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FINITE ELEMENT MODELING OF THE RIO DE LA PLATA

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Abstract: A two-dimensional (2-D) hydrodynamic model was applied to study water surface elevations and tidal currents in the Rio de la Plata. In order to properly reproduce water surface elevations and currents, optimal location and shape of the ocean open boundary were determined. The deep ocean numerical model FES95.2 was used to generate the forcing function at the open boundary. Due to its shallowness, meteorological tides in the Rio de la Plata are mainly produced by storm surges coming from the ocean. Water level modifications generated by local winds blowing inside the estuary are relatively small. Comparisons of calibrated RMA-2 model output with observational data for the Rio de la Plata have shown that the model is capable of simulating water surface elevation with a relatively high degree of accuracy.

Key words: Surges, tides, Numerical model, Río de la Plata

1. INTRODUCTION

The Rio de la Plata is located on the east coast of South America, between 34° and 36° South Latitude and 54° 50' and 58° 30' West Longitude, between Uruguay and Argentina. It flows from the northwest towards the southeast for approximately 280 km. Its surface area is about 35,000 km^2 and its width increases from about 2 km at the inner part to approximately 220 km at its mouth.

The two major tributaries are the Paraná and Uruguay Rivers, with annual average discharges of 16,000 m^3/s and 6,000 m^3/s, respectively, with minor tributary discharges being several orders of magnitude smaller.

Two main regions can be identified based on the morphology and dynamics of the Rio de la Plata (Framiñan and Brown, 1996). Barra del Indio, a shallow area located in the line Punta Piedras and Montevideo (Fig. 1), separates the inner from the outer region. The inner region has a fluvial regime. In the outer region, the estuary increases in width and this change in the geometry imply a new forcing balance that generates complex flow patterns.

The general circulation of atmospheric conditions in the region is controlled by the influence of the quasi-permanent South Pacific high pressure that generates southwesterly and southerly winds. This general circulation is modified by the action of a low-pressure system located at the northern part of Uruguay that generates winds from the northwest and southeast. Other important events occurring in the Rio de la Plata region are frontal systems with southwest-northeast trajectories that interact with littoral low-pressure systems. This interaction can generate strong winds over 30 $\mathrm{m \cdot s^{-1}}$ (Framiñán and Brown, 1996) from the southeast and storms that affect the area for several days. This phenomenon is called sudestada (southeastern) and is responsible for disastrous flooding in inner region of the Rio de la Plata area.

The astronomical tides in the Rio de la Plata have semi diurnal regime and are classified as micro tidal. The amplitude of the main semi diurnal component (M$_2$) inside the Rio de la Plata oscillates between 0.30 m and 1.0 m, and is larger over the Argentinean coast. The tide wave takes about 12 hours to reach the interior limit, causing that at every moment a full cycle of the M_2 component is present inside the Rio de la Plata.

The tide can be strongly modified by meteorological events (Balay, 1961). Storm surges of over 3-4 m have been registered during southeastern events. The tidal currents are on the order of 0.5 $m \cdot s^{-1}$ with higher values at the southern coast. Currents are also strongly modified by meteorological events. Values ranging between 1.0 and 1.5 $m \cdot s^{-1}$ have been observed in Montevideo during periods with southeasterly winds.

Due to its shallowness, average depth of 5 m, meteorological perturbations in the Rio de la Plata are mainly produced by surges coming from the ocean. Water level modifications generated inside the estuary are relatively small.

