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Effect of large scale atmospheric pressure changes on water level in the Tagus Estuary

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ABSTRACT

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Previous research shows that storm surge episodes occur frequently at the mouth of the Tagus Estuary, causing important water level anomalies in Lisbon and Cascais tide gauge records and having important effects in coastal erosion. Atmospheric pressure is indicated as the main driver of storm surge events in the West Iberian Peninsula. However, the extent of the effect of atmospheric pressure induced surges on inner estuary water level, an important issue for the estuary management using hydrodynamic forecast systems, is still poorly known with tide gauge records analyses concentrating outside the estuary.

In this work a set of tide gauge records, between October 1972 to January 1973, for 11 locations in the Tagus Estuary and adjacent coast and a numerical model of Tagus Estuary hydrodynamics (MOHID Water) are used to test the importance of large scale atmospheric pressure changes in explaining inner estuary non-tidal water level anomalies with period larger than 30 hours. The results of two model simulations, with and without the effect of atmospheric pressure considered according to the inverted barometer approximation based on atmospheric pressure reanalysis data, are contrasting with the tide gauge records.

The research finds that the account of atmospheric pressure can reduce the importance of the model centered RMSE in 5-20% and improve considerably the model results correlation coefficient in the lower and middle estuary, particularly in low depth locations not directly affected by river discharges. These results suggest that these should be the estuarine locations more sensible to storm surges episodes.

ADDITIONAL INDEX WORDS: *Tide gauges, Storm surge, Inverted barometer*

INTRODUCTION

The Tagus Estuary (Figure 1), located in the West Iberian Peninsula, is one of the largest Western European estuaries, supporting important human communities and natural resources supply. It is an inundated valley with a submerged area of 370Km^2 in high tide maximum and 265 Km^2 in low tide minimum, with about one third of its surface being composed of intertidal areas.

It is composed, from Tagus River to mouth, of three morphologically different areas: the upper, middle and lower estuary. The upper estuary has an inner delta and large marshland with small depth (5m maximum), directly influenced by the Tagus River flow. The middle estuary is a wide (maximum 14km) small depth (7m on average) area. Finally, the lower estuary has a small width (2km) and large depth (30m) channel with the cities of Lisbon (the Portuguese capital city) and Almada at its banks.

Besides the fresh water inlets, the dominant driver of hydrodynamics in the area is the astronomic tide, with a dominant semidiurnal period and maximum amplitude of 2m in spring tides. However, storm surge, a significant elevation of the water level (relative to astronomical tide) caused by meteorological forcing (GILL, 1982), is reported to be frequent in the Tagus Estuary mouth, being observed at Lisbon and Cascais tide gauge records (GAMA *et al.*, 1994; SEBASTIÃO *et al.*, 2008).

This is an important cause of coastal erosion south of the estuary at Costa da Caparica (FERREIRA, 2004). The phenomenon is also known to affect considerably the hydrodynamic and water quality conditions in estuaries and coastal lagoons, namely due to severe changes in circulation, wave activity, sediment transport and turbidity and also exposure of wetlands to coastal processes (e.g. ANDRADE *et al.*, 2004; VALDEMORO *et al.*, 2007). However, the specific effect of storm surge on environmental change inside the Tagus Estuary is still poorly studied. This change could be potentially very relevant since an important part of the local economy is linked directly or indirectly to estuarine activities relying on water quality and hydrodynamics such as fishing (BAETA *et al.*, 2005) and navigation (FORTUNATO *et al.*, 1999).

In the Iberian Peninsula coast storm surge is connected with the occurrence of extratropical storms (LOZANO *et al.*, 2004), originating in southwestern part of the North Atlantic and lasting for about 4 days on average (LOZANO *et al.*, 2004; ANDRADE *et al.*, 2004). These concentrate in the winter (GAMA *et al.*, 1994; LOZANO *et al.*, 2004) and are reported to be frequent: an account for the Azores region (ANDRADE *et al.*, 2008), which is affected by

