident in situations where a large vertical land motion is observed, namely La Coruna I and La Coruna III.

## 5. **CONCLUSIONS**

In this study we used GPS time series from 35 stations spanning at least 8 years' worth of data to estimate vertical land motion along the Iberian Atlantic coast, a fundamental aspect to correct sea level trends obtained from tide gauge recordsThe observed vertical land motion is mostly characterized by slow to moderate subsidence rates, with a mean value of ~0.6 mm yr$^{-1}$, partially explained by glacial isostatic adjustment, but with significant deviations for some sites, reflecting local effects, strengthening the need of having GPS receivers co-located with tide gauges.

Relative sea level estimated from 20 tide gauges located along the same coastline is characterized by a noteworthy spatial variability, that is associated not only to difference in the length of the time series, but also to possible undocumented problems with the tide gauge records, such as datum shifts, which are evident when nearby tide gauges provide different trends for identical periods of observation. Having better documentation for tide gauge operations, such as changes in equipment or data handling procedures, is an important issue for obtaining reliable trends.

Geocentric sea level was estimated by satellite altimetry around the Iberian Peninsula for the period 1993-2018. Based on a set of near 500 grid points, we obtained a mean of 2.5 mmyr$^{-1}$ for the region. Regional variability is observed, with higher rates in the Mediterranean Sea and lower rates off the northwest of the Iberian Peninsula. The comparison of sea level trends estimated from tide gauges for a similar period against a set of selected satellite altimetry grid points showing the highest correlation with the tide gauge records gives a large range of trend differences and dispersion. The correction of tide gauge trends with vertical land motion does not reduce the amplitude of these differences but reduces its variance. In general, trends from satellite altimetry are larger than those obtained from GPS-corrected tide gauge records.

## Acknowledgments

The authors would like to thank Alvaro Santamaría-Gómez and an anonymous reviewer for their insightful suggestions and careful reading of the manuscript. We thank all institutions providing access to GPS data. We thank the Portuguese Instituto Hidrográfico and Direção-Geral do Território for making available unpublished tide gauge data. Tide gauge data from the Permanent Service for Mean Sea Level and the University of Hawaii Sea Level Center and satellite altimetry data provided by the Radar Altimeter Database (RADS) are also gratefully acknowledged. Maps were created using Generic Mapping Tools [90] and R [91].

This work is financed by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia within projects UIDB/50019/2020 – IDL and UIDB/50014/2020.

## References

[1] Cazenave A, Le Cozannet G. Sea level rise and its coastal impacts. *Earth's Future* 2, 15-34, doi:10.1002/2013EF000188, 2013.

[2] Ponte RM, Carson M, Cirano M, et al. Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level. *Frontiers in Marine Science* 6:437, doi: 10.3389/fmars.2019.00437, 2019.

[3] Eurostat. Eurostat regional yearbook 2011. Publications Office of the European Union, Luxembourg, doi:10.2785/1392, 2011.

[4] Pfeffer J, Allemand P. The key role of vertical land motions in coastal sea level variations: A global synthesis of multisatellite altimetry, tide gauge data and GPS measurements. *Earth and Planetary Science Letters* 439, 39-47, doi: 10.1016/j.epsl.2016.01.027, 2016.

[5] Wöppelmann G, Martin Miguez B, Bouin M-N, Altamimi Z. Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide. *Global and Planetary Change* 57(3-4), 396-406, doi: 10.1016/j.gloplacha.2007.02.002, 2007.

[6] Wöppelmann G, Marcos M. Vertical land motion as a key to understanding sea level change and variability. *Reviews of Geophysics* 54(1), 64-92, doi: 10.1002/2015RG000502, 2016.

[7] Cazenave A, Dominh K, Ponchaut F, Soudarin L, Crétaux J-F, Provost CL. Sea level changes from Topex-Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS." *Geophysical Research Letters* 26, 2077-2080, doi:10.1029/1999GL900472, 1999.

