PROCESSES THAT CONTROL THE FINE SEDIMENTS TRANSPORT IN THE RÍO DE LA PLATA ESTUARY

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ABSTRACT – The Rio de la Plata (RdP) is one of the most turbid estuaries in the world and one of the most important in terms of continental discharge and drainage area. The RdP has large social, ecological and economic importance for the countries along its shores and along the tributary rivers of its basin. Numerical models are excellent tools for conducting process studies and testing hypotheses based on observations. They constitute a "virtual laboratories" in which the forcings can be set "on" or "off", or even the environmental conditions can be modified. Observations of suspended fine sediments, particularly those remote and *in situ* collected on recent studies have driven to the statement of several hypotheses about the processes that would control the concentration of suspended sediments in the different parts of the estuary. Nevertheless, the relative scarcity of data does not allow to demonstrate the validity of those hypotheses, the role of several physical processes and of the morphology remain unknown. The objective of this work is, therefore, to analyze the role of the different forcings and the environmental conditions in the determination of the distribution of suspended fine sediments in the RdP applying processes oriented numerical simulations.

Keywords – Modeling sediment transport, Río de la Plata estuary, processes.

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1- INTRODUCTION

The RdP is one of the most turbid estuaries in the world, with extreme concentrations of more than 400 mgl^{-1}. The amount of sediments transported has been estimated between 80 and 160 Mtons y^{-1} (Urien 1972, Menéndez and Sarubbi, 2007), representing more than 1% of the global input of suspended sediments that reach the oceans in the entire world. It has been estimated that 90% of the suspended sediments that reach the RdP are silts and clays, whereas the rest correspond to fine sands. The fresh water plume of the RdP flows more than 500 km to the north (Campos *et al.*, 1999) carrying sediments, carbon and nutrients, which have obvious impact on the adjacent shelf and on ocean processes. Many environmental characteristics and processes in the RdP and the adjacent shelf are linked to the distribution, variability and major drivers of the dynamics of suspended sediments. The most significant issues related to the load of sediments in the RdP include the need for optimizing dredging operations, designing effective flood alerts, understanding geomorphological changes, pollution, benthic ecology, primary productivity and fisheries. Also, the estuary constitutes the main source of drinking water for millions of inhabitants in the region, for whom it is also an important amusement area. Despite their importance, sedimentological processes in this area still need to be fully understood.

1.1 Study area

The RdP, located on the eastern coast of southern South America at approximately 35°S, is one of the largest estuaries in the world. It has a northwest to southeast oriented funnel shape approximately 300 km long, which narrows from 220 km at its mouth to 40 km at its upper end. The estuarine area is 35,000 km^2 and the fluvial drainage area is 3.1×10^6 km^2. The RdP displays a complex geometry and bathymetry, and drains the waters of the Paraná and Uruguay rivers, which constitute the second largest basin of South America, after the Amazon. The estuary exhibits a very high discharge of 22,500 m^3s^{-1} on average, and extremes peak from more than 90,000 m^3s^{-1} to less than 8,000 m^3s^{-1}. The Paraná River converges to the estuary in two main branches (Paraná Guazú-Bravo and Paraná de las Palmas) after forming the large Paraná Delta. Considering the orientation and the relative low depth (less than 10 m on the upper and intermediate parts of the RdP), only the continental waves coming from the southeast can reach the interior, and they are dampen and break as they propagate inward (Dragani and Romero, 2004). The RdP estuary is a microtidal system. Tidal waves associated with the South Atlantic amphidromes reach the Continental Shelf while propagating northward. Over the shelf, the geographic setting modifies their direction and they enter the estuary mainly from the southeast (Simionato *et al*., 2004). Tidal amplitudes are not amplified towards the upper part. The estuary is long and converges only at its innermost part, where it is extremely shallow and bottom friction plays a fundamental role in controlling wave amplitude (Simionato *et al*. 2004). As a result, tidal amplitudes and currents are larger along the southern coast of the estuary than along the northern one. Maximum tidal current speeds occur along the southern coast of the estuary and, particularly, at the northernmost and southernmost limits of Samborombón Bay (Simionato *et al.*, 2004).

