A numerical study of the barotropic circulation of the Río de la Plata estuary: sensitivity to bathymetry, the Earth’s rotation and low frequency wind variability

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Abstract

The barotropic circulation of the Río de la Plata is studied by means of process oriented high resolution 3-D numerical simulations, where its relation to the bathymetry, the Earth’s rotation, river runoff and low frequency wind fluctuations is explored. The model solutions indicate that the circulation at the Río de la Plata is sensitive to bathymetry and the Earth’s rotation. Even though a bimodal circulation pattern has been reported in previous papers, our simulations suggest that in the absence of winds the normal path of the estuary flow should be a buoyant plume to the north. When the mean wind blows from directions between SSE and NNW this pattern is intensified. The southward path observed seems to be the result of the wind forcing when it acts from some directions, which explains why this path has only been sporadically registered. The wind driven circulation at the estuary can be explained in terms of two modes of circulation. The first, prevailing for winds with a cross-river component, is related to an inflow–outflow of water at the exterior part of the estuary and accounts for the seasonal signal observed in the salinity field. The second mode dominates when the wind blows along the estuary axis and has a very distinctive pattern of significant sea level increase or reduction at the upper part of the estuary. This mode accounts for two extreme situations often observed with important social implications: the Sudestada, which produces disastrous flooding, and the persistent northwest wind, which on occasions results in the collapse of the drinking water supply to the city of Buenos Aires. From the numerical experiments a dynamic classification of the estuary into three different regions with regard to bathymetry, the Earth’s rotation and winds is proposed. They are the upper-central estuary, the exterior estuary and Samborombón Bay. Our solutions indicate that during the summer this bay has a weak and retentive circulation pattern that favors the biota, allowing the region to become an area of spawning and nursery for several coastal species. Nevertheless, our results also indicate that the situation that favors the fisheries could change sensitively if the mean wind direction suffers even a small shift to the south as a result, for example, of climate change. Results from historical water level data analyzed by other authors suggest that such a shift could already be taking place.

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1. Introduction

The Río de la Plata, located on the eastern coast of South America at approximately 35° S, is one of the largest estuaries in the world. It has a northwest to southwest oriented funnel shape, 320 km long, and 230 km wide at the open mouth, and an average runoff of 22,000 m$^3$ s$^{-1}$ (Nagy et al., 1997). The most important cities, including the capitals of Argentina and Uruguay, resorts, harbors and industrial towns of both countries lie on its shores. The river is the most important source of drinking water for millions of inhabitants. Due to the

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intense discharge the fresh water plume influence has be
tracked up to 23° S (Campos et al., 1999). This plume is
not only important for local biodiversity and fisheries
(Mianzan et al., 2001), but also modifies the coastal
circulation and mixing and convection conditions (Piola
et al., 2000) with important oceanographic implications.

Despite its social and oceanographic importance, not
much is known yet about the Río de la Plata circulation
in time scales longer than the tidal one. Due to the lack
of comprehensive current meter measurements, most of
what is affirmed about the system currents has been
inferred from the salinity, the parameter that controls
the density in the estuary, and other hydrographic
parameters as well as from the sediment’s distribution.
Given that those data are in turn scarce in space and
time, very few aspects of this circulation could be well
determined.

Based on these kinds of observations, Ottman and
Urien (1965) suggested that the shallow banks in the
outer estuary split the river flow into two branches. One
of them flows along the northern coast reaching Punta
del Este and the other one turns to the south, entering
into Samborombón Bay and reaching Cabo San
Antonio. Brandhorst and Castello (1971) and Brand-
horst et al. (1971) concluded that the estuary discharge is
more important to the north. According to them, the
circulation to the south could be a ‘periodic’ event, even
though they have not explained the characteristics and
frequency of these events. Urien (1967, 1972) suggested
that the saline water movement is more important in the
north along the deep channels and that at Sambor-
ombón Bay the saline water movement is quite restricted
due to its shallowness. The influence of the water plume
in the north has been inferred or suggested by several
other papers (Hubold, 1980; Carreto et al., 1986;
Lusquiños and Figueroa, 1982; Nagy et al., 1987;
Guerrero et al., 1997; Simionato et al., 2001) whereas
some have reported a southward discharge pattern
(Carreto et al., 1982).

