

Potential impacts of the mean sea level rise on the hydrodynamics of the Douro river estuary

Renato Mendes†, Nuno Vaz†, João M. Dias†

†CESAM, Physics Dept, University of Aveiro, 3810-193 Aveiro, Portugal
rpsm@ua.pt, nuno.vaz@ua.pt,
joao.dias@ua.pt



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ABSTRACT

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Numerous studies based on tide gauge records demonstrated the sea level rise on the Portuguese coast during the last century. Different climatic models predict a mean sea level rise for this coast ranging between 0.28 m and 0.42 m, for the period 2091–2100 relative to 1980–1999. Thus, the potential evaluation of the sea level rise impact on the Portuguese coast becomes critical, especially in sensitive areas as estuaries. The main aim of this work is to evaluate hydrodynamic changes in the Douro estuary induced by the sea level rise. A baroclinic finite volume numerical model was implemented to the Douro estuary in a 2D mode. The model calibration was performed comparing predicted and observed sea surface elevation time series for several stations. The tidal input at the ocean open boundary forces the 2D hydrodynamic model considering actual and future mean sea levels. At the landward boundary the model is forced with the freshwater discharge. The research explores changes in current velocity and amplitude and phase differences of the main diurnal and semi-diurnal tidal constituents along the estuary. The results suggest local significant changes in the Douro hydrodynamics in response to the sea level rise. Nevertheless, the differences don't affect the general estuary's circulation. Concerning the main tidal constituents, the amplitude increases and the phase decreases, revealing that the tide tends to propagate faster upstream and with higher tidal ranges. Owing to the increasing of the amplitude and the water level, the current velocity values tend to decrease in the estuary, mainly near the low-lying areas.

ADDITIONAL INDEX WORDS: *climate change, hydrodynamic, numerical modeling, harmonic analysis, MOHID.*

INTRODUCTION

Nowadays, there is a growing interest in the prediction of the climate change effects on marine ecosystems. The trends observed have been providing a glimpse of future changes, such as global warming and sea level rise (FitzGerald *et al.*, 2008; Houghton *et al.*, 2001).

Sea level rise (SLR) poses a particularly warning threat, since 10% of the world's population (634 million people) lives in low-lying coastal regions. According to Church and White (2006), the global mean sea level has been rising during the 20th century, at a rate of 1.7 ± 0.5 mm/year. It is expected its continue rising through the 21st century at an increasing rate, although estimated by several authors with a significant ambiguity, since the projection of future sea-level rise involves many uncertainties and depends on the storyline considered as well on the global circulation model used. As examples, Meehl *et al.* (2007) predicted a global sea level rise for 2100 ranging between 0.18 m and 0.59 m, while for Rahmstorf (2007) it will range between 0.5 m and 1.4 m. The cause of SLR, due the climate change, is not clear. Some authors pointed out the thermal expansion (response of the ocean to global atmospheric temperature rise), mass exchange (melting of mountain glaciers and ice caps and changes in Greenland and Antarctic ice sheets), dynamic changes (result of density gradients) and land subsidence (vertical movements in the solid earth related to tectonics and isostatic adjustment) as possible

causes (Chao *et al.*, 2002).

In a local scale, the rate of SLR can differ significantly from the global mean due to local circulation characteristics or to vertical movements of the land, which can be of similar order (mm/yr) as sea level changes. The unequally change of the sea level around the world becomes it clear from by tidal gauge and satellite imagery data. Therefore it is crucial to consider the results of local studies. Several studies analyzed the SLR along the Portuguese coast, during the last century, using the tide gauge records (Dias and Taborda, 1988; Araujo, 2006; Antunes and Taborda, 2009) and found values ranging from 1.15 to 2.1 mm/year. Recently, Lopes *et al.* (2011) projected for the Portuguese coast a maximum sea level rise of 0.42 m for the period 2091-2100 relative to 1980–1999 for the A2 SRES (Special Report on Emission Scenarios) scenario developed by the IPCC (Intergovernmental Panel on Climate Change).

Although considerable research is being devoted to the climate change impacts on the Portuguese coastal area, rather less attention has been paid to these impacts on local scale estuaries, such as the Douro estuary.