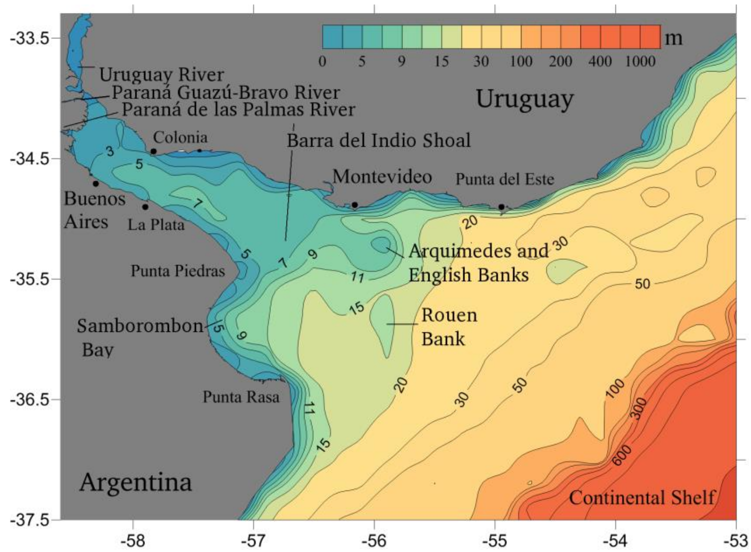

Figure 1. Bathymetry of the RdP (in m) and main geographical features and bedform geometry.

2- MODEL AND SIMULATIONS DESCRIPTION

For the simulation discussed in this work, we have used the three-dimensional Model for Applications at Regional Scale, MARS-3D (Lazure and Dumas, 2008). MARS is a hydrodynamic model for coastal regions, bays, estuaries, adjacent shelf and open ocean, applied for modeling processes at time scales that range from hours to decades. MARS code solves the primitive equations of an incompressible fluid, with the assumption of hydrostatic balance and the Boussinesq approximation. It is based on traditional finite differences on an Arakawa C grid (vertical and horizontal). The vertical coordinate used is of generalized sigma-type. The sediment dynamics module includes processes of erosion, transport in suspension and simultaneous deposition of different types of sedimentological particles: gravel, sand and mud.

Three types of sediment were considered in the simulations: (i) fine sand, with settling velocities between 0.001 and 0.002 m s^{-1}; (ii) silt, with settling velocities between 0.000015 and 0.000075 m s^{-1}; and clay, with settling velocities between 0.000010 and 0.000015 m s^{-1}. The shear stress of deposition was fixed at 0.1 N m^{-2} for fine sand and at 0.07 N m^{-2} for silt and clay, following previous studies (van Rijn, 1984, Fosatti, 2013). Liquid and solid discharges of the three main tributaries, Uruguay, Paraná Guazú-Bravo and Paraná de las Palmas (Figure 1), were kept constant in time in all the simulations. The sediment settling velocity is expressed as a function of sediment concentration to take into account the flocculation processes (Le Hir *et al.*, 2000).

To provide realistic weather conditions, surface winds and sea level pressure data from the 6-hourly Reanalyses of the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) were used. Wind waves were considered in the simulation in an idealized way, generated locally from wind data through a simple model of regression between observed winds and waves.

2.1 Model implementation

The implementation for the RdP was made using two nested grids. The father grid "Rank 0" covers the southwestern region of the South Atlantic Ocean, spanning from 69.35°W to 45.5°W and from 25.5°S to 54.8°S, with resolutions of 0.10° (~10 km) and 0.15° (~12 km) in latitude and longitude respectively, and one layer. This barotropic and bi-dimensional implementation permits the free propagation of the tidal waves and provides open boundary conditions for free surface height to the child domain ("Rank 1"). This last covers the RdP estuary and large part of the adjacent continental shelf, spanning from 32.9°S to 38.139°S in latitude and 60.67°W to 50.62°W in longitude, with a regular grid of 0,027° (~3 km) resolution. In the vertical ten not equidistant sigma levels were used. The child model is three-dimensional and baroclinic and was rotated in the direction of the estuary axis to simplify the application of boundary conditions.

