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# Hydrodynamic and fine sediment transport numerical modelling, application to the Río de la Plata and Montevideo Bay

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*Abstract*— **The objective of this work is to develop a high resolution wave-current-sediment transport model to simulate the flow field and sediment transport processes of the Río de la Plata estuary and specifically at Montevideo Bay area. Numerical results using the depth-averaged modules of the TELEMAC-MASCARET Modelling System show excellent agreement when compared with observed sea surface elevation, currents, and wave parameters at several stations in the estuary. Preliminary results show a good representation of the suspended sediment concentration series near Montevideo Bay.**

## I. INTRODUCTION

Montevideo Bay hosts the main port of Uruguay along with a large industrial development. Nowadays there are many maritime engineering projects in the area, including the construction of new breakwaters, land reclamation for container terminals, navigation channels deepening, etc. All these projects need a reliable characterization of the hydrodynamics in the area and also for some of them the sediment dynamics. Numerical modelling is a powerful tool in that sense, not only for the design of these projects but also to assess their impact on the whole area.

In this work the open source TELEMAC-MASCARET Modelling System (TMS) is implemented for the Río de la Plata estuary with special attention to Montevideo Bay in order to study the fine sediment dynamics. Previous studies of our group have been focused on the general hydrodynamic and fine sediment dynamics for the whole estuary [1],[2]. By using the finite elements/volumes technique the TMS works with non-structures meshes allowing to cover big domains increasing the resolution on the areas of interest which can have complex geometries e.g. harbours. As a first approach we started to work using the depth averaged modules of the TMS. Although we know the limitations of this approach for an estuarine application, it aims to be an efficient tool in terms of computation times, which is very important for example during the evaluation of several "what-if" scenarios for engineering projects.

## II. STUDY AREA

The Río de la Plata is located on the east coast of South America. Its axis runs from NW to SE and is approximately 280 km long. Its surface area is approximately 35,000 km2, and its width varies from 20 km at the innermost part to approximately 220 km at its mouth (Fig. 1). The river communicates freely with the ocean and experiences seasonal freshwater discharge from its two major tributaries (the Paraná and Uruguay rivers), with annual average discharge of approximately 16,000 m3/s and 6,000 m3/s, respectively. Two main regions can be identified based on the morphology and dynamics of the Río de la Plata. A shallow area located along the Punta Piedras-Montevideo line separates the inner region from the outer region. The inner region has a fluvial regime, with no stratification or preferential flow direction. In the outer region, the increase in river width generates complex flow patterns. This outer region is formed by brackish waters of variable salinity that are influenced by the tides, the winds, and the contribution of fresh water from the river basin.

The tidal regime is dominated by the M2 component, followed by the O1 component which is responsible for the diurnal inequality. The tidal amplitude is greater along the Argentinean coast (order of 1 m), while it is about 0.4 m along the Uruguayan coast. The meteorological tide (storm surge events) is of great importance being of the same order of magnitude as the astronomical tide [2]. Currents at the estuary are controlled by the oceanic tides that penetrate the river mouth. Although the amplitude of the tides is small, the very large river mouth generates a tidal prism that can dominate the flow regime despite the significant discharge received from the tributaries.

The outer Rio de la Plata and the adjacent continental shelf are covered with sands, while silty clays, clayey silts and silts, are confined to the upper and the middle portions of the estuary. The suspended sediment load is mainly carried by the Paraná river in amounts up to 160 million tons/year of fine sand, silt, and clay. Fine sands mostly settle in the innermost part of the Río de la Plata and are responsible for the Paraná Delta Front progradation. Fluvial fine cohesive sediments are further advected to the inner part of the estuary.

Montevideo Bay covers an area of approximately 12 km2 and is part of the Río de la Plata (Fig. 2c). The water depth reaches 5 m in the outer part of the bay and between 1 m and 1.5 m in the inner area. The navigation channels are approximately 11 m deep. The bay receives two urban streams, Pantanoso and Miguelete. Water circulation in the bay mainly occurs due to the sea level variations along the bay mouth and due to shear induced by the outer flow and the local winds.