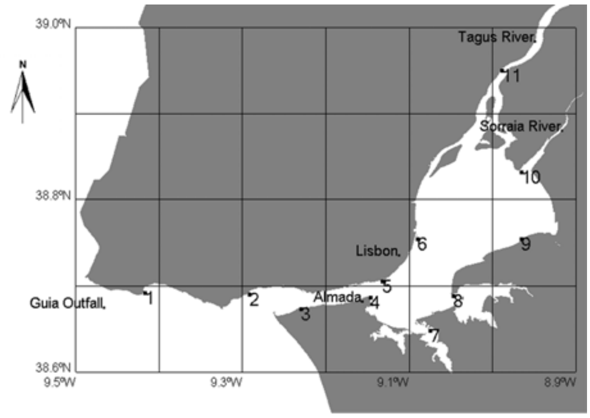

Figure 1. The Tagus Estuary. The cities of Lisbon and Almada and the two most important rivers that drain to the estuary, Tagus and Sorraia, together with the Guia wastewater submarine outfall are presented. The tide gauges network is indicated by the numbered locations (see Table 1 for names).

storms mostly with the same origin as the West Iberian Peninsula (LOZANO *et al.*, 2004), found an average frequency of 3 storms per year and an extreme storm every seven years.

These storms have been associated with large scale atmospheric features such as the North Atlantic Oscillation index, an atmospheric pressure gradient between North and South North Atlantic (KEIM *et al.*, 2004; TSIMPLIS and SHAW, 2008). There is evidence that winter storms have been increasing in frequency in the last three decades of the past century in the Northeast Atlantic (SCHMITH *et al.*, 1998; ANDRADE *et al.*, 2008) and there has been considerable concern on the possible intensification of storminess in a future climate change scenario (LOZANO *et al.*, 2004). Late studies do not show a clear increasing storminess trend but suggest that storm episodes are expected to remain, at least in intensity, as important under this scenario as they are today (KEIM *et al.*, 2004; LOZANO *et al.*, 2004).

The storm surge can be produced directly through atmospheric pressure gradients or through the resulting wind forcing. However, past research suggests that the determinant process in the West Iberian Peninsula coast is atmospheric pressure forcing (FANJUL *et al.* 1998; TSIMPLIS and SHAW, 2008). In this region this relationship is considered to be reasonably well expressed by the inverted barometer approximation (FENOGLIO-MARC *et al.*, 2005; PONTE, 2006).

In this work the anomalies detected in detrended (tide removal) water level from several historical tide gauge records for the Tagus Estuary and adjacent coast, comprising the period from October 1972 to January 1973, are related to atmospheric pressure anomalies using a numerical model for Tagus Estuary hydrodynamics and the inverted barometer approximation.

METHODS

Tide Gauge Measurements

Tide gauge records are available for 11 locations in the Tagus Estuary and adjacent coast (Figure 1). Most of the records span for the whole year 1972, with the exception of tide gauges 2 (Paço de Arcos), available for 26/01/1972-25/01/1973, and 9 (Alcochete), available for 05/01/1972-31/12/1972. For analysis the measurements are detided using T_Tide software (PAWLOWICZ *et al.*, 2002). The correspondent detided residuals are subjected to filtering to remove perturbations with period below 30 hours, in order to contrast with results of model simulations.

Model Simulations

MOHID Water Modelling System (MIRANDA *et al.*, 2000; MARTINS *et al.*, 2001; LEITÃO *et al.*, 2005) includes a primitive equations hydrodynamic module with hydrostatic and Boussinesq approximations. MOHID Water has been used previously in the Tagus Estuary (BRAUNSCHWEIG *et al.*, 2003) as well as in other estuarine and coastal hydrodynamic studies (RUIZ-VILLARREAL *et al.*, 2002; SANTOS *et al.*, 2002; LEITÃO *et al.*, 2005; VAZ *et al.*, 2007).

The model used in this work is composed of two barotropic 2D domains (Figure 2). The larger domain 1 contains the Portuguese and Galician coast (from 36ºN to 45ºN and from 12ºW to 6º9'W), with grid resolution from 4km (at boundary) to 2km (at area of domain 2), providing tidal boundary conditions for a smaller domain 2. This domain (from 38ºN to 40ºN and from 10º30'W to 9ºW), with grid resolution from 2km (at boundary) to 300m (at Guia outfall location), contains the Tagus Estuary and adjacent coastal interest area. For both domains an Arakawa C grid is applied. The number of grid cells is 218x324 for domain 1 and 162x162 for domain 2 (longitude x latitude).

