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Sea Level at Cascais Tide Gauge: Data, Analysis and Results

C. Antunes † and R. Taborda †
† LATTEX, IDL
University of Lisbon
1749-016, Portugal
cmantunes@fc.ul.pt
rtaborda@fc.ul.pt

ABSTRACT

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CASCAIS tide gauge has one of the longest time series, and for this reason the most important studies on global sea level change using tide gauges have included its data. The magnitude of global level rise is similar to the results obtained at this tide gauge. Its continuity, quality and reliability are the reasons for its widespread use and importance. From 2003, sea level has being acquired by a modern acoustic and digital tide gauge with different sensors, turning it part of the international networks for the sea level changes monitoring, as SLEAC and GLOSS. The quality of the data set and its availability online gives the possibility to extend the studies to other research areas, such as the real-time determination of storm surge and tsunami waves. The complete time series, including both analog and digital data, has been integrated, processed and analyzed, and new preliminary results have been obtained. In what concerns to the relative mean sea level, results point out to rates of 2.1 mm yr^{-1} and 2.5 mm yr^{-1} for the decades of 1990 and 2000, respectively, which compares to 1.8 mm yr^{-1} obtained at earlier studies for the 1920-1990 period. Such rates, compatible with a sea level rise acceleration scenario, enabled a preliminary projection of the absolute and relative sea level rise for the next decades. For these results a value of ICE-5G isostatic model and a velocity of the CASCAIS permanent GPS station from EUREF solutions have been used to compute the absolute SLR rates.

ADDITIONAL INDEX WORDS: *Sea level rise, sea rise acceleration, tide gauge.*

INTRODUCTION

The tide gauge of CASCAIS is the oldest gauge in Portugal and in all Iberian Peninsula. It has been working since 1882, corresponding to a data series longer than 100 years, more than 80% complete, representing one of the longest tide gauge time series in the world. The gauge is located at an open coast, at a site of low tectonic activity, free of ice coverage during the last glacial period and with considerable agreement with records from nearby gauges. It is therefore considered an important and reliable data set for relative sea level (RSL) studies that has been used in a large number of research works (*e.g.*, MAKSIMOV, 1971; GORNITZ *et.al.*,1982; BARNET, 1983, 1984; LAMBECK and NAKIBOGLU, 1987; PELTIER and TUSHINGHAN, 1989; DOUGLAS, 1997).

Sea level measuring at this site has been improved in order to meet the standards of international sea level change monitoring networks, such as SLEAC – "Sea Levels along the European Atlantic Coastline" or GLOSS – "The Global Sea Level Observing System". In 2003 the Portuguese Geographic Institute (IGP) has installed a new equipment near the previous gauge site, composed by an acoustic device with temperature and atmospheric pressure sensors, and with internet connection, enabling digital real-time access data. Nearby, is located the IGS permanent station of GPS, to which the tide gauge ortometric high is verified in a yearly basis, in order to determine the stability and the vertical movements of the site.

The main goal of this work is to analyze the long-standing Cascais tide gauge data, by integrating the results obtained with the new gauge and GPS data, in order to find up-to-date estimates of sea level rise and possible evidences of accelerating trends, in line with the Intergovernmental Panel on Climate Change (IPCC) estimates.

SEA LEVEL RISE DURING THE 20th CENTURY

The data used to estimate the RSL rise at Cascais for the last century are the annual and month average data series available at the Permanent Service for Mean Sea Level (PSMSL) website, completed with recent data from IGP.

Earlier studies based on the Cascais tide gauge data are unanimous in the identification of an upward trend for RSL with a magnitude ranging from 1 to 2 mm yr^{-1}. The differences in these estimates are mainly related with the actual extend data used for RSL computation. In fact, tide gauge data of Cascais shows two main long-term trends, separated around 1920. Based on the annual average data set, the earlier data shows a stable trend for the RSL while the later data, from 1920 to 2000, shows an upward trend with an average rate of 1.6 ± 0.13 mm yr^{-1} (in 1992, DIAS and TABORDA estimated a value of 1.7 ± 0.2 mm yr^{-1}). It is, therefore, clear that any tentative to determine a long-term rate for the 20th century at Cascais tide gauge should account form long term variations in the trend, splitting the data series into two sections: an earlier section, which some authors relate to the end of the "Little Ice Age" (DIAS and TABORDA, 1992), and a later section, related with global climate change, mostly resulting from the thermal expansion of the North Atlantic Ocean (GORNITZ *et.al.*, 1982; GORNITZ and LEBEDEFF, 1987, DIAS and TABORDA, 1992).

