The long sea level record at Cadiz (southern Spain) from 1880 to 2009

Marta Marcos, Bernat Puyol, Guy Woppelmann, Carmen Herrero, Maria-Jesus Garcia-Fernandez

The long sea level record at Cadiz (southern Spain) from 1880 to 2009

Marta Marcos,[1] Bernat Puyol,[2] Guy Wöppelmann,[3] Carmen Herrero,[4] and M. Jesús García-Fernández[5]

Received 31 August 2011; revised 4 October 2011; accepted 5 October 2011; published 13 December 2011.

[1] Mean sea level observations from an historical tide gauge located in Cadiz (Southern Spain) spanning the period 1880–1924 were recovered from national archives. Daily sea level averages stored in handwritten log books were digitized, quality controlled, and referred to the same benchmark. A careful analysis of all the high precision leveling surveys available in the area of the tide gauge enabled the establishment of a common datum with a modern record starting in 1961 from another tide gauge located only 2.5 km apart, with accuracy better than 5 mm. As a result, a consistent daily mean sea level record from 1880 to 2009 was constructed. The 20th century relative mean sea level rise in Cadiz is 0.7 ± 0.1 mm yr^{-1}, which becomes 1.0 ± 0.2 mm yr^{-1} once corrected for vertical land movement with high precision GPS data, in agreement with nearby records. The analysis of the seasonal sea level cycle indicated that the amplitude of the annual cycle has increased during the 20th century. This work evidences the significance of sea level data rescue for present-day climate research.

Citation: Marcos, M., B. Puyol, G. Wöppelmann, C. Herrero, and M. J. García-Fernández (2011), The long sea level record at Cadiz (southern Spain) from 1880 to 2009, *J. Geophys. Res.*, *116*, C12003, doi:10.1029/2011JC007558.

1. Introduction

[2] Tide gauges have been measuring sea level changes relative to land since the 18th century [e.g., *Wöppelmann et al.*, 2006], providing a valuable tool for the investigation of sea level variability and its forcing mechanisms. The global sea level network has been developed since then, especially during the second half of the 20th century and currently reaches more than 2000 tide gauge records [*Woodworth and Player*, 2003]. Despite the large number of tide gauge stations, the number of sea level records longer than 100 years is very small. The estimation of sea level trends at centennial time scales and the rate of sea level acceleration during the 20th century are hence limited to a few places worldwide. The scarcity of observations also limits the application of sea level reconstructions based on the long-term changes provided by coastal tide gauges in combination with spatial patterns of sea level variability as given by the satellite altimetry or by numerical ocean models [*Church et al.*, 2004; *Llovel et al.*, 2009], as these have been proven to be sensitive to the number and spatial distribution of tide gauges used. Therefore, any attempt to increase the sparse historical coastal sea level database is a very relevant scientific issue.

[1]IMEDEA, UIB-CSIC, Esporles, Spain.
[2]Instituto Geográfico Nacional, Madrid, Spain.
[3]LIENSS, Université de la Rochelle-CNRS, La Rochelle, France.
[4]Instituto de Ciencias del Mar, Barcelona, Spain.
[5]Instituto Español de Oceanografía, Madrid, Spain.

0148-0227/11/2011JC007558

[3] In current research, different approaches are followed that pursue the extension of sea level data, including the use of salt marsh sediments [*Leorri et al.*, 2010], archeological remains [*Auriemma and Solinas*, 2009], and geomorphological markers [*Lambeck et al.*, 2011] as sea level indicators. Recovery of ancient tide gauge observations has also been demonstrated to be a powerful approach to increase the historical sea level data set. *Woodworth* [1999] showed how mean high water levels acquired at Liverpool harbor since 1768, which were recovered in what he named an exercise of "data archaeology," could provide information on long-term mean sea level changes. The estimated mean sea level trend for the 20th century was 1.22 ± 0.25 mm yr^{-1}. In Brest, *Wöppelmann et al.* [2006] rediscovered, digitized, and assembled old sea level observations dating back to the early 18th century. Datum continuity in the Brest long sea level record was further investigated by *Wöppelmann et al.* [2008] through the analysis of historical leveling information, providing evidence for the stability and reliability of the series. They found consistency with the Liverpool historical record about 570 km apart, with a mean sea level rise of 1.14 ± 0.18 mm yr^{-1} over the 20th century. In the Mediterranean Sea, the tide gauge record of Marseille was digitized from the original tidal charts allowing the construction of an hourly sea level time series spanning the period 1885–1988. After a comprehensive quality control [*Woppelmann et al.*, 2009], this time series was successfully used to investigate the temporal variability in storminess during the past century [*Letetrel et al.*, 2010]. Other valuable attempts of sea level data rescue have been carried out in the southern hemisphere, where the lack of data is especially marked. *Hunter*

et al. [2003] combined sparse sea level observations at Port Arthur (Tasmania) from 1841 to 2002 to infer a mean sea level rise rate of 1.0 $\pm$ 0.3 mm yr^{-1}, once land uplift was removed. More recently, *Woodworth et al.* [2010] reached a similar low rate of 0.75 $\pm$ 0.35 mm yr^{-1} based on sea level measurements in the Falkland Islands during 1841–1842 compared with current mean sea levels. In both cases the mean sea level trends showed evidences for acceleration during the last few decades. *Testut et al.* [2010] collected and examined historical sea level observations dating from 1874 and recent observations in Saint Paul Island (southern Indian Ocean) to conclude that relative sea level rise was not significantly different from zero at this site. *Watson et al.* [2010] found a rate of relative sea level rise 4.8 $\pm$ 0.6 mm yr^{-1} at Macquarie Island (southwestern Pacific) using recovered sparse sea level observations during 1912–1913, 1969–1971, and 1982 connected to modern data since 1998.

[4] Given the highly heterogeneous nature of sea level rise and the scarcity of long-term (centennial) observations, the historical data rescue and analysis are proven to be worthwhile in the framework of climate research, as demonstrated by a growing number of recent works devoted to the examination of historical records. In this paper we present a new sea level record starting in 1880 at the city of Cadiz (Southern Spain) recovered from national archives. We also show how this historical time series of observations is connected with a modern sea level record from a nearby tide gauge in order to build a consistent single time series. In section 2 we describe the data from both instruments, paying special attention to the calibration of the historical observations. In section 3 we explain how both time series have been referred to a common datum thanks to the detailed information obtained from the high precision leveling surveys. Results derived from the analysis of the complete mean sea level record, including seasonal and long-term sea level variability and comparison with nearby tide gauge stations, is presented in section 4. Discussion and some final remarks are outlined in section 5.

2. Sea Level Data in Cadiz

[5] Sea level observations were provided by two tide gauges installed in the city of Cadiz at a distance around 2.5 km from each other (Figure 1). The instruments operated almost continuously during different periods during the late 19th and 20th centuries. The description of each record is addressed separately.