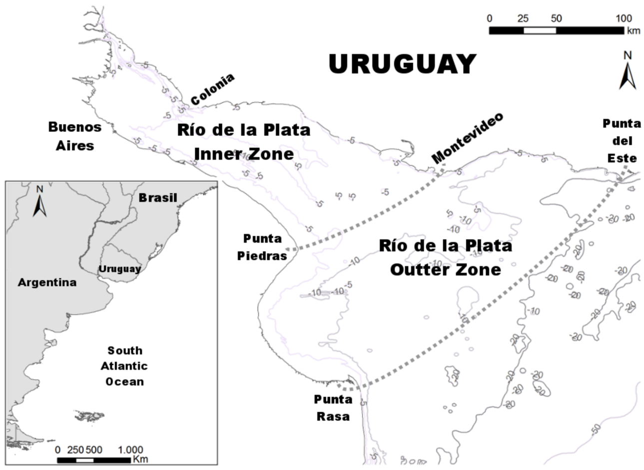


Figure 1. Río de la Plata location and bathymetry.

## III. HYDRO-METEOROLOGICAL DATA

### *A. Meteorological data*

Data from the European Centre of Medium Weather Forecast was used, in particular the ERA-Interim product [3] with a 0.125° spatial resolution and 6 hours temporal resolution.

### *B. Sea surface elevation data*

Sea surface elevation (SSE) measurements at eight mareograph stations were used in this work, named Mar del Plata (MP), La Paloma (LP), Punta del Este (PE), Montevideo (MVD), Torre Oyarvide (TO), Pilote Norden (PN), Colonia (COL) y Buenos Aires (BA). Fig. 2a shows the location of each one of these stations.

Particularly for this work the analysed periods were the years 2004 and 2009. During the first one there is available information in the eight stations (with some missing gaps). During 2009 we have only available information at MP, MVD y PN stations. In all cases we worked with hourly sea level series.

### *C. Currents data*

Current data from ADCPs (Acoustic Doppler Current Profiler) instruments are available at two locations near to Montevideo coast referred as Punta Brava (PB) and Punta Yeguas (PY) (see Fig. 2c). These instruments were installed at the end of 2003 and were measuring until the end of 2009 (with several gaps due to maintenance). These instruments provided simultaneous data of currents direction and intensity at different depths in the water column. The instruments were set to save a register each 30 minutes.

### *D. Wave data*

Two wave database were used in this work. The first one correspond to PB ADCP time series of significant wave height, mean period, peak period and peak direction. The available period is 2007 to 2009 with several gaps, the temporal resolution of this series is 3 hours.

The second dataset comes from a wave rider buoy here called Hidrovia (HV), (see Fig. 2a). There is available data from 1996 to 2006 with several gaps, the temporal resolution is variable but it is close to 1 hour.

### *E. Suspended sediment data*

Suspended sediment concentration data was obtained indirectly from the backscatter intensity from PB ADCP. The backscatter-SSC calibration was done using water samples taken at two different water depths during the initial deployments [4].

## IV. MODEL SETUP

### *A. Domain and computational mesh*

The modelled domain includes the Rio de la Plata and its maritime front zone approximately until the 200 m depth on the continental shelf (Fig. 2a). The main freshwater inflows are included, rivers Paraná and Uruguay at the west boundary (Fig. 2b). As it was mentioned before the TMS works with finite elements based on triangular meshes. The mesh elements size ranges from approximately twelve kilometres at the oceanic boundary to ten meters in the vicinity of the Montevideo Bay, it has 30059 nodes and 58594 elements. Fig. 2c shows in more detail the mesh at Montevideo Bay zone and includes its bathymetry. It can be seen the navigation channel which gives access to Montevideo's harbour and the harbour basins and internal channels in the bay.

