Modelling storm surges on the Portuguese coast

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ABSTRACT

This work aims at modelling storm surges on the Portuguese coast which were previously estimated by Pinotes (2014) for the last forty years in three different locations, Viana do Castelo, Aveiro and Cascais, the water level during these storms were not registered by the tide gauges.

Yet, another goal is to verify the values of the water level estimated by the same author based on empirical methods, whenever the difference is greater or equal to 20 cm than registered by the gauge.

For hydrodynamic modeling, the ADCIRC (ADvanced CIRCulation) was used, which includes different forcing mechanisms: astronomical and meteorological.

The Meteorological forcing was wind, water column and inverse barometric effect. Wind and water column pressure was applied in each node of the domain and the inverse barometric effect was applied in the ocean boundaries. For the astronomical simulations harmonic constituents were retrieved from the Le Provost's dataset (Le Provost *et al*., 1998).

The model has a non-linear interaction between astronomy and meteorology. Therefore, for the determination of storm surge, the meteorology and astronomy had to be simulated together, removing the astronomy results after that.

In this work, similarities between the extreme values of the model and the values estimated by Pinotes (2014) were verified.

Finally, it was concluded that besides the wave breaking effect was not being considered in this study, it has a large importance because the values of simulations are lower than the results of Pinotes (2014) and lower than some values recorded by tide gauges.

Keywords: Storm surge, ADCIRC, hydrodynamic modelling, astronomy, meteorological forcing, astronomical constituents

Introduction

Portugal has a long coast and there are not many studies about surges and the main surging agents. Studies on the coast and about storm surges are important because there are some regions at risk of coastal flooding. The risks and consequences of floods were due to population movement from inland regions to coastal and estuarine areas, resulting in a densification of the main cities.

One of the last studies about storm surges in Portuguese coast was Pinotes (2014) thesis. This author analyzed the path of main storms and estimated a large period when storms surges (the biggest storm in each year) could happen and make the sea level rise and affect the Portuguese coast. However, the method of Pinotes (2014) is a cause-effect method and needs further verification and hydrodynamic modelling was suggested by the author (Pinotes (2014)).

The first goal of this thesis was to obtain the values of the sea surface elevation that the three different tide gauges did not register. The second objective, was to verify some values estimated by Pinotes (2014)), whether they have a difference equal or higher than 20 cm than the observed that they have a difference equal or higher than 20 cm than the observed values. In the end both values obtained from the two methods (empirical relationships and hydraulic modeling) were compared.

The modeling strategy in this work comprises a step-by step approach introducing one agent at a time: the astronomical tide is reproduced first in the model and then the meteorological atmospheric. It has already been by some researchers that the most important surging agents are pressure, wind and radiation stresses which are due to wave-breaking and the sea bottom morphology. The wave set up effect was not considered. Araújo *et al*., (2011) showed that this is an important effect and contributed 38% in the surge between 13^{th} and 18^{th} October, in Viana do Castelo.

Model description

- ADCIRC Model

The hydrodynamic modelling ADCIRC was used and this operates on the basis SMS software.(Luettich, Westerink, and Scheffner, 1992).

In this work, the ADCIRC-2DDI model is used, it applies the shallow water equations and these equations are integrated into mass and into the depth from Navier Stokes. These equations are solved under the hypothesis of incompressibility, Boussinesq and hydrostatic pressure (Westerink *et al*., 2008).

The elevation is obtained from the solution of the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) ("Introduction", accessed in September, 2016, http://www.adcirc.org). As the Navier Stokes equation does not have an analytic solution, discretization methods could give the solution that is closest to reality. In this work, the methods of discretization used were: the finite element method, in space, and the difference finite method, in time.

ADCIRC is used because of its performance level, which has a high efficiency and degree of accuracy. A good model performance is a consequence of the extreme grid flexibility and reduction of number of degrees. The equation (1) is the continuity equation and the equations (2), and (3) are equations that can be integrated over the vertical to yield equations for free surface elevation and the 2D depth-average velocity.

