Sea level rise impact in residual circulation in Tagus estuary and Ria de Aveiro lagoon

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ABSTRACT

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Nowadays, there is a special concern about the possible impact of sea level rise in hydrodynamic patterns of coastal systems and its consequence in contingent ecosystems. In the present work, the effects of sea level rise in residual circulation are analyzed in two of the most important Portuguese coastal systems, Ria de Aveiro lagoon and Tagus estuary. The role of rivers inflow on residual circulation is also analyzed under different sea level scenarios. Several projections of river discharges were considered and two scenarios for sea level were adopted: actual and locally predicted sea level rise. The methodology followed comprises the exploitation of previously validated 2D hydrodynamic numerical models (MOHID) developed for both systems. Results indicate that rivers discharge effect cannot be unconsidered in the long term hydrodynamic analysis for both systems, once residual currents intensity could be at least 40% and even 100% higher in maximum inflow than in typical inflow and no discharges scenarios, respectively. In Tagus estuary, the upper bay is the most affected area in a sea level rise scenario, namely in the upper zone (with extensive intertidal areas) where differences in the residual currents intensity can be higher than 100%. In Ria de Aveiro lagoon, differences between actual and sea level rise could be higher than 80%. Narrow and shallow channels are the most affected areas, revealing the significant impact of sea level rise in the intertidal zones. Consequently, the predicted changes in these systems hydrodynamics could influence the long term transport and their actual equilibrium and, as such, affect the natural state of the contingent biological communities.

ADDITIONAL INDEX WORDS: *Hydrodynamics, numerical modeling, MOHID.*

INTRODUCTION

Coastal systems, such as estuaries and lagoons, are considered very important not only by the scientific community, but also by the populations who live around these areas. As interface zones where land, water and atmosphere interact in a dynamic balance that is constantly being changed by natural and human influence, coastal regions represent extremely productive and accessible areas which intensify the anthropogenic pressure (Lopes *et al.*, 2011). Natural pressures are also being intensified as a result of climate change. An important consequence of climate change is sea level rise (SLR) due to its impact on society and ecosystems. Several studies reveal that global mean sea level has been rising during the 20th century at a rate of 1.7 ± 0.5 mm/year and it is expected to continue rising during the 21st century at an increasing rate (Church and White, 2006). The response of each coastal region to SLR depends on the physical features of the coastal system and on the rate of local relative SLR. Thus, the SLR effects should be locally evaluated in order to improve the tools for vulnerability assessment (Nicholls and de la Vega-Leinert, 2008).

In terms of estuarine hydrodynamics, tidal currents structure analysis is essential to understand problems like pollutants dispersion rates, sediment transport and erosion processes (Prandle, 1982). Long-term residual currents play an important role in the transport of sediment, nutrients and organic matter in lagoons and estuaries, namely, in their exportation toward coastal seas. In these systems, residual transport and circulation are essentially dominated by tidal asymmetries, but rivers influence should also be considered (Lopes and Dias, 2011). Therefore, understanding residual circulation changes induced by sea level rise in coastal systems seemed to be crucial to obtain an overview of the different uses of coastal systems.

The main goal of the present study is to evaluate the residual circulation pattern in two of the most important Portuguese coastal systems. The role of rivers inflow in this hydrodynamic parameter and possible effects of SLR are evaluated. Therefore, several projections of rivers inflows and actual and locally predicted sea level rise scenarios were adopted.

The coastal systems under study are the Tagus estuary and the Ria de Aveiro lagoon. The Tagus estuary, located in the highest population density area of Portugal, crossing the capital Lisbon, is one of the largest estuaries of Europe and is the most extensive wetland area of Portuguese territory (Dias, 1993). Likewise, Ria de Aveiro lagoon constitutes a very important area, being the most extensive shallow lagoon system in Portugal and the most dynamic in terms of physical and biogeochemical processes (Picado *et al.*, 2010). Both systems provides natural conditions for