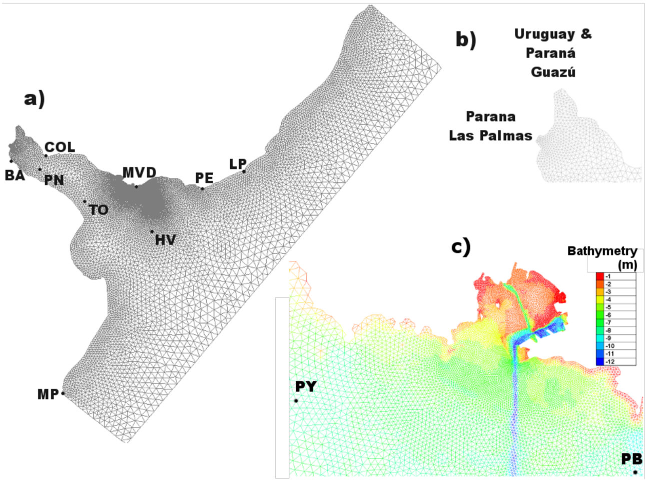


Figure 2. (a) Río de la Plata unstructured mesh, (b) detail of river discharges, (c) Montevideo Bay zone including its bathymtery.

*B. Circulation model:*

The hydrodynamic model Telemac 2D (T2D) takes into account the fluvial discharges of Paraná and Uruguay rivers, tides at the oceanic boundary (astronomical and meteorological from a regional model), and wind and sea level pressure from ERA-Interim ReAnalysis. The model takes into account the effect of the salinity horizontal gradients.

The daily flow information of the Parana and Uruguay rivers was provided by the Argentinean National Water Institute. Fig. 2b shows the two sections of stream flow contribution defined in the inner region of the Rio de la Plata, one corresponds to the income flow of Uruguay and Parana-Guazu rivers and the other to the Parana Las Palmas river.

Relevant tidal waves, both astronomical and meteorological, are imposed at the oceanic open boundary. Sea surface elevation values provided by a regional tidal model [5] are prescribed at oceanic boundary nodes.

For the bottom friction computation the Manning formulation was chosen and the Manning coefficient was considered as a calibration parameter.

On the free surface, wind and sea level pressure forcings are considered. For the wind surface stress an aerodynamic bulk formula is employed with a constant drag coefficient. This drag coefficient was the other calibration parameter.

After several tests the final configuration solves the quasi-bubble approximation of the primitive form of the shallow water equations [6] using a time step of 60s. The characteristics method is applied as advection scheme for the velocity computation and the distributed PSI method is used for the free surface elevation.

As it was mentioned before the chosen calibration parameters are the Manning coefficient, and the drag coefficient in the surface wind stress formulation. It was carried out a set of simulations varying these parameters in a wide range of reasonable values. The simulation period for the calibration was January – June 2004, while the validation period was January - May 2009. In order to evaluate the quality of the results, the simulated sea level series were compared against the observed values in the mareographs stations presented in Fig. 2a. Also the depth averaged currents at PB and PY were compared.

*C. Wave propagation model:*

The third generation spectral wave model TOMAWAC (TWAC) is forced with 10m wind from the European Centre of Medium Weather Forecast ERA-Interim Reanalysis. At the oceanic boundary the model is forced by wave statistics from a regional model [7]. A Jonswap spectrum is constructed at each boundary node based on the significant wave height, peak period, mean direction, and directional spread given by the regional model with a temporal resolution of 3 hours.

The model was configured to takes into account the following processes: white capping, bottom friction, depth breaking, and quadruplets interactions.

Model results were validated against observed data at PB and HV stations.

*D. Coupled Circulation and Wave model*

The TMS allows to perform a two way coupling between T2D-TWAC to represent wave current interactions: T2D transfers to TWAC the updated values of current velocities and water depths, while TWAC solves the wave action density conservation equation with reference to those current and water depth values and returns to T2D the updated values of the wave driving radiation forces acting on the current.

As mentioned before the time step for both models is 60s, the selected coupling period is 60 which means both models communicate with each other every 1h.

*E. Sediment transport model*

SISYPHE (SIS) was coupled with the circulation model T2D. Even though it is possible to implement a three way coupling including the wave model (SIS+TWAC+T2D), the wave model increases the computation time considerably. For this reason for sensitivity analyzes and preliminary calibration we modified the SIS code in order to read the wave results of the coupled wave and circulation model. Having read the wave results the wave bottom stress was computed using the Swart formulation [8] for the friction factor considering a bed roughness of 0.1mm and using the peak period for the orbital velocity computation.