[8] Ray R, Beckley B, Lemoine F. Vertical crustal motion derived from satellite altimetry and tide gauges, and comparisons with DORIS measurements. *Advances in Space Research* 45, 1510–1522, doi: 10.1016/j.asr.2010.02.020, 2010.

[9] Raucoules D, Le Cozannet G, Wöppelmann G, de Michele M, Gravelle M, Daag A, Marcos M. High nonlinear urban ground motion in Manila (Philippines) from 1993 to 2010 observed by DInSAR: implications for sea-level measurement. *Remote Sensing of Environment* 139, 386-397, doi: 10.1016/j.rse.2013.08.021, 2013.

[10] Poitevin C, Wöppelmann G, Raucoules D, Le Cozannet G, Marcos M, Testut L. Vertical land motion and relative sea level changes along the coastline of Brest (France) from combined space-borne geodetic methods. *Remote Sensing of Environment* 222, 275-285, doi: 10.1016/j.rse.2018.12.035, 2019.

[11] Santamaría-Gómez A, Gravelle M, Collilieux X, Guichard M, Martín Míguez B, Tiphaneau P, Wöppelmann G. Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field. *Global and Planetary Change* 98-99, 6-17, doi: 10.1016/j.gloplacha.2012.07.007, 2012.

[12] Bouin MN, Wöppelmann G. Land motion estimates from GPS at tide gauges: a geophysical evaluation. *Geophysical Journal International* 180, 193-209, doi: 10.1111/j.1365-246X.2009.04411.x, 2010.

[13] Santamaría-Gómez A, Bouin M-N, Collilieux X, Wöppelmann G. Correlated errors in GPS position time series: implications for velocity estimates. *Journal of Geophysical Research* 116, B01405, doi: 10.1029/2010JB007701, 2011.

[14] Mendes VB, Barbosa SM, Romero I, Madeira J, Brum da Silveira A. Vertical land motion and sea level change in Macaronesia. *Geophysical Journal International* 210(2), 1264-1280, doi: 10.1093/gji/ggx229, 2017.

[15] Montillet J-P, Melbourne TI, Szeliga WM. GPS vertical land motion corrections to sea-level rise estimates in the Pacific Northwest. *Journal of Geophysical Research Oceans* 123, 1196-1212, doi: 10.1002/2017JC013257, 2018.

[16] Martínez-Asensio A, Wöppelmann G, Ballu V, et al. Relative sea-level rise and the influence of vertical land motion at Tropical Pacific Islands. *Global and Planetary Change* 176, 132-43, doi: 10.1016/j.gloplacha.2019.03.008, 2019.

[17] Yang L, Francis OP. Sea-level rise and vertical land motion on the islands of Oahu and Hawaii, Hawaii. *Advances in Space Research*, doi: 10.1016/j.asr.2019.08.028, 2019.

[18] Bevis M, Scherer W, Merrifield M. Technical issues and recommendations related to the installation of continuous GPS stations at tide gauges. *Marine Geodesy* 25, 87-99, 2002.

[19] Woodworth PL, Wöppelmann G, Marcos M, Gravelle M, Bingley RM. Why we must tie satellite positioning to tide gauge data. *EOS* 98. doi: 10.1029/2017EO064037, 2017.

[20] Wöppelmann G, Marcos M. Coastal sea level rise in southern Europe and the nonclimate contribution of vertical land motion. *Journal of Geophysical Research* 117, C01007, doi: 10.1029/2011JC007469, 2012.

[21] García F, Vigo M, García-García D, Sánchez-Reales J. Combination of multisatellite altimetry and tide gauge data for determining vertical crustal movements along northern Mediterranean coast. *Pure and Applied Geophysics* 169(8), 1411–1423, doi: 10.1007/s00024-011-0400-5, 2012.

[22] Grgić M, Nerem RS, Bašić T. Absolute sea level surface modeling for the Mediterranean from satellite altimeter and tide gauge measurements. *Marine Geodesy* 40(4), 239-258, doi: 10.1080/01490419.2017.1342726, 2017.

