Journal of Coastal Research	SI 64	pg - pg	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Monitoring sea level change at Cascais tide gauge

C. Antunes†
† IDL
University of Lisbon,
Lisbon, 1794-016
Portugal
cmantunes@fc.ul.pt

ABSTRACT

Antunes, C., 2011. Monitoring sea level change at Cascais tide gauge. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), pg – pg. Szczecin, Poland, ISSN 0749-0208

Sea level change (SLC) real-time monitoring has being developed and improved for the Portuguese tide gauge, based in FTP access to the internet server of the Portuguese geographical institute. A software application, named *MareVB* and in development since 2008, gets a 3 minute stream input of sea level height and a 10 minute stream input of air-pressure. Based on a predicted tide model, the sea level height is compared and analyzed, and storm-surge amplitude is determined, as well as the high frequency oscillation (seichas) due to the storm and tsunami waves. Using such real-time SLC data analysis, the application is now running as a coastal hazard warning system, emailing automatic warnings in real-time to national authorities and to other institutions and coworkers, where the levels of coastal hazards of SLC are considered. A post-processing monitoring of SLC is also performed and a time series is evaluated and actualized. Such SLC time series enables the statistics of storm-surges and the determination of the sea level rise rate associated to the global climate change and other regional phenomena. The computational methodology, the application for real-time monitoring and the statistics of storm-surges at Cascais for the period of last 10 years are presented here.

ADITIONAL INDEX WORDS: *Sea level change, real-time monitoring, storm-surge, Cascais tide gauge*

INTRODUCTION

The modern tide gauge with an internet connection available allows a permanent and real-time monitoring for Sea Level Change (SLC), caused by atmospheric and oceanic forcing, namely, the storm-surges and the seismic and meteorological tsunamis. Based on adjusted and precise tide models and through an application connected by FTP to a tide gauge, it is possible to monitor in real-time the sea level variation due to different causes and send email warnings to the national institutions for rescue and civil protection. The FTP access to the Cascais and Lagos national tide gauges has enabled this strategy for SLC monitoring, where every storm, surge, and even a meteo-tsunami has been detected in Cascais since the application *MareVB* started to be developed in 2008 at the FCUL (*Faculdade de Ciências da Universidade de Lisboa*). Due to its capability to send automatic email warnings, this application has become a coastal hazard warning system for SLC events. Recently, new facilities have been added to the *MareVB* application, a warning information table with surge elevation and sea oscillation values, and a tide graph are created every 20 minutes and then sent to the FCUL tide webpage (Antunes, 2007), enabling the visualization and updating of data related to SLC at these two Portuguese tide gauges.

For each day, a post-processed monitoring of the mean SL (MSL) and the respective surges associated to the ongoing storms is also preformed. This pos-processing, done outside the *MareVB* application, is mainly performed to determine the evolution of the Sea Level Rise (SLR), although, the daily storm-surge amplitude and respective statistics are also determined. This statistics enable the study of the evolution of such events, in amplitude and frequency, and the possible association to the global climate change and other eventual regional forcing phenomena.

This paper presents the computational methodology, as well as the application for real-time monitoring and the email warning system. It also presents the statistics of the storm surges at Cascais along the last 10 years**.**

PRECISE HARMONIC TIDE MODEL

The actual amplitude of storm surge, due to meteorological effects, is determined by comparing directly the instantaneous sea level height with a precise harmonic tide model. This is the principle of the *MareVB* application, where achieved precision of 2 cm of the harmonic tide model for the respective tide gauge plays a very important role, since it contributes for the reliability of the SLC monitoring.

Such tide model for the Cascais tide gauge was evaluated based on hourly data from 2007. The numerical model was determined by harmonic analysis through the least square adjustment (LSA), where the correspondent parametric model is composed by a maximum of 37 local harmonic constituents (amplitude, H_i, and phase lag, g_i), with the additional amplitude of the zero order harmonic constituent (Z_0), corresponding to the actual MSL referred local tide datum.

Mathematically, the harmonic model, according to Godin (1972), assumes that the one-dimensional time series of astronomic tide can be expressed by

$$Z(t) = Z_0 + \sum_{i=1}^{n} f_i(t_0) H_i \cos\left(\omega_i (t - t_0) + V_i(t_0) + u_i(t_0) - g_i\right) \quad (1)$$

Where, $Z(t)$ is the measured tide height; f_i and u_i are the nodal corrections to amplitude and phase for the constituents $i=1,...,n$ with frequency ω_i: and, V_i is the astronomical argument at the initial instant t_0 (00:00 of 1 of January of each year).