Only one sediment class is considered, which is defined as cohesive. Our main interest is to study the fine sediment dynamics and specifically at Montevideo Bay zone the non-cohesive sediment fraction is negligible. The model computes the erosion flux using the Partheniades classical formula and the deposition flux using the Krone formula [9]. Based on these equations the parameters to be defined are: the settling velocity, the Partheniades coefficient, and both the critical shear stress for deposition and erosion. In SIS the settling velocity is considered as a constant value given by the user. In order to represent indirectly the effect of flocculation in settling we modified the code and made the settling velocity proportional to the SSC. So it is needed to define both a settling velocity and the SSC associated to it.

The bottom bed is uniform all over the domain, however areas where non-cohesive sediments are predominant were set as non-erodables. As it was said before only the fine sediment fraction is being modelled in this implementation. The consolidation process is not taken into account yet.

The SSC imposed at the boundaries is null except for the two sections corresponding to Uruguay and Paraná Rivers (see Fig. 2b). At Paraná Las Palmas boundary the imposed SSC is 47mg/L, while at Uruguay and Paraná Guazú boundary it is 154 mg/L. These are annual mean values for the fine sediment fraction from [10].

By the time being it was made a sensibility analysis to the parameters mentioned before and a preliminary calibration procedure comparing the SSC results against the PB observations.

## V. Results

### *A. Circulation model*

After the calibration process the wind drag coefficient showed to be the main parameter to adjust the meteorological tide events representation. The Manning coefficient influence is also noticeable, especially on the astronomical tide presentation. After comparing the results against SSE series and currents series at the stations mentioned before, it was selected the configuration with drag coefficient equals 3e-6 and Manning coefficient 0.02.

In order to illustrate the sensibility of the model results to these parameters, Figs. 3 and 4 show Taylor diagrams of the sea surface elevation series at Montevideo station. This diagram allows to summarize three statistics for a set of simulated series: the Pearson correlation between the observed and simulated series (blue), the standard deviation of each series (black), and the centred root mean squared error of the simulated series (green). Fig. 3 shows the results corresponding to nine simulations varying the wind drag coefficient (Cd) from 1e-6 to 5e-6 with step 0.5e-6. It can be seen that simulation 5, corresponding to a wind drag coefficient equals 3e-6, gives the best results.

Fig. 4 shows the results of seven simulations where the Manning coefficient (n) took these values: 0.015, 0.018, 0.019, 0.020, 0.021, 0.022, 0.025. Simulation 4, corresponding to a Manning coefficient equals 0.020, gives the best results.

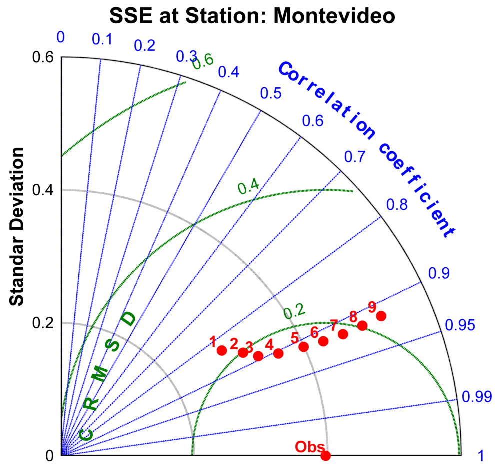


Figure 3. Taylor diagram of sea surface elevation series for different wind drag coefficients (1 correspond to Cd=1e-6 and 7 to Cd=5e-6).