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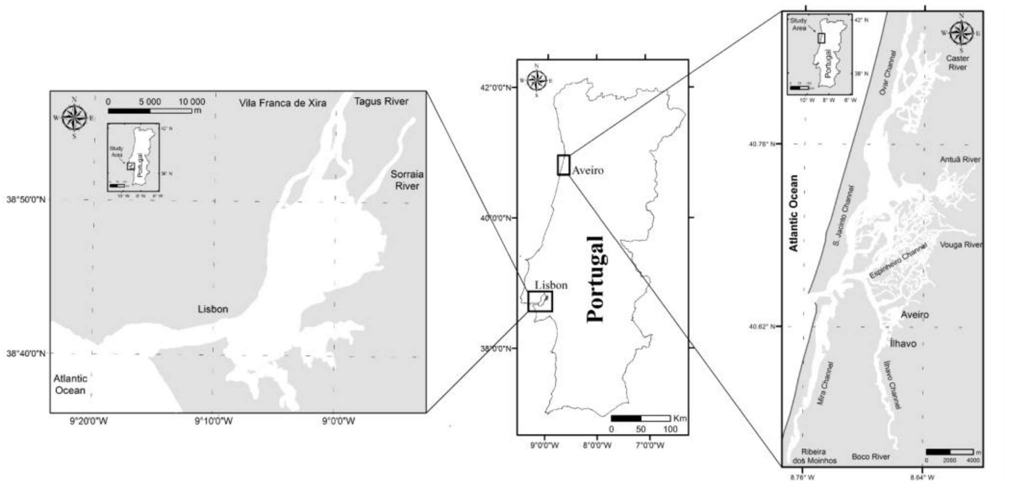

Figure 1. Tagus estuary (on the left) and Ria de Aveiro lagoon (on the right).

economic activities, like industry, navigation and recreation, enduring pressure from the large human population that inhabits its margins and depends upon its resources (Araújo *et al.*, 2008).

STUDY AREAS

Tagus estuary

The Tagus Estuary (Fig.1) is a mesotidal coastal plain estuary with a surface area of about 320 km^2 and a mean volume of 1900×106 m^3. About 40% of estuary's total area is tidal flats, which are important features of many estuaries slowing tidal propagation and highly dissipating tidal energy or, from an ecological perspective, contributing significantly to primary production (Fortunato *et al*., 1999; Dias and Valentim, 2011). The estuary width varies between 2 and 15 km and the average depth is 10.6 m. Morphologically, Tagus can be divided in two distinct regions, the lower and upper estuary. The lower estuary is a channel of about 30 m depth that connects with the Atlantic Ocean and opens in a large bay (upper estuary) on the east side. The upper estuary (bay), widest and shallowest, extends from Vila Franca de Xira to the main channel (lower estuary) and is characterized by extensive zones of tidal flats, salt marshes, small islands and a net of narrow channels (Fortunato *et al*., 1997).

Tidal propagation and fluvial discharge from the major tributaries modulate the hydrology of the estuary (Vaz *et al*., 2011). The Tagus river is the major source of freshwater with an annual average flow of approximately 400 m^3/s (Neves, 2010). Other freshwater inputs to the estuary, the Sorraia and the Trancão rivers, are comparatively small, with average annual discharges of about 35 and 2.5 m^3/s, respectively (Neves, 2010). The Tagus is ebb dominated, with floods typically one hour longer than ebbs (stronger velocities during ebbs), and thus inducing a net export of sediments (Fortunato *et al*., 1999). The area affected by tides reaches 80 km landward of Lisbon and the maximum tidal currents achieve about 2.0 m/s (Gameiro *et al*., 2007).

Ria de Aveiro lagoon

The Ria de Aveiro (Fig.1) is a mesotidal lagoon located in the Northwestern Portuguese coast. It presents a very complex geometry and is characterized by large intertidal flats and a net of narrow channels (Dias and Picado, 2011). The lagoon covers an area of 83 km^2 at high tide (spring tide) and 66 km^2 at low tide (Dias and Lopes, 2006). The lagoon is 45 km long, 10 km wide and is connected to the sea by a 350 m wide inlet, fixed by two jetties. Four main branches radiate from this sea entrance: Mira, S. Jacinto, Ílhavo and Espinheiro channels (Picado *et al.*, 2010). This system is also characterized by a large number of other smaller channels between which lie significant intertidal areas, essentially mudflats, salt marshes and old salt pans (Picado *et al.*, 2010). The average depth of the lagoon relative to the mean sea level is about 3 m, although the inlet channel can exceed 28 m deep (Picado *et al.*, 2010).