Either by harmonic or by spectral analyzes it can be verified that a certain number of harmonic constituents are absent or mixed with the noise data, which implies only 24 harmonic constituents to be estimated by LSA at the Cascais tide gauge.

In the present case, for each harmonic constituent, the parameters *f* and *V* are known and evaluated for each year, and the long term nodal argument, *u*, is assumed as a small and negligible constant. Thus, the linearization of the function model (1), due to the need of a fast convergence of the unknown local phase arguments, rather than the usual Taylor series expansion, must follow a variable change approach, such as

$$X_i = H_i \cos(g_i);\ \ Y_i = H_i \sin(g_i) \qquad (2)$$

Transforming (1) into

$$Z(t) = Z_0 + \sum_{i=1}^{n} A_i X_i + B_i Y_i \qquad (3)$$

where,

$$\begin{aligned} A_i &= f_i \cos(\omega_i(t - t_0) + V_i(t_0)) \\ B_i &= f_i \sin(\omega_i(t - t_0) + V_i(t_0)) \end{aligned} \qquad (4)$$

After applying LSA to the functional model (3), the original parameters, H_i and g_i, can be recovered from the estimates X_i and Y_i, by:

$$H_i = \sqrt{X_i^2 + Y_i^2};\ \ g_i = arctg\left(\frac{Y_i}{X_i}\right) \qquad (5)$$

Being Σ_{Hg} the respective variance-covariance matrix obtained by the following transformation

$$\Sigma_{Hg} = J_{Hg} \Sigma_{XY} J_{Hg}^{T} \qquad (6)$$

where J_{Hg} is the Jacobean matrix of (5), a bloc diagonal matrix composed with the H_i and g_i derivatives in respect to X_i and Y_i.

This linearization approach avoids the need of a good initial set of parameters (local harmonic constituents) close to the final adjust solution of LSA (as it would have happened if a Taylor series expansion had been used for linearization of the function model), enabling a fast convergence of the phase component.

The strategy that was used to correct data from known effects, to correctly fit function model (1) to the data, such as air-pressure and wind forced surges (atmospheric tide), and the seasonal variation of MSL, was determinant to achieve a good accuracy and precision into the tide model. The tide height was corrected from the inverse barometric effect (IBE) expressed in equation (7), using the theoretical rate of -1 cm/mbar (which closely agree with the Cascais data correlation), where the mean value of the air-pressure in 2007 was assumed to be 1019 mbar (hPa).

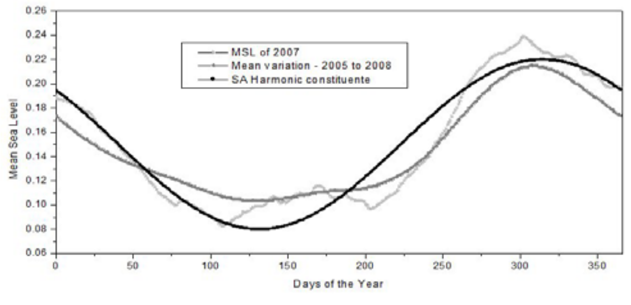


Figure 1. Seasonal variation of Cascais MSL from 2005 to 2008; MSL of year 2007; and, fitted SA harmonic constituent.

$$Z'(t) = Z(t) - \frac{1019 - AP(mbar)}{100} \qquad (7)$$

The residual atmospheric effect caused by wind spread was removed by a numerical residual function, based in a daily centred moving average of the previous remaining residuals (after all effects have been removed), representing a corrective trend function. Finally, the seasonal variation of MSL was independently estimated by the annual harmonic constituent (SA – solar annual) adjusted to a seasonal variation average for a period of 4 years, from 2005 to 2008 (Figure 1), and removed from the tide height data.

The annual harmonic constituent, SA, estimated outside of LSA, includes in its own constituents, the amplitude and the phase tag, all the seasonal variation of the tides, i.e., the astronomic component (solar annual) and the atmospheric wind regime influence (Antunes and Taborda, 2009; Relvas *et al*., 2007). This harmonic constituent is, in this way, LSA-independently estimated and converted to a dependent variable in the LSA model (3).