The purpose of this investigation is to evaluate the potential effect of sea level rise on the hydrodynamics of the Douro estuary. In this frame a 2D numerical model MOHID (www.mohid.com) was implemented for the study area and subsequently, the SLR scenarios projected were imposed as boundary condition. The study is focused on three different SLR projections: 0.28m, 0.42 m and 1.00 m. The first two scenarios were determined by Lopes *et al.* (2011), while the third scenario corresponds to a value adopted

recently in several SLR studies (e.g. Yates *et al.*, 2011; Sano *et al.*, 2011).

STUDY SITE

The Douro river is a granitic drowned valley river (927 km length), draining to the N–W coast of Portugal. The river basin is the largest hydrographical basin in the Iberian Peninsula, with an area of 97 682 km², and its estuary is located in the Western Portuguese coast, subject to the North Atlantic meteorological and hydrodynamic conditions (Figure 1).

The Douro estuary is limited upstream by a dam, built in 1985 at 21.6 km from the mouth, for electric power production. Consequently, river inflow to the estuary is characterized by high short-term variability, ranging between zero flow and $>1000\text{m}^3\text{s}^{-1}$, in a temporal scale of hours. The Atlantic tides, which propagate along the estuary, are also an important local hydrodynamic forcing. The tides are semi-diurnal and the average tidal range is 2.8 m at the mouth and 2.6 m at the head of the estuary (Vieira and Bordalo, 2000). Residence time ranges from 8 hours to more than two weeks, depending on river flow discharge (Vieira and Bordalo, 2000). These authors classified the Douro as a salt-wedge estuary, although its establishment under low river flows (Ibañez *et al.*, 1997). The stratification found in the Douro estuary is explained by the dominant standing wave pattern described for the tide, which decreases the water column mixing. This phenomenon is caused by the presence of the dam at the estuary head, reflecting the tidal wave and promoting its interference with the original incident tidal wave. Therefore the estuary acts as a quarter wave resonator, with the node of the standing wave located at the mouth and only its final portion fitting inside the estuary (Vieira and Bordalo, 2000).

METHODS

The numerical modeling application developed in this study is an implementation of the MOHID circulation model (Martins *et al.*, 2001). MOHID is a baroclinic finite volume model, designed for coastal and estuarine shallow water applications, like the Douro estuary. The model allows an integrated modeling approach of physical and biogeochemical processes. A complete description

of the model's physics can be found in several works by Martins *et al.* (2001), Leitão *et al.* (2005) or Vaz *et al.* (2005; 2007; 2009).

The first step on the model implementation consisted in developing a numerical grid for the Douro estuary. It was built from bathymetric data provided by the Hydrographic Institute of Portuguese Navy (IH), updated with topographic data from an available Digital Terrain Model for the adjacent offshore area. The numerical bathymetry has 233 and 527 cells in N-S and W-E directions, respectively, and has cells with 40 m resolution.

After, the model configuration was developed imposing the tidal forcing on the grid oceanic open boundary and performing several modeling experiences to optimize the choice of the time step, that was defined as 6 s. This tidal open boundary condition is determined from fifty harmonic constituents calculated from a SSE data set measured in the tide gauge located near Leixões harbor during 2007. At the bottom boundary, a null normal velocity was imposed and a free slip condition was assumed. The model initial conditions were null free surface gradients and null velocity in all grid points.

The model configuration developed was calibrated and validated using the methodologies proposed by Dias and Lopes (2006a; 2006b) and Dias *et al.* (2009). As a first approach is performed a qualitative comparison of the temporal evolution between model predictions and sea surface elevation (SSE) data measured in September 2005 at several locations throughout the Douro estuary (by ADCPs and current meters (RCM9) (Figure 1). The validation procedure was performed using independent data sets, which includes observations of current velocities and SSE values (February/March 2006 data). After, the model's accuracy was evaluated through the determination of the Root Mean Square Error (RMSE) and the Skill parameter (Warner *et al.*, 2005), and also through the comparison between amplitude and phase of the main tidal constituents determined from harmonic analysis (Dias and Lopes, 2006a; 2006b; Dias *et al.* 2009). It should be noted that the low frequency signal was removed from the observation data, considering a cut-off frequency of 0.000093 Hz (30 h).