2.1. The Historical Tide Gauge Record: 1880–1924

[6] The historical tide gauge first installed in Cadiz in 1880 was a classical float instrument and stilling well complemented by a unique recording device [*Reitz*, 1878] (Figure 2). It was installed inside a shed especially built to host the tide gauge and it measured in a well connected to the open sea through a channel. Sea level oscillations were continuously being recorded on tidal charts, whereas daily averages were obtained from a device that enabled the mechanical integration of the float gauge recordings into averaged values as described by *Reitz* [1878] and also implemented in Marseille and Helgoland tide gauges. Unfortunately, the information registered on the tidal charts has been lost. The data that has been preserved consist of daily sea level averages, maxima, and minima handwritten in log books that are archived at the Spanish National Geographical Institute (IGN) in Madrid. Daily averages corresponded to calendar days (0–23 h) of local time. The period spanned is 1880–1924, although with some data gaps. Each book page, corresponding to a single month of historical observations, was converted into electronic format manually. In this work we will only focus on averaged daily values.

[7] Archived data provided two types of averaged daily observations: on one hand, values measured by the mechanical integrator of the tide gauge, which were noncalibrated values referred to an internal reference of the instrument. On the other hand, heights corresponding to sea level values referenced a known benchmark and leveling datum were calculated by adding to each measurement a certain correction, which was obtained through calibration of the instrument with respect to the leveling datum. This difference between the noncalibrated values and the calibrated heights is known as the tide gauge constant and is an important parameter of the tide gauge to ensure continuity and consistency of the recorded time series. Under a perfect functioning of the instrument and ideal environmental conditions, the tide gauge constant remains unchanged, as its name suggests. However, technical problems eventually occur, which forced a recalibration of the instrument and recalculation of the constant. Such changes are generally documented in the log books, although other small and undocumented variations cannot be excluded. The definition of the datum to which the heights are referred was also subject to changes during the period of operation. Two changes were documented during the operation period, in 1883 and 1904 (see Figure 3a).

[8] Past changes in the datum definition, i.e., the reference of the sea level heights, resulted in a corresponding change in the tide gauge constant, in order to keep the same conventional reference throughout the entire period. A consistent time series is therefore obtained by adding the tide gauge constants referred to the same datum to the noncalibrated daily averages. In this study, the chosen datum is given by the "M" reference benchmark of the instrument (see Figure 4), which has been preserved since its installation in 1880. To do so, documented changes in the tide gauge constant marked in the log books were used. These changes with respect to the M benchmark are plotted in Figure 3b. Short suspicious periods with large undocumented changes were removed from the time series, totalling 12 months in all.

[9] Daily averages do not completely remove the tidal component of mean sea level oscillations. The Bay of Cadiz has a semidiurnal tidal regime with sea level oscillations ranging between $\pm$2 m [*REDMAR*, 2005], which reduce to $\pm$6 cm when daily averages are computed. This residual astronomical tidal signal was removed by subtracting a daily time series of tidal oscillations computed with the harmonic constituents provided by the modern tide gauge (see section 2.2). Yearly tidal constituents for the period 1961–2009 were intercompared and only those displaying small interannual variability were selected for the final tidal harmonic analysis. In particular, the constituents whose phase displayed a standard deviation larger than 40° were discarded. Likewise, yearly values of selected constituents whose

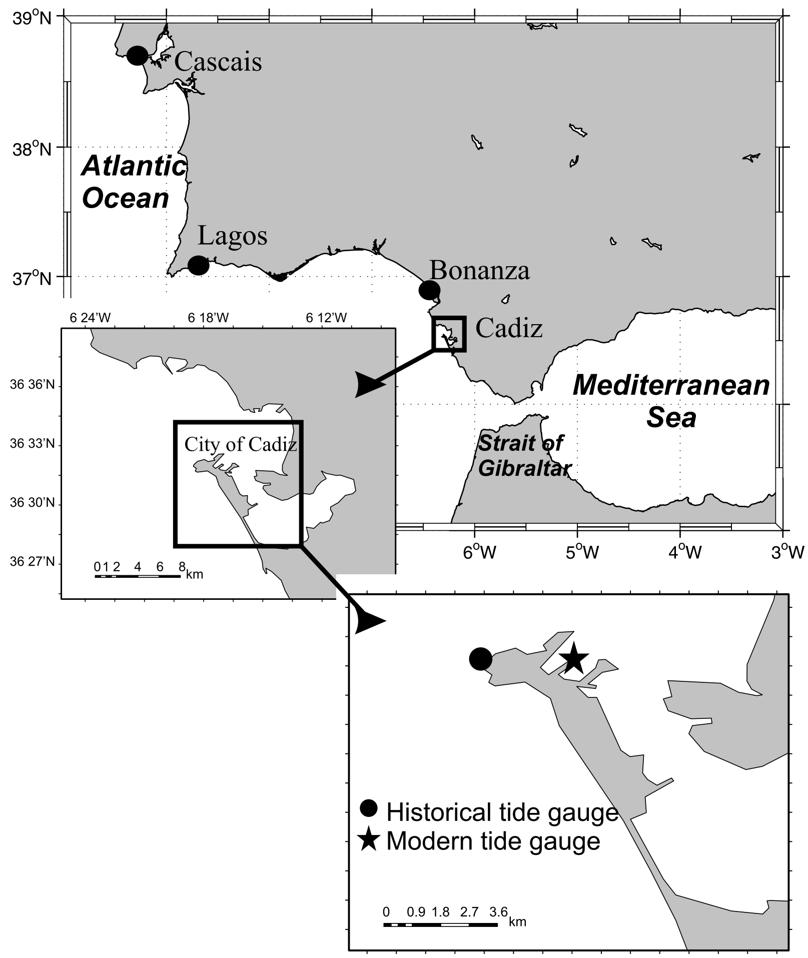

Figure 1. Location of Cadiz and the two tide gauge sites corresponding to the historical and modern tide gauges. Nearby tide gauge stations are also indicated.

amplitude was 70% larger than the median or whose phase differs by more than 20° from the median were removed. A total of 22 tidal constituents fulfilled the criteria, with periods ranging between 4 and 28 h. The largest amplitudes corresponded to the constituents M2, N2, S2, K2, O1, K1, MU2, NU2, 2 N2, Q1, P1, L2, and M4, whereas the rest presented amplitudes below 1 cm. The median values of the selected constituents were then used to build the hindcasted tidal time series for the period 1880–1924.

[10] The resulting daily mean sea level time series after adding all the documented corrections in the tide gauge constant and removing the tidal component is plotted in Figure 3c.

2.2. The Modern Tide Gauge Record: 1961–2009

[11] The modern tide gauge is part of the observational sea level network of the Spanish Institute of Oceanography (IEO). It is located in the city of Cadiz, only 2.5 km away from the historical instrument (Figure 1). The measurement equipment is a mechanical float gauge located in a protective well in a small building at the edge of the pier. It was installed in 1945 with a tidal chart recorder and upgraded in 1999 by connecting the mechanical system to an encoder that provides a digital output. Since then this station has been configured to perform sampling at 10 min intervals. The data are nowadays transmitted by modem in real time to the IEO Operational Data Centre located in Madrid.

