Coastal wave regime influence on Ria de Aveiro inlet dynamics

Leandro Vaz†, Sandra Plecha† and João Miguel Dias†

† CESAM, Physics Department,
University of Aveiro, Portugal
leandrovaz@ua.pt
sandraplecha@ua.pt
joao.dias@ua.pt

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ABSTRACT

Vaz, L., Plecha, S., Dias, J.M., 2013. Coastal wave regime influence on Ria de Aveiro inlet dynamics. In: Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), Proceedings 12th International Coastal Symposium (Plymouth, England), Journal of Coastal Research, Special Issue No. 65, pp. 1605-1610, ISSN 0749-0208.

The adjacent coastal zone of Ria de Aveiro lagoon is exposed to a highly energetic wave climate, with a yearly mean significant wave height of 2-2.5 m and wave periods of 9-11 s, corresponding to WNW to NNW swell. Consequently, it should be expected that the lagoon inlet hydrodynamic be dependent on the coupled forcing of tidal wave and wave regime. Thus, the main goal of this study is to assess the influence of the coastal wave regime at the inlet channel dynamics. The modeling system MORSYS2D, comprising the hydrodynamic model ELCIRC coupled with the wave model SWAN, is used to perform this study. The methodology developed consists in forcing the numerical models with local tidal harmonic constituents and with different constant regular wave scenarios typical of the northern Portuguese coast (high and normal wave activity and absence of waves). Under the normal wave activity scenario results show that the inlet channel hydrodynamics is mainly dominated by the tidal forcing. For the highest wave regime are found higher sea levels induced by the wave set-up. Consequently, it was found that the storm events induce important wave's set-up that change the inlet hydrodynamics, requiring that the coupling between waves and tides should required to accurately represent the physical processes of the lagoon. Although the dominant forcing of the Ria de Aveiro inlet hydrodynamics is the tide, it may be concluded that fluctuations at the wave regime influences the sea level and current velocity at the Ria de Aveiro inlet.

ADDITIONAL INDEX WORDS: *ELCIRC, SWAN, swell, sea surface elevation, current velocity.*

INTRODUCTION

The coastal shoreline includes a considerable extension of lagoons and estuaries, often characterized by dynamic tidal inlets. These environments are normally sheltered and the wave action is minimal when compared with exposed coasts (Short, 2007; Vila-Concejo *et al*., 2010). However its effects should be researched since the economic and environmental importance of tidal inlets has been growing worldwide. The management of these systems is no longer restricted to the maintenance of navigation channels, but also addresses new challenges, such as the adjacent shoreline stability or the water renewal in the inner part of the system, which is often under a high anthropogenic pressure, as for example that derived from aquaculture. Portuguese lagoons illustrate very well this phenomenon since many social and economic activities are concentrated in these coastal areas and include (Bertin *et al*., 2009):

- Habitation and construction development on the barrier islands, despite the shoreline threat hazard;
- Aquaculture and fishing;
- Commercial maritime traffic;
- Recreational activities.

Besides the oceanic tidal effects the adjacent coastal zone of Ria de Aveiro lagoon (Figure 1) is exposed to a highly energetic wave climate, with a yearly mean significant wave height (H_s) of 2-2.5 meters, wave periods of 9-11 seconds corresponding to WNW to NNW swell (Andrade *et al*., 2002). During the winter, North Atlantic storms give rise to high amplitude waves, whose significant height frequently exceeds 5 meters, while milder conditions are observed during the summer (Ferreira *et al*., 2008).

The physical processes in the lagoon have been studied in the last decades. One of the first steps in this task was the study made by Dias *et al*., (1999). The authors concluded that the tide in the Ria de Aveiro is semi-diurnal and is the main hydrodynamic forcing. They also showed that the lagoon should be considered vertically homogenous with exception to periods of important rainfalls. Several studies based on numerical modelling were performed to investigate subjects such as the tidal propagation in the lagoon (Dias and Fernandes, 2006; Dias and Picado, 2011), the Lagrangian transport of particles (Dias et al., 2001; Picado *et al*., 2011) and the sediment transport (Lopes *et al*., 2006; Plecha *et al*., 2011; Lopes *et al*., 2011; Plecha *et al*., 2012). However, the effects of the wave climate in the lagoon hydrodynamics were never researched until the present work.

