Influence of mean sea level rise on tidal dynamics of the Ria de Aveiro lagoon, Portugal

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ABSTRACT

Global mean sea level rise is an important consequence of climate change because of its impact on coastal regions. Recent studies highlight that tidal propagation in shallow waters tends to be modified with mean sea level rise, intensifying coastal threats. This study aims to quantify changes in tidal patterns in Ria de Aveiro coastal lagoon, Portugal in response to the local mean sea level rise. To achieve this goal the hydrodynamic model ELCIRC, previously calibrated and validated for Ria de Aveiro, was applied, considering the present mean sea level and a local mean sea level rise projection of 0.42 m for the end of the 21st century, assuming no change in bed elevation. The model results for present mean sea level show that the amplitude of the main semi-diurnal (M2) and diurnal (K1) constituents decrease whereas the respective phase increases towards the head of the estuary, while the M4 constituent shows an opposite pattern, due to the upstream lagoon shallowness. As consequence, the tidal distortion is higher in the lagoon upper reaches than at the lagoon mouth. Under mean sea level rise conditions, the tidal wave tends to be less distorted in the upper lagoon, given that the M2 amplitude tends to increase while the M4 amplitude tends to decrease. The results highlight that tidal current magnitude decreases toward the channel’s head for both scenarios, but their magnitude tends to increase with mean sea level rise. The residual currents showed a net export of materials to the ocean, which will increase with mean sea level rise.

INTRODUCTION
Global mean sea level has risen over the 20th century and several studies predict that the mean sea level will continue to rise during the 21st century as consequence of climate change. In general, the physical impacts of mean sea level rise on coastal areas are inundation of low-lying coastal areas, landward intrusion of salt water in estuaries and aquifers, landward migration of sandy beaches and barrier island coasts and habitat loss. Recent studies also show that tidal propagation in shallow waters will be modified, intensifying coastal threats (Pickering et al., 2012; Ward et al., 2012; Pelling et al., 2013). These works show that the tidal modifications are strongly dependent on coastal geometry, presenting opposite tendencies in resonant and non-resonant areas. Therefore understanding the local tidal modification is crucial.

Coastal lagoons are shallow coastal landforms particularly sensitive to the mean sea level rise because they are found in low-lying coasts worldwide. Considering that they are extremely rich in fauna and flora, and that lagoonal species are dependent on the lagoon tidal conditions, it is crucial to quantify tidal changes in this environments induced by the mean sea level rise. Attending to these issues, the present study aims to quantify tidal changes in Ria de Aveiro coastal lagoon in response to the local mean sea level rise. To achieve this goal the hydrodynamic model ELCIRC, previously calibrated and validated for Ria de Aveiro (Lopes et al., 2013a; Lopes and Dias, submitted), was applied to this system, considering two scenarios: the present mean sea level and a local mean sea level rise projection of 0.42 m for the end of the 21st century. The 0.42 m sea level rise scenario corresponds to Lopes et al. (2011) estimation, considering the SRES A2 storyline and the results from the Atmosphere Ocean General Circulation Model GISS-ER for the Portuguese coast.

STUDY AREA
The Ria de Aveiro is a shallow lagoon with a complex geometry, located on the northwest Portuguese coast (Figure 1). It is 45 km long and 10 km wide and covers an area of 89.2 km² at spring tide which is reduced to 64.9 km² at neap tide (Lopes et al., 2013a). The lagoon contains four main channels Mira, S. Jacinto, Ílhavo and Espinheiro, and a large number of shallow narrow channels and is characterized by large areas of mud flats and salt marshes. The average depth in the navigation channel (15 m relative to chart datum) is higher than the average depth of the remaining lagoon (1 m relative to chart datum).

DOI: 10.2112/SI70-097.1 received 25 November 2013; accepted 21 February 2014. © Coastal Education & Research Foundation 2014
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METHODOLOGY

The 2D hydrodynamic model ELCIRC (Zhang et al., 2004) was applied to Ria de Aveiro lagoon in order to study the tidal propagation under different mean sea level conditions. The model configuration used was previously calibrated for tidal propagation by Lopes et al. (2013a) and Lopes and Dias (submitted) and validated for storm surge propagation by Lopes and Dias (submitted). Besides the description of water dynamics in the lagoon channels, the numerical grid allows the inundation of its marginal lands. This model ability is extremely important in sea level rise studies, considering that the channels marginal regions of Ria de Aveiro present low altitude and are potentially flooded during high sea levels.

