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Hydrodynamic numerical simulation at the mouths of the Parana and Uruguay rivers and the upper Rio de la Plata estuary: A realistic boundary condition

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A B S T R A C T

A hydrodynamic numerical study at the mouths of the ?tul=1?>Paraná and Uruguay rivers and the upper Río de la Plata is presented in this paper. Water Quality Mapping numerical model was implemented and realistic and very simple boundary conditions were specially developed for this complex estuarial system. A set of numerical experiments were carried out using different constant discharges for the Paraná and Uruguay rivers but unrealistic currents were generated. In order to obtain more realistic results, a set of numerical simulations were carried out imposing water level timeseries at the open boundaries. M_2, S_2, K_1 and O_1 harmonic constants were used to generate water levels at Zárate (Paraná river), Nueva Palmira (Uruguay river) and the eastern boundary of the domain (La Plata–Colonia). A mean water level equal to zero was set between La Plata and Colonia. Positive mean water levels (0.3–0.4 m) were imposed at Zárate and Nueva Palmira to simulate the hydraulic slope of both rivers and, consequently, to generate realistic and unsteady discharges. These boundary conditions, built by means of the addition of a mean water level and the astronomical tide, significantly improve the simulated currents at the northernmost region of the RDP estuary.

1. Introduction

The Río de la Plata (RDP) is a shallow and extensive estuary located on the eastern coast of South America, between 34° and 36°S and 54.5° and 58.5°W (Fig. 1). It is approximately 280 km long, has a total area of about 30,212 km^2 and a mean depth of 10 m [1,2]. Its width increases from about 2 km at the upper RDP to 220 km at the mouth. The RDP is formed by the confluence of two of the most important rivers of South America. These are the Paraná and Uruguay rivers with mean discharges of 16000 m^{3}s^{-1} and 6000 m^{3}s^{-1}, respectively [3]. This discharge substantially contributes to the nutrient, sediment, carbon and fresh water budgets of the South Atlantic Ocean [4]. It affects several processes in the adjacent continental shelf, impacts on the coastal fisheries, and interacts in the coastal dynamics up to 400 km northward of the estuary, on the Brazilian continental shelf [5,6].

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There are many papers in the peer-reviewed literature that offer a very comprehensive physical characterization of the RDP, including the adjacent continental shelf [4–9]. The regime of tides can be classified as a semidiurnal one in the RDP [10]. Mean amplitudes are 0.59, 1.10 and 0.25 m at Buenos Aires, Punta Rasa and Punta del Este (Fig. 1), respectively; therefore the RDP can be classified as a microtidal estuary. The main tidal constituent is the semidiurnal lunar tide (M_2). The tidal wave takes about 12 h in propagating along the whole RDP estuary. Consequently, as this travel time is very close to the M_2 period, two high (or low) water levels can simultaneously exist in the estuary twice a day [11]. During normal whether conditions the tidal wave usually reaches Escobar Port, located approximately 23 km north of the mouth of the Paraná river (Fig. 2). The measurements of current in the Río de la Plata started approximately 40 years ago but, as they have been developed mainly for navigation safety, the time series data collected are usually rather short.

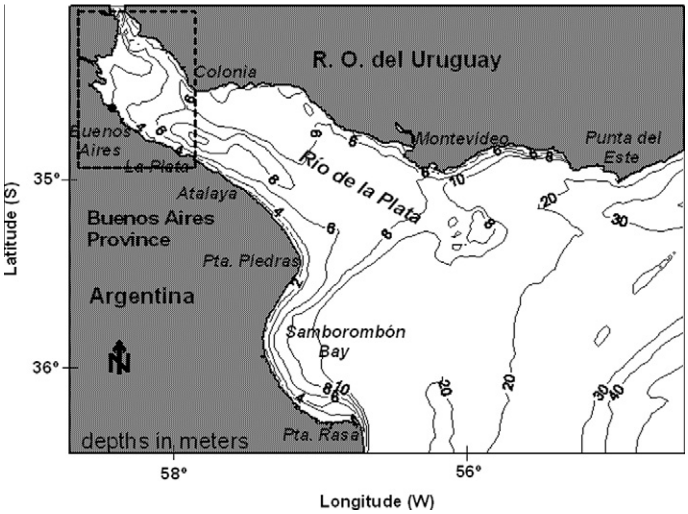

Fig. 1. Río de la Plata estuary. The rectangle in dashed line denotes the computational domain. Depth contours in meters.

Fig. 2. Computational domain and implemented model grid. Locations where water level or/and currents were measured are indicated.