$$\frac{\partial \zeta}{\partial t} + \frac{\frac{\partial UH}{\partial \lambda} + \frac{\partial (VH cos\phi)}{\partial \phi}}{R cos\phi} = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + \frac{U}{R\cos\phi}\frac{\partial U}{\partial \lambda} + \frac{V}{R}\frac{\partial U}{\partial \phi} - \left(\frac{U\tan\phi}{R} + f\right)V = -\frac{g}{R\cos\phi}\frac{\partial}{\partial \lambda}(\zeta - \alpha\eta) + \frac{V_t}{H}\frac{\partial}{\partial \lambda}\left[\frac{\partial UH}{\partial \lambda} + \frac{\partial UH}{\partial \phi}\right] - \tau_* U \quad (2)$$

$$\frac{\partial V}{\partial t} + \frac{U}{R\cos\phi}\frac{\partial U}{\partial \lambda} + \frac{V}{R}\frac{\partial U}{\partial \phi} + \left(\frac{U\tan\phi}{R} + f\right)U = -\frac{g}{R}\frac{\partial}{\partial \phi}(\zeta - \alpha\eta) + \frac{V_t}{H}\frac{\partial}{\partial \phi}\left[\frac{\partial VH}{\partial \lambda} + \frac{\partial VH}{\partial \phi}\right] - \tau_* V \quad (3)$$

Where:

t is the Time (s*),* λ and ϕ the Longitude and latitude (radians), *U* and *V* the depth-average horizontal velocity (ms^{-1}), *H* the water column (m), ζ the surface of sea (m), *h* the bathymetry (m), *f* the Coriolis parameter(-), *R* the Earth radius (m), $\tau_*$the bottom stress, (Nms^{-2}), V_t the horizontal eddy viscosity (m^{2}s^{-1}), *g* the acceleration of gravity (ms^{-2}), *α* the effective Earth elasticity factor (-), *η* the Newtonian equilibrium tide potencial (m).

- Domain and bathymetry

Figure 1 – Drawn the studied area, Portuguese coast and part of Atlantic Ocean. The boundaries are ocean (blue) and coast (brown).

Pinotes (2014) examined the path of the storms that created the strongest surges that affected on the Portuguese coast. After that, one approximately rectangular domain was drawn trying to include the highest number of storm surges as possible within. Before this domain, another smaller domain was also considered.

The results in the 3 tide gauges were similar and the time of simulation did not change very much for the two domains, however, this could not include as many storm surges.

The bathymetry was acquired from different sources: Portuguese nautical charts scaled 1:150 000 and 1:1 000 000 from the coastline up to a depth of 4000 m were digitized. For the rest of the region the Global seafloor database from the Institute of Geophysics and Planetary Physics was used.

- Mesh generation

A good mesh should have elements with a reasonable size, being more refined along the coast.
The most recurrent Node Spacing Function - the wavelength function, equation (4) – it was applied for the ocean and continental shelf – (Le Provost and Vincent, 1986).

$$\Delta \boldsymbol{x_1}(\boldsymbol{x},\boldsymbol{y}) = \frac{\boldsymbol{\lambda}(\boldsymbol{x},\boldsymbol{y})}{\boldsymbol{r}} = \frac{\boldsymbol{T}\sqrt{\boldsymbol{gh}(\boldsymbol{x},\boldsymbol{y})}}{\boldsymbol{r}} \tag{4}$$

In which *T* is the tide period, *h(x, y*) the water depth and *r* a constant.
To improve some proprieties of the mesh a filter was applied to smoother the elements the wavelength function will be created. The smoother allows minimizing the area of the elements or the maximum slope among the elements.
Finally, the nodes inside the polygon were generated and connected. There are some methods to do Scalar Paving Density was the mode used because it offers a good flexibility to the mesh. To narrow the edge each element, the truncate value was used.
Finally, the quality of mesh was analyzed: the playback of contour lines, the minimum and maximum interior angle, and others.
In some situations, there are local instabilities, that water is higher than expected.
To solve this situation, mesh should be refined in critical zones. However, a mesh which is too refined could bring other instabilities.
These instabilities occur mainly with the meeting of different kinds of boundaries in land border, where mesh is more refined, but the reason of this problem is unknown.
In this mesh, the instabilities were close to La Coruna and close to Sines.

