EVREST Project Report:
Analysis of Sea-Level Rise

EVREST Evolution and Resilience of Barrier Island Systems

Project Funding: Fundação para a Ciência e a Tecnologia (FCT)

Scientific Domain: Marine Sciences and Earth Sciences - Estuarine Coastal and Littoral Systems

Project reference: PTDC/MAR-EST/1031/2014

Report Title	Analysis of Sea-Level Rise
Reporting Period	01/11/2016 to 31/10/2017
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Delivery Date	10/09/2019
Related Task	Task 1: Data collection and GIS integration; T1.1. Compilation of existing datasets and data acquisition Task 2: Quantification of hydrodynamic and morphologic variables; T2.2. Analysis of relative sea-level variations
Participants	Carlos Antunes, Fábio Madeira, Rui Taborda

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Funded by FCT Fundação para a Ciência e a Tecnologia

Project reference: PTDC/MAR-EST/1031/2014

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1. Introduction

This report covers the activities performed in the framework of the following tasks: 'Task 1: Data collection and GIS integration', subtask 1.1. Compilation of existing datasets and data acquisition; and 'Task 2 – Quantification of hydrodynamic and morphologic variables', subtask 2.2. Analysis of relative sea-level variations. The objectives of these tasks were the analysis of tide gauge records and local sea level observations collected by pressure transducers well referenced to the national vertical datum, with comparison to tide gauge data, to evaluate the present sea-level rise rate and its acceleration for future projections. The team possess century-long records of Portuguese tide gauges (e.g., Cascais tide gauge), which will serve as reference for sea level rise rates of the region.

These tasks were programmed for a duration of 12 months (T1) and 12 months (T2), and subtasks T1.1. and T2.2., to which this report refers, were coordinated by Carlos Antunes.

Activities and results are described in detail in sections 3 to 5, including references to publications and websites.

This report provides information about a project deliverable (Milestone 2 of the proposal, tasks and milestones here: https://evrest.cvtavira.pt/about-evrest/project-tasks/), which is M2 – Time-series of mean sea-level for Lagos tidal gauge.

One of the main goals of the Task was to evaluate sea level rise (SLR) rates at Lagos Tide Gauge (LTG) and compare it to Cascais Tide Gauge (CTG) rates, to assess the differences and the behaviour of SLR between the two Atlantic coastal regions, west and south coast. At the same time reference sea level between LTG and Ria Formosa.

To attain the main goals, firstly, the complete century-long time series of LTG had to be collected, validated and reanalysed, secondly, observation between LTG and Faro region had to be carried out to establish the vertical reference of tides and compare mean sea level of both sites.

Data from satellite altimetry and information from time series of Lagos permanent GPS station must be used and analysed to evaluate and assess the absolute SLR comparison of the region, based on the scientific knowledge of regional geological uplifting. Conclusion must be made only on the results' consistency bases.

2. MONTHLY SERIES OF MSL

The analysis of the monthly data series was made in two steps: the processing of data from the period 1908-1987, from the Permanent Service of Sea Level (PSMSL) dataset and from the 1986-2000 period dataset of the Direção Geral do Território (DGT).

2.1 SERIES 1908-1987

The PSMSL official link http://www.psmsl.org/data/obtaining/stations/162.php was accessed to download the LTG dataset. Revised Local Reference (RLR) used by PSML was removed to turn the vertical reference compatible to local MSL.

Some old tide graphs from DGT were digitalized and a few month daily tides were obtained to validate data and vertical reference. LTG infrastructure interventions for repairing and relocation of LTG, due to an extreme storm in the end of 1950' decade, were verified and levelling data series was checked to access the vertical reference data quality and consistence.

The behaviour of LTG mean sea level, along the data set period, is consistent with CTG mean sea level (Figure 1) and the total mean sea level rise is of same order.