A set of process oriented numerical simulations was performed to study the effect of different forcings (runoff, tides, winds and wind waves) on the sedimentological process in the RdP. To favor interpretation, some of the simulations were repeated with and without bottom erosion. When considered, the bottom erosion parameter E_0 was set to 0.0001 kg m^{-2} s^{-1}. Consolidation of the sediments deposited at the bottom was allowed. Simulations were run for wind, and waves, and tides over 20 months (1 April 2009 to 31 December 2010).

3- RESULTS

To favor comparison, the hourly numerical solutions for 2010 were averaged. Continental discharge, tides, winds and waves were incorporated one at a time in the simulations.

3.1 Case I forced by continental discharge

Figure 2 (left two panels) show that after the period of simulation, silts are almost entirely deposited in the upper region of the estuary, close to the tributaries where they are discharged. The surface concentration maximizes at the mouth of the Paraná de las Palmas and Parana Guazú-Bravo rivers. The effect of the difference in the liquid and solid volumes discharged by those two tributaries is evident; under the conditions of the simulation, without horizontal mixing and resuspension by tides, the path of the plumes of the tributaries remain separate. The low levels of mixing and resuspension also are evident through the little extension of those plumes, which hardly cross the imaginary line between Buenos Aires and Colonia. In the upper estuary, suspended sediments in the bottom layer display a distribution similar to that of the surface layer, but with higher concentrations at the mouth of the tributaries. In this last case, the plumes extend more over the intermediate and exterior estuary, particularly along the southern coast.

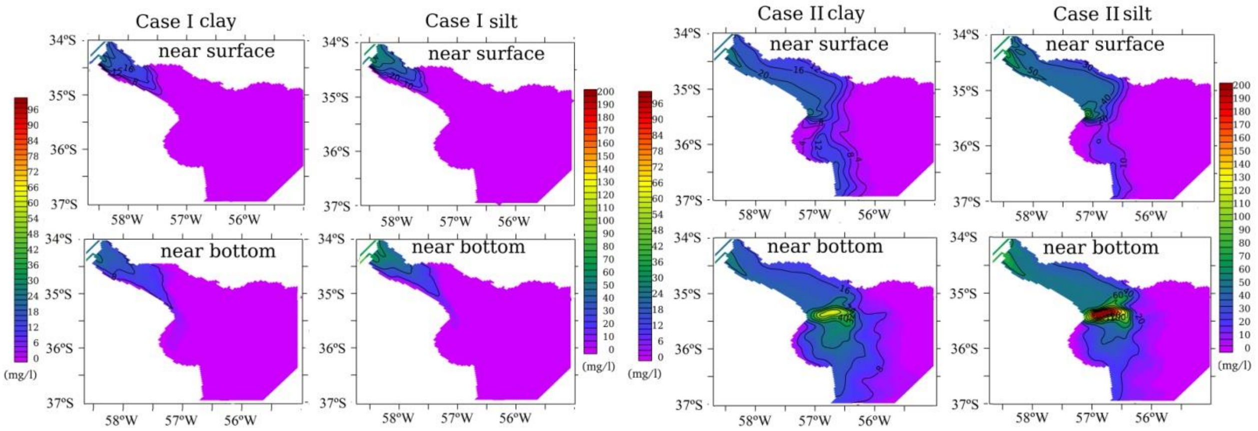

Figure 2. Average distribution for the last year of simulation for the concentration of suspended clays and silts on the surface (upper panel) and bottom (lower panel) layers for Case I (left panels), forced only with continental discharge, and Case II (right panels) adding tide.