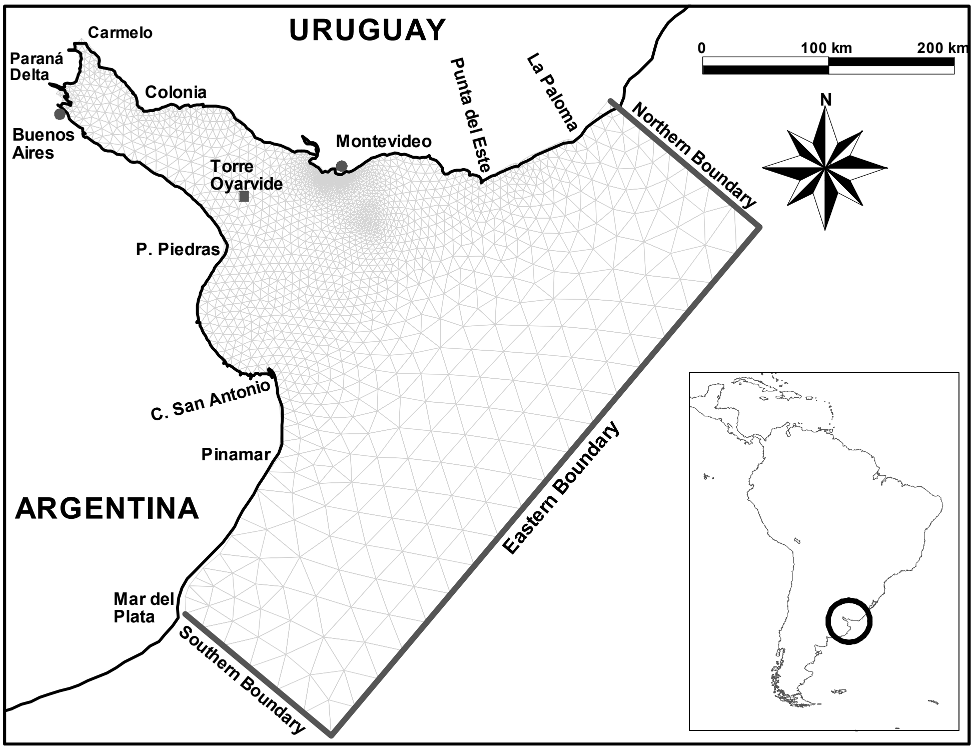

Fig. 1 The Río de la Plata study area and modeled domain

2. MODEL

Since the Rio de la Plata is a shallow, well-mixed system, the unsteady, two-dimensional (2-D) vertically integrated, shallow water equations have been used to model tides and tide induced currents.

In this study, the 2-D finite element hydrodynamic numerical model RMA-2 has been implemented (King, 1998). It computes water surface elevations and horizontal velocity components for free-surface two-dimensional flow fields. Friction can be calculated with the Manning or Chezy equations, and eddy viscosity coefficients are used to define turbulence characteristics. The equation of momentum and mass conservation are solved by the finite element method using the Galerkin Method of weighted residuals (Donnell et al. 2000).

The modeled domain is the Rio de la Plata limited by the coasts of both shores and the continental shelf (Fig. 1). The inland boundary, where the fresh water is input, is the cross section defined by the line that goes from Carmelo on the Uruguayan coast to the Paraná River delta on the Argentinean coast. The open boundary extends into the continental shelf until approximately the 200 m isobath. The southern open boundary, located at Mar del Plata, has been selected so that the wave front of the semidiurnal M_2 arriving from the south enters the model domain parallel to it. The northern open boundary, located 80 km north of La

Paloma, was selected parallel to the southern boundary. The eastern (outer) open boundary was selected perpendicular to the southern and northern open boundaries.

3. TIDES

The principal tide affecting the Rio de la Plata is the semidiurnal lunar tide (M_2). From the cotidal charts found in the literature, the main features known to occur are three amphidromic systems in the Southern Atlantic (Genco, 1993; Schwiderski, 1980; Schwiderski, 1983). An amphidromic point east of Rio Grande, Brazil, north of the modeled region at 20S and 15W produces a cotidal line system that runs anti-clockwise. Another amphidrometric point located near the Antarctic runs in a clockwise way, causing the M_2 component to enter the Rio de la Plata both from the south and from the north. Moreover, east of Bahía Blanca (Argentina), south of the modeled region, there is a clockwise amphidrometric center located at 41S and 60W (Genco 1993, Glorioso and Simpson 1994).

The Rio de la Plata and the continental shelf have insufficient water mass to be affected directly by the tide generating forces, but have co-oscillating tides forced by the global tide oscillation along the shelf break. In the deep ocean off the shelf break, the M_2 tidal amplitude varies from 20 cm south of the estuary to 5 cm north of it.

The normal tide range varies from over 1.0 meter on the Argentinean coast to about 0.4 m on the Uruguayan coast. This is the result of the higher tides on the shelf to the south of the estuary, and the Coriolis force which is directed to the left of the motion in the southern Hemisphere. The co-oscillating tide takes about 12 h to travel along the Rio de la Plata. Since this time is close to the tidal forcing period, there can be two tidal sea level maxima or minima in the estuary at the same time. The progression of the tidal maxima up the estuary, and the decay in tidal amplitude away from the Argentinean coast, are consistent with a Kelvin wave response to the tidal forcing on the shelf.