The bathymetries are constructed from detailed bathymetric surveys data, available for Tagus Estuary and adjacent coast (informing most of the area comprised in domain 2) and Galician coastal areas (the Spanish data is produced by Instituto Hidrográfico de Cádiz and provided by METEOGALICIA), which are completed with ETOPO 2' resolution data.

The model boundary conditions consist in open, surface and land (river input) boundary conditions. The sea level open boundary condition in domain 1 is defined using a clamped condition along the entire open boundary except near land where the BLUMBERG and KANTHA (1985) radiation boundary condition is used. The sea level imposed in the open boundary is derived from the tidal global solution FES 95.2 (LE PROVOST *et al.*, 1998) and the inverted barometer approximation following the procedure of VRIES *et al.* (1995) and CAÑIZARES (1999) considering a reference sea level of 2.08m. The reference sea level is determined as the average of a long time series of the Cascais tide gauge measurements. One-way nesting is applied imposing FLATHER (1976) radiation boundary condition in domain 2, with water level and fluxes from domain 1 as a reference solution (LEITÃO *et al.*, 2005).

Daily averaged flows for Tagus River are obtained from the Omnias hydrometric station (provided by INAG - Instituto Nacional da Água). For the other two main rivers, Sorraia and Trancão (together representing less than a quarter of the Tagus River flow), a constant daily average flow is assumed. Other water sources have negligible effect on barotropic hydrodynamics of the estuary (FERNANDES, 2005).

The time evolution of the sea level due to atmospheric pressure gradients is calculated according with the time evolution of the atmospheric pressure using the inverted barometer approximation as in CAÑIZARES (1999). A reference atmospheric pressure value equal to 101330 Pa is considered (DORANDEU and LE TRAON, 1999; CAÑIZARES, 1999). The atmospheric pressure data is obtained from the ECMWF ERA40 re-analysis daily fields (http://data.ecmwf.int/data/d/era40_daily/) following TRIGO (2006), which has 6 hours time resolution and 2º30'x2º30' spatial resolution. No other meteorological forcing is considered for this work.

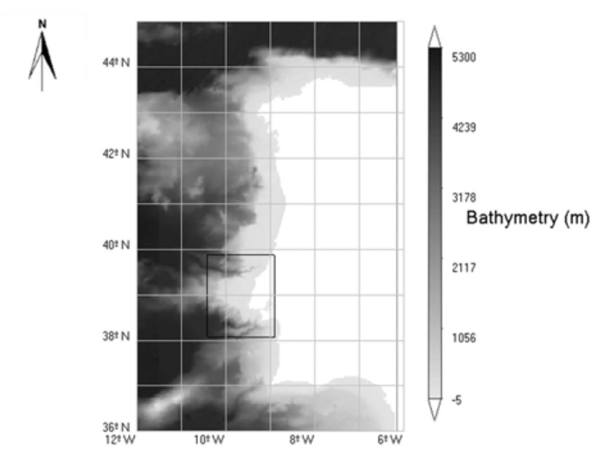

Figure 2. The Tagus Estuary model two domains. Domain 1 contains the Portuguese and Galician coast and domain 2 includes the Tagus Estuary and adjacent coast. Bathymetry is shown.

Two model simulations are run for the autumn/winter season of 1972 (01/10/1972 0h to 31/01/1973 0h), comprising the period when both daily averaged river flow from Tagus and tide gauge measurements for 11 locations are available. One of the simulations considers only tidal forcing; in the other tidal forcing as well as the inverted barometer approximation are considered.

The water level results of both simulations for tide gauge locations and the tide gauge measurements are detided using T_Tide software (PAWLOWICZ *et al.*, 2002). Since only three months of model results are considered for harmonic analysis some important semi diurnal and diurnal tide components (K_2 and P_1) are not estimated and so the tide residuals are filtered to remove the perturbations with period bellow 30 hours, which should be a consequence of imperfect detiding. This should not significantly reduce the representativeness of storm periods in detided residuals since storms in the Portuguese Coast are documented, as referred before, as lasting typically for a few days.