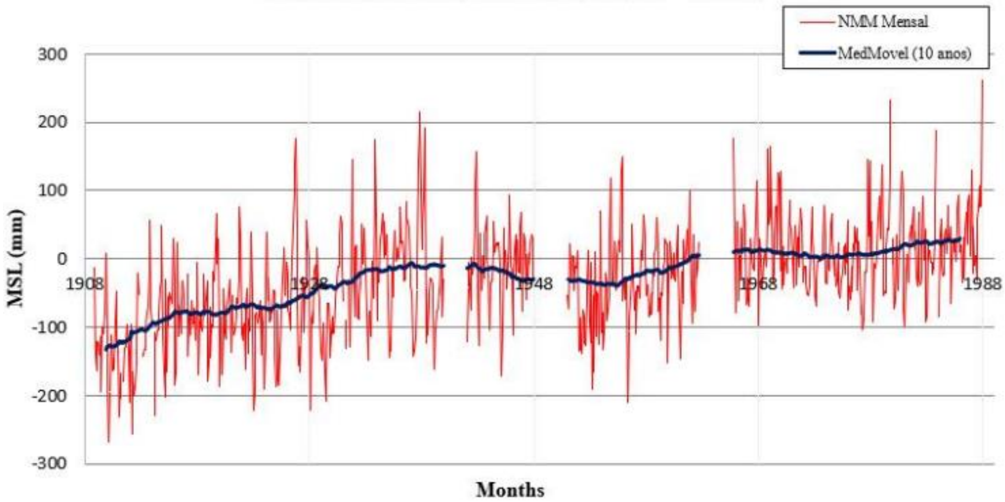

Figure 1: LTG mean sea level time series for the 1908-1987 period.

2.2 SERIES 1988-2000

A file provided by the DGT with the hourly mean tide enabled the daily and monthly average computation for the period 1988-2000, to complete the old tide gauge secular series for the XX century. This was the whole observation period for this analogue tide gauge. From free data available at University of Hawaii Sea Level Centre, the reference information of the 1988-2000 LTG series was considered for vertical reference and the series reconstructed.

The hourly tidal series was organized and processed in order to make the daily average and, consequently, the monthly average. Thus, being possible to obtain its mean sea level and the respective moving average (24 months). However, some anomalies were detected at beginning of the 1988-89 period.

The detected over-elevations, in the order of decimeters relative to MSL, were compared to the astronomical tide model to assess expected errors possibly related with vertical reference bias. Through the comparison with the astronomical tide model, together with the correlation between storm surge and atmospheric forcing, by access to the meteorological models for the region, it was possible to detect and assess the anomalies. Therefore, the respective errors were found and

assessed. A restricted numerical treatment was performed, and a corrected series was obtained with a realistic and compatible behavior. Figure 2 shows the corrected series after detected anomalies have been corrected.

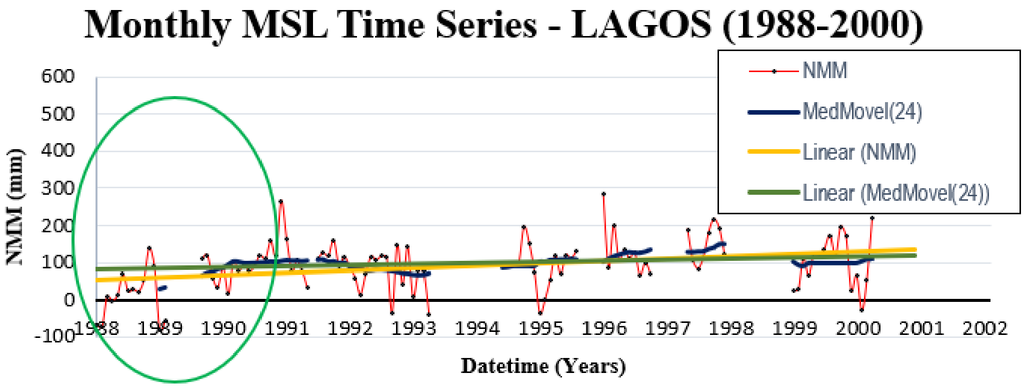

Figure 2: LTG time series of monthly averages, overlapping with a 24-month moving average and respective linear regression (after corrected anomalies).

3. Daily MSL series

Once the available data made possible the daily mean sea level assessment, the daily series was processed and considered in the study of SLR.