TIDAL BOUNDARY CONDITIONS

The astronomic tides in the deep ocean up to the continental shelf can be specified from global ocean tide models. One of such model is the Grenoble model FES95.2. The United States' National Aeronautics and Space Administration (NASA) releases global water surface elevation data obtained using the model FES95.2, which is part of a new generation of models developed using TOPEX/Poseidon data. From this model it was possible to define amplitudes and phases of astronomical tides along the eastern open boundary. Ocean tide models, although reliable, do not have sufficient accuracy in order to perform the calibration procedure and thus amplitude and phase were then fine-tuned during calibration.

It is more difficult to prescribe the tidal boundary conditions along the continental shelf part of the open boundary, especially the southern boundary, because of the presence of the amphidrometric system to the south, which cause both amplitude and phase to vary rapidly. Moreover, over the continental shelf, deep ocean tidal models are less accurate due to bottom friction. Information on tidal constituents obtained from observations at tidal gauges stations in Mar del Plata and La Paloma were used to generate water surface elevation boundary conditions at the northern and southern boundaries on the continental shelf.

Since the model is semi-implicit, the stability was verified with a time step of 30 min. The data fields were stable after 48 hrs. Surface elevation prescribed on the open boundaries was unfiltered; however, in order to increase stability due to large sea level tidal forcing variations over the continental shelf, a boundary ring with higher viscosity was defined for the first time steps.

First, the hydrodynamic model was forced using astronomical tide projections for January and February of 1983 at the ocean open boundaries. The astronomical tide modeling was performed with the five principal tidal components M_2, N_2, S_2, O_1 and Q_1. Model results were compared to astronomical tide projections, obtained from the harmonic analysis, at gauge stations inside the estuary. This calibration was used to assure that the model was accurately representing the progression of the tidal wave through the system.

Fig. 2 and 3 present comparisons between the simulated and measured water surface elevation during the simulation period. The gauge stations used for calibration are La Paloma, Punta del Este, Montevideo and Colonia on the Uruguayan coast and Pinamar, Torre Oyarvide and Buenos Aires on the Argentinean coast (Fig. 1). These values represent the best overall results achieved under the calibration adjustments listed above. The final value of Manning's friction coefficient was n=0.013. Examination of the plots shows that the model captures both the phasing and amplitude of the tidal wave at each location.