Two scenarios were simulated, one considering the present mean sea level and other one considering the local mean sea level rise projection of 0.42 m obtained by Lopes et al. (2011) for the end of the 21st century. No change in bed elevation was considered. The model was forced by thirteen harmonic constituents (M_2, O_1, K_1, P_1, Q_1, N_2, M_2, S_2, K_2, M_4, M_N, MS_2 and M_6) taken from the regional model developed by Fortunato et al. (2002). The freshwater input and wind effects were neglected considering their minor importance relative to the tide. The time step was 90 s and the model was run for 34 days. The numerical results were then analyzed discarding the first four days of outputs (spin up period). For both simulations, harmonic analysis of water levels and velocity was made at the numerical nodes which are permanently under water for the each scenario. The amplitude and phase of the most important water level harmonic constituents were determined using the matlab package T_tide (Pawlowski et al., 2002) and the results were analyzed independently and used to assess tidal asymmetry for both simulations, through:

\[ A_i = \frac{A_{M_i}}{A_{M_2}} \]

\[ \varphi = 2\theta_{M_i} - \theta_{M_2} \]

Where \( A_i \) is the amplitude ratio, \( A_{M_i} \) and \( A_{M_2} \) are the amplitudes of \( M_i \) and \( M_2 \) constituents, respectively. \( \theta \) is the phase of \( M_i (\theta_{M_i}) \) relative to the phase of \( M_2 (\theta_{M_2}) \). The \( A_i \) indicates the magnitude of tidal asymmetry; as the larger the amplitude ratio the more distorted is the tide. The \( \varphi \) indicates flood or ebb dominance (\( 0^\circ < \varphi < 180^\circ \) indicates flood dominance and \( 180^\circ < \varphi < 360^\circ \) indicates ebb dominance). The tidal asymmetry differences were assessed computing the ratio between \( A_i \) for both scenarios under analysis. Also, the regions that changed their dominance were identified.

The harmonic analysis of velocity was performed to compute tidal ellipses of \( M_2 \) constituent for both scenarios, using the matlab package developed by Xu (2002). The semi-major axis and the eccentricity of tidal ellipses were analyzed. The differences in the tidal ellipses motivated by the increase in the mean sea level were assessed computing the ratio between the semi-major axis for the present and for the future mean sea level. Also, changes in the eccentricity were assessed identifying the regions with modifications in its rotation.

Finally, the residual currents were assessed averaging the currents over 29.56 days (two times the \( M_2 \) constituent period). The changes in the magnitude of residual currents were found...
computing the ratio between residual currents intensity for both scenarios under analysis.

RESULTS AND DISCUSSION

The model results were used to characterize the tide along the lagoon for both scenarios. Figure 2 presents the distribution of amplitude and phase of M₂, K₁ and M₄ constituents for the present mean sea level. The results show that the M₄ constituent is the most important in the establishment of the overall lagoon water levels. Indeed, its amplitude ranges from 0.5 m at the upper reaches of the lagoon channels to 1.1 m at the lagoon mouth. The diurnal contribution is one order of magnitude smaller, and ranges from 0.04 m at the upper reaches of the main channels to 0.05 m at the lagoon mouth. The M₄ amplitude presents an opposite pattern, with amplitude values increasing towards the channel’s head, following the decrease in lagoon depth. The M₄ constituent amplitude at the lagoon mouth is close to zero while it can reach 0.2 m at the shallow channel’s extremities. Concerning the phase results, M₂ and K₁ constituents show identical patterns, with values increasing towards the channel’s head. Concerning the M₄ constituent, the phase is almost constant between the lagoon mouth and the middle of the main channels, decreasing from there to the end of the narrow channels. The amplitude and phase patterns for the 0.42 m mean sea level rise scenario are identical to those described for the present and therefore are not shown here. Despite the similarities in the patterns, important changes are identified in the phase and amplitude magnitudes in response to the decrease of friction motivated by the mean sea level rise. Indeed, the amplitude of M₄ constituent decrease between 2% and 5% at the lagoon central area and increase between 5% and 20% at the channel’s head. Its phase increases at the lagoon central area and decreases at the channel’s head. Moreover, the differences found in the amplitude and phase of M₄ constituent close to the lagoon mouth are negligible. Nevertheless, in the lagoon central area and channel’s head its amplitude decreases between 10% and 20%.