The lagoon hydrodynamics is tidally dominated and the tide is semidiurnal, with a mean tidal range of about 2.0 m at the inlet (Dias *et al.*, 1999). The tidal range at the inlet varies from 0.6 m (neap tide) to about 3.2 m (spring tides) (Dias *et al.*, 2000). The strongest currents are observed at the inlet channel, reaching values higher than 2 ms^{-1} (Vaz *et al.*, 2009a).

The lagoon receives freshwater from the rivers Vouga, Antuã, Boco, Caster and Ribeira dos Moinhos (Fig.1). The major fluvial input comes from the Vouga (50 m^{3}s^{-1} average flow), which is responsible for about 66% of the freshwater input in the lagoon, and Antuã rivers (5 m^{3}s^{-1} average flow) (Moreira *et al.*, 1993; Dias *et al.*, 1999). The total mean estimated freshwater input is approximately 1.8×10^6 m^3 during a tidal cycle (Moreira *et al.*, 1993). Hence, the total mean estimated freshwater input is very small (2.5%), when compared to the mean tidal prism at the mouth, which is approximately 70×10^6 m^3 (Picado *et al.*, 2010).

METHODS

In this study is used the numerical model MOHID (Martins *et al*., 2001), a three-dimensional baroclinic finite volume model, designed for coastal and estuarine shallow water applications. MOHID solves the three-dimensional incompressible primitive equations, and assumes the hydrostatic equilibrium, as well as the Boussinesq and Reynolds approximations.

Two previously validated set-ups of the MOHID-2D model for the Tagus estuary (Vaz *et al*., 2011) and Ria de Aveiro lagoon (Vaz *et al*., 2007) were applied in this study. Details on model's accuracy to reproduce the tidal dynamics for both estuaries are described in Vaz *et al*. (2007; 2011). The main forcing considered are tidal propagation and river discharges (for both coastal systems). The wind forcing was not considered once it is only important during short periods for both systems.

The numerical grid developed for Tagus estuary presents 335×212 cells of 200 m each. On the open ocean boundary, the model input was the tidal forcing from a coastal 2D model (Vaz *et* *al.*, 2009b). The rivers inflows were imposed in the landward boundaries considering *Typical*, *Maximum* an *No Discharges* values for Tagus, Sorraia and Trancão rivers (Table 1) (Neves, 2010). The spin-up time was 2 days, the time step of the model was 15 s and a horizontal viscosity of 5 m^2s^{-1} and a rugosity of 0.0025 were considered.

The Ria de Aveiro grid has 429×568 cells, with dimensions of 40×40 m in the central area of the lagoon and 40×100 m in the northern and southern areas (Vaz *et al*., 2007). The time step of the model was 6 s and a horizontal viscosity of 5 m^2s^{-1}, as well as a varying Manning's coefficient between 0.022 and 0.045 ($m^{1/3}s^{-1}$) were considered. At the sea open boundary, water elevation over the reference level was imposed using tidal harmonic constituents determined using T_TIDE package (Pawlowicz *et al*., 2002). Rivers inflow were also imposed in the landward boundaries considering *Typical*, *Maximum* an *No Discharges* values for Vouga, Antuã, Boco, Caster and Ribeira dos Moinhos rivers (Table 2). River discharges values were obtained from the Ria de Aveiro Polis Litoral program, which considered the data presented in the Plano de Bacia Hidrográfica (www.arhcentro.pt).

To study SLR effects in local hydrodynamic parameters, two scenarios in numerical simulations were evaluated: actual and locally predicted SLR. Model parameters were kept except the mean sea level value. For actual sea level simulation was considered the value 2.08 m, while for SLR scenario was considered a mean sea level of 2.50 m. This sea level rise of 0.42 m was adopted based on local projections of sea level rise for the Portuguese coast for the IPCC A2 storyline (Lopes *et al.*, 2011).

Values of the residual circulation were obtained directly by the model results averaging the predicted velocities for all the grid cells during a simulation period of 14 days, 18 hours, 32 minutes and 24 seconds, once this is a multiple period of the tidal constituents M_2 and S_2. With this procedure, the main tidal constituents are filtered, including the fortnight constituents related with the spring and neap tidal cycle.

Horizontal fields for residual circulation were determined for river inflows projections and for sea level scenarios. Moreover, differences between the results for actual and SLR situations were calculated in order to assess SLR effects in the residual circulation patterns. The results are presented in Figures 2 (Tagus estuary) and 3 (Ria de Aveiro lagoon).