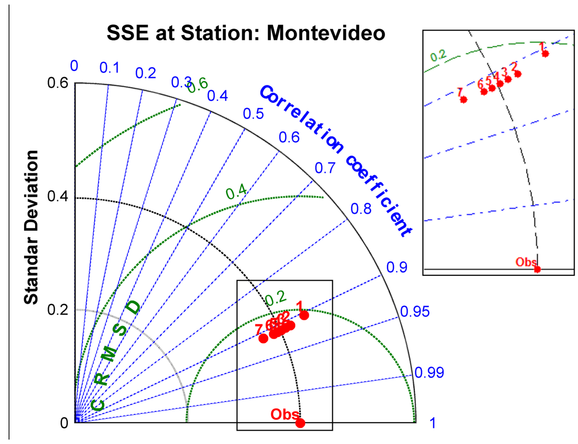


Figure 4. Taylor diagram of the sea surface elevation series for different Manning coefficients (1 correspond to n=0.015 and 7 to n=0.025).

Fig. 5 shows the SSE series at MVD and PN stations during Feb-Mar 2009. It can be seen that the model is able to properly represent both the astronomical tide oscillations and the meteorological tide events.

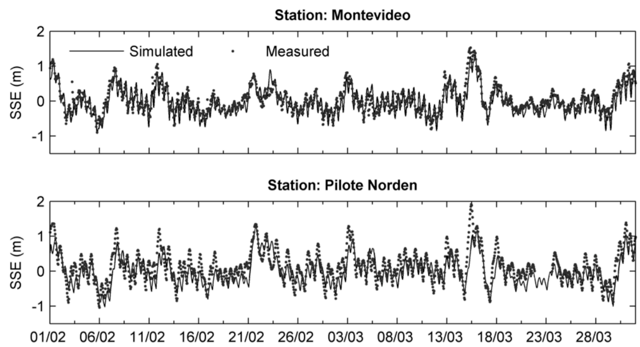


Figure 5. SSE time series comparison during Feb-Mar 2009 at MVD and PN stations.

Table 1 shows a summary of statistics resulting from comparing the simulated and measured SSE series. It includes the Normalized Standard Deviation (NSDV) (modelled SDV / measured SDV), Centred Root Mean Squared Error (CRMSE), and Pearson Correlation (Corr). Finally the amount of data employed for the calculation is showed.

TABLE I. SSE STATISTICS.

| Period | Station | NSDV | CRMSE (m) | Corr | # Data |
|---|---|---|---|---|---|
| 2004 (Jan to Jun) | MP | 0,80 | 0,21 | 0,87 | 4209 |
| | LP | 1,08 | 0,19 | 0,81 | 3287 |
| | PE | 0,97 | 0,17 | 0,86 | 3935 |
| | MVD | 1,01 | 0,19 | 0,87 | 4367 |
| | TO | 0,89 | 0,28 | 0,81 | 4367 |
| | PN | 0,95 | 0,25 | 0,84 | 4367 |
| | COL | 0,95 | 0,27 | 0,81 | 4367 |
| | BA | 0,93 | 0,28 | 0,84 | 4367 |
| 2009 (Jan to May) | MVD | 0.97 | 0.19 | 0.89 | 3060 |
| | PN | 0.90 | 0.26 | 0.84 | 3234 |

Fig. 6 shows a comparison of the simulated and measured currents series during different periods of 2004 at PB and PY stations. The results show a good agreement between the model results and observed values. Table 2 shows the statistics for the depth averaged currents series.

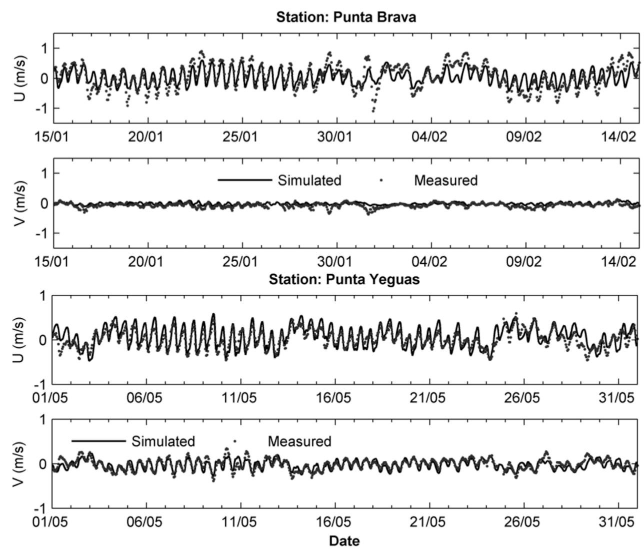


Figure 6. Depth averaged currents comparison at PB and PY stations during 2004.

