Salinity evolution in the Tagus estuary relative to climate change

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Abstract: Climate change represents a potential threat for estuaries, via potential landward intrusion of saltwater, inundation of low-lying areas, acceleration in the nutrients cycling and disruption of aquatic ecosystems. The Tagus estuary, one of the largest estuaries in Europe, holds a major natural reserve and supports diverse activities, some of which may be negatively affected by the landward intrusion of saltwater (e.g. agriculture). In this study, a new three-dimensional hydrodynamics baroclinic model is implemented and validated in the Tagus estuary. A preliminary analysis of the salinity distribution relative to different river flows and sea level rise is also performed. Results show that the model adequately represents the main patterns observed, with significant improvements from previous applications. The classification of the estuary, based on the Venice system, shows contrasting situations regarding the salinity distribution for extreme river flows, and the progression further upstream of the saltwater due to mean sea level rise.

Key words: Numerical modelling, salinity, sea level rise, river flow, Venice system.

1. INTRODUCTION

Estuaries are among the most productive ecosystems on Earth and provide multiple services (e.g. Barbier *et al.*, 2011). They harbour ecologically important habitats for fish, shellfish and birds, protect the coastal ocean from increased contaminant loads and support diverse human activities (e.g. marine transportation, fishing and tourism), providing economic resilience to coastal communities and protecting them from natural hazards.

Climate change represents a potential threat for estuaries and may increase the hazards in these systems (Statham, 2012). Although the full extent of climate change remains uncertain (IPCC, 2013), sea level rise and changes in the hydrological regimes, in particular, can represent major threats to world's estuaries, by increasing the landward intrusion of saltwater, the inundation of low-lying coastal areas, the acceleration in the nutrients cycling and the disruption of aquatic ecosystems, among others (e.g., Statham, 2012). Evaluating the impacts of climate change is thus fundamental when developing management strategies for estuaries and its surrounding activities, to support the adoption of adequate adaptation measures.

The Tagus estuary (West of Portugal), one of the largest estuaries in Europe, may face some of the hazards of climate change. The estuarine margins are intensively occupied and support diverse activities, some of which may be negatively affected by the landward intrusion of saltwater (agriculture, shellfish harvesting, and sewage networks). The estuary itself holds a major natural reserve in the upstream area, which ecosystem dynamics may also be affected by changes in the salinity.

This study aims thus at analysing the salinity evolution in the Tagus estuary, relative to the climatic variability and to climate change. The study is being developed in the scope of the project BINGO (Bringing innovation to ongoing water management - a better future under climate change), which aims at providing practical knowledge and tools to end users, water managers and decision-makers to better cope with changes in climate, including extreme events such as droughts and floods. As a first contribution to these objectives, a new three-dimensional baroclinic model is implemented and validated in the Tagus estuary, and a preliminary analysis of the salinity distribution relative to different river flows and sea level rise scenarios is performed.

2. STUDY AREA

The study area covers the Tagus estuary and, in particular, its upstream area near the Lezíria de Vila Franca de Xira, where an important agricultural area is located. The Tagus Estuary Natural Reserve and some important shellfish areas are also located in the upstream part of the estuary. The Tagus estuary has an area of about 320 km^2 and a complex morphology, with a deep and narrow inlet channel and a broad and shallow inner basin. The intertidal area represents about 43% of the total estuarine surface (Nogueira Mendes *et al*., 2012). The tides are semi-diurnal, with tidal ranges varying between 0.6 m and 3.8 m in Cascais (Guerreiro *et al.*, 2015). The main source of freshwater into the estuary is the Tagus river, with an average flow of 370 m^3/s (Neves, 2010), followed by the Sorraia river.

3. NUMERICAL MODEL

3.1. Model setup

The three-dimensional baroclinic circulation in the Tagus estuary is simulated with the system of numerical models SCHISM (Zhang *et al.*, in review). This application is based on the previous applications by Costa *et al.* (2012) and Rodrigues *et al.* (2013, 2016) of the hydrodynamics model SELFE (Zhang and Baptista, 2008) in this estuary.