RESULTS

Tagus estuary

Figure 2 presents residual circulation results in the Tagus estuary for the three scenarios of river discharges, in actual and sea level rise scenarios. Difference between actual and sea level rise scenarios was also calculated (Figs.2c,f,i). Model results reveal that, in general, residual circulation is two orders of magnitude lower than tidal current, as was expected. In a significant part of the estuary, residual circulation is lower than 5 cm.s^{-1}, but it can rise to more than 20 cm.s^{-1} in the deepest channels of the upper bay as well as in the main channel of the system mouth.

In actual sea level scenario, *Typical* inflow presents a residual circulation of about 7 cm.s^{-1} (Fig.2a) in the deepest channels of the upstream part of the upper estuary while in *Maximum Discharge* (Fig.2d) this value is more than 10 cm.s^{-1}. In the zone closest to the river mouth (Vila Franca de Xira), values rise from about 14 to more than 30 cm.s^{-1} from the scenario of *Typical* discharges to the *Maximum Discharges*, respectively. In *Maximum Discharges* scenario (Fig.2d), the influence of topography and system morphology is notorious inducing strongest currents in the deepest channels of the system, where residual circulation intensity is higher than 30 cm.s^{-1}.

The highest differences between scenarios are more important in the upper bay, due to freshwater inputs in that area and also as a result of the complex morphology of that specific zone. Differences between *Typical* and *Maximum Discharges* could be more than 10 cm.s^{-1}. Comparison between *Typical* and *No Discharges* scenarios shows that river effect could increase residual current intensity more than 30%, namely in the upper estuary (from 2 to more than 6 cm.s^{-1} higher in the lower and upper bay, respectively, in *Typical Discharges*) which reveal the effect of the Tagus river in the residual circulation.

In general, SLR (Fig.2b,e,h) and actual sea level scenario (Fig.2a,d,g) presents similar patterns of residual circulation. Nevertheless, generally, residual circulation increase about 1 cm.s^{-1} in some areas near the Tagus estuary mouth and in some shallow areas of the bay, while in the deepest channels of the bay residual circulation decreases about 1 or even more than 3 cm.s^{-1} in SLR scenario. In *Typical Discharges*, residual circulation values are between 10 and 30% lower than those in actual scenario, namely in the upper bay (Fig.2c). A similar situation is found in *No Discharges* projection (Fig.2i). In *Maximum* scenarios, differences are not so high and SLR scenario results present a decrease of 20% in some channels of the upper bay. The majority of the bay area presents values 10% lower than for actual sea level scenario (Fig.2f).

Model results also reveal that the higher differences between actual and SLR projections (Fig.2c,i) arise in *No* and *Typical Discharges* situations, which indicates the important effect of the system morphology, as well as tidal forcing in this coastal system, even when a large river discharges into the estuary (Tagus is the longest river of the Iberian peninsula). In fact, results suggest that, comparatively to *Typical Discharges* (Fig.2b), in *Maximum* river flow situation (Fig.2e), the higher water column due to the river inflow attenuate sea level rise effects. As such, differences between the two sea level scenarios are sharpest in *Typical Discharges*. The differences similarity between *Typical* and *No Discharges* situations (Fig.2c,i) indicate the significant effect of tidal forcing in this coastal system, in such a way that an usual river inflow shows small differences comparing to a *No Discharge* scenario.

Table 1. River discharges values for Tagus estuary.

Discharges (m^3s^{-1})	***Tagus***	***Sorraia***	***Trancão***
Maximum	2000	200	20
Typical	400	40	5

Table 2. River discharges values for Ria de Aveiro lagoon.

Discharges (m^3s^{-1})	***Vouga***	***Antuã***	***Boco***	***Caster***	***Rª dos Moinhos***
Maximum	517.0	39.0	8.6	13.8	25.6
Typical	60.0	4.5	1.0	1.6	3.0

Ria de Aveiro lagoon

In Ria de Aveiro, residual circulation (Figure 3) is generally two orders of magnitude lower than tidal currents, as it was verified in previously studies (e.g. Vaz *et al*., 2009a, Lopes and Dias, 2011). In actual scenario (and in *Typical* flows condition) (Fig.3a), is in S. Jacinto channel that residual circulation reaches its higher intensity, with values of approximately 9 cm.s^{-1}. Close to the Vouga river mouth, residual circulation could reach 17 cm.s^{-1}and