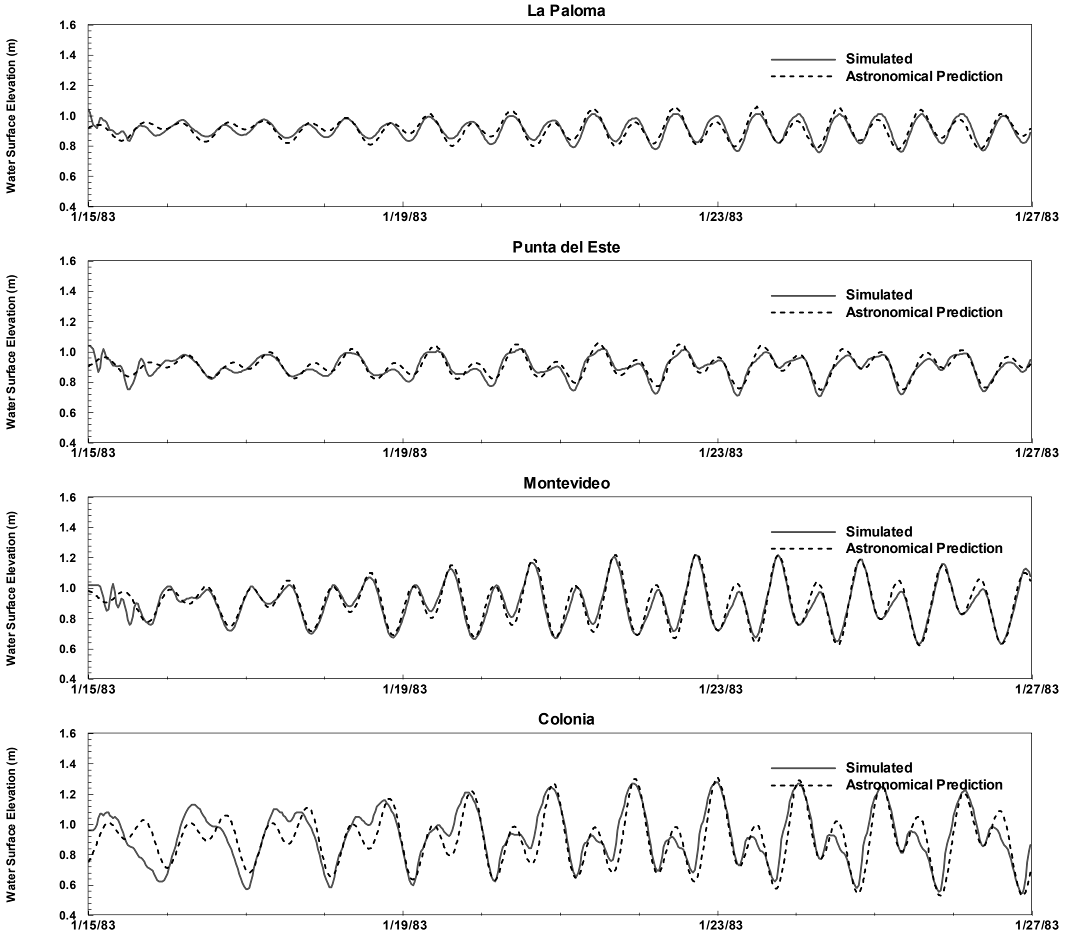

Fig. 2 Simulated vs. Astronomical Prediction Water Surface Elevation at La Paloma, Punta del Este, Montevideo and Colonia

4. STORM SURGES

Storm surges are very important phenomena that occur in the Rio de la Plata. Water surface elevation change from 0.5 – 1.0 m to 3.0 – 4.0 m over short periods of time, in the order of hours to a couple of days. Wind effects on sea level in the Río de la Plata were discussed by Balay (1961), who reported that water surface elevation at Buenos Aires is closely related to winds over the outer estuary and shelf.

Due to the shallowing and narrowing of the Rio de la Plata and the long fetch over which the wind acts, the largest water surface elevations are found in the inner region of the estuary.

Strong southeast winds blowing into the Río de la Plata are the result of higher pressure to the south-southwest and lower pressure to the north-northeast of the estuary, so that the isobars are aligned generally northwest southeast along its axis (Balay, 1961). A moving atmospheric pressure system can set up a larger surge, due to resonance when the speed of the storm system is close to the free gravity wave speed on a shelf, however, the southeast wind events causing the greatest surges in the Rio de la Plata are the result of cyclones moving slowly offshore from the continent (O'Connor, 1991). Surges of several meters in the Rio de la Plata are the result of wind stress, which is usually the dominant forcing in shallow coastal regions (O'Connor, 1991). Therefore the forcing of the horizontal gradient of atmospheric pressure has been neglected in this study.