The domain is discretized with a horizontal grid of about 270 000 elements (Fig. 1) and a resolution that varies from about 2 km near the oceanic boundary to 30 m in some marginal areas. A smaller horizontal grid (of about 166 000 elements) that excludes the low-lying areas (Mouchões and Lezíria) is used in the simulations where no inundation of these areas is expected. The vertical domain is discretized in a hybrid grid with 39 SZ levels (30 S levels and 9 Z levels) based on preliminary data-model comparisons. Three open boundaries are considered: the Atlantic Ocean, and the Tagus and Sorraia rivers. The oceanic boundary is forced with 23 tidal constituents from the regional model of Fortunato *et al.* (2016). The river flows were established based on the data available at SNIRH (http://snirh.pt). The atmospheric forcing was implemented using the NCEP Reanalysis data (http://www.esrl.noaa.gov/).

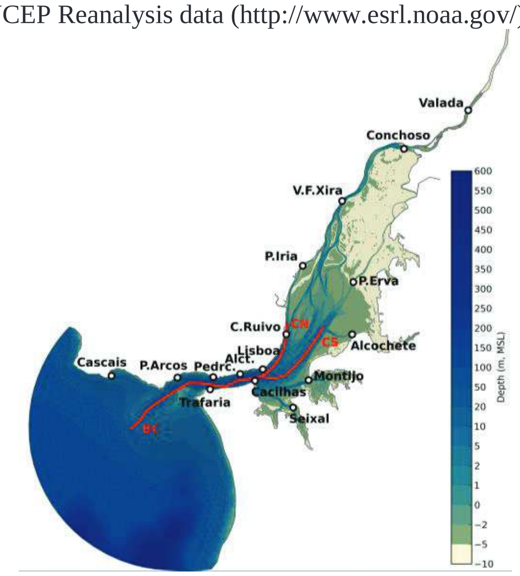

Fig. 1. Horizontal grid and bathymetry (MSL - mean sea level).

3.2. Scenarios definition

The scenarios definition aimed to represent extreme situations regarding the river flow, which is the main driver of the salinity in the Tagus estuary (Rodrigues *et al.*, 2016). Two scenarios were simulated based on the following periods: July 2005 and February 1979. In July 2005 the estimated average Tagus river flow was 22 m^3/s (estimation based on Macedo, 2006), although some uncertainty remains since for this period no data are available at Almourol or Ómnias stations. In contrast, in February 1979 the average river flow was 3730 m^3/s and 5464 m^3/s in Almourol and Ómnias, respectively (Macedo, 2006). For both scenarios, the simulations were performed for the present mean sea level and considering a mean sea level rise of 0.5 m.

4. RESULTS AND DISCUSSION

4.1. Data-model comparison

Water levels data measured in 1972 were used to calibrate the model. Data and model results were both harmonically analysed and synthesised for eleven tidal constituents (Z0, MSF, O1, K1, N2, M2, S2, M4, MS4, M6, 2MS6). Root mean square errors ranged between 4 cm and 15 cm (Table I) showing that the model represents adequately the tidal propagation. At most stations, particularly the ones located upstream, these errors are lower than the ones from previous applications (Table I). The improvements obtained may result from the higher horizontal grid resolution, namely upstream, and the updates in the bathymetry (see Fortunato *et al.*, in prep.), both contributing for a better propagation of the tide, and from the model itself.

Table I. Root mean square errors (RMSE) of the water levels. The location of the stations is shown in Fig. 1.

	RMSE (cm) SCHISM3D	RMSE (cm) SELFE 3D
Cascais	3.6	1.8
P. de Arcos	4.6	5.8
Trafaria	10.7	9.6
Lisboa	7.6	10.8
Pedrouços	5.4	5.9
Cacilhas	3.9	6.4
Seixal	5.7	9.4
Montijo	8.8	12.2
Cabo Ruivo	9.7	13.5
Alcochete	7.3	12.3
P. Sta. Iria	8.6	17.3
Ponta da Erva	8.8	20.2
V. F. de Xira	15.1	21.5

Salinity and temperature were validated with data obtained along longitudinal profiles (Fig. 1, red lines) on February 1988 (Neves, 2010). Results show that the model reasonably represents the main patterns observed, namely the stratification of the water column (Fig. 2). The model, however, tends to overestimate the vertical mixing, in comparison with the observations that present a more pronounced stratification. A reduced stratification had already been observed in the previous applications (Costa *et al.*, 2012), but significant improvements were achieved in the present application. A reasonable agreement was also observed for temperature (results not shown), with significant improvements in comparison with the application by Costa *et al.* (2012), in particular regarding the thermal stratification. The improvements achieved are mainly related with the increase of the vertical grid resolution, from 20 SZ to 39 SZ levels, which reduced the simulated mixing in the water column.