[23] Fenoglio-Marc L, Fehlau M, Ferri L, Becker M, Gao Y, Vignudelli S. Coastal sea surface heights from improved altimeter data in the Mediterranean Sea. In: Mertikas S. (eds) Gravity, Geoid and Earth Observation. International Association of Geodesy Symposia, vol 135. Springer, Berlin, Heidelberg, 2010.

[24] Cazenave A, Palanisamy H, Ablain M. Contemporary sea level changes from satellite altimetry: What have we learned? What are the new challenges?. *Advances in Space Research* 62(7), 1639-1653, doi: 10.1016/j.asr.2018.07.017, 2018.

[25] Fernandes MJ, Lázaro C, Ablain M, Pires N. Improved wet path delays for all ESA and reference altimetric missions. Remote Sensing of Environment 169, 50-74, doi: 10.1016/j.rse.2015.07.023, 2015.

[26] Cipollini P, Birol F, Fernandes MJ, et al. Satellite altimetry in coastal regions. In: Satellite Altimetry Over Oceans and Land Surfaces, edited by: Stammer D, Cazenave A. (Eds), 1st Edition, CRC Press, Taylor & Francis, Boca Raton, 2017.

[27] Cipollini P, Calafat FM, Jevrejeva S, Melet A, Prandi P. Monitoring sea level in the coastal zone with satellite altimetry and tide gauges. *Surveys in Geophysics* 38(1), 33-57, doi: 10.1007/s10712-016-9392-0, 2017.

[28] Benveniste J, Cazenave A, Vignudelli S, et al. Requirements for a Coastal Hazard Observing System. Front. Mar. Sci. 6:348. doi: 10.3389/fmars.2019.00348, 2019.

[29] Jevrejeva S, Grinsted A, Moore JC, Holgate S. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research* 111, C09012, doi: 10.1029/2005JC003229, 2006.

[30] Nerem RS, Chambers, DP, Choe C, Mitchum GT. Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions, Marine Geodesy, 33:sup1, 435-446, doi: 10.1080/01490419.2010.491031, 2010.

[31] Zhang X, Church JA. Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters* 39, L21701, doi: 10.1029/2012GL053240, 2012.

[32] Cheng X, Xie S-P, Du Y, Wang J, Chen X, Wang J. Interannual-to-decadal variability and trends of sea level in the South China Sea. *Climate Dynamics* 46(9-10), 3113-3126, doi: 10.1007/s00382-015-2756-1, 2016.

[33] Karabil S, Zorita E, Hünicke B. Mechanisms of variability in decadal sea-level trends in the Baltic Sea over the 20th century. *Earth System Dynamics* 8, 1031-1046, doi: 10.5194/esd-8-1031-2017, 2017.

[34] Holgate SJ, Matthews A, Woodworth PL, et al. New data systems and products at the Permanent Service for Mean Sea Level. *Journal of Coastal Research* 29(3), 493-504, doi: 10.2112/JCOASTRES-D-12-00175.1, 2013.

[35] Permanent Service for Mean Sea Level (PSMSL). Tide gauge data, Retrieved Aug 2019 from http://www.psmsl.org/data/obtaining/, 2019.

[36] Caldwell PC, Merrifield MA, Thompson PR. Sea level measured by tide gauges from global oceans - the Joint Archive for Sea Level holdings (NCEI Accession 0019568), Version 5.5, *NOAA National Centers for Environmental Information*, Dataset, doi:10.7289/V5V40S7W, 2015.

[37] Miller L, Douglas BC. Mass and volume contributions to twentieth-century global sea level rise. *Nature* 428, 406-409, doi: 10.1038/nature02309, 2004.

[38] Marcos M, Tsimplis MN. Coastal sea level trends in Southern Europe. *Geophysical Journal International*, 175(1), 70–82, doi: 10.1111/j.1365-246X.2008.03892.x, 2018.

[39] Antunes C, Taborda R. Sea level at Cascais tide gauge: data, analysis and results. *Journal of Coastal Research*, 218-22, http://www.jstor.org/stable/25737569, 2009.