Several numerical studies were carried out in order to simulate the hydrodynamics in the RDP. Molinari [12], Albarracín [13] and Olalde [14] show the first efforts in modeling the tidal dynamics using a depth-integrated model [15] with a very simplified tidal forcing imposed at the RDP mouth. Guarga et al. [16] implemented a depth-integrated model forced with four tidal constituents at the mouth and included a highly simplified atmospheric forcing to study the surge. Subsequently, CARP (1992) presented the first hydrodynamic model for the RDP in which the sediment transport was included [17]. Glorioso et al. [18–20] and Glorioso [21] studied the tidal propagation in the Patagonian continental shelf by means of 2D and 3D barotropic models. These models included marginally the RDP, but as the estuary was very close to the boundary condition, their solutions were not very reliable for the RDP. O'Connor [22] and Veira and Lanfredi [23] presented very simple numerical models implemented for the qualitative study of tides and surges in the RDP. Etala [24] implemented the first operative (depth-integrated) model for forecasting the storm surges in the upper RDP. More recently Piedra-Cuevas and Fossati [25] modeled the residual currents, Fossati and Piedra-Cuevas [26] modeled the residual flows and salinity in the RDP and Simionato et al. [27–31] implemented a 3D baroclinic model (HamSOM: Hamburg Shelf Ocean Model) concluding that HamSOM is a very suitable tool to reproduce and study the observed heights, currents and salinity fields at the estuary. Finally, Tessier et al. [32] in the frame of FREPLATA-IFREMER project presented the first results of MARS-3D model and *in-situ* measurements in order to explain the dynamics of fine sediments at the RDP.

All the aforementioned studies had particular and specific objectives and even though they were carried out using different numerical models and techniques they presented a common and unrealistic feature: the discharge of the Paraná and Uruguay rivers have been imposed like constant flows (non-variable with the tide). Evidently these simple boundary conditions do not affect the hydrodynamic solution neither in water levels (tide and storm surges) nor in currents in the intermediate and outer RDP, that is to say, in the regions of the RDP where the models were widely validated. Nevertheless, this unrealistic condition produces misleading solutions at the upper RDP, especially near the Paraná and Uruguay mouths. The aim of this paper is to present a realistic and very simple boundary condition for the Paraná and Uruguay discharges which is implemented in a numerical model to simulate the complex hydrodynamics of the system formed by the Paraná and Uruguay river mouths and the upper RDP estuary.

2. Data

Amplitudes (H) and Greenwich phases (G) for the four main tidal harmonic constituents (M_2, S_2, K_1 and O_1) were computed from historical water level records gathered at La Plata (RDP, on the Argentine coast), Colonia (RDP, on the Uruguayan coast), Zárate (on the Paraná river) and Nueva Palmira (on the Uruguay river). These harmonic amplitudes and phases, which are used for generating water level series at the boundaries of the computational domain (Fig. 2), are shown in Table 1.

Based on short water level data series gathered at Carmelo (located 18 km southeastward of Nueva Palmira, Fig. 2), it can be concluded that the differences between the tidal harmonic constants corresponding to Nueva Palmira and Carmelo are lower than 0.01 m and 5°, for the analyzed tidal amplitudes and phases (M_2, S_2, O_1 and K_1), respectively. The available measurements indicate that the same height for high water is observed at Nueva Palmira no more than 10 min later than at Carmelo. Consequently, from the practical point of view, the tidal harmonic constants corresponding to Nueva Palmira can be used to work out water levels at Carmelo. Therefore, in this work, the boundary condition at Carmelo is imposed using the harmonic constants computed from water level records at Nueva Palmira since these data series are longer and more reliable than the ones measured at Carmelo. On the other hand, in the study area, the Paraná Bravo-Sauce and Paraná Guazú rivers have sections which are no more than 700 m wide whereas the Uruguay river has a section of, approximately, 7 km wide.

Table 1
Amplitudes (H) and Greenwich phases (G) of the tidal constituents used to generate water level series at the boundaries of the computational domain.

Location	Harmonic constant	H (m)	G (°)
La Plata	M_2	0.23	245.6
	K_1	0.07	63
	O_1	0.14	242.5
	S_2	0.04	329.9
Colonia	M_2	0.15	280.4
	K_1	0.07	76.6
	O_1	0.13	260.3
	S_2	0.03	12.5
Zárate	M_2	0.07	35.7
	K_1	0.05	127.0
	O_1	0.05	325.3
	S_2	0.02	139.7
Nueva Palmira	M_2	0.10	51.5
	K_1	0.05	156.4
	O_1	0.09	345.1
	S_2	0.02	125.5

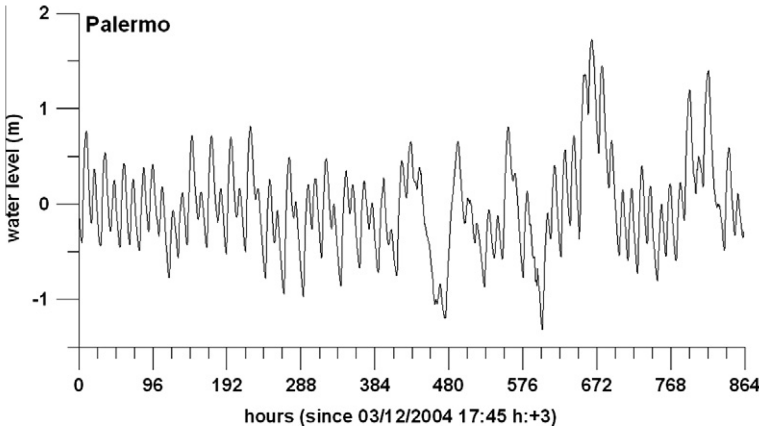

Fig. 3. Water level (m) observed at Palermo.