After all the known correction effects had been applied, the residuals, with amplitude less than 10 cm, showed up to be a white noise with a normal distribution (Gaussian noise). This proves that all non-astronomic tidal effects were correctly removed from the tide height data and that the harmonic tide functional (1) through expression (3) was accurately fitted to the data.

Therefore, the harmonic model obtained for the Cascais tide has a daily precision of 2 cm (posterior mean square error of the LSA) and accuracy greater than 5 cm, after removing the IBE. The mean square error for the estimated parameters (5) resulted, by (6), greater than 1 mm, for the amplitudes, and greater than 0.1º, for the phase arguments. On the respect to the phase, and based on the differences of low and high tide arrival instant to the recorded tides, the tide model was estimated to have less than 3 minutes of error.

Table 1: Main harmonic tide constituents of Cascais tide gauge.

Constituent	Amplitude (m)	Phase tag (º)
M_2	0.991	93.34
S_2	0.346	120.20
N_2	0.212	75.76
K_1	0.069	69.36
K_2	0.098	117.31
O_1	0.061	328.63
SA	0.070	230.00

The seasonal component fitted through the SA harmonic constituent shows a great variability along different years (see Figures1 and 3). This variability supports the approach that has been used to fit the SA constituent to a seasonal variation average of several years (from 2005 to 2008). The estimated harmonic model and its error values are daily confirmed, in *MareVB* application, to be an accurate and precise model for its purpose, the daily and real-time monitoring of SLC at tide gauges.

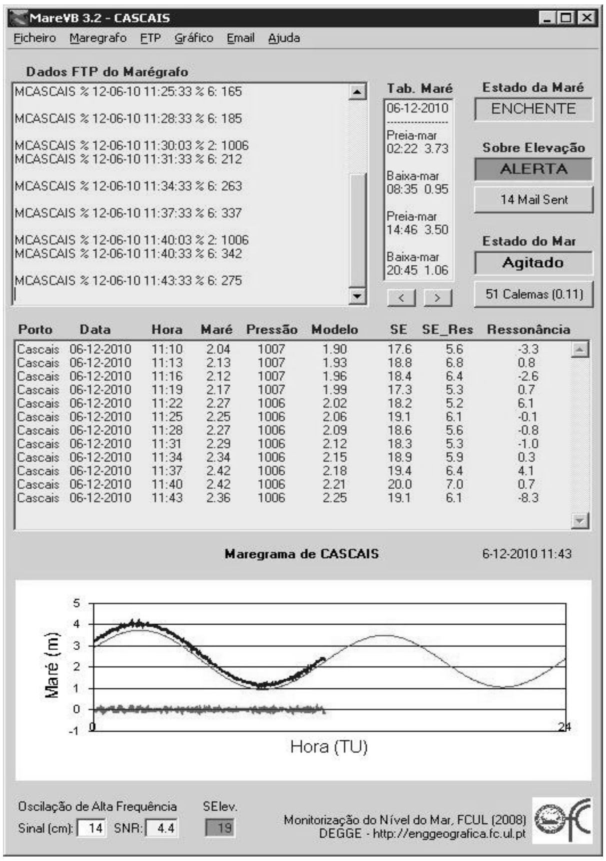
REAL-TIME MONITORING

The application *MareVB*, based on the received Internet Protocol (IP) streams of data sent by tide gauges of IGP (*Instituto Geográfico Português*), started being developed at FCUL in the beginning of 2008, to monitor in real-time the storm-surges that reach the Portuguese coast and any unpredictable event of SLC.

Through a FTP connection, to a selected tide gauge, the *MareVB* application receives two streams, the water level and the air-pressure measured at the gauge site, respectively, at 3 and 10 minute rates. The application converts the water level into tide height, according to the local tide datum (hydrographical zero = 2.08 m at Cascais), and computes the difference to the respective harmonic model height, resulting in the surge of the SL. Depending on the amplitude of the surge, and based in pre-defined warning levels of storm-surge (green, yellow, orange and red), the application sends warning emails to the national institutions for rescue and civil protection, and then forwarded to a mailing list. Additionally, and based on the high frequency of water level oscillation, the application, through an empirical correlation, can estimate the level of sea waves caused by storm winds or by any other excitation source, such as the meteorological tsunami detected on 6-7 July 2010 (Figure 3), on the south coast of Portugal mainland, or any tsunami generated from a ocean seismic source.