[40] Scharroo R, Leuliette E, Naeije M, Martin-Puig C, Pires N. RADS Version 4: an efficient way to analyse the multi-mission altimeter database, In: Ouwehand L. (ed), Proceedings of the ESA Living Planet Symposium, 9-13 May 2016, Prague, Czech Republic, ESA Special Publication SP-740, 2016.

[41] Scharroo R. RADS Data Manual version 4.2.10., 2/2018, 2018.

[42] Johnston G, Riddell A, Hausler G. The International GNSS Service. In: Teunissen PJG, Montenbruck O (Eds.), *Springer Handbook of Global Navigation Satellite Systems*, 1st ed., Cham, Switzerland, Springer International Publishing, 967-982, 2017.

[43] Bruyninx C, Habrich H, Söhne W, Kenyeres A, Stangl G, Völksen C. Enhancement of the EUREF Permanent Network Services and Products. In: Kenyon S, Pacino M, Marti U (eds) *Geodesy for Planet Earth*. International Association of Geodesy Symposia, 136. Springer, Berlin, Heidelberg, 2012.

[44] Herring TA, King RW, Floyd MA, McClusky SC. GAMIT Reference Manual, Release 10.6. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, 2015.

[45] Herring TA, King RW, Floyd MA, McClusky SC. GLOBK Reference Manual, Release 10.6, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, 2015.

[46] Lyard F, Lefèvre F, Letellier T, Francis O. Modelling the global ocean tides: modern insights from FES2004. *Ocean Dynamics* 56(5-6), 394-415, doi: 10.1007/s10236-006-0086-x, 2006.

[47] Petit G, Luzum B (eds.). IERS Conventions (2010), IERS Technical Note 36, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 179 pp, 2010.

[48] Lagler K, Schindelegger M, Böhm J, Krásná H, Nilsson T. GPT2: Empirical slant delay model for radio space geodetic techniques. *Geophysical Research Letters* 40, 1069-1073, doi: 10.1002/grl.50288, 2013.

[49] Boehm J, Werl B, Schuh H.Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. *Journal of Geophysical Research* 111, B02406, doi: 10.1029/2005JB003629, 2006.

[50] Altamimi Z, Collilieux X, Métivier L. ITRF2008: An improved solution of the International Terrestrial Reference Frame. *Journal of Geodesy* 85(8), 457-473, 2011.

[51] Zeileis A, Kleiber C, Krämer W, Hornik K. Testing and dating of structural changes in practice. *Computational Statistics & Data Analysis* 44(1-2), 109-123, doi: 10.1016/S0167-9473(03)00030-6, 2003.

[52] Killick R, Eckley I. Changepoint: An R Package for changepoint analysis. *Journal of Statistical Software 58*(3), 1-19. doi: 10.18637/jss.v058.i03, 2014.

[53] Ross GJ. Parametric and nonparametric sequential change detection in R: The cpm package. *Journal of Statistical Software* 66(3), 1-20. http://dx.doi.org/10.18637/jss.v066.i03, 2015.

[54] Ploberger W, Krämer W. The CUSUM test with OLS residuals. *Econometrica* 60(2), 271-285, doi: 10.2307/2951597 , 1992.

[55] Andrews DWK, Ploberger W. Optimal tests when a nuisance parameter is present only under the alternative. *Econometrica* 62(6), 1383-1414, 1994.

[56] Araújo IB, Bos MS, Bastos LC, Cardoso MM. Analysing the hundred year sea level record of Leixões, Portugal. *Journal of Hydrology* 481:76-84, 2013.

[57] Piecuch CG, Bittermann K, Kemp AC, Ponte RM, Little CM, Engelhart SE, Lentz SJ. River-discharge effects on United States Atlantic and Gulf coast sea-level changes. Proceedings of the National Academy of Sciences 115(30), 7729-7734, 2018.

[58] Woodworth PL, Melet A, Marcos M. et al. Forcing Factors Affecting Sea Level Changes at the Coast. Surveys in Geophysics 40, 1351–1397, doi: 10.1007/s10712-019-09531-1, 2019.