Table 2
Locations where water levels and/or currents were measured. Geographic location, period of measurement, sampling interval (Δt) and type of device are indicated.

Location	Lat. S (°)	Lon. W (°)	Period	Δt (min)	Variable	Type of device
Palermo	34.553	58.401	03/12/04 – 04/19/04	15	Water level and current	Interocean, S4
Bernal	34.681	58.226	03/12/04 – 04/19/04	15	Water level and current	Interocean, S4
Olivos	34.485	58.451	05/11/09 (from 10:00 to 17:00)	10	Current	Aanderaa, RCM9
Martín García	34.193	58.257	07/14/09 13:30 – 07/16/09 12:30	10	Current	Aanderaa, RCM9
Escobar	34.246	58.730	09/14/09 11:00 – 09/15/09 14:20	10	Current	Aanderaa, RCM9
Buenos Aires	34.566	58.383	01/01/82 – 12/31/00	60	Water level	Standard Floater
La Plata	34.833	57.883	01/01/99 – 09/30/03	60	Water level	Pressure sensor
Colonia	34.466	57.850	11/30/80 – 05/31/81	60	Water level	Standard Floater
Zarate	34.050	59.016	06/09/03 – 02/15/04	60	Water level	Pressure sensor
Nueva Palmira	33.877	58.424	08/21/96 – 09/23/96	60	Water level	Standard Floater

Then, the corresponding discharges of the Paraná Bravo-Sauce and Guazú rivers are suitably redistributed in the Uruguay river, a watercourse with a section which is ten times wider. Even though the effects of the discharges of the Paraná Bravo-Sauce and Guazú are located outside the computational domain (Fig. 2) they are included in the numerical model by means of the imposition of a realistic water level variation at the open boundary located at Carmelo.

Water level data records at Palermo and Bernal, which were used to validate the solutions, show a very clear semidiurnal signal (two high and two low water levels per day) and the presence of high water level events (storm surges; see, for example, around 672 h in Fig. 3) induced, in general, by persistent south easterlies winds. For space reasons, Bernal data series are not shown in this paper.

Data series of currents (intensity and direction) measured at Palermo, Bernal, Olivos, Martín García and Escobar (Fig. 2) were used to validate the hydrodynamic model. Data series corresponding to Palermo and Bernal are approximately 45 days long; the other data series were rather short to prevent possible acts of vandalism (by local fishers). Geographic locations, types of device, periods of measurements and sampling intervals are indicated in Table 2. There is a very scarce amount of current data northward of Escobar, at the Paraná river. The unique available current data series was measured at San Pedro (located on the Paraná river, 130 km north of Escobar, outside the domain presented in Fig. 2). It covered a short lapse of 24 h and was gathered during very fair weather conditions and spring tidal state. This single data series shows that the tide effect is practically not perceived in this part of the Paraná river, at least, during normal conditions without the presence of storm surges (Fig. 4). However, it should be clearly remarked that this statement is supported by only one, and rather short, data series of currents. Nevertheless, although the observed currents present a practically steady southward direction at Escobar, the range of intensity, from 0.25 to 0.5 ms^{-1}, indicates an evident tidal effect (Fig. 5). The observed currents present a practically constant direction at Martín García, located slightly south of the Uruguay river mouth (Fig. 2). Evident fluctuations in the current intensity (ranging from 0.20–0.65 ms^{-1}) with a noticeable semidiurnal period and a practically constant direction ($\sim$112°) show that the tidal wave is able to modulate the current speed but is not intense enough to invert the river flow in this region of the RDP, at least, during normal situation without the presence of strong S-SE winds or storm surges (Fig. 6). On the contrary, a classic rotatory pattern, where flood and ebb currents occur accordingly with the tide can be appreciated at the Upper RDP, a few kilometers from the Paraná and Uruguay river mouths, for example, at Palermo (Fig. 7).

The atmospheric forcing for the hydrodynamic model were the four daily fields (0, 6, 12 y 18 GMT) of the wind components at 10 m from the NCEP/NCAR reanalyses. Reanalyses are not direct observations but the result of an objective analysis combining rawinsonde observations around the world, remote observations collected via satellite born instruments and a

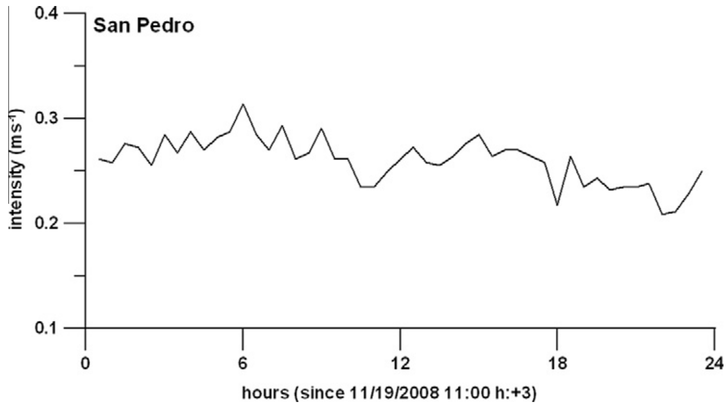

Fig. 4. Current intensity observed (ms^{-1}) at San Pedro (Paraná river).