To analyze the impact of the SLR in the Douro estuary, three simulations of one month (including an equinoctial tidal period) were performed, considering the scenarios presented in Table 1.

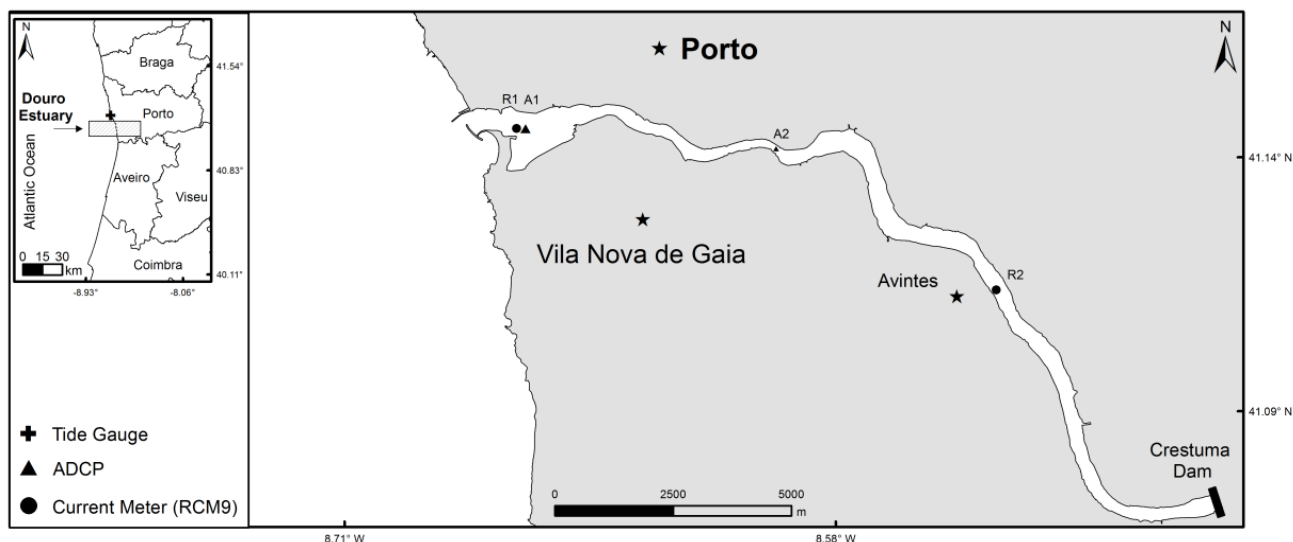


Figure 1. Douro estuary with reference to the location of the stations used on the model calibration and validation.

Table 1. Sea level change projections for the Portuguese coast at the end of 21st century used in this work.

Scenarios	SLR (m)	References
S1	0.28	Lopes <i>et al.</i> (2011)
S2	0.42	Lopes <i>et al.</i> (2011)
S3	1.00	Yates <i>et al.</i> , 2011; Sano <i>et al.</i> , 2011

Another simulation with the actual sea level was carried out in order to define the reference scenario conditions, used to assess the hydrodynamic differences between future and present model results.

Patterns of harmonic constants of the main tidal constituent determined using T-Tide package (Pawlowicz *et al.*, 2002) and of current velocity were analyzed to evaluate the changes induced by the SLR in the hydrodynamic features of the Douro estuary for the scenarios considered.

CALIBRATION AND VALIDATION

It is known that the depth of the water column, the estuary geometry and the bottom friction strongly influences the propagation of the tidal wave. The first two factors depend on the estuarine and coastal tidal characteristics and therefore the calibration was performed by tuning the bottom friction coefficient for the entire estuary. In this study the best overall adjustment between model results and field observations was achieved using the Manning's coefficient of 0.025, which was the same adopted for a previous MOHID implementation in the Tagus estuary (Vaz *et al.*, 2011).