In fact, the only publication found concerning the coastal wave regime influence in the hydrodynamics of a Portuguese lagoon was performed by Malhadas *et al*. (2009). The authors analysed the coastal waves effect on sea level in Óbidos lagoon and concluded that there is a correlation between the wave height and the sea-level elevation only during high wave activity periods and that a significant super-elevation on lagoon sea level occurs during storm wave periods.

It should be pointed out that according with Nielsen and Apelt (2003), the presence of waves can cause large differences in terms of sea-level variations. Their relative importance depends upon the morphology of the lagoon entrance, as well as the local wave regime. In shallow and narrow entrances, the sea-level elevation

DOI: 10.2112/SI65-271.1 received 07 December 2012; accepted 06 March 2013.

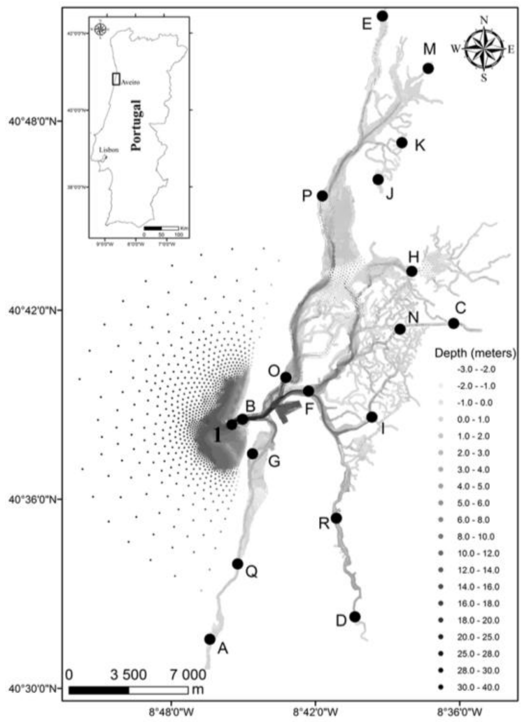

Figure 1. Ria de Aveiro bathymetry with depth in meters and with the location of the stations used in the model calibration (letters), and with the station used to study the hydrodynamic changes induced by the waves (number 1).

caused by wave motion, such as wave breaking, is an important mechanism. This rise in sea level, or set-up, induced by waves is commonly termed as 'wave set-up' (Angwenyi and Rydberg, 2005).

Thus, the main goal of this work is to study the influence of the wave regime on the hydrodynamics of Ria de Aveiro inlet through the analysis of numerical model results. Combined with this primary aim, there are other specific goals such as: improve a previous implementation to Ria de Aveiro of the hydrodynamic numerical model ELCIRC, updating the lagoon bathymetry using the most recent bathymetry data sets and consequently recalibrating the model; use MORSYS2D to couple the wave model SWAN to ELCIRC, to make the study of the combined effects of tidal and wave regime.

Consequently, this work was driven not only by the need to improve and develop the numerical tools available to study Ria de Aveiro dynamics, but also due to the influence of the coastal waves in the lagoon hydrodynamic has never been the subject of study.

STUDY AREA

The Ria de Aveiro is a shallow coastal lagoon located on the northwest coast of Portugal, the most extensive in Portugal (Teixeira, 1994), separated from the Atlantic Ocean by a sand dune barrier. It has an irregular geometry, and its only connection with Atlantic Ocean is through an artificial channel constructed in 1808 (Dias, 2001: Dias and Mariano, 2011). The lagoon has a maximum width of 8.5 km and a length of 45 km, being constituted by four main channels: Mira, São Jacinto, Ílhavo and Espinheiro. The Mira channel is an elongated shallow arm, with 29 km length, the S. Jacinto channel is about 29 km long, and the Ílhavo and Espinheiro have 15 and 17 km long, respectively (Dias, 2001).