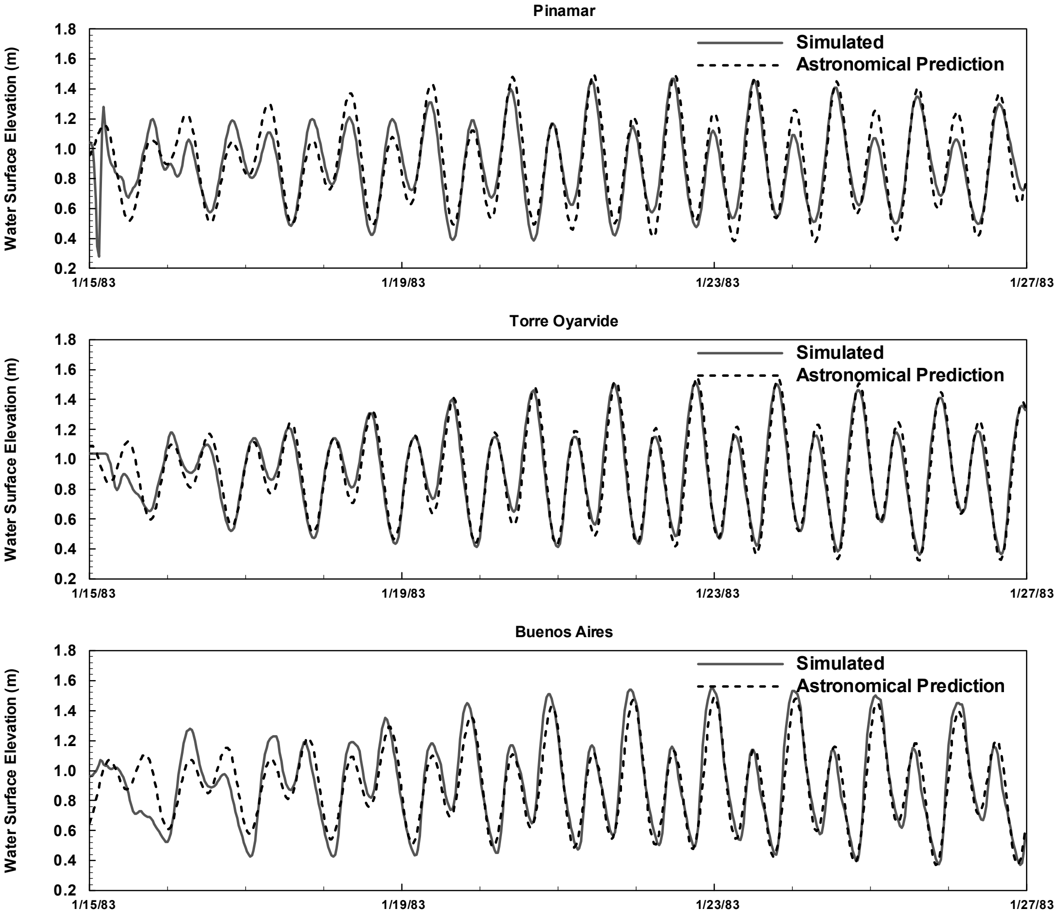

Fig. 3 Simulated vs. Astronomical Prediction Water Surface Elevation at Buenos Aires, Torre Oyarvide and Pinamar

BOUNDARY CONDITIONS

The appropriate boundary conditions on the open boundaries depend on the particular problem. Usually, the sea level on the boundary parallel to the coast is set as cons(clamped condition). Various cross shelf boundary conditions has been tested for wind forcing in the cross shelf and along shelf directions. Most successful techniques employ some form of the radiation condition. There is not definite agreement as to which boundary condition is the best in all circumstances, but the radiation conditions represents the physics better than the others (O'Connors 1991).

Although Roed and Smedstad (O'Connor, 1991) examined cross channel boundary conditions and pointed out that free gravity wave radiation conditions are strictly valid only if there is no wind forcing at the boundary, they generally give reasonable results.

For this study a different approach was taken. First, taking advantage of the extended domain over the continental shelf, astronomical tides were set on all three open boundaries. Some successful results were obtained but it was not possible to reproduce various. Wind effects over the modeled domain alone were not sufficient to properly reproduce storm surge levels in the interior of the Rio de la Plata. It was found that meteorological effects are mainly forced by storm waves created in the continental shelf. In order to simulate storm water level with an acceptable degree of accuracy the storm wave that penetrates through the open boundaries had to be considered. Therefore, the open boundary conditions were changed to account for this storm wave. The difference between the measured sea level and the astronomical water surface elevation was obtained for tidal gauging station at Mar del Plata and La Paloma and distributed along the southern and northern boundaries respectively. Along the eastern boundary, parallel to the coast, even though depths are about 200 m, a constant sea level was found inappropriate. A linear distribution between the water surface elevation applied on the southern and northern boundaries was applied.

In order to calibrate the wind drag coefficient, a storm that occurred between March 5 and 14, 1987 was selected. Hourly winds registered at the Carrasco Station (Montevideo) were used. Wind shear stresses were calculated by using van Dorn formulation given by the following expression:

$$\tau = \alpha^2 W^2 + \beta^2 (W - W_c)^2 \qquad \text{with:} \quad \begin{aligned} \alpha &= 0.0012 \\ \beta &= 0.0016 \\ W_c &= 9.0 \ \text{m/s} \end{aligned}$$

Fig. 4 shows a comparison of registered and simulated water surface elevation that occurred in Montevideo during the selected storm. A good fit was obtained, both in the phase and peak values of the wave.