Figure 2a) shows the comparison between model predictions and observed SSE values in the station R2 (Figure 1). For this station the deviation between the predicted and measured data presents a low RMS error (~2% of local tidal amplitude). Considering the comparison for the other stations (not shown), the results present a RMS error ranging between 2 and 3% of local tidal amplitude. According to the criterion proposed by Dias *et al.* (2009) these values demonstrate an excellent calibration of the Douro estuary model. Regarding the Skill, the values are higher than 0.998 in all calibration stations, also showing an excellent agreement between model predictions and observations.

The comparison between the harmonic constants for the main tidal constituents determined using model predictions and *in situ* data also attest the excellent adjustment in the calibration procedure (Table 2). According to the results, the agreement in amplitude and phase for the tidal constituents analyzed is excellent. The higher difference in the amplitude of the main local constituent (principal lunar semidiurnal - M_2) was found in the R2 station (~4 cm) while the phase differences for this constituent are

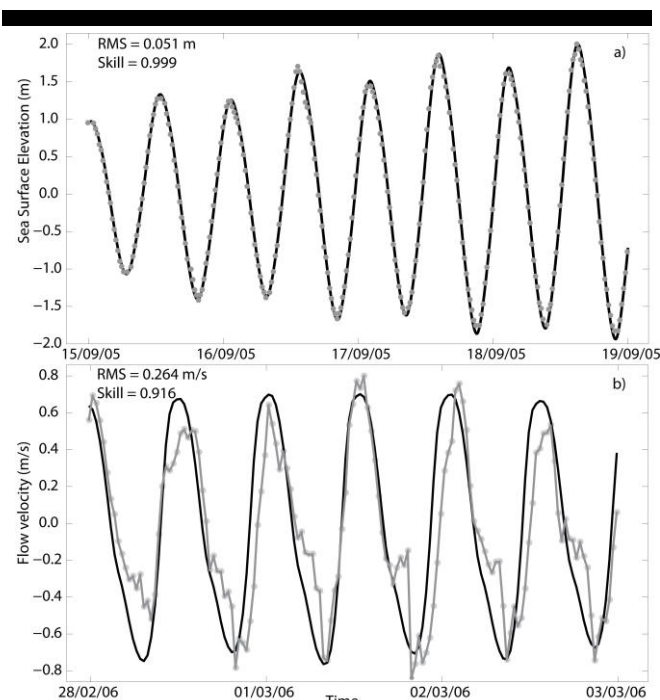


Figure 2. a) Comparison between predicted and measured SSE values for the calibration procedure. b) Comparison between predicted and measured current velocity values (along the flow direction) for the validation procedure. (grey: data; black solid line: model)

lower than 4 minutes for all stations analyzed.

The mean amplitude difference for the principal solar semidiurnal constituent (S_2) is ~2 cm for the stations under analysis, whereas the mean phase lag is ~8 minutes. For the lunar diurnal constituents, K_1 and O_1 , the amplitude differences are about 2 cm for both, while the phase lags are 18 and 30 minutes, respectively. Furthermore, it is found the standing wave pattern of the tide along the estuary as pointed out by Vieira and Bordalo (2000).

Regarding the model validation, the predictions and observations of SSE and current velocity data were compared for periods independent of those analyzed in the model calibration. The RMS errors of SSE values have the same order of magnitude of those determined in the calibration process for all stations (<3% of local tidal amplitude). The Skill parameter has values higher than 0.997 for all the stations. Both parameters indicate an

Table 2. Phase and amplitude of the main tidal constituent from model and observations SSE time series for the calibration procedure.

Station		A1		A2		R1		R2	
		OBS	MOD	OBS	MOD	OBS	MOD	OBS	MOD
M_2	Amp	1.109	1.084	1.137	1.153	1.109	1.071	1.161	1.116
	Pha	80.5	81.8	83.6	85.4	81.9	81.8	87.1	87.2
S_2	Amp	0.501	0.482	0.509	0.505	0.501	0.476	0.535	0.501
	Pha	109.3	113.6	113.3	118.1	110.8	113.6	117.1	120.7
K_1	Amp	0.048	0.062	0.051	0.072	0.048	0.058	0.050	0.067
	Pha	77.8	74.1	76.5	73.5	78.2	73.9	78.3	69.5
O_1	Amp	0.067	0.052	0.064	0.053	0.067	0.051	0.067	0.047
	Pha	311.9	319.5	316.8	324.2	312.6	319.4	321.4	326.0

excellent fit between predictions and observations in an independent period, demonstrating that the model is adequately validated.