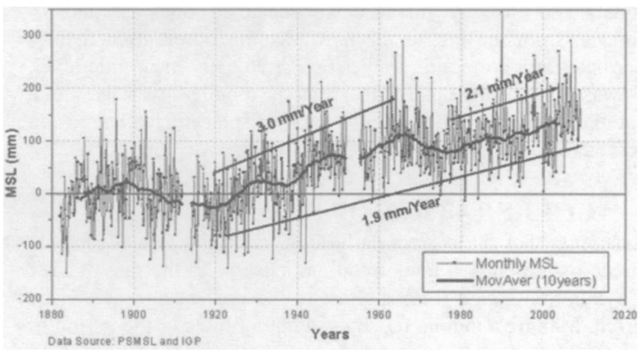

Figure 1. Complete (1882-2008) monthly average time series of sea level at Cascais tide gauge with a 10-year moving average superimposed.

Figure 1 displays the completed monthly average Cascais tide gauge time series, which extends from 1882 to 2008. This series, which at first seems relatively noisy, includes not only long term variations in sea level but also seasonal and inter-annual oscillations related to the global ocean circulation regime and the influence of the pressure and wind regimes. The amplitude of these variations is larger than the underlying long term sea level trend, which make difficult to compute reliable estimates for SLR rates.

In order to remove the seasonal and inter-annual oscillations, a moving average over the entire data series was performed. The range of the running window (10 years) was chosen in to keep the inter-decal and part of the decal variations. The results, displayed in Figure 1, show a quite agreement with some of global models of SLR based in tide gauge data, namely CHURCH and WHITE, (2006) and JEVREJEVA *et.al.* (2006).

From the smoothed data it was possible to identify different sections in the time series where the rate of RSL has changed, enabling the estimation of individual RSL rates. These rates, displayed in the Table 1, supported with the visual interpretation of the graph, indicate that the RSL has had different periods of acceleration and deceleration, i.e., the rate has not been constant over the entire century.

To determine an overall RSL rise rate at Cascais for the 20th century, the slope of the 10-year period moving average curve between 1920 and 2000 was established and a mean rate of 1.9 mm yr^{-1} was obtained. This value is in good agreement with the 1.84 mm yr^{-1} GSL estimate of DOUGLAS and PELTIER (2002) for the last 70 years of the century. To support this comparison is the fact that the version of the glacial isostatic adjustment model ICE-5G (PELTIER,2004; http://www.pol.ac.uk/psmsl/peltier/index.html) indicates a value of 0.0 mm yr^{-1} for the respective relative sea level rise.

The pattern of the moving average curve suggests the existence of a mechanism of action/reaction on the ocean system as a response to certain external events related to the eustatic process of SLR. However, the last period of the series, including already the most recent data, shows linear behavior, presenting a much longer period of quasi constant rate. Such behavior suggests an interruption of the earlier forcing pattern.

The linear trend by least squares fitting on the 10-year moving average of the latest two decades of the 20th century indicates a rate of 2.1 ± 0.1 mm yr^{-1}. Such rate is in good agreement with the GSL rise of 2.4 mm yr^{-1} yield by TOPEX/Poseidon for the first nine-year base line (DOUGLAS *et al.*, 2001). Since the ocean circulation shifts the SL in a decal period of time from the global mean, this small difference of 0.3 mm yr^{-1} is quite acceptable on the supposition that Cascais is not significantly under the influence of any type of vertical movement.

From the 20th century data series we conclude that in its last decade the relative SLR at Cascais has the rate of 2.1 mm yr^{-1}. This rate can be later on compared with posterior rates and acceleration values can be determined.

Table 1: Rates of relative SLR at Cascais Tide Gauge, from 1900 to 2000.

Period	Rate (mm yr^{-1})
1900 - 1920	-1.8
1920 – 1930	4.8
1930 - 1937	-1.1
1937 - 1949	5.2
1949 - 1956	-0.7
1956 - 1966	4.5
1966 -1977	-3.0
1977 -2000	2.1

NEW TIDE GAUGE DATA PROCESSING

The new instrument at Cascais tide gauge started to register on 1st of November of 2003, and has been working continuously ever since. The data is transmitted by FTP protocol with a measurement rate of 6 minutes for sea level and 10 minutes for air-pressure at sea level, and it is stored in 1-hour files every day in the public FTP site of IGP. For security reasons, a copy of the data is also kept in the instrument memory card, which is removed safely at every 11 days.