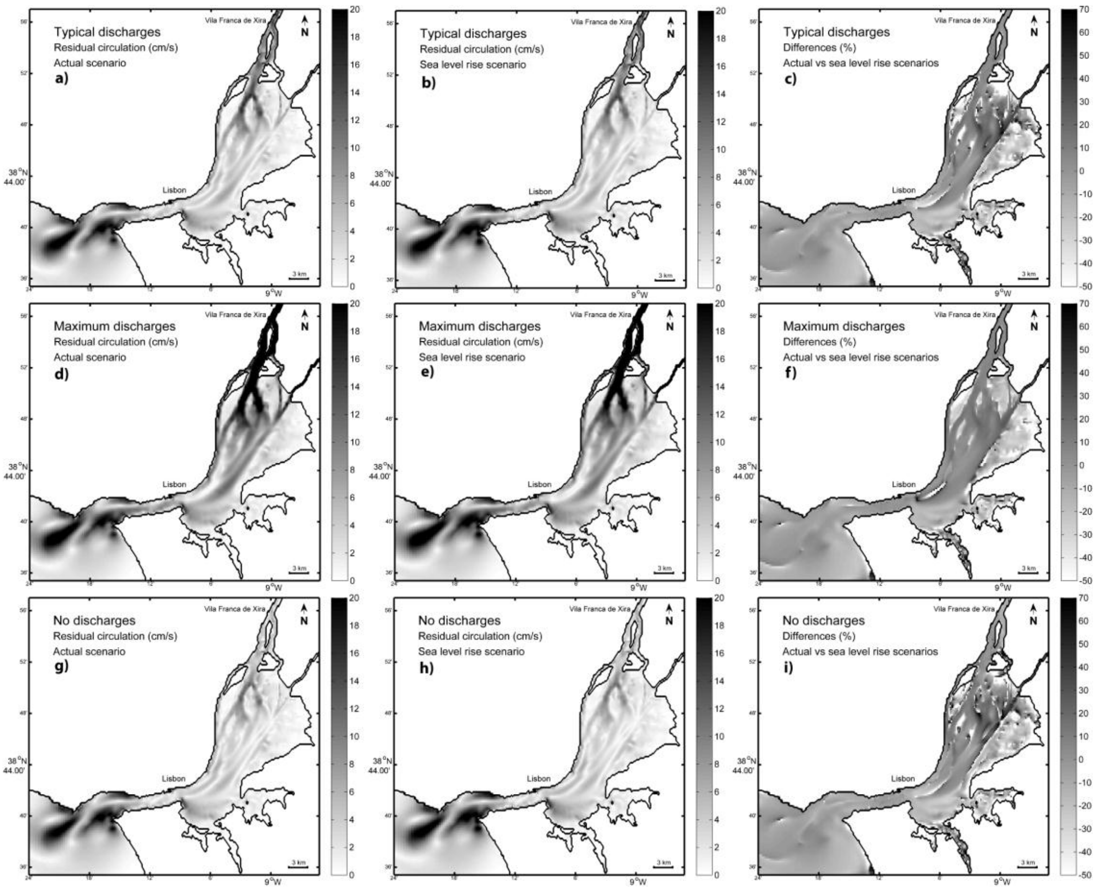

Figure 2. Residual circulation (cm/s) in Tagus estuary for *Typical* (a,b,c), *Maximum* (d,e,f) and *No Discharges* (g,h,i) projections. The results for actual (a,d,g) and sea level rise scenarios (b,e,h) are also represented for *Typical*, *Maximum* and *No Discharge* situation, respectively, as well as the percentage differences (c,f,i) between the actual and the sea level rise scenarios.

near lagoon mouth is about 5 $cm.s^{-1}$ In *Maximum Discharges* (Fig.3d) it increases to more than 12 $cm.s^{-1}$ in this area (Fig.3d). In Vouga river influence area and in the S. Jacinto channel, residual circulation increases to about 14 $cm.s^{-1}$ in the *Maximum* inflow scenario, but the Espinheiro channel is now where residual current reaches its maximum value, more than 18 $cm.s^{-1}$ (Fig.3d). These results of *Maximum Discharge* indicate that, under this condition, residual circulation suffers a significant change in the Ria de Aveiro and the strength of this hydrodynamic parameter is strongly modified, appearing new areas of maximal residual circulation. *Maximum Discharges* means an increase of at least 60% of *Typical Discharges* residual circulation for most of the lagoon.