The harmonic analysis enables the estimation of the harmonic constituents and the assessment of storm surge events through the residual component. The main purpose of hourly tide series harmonic analysis is to build a reliable tide prediction model and storm surge estimation. The results of such strategy were used to enable the data error detection of the hourly tide series to obtain a reliable daily MSL series.

3.1 Series 1988-2000

The treatment performed in this series was very similar to the treatment performed in the monthly series. Harmonic analysis of hourly time series and atmospheric data were used to correct the error of the first two years of this data series.

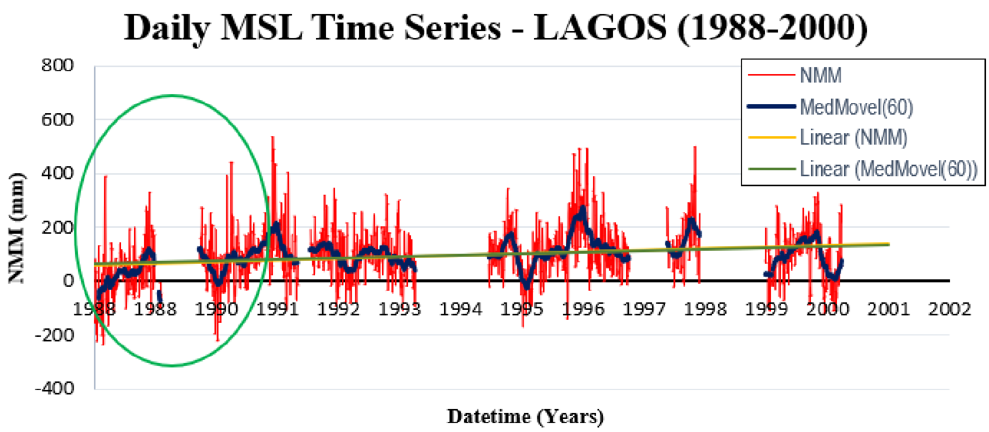

Figure 3: Lagos tide time series of daily averages, overlapping with a 60-day moving average and respective linear regression (in millimetres), after errors correction made.

3.2 Series 1908-2000

One of the main objectives was to join the data MSL series [1908, 1987] and [1988, 2000]. By comparing the common years between the two series (1987-88) and adjusting the overall vertical reference of the series (MSL 1908-1917), it was possible to arrive to the Lagos time series of MSL between 1908 and 2000 (Figure 4).

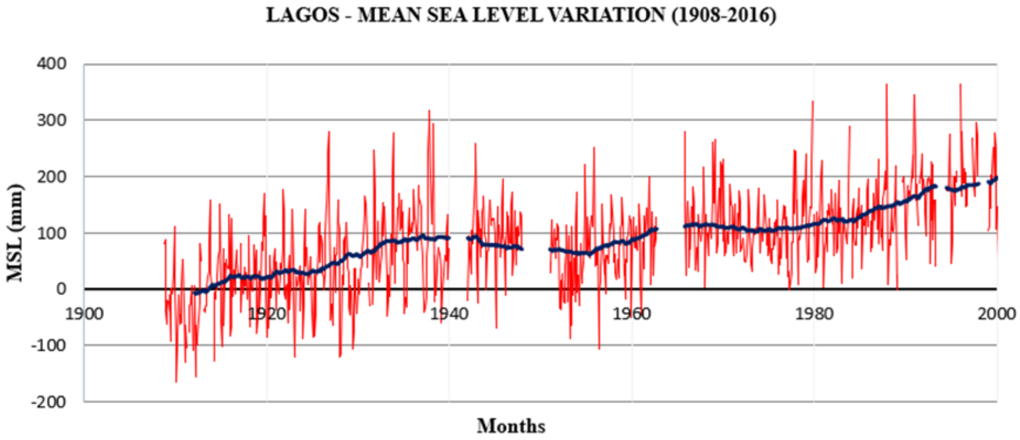

Figure 4: Lagos time series of monthly averages (in red) and 24 months moving average (in blue), between 1908-2000.

Therefore, from the completed data series 1908-2000 it is possible to observe that MSL has risen in the last century (90 years) about 20 cm, corresponding to an average rate of 2.2 mm/yr.