The filtered detided residuals of model simulation are contrasted with the filtered detided residuals of tide gauge measurements for the period 01/11/1972 to 31/12/1972 by calculating the centered Root Mean Square Error (RMSE) and correlation coefficient.

RESULTS

The descriptive statistics of the detided filtered residuals from model simulations and measurements are presented in Table 1.

The study of average detided water level is not the scope of this work and is presented here only as reference: an important average difference exist between model simulations and measurements which is though to be probably caused by the reference sea level prescribed in the boundary condition.

In terms of variability, as expressed by the standard deviation, both simulations present a smaller variability than measurements. The representation of this variability is considerably improved with the inclusion in the model of the inverted barometer approximation, particularly along the coast and in lower and middle estuary.

ANALYSIS

The statistics of the contrast between detided residuals from measurements and both model simulations are presented in Table 2.

In terms of centered RMSE it can be observed that, except in the upper estuary, the account of the inverted barometer approximation causes generally a reduction of this statistic by more than 5%, and 13% on average for gauges where improvement is found. This result is more pronounced in the coast (Cascais and Trafaria) and in estuarine areas constrained by the coastline (Seixal). Contrastingly, in the upper estuary the inverted barometer approximation causes a centered RMSE increase while at the lower estuary deep location of Lisboa this approximation does not provide a significant reduction of the RMSE.

The correlation coefficient results (Table 2) evidence a more pronounced influence of the account of the inverted barometer approximation in model performance. The results from the simulation without this approximation show that the model provides a poor representation of the detided water level evolution, with model results and measurements inversely correlated in all locations except the upper estuary. This situation evidences that important hydrodynamic effects affecting water level variability in most of the estuary and adjacent coast are being neglected by the model.

The correlation coefficient improves considerably in these locations with the account of the inverted barometer approximation: measurements and model results become directly correlated. The pattern of relative correlation coefficient values within the estuary and coast perfectly match the pattern found in the centered RMSE, with the approximation being more important in describing the variability outside the estuary and in Seixal. This

Table 1: Descriptive statistics for detided water level filtered to remove perturbations with period bellow 30 hours.

Tide gauge	Measurements		Model without inverted barometer		Model with inverted barometer	
	Average (m)	Standard deviation (m)	Average (m)	Standard deviation (m)	Average (m)	Standard deviation (m)
Cascais - 1	2.19	0.06	2.08	0.00	2.01	0.04
Paço de Arcos – 2	2.18	0.07	2.08	0.00	2.01	0.05
Trafaria - 3	2.23	0.08	2.08	0.00	2.01	0.04
Cacilhas – 4	2.15	0.07	2.07	0.00	2.00	0.04
Lisboa – 5	2.22	0.06	2.08	0.00	2.00	0.04
Cabo Ruivo – 6	2.26	0.07	2.10	0.01	2.03	0.05
Seixal – 7	2.21	0.06	2.10	0.01	2.03	0.05
Montijo – 8	2.25	0.07	2.10	0.00	2.03	0.05
Alcochete – 9	2.28	0.08	2.12	0.01	2.05	0.04
Ponta de Erva - 10	2.22	0.09	2.22	0.02	2.15	0.04
Vila Franca de Xira - 11	2.48	0.10	2.42	0.04	2.36	0.06

approximation is also important in Lisboa, although the model error in this location should be dominated by other effects. The upper estuary locations show a degradation of correlation with the inclusion of the inverted barometer approximation in modeling.

DISCUSSION

The results obtained in this work show that the inverted barometer approximation provides useful explanation of detided water level anomalies with period above 30 hours present in tide gauge records for the lower and middle estuary and estuary mouth, particularly in locations with shallow bathymetry or constrained by the coastline.

It is interesting to note that the importance of the inverted barometer approximation determined (typically 10% of measurement detided water level standard deviation) is very consistent with the values obtained by PONTE (2006) for the extratropical North Atlantic latitudes (above 10%) based on monthly average time series. This suggests that most of this above 30 hours variability should be connected with seasonal variability of atmospheric circulation. Also the centered RMSE obtained in Cascais tide gauge is sensibly the same (0.045m) as the one obtained in the much lower resolution (17kmx25km, longitude x latitude) model study of SEBASTIÃO *et al.* (2008) for the year of 1990 and the Northeast of North Atlantic, which considers explicitly the atmospheric pressure and wind forcing. This last concordance suggests that the large scale gradients in atmospheric pressure should be the determinant driver of storm surge as suggested by FANJUL *et al.* (1998) and TSIMPLIS and SHAW (2008).