Therefore, a kind of bimodal circulation pattern has
been reported in the literature. The most often registered
path, and also the most accepted one, is to the north,
along the deeper channels of the upper part of the
estuary. This path is consistent with a buoyant plume
that spreads over the Southern Hemisphere deviated to
the left by the Earth’s rotation. The low salinity along
the southern coast has been explained in terms of a more
complex tidal regime and mixing processes associated
with the shallowness of Samborombón Bay. Neverthe-
less, no clear explanation of the patterns that generate
this bimodal discharge pattern has been proposed, and
the frequency of occurrence has not been established.

Even though several modeling studies have been
reported in literature, they were mostly oriented to tides
propagation and storm surges (O’Connor, 1991; Vieira
and Lanfredi, 1996; Simionato et al., 2004a), while one
paper tried to explain the observed seasonal variability
of the surface salinity front (Simionato et al., 2001).

A better knowledge of the estuary circulation is
needed as a first stage for any further study. It would not
only constitute the basis for dynamical investigations,
but would be extremely useful to provide indications
about the estuary circulation with obvious applications
to contamination and fisheries in an area of spawning
and nursery (Cousseau, 1985; Boschi, 1988) that is
impacted by anthropogenic actions. Also, the estuary is
the object of an observational campaign in the context
of the UNDP/GEF Project “Environmental Protection
of the Río de la Plata and its Maritime Front, FREPLATA”,
that will provide the first long period currents time series for the region. Well-founded
indications about the circulation will contribute to
make this observational research more efficient by
providing information about the most important zones
to be sampled.

Therefore, the aim of this work is, by means of
process-oriented numerical simulations, to study the
circulation patterns at the Río de la Plata estuary and
their response to the main driving forces. The primitive
equations HamSOM (Hamburg Shelf Ocean Model)
model, developed at the University of Hamburg has
been used in this study. In a set of high-resolution
barotropic simulations the circulation and its relation
to the bathymetry, the Earth’s rotation, river runoff and
low frequency wind fluctuations are explored. As a result
a dynamic classification of the estuary into different
regions with diverse responses to the main driving forces
is proposed.

2. The numerical model

The HamSOM model applied in the simulations
presented in this paper is a widely used three-dimen-
sional primitive equation model developed at the
University of Hamburg by Backhaus (1983, 1985). It
has been applied to many shelf seas worldwide (see, for
example, Backhaus and Hainbucher, 1987; Rodriguez
and Alvarez, 1991; Stronach et al., 1993) and also to the
study of the Río de la Plata Estuary (Simionato et al.,
2001, 2004a); it has been shown to be very robust in
studying the shelf sea and estuarine dynamics.

The domain chosen for the simulations, which spans
from 36.5° S to 34° S and from 59° W to 54.5° W,
bathymetry and coastline as seen by the model are
shown in Fig. 1. High-resolution bathymetry data for
this model were provided by the Servicio de Hidrografía
Naval (SHN) of Argentina and come from digitalization

The horizontal resolution has been set to 1.8’ in
latitude and 1.5’ in longitude (approximately 2700 m),
small enough to properly describe the problem involving
dynamics, bottom topography and coastline. Thirteen vertical levels, with bottoms at 1, 2, 3, 4, 5, 6, 7, 10, 15, 25, 35, 45 and 55 m have been used. An advantage of using a multi-layer model even when density is constant is to allow for a better representation of the bottom friction. In the HamSOM model, the bottom stress is parameterized by means of a quadratic law in terms of the horizontal velocity vector at the bottom layer of the model and the vertically averaged horizontal velocity in a frictional layer close to the bottom (see, for example, Simionato et al., 2004a). The bottom friction factor was reduced to \(3/5\) of the exterior value \(2.5 \times 10^{-3}\) at every point where the depth is shallower than 10 m; this approach allows for reproduction of the observed tidal amplitudes and phases (Simionato et al., 2004a). The horizontal eddy viscosity has been set to \(50\) m\(^2\) s\(^{-1}\); the vertical eddy viscosity is computed by the model following Pohlmann (1996). The time step was set to 5 min for all runs.