3.3 Series 2004-2016

Initially this series would include the years of [2000: 2003]. This interval resulted from a digitization process performed from raster images of tidal graphs provided by the DGT Geodesy department. However, when georeferencing tidal graphs for this range, it was observed that those years were incomplete, and the existing data presented several problems at the technical level of the tide gauge.

In order to obtain greater accuracy of daily data for the most recent years, 3 corrections were applied, the local vertical velocity correction, the Inverse Barometric Effect correction (IBE) and the seasonal variation.

Using geometric leveling observations made by DGT Geodesy services, it was possible to recover relative vertical velocity corrections, which were applied to the observed daily MSL data series (Table 1).

Table 1: Orthometric altitude variation of the acoustic tide reference level mark (ΔH - annual altitude change; ΔH / Δt - annual vertical velocity in mm / year).

Years	2004	2006	2007	2014	2015	2016
H (m)	2.933	2.934	2.933	2.931	2.931	2.931
ΔH (mm)	-2.2	0.4	-0.6	-1.8	0.0	-0.2
ΔH/Δt (mm/year)	-0.20	0.18	-0.64	-0.26	-0.02	-0.25

Correction of the daily MSL values due to settlement was performed by direct adjustment based on the annual vertical velocity values resulting from leveling. Failure to correct this error would lead to errors in the SLR rates.

The following graph (Figure 5) represents daily average tidal values, only corrected from structural settlement effects.

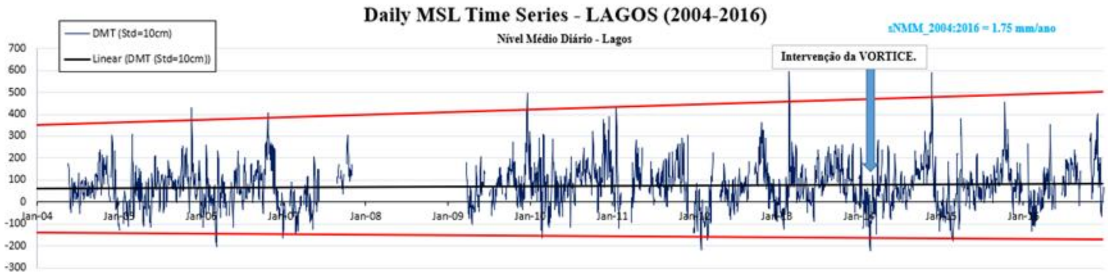

Figure 5: Lagos daily MSL series (in meters and with 10 cm of SD), between 2004 and 2016.

The maximum and minimum red limits identified in Figure 5 serve to identify the trend of extremes of daily MSL. These trend lines identify the increase of maximum extremes in the MSL variation, thus corresponding to the occurrence of storm events. The observed SLR rate is 1.75 mm/year, which by comparing to other adjacent stations for similar periods, is underestimated. It is possible to observe in Figure 6 the difference of the respective MSL series between the Lagos and Cascais tide gauges.

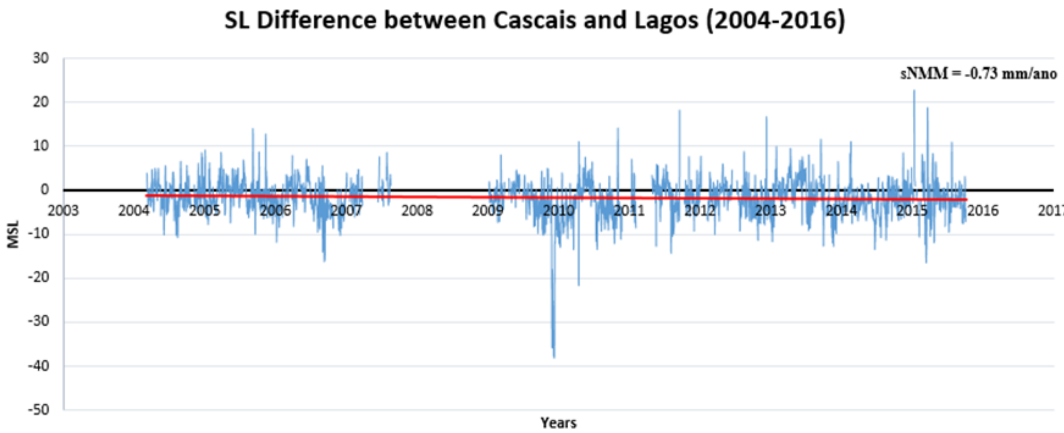

Figure 6: Sea level differences between Lagos and Cascais tide gauge daily MSL series.