The actual version of the *MareVB* application (V3.2) builds a graphical chart of the measured and predicted tides, and the high frequency of oscillation (resonance). Within an interval of 20 minutes, the tide chart and a file-report is sent, by FTP, to the prediction tides webpage of FCUL website (Antunes, 2007), reporting the actual surge sea level warning, wave conditions, water height and air-pressure.

On the Figure 2, the running *MareVB* application window is divided in four main parts: on top-left window - the raw data streams sent by the tide gauge; top-right window - the tide table and the warning levels; centered window - processed tide data; and, bottom window - the tide chart. This figure shows the monitoring of tide gauge of Cascais on the day 06 December 2010, where at that instant a storm-surge of 19 cm was being observed, which was caused by a low atmospheric pressure of 1007 mbar. On the same day, the oscillation of high frequency indicates a SNR (signal noise ratio) of 4.4, with amplitude *seichas* of about 7 cm, indicating a sea storm with relative high waves. At that same time the application had already sent 14 emails of warnings related to storm-surges and sea state.



```
MCASCAIS % 12-06-10 11:25:33 % 6: 165

MCASCAIS % 12-06-10 11:28:33 % 6: 185

MCASCAIS % 12-06-10 11:30:03 % 2: 1006
MCASCAIS % 12-06-10 11:31:33 % 6: 212

MCASCAIS % 12-06-10 11:34:33 % 6: 263

MCASCAIS % 12-06-10 11:37:33 % 6: 337

MCASCAIS % 12-06-10 11:40:03 % 2: 1006
MCASCAIS % 12-06-10 11:40:33 % 6: 342

MCASCAIS % 12-06-10 11:43:33 % 6: 275
```

06-12-2010

Preia-mar
02:22 3.73

Baixa-mar
08:35 0.95

Preia-mar
14:46 3.50

Baixa-mar
20:45 1.06

Estado da Maré: ENCHENTE

Sobre Elevação: ALERTA

14 Mail Sent

Estado do Mar: Agitado

51 Calemas (0.11)

Porto	Data	Hora	Maré	Pressão	Modelo	SE	SE_Res	Ressonância
Cascais	06-12-2010	11:10	2.04	1007	1.90	17.6	5.6	-3.3
Cascais	06-12-2010	11:13	2.13	1007	1.93	18.8	6.8	0.8
Cascais	06-12-2010	11:16	2.12	1007	1.96	18.4	6.4	-2.6
Cascais	06-12-2010	11:19	2.17	1007	1.99	17.3	5.3	0.7
Cascais	06-12-2010	11:22	2.27	1006	2.02	18.2	5.2	6.1
Cascais	06-12-2010	11:25	2.25	1006	2.06	19.1	6.1	-0.1
Cascais	06-12-2010	11:28	2.27	1006	2.09	18.6	5.6	-0.8
Cascais	06-12-2010	11:31	2.29	1006	2.12	18.3	5.3	-1.0
Cascais	06-12-2010	11:34	2.34	1006	2.15	18.9	5.9	0.3
Cascais	06-12-2010	11:37	2.42	1006	2.18	19.4	6.4	4.1
Cascais	06-12-2010	11:40	2.42	1006	2.21	20.0	7.0	0.7
Cascais	06-12-2010	11:43	2.36	1006	2.25	19.1	6.1	-8.3

6-12-2010 11:43

Sinal (cm): 14 SNR: 4.4

SElev.: 19

Monitorização do Nível do Mar, FCUL (2008)
DEGGE - http://enggeografica.fc.ul.pt

Figure 2. *MareVB* application window, running at 12-06-2010.

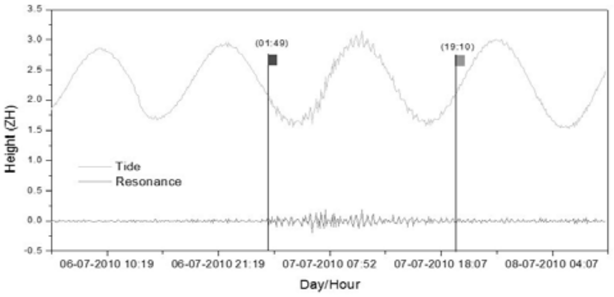


Figure 3. Meteo-Tsunami occurred on 6-7 July 2010 and detected at Cascais tide gauge by the *MareVB* application.

