

## Determination of Extreme Sea Levels along the Portuguese Coast

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**Abstract:** This work aims at determining extreme water levels associated with different return periods through the development and application of a circulation model for tides and surges. The model covers a large portion of the NE Atlantic, and has a resolution of 250 m in the Portuguese shelf. The model was extensively validated for tides, surges and extreme sea levels. In the Portuguese shelf, RMS errors of tides are of the order of 5 cm, and the model under-estimates extreme water levels by about 10 cm. Simulation of water levels between 1979 and 2010, followed by a statistical analysis of the results, provided the relation between return periods and extreme levels along the Portuguese coast. Results reveal the growth of extreme water levels from south to north.

**Key words:** circulation model, statistical analysis, tides, storm surges

### 1. INTRODUCTION

There is an increasing concern over the flooding of coastal areas by the combined action of tides and storm surges. On the one hand, the hazard is increasing due to climate change (sea level rise and, in some areas, growing storminess); on the other hand, the vulnerability is also increasing due to the continuous migration of the populations and economic activities to the coast.

Determining the hazard from tidal gauge data entails major difficulties. Firstly, few tide gauges have time series long enough to provide reliable statistics. In Portugal, only the Leixões (Araújo *et al.*, 2013), Aveiro (Fortunato *et al.*, 2013), Cascais and Lagos tide gauges have multi-decadal time series. Secondly, some of these stations are not representative of coastal conditions, since they are located inside estuaries. Thirdly, most annual time series have gaps due to instrument malfunctioning, which severely limit the applicability of statistical methods to determine return periods associated to extreme water levels.

As an alternative to measured sea levels, process-based numerical models avoid the three previous difficulties. Provided adequate computational resources and proper data for setup, forcing and validation, models can produce long and continuous time series of sea surface height, which can be used to determine the return periods associated to extreme sea levels (Batstone *et al.*, 2013).

The present paper presents an application of the shallow water model SELFE (Zhang and Baptista, 2008) to simulate tides and surges in the Portuguese shelf from 1979 to 2010. Once the model is properly validated, maps of extreme levels associated to selected return periods are determined.

### 2. METHODS

#### 2.1 Numerical model

Water levels are simulated with the 2D version of hydrodynamic model SELFE (Zhang *et al.*, 2011). SELFE is an unstructured grid community model targeting river to ocean applications, and includes modules for waves (Roland *et al.*, 2013), morphodynamics (Pinto *et al.*, 2012), ecosystem dynamics (Rodrigues *et al.*, 2009), fecal contamination (Rodrigues *et al.*, 2011), oil spills (Azevedo *et al.*, 2014), among others.

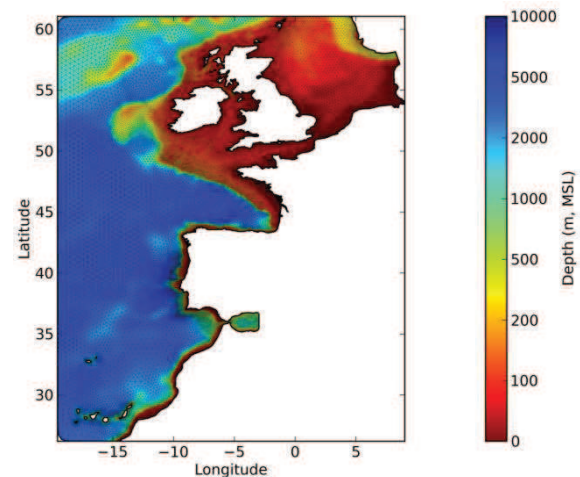


Fig. 1. Finite element grid, with about 150 000 nodes. In the Portuguese shelf, the resolution is about 250 m.

The present application builds on previous efforts by Bertin *et al.* (2012). The domain extends between latitudes 26.2°N and 61.0°N, and from the European and African coasts to longitude 19.5°E (Fig. 1). The grid resolution is particularly fine in the Portuguese shelf, where it reaches 250 m. The time step is set to 5 minutes. The model is forced at the boundary by 18 tidal constituents from FES2004 (Lyard *et al.*, 2006) and the inverse barometer effect. Tidal potential and wind and atmospheric pressure from the CSFR are considered inside the domain.

## 2.2 Statistical analysis

Time series of elevations produced by the model are analysed following the approach of Fortunato *et al.* (2013). This approach starts by splitting the simulated signal into a tidal component (obtained by harmonic analysis) and a residual (obtained by differencing). Synthetic yearly time series are then obtained by varying:

- Tides, from 19 consecutive years;
- All the residuals computed from the model (31 years in this case);
- The phase lag between the tides and the residuals, between -15 and +15 days, with an interval of 1 hour.

The number of annual time series thus obtained is very large ( $19 \times 31 \times 721 = 424669$  in this case), and all these synthetic time series have the same probability of occurrence. Indeed, using 19 consecutive years for tides takes into consideration the nodal tidal cycle, which has 18.6 years. These time series also contain maxima larger than the ones observed, since the largest surges are allowed to occur at high spring tide, even if they effectively occurred at other phases of the tide.