The area of the lagoon has a large variability according with the tidal influence in its hydrodynamics. In spring tides the lagoon area reaches a maximum area of 83 km^2 at high tide, which decreases to a minimum of 66 km^2 at low tide. The average depth in Ria de Aveiro is about 1 meter, relative do local datum, although the inlet channel can exceed 30 m deep, due to dredging operations that are frequently carried out to allow the navigation (Dias and Lopes, 2006a).

The main forcing agent driving water circulation in Ria de Aveiro is the tide, which is mesotidal, presenting an average tidal amplitude at the inlet of 2 m, and amplitudes of 0.6 m in neap tides and 3.2 m in spring tides (Dias *et al*., 2000; Araújo *et al*., 2008). The estimated tidal prism of the lagoon is about 136.7×10^6 m^3 for a maximum spring tide and 34.9×10^6 m^3 for minimum neap tide (Dias and Picado, 2011). These values are much higher when compared with the total freshwater input in a tidal cycle of approximately 1.8×10^6 m^3(Moreira *et al*.,1993). The tidal prism of each channel relative to it its value at the mouth is: 35.4% for S. Jacinto channel, 25.6% for Espinheiro channel, 10.0% for Mira channel and 13.5% for Ílhavo channel (Dias and Picado, 2011). Likewise, the semidiurnal tides are the main factor influencing the hydrodynamics of the lagoon (Dias *et al*., 2000). Thus, the most important harmonic constituents in Ria de Aveiro are M_2 and S_2, corresponding to about 88% and 10% of total tidal energy, respectively (Dias, 2001).

The lagoon has five main rivers, discharging in all of the main channels: Vouga, Antuã, Caster, Boco and Ribeira dos Moinhos, being the most important the Vouga river. According with Ria de Aveiro Polis Litoral program, which considered the data presented in the *Plano de Bacia Hidrográfica* (www.arhcentro.pt), the mean freshwater inflow for Vouga River is 60.0 m^{3}s^{-1}, 4.5 m^{3}s^{-1} for Antuã, 1.6 m^{3}s^{-1} for Caster, and 1.0 and 3.6 m^{3}s^{-1} for Boco and Ribeira dos Moinhos, respectively. The lagoon is vertically homogenous during most of the time (Dias *et al*., 1999), although during strong freshwater flows, is classified as weakly stratified (Vaz and Dias, 2008). Additionally to the tidal forcing, and in extreme situations, also the wind and freshwater discharge (mainly from the Vouga river) influence the Ria de Aveiro hydrodynamics.

METHODS

The numerical simulations were performed with the 2DH morphodynamic modeling system MORSYS2D (Fortunato and Oliveira, 2004). This modelling system integrates the hydrodynamic model ELCIRC (Zang *et al*., 2004), which calculates tidal elevations and currents, the wave model SWAN (Booij *et al*., 1999), which computes wave propagation and the model SAND2D (Fortunato and Oliveira, 2004) that computes sand transports and updates the bottom topography. In this study, the module SAND2D was not activated.

Model Implementation

The first step in this study consisted in the improvement of a previous implementation of the numerical model ELCIRC to Ria de Aveiro (Picado *et al*., 2010), updating the original model bathymetry. The topo-hydrographic data used in that study was mainly from 1987/88, while for this study was available data collected until November 2011 by Ria de Aveiro Polis Litoral program (Figure 1). The bathymetric data is referenced to the average mean sea level (2 m) and was numerically discretized in a finite-element grid with 103515 elements and 74094 nodes.

The hydrodynamic model ELCIRC was forced by 11 harmonic constituents (MSF, O_1, K_1, N_2, M_2, S_2, M_4, MN_4, MS_4, M_6 and $2MS_6$) computed through the high-resolution finite element model of barotropic tides for the Iberian Atlantic shelf, developed by Fortunato *et al*. (2002). The largest time step that prevents the appearance of oscillations was set to 90 seconds.