[12] For the period 1945–1999 before the encoder was installed, the tidal charts were digitized and converted into electronic format with hourly sampling. Unfortunately, the information on the leveling for the initial period 1945–1960 is not available. This period presents a significant amount of reference shifts not well documented, which is why we were unable to link it with the rest of the record. Therefore the period analyzed in this study from the modern tide gauge starts in 1961, discarding the 1945–1960 data. The time series is referenced to a known benchmark that is part of the national leveling system (see section 3). Monthly averages of this record are available at the Permanent Service for Mean Sea Level (PSMSL) web site (www.psmsl.org) from 1961 to present (named as Cadiz III, with station ID 985).

[13] Tidal analysis was carried out on the hourly sea level time series on a yearly basis. The yearly tidal constituents were quantified and used to extract tidal residuals by subtracting the tidal components to the observations. Hourly

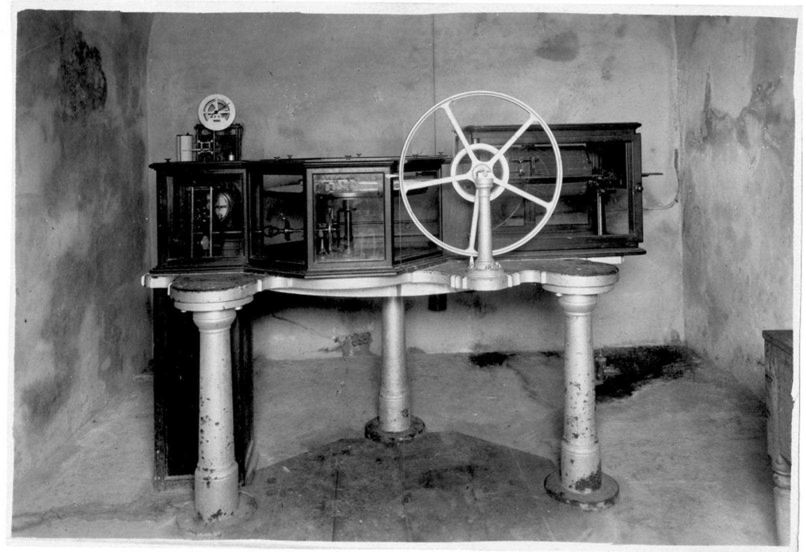

Figure 2. Historical tide gauge installed in Cadiz in 1880.

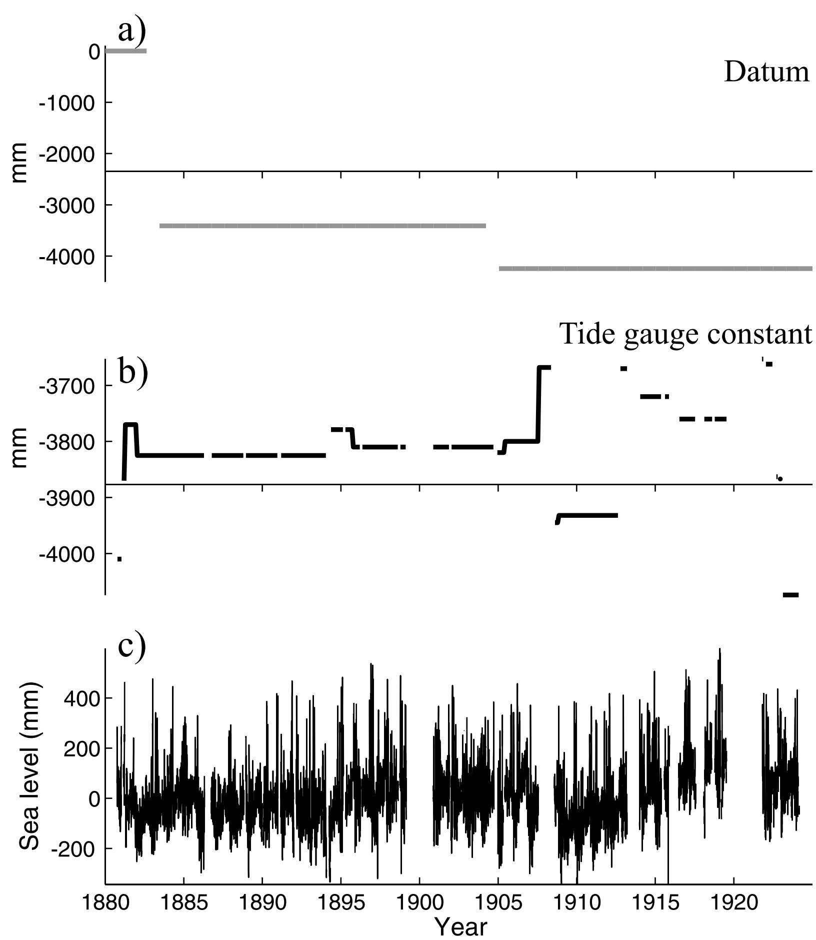

Figure 3. (a) Changes in the tide gauge datum during the operation period, (b) tide gauge constant referred to the "M" benchmark, and (c) calibrated daily sea level time series with the mean value removed.

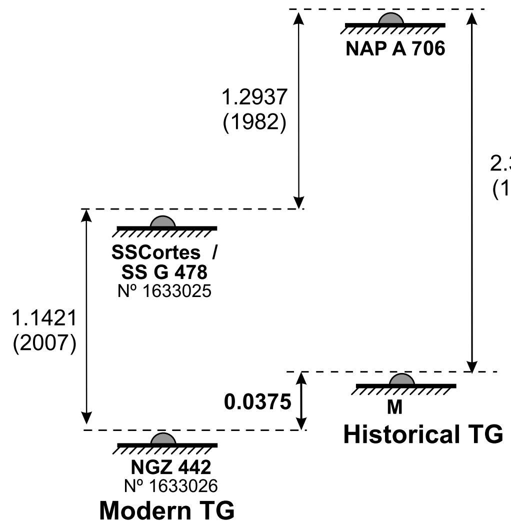

Figure 4. Summary of the leveling surveys and relative heights of the historical and modern tide gauges in Cadiz. Heights are in meters and the year of each survey is indicated in brackets.

tidal residuals were then used to compute the daily averages discussed above.