The miscounting of this large scale circulation is shown to cause coarse detided water level variability errors. However, the hydrodynamic model can still be improved. Firstly, there is a water level bias which must be corrected. The works of FENOGLIO-MARC *et al.* (2005) and GOMIS *et al.* (2008) indicate that interannual variability of mean sea level is important in the Iberian Coast. In particular, FENOGLIO-MARC *et al.* (2005) find a positive time linear trend in mean sea level from Iberian Coast tide gauge data, which could explain the too small average water level observed in model results in Table 1. Therefore, the calculation, in the present work, of the reference sea level by averaging several years' data is possibly causing the neglect of significant trends (as suggested by DORANDEU and LE TRAON, 1999) and should be avoided if realistic modeling of the Tagus Estuary is intended.

Secondly, the poor results in the upper estuary and the relatively small effect of the inverted barometer approximation in the centered RMSE evidence that bathymetry is deficient. In fact, the poor correlation results in the upper estuary, where the inverted barometer approximation appears as inadequate, can be the result of the combined effect of a bad quality or resolution of bathymetry with a too small reference sea level, which reduces the water level variability.

Even discounting the inadequate reference sea level effect in model results there is evidence that a large part of detided water level variability with period above 30 hours remains unexplained by the inverted barometer approximation. Of course, bathymetry quality and resolution can also have an influence on this. However, it is still controversial the relative importance of local wind in these storm surge events and, hence, wind can also play a role in this lacking variability. In fact, GOMIS *et al.,* (2008) suggest that wind forcing should have an important role relative to atmospheric pressure in the Western Iberian Coast at these time scales (larger than one day) only in the summer, through upwelling (GILL, 1982). However, the work of VITORINO *et al.* (2002) evidences that typical wind forcing, in the form of southerly winds, appears to be associated to winter coastal storms in the coast north of the Tagus Estuary (latitude between 41ºN and 42ºN).

CONCLUSION

The research comprised in this work indicates that the large scale circulation driven by the atmospheric pressure is important in explaining the variability with period more than 30 hours, representative of winter storms, of the detided water level at the lower and middle Tagus Estuary. Together with previous research, the results obtained indicate that the atmospheric pressure should be more important than wind in driving storm surge episodes in the Portuguese Coast.

Due to the frequency of storm surge episodes reported at the estuary mouth, the prospect of their maintenance in a climate change future and the potential effects in estuarine environmental change, this indicates that large scale atmospheric pressure forcing should be accounted in hydrodynamic modeling used for estuary management. Also, the effects of storms in the inner estuary, in terms of hydrodynamics, biology and water quality, deserve further investigation.

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Table 2: Centered RMSE and correlation coefficient of model filtered detided water level results relative to filtered detided tide gauge measurements. Percentages are calculated referring to the measurement detided water level standard deviation.

Tide gauge	Centered RMSE				Correlation coefficient	
	Without inverted barometer		With inverted barometer		Without inverted barometer	With inverted barometer
	(m)	(%)	(m)	(%)		
Cascais - 1	0.06	102	0.05	78	-0.22	0.63
Paço de Arcos – 2	0.07	101	0.06	92	-0.22	0.44
Trafaria – 3	0.08	101	0.07	85	-0.20	0.53
Cacilhas – 4	0.07	101	0.06	95	-0.11	0.40
Lisboa – 5	0.06	101	0.06	100	-0.11	0.36
Cabo Ruivo – 6	0.07	103	0.07	92	-0.32	0.44
Seixal – 7	0.07	103	0.06	87	-0.28	0.53
Montijo – 8	0.08	101	0.07	99	-0.12	0.32
Alcochete – 9	0.08	102	0.08	107	-0.22	0.15
Ponta de Erva – 10	0.09	98	0.10	106	0.2	0.06
Vila Franca de Xira - 11	0.11	104	0.11	111	0.13	0.10

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