3. System forcing: bathymetry, runoff and winds

The Río de la Plata (Fig. 1) is located on the eastern coast of South America, at approximately 35° S. It is shallow and extensive, covering an area of around 35,000 km\(^2\). The estuary has a funnel shape 320 km long and a width that varies from 38 km at its upper part to 230 km at the mouth between Punta Rasa (Argentina) and Punta del Este (Uruguay). The Río de la Plata displays a complicated geometry and bathymetry. A complete description of its morphology and sedimentology can by found in Ottman and Urien (1965, 1966), Urien (1966, 1967, 1972), Depetris and Griffin (1968), Parker et al. (1986a,b), and López Laborde (1987a,b). A brief description of the main morphological features is given in what follows. Based on its morphology and what it is known or inferred about its dynamics, the estuary has been classically divided into two regions. They are split by the Barra del Indio, a shallow area that crosses the river between Punta Piedras and Montevideo (Fig. 1). The upper region is almost occupied by fresh water and is characterized by shallow banks with depths ranging from 1 to 4 m (Playa Honda and Ortiz Banks), which are separated from the coasts by deeper channels with depths varying from 5 to 8 m (North, Oriental and Intermediate Channels). This region is limited to the south by the Barra del Indio, with a slightly convex shape and depths of 6.5–7 m. Eastwards Barra del Indio, the Maritime Channel, a wide depression with depth increasing from 12 to 14 m at the north to 20 m at the south, separates Samborombón Bay to the west from a region of banks known as Alto Maritimo to the east. The Alto Maritimo is formed by the Arquímedes and English Banks, with depths ranging from 6 to 8 m, and the Rouen Bank with a depth of 10–12 m. Northwards the first two of these banks, the Oriental Channel, the deepest channel of the estuary with depths of up to 25 m, extends along the Uruguayan coast. Samborombón Bay is a very shallow and extensive area with depths ranging from 2 to 10 m that extends between Punta Piedras in the north and Punta Rasa in the south.

More than 97% of the total Río de la Plata water input is supplied by the Paraná and Uruguay rivers, which drain from two different basins. Over very long periods, the mean discharge does not exhibit a clear seasonal cycle; even though both river runoff has a seasonal signal, the variation is moderate and the cycles are partly opposed and mutually compensated. Even though the historical mean flow of both rivers together is around 20,000 m\(^3\) s\(^{-1}\), during recent decades...
(1961–1995), Paraná river flow has shown an increasing linear trend; since 1978 even relatively dry years have been wetter than the historical and 30-year mean (Nagy et al., 1997). During the last decades of the 20th century, the mean discharge has been 25,000 m³ s⁻¹, which represents an increment of 25% with respect to historical values (Nagy et al., 1997). Moreover, during this period, the discharge exhibits a clearer seasonal pattern, with a minimum during the austral summer period of around 20,000 m³ s⁻¹, and a maximum of around 30,000 m³ s⁻¹ during the fall and winter. Since most of the oceanographic observations have been taken during the last part of the 20th century, these values have been chosen as representative in our simulations.

The atmospheric general circulation in the area is controlled by the influence of the quasi-permanent South Pacific and South Atlantic high-pressure systems. An analysis of the wind variability in the region was recently performed by Simionato et al. (2004b). There is a marked seasonal variability with mean westward winds during the summer and mean smaller east-southeastward winds during the winter. Meanwhile the spring has a feature that resembles the summer but with less intense winds, the fall has a distinctive transitional pattern with low winds. Even though the seasonal signal accounts for an important part of the variability of the zonal wind component, the meridional component variability is mostly related to higher frequencies.

4. The Río de la Plata circulation response to the geometry, bathymetry and the Earth’s rotation

In order to analyze the system response to the simplest forcing, in a first set of experiments the circulation driven by the continental runoff and the tides was studied. Two experiments were run, in which river discharges representative of summer and winter scenarios (20,000 m³ s⁻¹ and 30,000 m³ s⁻¹, respectively) were considered. In order to introduce the effect of the tides in the simulation, a boundary condition that represents the evolution of the M₂ tidal component coming from a larger scale model was imposed to the sea surface elevation (Simionato et al., 2004a). Given that M₂ is the main component and in order to simplify the analysis and interpretation of the results, the other components were not included in the simulations. Simulations were started from rest and run until stabilization of the solution. Then, the residual mass transport, defined as the mean transport in a tidal period (12.42 h) was computed and its stream function was obtained. The results for both runoff conditions, 20,000 m³ s⁻¹ and 30,000 m³ s⁻¹, are shown in the upper and central panels of Fig. 2, respectively. The lines represent the mass transport stream function in thousands of m³ s⁻¹.