3. Datum Continuity

[14] The short distance between the two tide gauges (~2.5 km) enabled us to accurately refer their observations to a single datum. With the aim of linking the two independent mean sea level time series the high precision leveling surveys carried out in the city of Cadiz that are available at the IGN archives were examined in detail. A total of 10 leveling surveys were performed between 1876 and 2007. Every path and set of leveling differences among all sites for each survey were inspected and carefully compared between different years in order to establish the most stable and reliable leveling benchmarks. Some of these benchmarks were identified as suspect of having suffered vertical movements and were clearly not stable during two subsequent surveys; they were consequently discarded. All the information in the archives will be made available for interested researchers upon request. A total of six high precision leveling surveys carried out between 1927 and 2007 and linking six different benchmarks of the national leveling system were assessed as stable and used to define the selected stable path from one tide gauge to the other. The benchmarks, their distance, and their relative heights are detailed in Table 1. When closed loops between two benchmarks were available, the closure errors have also been quoted and the relative height was computed as the averaged value. The selected relative heights that were used to define the path between the primary benchmarks of both tide gauges are marked in bold in Table 1. The first leveling between the M benchmark and NAP 706 was stable between 1927 and 1931. The connection between the benchmarks NAP 706 and NAPG 807 seemed stable during 1958–1982; however, the leveling between NAPG 807 and SSG 478 indicated a possible datum shift prior to 1973 and stability afterwards. The most recent survey in 1982, which is also the one with the smallest closure error, was therefore chosen. For the last step, the path was defined using the most recent survey in 2007. These results have also been summarized in Figure 4.

[15] The information detailed above allowed linking the reference benchmark M, to which the historical tide gauge observations are referred, with the NGZ442 benchmark presently used at the modern tide gauge. The latter benchmark is part of the Spanish national height system and has been defined as the primary tide gauge benchmark of the modern instrument. The results determined that the M benchmark is 37.5 mm above NGZ442.

[16] The leveling methodology has evolved and improved with time. Until the 1930s, the observational methodology implied a maximum formal uncertainty in the leveling of $3\sqrt{D}$ mm, with D being the distance between two benchmarks (in km) [*Galbis and Cifuentes*, 1925]. From 1930s onwards, a higher precision was achieved during the surveys and the maximum formal error reduced to $1.5\sqrt{D}$ mm. For all cases the closure errors are smaller than the maximum uncertainty, thus indicating that the measured heights were properly determined within the accuracy allowed by the methodology. The maximum error in the total leveling between the two tide gauge benchmarks is therefore estimated by $\sqrt{E_1^2 + E_2^2}$, where the first term corresponds to the error during survey in 1931 (E_1 = 2.85 mm) and the second to the errors in surveys in 1982 and 2007 (E_2 = 2.96 mm). The resulting total uncertainty associated with the leveling is 4.1 mm.

[17] Sea level observations recorded by the historical tide gauge and initially referred to the M benchmark were transformed into the present-day reference system by adding 37.5 mm, according to the height difference estimated between the two benchmarks. The resulting complete time

Table 1. Leveling Information: Benchmarks, Distances Between Them, Year of the Surveys and Their Relative Height (in m)[a]

Benchmarks	Distance (km)	1927	1931	1958	1973	1982	2007
M → NAP 706	0.9	−2.3962 (1.9)	−2.3987 (−0.7)				
NAP 706→SSG 478							
NAP 706 → NAPG 807	1.071			5.6853 (−2)	5.6844	5.6862 (−0.1)	
NAPG 807 → SSG 478	1.2			−6.9694 (0.6)	−6.9785	−6.9799 (−0.2)	
SSG 478 → NGZ 448							
SSG 478 → SSMalecon	0.641						0.84026 (−1.1)
SSMalecon → NGZ 442	0.995						−1.98234 (−0.3)

[a]Positive values indicate first marker below second. Numbers in parenthesis correspond to closure errors in mm where available. The overall conclusion on the datum connection between the two sites is −0.0375 for M → NGZ442.

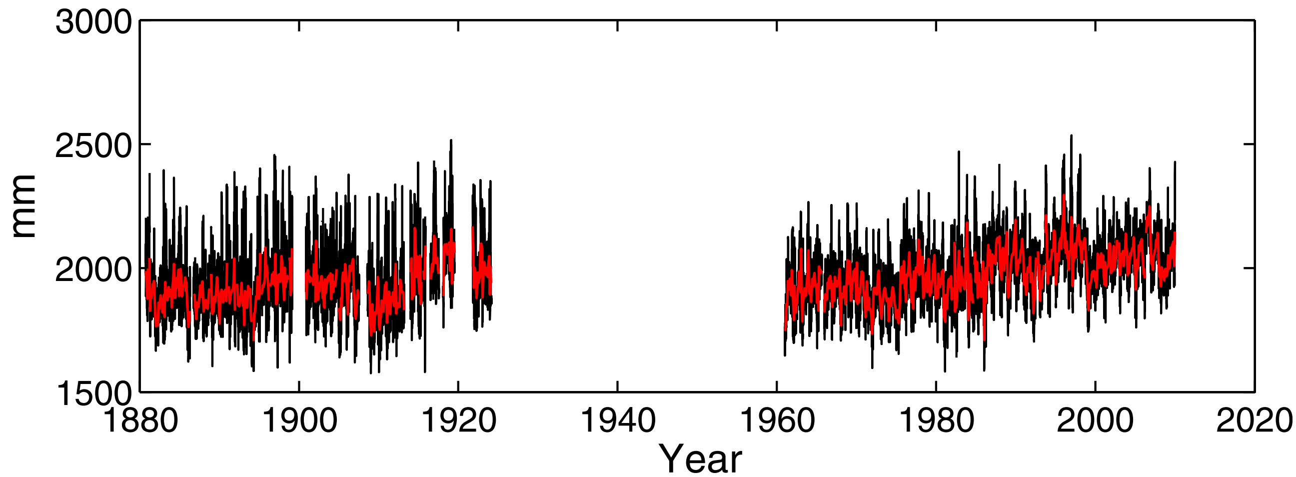

Figure 5. Daily (black) and monthly (red) mean sea level time series in Cadiz for the complete period 1880–2009 referenced to a common datum (see text).

series is a coherent daily mean sea level record starting in 1880 until 2009. The total daily record is plotted in Figure 5.

4. Long-Term and Recent Sea Level Changes

[18] Long-term sea level changes and variability since 1880 in Cadiz and at nearby locations were explored and intercompared. As we were only concerned with low frequency variations, monthly mean sea level time series were computed from the original daily time series in Cadiz (Figure 5, red line). Only those months when at least 80% of daily data are available were used; otherwise they were taken as data gaps.

[19] Additional observations were also employed. Monthly mean sea level records from the tide gauges in Cascais (1882–2005), Lagos (1908–1999), and Bonanza (1992–2009), all located along the Iberian Atlantic coasts (Figure 1) were collected from the PSMSL database, except for the last years in Cascais. Cascais information from the period 1985–2005 was kindly provided by the national authority (Instituto Geográfico Português) and added to the PSMSL long record after they were quality checked [*Marcos and Tsimplis*, 2008]. These three sea level records are included in the Revised Local Reference (RLR) data set of the PSMSL, implying their datum continuity within each time series.

