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Impact of climate change on the hydrodynamic patterns of the Gironde estuary

Mohammad TRABOULSI [1], Vanessya LABORIE [1], Nicolas HUYBRECHTS [1]

1. Cerema REM, HA Research Team, 134 rue de Beauvais, 60280 Margny-lès-Compiègne, France.
vanessya.laborie@cerema.fr; nicolas.huybrechts@cerema.fr

Abstract:
Within the Interreg-Sudoe European project ECCLIPSE (2019-2022), several numerical tools are developed to forecast the influence of climate change inside the Gironde estuary. The meteorological forcings come from 3 Global Climate Models (GCMs) combined with 2 emission scenarios (RCPs 4.5 and 8.5). Upstream of the Dordogne and Garonne rivers, the discharges time-dependent chronicles are predicted using both the meteo inputs (precipitations and temperatures), and a hydrological model based on GR4J software (PERRIN, 2007). Offshore, a Telemac 2D surge levels numerical model (LABORIE *et al.*, 2015), supplied by meteorological forcings (winds and pressure fields) and contributions of the mean sea level rise (MSLR) provides the predicted surge levels' chronicles at the maritime boundary of the estuary. The impact due to the evolution of external forcings (rivers and sea) on the hydrodynamic pattern (salinity) are then analysed for short and middle-term horizons 2050 and 2070 using a Telemac 3D model

Keywords:
Climate change, IPCC5, Gironde estuary, Hydrology, Hydrodynamics, Salinity, RCP4.5, RCP8.5, Telemac 2D.

1. Introduction

With respect to climate change, maritime ports need to forecast their adaptation. In the framework of the Sudoe Ecclipse project, we focus on different ports located in south-western Europe, i.e. in Valencia, Aveiro and Bordeaux, and their adaptation to climate change using prediction models, prevention, and action strategies. The port of Bordeaux has been selected as a typical port located inside an estuary. Such ports expect modifications from both maritime and river boundaries induced by the evolution of hydro-meteorological conditions in the middle and far future. In this contribution, particular attention is paid to saline intrusion considered as a proxy of the maximum turbidity. The saline intrusion is predicted using a 3D hydrodynamic model (HUYBRECHTS *et al.,* 2021) built with the software Open Telemac (http://www.opentelemac.org/).

The meteorological forcings come from 3 Global climate models (GCMs) combined with 2 emission scenarios (RCPs 4.5 and 8.5). Upstream of the Dordogne and Garonne rivers, the discharges chronicles are predicted using both the meteo forcings, and a hydrological model based on GR4J software. Offshore, a Telemac 2D surge levels numerical model (LABORIE *et al.,* 2015), supplied by a meteorological scenario and contributions of the mean sea level rise (MSLR), provides the predicted surge levels' chronicles at the maritime boundary of the estuary. The impact due to the evolution of external forcings (river and sea) due to climate change on the hydrodynamic pattern will then be analysed for horizons 2050 and 2070.

2. Studied site and climate change scenarios

The Gironde Estuary, located in the southwest of France (Nouvelle-Aquitaine region), is the largest macrotidal estuary in Western Europe. It extends from the Bay of Biscay (Golfe de Gascogne) for 170 km landward and covers a total area of 635 km^2. The estuary is formed from the confluence of two rivers: the Dordogne river in the North and the Garonne river in the South. Upstream of the Gironde estuary, the average flow of the Dordogne is 350 m^3/s and that of the Garonne is 650 m^3/s.

The ECCLIPSE project involves the analysis of 2 climate change scenarios, i.e. RCP4.5 (resp. RCP8.5) representing a stabilization before 2100 (resp. growing without climate change politic) concerning the greenhouse gases profile, using 3 climate change models (table 1). The historical period 1986-2005 serves as a reference. The data from the RCMs cannot be used directly but need to be corrected to properly reproduce the observed data (discharges at La Reole on the Garonne river and Pessac on the Dordogne river here) and give accurate statistical indicators.

Table 1. RCP scenarios adopted since the IPCC AR5 (OUZEAU et al., 2014) and used inside ECCLIPSE project.