TABLE II. DEPTH AVERAGED CURRENTS STATISTICS.

| Station | NSDV | CRMSE (m/s) | Corr | # Data |
|---|---|---|---|---|
| PB U | 0.66 | 0.26 | 0.73 | 3772 |
| PB V | 0.71 | 0.06 | 0.38 | 3772 |
| PY U | 1.08 | 0.17 | 0.71 | 2815 |
| PY V | 0.89 | 0.09 | 0.70 | 2815 |

*B. Wave propagation model*

Figs. 5 and 6 show a comparison of the wave parameters time series at HV and PB during 2006 and 2009 respectively. At both stations the significant wave height (Hs) is well represented. The mean period (TM02) is underestimated specially at PB, which is probably related to the frequency discretization chosen in the model. The peak period (TP) and direction (Dp) are reasonably well represent by the model at both locations.

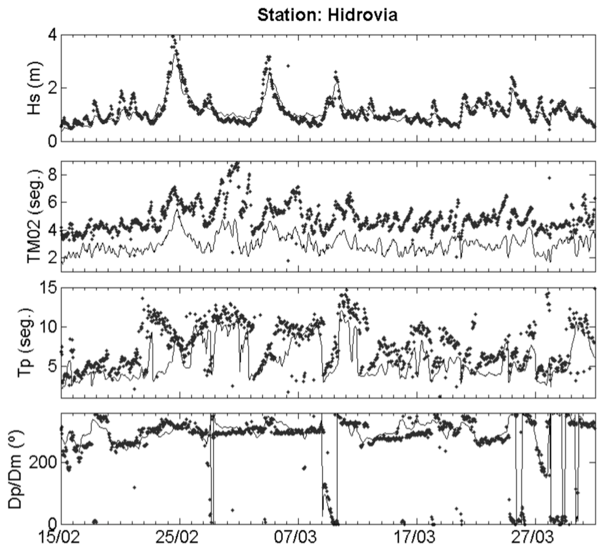


Figure 7. Wave parameteres time series comparison at Hidrovia station during Feb - Mar 2006.

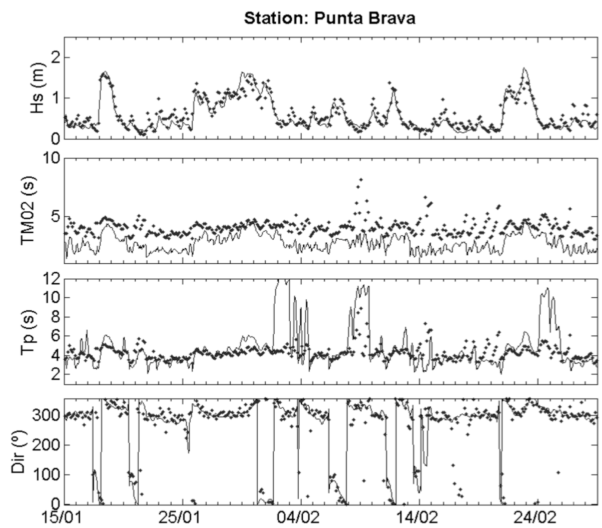


Figure 8. Wave parameters time series comparison at PB station during Jan – Feb 2009.

Table 3 shows a summary of statistics for the significant wave height and peak period time series, including the Root Mean Squared Error (RMSE), the Mean Error (ME), and Pearson Correlation (Corr). These two variables are of most interest as they will be used for the wave bottom stress shear computation.

TABLE III. WAVE PARAMETERS STATISTICS.

| Wave Parameter | Statistic | PB 2009 | HV 2006 |
|---|---|---|---|
| Hs | RMSE (m) | 0.16 | 0.21 |
| | ME (m) | -0.02 | -0.002 |
| | Corr | 0.89 | 0.86 |
| Tp | RMSE (s) | 2.4 | 3.9 |
| | ME (s) | 0.5 | 3.4 |
| | Corr | 0.34 | 0.42 |
| # Data | | 916 | 2180 |

To evaluate the relative importance of the oceanic boundary conditions (swell waves) and the local wind effect (sea waves), two idealized simulations were made. One considering only the wind as forcing, and other taking into account only the oceanic boundary conditions propagation. The results (Fig. 7) show that at PB station the local wind is the main forcing.