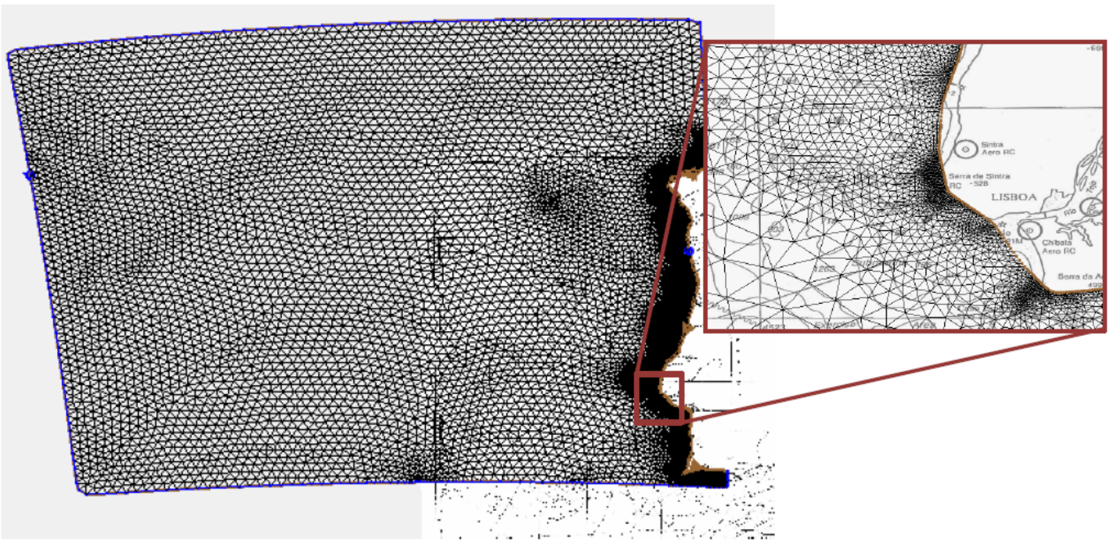

Figure 2–Domain used with triangular mesh. The oceanic boundary, line is blue and the land boundary, line is brown.

Simulation with meteorological and astronomical forcing

The Meteorological factors considered for modeling in this work were wind and pressure. These factors have the highest contribution to change mean sea level.

To acquire necessary meteorological data two forecasting databases were used: ERA 40 for period 1958-1970, and ERA Interim, for 2011-2013. To introduce this data in software, MATLAB was used. In MATLAB, a script was used to convert the format of meteorological databases, (.netcdf), to another format accepted by ADCIRC, (.sup). In the end, the units of pressure were changed to meters and the vector of wind was created.

In the mesh, the vector of wind and water column pressure was applied in every node of the domain and the inverse barometric effect was applied in the ocean boundaries.

In astronomical simulations, the same Pinotes (2014) harmonic constituents present in Table 1, were used. The harmonic constituents were extracted from the Le Provost global tide dataset (Le Provost *et al*., 1998). In this thesis, harmonic analysis was not done because finding the best constituents for each place was not the objective of this study.

Tidal potential forcing was applied in the interior nodes of the domain.

Table 1 – Harmonic constituents used in astronomical tides.

	Harmonic Constituintes						
Aveiro	O1	K1	N2	M2	S2		
Cascais	O1	K1	N2	M2	S2		
Viana do Castelo	O1	K1	N2	M2	S2	K2	NU2

Interaction between meteorological and astronomical tides

Sometimes there is an interaction between astronomical and meteorogical tides. To see if this interaction takes place it was necessary to make meteorological and astronomical simulations together, and then separately, looking at the calculations of the meteorological and astronomical simulations which were run separately.

The joint simulation indicates the non-linear interaction in the storm and it changes over the time, the highest energy transfer happens in spring tide, Figure 3.

When a non-linear interaction happens it could be: an insufficient domain extension; the depth along the coast is very deep, a possible contradiction in the weather data used, a faulty refinement of mesh mainly on the coast line, and others.