On 6 to 7 of July 2010, an unusual phenomena has occurred on the south-west coast of the Portuguese mainland, specifically a meteorological tsunami (Figure 3) caused by convective cells, which rapidly generated high pressure variations, causing local resonance waves that reached, at Lagos tide gauge, 51 cm of amplitude and a period of 57 minutes. Unfortunately, by that time the *MareVB* was only connected to the Cascais tide gauge (the connection to the Lagos tide gauge was off), however the *MareVB* application has behaved with a good performance to the phenomena, as it lately reached Cascais area. The application sent a first email warning at 1:10 AM of day 7 (yellow warning) and at 6:43 AM has sent its first red warning level email, related to high frequency oscillation of SL and significant amplitude. This fact together with every warning that is sent whenever there is a storm-surge, makes the *MareVB* a valuable tool as a coastal warning system for the Portuguese coast.

The application saves several daily data files, that can lately converted to a database, namely: the sea level height and air-pressure raw data; the computed data with tide, the tide model, the storm-surge amplitude and the resonance; a warning data file to be delivered to the tide webpage of FCUL; and, an emailing log, to record the number, the type and the warning level of the emails sent each day.

DECADAL SEA LEVEL TIME SERIES

The daily data files from the tide gauge of Cascais, with the water level and the air-pressure is downloaded each day by FTP. This data is merged into a decadal time series of MSL and storm-surge evaluation data set, from which a SLR evaluation statistics and frequency of storm-surges are determined.

Time Series of Decadal MSL

The daily MSL and the air-pressure mean are determined from daily data and included in a 10 year base series, to monitor SLR and evaluate the surge events associated to storms (Figure 4).

From this time series, the monthly mean is also evaluated to increment and actualize the MSL secular time series of the Cascais tide gauge, which has been gathering data since 1882, being one of the oldest time series of SL in the world.

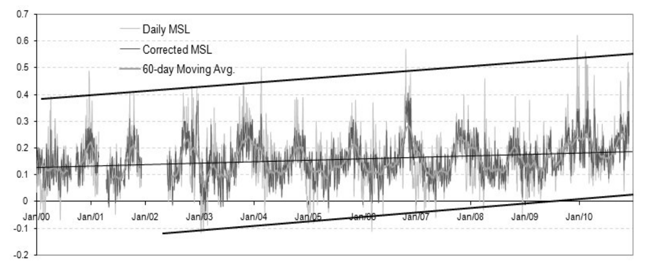


Figure 4. Time series of MSL and MSL corrected from IBE, of last ten years. Top and bottom lines represent trends of extremes.

On daily MSL time series, as shown in Figure 4, the seasonal variations of SL is perfectly evident, from which one can adjust a numerical model to be applied for the prediction of tide models, as show before (Figure 1). These variations, with average amplitude of 14 cm, are mainly explained by the meteorological forcing caused by the winter/summer regime of winds that cross the west coast (Relvas *et al*., 2007). The summer winds, coming from N and NW, together with the Coriolis effect, imply a movement of the surface waters near the coast towards offshore/west direction (responsible for the well known upwelling phenomena), generating a convergence (lowering) of the water surface to the topographical seabed (corresponding to the lowest annual MSL of 8 cm). While the winter winds, coming from S and SW, generate the divergence (up lifting) of the water surface (corresponding to the highest annual MSL of 22 cm). If, for any reason, this regular regime of winds changes for a while, one can observe slightly perturbations in the behavior of the seasonal variation.

The IBE (corrective term of equation (7)) is removed from the daily MSL, which results in a new time series of IBE-corrected MSL (Figure 4). Such data corresponds to a SL series without the influence of high and medium frequency of the air-pressure oscillation. The differences between both series denote the occurrence of surges forced by air-pressure oscillation, usually associated to storms. This is identified as barometric surge. The storm-surge, as the total amount of surge (total atmospheric effect), is computed as the difference between the daily MSL and the average of MSL (now at 15.9 cm above MSL of Cascais 1938), when it is greater than 10 cm.