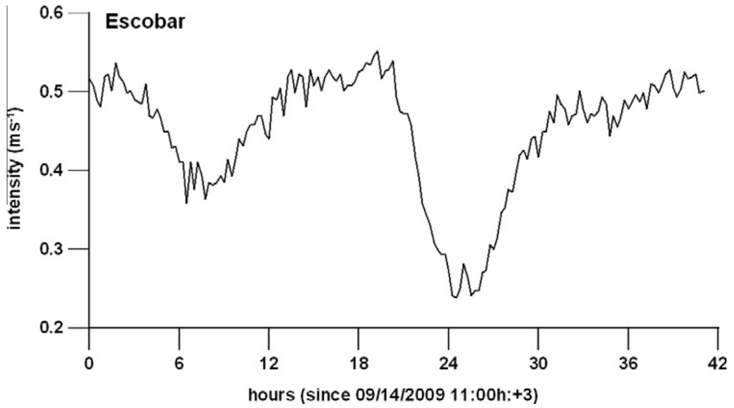

Fig. 5. Current intensity observed (in ms^{-1}) at Escobar (Paraná river).

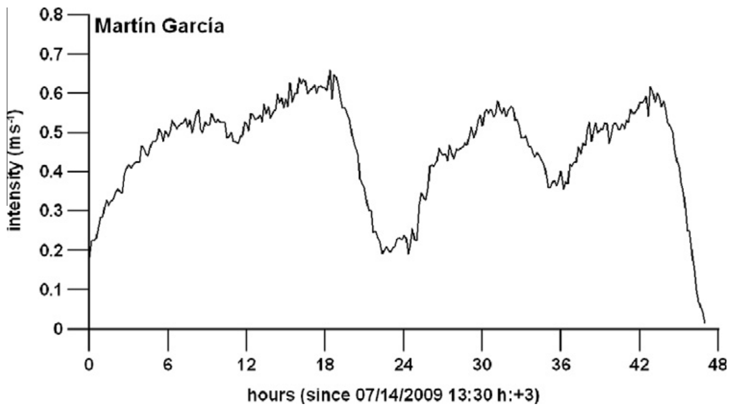

Fig. 6. Current intensity observed (in ms^{-1}) at Martín García (at the mouth of the Uruguay river).

physical numerical model. Full details of the NCEP/NCAR project and the dataset are given in Kalnay et al. (1996) [33] and discussions about product quality over the Southern Hemisphere can be found in Simmonds and Keay (2000) [34], among others. These reanalyses were complemented with hourly intensities and directions gathered at the Jorge Newbery Airport (very close to Palermo station) in Buenos Aires City (Fig. 2).

3. Numerical model

The model used for the numerical investigations is WQMAP version 5.0 (Water Quality Mapping) [35]. The mathematical description of water levels and currents requires the simultaneous solution of the dynamic equations of motion and the con-

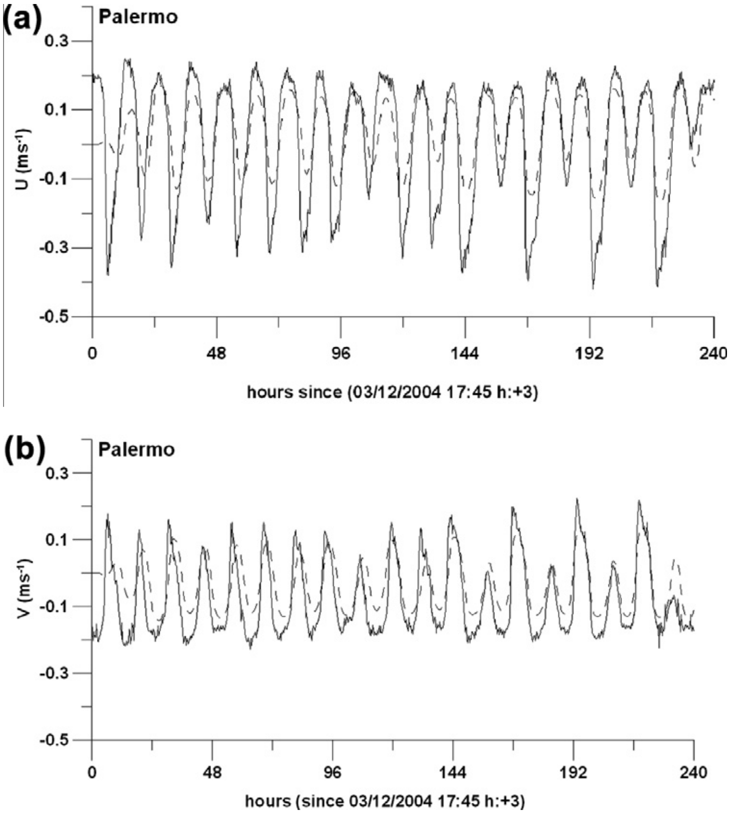

Fig. 7. Observed (solid) and simulated (dashed) east–west (a) and north–south (b) current components at Palermo (ms^{-1}).