Model	***GCM***	***RCM***	***Institution for RCM***
1	*CNRM-CERFACS-CNRM-CM5*	*CNRM-Aladin63*	*Météo-France / Centre National de Recherches Météorologiques*
2	*IPSL-IPSL-CM5A-MR*	*SMHI-RCA4*	*Swedish Meteorological and Hydrological Institute, Rossby Center*
3	*MOHC-HadGem2-ES*	*DMI-HIRHAM5*	*Danish Meteorological Institute.*

3. Models set up

3.1 3D hydrodynamic model

The flow field is computed by Telemac 3D (*www.opentelemac.org*). The horizontal mesh is unstructured with around 30000 nodes (see figure 1). The vertical mesh is formed of 9 planes spaced using a geometric progression. The bed friction is imposed using a space variable Nukuradse coefficient and a k-epsilon model is used for the turbulence closure. The computational domain extends offshore up to 70 km from the mouth and about 200 km alongshore such as the boundary condition for salinity is sufficiently far away from the mouth. A tide signal and some time-dependent instantaneous surge levels are imposed at the offshore open boundary (in blue on figure 1). The tidal signal is extracted from the North East Atlantic tidal model (PAIRAUD *et al.,* 2008). Flowrates are imposed at both tributaries, namely the Garonne and Dordogne rivers. Salinity is considered as a passive tracer with 35 psu (practical salinity unit) imposed offshore and 0 psu for both tributaries.

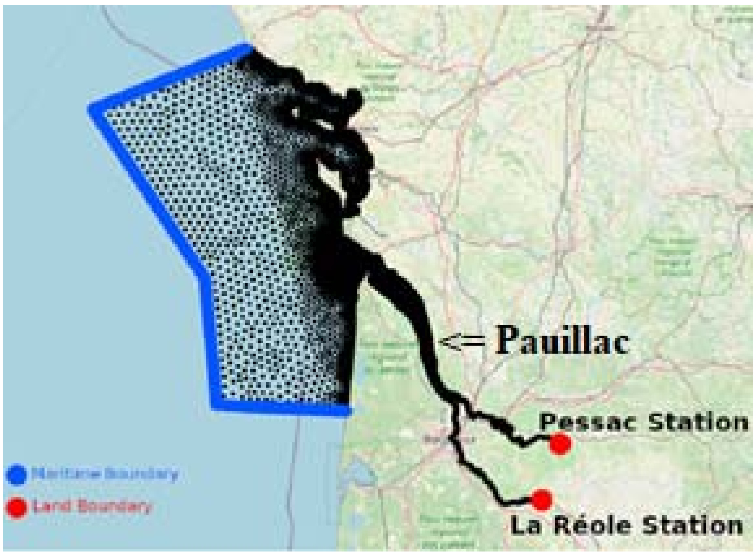

Figure 1. Telemac3D model mesh developed by Cerema with the boundary conditions labelled.

3.2 Conceptual hydrological model

While the climate models study the general behavior of the climate, hydrological models are necessary to convert the rainfall data and air temperatures to evapotranspiration, runoff or flows at a given outlet of the watershed. The open-source conceptual model GR4J (*https://webgr.inrae.fr/en/models/daily-hydrological-model-gr4j/description-of-the-gr4j-model/*) is selected here. It is based on the assumption of several stores interacting with each other, with the underground and the river. The model has been calibrated and validated on SAFRAN analysed data provided by METEO-FRANCE. The hydrologic model is then exploited to predict the flowrate chronicles up to 2100 for the different RCM and scenarios specified in table 1.

3.3 The Telemac2D-based storm surge numerical model

Storm surges are the sea-level response to meteorological conditions, such as wind effects and pressure gradients. Based on Telemac 2D, a storm surge numerical model has been developed by LABORIE *et al*., 2015. It allows the modeling of surge levels induced by meteorological forcings near the front of the European Atlantic zone. The model covers the area between the longitudes 9◦ W and 10◦ E, and the latitudes 43◦ S to 62◦ N. The bathymetry and the mesh of the model are shown in figure 2. The mesh contains 32644 nodes and 59159 elements. The model is forced by an instantaneous mean sea level (including a mean sea level rise described in section 4.1) at the maritime boundaries and by the wind/pressure fields for each couple (RCM, RCP) modelled.