[20] Monthly mean sea level anomalies for the period 1993 onward were also obtained from the satellite multimission product of the AVISO data server (http://www.aviso.oceanobs.com). Data are provided with a grid spacing of 1/4° × 1/4° and with all geophysical corrections applied, including the Dynamic Atmospheric Correction to remove atmospheric effects [*Carrère and Lyard*, 2003]. This correction was added back to the altimetric measurements in order to make them comparable to the observed sea levels of the tide gauge observations. In order to compare with tide gauge observations in Cadiz, the most highly correlated grid point of altimetry observations (computed using detrended and deseasoned records) was selected.

4.1. Changes in the Seasonal Sea Level Cycle

[21] Changes in seasonality were explored in the Cadiz sea level time series during 1880–2009. Amplitudes and phases of the annual and semiannual cycles were estimated by least squares fitting of two sinusoidal signals to monthly sea level observations. The mean annual cycle in Cadiz for the entire record (1880–2009) was found to have amplitude of 3.5 ± 0.5 cm and phase of 248 ± 7 days (peaking in September). These quoted errors and those quoted below are standard errors. When the two periods of the original sea level records were used separately, results revealed a different behavior: the mean annual signal during 1880–1924 had amplitude of 2.6 ± 0.5 cm and phase 259 ± 12 days, whereas during 1961–2009 the amplitude was found to be 4.2 ± 0.5 cm and the phase 244 ± 7 days, in agreement with the findings of *Marcos and Tsimplis* [2007]. Results indicated that the amplitude of the annual cycle clearly increased by 1.6 cm during the 20th century, a value larger than the statistical uncertainty observed for each set separately. By contrast, the phase remained mostly unchanged. Changes in the semiannual signal were negligible, though, with an average value for the entire period of 1.4 ± 0.4 cm and 79 ± 8 days for the amplitude and phase, respectively. In order to check whether such variability is a particular feature of the record in Cadiz, the same methodology was applied to the sea level record in Cascais, the only nearby sea level time series of similar length. Differences found in the annual amplitudes for the same two periods reached 1.2 cm, with values of 2.2 ± 0.4 cm during the first period and 3.4 ± 0.3 cm during the second. As for the Cadiz time series, the annual phase and the semiannual cycle remained unchanged. Therefore, results indicated that the amplitude of the annual cycle has likely increased during the 20th century in our region of study.

[22] A different way to investigate changes in seasonality that also provides information on its variability is to compute the mean seasonal cycle for shorter overlapping periods. Temporal evolution of annual sea level amplitudes and phases were estimated for 5 year periods overlapping year to year. Annual amplitudes are plotted in Figure 6 for the

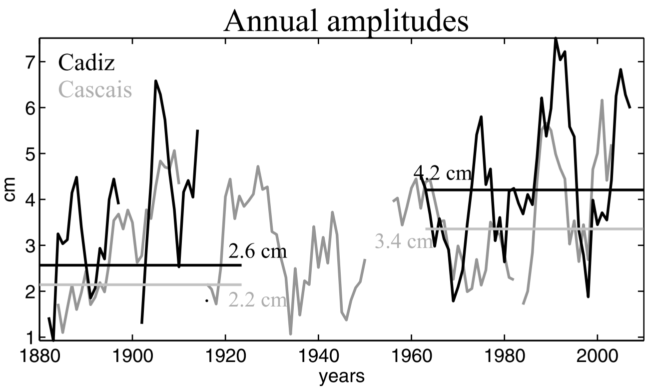

Figure 6. Changes in the amplitude of the annual cycle in Cadiz (black) and Cascais (gray) tide gauges computed for 5 year periods overlapping year to year. Mean annual amplitudes for the periods 1880–1924 and 1961–2009 are also marked (horizontal lines).

Cadiz and Cascais records. In spite of the large interannual variability of the annual cycle, already pointed out by *Marcos and Tsimplis* [2007], with amplitudes changing up to 4 cm from year to year, an increase is evidenced at both locations. Mean values for 1880–1924 and 1961–2009 are marked in the figure for comparison. The largest annual sea level amplitudes since 1880 were found during the last two decades. For the altimetric period 1993–2009 the mean annual amplitude in Cadiz was 4.6 $\pm$ 0.7 cm, whereas the amplitude obtained from the altimetric observations was slightly larger, with a value of 5.7 $\pm$ 0.4 cm.

[23] Changes in the amplitude of the seasonal sea level cycle occur because either the sea level becomes higher during the summer or it becomes lower during winter or a combination of both. With the aim of finding out which is the mechanism that dominates, the averaged summer (JJA) and winter (DJF) mean sea level values were computed for the Cadiz sea level record and for the two periods 1880–1924 and 1961–2009. During the former period averaged winter (summer) sea level was -4.9 cm (-2.7 cm) while during the latter averaged winter (summer) sea level was -0.5 cm (3.3 cm), computed with respect to the same reference. That is, averaged mean sea level rose for all seasons but with different rates: summer sea level rose 6 cm on average between the two periods, while winter sea level rose 4.4 cm. While with the present observations it cannot be inferred which part of the total sea level rise in Cadiz is of thermal origin and which part is attributed to other mechanisms, our results indicated that the increase in the annual sea level amplitude was attributed to the occurrence of warmer summers during the last decades in relation to the late 19th to early 20th centuries.

4.2. Long-Term and Interannual Sea Level Variability

[24] Sea level time series from tide gauges and altimetry records were deseasonalized in order to explore their interannual variability and consistency at long time scales. Linear correlations between the detrended tide gauge record in Cadiz and nearby stations, for their overlapping periods of operation, were first computed. Results are listed in Table 2, where all values quoted are significant at the 99% confidence level. The correlation between the sea level record in Cadiz and the nearby station in Bonanza was found to be very high, with a value of 0.67 for the last two decades. The same applied to the altimetric record, demonstrating the consistency of mean sea level changes within the Gulf of Cadiz. The correlations for longer time periods with Lagos and Cascais were lower: 0.46 with Lagos during 1908–1999 and only 0.35 with Cascais during 1882–2005. Interestingly, when the two periods 1880–1924 and 1961–2009 were considered separately, the correlations increased with Lagos up to 0.61. However, the overlapping during the first period is too short (see Figure 6) so as to prevent from drawing any definitive conclusion. In Cascais the correlation was high (0.66) during the recent period and low (0.34) during the first one. This result suggested that, at interannual time scales, the quality of the tide gauge sea level record in Cadiz was improved with the modern tide gauge.

[25] Decadal linear sea level trends were compared between tide gauges and altimetry observations for their overlapping periods (Lagos was discarded due to its short overlap). Whereas in Cascais and Bonanza sites the estimated decadal trends showed consistency, large differences were found in Cadiz for the period 1993–2009, with values of -0.3 ± 1.0 and 3.1 ± 0.5 mm yr^{-1} for the tide gauge and altimetry, respectively. A closer inspection of the comparison (not shown) reveals that such large discrepancy was attributed to a likely datum shift in the tide gauge record in 2006, which is probably related with recent works carried out at the harbor beside the tide gauge location during 2006–2007.