The SWAN model runs considering wave and wind fields as driving forces, more specifically the significant wave height, wave period and direction and the velocity and direction of the wind. In the present study two nested grids are used in the wave model with different dimensions and characteristics, as reported in Plecha (2011) and Plecha *et al.*, (2012). The grid with higher dimensions extends from the offshore area with a coarser resolution. In this grid are imposed the waves boundary conditions: a regular monochromatic wave or a wave regime. The second grid encompassing the inlet area is curvilinear in space and with finer resolution. The calibration of SWAN was performed by Plecha (2011), by comparing model predictions with buoy records at Leixões (41°19'00"N, 8°59'00"W).

The inputs were defined and considered constant for the entire simulation period, and are defined from the analysis of the wave and wind regime conditions from the Figueira da Foz buoy records and of the meteorological station Casal do Rato, respectively.

Hydrodynamic Model Calibration

The calibration of the hydrodynamic model was performed comparing model predictions and observations of sea surface elevation data at 18 stations within the lagoon (Figure 1), and is based on the adjustments of the parameters to which the model is most sensitive. According to Dias and Fernandes (2006), the magnitude of the bottom friction coefficient induces changes in the tidal wave propagation within the Ria de Aveiro. Based in previous works (Dias and Lopes, 2006a,b; Dias *et al*. 2009; Picado *et al*., 2011), it was decided to use the Manning coefficient dependent of the depth (ranging between 0.014 and 0.029) as calibration parameter. The data available are from field works carried out in Ria de Aveiro in the years 2002 and 2003 (Araújo *et al*., 2008).

The model was calibrated following the methodology proposed by Dias and Lopes (2006a), by initially comparing visually the observed sea surface elevation data with the hydrodynamic model results. After the model's accuracy is evaluated through the computation of the Root Mean Square (RMS) error and the Skill parameter (Warner *et al*., 2005). The comparison between the observed and predicted amplitude and phase of the main tidal constituents determined from harmonic analysis is also performed, in order to quantify separately the amplitude and phase lags of the major tidal constituents for the all monitoring stations. In this work the harmonic analysis is performed using Pawlowicz *et al*. (2002) package.

Model Setup

To research the wave effect on the Ria de Aveiro inlet hydrodynamics the simulations were performed for a period of 8 days (including 2 days of spin up period) and for scenarios of normal and high wave energy, as well as a reference scenario that consider the absence of wave forcing. The results are analyzed by comparing the sea surface elevation and current velocities for all the simulations.

The wave and wind regime conditions were defined through the analysis of the Figueira da Foz buoy records (40°11.13' N; 9°8.73' W, depth 92m ZH) and of the meteorological station Casal do Rato (40°09'12.52" N, 8°50'36.07" W) (http://snirh.pt), respectively.

The normal regime has a typical WNW to NNW swell, with periods between 9 and 11 seconds, and moderate wind from North. In the storm events, the H_s (Significant Wave Height) may reach 8 meters, and the waves are propagated from SSW. In these events, the wind is stronger (can reach 16 ms^{-1}) and has a provenience from SE.

Thus, the scenario 0 considers the absence of waves and wind, meaning that only tidal forcing is simulated. The scenario 1 is referent to the normal wave climate of the Norwest Portuguese coast. Thus, the model inputs are: 2 meters of significant wave height (H_s), wave period of 9 seconds and waves coming from Northwest. The wind velocity was set to 4 m/s coming from Northwest. The scenario 2 corresponds to the high wave activity. Therefore, it was inputted a wave with H_s of 8 meters, wave period of 12 seconds and waves coming from Southwest. The wind velocity was set to 16 m/s coming from Southeast.

RESULTS AND DISCUSSION

Hydrodynamic Model Calibration

The hydrodynamic model calibration results reveal a good agreement between predictions and observations. In Figure (2), as example, is illustrated the Sea Surface Elevation (SSE) for the station B (Barra), located in the lagoon inlet. With the exception of the stations E, M, K and J, the RMS values ranges from 2.5% to 13.3% of the local amplitude in all stations. The stations B, F, G, H, I, L, N, O, P, Q and R have a RMS value between 0 and 10%. Thus, the agreement between predictions and observations, in the most of the stations, ranges from very well to excellent, according to the classification presented by Dias and Lopes (2006). In general, it was found that the errors increase with the distance between the station and the lagoon mouth.