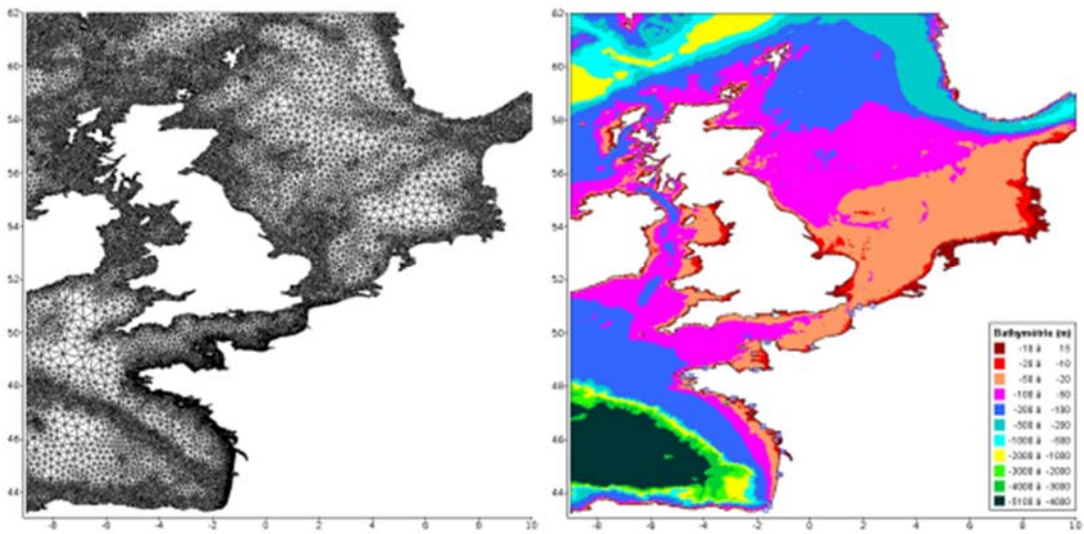

Figure 2. Storm surge model (ref) Mesh (left) and bathymetry (right) of the surge level numerical model (source : LABORIE et al., 2015).

4. Results

4.1 Evolutions of the maritime forcings

The mean sea level rise is composed of oceanic and non-oceanic contributions (CAZENAVE *et al.*, 2014). The sum of all contributions provides an estimate of the increase in mean sea level due to climate change. Figure 3 presents the sum of all contributions to mean sea level rise as a 20-year moving average relative to the period. The increase near the French coast is between 0.3 − 1.1 m for the RCP4.5 scenario and 0.4 − 1.3 m for the RCP8.5 scenario. This contribution is slightly higher than the average global mean sea level rise as reported in the IPCC AR5 (ALLEN *et al.*, 2019). The non-oceanic contributions represent around 65% of the total mean sea level rise while the rest is due to oceanic contributions.

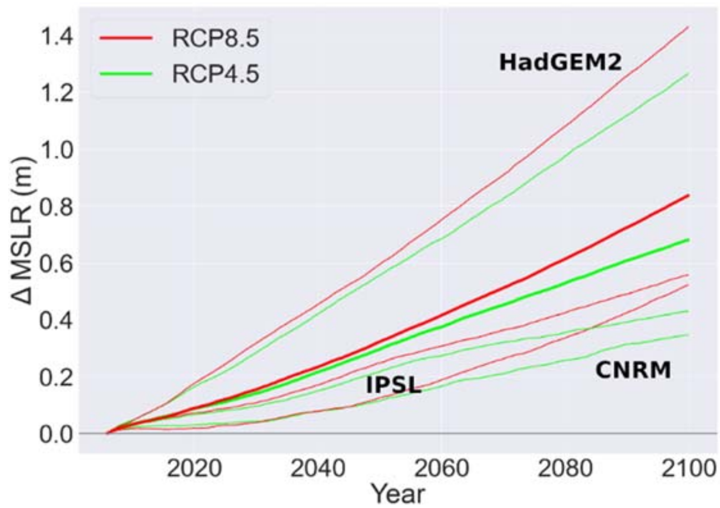

Figure 3. Evolution of the mean sea level rise (ΔMSLR) for the 3 Regional Climate models coupled either with RCP4.5 (in green) or with RCP8.5 (in red).

Skew surges were modeled using a Generalized Pareto Distribution (GPD) and an Exponential distribution using a Peak Over Threshold method (POT) to estimate the quantiles for return periods up to 100 years. The values were first validated by comparing them with previous reports (PERHERIN *et al.*, 2013) at 20 different ports on the west coast of France. The model shows good estimates for most ports except for ports that are in the extreme north or south (e.g. Bayonne and Calais). For the region near the mouth of the estuary (e.g Port-Bloc and Le Verdon), low error about 6% for the 100-years return period quantile is reached. The impact of climate change on skew surges near Le Verdon is represented in figure 4 for the 100-years return period quantile which increases by around 20 cm increase for the RCP4.5 scenario and by an average of 30 cm for the RCP8.5 scenario. Overall, this increase remains constant until the end of the century.

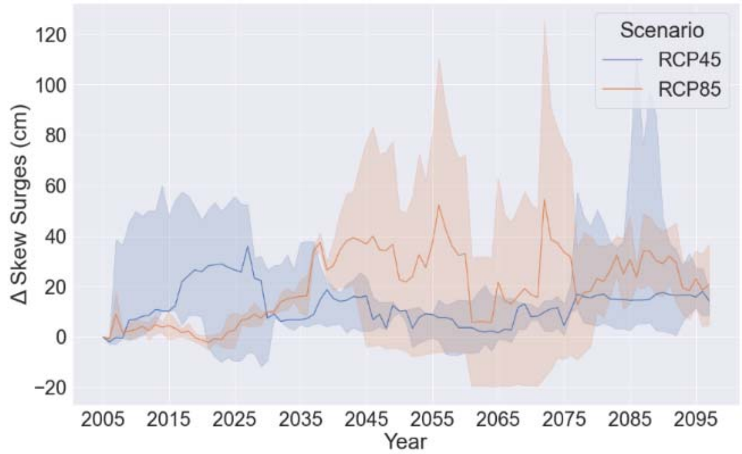

Figure 4. Evolution of the average and standard deviation for a 100-years return period quantile for storm surges for 3 RCM (see table 1) coupled with 2 RCP (4.5 in blue, 8.5 in red).