tinuity equation. If it is assumed that vertical accelerations are negligible, pressures are hydrostatic over depth, and fluid density is everywhere homogeneous, the two-dimensional, depth-averaged nonlinear equations can be written as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U(\eta + h)}{\partial x} + \frac{\partial V(\eta + h)}{\partial y} = 0, \tag{1}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -g\frac{\partial \eta}{\partial x} + \frac{(\tau_{sx} - \tau_{bx})}{\rho(h + \eta)} + A_H \nabla^2 U, \tag{2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU = -g\frac{\partial \eta}{\partial y} + \frac{(\tau_{sy} - \tau_{by})}{\rho(h + \eta)} + A_H \nabla^2 V, \tag{3}$$

where U and V are the mean vertically-averaged velocities in the x (east–west) and y (north–south) directions, τ_{bx} and τ_{by} are the x and y components of the bottom shear stress, τ_{sx} and τ_{sy} are the x and y components of surface wind stress, A_H is the horizontal eddy viscosity coefficient, η is the free surface elevation above mean water level, h is the bottom depth below mean water level, ρ is the water density (constant, equal to 1000 kgm^{-3}), g is the acceleration due to gravity, f is the Coriolis parameter, ∇^2 is the horizontal Laplacian operator and t is the time.

The two-dimensional vertically averaged equations of motion and continuity are solved using a semi-implicit method [36] in which the surface elevation is solved implicitly while the other terms in the equation such as Coriolis, bottom stress and advective terms are solved explicitly. The momentum equations are substituted into the continuity equation to obtain a Helmholtz equation in terms of surface elevation. The spatial grid is based on a staggered grid system [36] and the time is discretized using a three level scheme with a weighting factor of 1.5 [37]. Thus the numerical discretization scheme used is second order accurate in space and time. The discretized Helmholtz equation is solved using sparse matrix method to obtain the surface elevation. The vertically averaged velocities are then obtained from the vertically averaged momentum equations, using the new surface elevation.

The expressions for the x and y components of surface wind stress are given by

$$\begin{aligned} \tau_{sx} &= \rho_a C_{da} |V_{10}| V_{10_x}, \\ \tau_{sy} &= \rho_a C_{da} |V_{10}| V_{10_y}, \end{aligned} \tag{4}$$

where $V|_{10}|$ is the wind velocity at 10 m above water level while V_{10x} and V_{10y} are the x and y components of wind velocity, ρa(1.25 kg m^{-3}) the density of air and C_{da} (0.0014) the wind drag coefficient. The bottom stress is parameterized by means of a quadratic law in terms of the depth averaged current velocity:

$$\vec{\tau}_b = (\tau_{bx}, \tau_{by}) = C_b \rho \vec{V} |\vec{V}, \tag{5}$$

Where C_b is the non dimensional bottom friction coefficient and $\vec{V}$ is the mean averaged depth current whose east–west and north–south components are U and V, respectively. A constant value of C_b equal to 0.002 was set for the solutions shown in this paper.

The model domain extends from 33.932°S to 34.884°S and from 59.062°W to 57.757°W. The bathymetry was obtained from digitized nautical chart [38]. A computational domain (40 × 70 nodes) with cells of variable size was used in these simulations. The size and shape of the cells gradually change because they must fit to the different geographic characteristics of the system. For example, the cell sizes are 1.71 × 0.09 km, 2.22 × 0.09 km and 1.60 × 0.218 km at the western, central and eastern part of the Paraná river, respectively; they are 0.034 × 0.97 km and 0.55 × 0.91 km at the northern and southern part of the Uruguay river, respectively; and they are 0.95 × 1.22 km, 1.32 × 1.88 km and 1.10 × 2.54 km at the northern, central and eastern part of the Río de la Plata. The open boundaries at the Paraná river, at the Uruguay river and at the Río de la Plata (between La Plata and Colonia) were constituted using 8, 27 and 40 cells, respectively (Fig. 2).