In order to help in the interpretation of the figure, arrows indicating the flow direction are overlaid. Note that the flow is parallel to the isolines and the magnitude of the transport is the gradient of the stream function; therefore those regions where the lines are close are areas of high transport. The lower panels display the difference between both simulations. Fig. 2 shows that in the absence of winds, fresh water discharge responds as a buoyant plume in the Southern Hemisphere. Probably due to the large amount of the discharges in any of the cases, only a relatively small difference (Fig. 2, lower panel) is observed in response to the fresh water discharge increment from 20,000 m³ s⁻¹ (Fig. 2, upper panel) to 30,000 m³ s⁻¹ (Fig. 2, central panel). It can be seen in the figure that the difference between both solutions follows the same path as the solution itself. So, the response to an increment in the river discharge seems to be merely an increment in the intensity of the mean transport.

The solutions for both runoff scenarios (upper and central panels of Fig. 2) indicate that the river plume tends to move eastward along the northern (Uruguayan) coast. The influence of the bottom topography in the water path is evident in the model solution. After entering the estuary at its northwest the main flow tends to follow the Uruguayan coast conducted by the North Channel. At the meridian of Colonia it turns to the southeast and displaces to the Argentinean coast, flowing along the Intermediate Channel. Deviated by the Coriolis force, acting to the left in the Southern Hemisphere, the flow continues its path north-eastwards. After approximately the meridian of Montevideo, the flow divides into two branches. Most of the water flows close to the Uruguayan coast along the Oriental Channel. The other branch continues its path south-eastward and after moving between the English and Rouen Banks, it turns back to the north and joins the main flow along the Uruguayan coast.

Another characteristic that is evident from Fig. 2 is the weak circulation associated the Samborombón Bay. The model produces two low transport circulation cells for this area. The larger scale one is cyclonic (clockwise) and occupies most of the northern portion of the bay. The smaller, anticyclonic, is positioned at its southern part. An outstanding apparently realistic feature of these simulations is the presence of a small but clear northward transport at Punta Rasa, the south-western-most extreme of the bay. The penetration of colder continental-shelf waters around this cape has been inferred from SST satellite data (Lasta et al., 1996; Framiñán et al., 1999).

It has been suggested that the circulation in this bay is inhibited by its shallowness and dominated by the tides (Urien, 1967; 1972). Our simulations suggest that in the absence of winds, the reduced circulation is mostly related to the geometry and the rotation of the
Earth, both favoring a northward offshore path of the fresh water, and to the bottom topography that channels the flow along the northern coast (see Fig. 2). To further analyze the effect of the bottom topography and the rotation of the Earth in the circulation, three additional simulations were conducted, in which the isolated and combined effects of these forcings were considered.

Fig. 2. Model derived residual transport stream function (thousands of m$^3$ s$^{-1}$) at the Río de la Plata (left) and the detail of Samborombón Bay (right). Upper panel: summer (20,000 m$^3$ s$^{-1}$) runoff condition. Central panel: winter (30,000 m$^3$ s$^{-1}$) runoff condition. Lower panel: difference between summer and winter solutions.
In the first, even though the coastline was kept realistic, the estuary depth was fixed to 10 m, a value representative of its mean depth, at every model grid point. The resulting residual mass transport stream function for a runoff of 20,000 m³ s⁻¹ after integration starting from rest is shown in the upper panel of Fig. 3. A comparison of the control case with real bathymetry and a runoff of 20,000 m³ s⁻¹ (upper panel of Fig. 2) and

Fig. 3. Model derived residual transport stream function (thousands of m³ s⁻¹) at the Río de la Plata (left) and the detail of Samborombón Bay (right). Upper panel: constant depth condition. Central panel: no rotation condition. Lower panel: constant depth and no rotation condition.
the case with constant depth (upper panel of Fig. 3) at the upper part of the estuary emphasizes the bathymetric effect on the fresh water plume spreading. In absence of bottom topography the water does not have a preferential path through the upper estuary and the resulting transports are weaker at an individual grid point but more homogeneously distributed across and along the channel. After leaving the upper and relatively narrow upper part of the estuary, the plume still moves to the east along the northern coast of the estuary favored by the Coriolis force but the concentration at the deep channels parallel to the Uruguayan coast is lost. In absence of bottom varying bathymetry (upper panel of Fig. 3) the circulation in Samborombón Bay is mostly cyclonic. The southernmost anticyclonic circulation cell observed in the case when real topography is considered almost disappeared (upper panel of Fig. 2). Therefore, simulations indicate that this last cell is topographically forced. In opposition to what has been argued historically and because of geometric reasons, even without a bottom varying depth, the freshwater coming from the north is not able to reach the area of the bay, but this last region is supplied with water coming from the south.