Concerning the current velocity comparison (depicted for station R1 in the Figure 2b), and considering the intrinsic differences between predictions and observations, it was expect a higher disagreement between *in situ* observations and model results. The figures analysis for all the stations shows that the velocity phase is well reproduced by the model, and that the velocity amplitude agreement is good for station R1 (RMS error of 18%). However, the velocity amplitude reveals some inconsistencies at station R2 (RMS error of 29%) that can be explained considering the station proximity to the Crestuma dam, which can induce high frequency variations in the current velocity due to the freshwater discharge.

According to these results it may be considered that model reproduces very well the SSE and current velocity data in different and independent conditions. Consequently it may be concluded that this hydrodynamic model implementation is validated for the Douro estuary.

RESULTS AND DISCUSSION

To evaluate the potential impacts of the SLR on the Douro estuary hydrodynamics, simulations of the present scenario and of three different future SLR scenarios were performed (see Table 1 for reference). The period of September 2011 was chosen, comprising spring and neap-tides with a large local tidal range.

In this study, only the results for the most important semi-diurnal constituent were explored. Figure 3 depicts the results for the amplitude and phase differences between the actual and the three future mean sea level scenarios, for the M_2 tidal constituent inside the Douro estuary.

From Figure 3 it is found that the M_2 amplitude differences

(left panel) are very similar for all SLR scenarios. There is a maximum amplitude difference of ~ 0.13 m near the mouth of the estuary, where it is visible a large intertidal area. Figure 3C1 shows that the area located near the estuary mouth (with larger amplitude differences) may no longer be intertidal under the scenario S3 (see Table 1). The difference in the area covered by water at the entrance of the estuary may induce some changes in the amplitude of the M_2 constituent along the estuary. This fact is evidenced when the differences in Figures 3A1), B1) and C1) (ranging between 0.02 and 0.03) m are compared. It is clear that in the upstream region of the estuary, the differences at the M_2 tidal range are larger under the scenario S1.

On the other hand, the patterns found for the phase differences are more consistent with the initial perspectives. In fact, the model results suggest similar difference patterns for the three SLR scenarios, but with different magnitudes. The larger differences were found near the Crestuma dam, in the upstream region of the estuary, with a maximum lag of 2, 3.3 and 5.4 minutes for S1, S2 and S3, respectively. Phase differences reveals that the tide will propagate faster along the estuary in the case of higher sea levels.

The difference between current velocities computed for the actual mean sea-level and for the future scenarios are depicted in Figure 4. The differences, during the September 2011 spring tide, at the flood and ebb moment are shown in the left and right panel of the figure, respectively. The results show that the current velocity will decrease in the future in response to the sea level rise, even in the most extreme scenario ($< 0.3 \text{ ms}^{-1}$). In detail, changes in the current velocity are almost negligible for the S1 scenario, whereas for the S2 and S3 scenarios the results show a decrease in the current velocity in the central area of the entrance of the estuary (~ 0.1 and $\sim 0.2 \text{ ms}^{-1}$, respectively) comparing with the actual scenario. This area is larger during the flood period in the future scenarios, but the difference in magnitude is the same