[59] Laiz I, Ferrer L, Plomaritis TA, Charria G. Effect of river runoff on sea level from in-situ measurements and numerical models in the Bay of Biscay Deep Sea Res. Part II: Topical Stud. Oceanogr. 106, 49-67, 2014.

[60] Barbosa SM, Fernandes MJ, Silva ME. Nonlinear sea level trends from European tide gauge records. Ann. Geophys. 22, 1465-1472, doi: 10.5194/angeo-22-1465-2004, 2004.

[61] Bos MS, Fernandes, RMS, Williams, SDP, Bastos L. Fast Error Analysis of Continuous GNSS Observations with Missing Data. J. Geod., Vol 87(4), 351-360, doi: 10.1007/s00190-012-0605-0, 2013.

[62] Williams S. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. *Journal of Geodesy* 76, 483–494, doi: 10.1007/s00190-002-0283-4, 2003.

[63] Amiri-Simkooei AR, Tiberius CCJM, Teunissen PJG. Assessment of noise in GPS coordinate time series: Methodology and results. *Journal of Geophysical Research* 112, B07413, doi:10.1029/2006JB004913, 2007.

[64] Langbein J. Noise in GPS displacement measurements from Southern California and Southern Nevada. *Journal of Geophysical Research* 113, B05405, doi:10.1029/2007JB005247, 2008.

[65] Santamaría-Gómez A, Bouin M-N, Collilieux X, Wöppelmann G. Correlated errors in GPS position time series: Implications for velocity estimates. *Journal of Geophysical Research* 116, B01405, doi:10.1029/2010JB007701, 2011.

[66] Langbein J. Estimating rate uncertainty with maximum likelihood: differences between power-law and flicker–random-walk models. *Journal of Geodesy* 86, 775–783, doi: 10.1007/s00190-012-0556-5, 2012.

[67] He X, Bos MS, Montillet JP et al. Investigation of the noise properties at low frequencies in long GNSS time series. *Journal of Geodesy* 93, 1271–1282, doi: 10.1007/s00190-019-01244-y, 2019.

[68] Marcos M, Gomis D, Monserrat S, Álvarez-Fanjul E, Pérez B, García-Lafuente J. Consistency of long sea level time series in the northern coast of Spain. *Journal of Geophysical Research* 110, C03008. https://doi.org/10.1029/2004JC002522, 2005.

[69] García MJ, Tel E, Moliner J. Sea-level variations on the north and northwest coasts of Spain. *ICES Journal of Marine Science* 69, 720–727, 2012.

[70] Dodet G, Bertin X, Bouchette F, Gravelle M, Testut L, Wöppelmann G. Characterization of sea-level variations along the metropolitan coasts of France: Waves, tides, storm surges and long-term changes. In: Castelle B, Chaumillon E. (eds.) Coastal Evolution under Climate Change along the Tropical Overseas and Temperate Metropolitan France. Journal of Coastal Research, Special Issue 88, 10-24. Coconut Creek (Florida), ISSN 0749-0208, 2019.

[71] Armitage P, Berry G, Matthews JNS. *Statistical methods in medical research*, 4th Edition, Wiley-Blackwell, 2002.

[72] Pérez B, Payo A, López D, Woodworth PL, Alvarez Fanjul E. Overlapping sea level time series measured using different technologies: an example from the REDMAR Spanish network. *Natural Hazards and Earth System Sciences* 14, 589-610, doi: 10.5194/nhess-14-589-2014, 2014.

[73] Jollife I. *Principal component analysis.* 2nd edition, Springer, NewYork, 2002.

[74] Barbosa SM, Fernandes MJ, Silva ME. Space-time analysis of sea level in the North Atlantic from TOPEX/Poseidon satellite altimetry. In: Jekeli C, Bastos L, Fernandes J (eds) Gravity, Geoid and Space Missions. International Association of Geodesy Symposia, vol 129. Springer, Berlin, Heidelberg, 2005.