4. Numerical simulations

The computational domain is built on a staggered grid system (Grid C, [36]) where values of depth, η, U and V are alternately disposed throughout the computational grid. Along the open boundaries oriented in the x (east–west) direction U is imposed equal to zero at all the nodes located left and rightward of those where η is defined. This condition allows that only normal currents ($V \neq 0$) can flow across these boundaries, which constitute a very simple but highly realistic boundary condition. At the open boundaries orientated in the y (north–south) direction, $V = 0$ is imposed at all the nodes located down and upward of those where η was defined. This condition only allows transversal flows ($U \neq 0$) across these boundaries. According to this, for example, $U = 0$ is alternately defined at the open boundary located at the Parana river and, in the same way, $V = 0$ is alternately defined at the open boundary located between La Plata and Colonia. On the other hand, at the closed boundaries (i.e. coasts) oriented in the x direction, $V = 0$ is imposed at the nodes located left or rightward of those where the depth was defined and, likewise, at the closed boundaries oriented in the y direction, $U = 0$ are set at all the nodes placed down or upward of those where the depth is defined. In other words, at the closed boundaries, the normal components of the current are set equal to zero, which is, a free slip boundary condition which is assumed. With regard to the initial conditions, the model is initially at rest, i.e. U, V, and η are zero everywhere. It was observed that after approximately 2 days of simulation most of the transients due to the spin up of the model were dissipated and therefore, the first two days of each simulation were disregarded.

Simulated water levels and currents obtained from different numerical experiments were compared with available observations. In general, water levels are well simulated independent of the imposed boundary condition. On the contrary, simulated currents result quite dependent of the adopted boundary conditions. Consequently, in this work, the main emphasis is focused on the comparison between observed and simulated currents which is carefully analyzed and discussed.

First of all, a set of numerical experiments were carried out using different constant discharges at the open boundaries located at the Paraná and Uruguay rivers. Steady values of approximately 630 m^{3}s^{-1} were imposed in every cell of these boundaries, constituting a total discharge of 22000 m^{3}s^{-1} [39]. Water level time series were imposed at the eastern boundary (La Plata–Colonia line) in the Río de la Plata. Numerical experiments were run from March 12 to April 19, 2004. Even though the model simulated ebb and flood currents at Olivos, intense and unrealistic current speeds were generated in the Paraná and Uruguay rivers and in the uppermost region of the Río de la Plata. On the other hand, slight but evident tidal effects were clearly appreciated at Zárate and Nueva Palmira (Table 1) which are not present when a constant discharge is imposed as boundary condition at these locations.

Thereupon, water level time series were imposed as forcing at the three open boundaries of the computational domain. On the eastern boundary (La Plata–Colonia) this condition constitutes a very classic one but, on the western and northern boundaries corresponding to the Paraná and Uruguay rivers respectively, it constitutes a completely new implemented boundary condition since monthly mean discharges have been imposed like forcing in all the preceding numerical studies. M_2, S_2, K_1 and O_1 harmonic constants (Table 1) were used to generate water levels at Zárate (Paraná river), Nueva Palmira (Uruguay river) and at the eastern boundary of the domain (La Plata–Colonia). A mean water level equal to zero was set between La Plata and Colonia, which is a realistic condition except during strong southesterlies winds ("Sudestadas") that produce significant storm surges. Positive mean water level (from 0.1 to 1 m) was imposed at Zárate and Nueva Palmira in order to simulate the hydraulic slope of both rivers and, consequently, to generate a realistic and unsteady discharge.

It was observed that mean water levels higher than 0.5 m at Zárate and Nueva Palmira produce asymmetric floods and ebbs at Olivos and very high, unrealistic and steady speeds at the Paraná and Uruguay rivers. On the contrary, mean water levels lower than 0.5 m produce non-reversible, fluctuating and realistic current intensities at the Paraná and Uruguay rivers. Several numerical experiments were carried out with values ranging from 0.1 to 0.5 m and, finally, a mean water level of 0.3 m gave the best results. Summarizing, harmonic constants (Table 1) were used to generate water levels at Zárate, Nueva

Palmira and at La Plata–Colonia boundaries. A mean water level equal zero was imposed between La Plata and Colonia and one equal to 0.3 m was set at Zárate and Nueva Palmira in order to simulate unsteady discharges.

Simulated currents are quite similar at Palermo and Bernal then, for space reasons, comparison between observed and simulated currents are only shown for Palermo. *U* and *V* current components are presented in Fig. 7. It can be seen that there is a very good matching in the instants of the modeled and observed maximum and minimum intensities for the *U* (Fig. 7a) and *V* (Fig. 7b) components. Maximum intensities of *U* and *V* are practically reproduced by the model but, in the case of the minimum intensities, they are slightly overestimated in approximately +0.2 ms^{-1}. *U* and *V* current components for Olivos are presented in Figs. 8a and b, respectively. It can be seen that there is a very reasonable agreement in the modeled and observed intensities and phases of *U* and *V* components. A slight overestimation of the modeled intensities can be appreciated during the lapses of minimum speed at Olivos.