The IBE-corrected MSL time series is then used to better estimate the SLR of the present decade as it is shown in Figure 4 by the centered trend line, which in present analysis corresponds to a linear regression of the 60-day moving average computed over the IBE-corrected MSL time series.

New SLR rate and acceleration

The long term time series, recorded since1882, use monthly mean values of the MSL, over which a 10-year period moving average representing an estimation model of the SLR at Cascais tide gauge is computed (Antunes and Taborda, 2009). Such time series disables the possibility to estimate the present SLR rate. Since the moving average must be centered, it would be necessary to have available the data for the next 5 to 10 years, which is presently impossible. Thus, the present decadal time series, as shown in Figure 4, is an alternative to enable the estimation of the present rate of SLR, which can be compared to the latest decade rate obtained through the secular time series, and induce an acceleration of SLR.

The time series in Figure 4 show an increase of the extreme values along the last 10 years, as shown by the bottom and top trend lines on the graph. However, these trends represent higher rates than the linear regression computed over the 60-day moving average of the IBE-corrected MSL time series (middle trend line). Running such computation of relative SLR evaluation (overall data trend), the rate of 2.6 mm/yr (±0.3 mm/yr) was obtained for the period of 2000 to 2009 (Antunes *et al.*, 2010), while considering the additional data of 2010 a much higher rate is obtained, around 4.8 mm/yr.

This abnormal increase of SLR rate, only in one year of data, is yet to be explained and its reliability needs to be confirmed with data for the next years. However, it can be observed that the MSL in 2010 is 7.0 cm higher (22.9 cm) than its decadal average (15.9 cm). Additionally, the minimum of annual MSL (seasonal variation determined by the 60-day moving average over the corrected MSL time series), occurring at the summer period (Figure 4), has been increasing since 2008, reaching its highest value of 16 cm in 2010.

What is causing such rate rise of SL? This is the question that has been posed lately. Analyzing the air-pressure time series of last ten years, one can indentify two main trends, one with a positive rate of 0.2 mbar/yr, from 2000 to 2006, and a second one, from 2006 to 2010, with a rate of -0.46 mbar/yr. The negative rate of the present air-pressure data series can be responsible for a forcing of the SLR, due to the release of the pressure that was acting in the earlier period of the air-pressure rise. This is a possible explanation for what is being observed in the SLR of Cascais tide gauge for the last three years, but additional data is required and correlation must be analyzed to prove such hypothesis.

As it was presented in Antunes *et al.* (2010), when comparing the SLR rate of 2.6 mm/yr estimated for the period of 2000-2009 with a 2.1 mm/yr rate for the 1990’s decade, an acceleration of 0.026 mm/yr^2 is obtained. However, if we use the series with the 2010 data included, the acceleration rises up to 0.150 mm/yr^2. Such high value for SLR acceleration, explained by the unexpected SL rate rise of the last three years, is not so unusual, once it has already occurred in the past century, namely, in the 20’s and 70’s decades (Antunes and Taborda, 2009).

Statistics of Storm-Surges for the last 10 years

The tide gauge data are stored and processed for each day to compute the MSL and air-pressure daily average values, as explained before. With such daily averages it is determined whether there is or not a storm-surge and, the amplitudes of storm-surge and IBE are computed. Both values are included in the statistics of the last 10 years, where the frequency is determined to obtain the percentile curve (Figure 5). For each year, the total number of storm-surge occurred for each percentile is determined

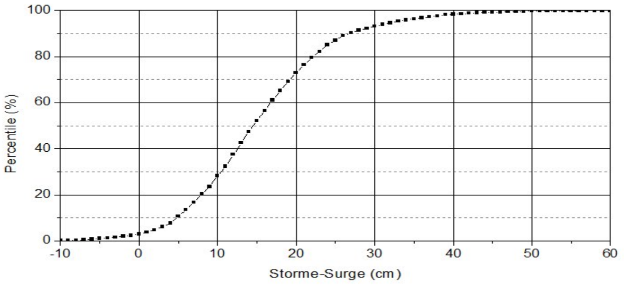


Figure 5. Percentile curve of the daily storm-surge occurred at Cascais tide gauge, since 2001 to 2010. Values of SS referred to the MSL reference of Cascais 1938.

and charted to obtain an evolution of the storms that has occurred along this period of 10 years.