At station B (Barra), the most important in this study since it is located at the lagoon inlet (Figure 2), the difference between predictions and observations is approximately 7 cm, which represents an error of 2.5% of the local tidal amplitude. The Skill value is 0.9905, which represents an excellent agreement between computed results and observations.

From the harmonic analysis results, the first conclusion that is possible to draw is that the M_2 and S_2 are the most important tidal constituents in the lagoon, representing ~ 90% of the tidal energy in Ria de Aveiro lagoon, in accordance to Dias *et al*. (1999) results. For the M_2 constituent (the major tidal constituent in the Ria de Aveiro (Dias *et al.,* 1999)), the results show that the mean amplitude difference is about 9 cm. The mean phase difference is about 10º, corresponding to a difference of about 20 minutes in the arrival of the tidal wave. Despite these differences, the results reveal a good agreement between the computed and measured

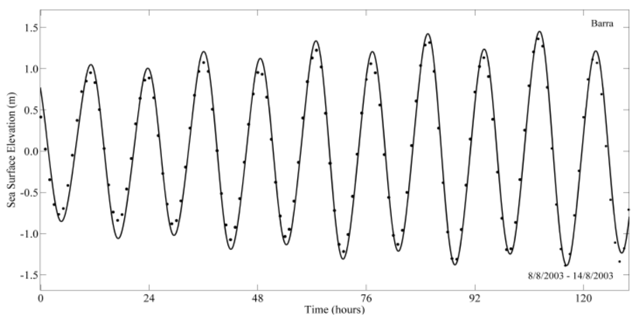

Figure 2. Comparison between predicted and measured SSE values for the calibration procedure. (● black: data; black solid line: model)

values. At station B (Barra), this difference is much smaller than the average value: less than 6 minutes in phase and 0.15 cm in amplitude.

It is important to note that the SSE comparison is performed using field data collected in 2003 and modeling results determined for a bathymetry of 2011. The results from several publications, including Araújo *et al.,* (2008), revealed that over the years the tidal range in the Ria de Aveiro has been increasing, while the phase is decreasing, in response to reported local bathymetric changes.

According to the results obtained, it may be considered that the model reproduces accurately the SSE data, and consequently the tidal processes in the lagoon. The numerical results obtained for the study area (inlet) should be considered in excellent agreement with the observed data. Therefore it may be concluded that the hydrodynamic model is calibrated and able to reproduce the tidal processes in the area of interest for this study.

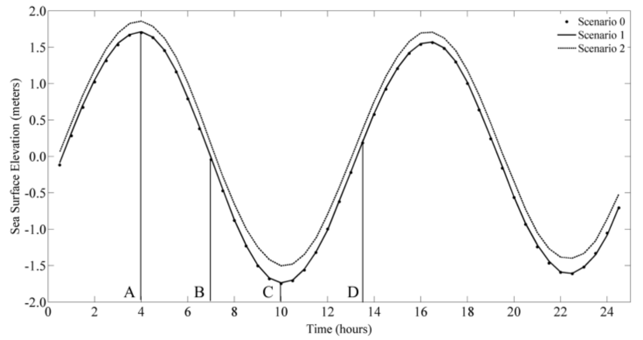

Figure 3. Comparison between normal and storm regimes as well as the reference scenario. The vertical lines correspond to instants chosen to illustrate horizontal sea surface elevation fields.

Hydrodynamic Changes

Primarily, the effect of waves on the sea surface elevation is analysed. The time series for the three scenarios mentioned before are illustrated in Figure 3 for a station located at the inlet (Figure 1).