The figure above tells us that the difference in MSL between Lagos and Cascais tide gauges increases over time. In order to find answers to this problem, GPS and tectonic data were used. GPS indicates a subsidence rate around 0.5 mm/year for Lagos, however tectonic data from several surveys refer to an uplift.

The next step was the IBE correction to the daily MSL series. Initially, an instrumental drift was detected in the digital barometer of the tide gauge, which caused an overestimation of 1.46 mm/year. In view of this and before any rectification or replacement through the Air Pressure (AP) values of the series was possible. The AP value, for which the IBE was calculated, was obtained by a 2-year moving average instead of the global mean barometer data for the Lagos tide gauge. The following Figure 7 shows the range of AP variation corrected MSL daily averages.

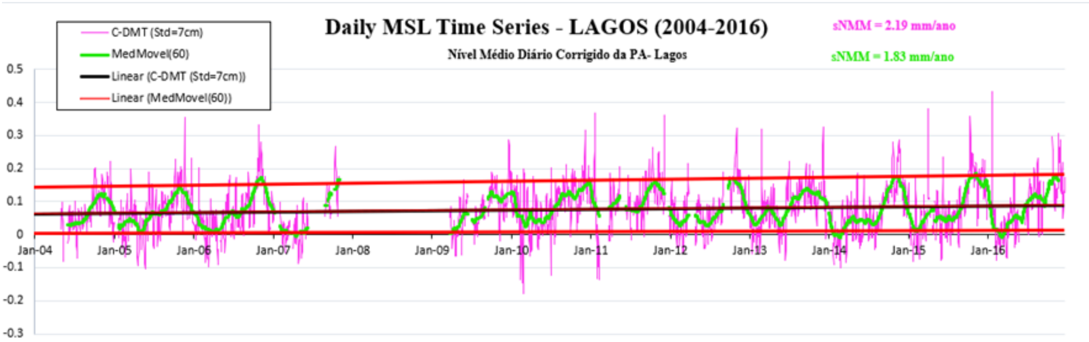

Figure 7: Lagos daily MSL series (meters and 7 cm SD) corrected by the IBE and respective 60-day moving average.

The 60-day moving average overlapping the series gave us the annual MSL change excepted from short-wind wind period variations.

The last step was the correction of seasonal variation. MSL intra-annual variation shows a pattern of variability, with which maximum values can be observed in the last quarter of each year and minimum values from May to July. Seasonal tidal variation, namely the annual harmonic component of the solar influence tide (SA) is a parameter to be considered (Figure 8).

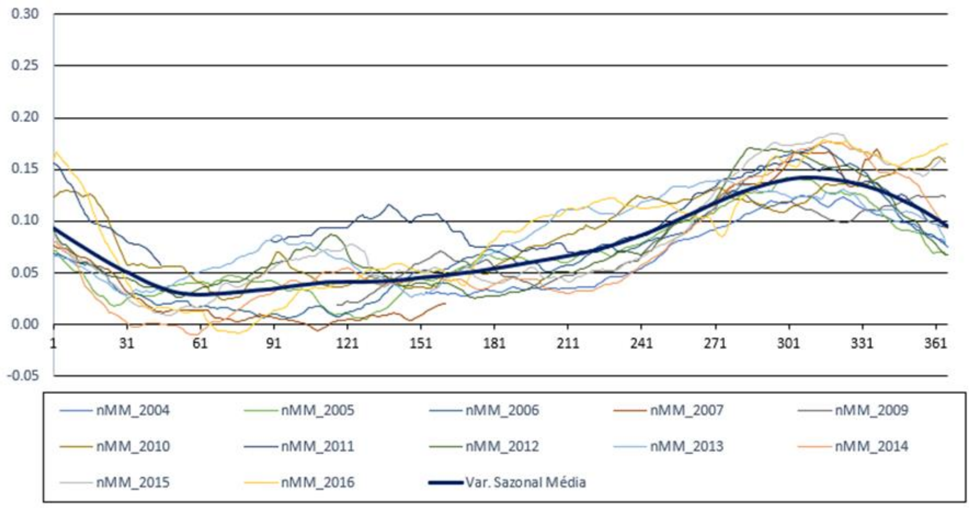

Figure 8: Seasonal MSL variations (in meters) from 2003 to 2015 and average change (bold).