Once the synthetic time series are generated, the function relating extreme sea levels with return periods is obtained with the Annual Maxima Method.

The application of the present statistical method to data from the Aveiro tide gauge and a comparison with the results obtained by Andrade *et al.* (2006) with traditional approaches showed a good agreement (Fortunato *et al.*, 2012). Yet, the present approach is more accurate than the straightforward application of the Annual Maxima Method because it uses more points of the time series (Fortunato *et al.*, 2013).

The approach used herein implicitly assumes that the residuals and the tidal signal are independent, a hypothesis which is not strictly correct. Indeed, while tides and storm surges have different origins, they can interact through non-linear processes. For instance, Horsburgh and Wilson (2007) show that the different celerity of a storm surge as it propagates over a high or a low tide modulates the residuals along the tidal cycle. Tides and surges can also interact through other non-linear processes, such as the increase in bottom friction at low tide (Rego and Li, 2010) and advection (Idier *et al.*, 2013). However, because the Portuguese continental shelf is very narrow and subjected to weak currents, non-linear processes in this region are assumed to be small, and the hypothesis is expected to be a good approximation.

## 3. RESULTS AND DISCUSSION

### 3.1 Model validation

The model was first validated for tides. Root mean square errors for the 5 major constituents (M2, S2, N2, O1, K1) at stations in the southern part of the domain are typically smaller than 5 cm (Fig. 2). These errors are smaller or equivalent than those presented in previous similar applications (Fortunato *et al.*, 2002, 2011).

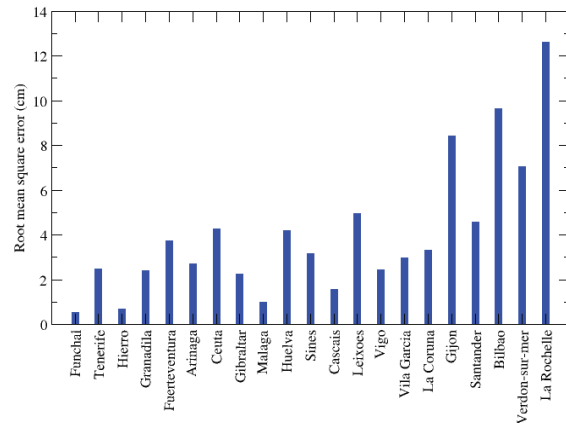


Fig. 2. Validation of the tidal model: root mean square errors for time series computed with five tidal constituents (M2, S2, N2, O1, K1).

The full tide and surge model was validated next for the 2009-2010 winter. This period was selected because it was a particularly violent winter. In February, the Xynthia storm generated surges over 1.5 m in the south-western French coast, killing 47 people and causing 1.5 billion euros damage (Bertin *et al.*, 2012). In the Tagus estuary, 500 thousand euros of damage were reported for the same event (Pereira, 2013). To evaluate the performance of the model in terms of storm surges, a Demerliac filter was applied to both the data and the model results to remove the tidal signal. Results show that model correctly captures both the amplitude and the phase of the surge (Fig. 3).

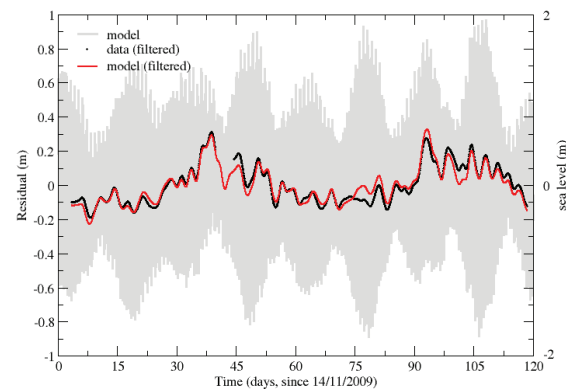


Fig. 3. Validation of the tide and surge model at Cascais during the 2009-2010 winter: both observations and model results were filtered to remove the tidal signal.

Further model-data comparisons showed that the accuracy is significantly lower in the northern part of the domain, probably due to the low spatial resolution of the grid, the larger amplitudes of tides and surges, and the higher importance of non-linear processes in that area. Hence, the analysis of model results concentrates on the Iberian shelf.

Finally, the return periods associated to extreme levels at three locations were computed with the model results and compared to a similar evaluation using data (Cascais and Aveiro) and another model (Bilbao) (Fig. 4). The discrepancy between the different curves (about 5 cm) is of the order of the uncertainty associated with the statistical method.

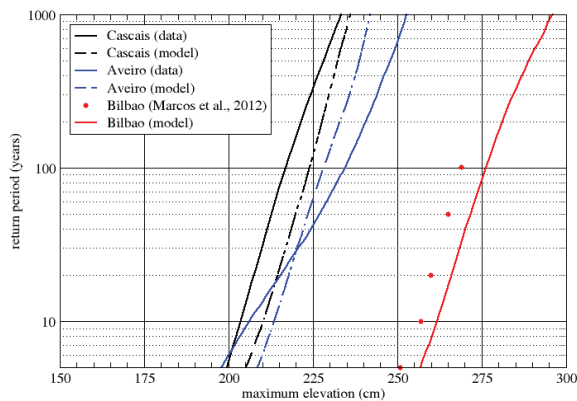


Fig. 4. Comparison of the return periods of extreme sea levels computed with the present model and others at Cascais (from Guerreiro *et al.*, 2013), Aveiro (from Fortnato *et al.*, 2013) and Bilbao (from Marcos *et al.*, 2012).