The analysis of the sea surface elevation time series (Figure 3) reveals that the normal wave climate (scenario 1) has no influence in the sea surface elevation, because there is an almost complete overlap of the lines of the scenario 1 and scenario 0. For the storm regime scenario (scenario 2) is found a clear over-elevation of the sea surface (wave set-up), and the high and low tides have higher elevations, in accordance with Nielsen and Apelt (2003). These results are also consistent with the findings of Malhadas *et al.* (2009) for the Óbidos lagoon that concluded that there is a correlation between the wave height and the sea-level elevation only during high wave activity periods, when a significant wave set-up on lagoon sea level is observed.

This analysis also shows that the differences induced by the wave regime are higher in low tide when compared with high tide. In the station analysed, the differences between the scenarios 1 and 2 results and the reference scenario is approximately 15 cm in the high tide, while in the low tide is about 25 cm.

To better visualize the effects of the wave characteristics, horizontal fields of the differences between scenarios 1 and 2 were performed and are presented in Figure 4. Positive values mean that there is a wave set-up in the scenario 2 relatively to scenario 1.

The trends found in the illustration of the SSE time series (Figure 3) are also perceptible in the horizontal fields of SSE differences (Figure 4). The image A corresponds to the high tide and the differences between the scenarios are minimal, approximately 15 cm in all the inlet area. The image B corresponds to an ebb condition, thus, the differences increase to

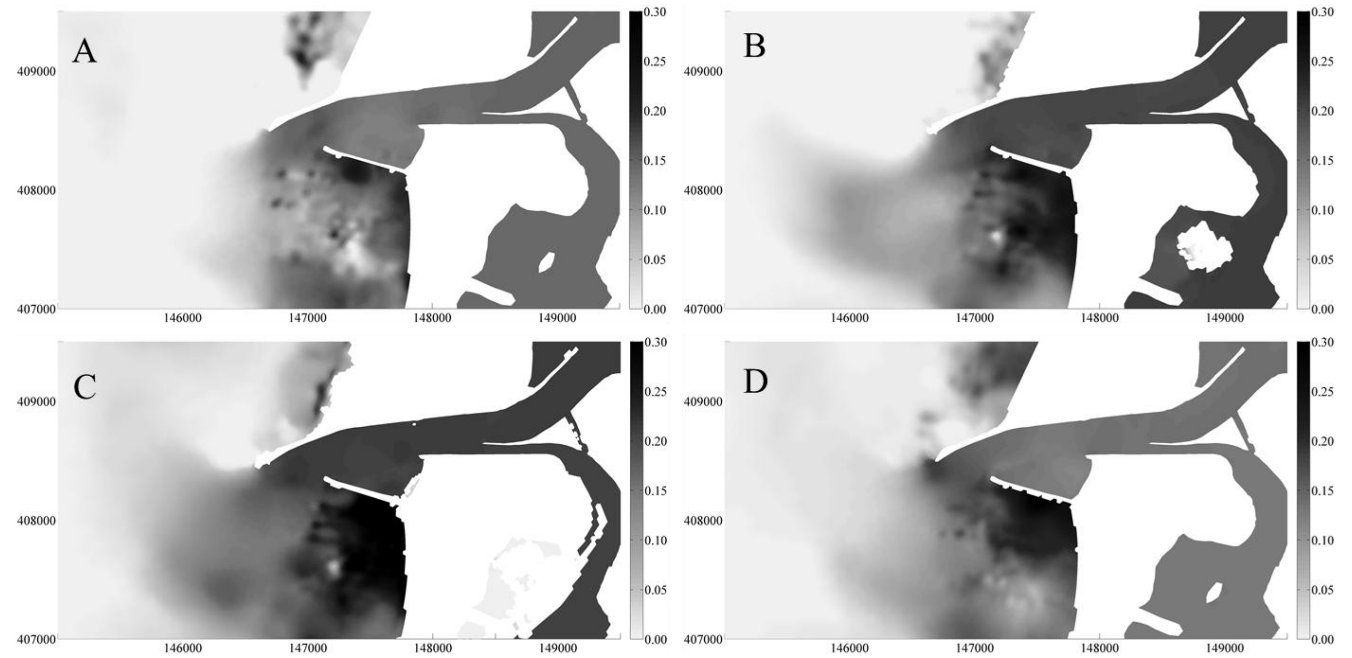

Figure 4. Horizontal fields of differences of sea surface elevation between scenarios 1 and 2, in meters. The letters corresponds to the instants chosen to compute the horizontal fields, represented in Figure 3.