Considering *No Discharges* inflow (Fig.3g), values of residual circulation decrease in entire system, comparing to other scenarios. In this case, residual circulation in whole lagoon is close to 3 $cm.s^{-1}$, except in some deepest areas near the lagoon's mouth, Mira and S.Jacinto channels, where values could reach 5 $cm.s^{-1}$.

The main differences between the three rivers projections, in actual scenario, occur in the deepest areas of the main channels. The comparison between *Typical, Maximum* and *No Discharges* demonstrate the influence of rivers inflow in residual circulation. In *Typical* situation, in some areas, such as the middle zone of S. Jacinto channel, values can be almost 80% higher than those found in the *No Discharge* scenario which reveals the importance of rivers discharges in this coastal lagoon. As such, changes in river discharges patterns are an important factor for the lagoon circulation and consequently for contingent ecosystems.

As for Tagus estuary, differences patterns of residual circulation for actual and sea level rise scenarios are similar. In general, with sea level rise, residual circulation decrease approximately 20 % and 15% in *Typical* and *Maximum* projections comparing to those found in actual sea level scenario (Fig.3c,f). However, model results indicate that residual circulation will slightly increase in narrow and shallow channels in the complex areas of the lagoon. In SLR scenario, results suggest that, for example, in S.Jacinto channel, considering average values, residual circulation will decrease 16% and 7%. This means that, in SLR scenario, these areas may present values of residual circulation close to 8 and 13 $cm.s^{-1}$ in *Typical* and *Maximum*, respectively. In Espinheiro channel, residual circulation will decrease 11% and 17%, which means that now residual circulation will be approximately 5 and 15 $cm.s^{-1}$ (in *Typical* and *Maximum* scenarios, respectively). The less significant differences were found in *No Discharges* scenario proving, once again, the importance of rivers in determining the residual circulation of the lagoon.

Moreover, differences between the two sea level scenarios show that tidal forcing is mainly important in S.Jacinto channel, presenting the remain lagoon areas unimportant differences, which once again reveal the significant role of the rivers pattern in lagoon residual circulation. Unlike what succeeds in Tagus estuary, model results for Ria de Aveiro reveal that in *Typical Discharges* differences between actual and SLR scenarios are not as important as in *Maximum Discharges*. In *Maximum* inflow,