[26] Mean sea level trends during the 20th century were computed for the longest time series, namely Cadiz, Lagos, and Cascais. The resulting rates are listed in Table 3. Relative mean sea level rise in Cadiz as estimated from the composite time series is 0.69 ± 0.12 mm yr^{-1}, whereas in Lagos and Cascais it reaches 1.5 ± 0.1 mm yr^{-1}. In Lagos and Cascais stations, uncertainties in linear trends correspond to standard errors. In Cadiz it was estimated taking into account the $\pm$4.1 mm accuracy in the leveling between the two periods of observation (section 3). This maximum error is translated into an uncertainty of $\pm$0.06 mm yr^{-1} for the secular trend. The total uncertainty was then computed, propagating the standard error of the linear trend (0.10 mm yr^{-1}) and the error associated to the leveling (0.06 mm yr^{-1}), assuming the variables were uncorrelated and resulting in 0.12 mm yr^{-1}. Relative rates of mean sea level rise in Cadiz resulted in a value about 0.8 mm yr^{-1} lower than in nearby Atlantic locations (Table 3).

[27] When secular mean sea level rise trends were corrected for vertical land movements that were estimated from

Table 2. Linear Correlations Between the (Deseasonalised and Detrended) Cadiz Sea Level Record[a]

Station	Correlation With Cadiz Sea Level: Entire Period	Historical Period	Modern Period
Altimetry	0.67 (1993–2009)	–	–
Bonanza	0.67 (1992–2009)	–	–
Lagos	0.46 (1908–1999)	*0.61* (1908–1924)	0.61 (1961–1999)
Cascais	0.35 (1882–2005)	0.34 (1882–1924)	0.66 (1961–2005)

[a]Other nearby time series for the periods given in parentheses. Quoted correlations are all significant at the 99% confidence level. The value in italic indicates a too short overlapping period (see the text for details).

Table 3. Mean Sea Level Trends for the Longest Time Series Relative to Land, GPS Vertical Rates of Land Movement and Sea Level Trends Corrected Using GPS Rates (in mm yr^{-1})

Station	20th Century Trend	GPS Trend	20th Century GPS-Corrected Trend
Cadiz	0.69 ± 0.12	0.33 ± 0.17	1.02 ± 0.21
Lagos	1.45 ± 0.09	−0.30 ± 0.16	1.15 ± 0.19
Cascais	1.51 ± 0.06	0.18 ± 0.16	1.69 ± 0.17

Global Positioning System (GPS) data [*Santamaría-Gómez et al.*, 2011], absolute (geocentric) rates of sea level rise became consistent between Cadiz and Lagos, 1.02 and 1.15 mm yr^{-1}, respectively (Table 3). The GPS solution from *Santamaría-Gómez et al.* [2011] was chosen because it is a recent and dedicated GPS solution at tide gauge sites applying state-of-the-art models and corrections in the reanalysis of the entire GPS data set considered. The length of the GPS records in Cadiz and Cascais is over 10 years while in Lagos it is more than 8 years, thus long enough to estimate accurately the vertical ground motion at better than 0.5 mm yr^{-1} level. It must be recalled here that the Lagos sea level record is shorter than the Cadiz record. When the linear trend was computed with the same starting year of 1908, Cadiz sea level rise became 1.20 mm yr^{-1}, thus virtually equal to Lagos. The Cascais site revealed a higher rate of 1.69 mm yr^{-1}. These time series, once corrected for vertical land movements, are further compared in Figure 7. The Bonanza record has also been included despite the land movement correction not being available at this site. Monthly records were low-pass filtered using a 6 months running average. It is worth noting here that the geoid change as predicted from the glacial isostatic adjustment (GIA) model SELEN used in *Tsimplis et al.* [2011] at Cadiz, Lagos, and Cascais, yields differences inferior to 0.03 mm yr^{-1}.

[28] The comparison between Cadiz and Cascais revealed periods of inconsistencies. In particular, there are large differences during 1908–1920. This period coincides with a large change in the tide gauge constant of the historical tide gauge (see Figure 3b) and suggests that the calibration of the instrument was not performed correctly. A second large discrepancy is found during 1961–1975, when the Cadiz record is clearly below Cascais by about 10 cm. The same discrepancy occurred when it was compared with the Lagos time series, although it is not evident from the series in Figure 7. This suggested an unreported leveling problem at the modern tide gauge in Cadiz during this period. In the light of these results, we recommend that these periods, 1908–1920 and 1961–1975, are considered with caution in any analysis of the sea level record of the Cadiz tide gauge.

5. Discussion and Conclusions

[29] The present work represents a contribution to the extension of the global coastal sea level data set through "data archaeology" as advocated by *Woodworth* [1999]. The major product is a consistent daily mean sea level time series in Cadiz from 1880–2009 that was constructed using two independent records located at a short distance from each other and separated by a time lag of 37 years. Many efforts were devoted to the time consuming process of converting the handwritten sea level measurements stored in log books into electronic format for the first period 1880–1924 as well as to the careful analysis of the notes and documented changes in the historical archives that allowed the establishment of a unique and stable local tide gauge datum for this first period. Despite the long discontinuity between the two originally independent sea level records (from 1924–1961), careful study of the leveling information available from different surveys enabled linking the historical tide gauge record with the modern one located 2.5 km apart, with an accuracy better than 5 mm. Although the recovery of

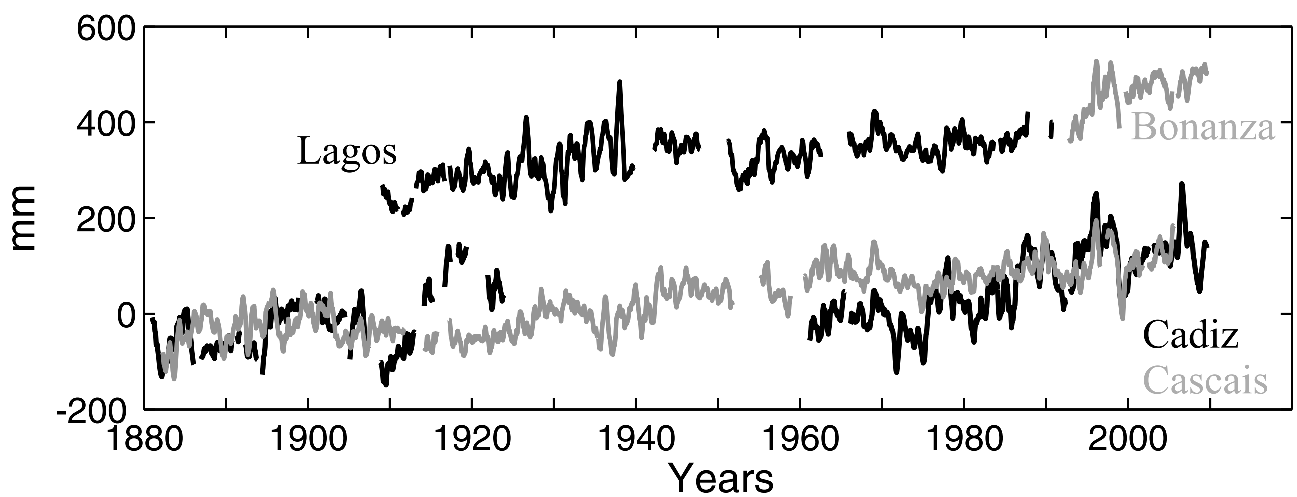

Figure 7. Monthly tide gauge sea level records deseasonalized and filtered with a 6 month running average. Time series were corrected for vertical land movements using GPS data where available. Tide gauge records in Lagos and Bonanza have been offset and adjusted to each other to equal their averaged values for 1990–1993, while those in Cadiz and Cascais were adjusted to have equal averaged values for 2003–2005 for representation purposes.