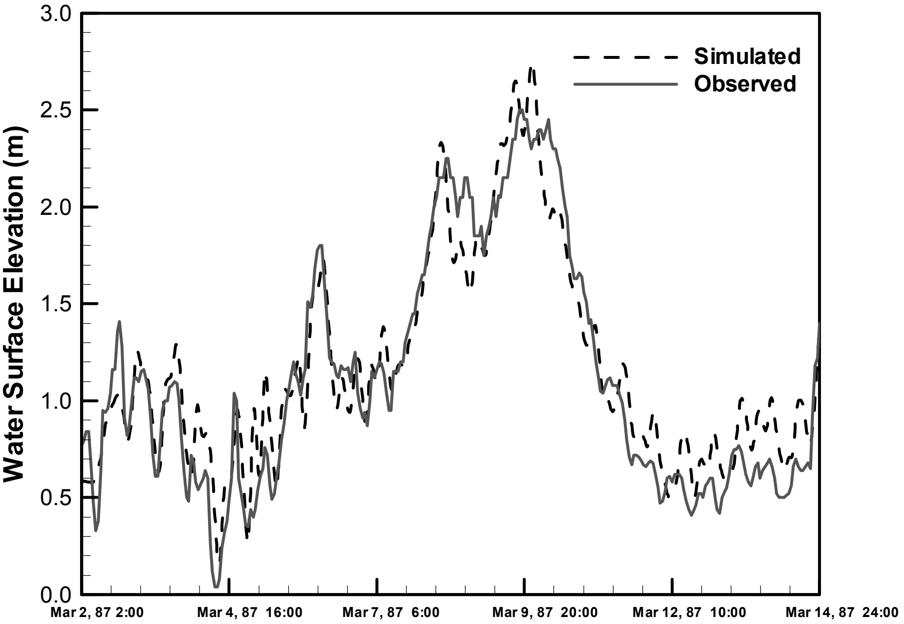

Fig. 4 Simulated vs. Measured Water Surface Elevation at Montevideo Station

5. CONCLUDING REMARKS

A 2-D hydrodynamic model, the RMA-2 code, was applied to simulate the Rio de la Plata estuary. The goal was to extend previous modeling (Guarga et al., 1992; Kaplan et al., 1992) to include tide and storm surges dynamic simulations. The model covered the entire Rio de la Plata and extended into the adjacent continental shelf.

Model inputs included tidal fluctuations at the ocean boundaries, freshwater inflow at the headwaters of the Rio de la Plata, and winds over the simulated domain. The model was calibrated for the summer of 1983. The hydrodynamic model was calibrated for the water surface elevation generated by astronomical tide and storm surges.

An optimal location and shape of the ocean open boundary were determined in order to properly reproduce tides and current inside the Rio de la Plata, especially during storm surges. The deep ocean numerical model FES95.2 was used to generate the forcing function at the open boundary parallel to the coast. The hydrodynamic calibrations show that the model is a valuable tool for the evaluation of the general circulation patterns of a complex system such as the Rio de la Plata.

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REFERENCES

Balay, M.A., 1961. El Río de la Plata entre la atmósfera y el mar, Publicación H-621, Servicio de Hidrografía Naval, Armada Argentina, Buenos Aires, 153 pp.

Framiñán, M.N.; Brown, O.B., 1996. Study of the Río de la Plata turbidity front, Part I: spatial and temporal distribution. *Continental Shelf Research*, vol. 16, Nº 10, pp 1259-1282.

Genco, M-L. 1993. Les marées dans l'Océan Atlantique: Modélisation et bilan énergétique. Ph.D. Thesis. Université Joseph Fourier, Grenoble, France.

Glorioso, P.D; Simpson, J.H., 1994. Numerical modeling of the M_2 tide on the northern Patagonia Shelf. *Continental Shelf Research*, vol. 14, Nº 2/3, pp 267-278.

Guarga, R.; Kaplan, E.; Vinzón, S.; Rodríguez, H., Piedra-Cueva, I., 1992. Aplicación de un modelo de corrientes en diferencias finitas al Río de la Plata. *Revista Latinoamericana de Hidráulica*, No 4, pp.93-115, San Pablo, Brasil.

Kaplan, E.; Vinzón, S.; Rodríguez, H., 1992. Application of a Tidal Currents Numerical Model to the Río de la Plata. HYDROSOFT 92, Valencia, España.

King, I.P., 1998. RMA2 – A two dimensional finite element model for flow in estuaries and streams. Dept. of Civil Engineering. University of California. Davis, California.

Molinari, G and Menéndez, A. 1986 Simulación numérica de la Circulación en el Río de la Plata. INCYTH, Buenos Aires, Argentina

O'Connor, W. P. 1990 A Numerical Model of Tides and Storm Surges in the Río de la Plata. *Continental Shelf Research*, vol. 12, No 12, pp 1491-1508.

Schwiderski, E.W., 1980. On Charting Global Ocean Tides. *Rev. of Geophysics and Space Physics*, Vol. 18, Nº 1.

Schwiderski, E.W., 1983. Atlas of Ocean Tidal Charts and Maps, Part I: The Semidiurnal Principal Lunar Tide M_2. *Marine Geodesy*, Vol. 6, Nº 3-4.