3.2 Case II, forced by continental discharge and tide

Results (Figure 2, right panels) show that tides play an important role in the distribution of suspended sediments in the RdP due the relatively high associated currents. Both clays and silts are transported by a much larger distance during the same period of time than in the case without tides, reaching the exterior estuary. This is due to both the increment in the currents, which inhibits the deposition of sediments and re-suspend them, and the lateral mixing (or stirring) associated with the tide. Concentrations decrease towards the exterior estuary and over the Barra del Indio region a large gradient is observed. A relative maximum is observed in the proximity of Punta Rasa. Sediments at the bottom layer show a pronounced maximum in the Barra del Indio shoal, off Punta Piedras.

3.3 Case III, forced by continental discharge, tide and winds

In the case that winds are included in the simulations, the distribution of the concentration of suspended silts at the surface layer is similar to that of the case without winds, even though the concentration increases in the upper and intermediate RdP, particularly along the southern coast of the estuary. Winds increase the dynamics of the system, maintaining the sediments suspended for a longer period of time, increasing mixing and exporting them, in part, to the Continental Shelf. Due to the increased mixing, on the other hand, the concentration of suspended sediments at both the upper and lower layers decrease in the area of Punta del Indio shoal and Punta Rasa. This result better resemble observations than Case II (Moreira *et al.*, 2013).

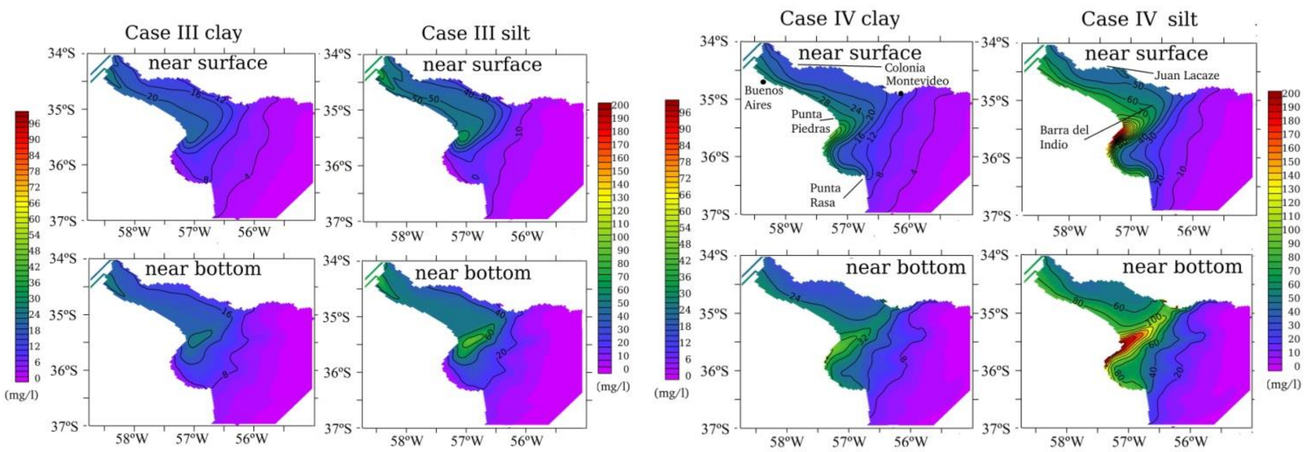

Figure 3. Average distribution for the last year of simulation for the concentration of suspended clays and silts on the surface (upper panel) and bottom (lower panel) layers for Case III (left panels), forced with continental discharge, tide and wind, and Case IV (right panels) adding wind waves.