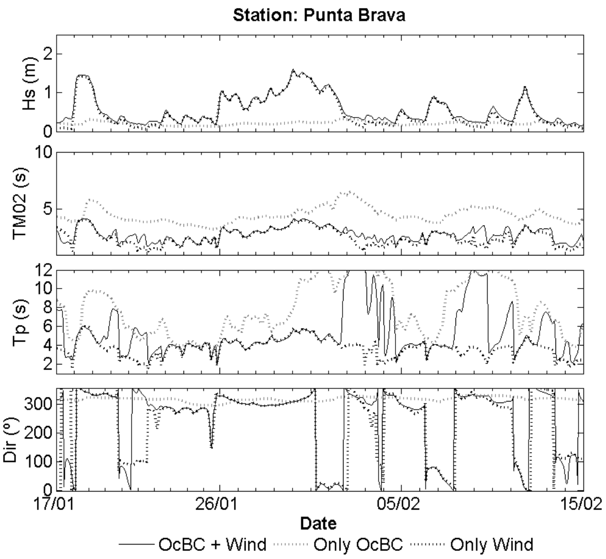


Figure 9. Wave boundary conditions influence. Comparison at PB station during Jan – Feb 2009.

However at HV stations it can be seen that the oceanic boundary conditions play a more important role (Fig. 8).

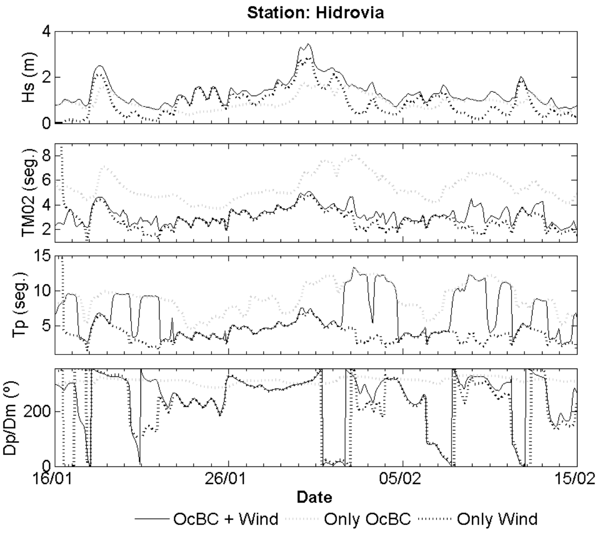


Figure 10. Wave boundary conditions influence. Comparison at HV station during Jan – Feb 2009.

### C. *Sediment transport model*

The sensitivity analysis showed that all the parameters have a great impact on the sediment transport model results. The critical shear stress for deposition was set at a very high value (10e4 Pa). It means we are considering the simultaneous deposition-erosion paradigm, where deposition take place continuously at a rate D=Ws.SSC. This configuration has been proposed for engineering applications at low-concentration cohesive sediment suspensions [11].

After a preliminary calibration based on the SSC observed at PB, the selected parameters are: settling velocity 1e-4m/s, reference concentration for settling velocity 0.1kg/m3, critical shear stress for erosion 0.1 Pa, Partheniades coefficient 2e-6 kg/m/s.

Fig. 11 shows the model results during May 2009 at PB station. The first two panels show some of the main hydrodynamic variables, the current intensity and significant wave height. The third panel shows the simulated total bottom stress; wave and current bottom stresses are also included. It is clearly seen that the highest values of bottom stress are related to strong waves which are associated to storm conditions at the Río de la Plata. Finally the last panel shows the suspended sediment concentration series. It can be seen that the model reproduce the general behaviour of the SSC series. During calm conditions (small wave heights) the model seems to overestimate the SSC. It represented reasonably well the re-suspension during the two storm events that took place in the presented period.