historical observations is sometimes hard and tedious, the information they provide is unique and original, and hence worthwhile and relevant for current and future research. Due to the scarcity of sea level observations dating back more than a century and because of the complexity of spatial and temporal sea level variability, such rediscovered measurements are a valuable complement to present-day understanding of mean sea level changes and their driving processes. Most important is the fact that if no efforts are undertaken aiming at the recovery and quality control of these unique data, they are at risk of being definitively lost for the scientific community.

[30] The comparison of the long mean sea level time series from Cadiz with nearby sea level observations from tide gauges and altimetry showed overall consistency at intra and interannual time scales, but also pointed out the existence of suspicious periods likely affected by nondocumented datum shifts, despite the thorough work performed with the historical tide gauge calibration. In particular, during the period 1908–1920 the sea level record in Cadiz presents an extremely high decadal sea level rise. Interestingly, a similar feature was found northward in Brest (France) and in Delfzijl (Netherlands) sea level records [*Douglas*, 2008]. These were related by *Douglas* [2008] to atmospheric pressure changes through the inverse barometer effect. In order to check whether the same effect is acting on Cadiz, a similar comparison was carried out using atmospheric pressure provided by the HadSLP2 reanalysis [*Allan and Ansell*, 2006]. Results (not shown) indicated that, although there is evidence of a significant reduction in mean atmospheric pressure nearby Cadiz between years 1914–1916 of approximately 2 mbar, other similar strong changes can be found (1883–1885, for example) without the same correspondence to such large changes in sea level. Therefore, the behavior of mean sea level in Cadiz during the period 1908–1920 is likely due to reference shifts. The facts that Cascais does not show the same feature and that significant changes in the datum took place during the same period, support this conclusion. Consequently, it is recommended that this period of the sea level record is used with caution; in particular, it should not be taken as representative of decadal sea level variability.

[31] A second period of time that showed significant differences with nearby records is the period 1961–1975 of the modern record. It was found to be on average about 10 cm below Cascais and Lagos and is thus also suspect of containing a datum shift. We therefore extend the same recommendation as above of not being used to study long-term (decadal) changes in sea level. However, seasonal and interannual sea level variability may be explored using the entire time series. The comparison of recent tide gauge observations with nearby altimetry measurements suggests a likely problem in the tide gauge record in 2006 too.

[32] Changes in seasonality were evidenced during the 20th century in the Cadiz sea level record and also consistently in the nearby long time series of Cascais. The results pointed at an increase of the annual amplitude of the seasonal sea level cycle, mainly attributed to higher mean sea levels during the summer season. Since the annual sea level cycle reflects the seasonal warming and cooling of the ocean waters this result suggested that temperature was rising faster during the summer than during the winter during the 20th century along the Iberian Atlantic coasts.

[33] Relative mean sea level rise during the 20th century derived from the long composite time series constructed in this study for Cadiz is 0.7 ± 0.1 mm yr^{-1}. It must be remarked that the trend is barely affected by the suspicious periods reported above, as they occur in the middle of the record. Rates of vertical land movements estimated from GPS observations indicated land uplift of $+0.33 \pm 0.17$ mm yr^{-1} near to the Cadiz tide gauge, leading to a rate of absolute (geocentric) mean sea level rise of 1.0 ± 0.2 mm yr^{-1}. This value is consistent with the nearby estimate of Lagos (1.2 ± 0.2 mm yr^{-1}) but lower than the estimated rate in Cascais (1.7 ± 0.2 mm yr^{-1}). The reasons for such differences remain unknown. Despite the geographical proximity of the stations the oceanographic conditions are different. The wind plays a relevant role in sea level in areas close to the Strait of Gibraltar, as pointed out by *Menemenlis et al.* [2007], whereas Cascais is located in the path of the poleward slope current flowing along the Portuguese continental shelf [*Frouin et al.*, 1990] and is under the influence of the atmospheric pressure changes in the middle of the Atlantic Ocean [*Miller and Douglas*, 2007]. Further research is needed in this respect beyond the scope of this study. In particular, in situ atmospheric data could eventually shed some light on the different processes at these nearby stations.

[34] The recovery of historical sea level observations and their availability to the scientific community are important issues in present-day climate research. Only a few stations worldwide are long enough to provide information and constraints on sea level changes at secular time scales. And their interpretation is clearly limited by the spatial heterogeneity of sea level rise patterns and variability. Recovered sea level observations are also useful in other complementary research fields: for example, they can be used to validate sea level reconstructions based on fossil foraminiferal assemblages and, when high frequency observations are available, as is the case in Cadiz, to investigate eventual changes in the storm surge sea level component. Therefore, any effort devoted to data rescue and quality control is considered to be worthwhile in sea level research.

[35] **Acknowledgments.** This work has been carried out in the framework of the project VANIMEDAT-2 (CTM2009-10163-C02-01), funded by the Spanish Marine Science and Technology Program and the E-Plan of the Spanish Government. M. Marcos acknowledges a "Ramon y Cajal" contract funded by the Spanish Ministry of Education. It was also partly funded by Universitat de les Illes Balears, which provided a visiting professor grant for G. Wöppelmann. The authors are also grateful to the Instituto Hidrográfico de la Marina (IHM) for providing support with the tide gauge leveling data. The SONEL data assembly center is also acknowledged for providing access to GPS data (see http://www.sonel.org). The authors are also grateful to Alain Coulomb for his interest and support with documentation in this research work, and to Phil Woodworth and Laurent Testut for their reviews of the manuscript.

References

Allan, R., and T. Ansell (2006), A new globally complete monthly historical mean sea level pressure data set (HadSLP2), 1850–2004, *J. Clim.*, *19*(22), 5816–5842, doi:10.1175/JCLI3937.1.

Auriemma, R., and E. Solinas (2009), Archaeological remains as sea level change markers: A review, *Quat. Int.*, *206*, 134–146, doi:10.1016/j.quaint.2008.11.012.

Carrère, L., and F. Lyard (2003), Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing—Comparisons with observations, *Geophys. Res. Lett.*, *30*(6), 1275, doi:10.1029/2002GL016473.

Church, J. A., N. J. White, R. Coleman, K. Lambeck, and J. X. Mitrovika (2004), Estimates of the regional distribution of sea level rise over the 1950–2000 period, *J. Clim.*, *17*, 2609–2625, doi:10.1175/1520-0442(2004)017<2609:EOTRDO>2.0.CO;2.