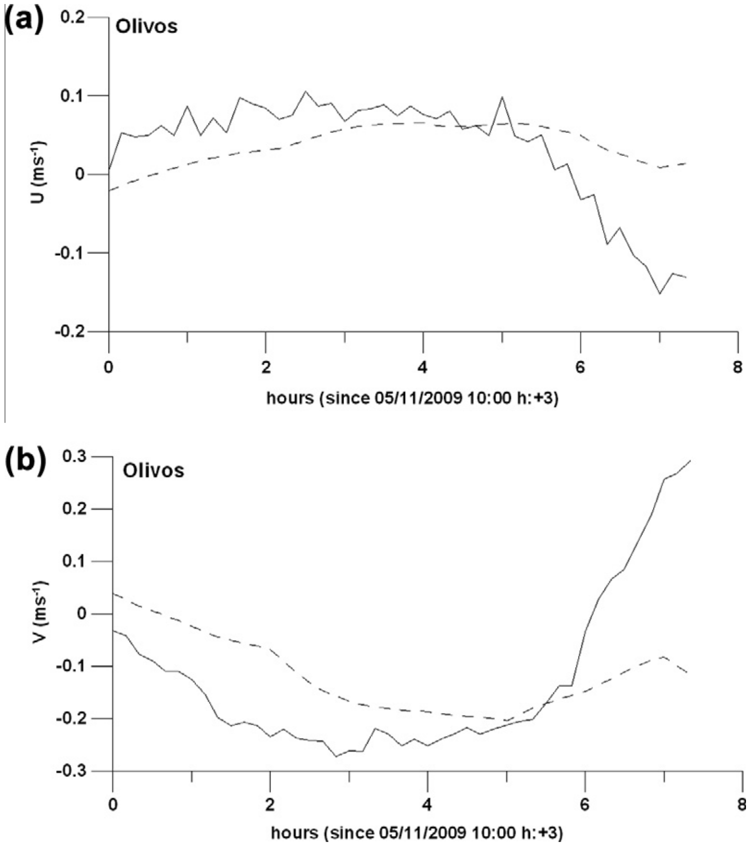

Fig. 8. Observed (solid) and simulated (dashed) east–west (a) and north–south (b) current components at Olivos (ms^{-1}).

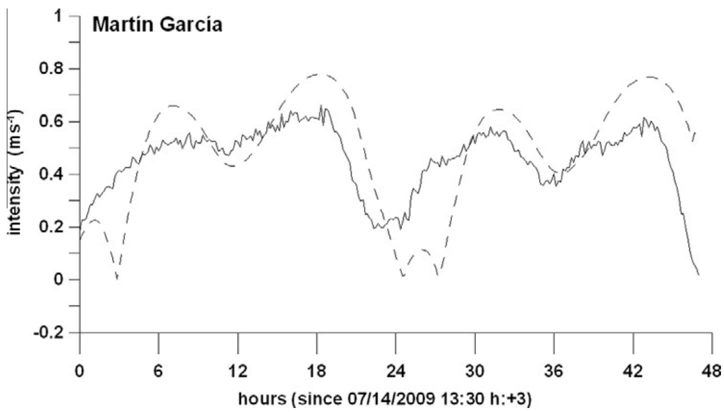

Fig. 9. Observed (solid) and simulated (dashed) current intensity (ms^{-1}) at Martín García. Mean water level of the Uruguay river set at 0.3 m.

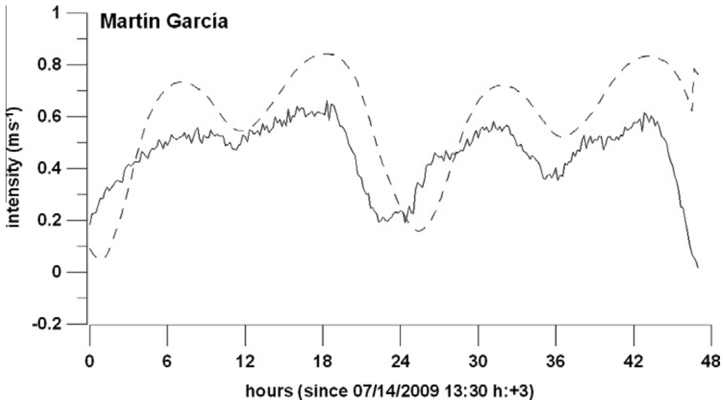

Fig. 10. Observed (solid) and simulated (dashed) current intensity (ms^{-1}) at Martín García. Mean water level of the Uruguay river set at 0.4 m.

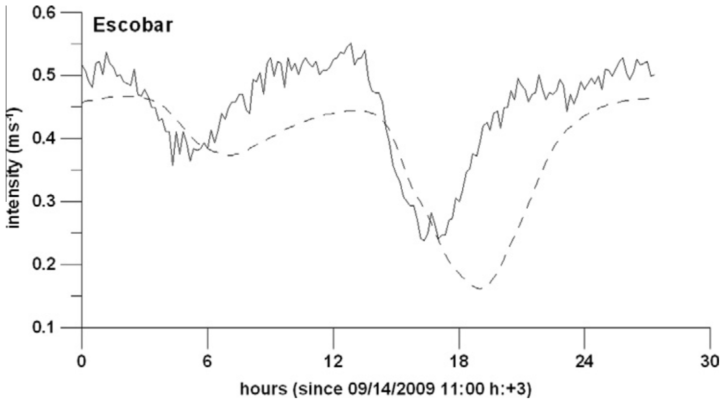

Fig. 11. Observed (solid) and simulated (dashed) current intensity (ms^{-1}) at Escobar.