A preliminary comparison with data measured at the Alcântara station (Fig. 1) also suggests that the model adequately represents the main salinity and temperature patterns observed, with errors of the same order of magnitude of those obtained by Rodrigues *et al.* (2016).

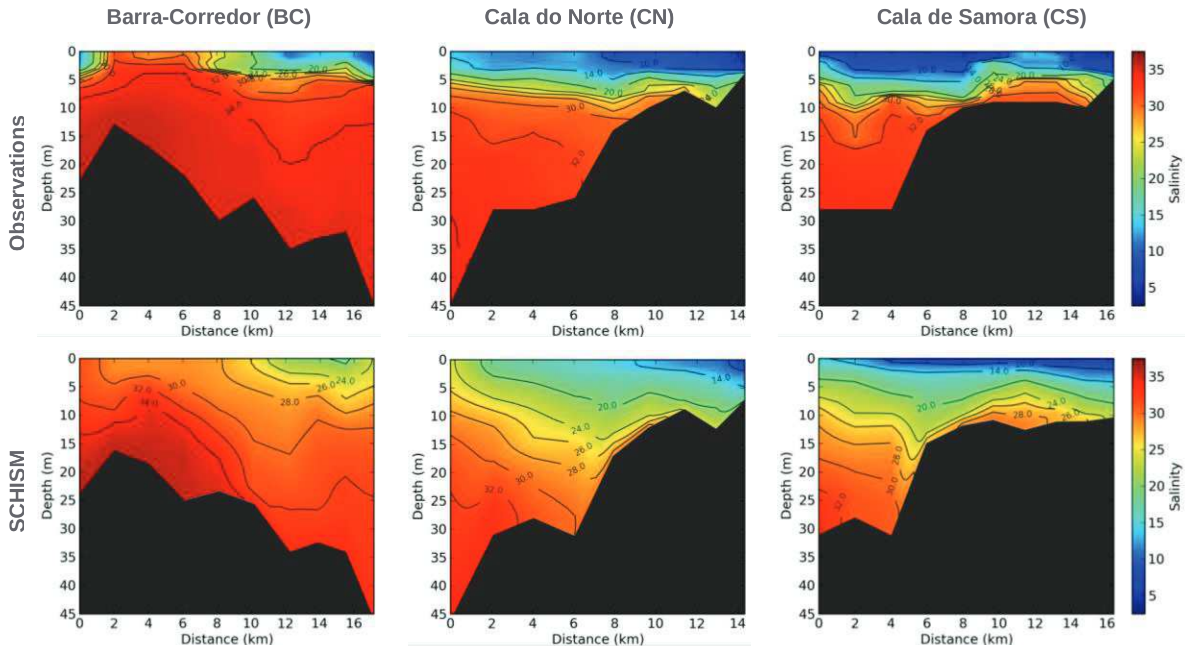

Fig. 2. Data-model comparison: vertical profiles of salinity measured during low-tide (February 11-13, 1988).

4.2. Salinity distribution and evolution

Salinity statistics were computed and the Tagus estuary was classified following the Venice system (after Carriker, 1967), which classifies waters with respect to the salinity into six classes: limnetic (freshwater, <0.5), oligohaline (0.5-5), mesohaline (5-18), polihaline (middle area, 18-25; lower area, 25-30), and euhaline (30-35).

Results show a pronounced progression of the saltwater upstream for low river discharges (Fig. 3). For the 2005 scenario most of the estuary presents polihaline or euhaline characteristics with mean salinities higher than 18 up to Vila Franca de Xira (Fig. 3). At the Conchoso station, where the water intake for irrigation is located, the simulated mean and minimum salinities were 9 and 3, respectively, preventing its use for agriculture (salinity < 1). Since some uncertainty remains regarding the river flow for the 2005 scenario due to the lack of data available, further analysis should proceed with a sensitivity analysis of salinity to low river flows. The 1979 scenario shows a contrasting situation with an extension of the limnetic area further downstream of Vila Franca de Xira (Fig. 4). For the 1979 scenario mean simulated salinity at Cascais was 30 (range: 15-36), comparatively with the mean salinity of 36 (range: 35-36) for the 2005 scenario.