Concerning the tidal asymmetry (Figure 3), the amplitude ratio results evidence that the tidal distortion patterns are similar for both scenarios, increasing its value from the lagoon mouth (close to zero) towards the channel’s head (between 0.3 and 0.4). Despite the similarities in pattern, the tidal distortion tends to increase with the mean sea level rise (see Figure 3 c) from the lagoon mouth surroundings until the main channel’s head and in one small area located at the S. Jacinto channel. For the remaining lagoon the tidal distortion tends to decrease with mean sea level rise. The tidal dominance results show that the lagoon is ebb-dominated at the lagoon mouth and central area, and flood-dominated at the channel’s head. This pattern was observed for both mean sea levels, however, it should be noted that the ebb-dominance tends to be extended further upstream at the S. Jacinto channel (see Figure 3c) with the mean sea level rise.

The tidal features and propagation within Ria de Aveiro lagoon for the present mean sea level were previously studied by several authors (Dias et al., 2000; Dias, 2001; Araújo, 2005; Lopes et al., 2006; Oliveira et al., 2006; Araújo et al., 2008; Picado et al., 2010; Lopes et al., 2011; Valentim et al., 2013). The patterns of amplitude and phase obtained in this study are similar to those obtained by these authors. Nevertheless, important differences in the magnitudes of amplitude and phase of tidal constituents were found. Generally, the amplitude of M₄ constituent is higher and the amplitude of M₄ constituent is lower than amplitudes obtained in those studies. Also, the phase of M₄ constituent obtained here is lower than those obtained in the previous studies. These differences can be explained in great part by the geomorphic changes in the last 25 years at the inlet regions and at the lagoon main channels, showing that the lagoon tidal features are highly dependent on bathymetric changes (Araújo et al., 2008). In fact, previous works are based on bathymetric records obtained in a global survey performed in 1987/88 and in a survey restricted to the inlet region obtained in 2001, whereas the bathymetry used here was updated for the lagoon main channels and the inlet region with data measured in 2011 and 2012, respectively. Indeed, a deepening of the lagoon main channels was found between 1987 and 2011, being the S. Jacinto and Espinheiro channels the most affected, with changes of about 8 meters in some areas (Lopes et al., 2013b).

The relation between tidal asymmetry and sediment dynamics was studied in other estuaries worldwide (Dronkers, 1986; Friedrichs and Aubrey, 1988; Bolle et al., 2010; Brown and Davies, 2010; Jewell et al., 2012). They found that in ebb-dominated estuaries there is a trend to export sediments, while in flood-dominated estuaries there is a trend to sediment import. Brown and Davies (2010) found that Dyfi Estuary presents a tidal dominance pattern similar to Ria de Aveiro lagoon, with ebb-dominance in the lower estuary and flood-dominance in the upper estuary. This pattern causes sediment export through the estuary.
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Given the non-linear dependence between the water elevation and the velocity, the tidal currents were also analyzed within the lagoon for both scenarios through the computation of $M_2$ constituent tidal ellipses (the most relevant). The ellipses semi-major axis and eccentricity are presented in Figure 4. The results show that the semi-major axis patterns are similar for both scenarios. The highest currents were found at the lagoon mouth (1.2 m/s), and its magnitude decreases towards the channel’s head, where the currents are close to zero. Although the similarity of patterns (Figure 4) shows that, with the exception of some small isolated regions scattered along the lagoon, the tidal currents increase with the mean sea level rise. Concerning the eccentricity of tidal ellipses (Figures 4d, 4e and 4f); the results show the existence of regions with clockwise and anticlockwise current rotation. It is interesting to note that in the Mira channel the anticlockwise rotation is dominant, while in the S. Jacinto channel the clockwise rotation dominates. The rotation of tidal currents remains unchangeable with the mean sea level rise, except in one small region located at the half of S. Jacinto channel where tidal currents exchange from anticlockwise to clockwise rotation (see Figure 4f).