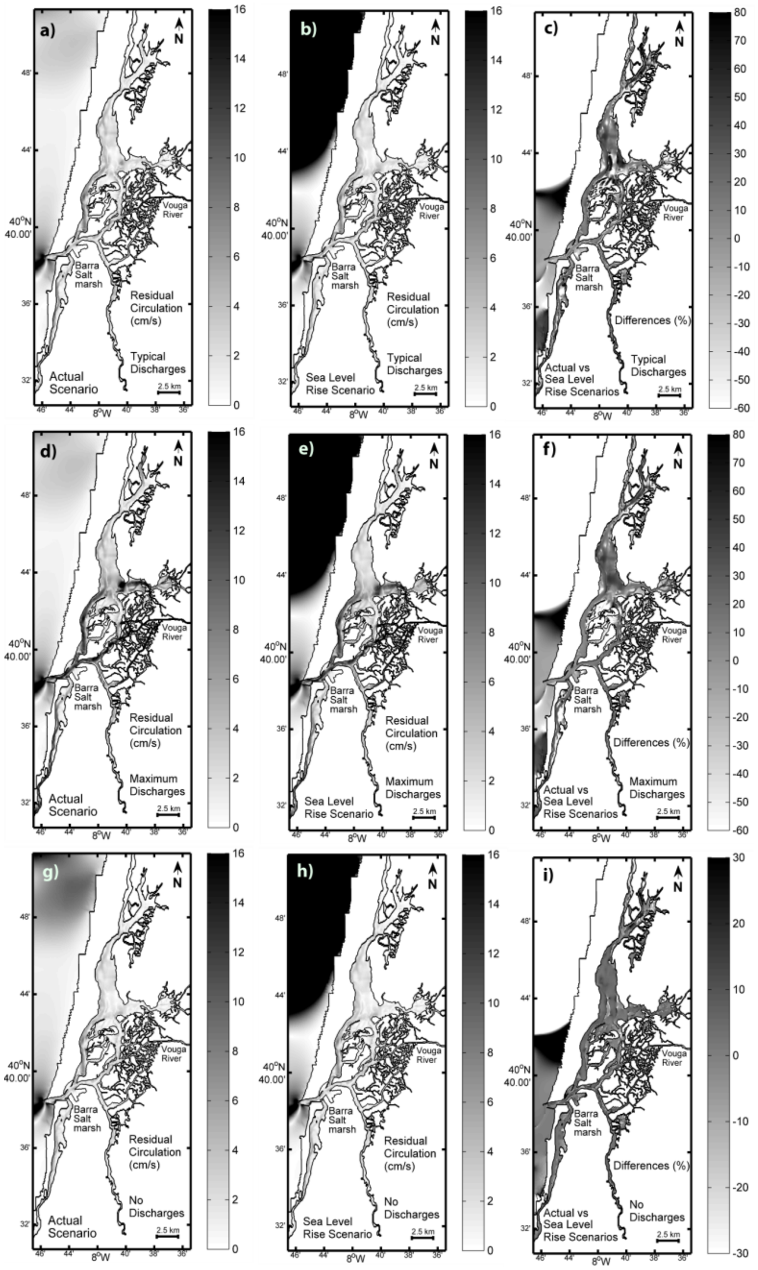

Figure 4. Residual circulation (cm/s) in Ria de Aveiro for *Typical* (a,b,c), *Maximum* (d,e,f) and *No Discharges* (g,h,i) projections. The results for actual (a,d,g) and sea level rise scenarios (b,e,h) are also represented for *Typical*, *Maximum* and *No Discharge* situation, respectively, as well as the percentage differences (c,f,i) between the actual and the sea level rise scenarios.

differences between actual and SLR scenario stand out mainly in the rivers' mouth. These areas are important intertidal lagoon regions, harboring a large number of wildlife communities, which will be forced to adapt their present equilibrium to a climate change scenario effects.

CONCLUSIONS

Model results analysis contribute to understand general patterns of residual circulation in the Tagus estuary and Ria de Aveiro lagoon, both in actual mean sea level and sea level rise scenarios. The exploration of SLR results indicates how systems will evolve in this scenario, showing that this hydrodynamic parameter will suffer important changes under climate change context.

Results showed that SLR scenario induces a significant decrease in residual circulation in Tagus estuary. Although residual circulation slightly increases in some areas of the estuary mouth, it decreases almost 30% in *Typical Discharges* and 10% in *Maximum Discharges* in the bay. Such in Tagus estuary, in the Ria de Aveiro lagoon, river discharges also represent an important forcing for long term processes. In the Tagus estuary, river inflow has a higher effect mostly in the upper bay (near to the river mouth). However, in the Ria de Aveiro lagoon, probably due to its complex morphology, shallow depth and to the large number of inflowing rivers, their impact seems to have a more global effect, once their influence extends far from the rivers' mouth, reaching the lagoon's mouth. In SLR scenario, results indicate a decrease of residual circulation in the entire lagoon, approximately 20% and 15% in the *Typical* and *Maximum* scenarios, respectively.

Changes in rivers discharges in actual scenario clearly affect residual circulation, and consequently the biotic and abiotic processes both in Tagus estuary and Ria de Aveiro lagoon. Additionally, model results indicate that SLR will affect significantly the actual residual circulation induced by the rivers inflow in these systems. As such, surrounding ecosystems will be forced to adapt their present balance to this crucial hydrodynamic parameter. The coastal ecosystems response to climate change scenario is uncertain, although some modifications are already expected. It is expected that low lying coastal areas will experience increased levels of flooding, accelerated erosion, loss of wetlands and low-lying terrestrial ecosystems, and seawater intrusion into freshwater sources. Rising sea level and erosion will also affect coastal habitats, including wetlands and nearshore ecosystems, such as beaches, sedimentary bottoms, submerged aquatic vegetation and oyster reefs. Consequently it endangers the habitats for many of the commercially important fisheries, which directly depend on sediment and nutrients transport, and consequently on residual circulation pattern. The trends found in the present study are unlikely to be unique to the Tagus estuary and Ria de Aveiro lagoon and it is suggested that similar analyses are replicated for other tidally dominated systems, to improve understanding and characterisation of uncertainty under climate change context. This would enable the development of risk scenarios based on prevailing conditions, which would inform and give support to policy makers.

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