Observed currents at Martín García, located at the RDP near the Uruguay river mouth, do not present a rotatory pattern. Measurements show a unidirectional flow in the 115° direction and a noticeable fluctuation in speeds associated with the tide. Simulated speeds at Martín García flow in the 141° direction and present a very good agreement with the observations (Fig. 9). Measured maximum speeds (approximately 0.60 ms^{-1}) are reasonably simulated (0.80 ms^{-1}) and the minimum speeds (0.20 ms^{-1}) are a little underestimated (almost 0 ms^{-1}) which indicates that the range of simulated speeds is a little overestimated. A numerical experiment was carried out imposing a slightly higher mean water level (0.4 m) at the boundary of the Uruguay river. Simulated speeds are presented in Fig. 10 and show a very small increase in maximum speeds (+0.05 ms^{-1}) but a significant increase in the minimum values (0.20 ms^{-1}). Consequently, this slight reduction in the speed range indicates that the simulated currents at this region of the Río de la Plata are very sensitive to the imposed boundary condition.

Observed currents at Escobar (Paraná river) present a unidirectional flow in the 111° direction and a slight fluctuation in speed associated with the tide. Simulated speeds at Escobar flow in the 100° direction and present an excellent agreement with the observations (Fig. 11). Measured maximum speed (approximately 0.50 ms^{-1}) is well simulated (0.40 ms^{-1}). The minimum speed (0.25 ms^{-1}) is a little underestimated (0.15 ms^{-1}) and delayed in approximately 2 h.

5. Discussion, summary and conclusions

This work constitutes the first effort in simulating the complex hydrodynamic system formed at the mouth of the Paraná and Uruguay rivers and the upper Río de la Plata estuary forced by the astronomical tide and the Paraná and Uruguay river discharges. It has been widely documented (Introduction) that steady discharges implemented as boundary conditions at the Paraná and Uruguay rivers do not affect the hydrodynamic solutions at the intermediate and outer RDP. On the another hand, an evident tidal effect can be appreciated, at least, up to Zárate (Paraná river) and Nueva Palmira (Uruguay river) and, consequently, a constant discharge imposed like boundary condition at these locations of the rivers constitutes an unrealistic condition that produces misleading solutions at the upper RDP, especially, close to the mouths of the rivers Paraná and Uruguay.

A realistic boundary condition for the discharges of the Paraná and Uruguay rivers is presented and analyzed in this paper. These conditions significantly improve the simulated currents at the northernmost region of the RDP estuary. In order to simulate realistic hydraulic slopes in the Paraná and Uruguay rivers a mean water level equal to zero was imposed between La Plata and Colonia and one equal to 0.3 m was set at Zárate and Nueva Palmira. Harmonic constants (Table 1) computed from observations were used to generate tidal water levels at Zárate, Nueva Palmira and at La Plata–Colonia boundary. Consequently, a forcing implemented by a hydraulic slope and a water level variation due to the tide are used to simulate realistic and unsteady flows at the final section of the Paraná and Uruguay rivers. Simulations were compared with observed currents at Palermo, Bernal, Olivos, Martín García and Escobar. This comparative study reveals that the implemented boundary condition is good enough to simulate the currents in this important zone of the RDP.

A numerical experiment was carried out using a mean water level equal to 0.4 m at the Uruguay river boundary. A small reduction in the range of speeds at Martín García indicated that the simulated currents, in this region of the RDP, are very sensitive respect to the variations in the selected mean water level imposed as boundary condition at the Uruguay river. The mean water level at the Uruguay river is higher than at the Paraná river because only 25% of the water of the Paraná river drains directly to the RDP through the Paraná de las Palmas river. The remaining 75%, flows into the Uruguay river [40,25] through the Paraná Guazú and Paraná Bravo-Sauce distributaries.

The proposed boundary conditions at the Uruguay and Paraná rivers are relatively easy to implement because they are obtained by the addition of the mean water level which is systematically measured at different points of both rivers, and the astronomical tide which is generated using the available harmonic constants (Table 1). If a storm surge was present in the RDP, the boundary condition at the La Plata–Colonia line could be easily implemented by means of the addition of the water level prediction (astronomical tides) and the mean water level gathered at La Plata tidal station.

In general, mean water levels ranging from 0.3 to 0.5 m are realistic values for Zárate and Nueva Palmira but they could be greater during events characterized by very significant discharges, for example, during El Niño. In such case mean water levels greater than 1 m at Zárate and Nueva Palmira should be adopted in order to simulate the hydraulic slopes at the Paraná and Uruguay rivers and the associated currents in the upper RDP. Mean water levels at Zárate and Nueva Palmira are very simple to measure and their values could be directly assimilated in an operative numerical model for the region. Finally, the development and advance of more systematic field measurements (mainly water currents) is crucial and highly recommended to validate and calibrate the available regional numerical models, particularly those implemented for the study of the Paraná and Uruguay river mouths and the adjacent RDP, where a gradual transition between a fluvial and an estuarine regimen is clearly evident.

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