The residual currents are also computed in order to characterize the exchange of water properties within the lagoon. The analysis of results is emphasized at the lagoon mouth, where the exchange between the lagoon and the ocean occur. The residual current patterns are similar for both scenarios. The highest residual currents were found at the lagoon mouth, decreasing in magnitude towards the channel’s head (Figure 5). The ratio between the magnitude of residual currents for both scenarios evidences that they tend to increase at the lagoon mouth and deeper channels, highlighting higher transport rates in these regions for the future. In shallow areas and narrow channels a decrease on the magnitude of residual currents was found and consequently a decrease in the transport rates. The patterns of residual current directions are similar for both scenarios (only shown at the inlet region). The inlet channel presents high inland residual currents at the northern part (~0.2 m/s) and currents of similar magnitude directed to the ocean in the southern regions. Along the channel axis the residual currents are weaker and the residual flow presents two vortices rotating in a clockwise direction. Moreover, between the jetties the residual currents are directed seaward, highlighting the export of water, sediments, nutrients, etc. to the ocean. The residual circulation on Ria de Aveiro lagoon was studied previously by Dias (2001), Lopes and Dias (2007) and Valentim et al. (2013). The first two studies assessed residual currents averaging tidal currents over a $M_2$ tidal cycle, and obtained similar residual patterns. The Valentim et al. (2013) study, investigated the influence of the mean sea level rise on residual currents in a small salt marsh located at the entrance of Mira channel. They found that residual currents direction remains unchangeable, while its intensity tends to decrease with the mean sea level rise in this salt marsh. The results described in this study are in accordance with those obtained in those studies.

Figure 3. a) and b) $A_r$ for present and sea level rise scenarios, respectively. c) Ratio between $A_r$ for both scenarios. d) and e) $\phi$ (º) for present and sea level rise scenarios, respectively. f) Tidal dominance changes motivated by the mean sea level rise.
CONCLUSIONS

This work reports the main features of Ria de Aveiro tidal dynamics and expected modifications motivated by mean sea level rise. The results proved that the tidal influence is greatest at the lagoon entrance and decreases towards the channel’s head. Indeed, as the lagoon depth decreases the amplitude of $M_2$ and $K_1$ constituents reduces, whereas their phase increases. The first harmonic of $M_2$, the $M_4$ constituent, presents an opposite pattern, increasing its amplitude as the lagoon depth decreases. As a consequence, the tidal wave is more distorted in the lagoon upper...
reaches, where the amplitude ratio can reach 0.4, than at the lagoon entrance where the amplitude ratio is close to zero. Moreover the tidal asymmetry results show that the upper lagoon is flood-dominated, while the lower lagoon is ebb-dominated. Important changes on the tidal wave propagation were found with the mean sea level rise, in response to the friction reduction within the lagoon, mainly at the lagoon upper reaches. Indeed, considering that M3 amplitude will increase and M4 amplitude will decrease, a reduction of the amplitude ratio at the upper lagoon is expected.

Concerning the tidal currents, the highest currents were found at the upper lagoon for both scenarios. Moreover, the tidal currents will be intensified and its direction remains unchangeable with mean sea level rise. The residual current patterns at the inlet show that the lagoon mouth tends to export material to the ocean and that this trend will remain with mean sea level rise. Globally, an intensification of residual currents with the mean sea level rise was found, highlighting the intensification of exchanges within the lagoon.

ACKNOWLEDGEMENT

The first author benefits from a Ph.D. grant (SFRH/BD/78345/2011) given by the Portuguese Science Foundation FCT (Fundação para a Ciência e Tecnologia). This work has been partly supported by FCT and by European Union (COMPETE, QREN, FEDER) in the frame of the research projects PTDC/AAC-CLI/100953/2008 - ADAPTAria; PTDC/AAC-AMB/112191/2010 - BioChangeR; PTDC/AAC-AMBI/113469/2009 - PAC:MAN; LTER/BIA-BEC/0063/2009 - LTER-RAVE. The European Commission, under the 7th Framework Programme, also supported this study through the collaborative research project LAGOONS (contract nº283157).

LITERATURE CITED


Computers & Geosciences, 28, 929-937.