Although the model can still be improved, it is considered reliable enough to investigate extreme sea levels along the Portuguese coast.

### 3.2 Extreme sea levels

Extreme sea levels at selected locations along the Portuguese shelf were determined based on 31 years of preliminary model hindcasts. The European Directive on floods requires that inundation maps are produced for high, medium and low probability events, which, in Portugal, has been defined as 20, 100 and 1000 year return periods. Extreme sea levels were thus computed for those return periods, even though the uncertainty for the 1000 year return period is very high.

Results show that extreme sea levels increase from South to North in this region (Fig. 5): the difference between the extreme sea level at the southernmost station (South of Tangier, Morocco) and the northernmost (East of Gijon, Spain) is about 0.6 m. This growth from South to North is consistent with a previous analysis based on tide gauge data (Andrade *et al.*, 2006). Also, extreme water levels associated with return periods of 1000 years are about 0.3 m higher than those obtained for return periods of 20 years.

## 4. CONCLUSIONS

The present results show that it is possible to determine extreme sea levels from model hindcasts with acceptable errors. The main limitation of the model is that waves are not modelled, thus wave setup and infra-gravity waves are neglected. Results provide new insight on the spatial distribution of sea level extremes and on their frequency.

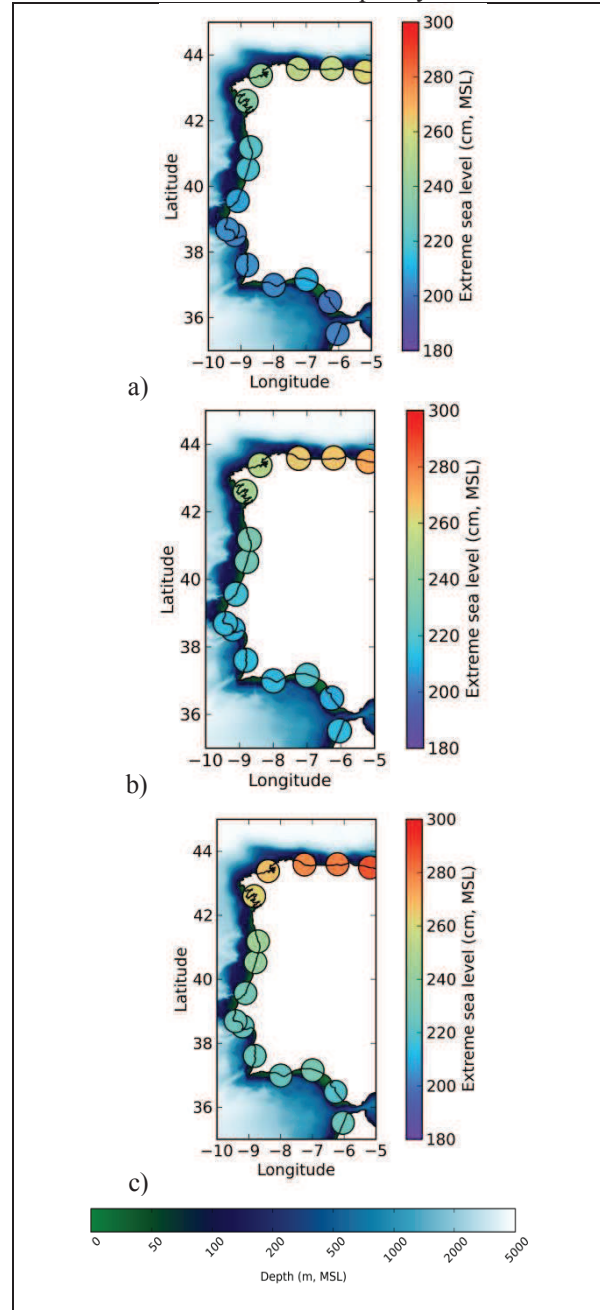


Fig. 5. Extreme water levels along the Portuguese coast for different return periods: a) 20 years; b) 100 years; c) 1000 years.

The model developed herein can have important applications for coastal management. The European Directive on floods requires all member states to develop risk maps for threatened riverine and estuarine areas. The present work can provide the boundary conditions for estuarine models to generate inundation hazard maps.

## Acknowledgements

This work was partially funded by the Fundação para a Ciência e a Tecnologia (projects MOLINES – PTDC/AAG-MAA/2811/2012 and ADAPTARIA – PTDC/AAC-CLI/100953/2008, and grants SFRH/BSAB/1308/2012 (ABF) and SFRH/BPD/87512/2012 (MR)) and by the Région de Poitou-Charente.

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