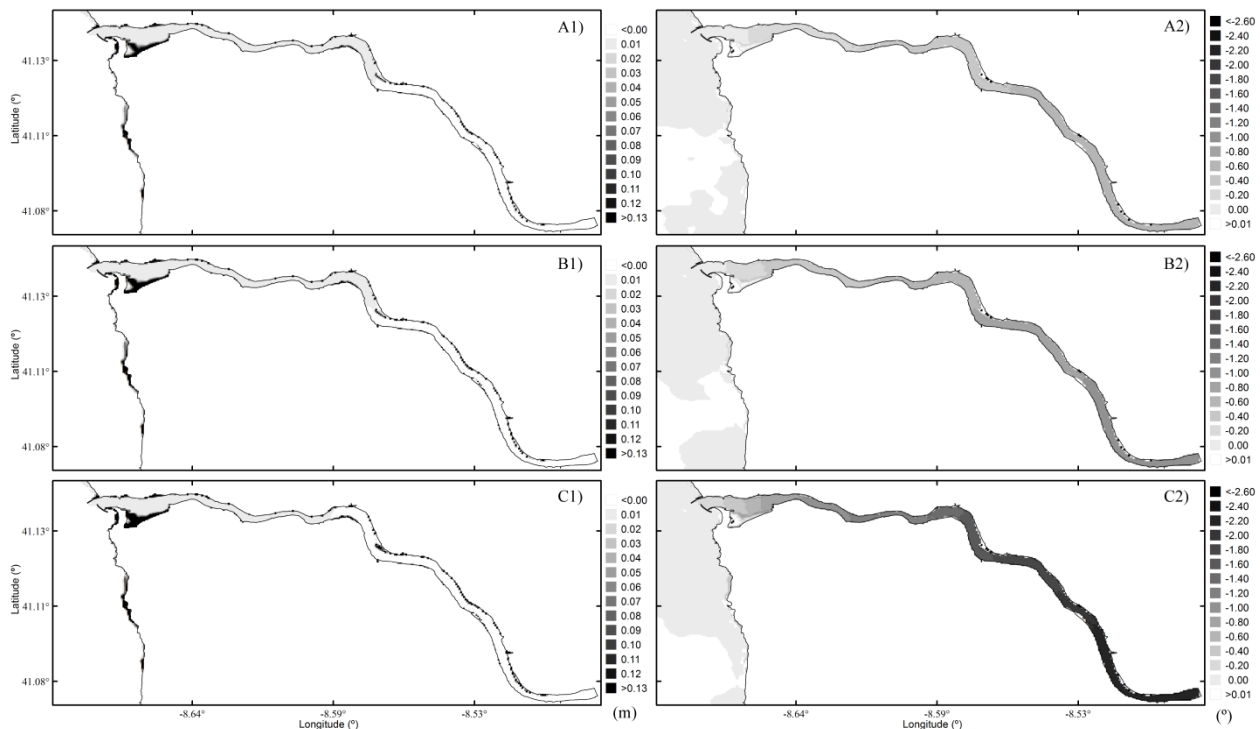


Figure 3. Amplitude (left panel) and phase (right panel) differences of the M_2 tidal constituent, during September 2011, between the actual mean sea level and future projections of SLR for the Portuguese coast: +0.28 m (A), +0.42 m (B) and +1.00 m (C).