Figure 8 shows the seasonal variations of the last 12 years, which allows to determine the average seasonal variation of MSL. Removing this seasonal variation average from the AP corrected MSL daily average, results in a reduced series (Figure 9) close to what may be called relative eustatic variation.

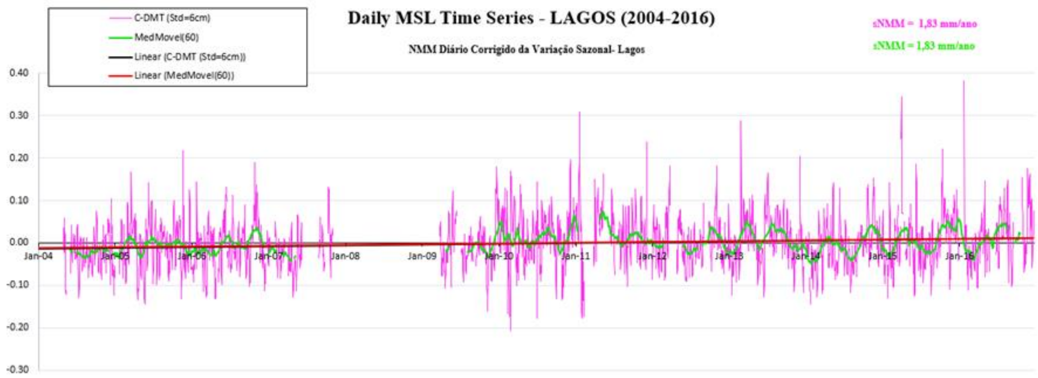

Figure 9: Reduced seasonal variation MSL series (in meters and 6 cm of SD) and respective 60-day moving average with the respective linear regression.

This reduced MSL variation has significantly lower intra-annual variability; however, the SLR rate remains unchanged at 1.83 mm/year. Table 2 shows the SLR rates and standard deviations for all the above series.

Table 2: Data series variability (SD in mm) and SLR rate (mm).

Series	SD Series (mm/year)	SLR rate (mm/year)
Original	9.6	1.8
IBE Corrected	7.2	2.2
MA60days_cor	4.7	1.8
Reduced	5.8	1.8
MA60days_red	2.3	1.8

Due to this contradiction in results, the Physical Oceanography Distributed Active Archive Center (PODAAC) database was accessed to obtain Sea Surface Height data. The average ocean surface has a topography, an irregular variation, much like what it is seen on a topographic map. These variations can be mapped using direct (satellite) or indirect sea surface elevation measurements relative to the Earth Geoid. Several locations were chosen along the Portuguese coast in order to get a clearer idea of the behavior of the ocean surface along the Portuguese coast and southern Spain. The period used was, according to the available data, the closest to the series under study (Figure 10), so the rates presented in Table 3 do not deviate much from the expected values.