4.2 <u>Evolution of flowrates and the impact on the saline intrusion</u>

For the CNRM model and both scenario RCP 4.5 and 8.5, the evolutions of flowrates and salinity are illustrated on figure 5. The salinity is extracted at Pauillac, located in the central part of the estuary. A threshold value of 5 psu is selected for the salinity whereas 200 m^3/s (for both Garonne and Dordogne river) is chosen to represent the influence of the low flowrate. For each threshold, we compute the number of days per year during which these values are reached. The period up to 2070 has been considered to run the different years with Telemac 3D. During this time slice, the mean sea level has increased up to 20 cm with a difference up to 5 cm between the two scenarios.

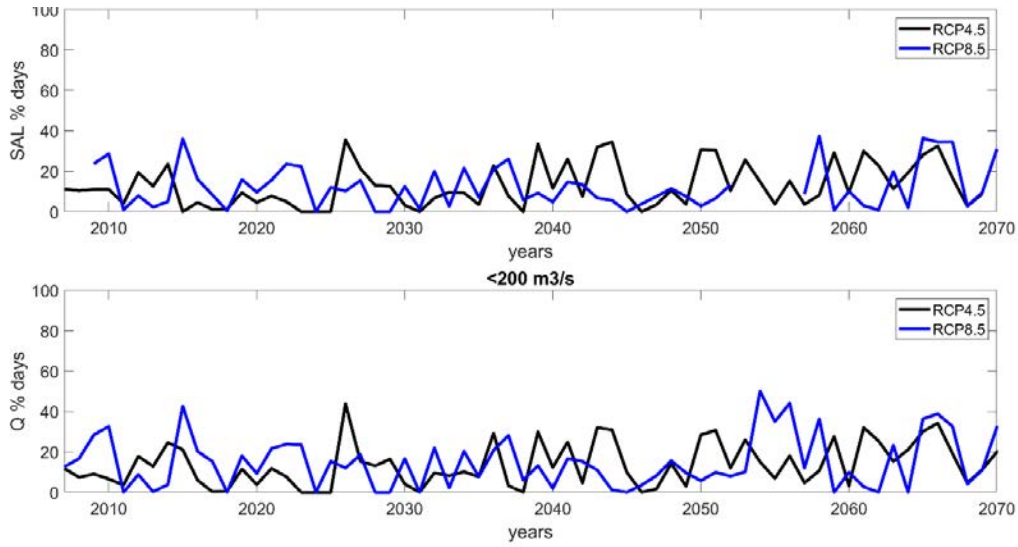

Figure 5. Percentage of time/year the salinity is above 5 PSU at Pauillac and the flowrate is lower than 200 m^3/s.

For RCP 4.5, the number of days with flowrate < 200 m3/s features a peak up to 40% (2027) and after that, the number of days regularly reaches 20%. For RCP 8.5, the number of days reaches 20 to 40% faster (2010 2015) than RCP 4.5. Within the time period [2010-2045], it often reaches 20%, and then it is decreasing to 10% during the time period [2040-2050]. Finally, it is increasing again during the time period [2050, 2070] (up to 30 and 40%). Figure 5 shows similar evolutions of the two thresholds (flowrate and salinity) which is probably due to the limited elevation of the mean sea level for the period considered. These observations still need to be completed with the evolutions of the other climate models and extended up to 2100.

4. Conclusions

In order to forecast the impact of climate change, several models have been developed to predict the evolution of the discharges and storm surges in the vicinity of the Gironde estuary and their impact of the saline intrusion. Concerning the river flows at the upstream part of the estuary, a decrease in the flows of the Dordogne and Garonne rivers by an average of 10 % and 40 % respectively is observed, consistent with the EXPLORE 2070 project's results (CHAUVEAU *et al.*, 2013). Concerning the Mean Sea Level Rise, an increase between 0.3 and 1.4 m near the French coast is obtained, consistent with the IPCC5 Assessment Report. Regarding storm skew surges, an increase between 20 cm to 30 cm is observed for the RCP4.5 and RCP8.5 scenarios at the mouth of the estuary.
Concerning the salinity, the increase of the level follows the decrease of flowrates. Both threshold values are more often reached after 2030 for the RCP 4.5 but without significant increase up to 2070. This is the contrary for RCP 8.5 for which the percentage of days increases faster first, then decreases before increasing again. These partial results need to be confirmed with the exploitation of the other climate model.

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