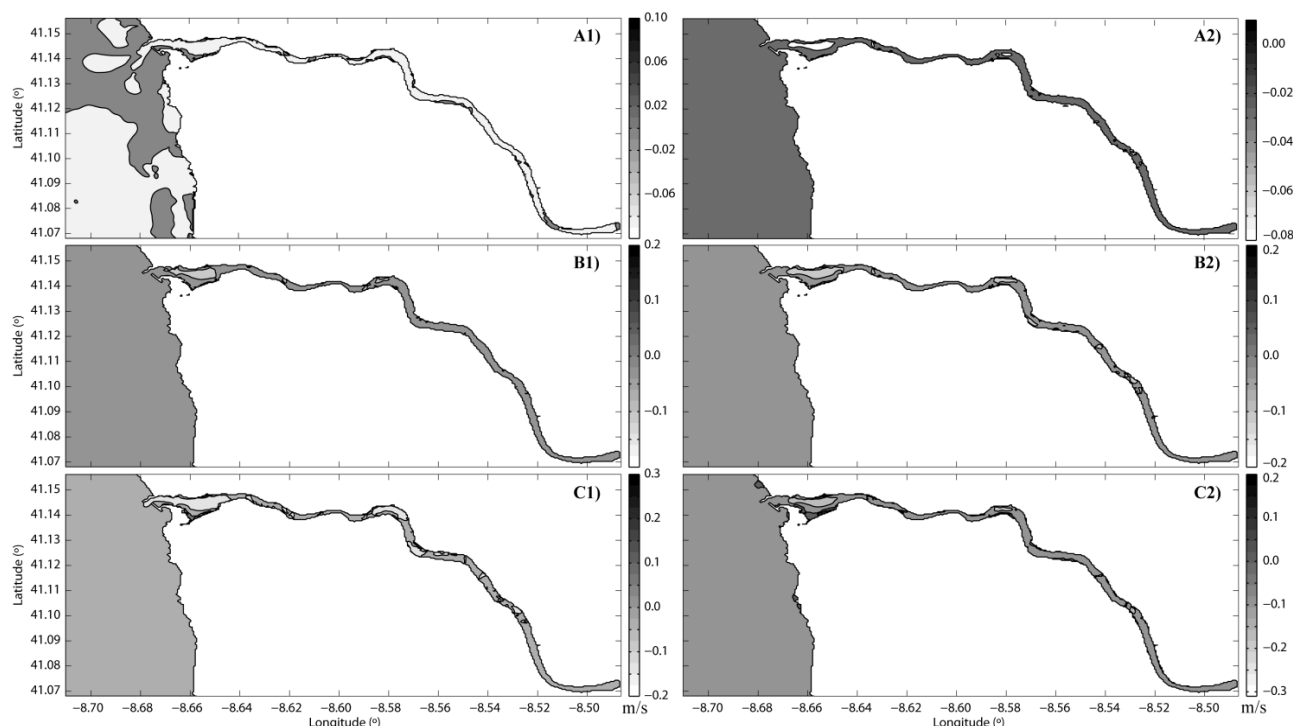


Figure 4. Velocity modulus difference at a flood (left panel) and ebb (right panel) moment, during a spring-tide in September 2011, between the actual mean sea level and future projections of SLR for the Portuguese coast: +0.28 m (A), +0.42 m (B) and +1.00 m (C).

also during the ebb peak. In this specific area the decrease of the current value of the velocity is always higher than -0.3 ms^{-1} . For the remainder estuarine areas, differences between current velocities are positive or negative, depending on their proximity to the lower areas considered in numerical grid which flood along the tidal cycle depending on the sea surface elevation. The maximum current velocities along the simulation period were also determined and analyzed for all the scenarios. The results also confirm the general decreasing of current velocity from the actual (1.37 ms^{-1}) to the future mean sea level scenarios. For S1 and S2 scenarios there is no difference between the maximum current velocities found (1.35 ms^{-1}) which is very close to the reference value, while it was found a more significant difference for the most extreme scenario S3 (1.31 ms^{-1}).

CONCLUSIONS

By considering three future scenarios of SLR for the 21st century, this study identified the main differences in the general hydrodynamics of the Douro estuary in view of the actual mean sea level (reference). The results from the model implementation developed in the frame of this research revealed that the possible changes in the general circulation of Douro estuary induced by the sea level rise are small, even in the scenario S3 (higher value of SLR). However, the study also reveals that:

- The amplitude of the M_2 constituent increases for almost the estuarine area, concerning the differences between the three future and reference scenarios. This pattern is more evident in the intertidal area near the estuarine mouth;
- The increase in land area flooded at the entrance of the estuary may possible modify the amplitude of M_2 along the estuary;

- The phase differences for M_2 tidal constituent could reach the 5.4 minutes in the S3 scenario, near the Crestuma dam (upstream region of the estuary);

- The differences in the current velocity patterns are almost negligible for the S1 scenario simulation;

- For the S2 and S3 scenarios the current velocity decreases in the central area of the inlet;

- The maximum velocities difference also present a general current velocity decreasing for future scenarios, reaching the maximum difference (0.06 ms^{-1}) for the most extreme scenario (S3);

As final conclusion, and considering the magnitude of the changes described, it was found that the climate change impact through the sea level rise on the general hydrodynamics of Douro estuary will be negligible. The differences presented may possibly be larger if other changes induced by climate change will be researched. Namely, the impact of changes in extreme cases of storm surges, fresh water discharges and wind forcing, especially in localized areas, such as the main channel at the mouth of the estuary.

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