values of around 25 cm. For image C, which corresponds to the low tide, the differences between the scenarios are maxima, with values of the same order of magnitude of those found in image B. However, in some places as for example between the jetties, the values are higher than those presented in image B. In flood conditions (image D) the values decrease again to 15 cm. The most affected area is the beach south of the lagoon mouth, where differences of about 30 cm were found in the low tide.

The wave set-up found at the inlet in all the numerical results may be explained by the gathering of water in the inlet zone caused by the constant wave propagation and consequently braking inside the Ria de Aveiro mouth. The differences are higher during ebbing and consequently in the low tide, because in this case the waves propagation and tidal currents have opposing directions. In this case there is a wave's compression, with a decrease in their wavelength and an increase in their amplitude. Thus, in the normal regime the tide acts almost as a single forcing agent, while in the storm regime scenario the constant wave propagation in the opposite direction of the tidal currents causes higher water retention in the inlet.

In Figure 5 are represented the horizontal fields of the differences of the intensity of current velocities for scenarios 1 and 2. Positive values represent higher velocities in the scenario 2, while negative values denote that the velocity is higher in the scenario 1.The pattern of the velocities difference between the scenarios is not as well defined as that found for the sea surface elevation. The regions with higher differences between the scenarios are offshore the inlet and near shore Northward and Southward the inlet. This is justified considering that there are important differences in the current velocities in the breaking zone (where they show a chaotic pattern), which are dependent on the characteristics of the wave's adopted for each scenario.

From the analysis of the panels shown in Figure 5, it is observed that the differences in the velocities are related with the bathymetry of the inlet. In fact, the higher differences are found in the deeper areas, corresponding to higher velocities in scenario 2. Nevertheless, in the shallower areas of the inlet there are regions where the velocity is higher in the normal regime (scenario 1). In this case, due the low depth of these areas the wave set-up becomes important, and therefore the velocity will be lower in scenario 2 since the increase in the total water column height is higher and therefore by continuity the velocity will decrease. These patterns are observed mainly in images A and D that corresponds to the high tide and flood conditions.

Regarding image A, which corresponds to the high tide, are found areas with higher velocities for both scenarios. Generally, the area where the velocity is higher in scenario 2 corresponds to the deepest areas of the inlet, with differences of about 0.3 m/s in main channel. The higher velocities in scenario 1 are found mainly in shallower areas of the lagoon, in accordance with the dynamics explained above. However, it should be noticed that these differences are small, and are only visualized because of the scale adopted.

For image B, corresponding to the ebb condition, the velocity is higher in scenario 2 for the majority of the inlet area, with differences of about 0.2 m/s. The same pattern is observed in image C (low tide), however with lower differences (approximately 0.1 m/s).

Concerning image D, which represents the flood condition, are found the same patterns identified in image A. Nevertheless, the velocities for the majority of the inlet area are higher for the storm scenario.

CONCLUSIONS

The MORSYS2D modelling system, integrating the hydrodynamic model ELCIRC coupled with the wave model SWAN, has been used to study the influence of coastal waves in the Ria de Aveiro inlet dynamics. This modelling tool has been successfully developed and applied in order to achieve the main