3.4 Case IV, forced by continental discharge, tides, winds and wind waves

When the waves are included a general increment of the suspended sediment concentrations throughout the RdP is observed. This evidence the importance of the effect of wind waves keeping sediment suspended and/or taking it to the surface. However, the increments in the concentration of both suspended silts and clays, are especially important along the entire southern coast of the RdP (maximizing close to Punta Piedras and the northern part of the Samborombón Bay) and along the northern coast, approximately offshore Juan Lacaze. It can also be observed an increment of the concentration of suspended sediments over the Barra del Indio shoal. Over the northern coast of the upper and intermediate RdP, the difference in concentration between cases IV and III decreases considerably, showing that this region is substantially less influenced by waves. It is important to note that this case much better displays the main observed characteristics of the suspended sediments (Moreira *et al*., 2013) than the case without waves. In fact, it can be concluded that, after tides, wind waves are the main driver of the dynamics of the suspended sediment in the RdP.

4- CONCLUSIONS

The set of process-oriented simulations, permitted to analyze the effect of every individual forcing and to assess its impact, contributing to the construction of a conceptual model of the processes that determine the distribution of suspended sediment in the RdP. The fine sands, being thicker and having a higher settling velocity, deposit immediately after the mouth of the tributaries, leading to the progress of the Delta of the Paraná River. Silts are mostly deposited along the upper and intermediate RdP and present low concentrations over the Barra del Indio shoal. Clays, however, can remain in suspension over a longer distance, because they are smaller than the other textures, and have lower settling velocity. Therefore, clays are observed over the entire estuary, even downstream the Barra del Indio shoal and on Samborombón Bay. Along this path, the hydrodynamic conditions of every region influence the concentration of textures in the water column. The results obtained from simulations lead to the following conclusions:

1) The discharge of the three main tributaries has its greatest impact at the upper and intermediate estuary. The differences in the liquid discharge and concentration of every type of sediment at every river determine the existence of a gradient across the estuary axis in the upper and intermediate RdP. It results from the fact that the Paraná River carries more sediment than the Uruguay River.
2) The simulations show that tides play a key role, increasing lateral mixing and kinetic energy in the estuary. Consequently, they inhibit the deposition of sediments, which thus can be transported towards the Barra del Indio. The erosion associated with tidal currents causes a general increment in the concentration of sediment all over the RdP that maximize in the areas where the dissipation of tidal energy by bottom friction is higher: around Punta Piedras and Punta Rasa. Results also suggest that the northeast-to-southwest oriented gradient in sediments concentration that emerges because of the differences in the discharges of the tributaries is augmented by the effect of mixing by tides. When the model is forced with runoff and tides it succeeds in producing an abrupt reduction in the concentration of suspended sediments in the region of Barra del Indio. There, several factors converge: an abrupt increment of depth; an abrupt increment of the width of the estuary; the occurrence of the bottom salinity front associated to the salt wedge. The first two factors contribute increasing the estuarine transversal section and, thus, reducing the strength of the mean transport. This, in turn, increases the sedimentation capacity. In the region of the bottom salinity front, flocculation processes occur; however, there the estuarine circulation also has an effect.
3) The wind helps maintaining sediment in suspension and this way increases lateral mixing throughout the estuary. This forcing has the largest impact on the Barra del Indio and to the south of Punta Piedras.
4) The effect of winds on the concentration of suspended sediments is magnified indirectly through wind waves. The bottom friction and vertical mixing due to waves increase the concentration of suspended sediments throughout the water column in a significant portion of the estuary. Waves enhance lateral mixing, particularly in the shallower areas of the RdP, homogenizing the distribution of the sediment discharged by the tributaries. It also increases the concentration gradient perpendicular to the estuary axis on its uppermost and central parts. When waves are included in the simulation, the largest increment in surface sediments concentration occurs at those areas where tidal currents maximize and erode bottom sediments (particularly, along the south coast of the intermediate and outer RdP). Those

sediments are moved to the surface by the vertical mixing effect due to waves. Thus, both observations and simulations suggest that whereas the pattern of the distribution of sediments at the RdP is geographically by determined by tides, in this microtidal estuary their energy is just enough to resuspend them on the lower layers, and waves rise them up to the surface.

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