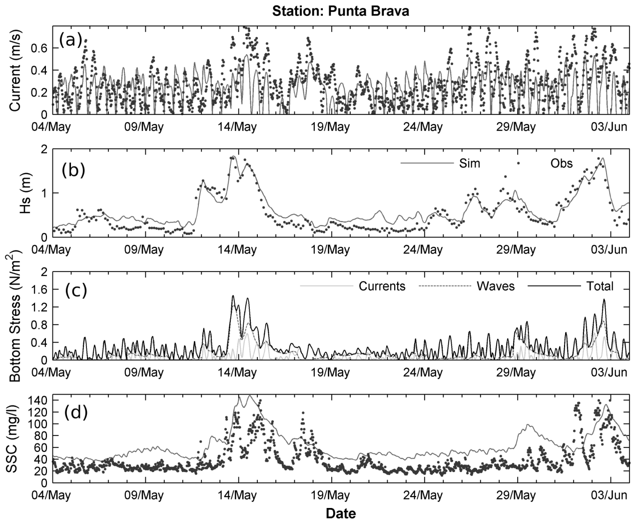


Figure 11. Time series of: (a) current intensities, (b) significant wave height, (c) simulated bottom stress, and (d) suspended sediment concentration, at PB station during May 2009.

Finally Fig. 12 shows the simulated bed evolution at Montevideo Bay area for the period May-June 2009. The model is able to reproduce the deposition of material in the navigation channel and harbour basin. Data about the sediment volume that is dredged from this channel will be compared against these results soon.

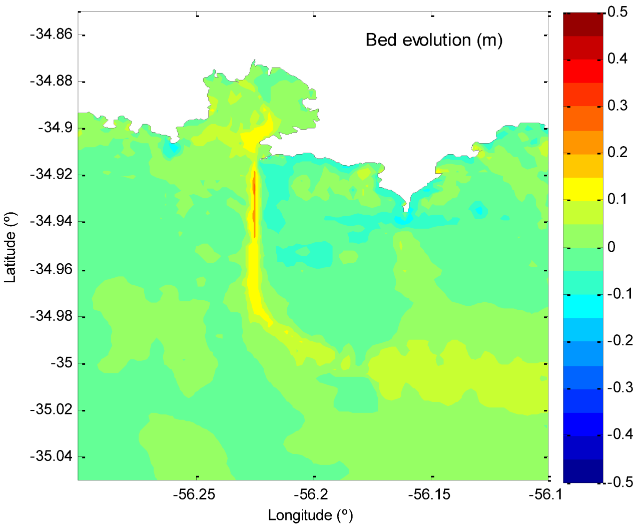


Figure 12. Simulated bed evolution during May - June 2009.

## VI. CONCLUSIONS AND FUTURE WORK

A high resolution bidimensional depth averaged hydrodynamic and sediment transport model was implemented for the Río de la Plata and Montevideo Bay. Hydrodynamic numerical results show excellent agreement with observed sea surface elevation, currents, and wave parameters at several stations in the estuary. During the circulation model calibration process the wind drag coefficient showed to be a key parameter to simulate properly the meteorological tide events, while the Manning coefficient influence is especially noticeable on the astronomical tide presentation. Idealized simulations with the wave model showed that at Montevideo Bay area the oceanic boundary condition plays a secondary role and local waves are dominant during the main events.

After a preliminary calibration the sediment transport and bed evolution model was able to reproduce the general behaviour of the suspended sediment concentration at Montevideo Bay area. The results show the importance of both currents and waves for the induced bottom stress computation and its role in the reproduction of the main resuspension events.

Work in progress includes a finer calibration of the bidimensional sediment transport model including more field data and depositions rates at Montevideo Bay. Also we are currently working on the implementation of the three dimensional model TELEMAC 3D including the fine sediment transport module SEDI3D.

These numerical tools will help to study the fine sediment dynamics at Montevideo Bay and evaluate the impact of different human interventions on it (navigation channel deepening, breakwaters, etc.).

## ACKNOWLEDGMENTS

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