Mean sea level rise scenarios suggest the propagation further upstream of the oligohaline and mesohaline areas (Fig. 3 and Fig. 4), and an increase of salinity at Conchoso of about 10% during low river discharge periods.

5. CONCLUSIONS

A new three-dimensional hydrodynamics baroclinic model was implemented and validated in the Tagus estuary. This model adequately represents the main patterns observed, with significant improvements from previous applications. A preliminary analysis to extreme river flows shows contrasting situations regarding the salinity distribution in the estuary, and a progression further upstream of the saltwater due to mean sea level rise. These results are a first contribution for the development of adaptation strategies to floods and droughts in the scope of the project BINGO.

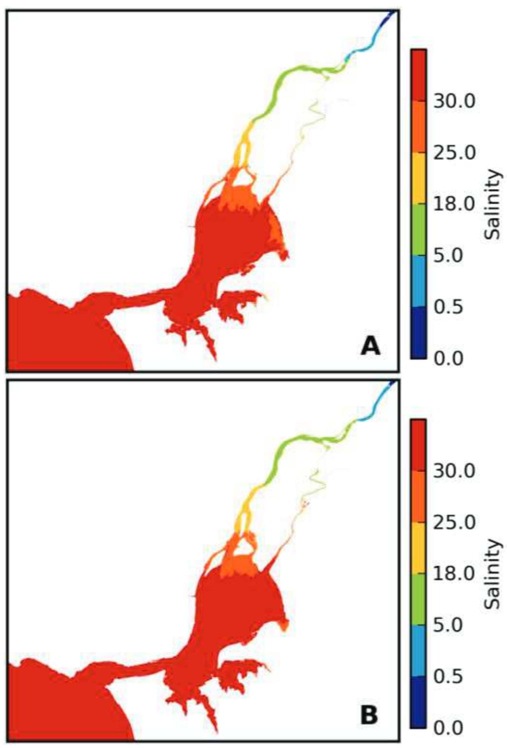

Fig. 3. Salinity classification in the Tagus estuary based on the Venice system regarding the 2005 scenario: present mean sea level (A), mean sea level rise of 0.5 m (B).

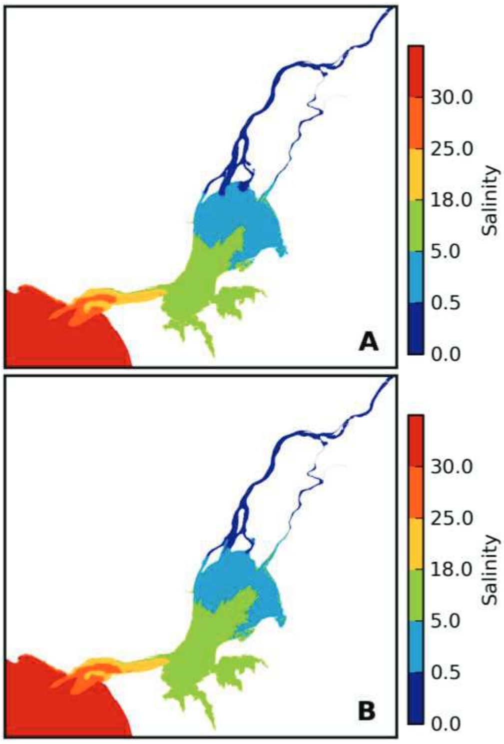

Fig. 4. Salinity classification in the Tagus estuary based on the Venice system regarding the 1979 scenario: present mean sea level (A), mean sea level rise of 0.5 m (B).

Acknowledgements

This study was funded by the EU's H2020 programme (Grant Agreement n. 641739) and by the FCT project UBEST (PTDC/AAG-AA/6899/2014). The first author was partly funded by the FCT (SFRH/BPD/87512/2012). This work used the resources from the FCT's National Distributed Computing Infrastructure. The authors thank the institutions that provided the data (IH, FCUL, APL, DGT, ABLGVFX, NOAA/OAR/ESRL PSD), and Han de Lange for treating the water levels results.

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