From the daily data a mean value of RSL is computed (referred also as daily mean tide – DMT) and any particular event that may occur, due to the meteorological and oceanographic effects, such as storm surges, seiches or wind waves is analyzed.

The available air-pressure data enables the correction for the inverse barometric effect over the daily-mean sea level, resulting in a sea level with a constant atmosphere pressure of 1019 mbar (the local instrumental mean value). Such correction reduces the annual variability of the MSL, reducing the standard deviation of the data from 9 to 7 cm, and removing the trend induced by long-term pressure variations.

If a linear regression is fitted over both, the uncorrected and the corrected series, the rates around the values of 0.2 and 3.3 mm yr^{-1} are obtained, respectively. These results show the importance of the inverse barometric correction, especially when MSL trend are based on short-term data series.

The analysis made over the corrected daily data enables the observation of the annual variations causing an up shift of 5 to 7 cm between Autumn and Winter and a down shift of about 5 cm from Springer to Autumn (Figure 2). In numerical terms such annual oscillation is modeled by a moving average of 60-days period, which shows clearly this effect that occurs each year with different amplitude and length. This annual oscillation of the mean free sea surface can be related with the wind regime that affects the sea surface at the west cost of Iberia Peninsula (BRINK, 1998; RELVAS *et.al.*2007) and with changes due to density variations of sea water and due to water mass redistribution within the Earth system (CHEN *et al.* 2007).

These types of variations make difficult any tentative to compute the SLR based in a short-term series of tide gauge data. The analysis over SLR estimates from this data revel that each data series (uncorrected, corrected and the moving average over the corrected data) have shown different values. Nevertheless, the moving average presents a more coherent value when compared with the rate of last decade of 1990 (2.1 mm yr^{-1}). Still, due to the short period of data available, from November of 2003, the estimated rate by the linear regression over the 60-day moving average data turned to be very sensitive, to the inclusion of new data. Therefore, it was concluded that additional data was necessary in order to find a more reliable rate value.

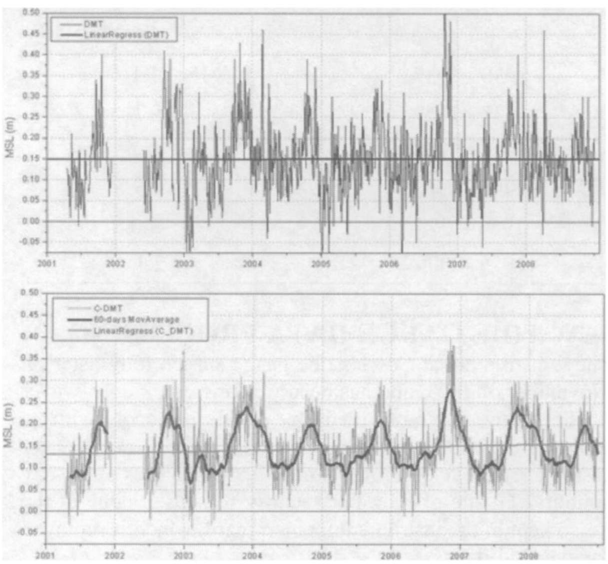

Figure 2. a) Raw daily Mean Tide; b) corrected daily Mean Tide by the inverse barometric effect and the respective 60-days moving average (regression lines are shown in both graphs).

Taking the advantage of having in the area one of the oldest meteorological station, from the Geophysical Institute of Dom Luis (IGDL), with a long data series of air-pressure, it was possible to transfer the air-pressure data to Cascais, by an estimated constant of +12 mbar, and apply it to the older tide gauge data. Using this simple approach, it was possible to recover and attach the missing 2003 data and part of 2001 and 2002. It has been difficult to recover earlier data, because by that time the older tide gauge operation was often interrupted due to the construction of the new marina of Cascais.

With this additional data, the estimation became more stable and the resulted rates of RSL rise more consistent.