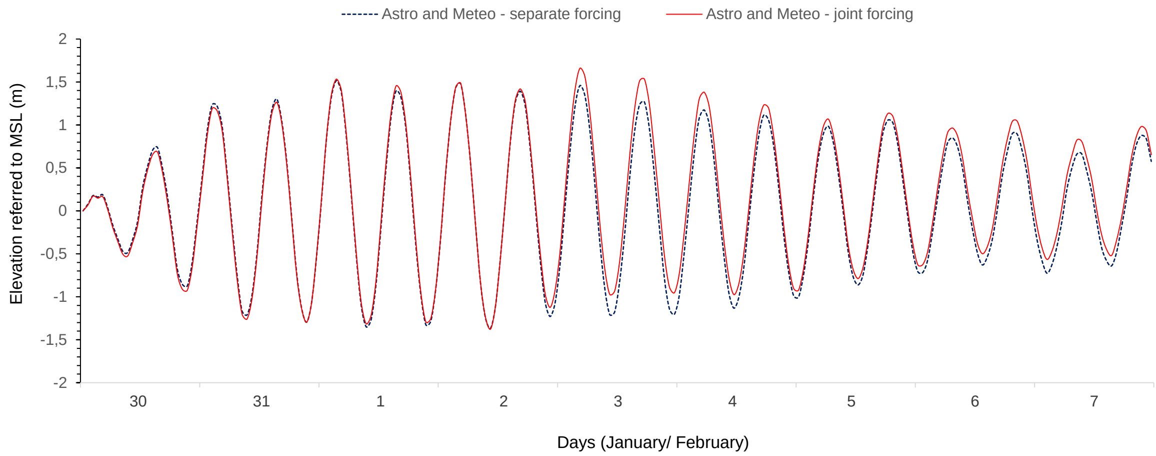

Figure 3– Computed time series for the astronomical and meteorological forcings applied jointly and separately, for storm surge between 1 January and 5 February 2009, with 2 days of ramp, in Aveiro.

Calibration and Validation of the model

Firstly, the data from the WXTide32 software was compared with the data from the astronomical tides from table from IH (Instituto Hidrográfico) to understand if WXTide32 is good enough to be used. WXTide32 is available on the web and it is very easy to apply and predicts tides from 1970 to 2037 with one minute intervals. IH tables are more precise but they do not give hourly values like the model being used (http://www.wxtide32.com, 2016)

In Viana do Castelo and Cascais, WXTide32 software was used and tide tables from IH for Aveiro were used, this fact is related to the tide gauge location.

The calibration consisted of the analysis of the influence of three input conditions: Wave continuity, Lateral viscosity and Friction coefficient. In table 2, we can see the best parameters of calibration with the best values tested

Table 2 – Values of parameters of model in different tide gauges after calibration.

Parameters/Location	Viana do Castelo	Aveiro	Cascais
Friction coefficient	0,04	0,4	0,2
Wave continuity	0,005	0,0005	0
Lateral viscosity	20	30	20

Different scenarios with different values of input conditions were created in order to calibrate the model. The procedure used to select the best scenario was using different indicators such as bias, skill, and accuracy (Sutherland *et al*., 2004) and others.

For calibration and simulations, ramp time was 2 days and for time step was 2 seconds. Time step could not to be very long because instabilities in the model could be created. Time step was chosen by the Courant number, equation (5).

This is a dimensionless number, which should be less than one to be stable.

$$C_N = \frac{\Delta t \sqrt{gh}}{\Delta x} < 1 \quad (5)$$

Where C_N is the *Courant* number (-), the Δt is computational time step (s) and the Δx is the grid size (m).

After the model calibration, it is possible to conclude the parameters variation, in three different places did not promote a significant change of the sea level.

The Validation was not done because astronomical tides have a regular cycle and the model used is reliable. On the one hand, in the calibration, a long enough period was considered and a low and high tides were included. On the other hand, the astronomical values are similar to the values of the values of the model. If people ever want to validate the results obtained, just the time of simulation could be extended.

Discussion of results

Firstly, after all simulations and all values were analyzed, it was concluded the highest storm surge happened in January 1973, in the 3 tide gauges studied. In Figure 7 is represented this storm in Viana do Castelo. This graph shows the computed residuals, the green line was obtained from the difference between the blue and red lines, astronomical and meteorological forcing less astronomical forcing values.

Secondly, the storm surge was analyzed to understand if the peak of the storm estimated by Pinotes (2014) happens on the same day as the model or if the peak of the storm is on a different day. According to the values of Table 3, the majority of peaks of storms surges by model take place on the same day as Pinotes (2014) estimated.

Table 3 –Balance between the peaks of storm surges simulated by model and estimated from Pinotes (2014).

	Viana do Castelo	Aveiro	Cascais
Same day	58%	54%	75%
1 day of difference	25%	29%	15%
2 or + days of difference	17%	17%	15%

After that, the values of the model and Pinotes (2014) are compared. As Figure 4, Figure 5 and Figure 6 show the values are fairly different: the values of the model are lower than the values registered because as it was said before, the wave set up effect was not considered, on the other hand, the values estimated by Pinotes (2014) are higher than the values that tide gauges registered, approximately 60%. In Viana do Castelo the values are higher than the values registered about 80%.

In this work, I have looked for a pattern between the values of the model and the values of Pinotes (2014), however it was not found. However, there are some similarities in the graphs, for example, the peaks of storm surges occurred at the same period in the model and Pinotes (2014), especially when it was the maximum.