The results have pointed out that the amplitudes of 27 and 33 cm of storm-surge correspond to 90 and 95 percentile, respectively, and has shown that the last winter of 2009-2010 has been the most sever period of storms for the last 10 years, since 44% of the storms of the percentile 90 and 63% of the percentile 95 occurred in this short period. This percentage values increase to 57.1% and 71.4 %, respectively, if we consider the complete year of 2010 (Figure 6). The analysis of the MSL series (Figure 4) shows that, also in the winter of 2009-2010, the daily MSL has hit several height records, namely in December of 2009, where the monthly average of SL hit 31.3 cm above the reference of MSL (Cascais 1938), and 33.7 cm in February; where the highest value of all, since 1882, has occurred in December of 1989 with 34.5 cm of monthly MSL height. Identical extreme value of MSL has occurred again at December 2010, with 34.2 cm of height.

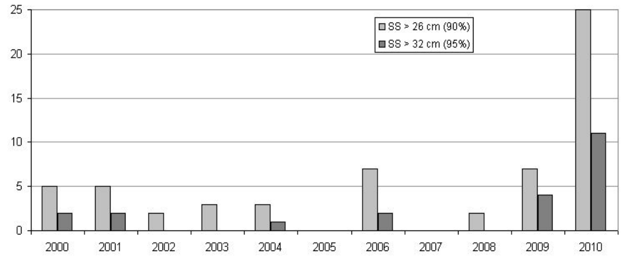


Figure 6. Number of storm-surges (SS), since 2000, of percentile 90 ad 95%, respectively, with amplitudes of 27 and 33 cm.

This data of storm-surge frequency reveals that the last winter of 2009-2010 was one of the most severing periods of extreme events on the Portuguese coast, considering the last 10 years. Such results may suggest some kind of correlation to the on-going climate changes or to the present negative period of the NAO Index, that needs to be studied.

CONCLUSIONS

The present paper presents a great tool that has been used to monitor the SLC in real time, which is very important nowadays to help on the coastal hazard management, especially when it can be truly useful for the institutions of rescue and civil protection, as it has been lately.

Another important result is the achievement on the accuracy and precision of the harmonic tide models, which was based in the correct numerical modeling of the non-astronomic tidal components. This approach made possible a reliable monitoring of the SLC in real time.

The actual and permanent monitoring of the SLR rate and storm-surge statistics through different time series of MSL is another achievement that has shown a great importance to help to understand and to manage the impact of the climate changes in the Portuguese coastal areas (Taborda *et al.*, 2010).

ACKNOWLEDGEMENT

The author would like to acknowledge the IGP for allowing full access to the data of Cascais Tide Gauge, as well as the colleague Ana Navarro, who have helped on the write revision of the paper.

LITERATURE CITED

Antunes, C., 2007. *Previsão de Marés dos Portos Principais de Portugal*. FCUL Webpages - http://webpages.fc.ul.pt/~cmantunes /hidrografia/hidro_mares.html

Antunes, C. and Taborda, R., 2009. Sea level a Cascais Tide Gauge: Data, Analysis and Results. Journal of Coastal Research, SI 56, *Proceedings of the 10th International Coastal Symposium* (Lisbon, Portugal), pp. 218-222.

Antunes, C., Taborda, R. and Mendes, V., 2010. Analysis of the most recent data of Cascais Tide Gauge. Geophysical Research Abstract, Vol. 12, EGU2010-1253, EGU General Assembly 2010.

Godin, G., 1972. *The Analysis of Tides*. University of Toronto press, 264 pp.

Relvas, P., Barton, E.D., Dubert, J., Oliveira, P.B., Peliz, A., da Silva J.C.B and Santos, A. M. P., 2007. Physical Oceanography of the Western Iberia Ecosystem: latest views and challenges. *Progress in Oceanography*, 74(2-3), 149-173.

Taborda, R., Andrade, C., Marques, F., Freitas, C., Filipa, R., and Antunes, C., 2010. *Zonas Costeiras*. In: PECAC (2010). Alterações Climáticas - Cascais. Plano Estratégico de Cascais face às Alterações Climáticas. Relatório Executivo e Integrador. F.D. Santos e R. Aguiar (Eds). Câmara Municipal de Cascais, Cascais. 59 pp.