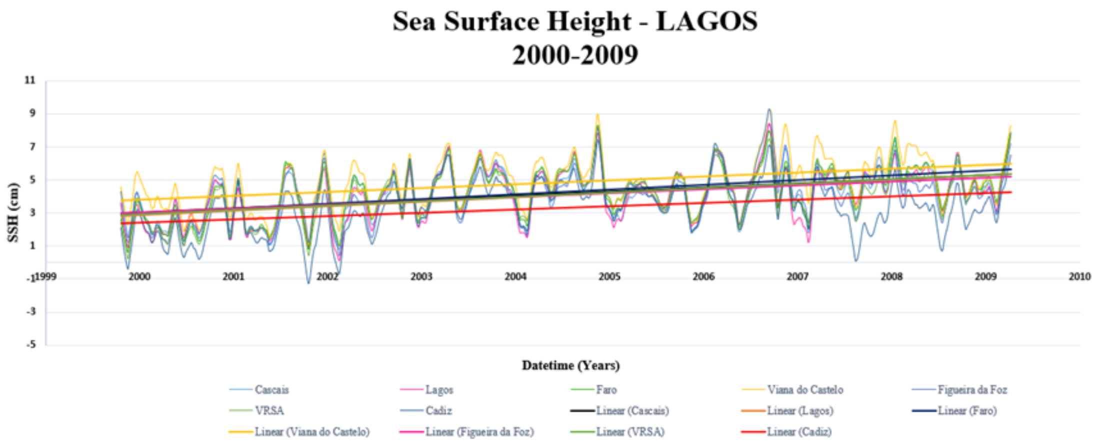

Figure 10: Time series of sea surface height anomalies (Viana do Castelo, Figueira da Foz, Cascais, Lagos, Faro, VRSA and Cadiz), from 2000 to 2009.

From the figure above and Table 3 it is possible to observe a common pattern between the various locations used, that is, if there is offshore the Portuguese coast an average sea surface elevation rate of around 2.13 mm, it would be expected to observe in Lagos a very close value for SLR rate.

Table 3: Sea Level Rates based sea surface height anomalies from satellite altimetry data.

Local	Viana do Castelo	Figueira da Foz	Cascais	Lagos	Faro	Vila Real Sto António	Cadiz
SLR (mm/year)	2.13	1.83	2.13	2.13	2.43	2.13	1.52

5. FIELDWORK CAMPAIGNS

To validate the MSL difference along the south coast of the Algarve, two tide observation campaigns were undertaken in three locations: Lagos (Cais da Solaria), Albufeira (Porto de Abrigo) and Barreta Island (ferry boat landing dock, at western Faro-Olhão Inlet jetty). The fist fieldwork campaign took place between 26 March 2017 and 1 May 2017. The second campaign took place between 19 September 2017 and 21 October 2017. Details about these fieldwork campaigns can be found in specific reports here: https://evrest.cvtavira.pt/about-evrest/project-deliverables/.

Three pressure transducers were deployed to measure the sea-levels, connected in elevation by GPS (including the regional geoid model), and so establish Mean Sea Level relation between locations.

6. Final remarks

One of the main remarks from this study is that the current SLR rate in Lagos tide gauge is underestimated, and instrumental problems of the tide gauge are suspected.

The monthly series [1908-1987] and [1988-2000] were handled and error corrected, allowing them to be combined into a single series of monthly averages with a 19.8 cm rise in relative MSL over this 90-year period estimated by the moving average of 10 years.

Access to historical documentation of the Lagos tide gauge in the DGT Geodesy archives allowed some data to be corrected for local leveling. The use of old tidal graphs for georeferencing made it possible to compare data from various sources with tide gauge data.

The most recent series (2004-2016), after correcting local vertical velocity, corrected for inverse barometric effect and reduced by seasonal variation, presents a discordant SLR rate from other sources of information. In both satellite and other tide gauge observations in the region, SLR rate is around 3 mm/year. There is some uncertainty about possible vertical movement of the location where the tide gauge is installed. The GPS indicates that Lagos is in subsidence with a vertical velocity rate of 0.5 mm/year, while neotectonics studies, by contrast, indicate that there is an uplifting on the southwest Algarve coast of around 0.1 to 0.2 mm/year.

Harmonic analysis made it possible to detect and correct a set of problems for the daily series 1986-2000 and 2004-2016. In the case of the first series an overestimation of around 20 cm was detected in some monthly averages of the first years. In the 2004-2016 series, it was possible to correct a problem involving the omission of tidal highs and lows. This made it possible to achieve tidal and overcapacity maximums for the period 1986-2016, although they still require more detailed validation.

Campaigns for sensor placement, with the objective of correcting and calibrating the measurements obtained from the Lagos tide gauge, give an idea of the problems that may exist in the Lagos tide gauge. However, it is still early to draw conclusions since the data need more detailed treatment.

It was also envisaged that a database would be set up that would imply a systematic tide data processing model. However, time did not allow this task to be carried out given the numerous problems that the Lagos tide gauge data provided.

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