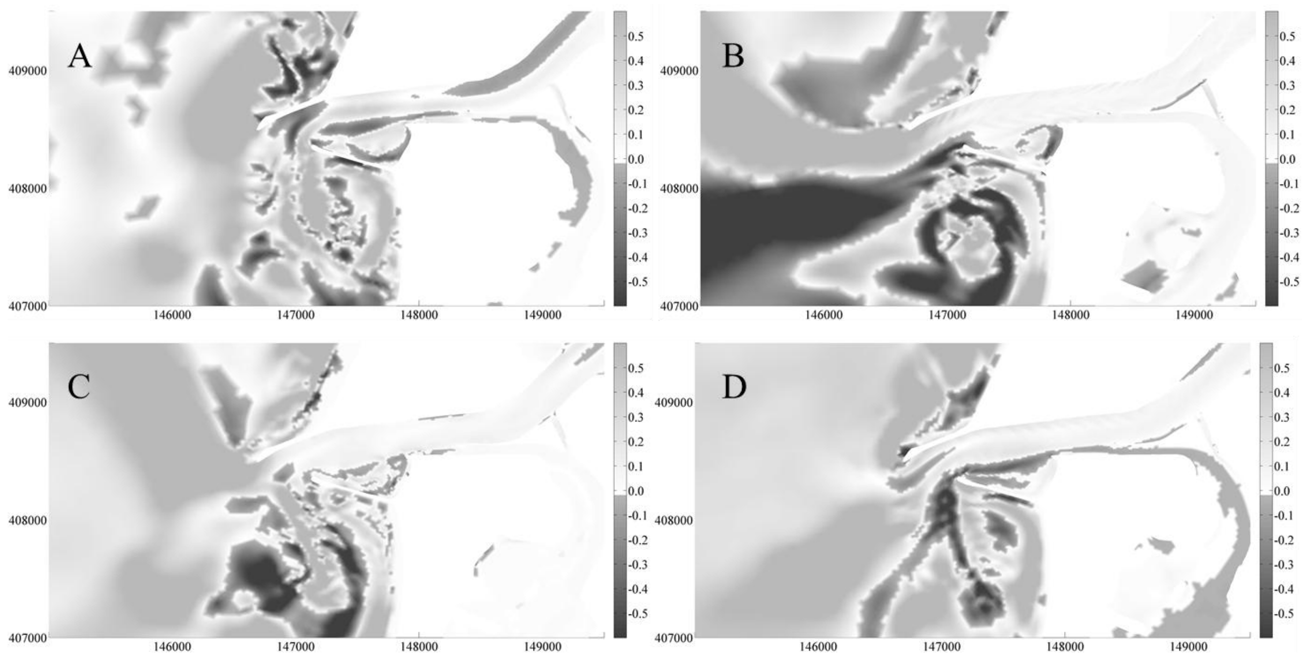

Figure 5. Horizontal fields of differences of the intensity of the current velocity between scenarios 1 and 2, in m/s. The letters corresponds to the instants chosen (presented in Figure 3) to represent the horizontal fields.

objective of this work.

The bathymetry was successfully updated with a recent bathymetry data set, and the results of the hydrodynamic model calibration confirm that the model is able to represent the Ria de Aveiro hydrodynamics.

The results found under the wave regime forcing show that for the low wave activity scenario (normal regime) the inlet hydrodynamics is mainly dominated by the tidal forcing. For the highest wave regime are found higher sea surface elevations at the inlet induced by the wave set-up when compared with simulations performed only with tidal forcing or with the normal regime. In fact, the modelling results show that the lagoon sea level remains above offshore sea level during storm wave periods.

Although the dominant forcing of the Ria de Aveiro inlet hydrodynamics is the tide, it may be concluded that the sea level and current velocity fluctuations at the Ria de Aveiro inlet depend also on the wave regime. Consequently, the storm events induce important waves set-up that change the inlet hydrodynamics, requiring that the coupling between waves and tides should be considered to represent accurately the processes which depend on the inlet dynamics.

ACKNOWLEDGEMENT

This work was been supported by FCT and by European Union (COMPETE, QREN, FEDER) in the framework of the research project PTDC/AAC-AMB/113469/2009 - PAC:MAN - Pollution accidents in coastal areas: a Risk management system. The authors thank Profs. Y. Zhang and A.M. Baptista for the model ELCIRC (www.stccmop.org/CORIE/modeling/elcirc) and to Anabela Oliveira, André Fortunato and Alberto Azevedo from the Portuguese National Laboratory of Civil Engineering (LNEC) for adapting and making available the numerical codes used.

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