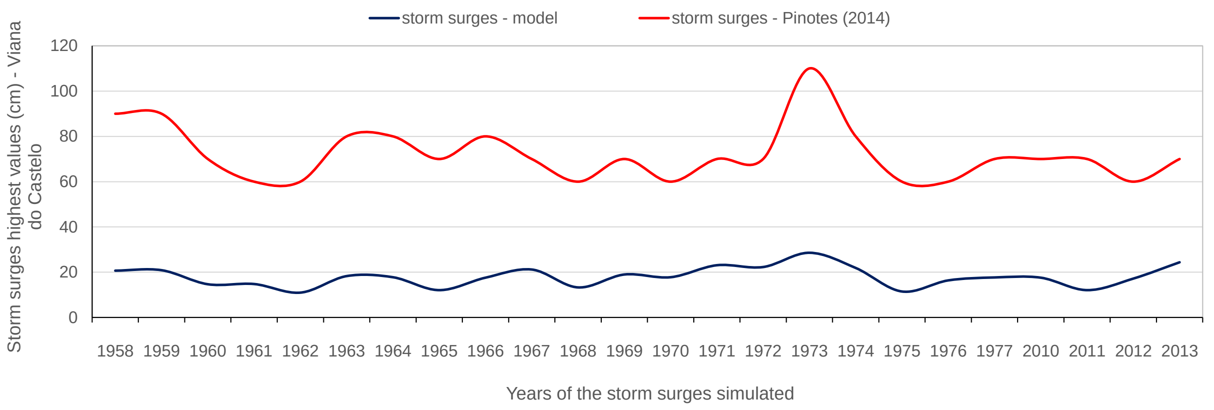

Figure 4 –Storm surges simulated by model (cm) and storm surges estimated by Pinotes (2014) (cm), in Viana do Castelo.

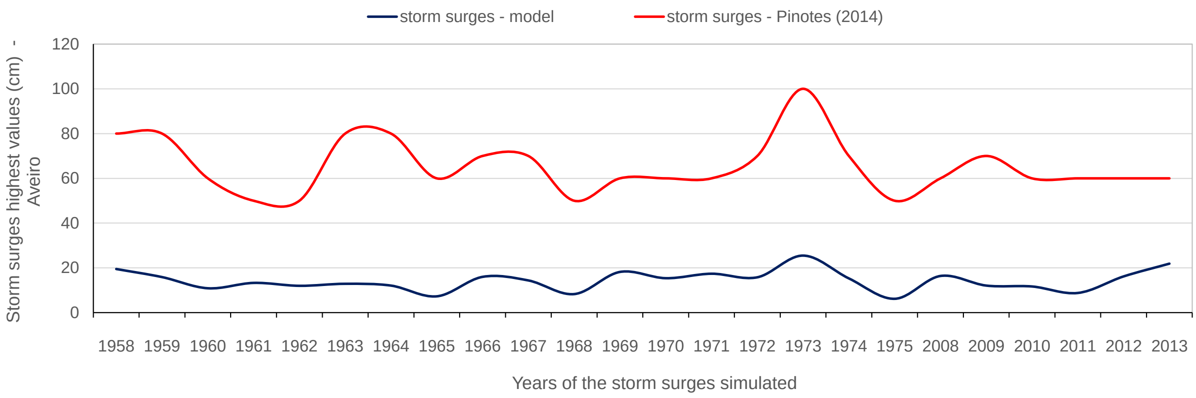

Figure 5 –Storm surges simulated by model (cm) and storm surges estimated by Pinotes (2014) (cm), in Aveiro