[75] Yan Z, Tsimplis MN, Woolf D. Analysis of the relationship between the North Atlantic oscillation and sea level changes in northwest Europe. *International Journal of Climatology* 24, 743-758, doi: 10.1002/joc.1035, 2004.

[76] Gomis D, Ruiz S, Sotillo MG, Álvarez-Fanjul E, Terradas J. Low frequency Mediterranean sea level variability: The contribution of atmospheric pressure and wind. *Global and Planetary Change* 63(2), 215-229, doi: 10.1016/j.gloplacha.2008.06.005, 2008.

[77] Barbosa SM. Atmospheric correction of satellite altimetry observations and sea-level variability in the NE Atlantic. *Advances in Space Research* 50(8), 1077-1084, 2012.

[78] Jung T, Vitart F, Ferranti L, Morcrette J-J. Origin and predictability of the extreme negative NAO winter of 2009/10. *Geophysical Research Letters* 38, L07701, doi: 10.1029/2011GL046786, 2011.

[79] Buchan J, Hirschi JJ-M, Blaker AT, Sinha B. North Atlantic SST anomalies and the cold north European weather events of winter 2009/10 and December 2010. *Monthly Weather Review* 142(2), 922-932, 2014.

[80] Goddard PB, Yin J, Griffies SM, Zhang S. An extreme event of sea-level rise along the northeast coast of north America in 2009-2010. *Nature Communications* 6:6346, doi: 10.1038/ncomms7346, 2015.

[81] Hurrell JW, Kushnir Y, Ottersen G, Visbeck M. An overview of the North Atlantic Oscillation. In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds). The North Atlantic Oscillation Climatic Significance and Environmental Impact. Washington D.C. Geophysical Monograph 134, 1-35, https://doi.org/10.1029/134GM01, 2003.

[82] Argus DF, Peltier WR, Drummond R, Moore AW. The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based upon GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories. *Geophysical Journal International* 198(1), 537-563, 2014.

[83] Peltier WR, Argus DF, Drummond R. Space geodesy constrains ice-age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research* 120, 450-487, doi: 10.1002/2014JB011176, 2015.

[84] Altamimi Z, Rebischung P, Métivier L, Collilieux X. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *Journal of Geophysical Research Solid Earth* 121, 6109-6131, 2016.

[85] Ballu V, Gravelle M, Wöppelmann G, et al. Vertical land motion in the Southwest and Central Pacific from available GNSS solutions and implications for relative sea levels. *Geophysical Journal International* 218(3), 1537-1551, doi: 10.1093/gji/ggz247, 2019.

[86] Santamaría-Gómez A, Gravelle M, Dangendorf S, Marcos M, Spada G, Wöppelmann G. Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth and Planetary Science Letters* 473, 24-32, doi: 10.1016/j.epsl.2017.05.038, 2017.

[87] Blewitt G, Hammond WC, Kreemer C. Harnessing the GPS data explosion for interdisciplinary science, *EOS* 99, doi: 10.1029/2018EO104623, 2018.

[88] Vinogradov SV, Ponte R M. Low-frequency variability in coastal sea level from tide gauges and altimetry. *Journal of Geophysical Research* 116, C07006, doi:10.1029/2011JC007034, 2011.

[89] Bonaduce A, Pinardi N, Oddo P, Spada G, Larnicol G. Sea-level variability in the Mediterranean Sea from altimetry and tide gauges. *Climate Dynamics*, 47(9-10), 2851-2 866, doi: 10.1007/s0038, 2016.

[92] Dieng HB, Dadou I, Léger F, Morel Y, Jouanno J, Lyard F, Allain D. Sea level anomalies using altimetry, model and tide gauges along the African coasts in the Eastern Tropical Atlantic Ocean: Inter-comparison and temporal variability. *Advances in Space Research*, doi: 10.1016/j.asr.2019.10.019, 2019.

[90] Wessel P0, Smith WHF, Scharroo R, Luis JF, Wobbe F. Generic Mapping Tools: Improved version released, *EOS Trans. AGU*, 94, 409-410, 2013.

[91] R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/, 2018.