At the present date, with the year of 2008 complete, the estimated rates by a linear regression fitting (in Figure 2) are:

- raw daily MSL data 0.2 mm yr^{-1}
- corrected daily MSL data 3.3 mm yr^{-1}
- 60-days moving average 2.5 mm yr^{-1}

To determine the relative vertical movements, the IGP had been measuring the relative vertical displacements of the new tide gauge by spirit leveling observations between the gauge and the IGS permanent station of GPS. Only the first six months after the installation of the gauge it has been detected a great vertical displacement of -36 mm. After that, the structure has shown a great vertical stability. The IGP has been correcting immediately any vertical movements detected, by changing the datum offset on the data. So, to any displacement detected one just has to introduce, from the last to the new leveling observation date, a linear date-ratio correction to the respective daily mean tide level. This was done to the data of the first six months of the new tide gauge data series. After that, only minor displacements have been observed (less than 1 mm) which does not justify a correction.

ACCELERATION OF SLR AT CASCAIS

Assuming that the correct daily MSL data gives an acceptable estimate of present sea level trend, an increase in the rate of SLR at Cascais tide gauge from the last to the present decade can be inferred. Making a simple test by estimating rates in the period of 1977 to 2008, over the smoothed data series within successive periods of range, it shows a successive increase of the SLR rate running from 1.9 to 2.9 mm yr^{-1}. These results support the existence of acceleration in the SLR at Cascais tide gauge.

Consider the estimated rates of 2.1 mm yr^{-1} for 1990 and 2.5 mm yr^{-1} at 2008, the acceleration value of 0.024 mm$\cdot$ yr^{-2} (2.4 mm/year/century) can be determined.

The rate of 1990 was estimated by a linear regression fitted to the 10-year moving average, resulting in a standard error of 0.1 mm yr^{-1}. For the rate of 2008 the estimation of the standard error resulted in a worst value, 0.3 mm yr^{-1}, due to the high annual variations presented on the 60-days moving average of the corrected daily MSL data. With such errors, the acceleration of SLR at Cascais was estimated with an error of 0.018 mm yr^{-1}. It is believed that this error will become smaller after the present decade will be completed.

DEDUCING THE ABSOLUTE SLR

The direct estimates from the tide gauge of Cascais result in relative values of SLR, since it provides sea level variations with respect to the land which it lays. To obtain absolute values, which may correspond to the global sea level rise (GSLR), the absolute vertical movements of the tide gauge must be considered.

Since the tide gauge of Cascais is located near an IGS permanent station of GPS, the absolute vertical movements can be derived by the vertical velocity estimated for the GPS station and the leveling made between both locations.

Extracting the GIA component of the vertical movement for this location from the model ICE-5G of PELTIER (2004), the value of 0.0 mm yr^{-1} is obtained. Therefore, any vertical movement found by GPS or other geodetic technique must result only from tectonic activity.

Consulting the cleaned time series solution of EUREF website (http://www.epncb.oma.be), we have found different estimates for the absolute vertical velocities for the site. The solution published on April 2008 corresponded to -1.3 mm yr^{-1}, while the new solution, published on October of 2008, corresponds to 2 mm yr^{-1}, both referred to ITRF2005. It is not yet clear the reason why the EUREF solution has changed so much (from a negative to a positive velocity), but certainly has to do with different processing approach.

Taking into consideration the two EUREF estimates of absolute vertical velocities and adding up the present estimated rate of 2.5 mm yr^{-1}, it gives two quite different absolute rates of SLR, 1.7 and 4.5 mm yr^{-1}, respectively. These estimates are quite different from the most reported global rate of SLR, and are also far away from the reported rate of 3.0 mm yr^{-1} by IPCC (2007).

It seems that short data span is still a problem in the geodetic technology of GPS to solve accurate rate measurements of vertical land movements at tide gauges. If precision is not a problem for GPS because the plenty data available in short-term, the presence of certain systematic influences may be the reason for such inaccuracy.

Considering a different approach, we have compared the 20-year moving average of tide gauge data set of Cascais with the global SLR model of JEVREJEVA *et.al.* (2006). The comparison resulted in a trend difference rate of 0.5 mm yr^{-1}, which certainly must be related to a uplift of Cascais site. Assuming this as a vertical velocity of 0.5 mm yr^{-1}, apart from the -36 mm shift of relative vertical displacement verified by leveling that occurred between 2003 and 2004, and which is related with stabilization of the built structure, the absolute rate of SLR becomes exactly with value of 3.0 mm yr^{-1}.