Douglas, B. C. (2008), Concerning evidence for fingerprints of glacial melting, *J. Coastal Res.*, *24*(2B), 218–227, doi:10.2112/06-0748.1.

Frouin, R., A. F. G. Fiuza, I. Ambar, and T. J. Boyd (1990), Observations of a poleward surface current off the coasts of Portugal and Spain during winter, *J. Geophys. Res.*, *95*(C1), 679–691, doi:10.1029/JC095iC01p00679.

Galbis, J., and M. Cifuentes (1925), *Catalogo de Altitudes de las Señales Metálicas de la Red*, Inst. Geogr. Nac., Madrid.

Hunter, J., R. Coleman, and D. Pugh (2003), The sea level at Port Arthur, Tasmania, from 1841 to the present, *Geophys. Res. Lett.*, *30*(7), 1401, doi:10.1029/2002GL016813.

Lambeck, K., F. Antonioli, M. Anzidei, L. Ferranti, G. Leoni, G. Scicchitano, and S. Silenzi (2011), Sea level change along the Italian coast during the Holocene and projections for the future, *Quat. Int.*, *232*, 250–257, doi:10.1016/j.quaint.2010.04.026.

Leorri, E., W. R. Gehrels, B. P. Horton, F. Fatela, and A. Cearreta (2010), Distribution of foraminifera in salt marshes along the Atlantic coast of SW Europe: Tools to reconstruct past sea-level variations, *Quat. Int.*, *221*, 104–115, doi:10.1016/j.quaint.2009.10.033.

Letetrel, C., M. Marcos, B. Martín-Míguez, and G. Woppelmann (2010), Sea level extremes in Marseille (NW Mediterranean) during 1885–2008, *Cont. Shelf Res.*, *30*, 1267–1274, doi:10.1016/j.csr.2010.04.003.

Llovel, W., A. Cazenave, P. Rogel, A. Lombard, and M. B. Nguyen (2009), Two-dimensional reconstruction of past sea level (1950–2003) from tide gauge data and an Ocean General Circulation Model, *Clim. Past*, *5*, 217–227, doi:10.5194/cp-5-217-2009.

Marcos, M., and M. N. Tsimplis (2007), Variations of the seasonal sea level cycle in southern Europe, *J. Geophys. Res.*, *112*, C12011, doi:10.1029/2006JC004049.

Marcos, M., and M. N. Tsimplis (2008), Coastal sea level trends in southern Europe, *Geophys. J. Int.*, *175*, 70–82, doi:10.1111/j.1365-246X.2008.03892.x.

Menemenlis, D., I. Fukumori, and T. Lee (2007), Atlantic to Mediterranean sea level difference driven by winds near Gibraltar Strait, *J. Phys. Oceanogr.*, *37*, 359–376, doi:10.1175/JPO3015.1.

Miller, L., and B. C. Douglas (2007), Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise, *Geophys. Res. Lett.*, *34*, L16602, doi:10.1029/2007GL030862.

REDMAR (2005), Resumen de parámetros relacionados con el nivel del mar y la marea que afectan a las condiciones de diseño y explotación portuaria, report, Organ. Publico Puertos del Estado, Madrid.

Reitz, F. H. (1878), Ein für das Königlich Preussische geodätische Institut der europäischen Gradmessung ausgeführter Fluthapparat, in *Mitteilungen der Geographischen Gesellschaft in Hamburg*, pp. 87–95, L. Friederischen, Hamburg, Germany.

Santamaría-Gómez, A., M.-N. Bouin, X. Collilieux, and G. Wöppelmann (2011), Correlated errors in GPS position time series: Implications for velocity estimates, *J. Geophys. Res.*, *116*, B01405, doi:10.1029/2010JB007701.

Testut, L., B. M. Miguez, G. Wöppelmann, P. Tiphaneau, N. Pouvreau, and M. Karpytchev (2010), Sea level at Saint Paul Island, southern Indian Ocean, from 1874 to the present, *J. Geophys. Res.*, *115*, C12028, doi:10.1029/2010JC006404.

Tsimplis, M. N., G. Spada, M. Marcos, and N. Flemming (2011), Multi-decadal sea level trends and land movements in the Mediterranean Sea with estimates of factors perturbing tide gauge data and cumulative uncertainties, *Global Planet. Change*, *76*, 63–76, doi:10.1016/j.gloplacha.2010.12.002.

Watson, C., R. Burgette, P. Tregoning, N. White, J. Hunter, R. Coleman, R. Handsworth, and H. Brolsma (2010), Twentieth century constraints on sea level change and earthquake deformation at Macquarie Island, *Geophys. J. Int.*, *182*, 781–796, doi:10.1111/j.1365-246X.2010.04640.x.

Woodworth, P. L. (1999), High waters at Liverpool since 1768: The UK's longest sea level record, *Geophys. Res. Lett.*, *26*(11), 1589–1592, doi:10.1029/1999GL900323.

Woodworth, P. L., and R. Player (2003), The permanent service for mean sea level: An update to the 21st century, *J. Coastal Res.*, *19*(2), 287–295.

Woodworth, P. L., D. T. Pugh, and R. M. Bingley (2010), Long-term and recent changes in sea level in the Falkland Islands, *J. Geophys. Res.*, *115*, C09025, doi:10.1029/2010JC006113.

Wöppelmann, G., N. Pouvreau, and B. Simon (2006), Brest sea level record: A time series construction back to the early eighteenth century, *Ocean Dyn.*, *56*, 487–497, doi:10.1007/s10236-005-0044-z.

Wöppelmann, G., N. Pouvreau, A. Coulomb, B. Simon, and P. L. Woodworth (2008), Tide gauge datum continuity at Brest since 1711: France's longest sea level record, *Geophys. Res. Lett.*, *35*, L22605, doi:10.1029/2008GL035783.

Woppelmann, G., et al. (2009), Marseille tide gauge: Review and rescue of its historical data (1885–1988), paper presented at Third ESF MedCLIVAR Workshop on Understanding the Mechanisms Responsible for the Changes in the Mediterranean Sea Circulation and Sea Level Trends, Eur. Sci. Found., Rhodes, Greece.

M. J. García-Fernández, Instituto Español de Oceanografía, Corazón de María 8, Madrid E-28002, Spain.

C. Herrero, Instituto de Ciencias del Mar, Passeig Marítim de la Barceloneta 37–49, Barcelona E-08003, Spain.

M. Marcos, IMEDEA, UIB-CSIC, Miquel Marques 21, Esporles E-07190, Spain. (marta.marcos@uib.es)

B. Puyol, Instituto Geográfico Nacional, General Ibáñez de Ibero 3, Madrid, E-28003, Spain.

G. Wöppelmann, LIENSS, Université de la Rochelle-CNRS, 2 Rue Olympe de Gouges, La Rochelle F-17000, France.