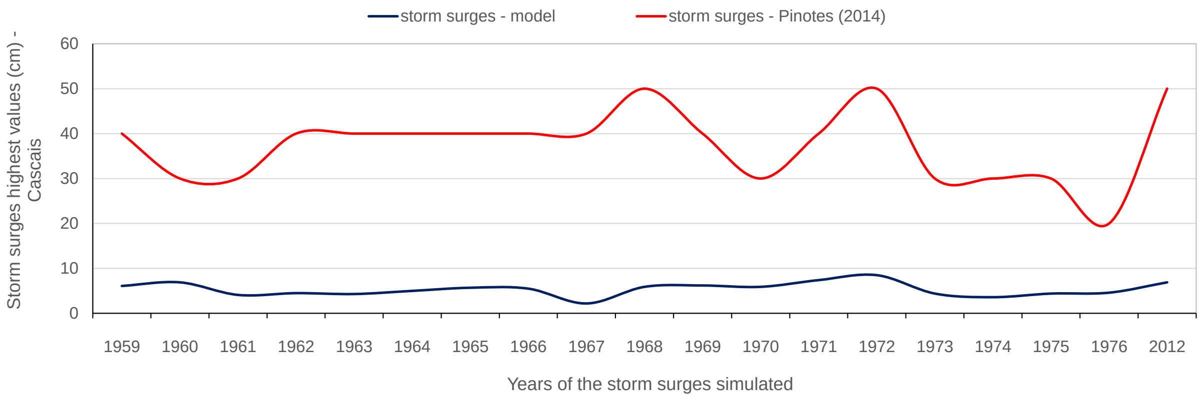

Figure 6 –Storm surges simulated by model (cm) and storm surges estimated by Pinotes (2014) (cm), in Cascais

Table 4 - Highest values of storm surges, media of storm surges and variation between the media of storm surges in 3 tide gauges.

	Viana do Castelo	Aveiro	Cascais
The Highest storm surge - model(cm)	28,6	25,5	8,5
The Highest storm surge - Pinotes (2014)	110	110	50
Average of storm surges values (cm)	18,00	14,31	5,44
Average of Pinotes (2014) storm surges (cm)	72,08	65,42	37,5
Variation between medias (cm)	54,08	51,11	32,06

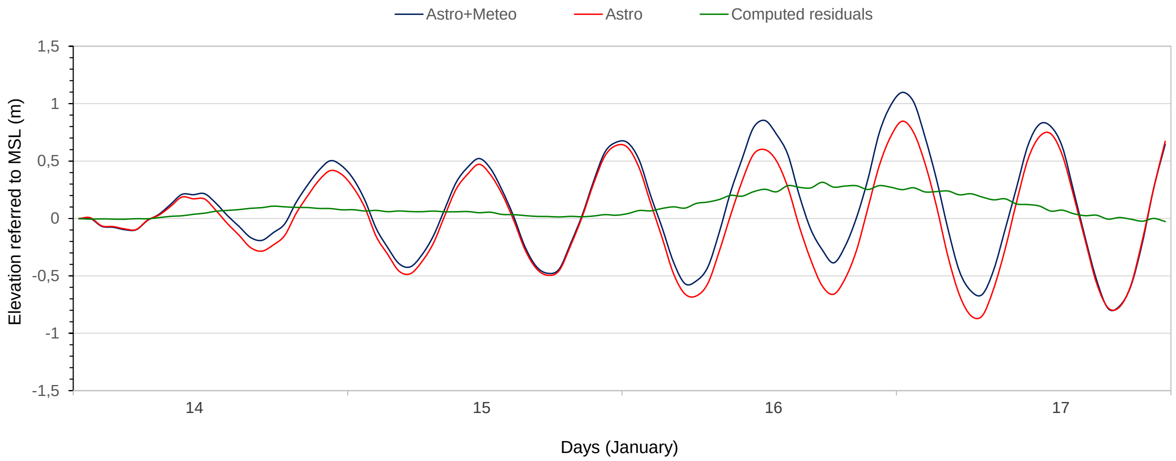

Figure 7 – Graph with the highest storm surge, in 16 until 17 January of 1973, with 2 days of ramp, the level of sea with astronomical forcing and the level of sea with meteorological and astronomical forcing, in Viana do Castelo.

Conclusions

Primarily, it is important to have good data sources and a good bathymetry to obtain a model as close to reality as possible.

Calibration is a very important step in modelling because choosing the calibration parameters is closely linked with having the best results in the end however, they do not change sea level substantially.

The joint tide and surge simulation suggested the presence of non-linear energy transfer between the two mechanisms.

This thesis is a detailed study about storm surges which have happened on the Portuguese coast (at specific points) from the hydrodynamic model. The model used has a performance level and it is greatly used in more affected areas. Besides the figures that tide gauges not registered, the evolution of storm surge was better realized and compare with the estimations of Pinotes (2014). Although Pinotes (2014) results are not very precise, the method was expeditious and it allows the estimation of a large period, in order to simulate the storms surges in ADCIRC. This demonstrates that this dissertation is complementary to and sequential to Pinotes (2014) studies and both results should be taken into account in engineering projects on the coast.

Further developments, in this model could be connected to another to study the effects of the waves on the coast, like SWAN or use another model as STWAVE (Hope *et al*., 2013).

Finally, in another similar work, Linear Truncation Error Analysis (LTEA) could be applied to limit the size of elements (Hagen, Zundel, and Kojima, 2006).

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