In the Table 2 it is represented the three possible scenarios, which combines the present relative rate o SLR at Cascais and the three hypotheses of absolute vertical movement for the site. The first two hypotheses for the vertical velocity (S1 and S2) seems to be incompatible with the tectonic setting of the region, where long-term tectonic uplift is estimated to be less than 0.1 mm yr^{-1} (CABRAL, 1995).

These results reinforce the idea that Cascais tide gauge data is consistent with the Global Sea Level trend, supporting the use of the global estimates of future sea level change for this region.

Table 2: Absolute rates of SLR at Cascais Tide Gauge, from 3 different vertical velocities estimates.

Solutions	Source	Vert. Velocity (mm yr^{-1})	SLR Rate (mm yr^{-1})
S1	EUREF Apr2008	-1.3	1.7
S2	EUREF Oct2008	+2.0	4.5
S3	Comparing GSLR	+0.5	3.0

PROJECTING THE SLR FOR THE FUTURE

One of most important contributions of sea level studies is to improve sea level projections for the future. This can be done essentially by two different methods: 1) using emissions scenarios and numerical models of ocean and atmospheric circulation to compute future sea levels, and 2) extrapolate for the future the behavior found in existing data. While the former methods have a greater potential as they rely on a processes based approach, the uncertainties in their results is still very large as much of physics involved is still poorly known (see MÖRNER, N.A., 2004 for a discussion reference). The later kind of approach, despite their intrinsic empiricism, still provides a valuable tool to test existing projections.

The results obtained in the scope of the present work enable a preliminary projection of relative sea level rise for the next decades which are compatible with an acceleration scenario.

With this estimated acceleration and the respective rate for 1990 is possible to project the RSL for Cascais tide gauge, running from 1990 to 2100 and fitted to the present values of MSL. This projection indicates a MSL for Cascais, relative to 1990, of 47 cm in 2100 with a 95% confidence interval between 19 and 75 cm.

The comparison of the present SLR projections with the IPCC (2001, 2007) estimates for the 2100 time frame (in Figure 3) revealed a reasonable agreement, which is quite remarkable considering the simplicity of the model used in this work. This means that the forcing, that is driven present sea level acceleration, is expected to be kept, more or less, constant through the 21st century. This assumption has been questioned by several works; for example, Ramhstorf (2007), using a semi-empirical relation that connects global SLR to the global mean surface temperature, predicts a much higher elevation.

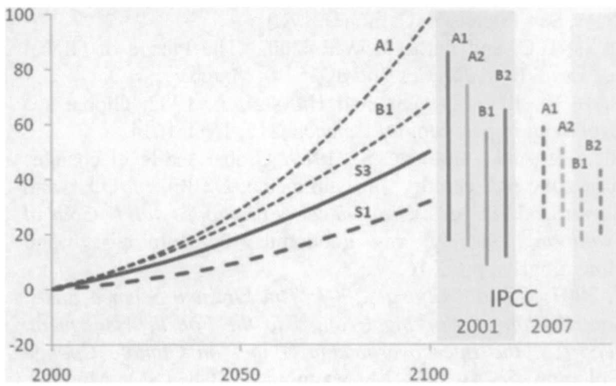

Figure 3. SLR projections (in cm) obtained in the scope of the present work (solutions S1 – long dash and S3 – solid line) overlapped with Ramhstorf (2007) (A1 and B1 dashed lines) and IPCC (2001, 2007) estimates using emissions scenarios A1, A2, B1 and B2.

CONCLUSIONS

The discussion of the different approaches is out of the scope of this work, although, it must be stressed that this kind of study can be used as a valuable tool to understand past changes and therefore build the foundations to predict future changes.

As it has been referred, the results reinforce the idea that Cascais tide gauge data is consistent with the Global Sea Level trend. Nevertheless, it is necessary to achieve a better knowledge of the local tectonics, with accurate vertical velocities, to obtain a more reliable absolute SLR for the region.

Since the values of the missing data on the years of 2001 and 2002, which would complete the data series of the present decade, are lower than the actual mean sea level (14.5 cm), it is expected that the presented rates of relative SLR at Cascais are underestimated. It is also expected, that when the data of the present decade will be completed, in 2010, better and more reliable estimates will be obtained through this analyses.

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