In a second experiment, the bathymetry was kept realistic, but the rotation of the Earth was suppressed by making the Coriolis parameter equal to zero in the model. The residual mass transport stream function resulting from this simulation after 5 months of integration for a river runoff of 20,000 m$^3$ s$^{-1}$ is shown in the central panel of Fig. 3. A comparison of this case with the control case in which rotation was included (Fig. 2, upper panel) permits an evaluation of the effect of the rotation in different parts of the estuary. At its upper part, due to its relatively reduced geographical extension, the effect of the Earth’s rotation is almost negligible. As a result, the bathymetry and the discharge dominate the regime in this region and no significant change is observed with respect to the control case. At the central part of the estuary, located approximately one barotropic Rossby radius of deformation (which is of the order of 100 km for a mean depth of 10 m at these latitudes) apart from the uppermost point of the estuary, the Coriolis effect begins to be felt by the flow. In a non-rotating system, this area displays a broadening of the main flow, as is evident from a comparison between Figs. 2 and 3. Consequently, a southward inflow into Samborombón Bay occurs and the northern cyclonic cell is narrower. Finally, the effect of the rotation is crucial in defining the flow characteristics at the exterior portion of the estuary, which behaves as a broad channel when the Coriolis effect is neglected.

In the third experiment (lower panel of Fig. 3), both the varying bathymetry and the rotation were suppressed in the simulation. The model was integrated starting from rest and the river discharge was set to 20,000 m$^3$ s$^{-1}$. As noted in the former experiment, at the upper part of the estuary the effect of rotation is almost negligible. The regime there is clearly dominated by the bathymetry and the discharge, being essentially a fluvial one. When bathymetry is suppressed (upper and lower panels of Fig. 3) this region behaves as a channel and the water is homogeneously transported across it. Nevertheless at the central part of the estuary the effect of the rotation becomes important as it produces a shift of the flow to the north. Eventually, this effect determines the circulation at Samborombón Bay. Without rotation and without varying bathymetry (lower panel of Fig. 3), the bay is fulfilled by fresh water from the north and displays an anticyclonic instead of cyclonic motion pattern of the upper panel of Fig. 3. The small amount of water that enters the bay from the south when rotation is included, is deviated to the east when the Coriolis parameter is set to zero. The effect of the rotation is also important in the north-easternmost portion of the domain. The intense circulation off Punta del Este is not only favored by the presence of a deep channel but also by the rotation that concentrates the flow to the north.

The set of experiments presented suggests that dynamically the estuary can be divided into three different regions with diverse responses to the geometry, bathymetry and the Earth’s rotation. Due to its narrowness and relatively small extent, the upper part of the estuary has the lower influence of the Earth’s rotation and has essentially a fluvial regime, mostly dominated by the continental runoff and the bathymetry. Because of its small geographical extension and its relatively intense currents, its mean circulation will probably exhibit the smallest sensitivity to changes in the mean winds as well. The second region is Samborombón Bay, isolated from the northern portion of the estuary because of its geometry and the Coriolis effect. In the absence of winds its circulation is weak and from the south, as a result of tidal rectification. The bathymetry induces a small anticyclonic gyre on the south, whereas the northernmost part is characterized by a cyclonic one. Due to its open mouth and its shallowness, this part of the estuary is sensitive, as shown in the next section, to winds. Finally, the exterior part of the estuary has more oceanic characteristics, and its circulation is not only related to the discharge and the bathymetry but is also the response to the rotation of the Earth. Sensitivity to the winds can be expected in this area as well.

5. The Rio de la Plata circulation response to local wind forcing

In order to analyze the system sensitivity to low frequency wind fluctuations a series of additional simulations were performed. Starting from a steady
solution for no wind and a river runoff of 20,000 m$^3$ s$^{-1}$, the model was run for 16 different wind directions, each 22.5° apart from the other. Wind stress was set to 0.02 N m$^{-2}$, the magnitude of the mean seasonal winds. The runs were repeated for winds of increasing speed, and it was found that, even though the intensity of the currents increases, the circulation patterns are maintained. Due to the shallowness of the system, the models develop a steady response to this forcing in a period of only a few days. The residual mass transport after 7 days of simulation was computed for the solution obtained for every wind direction. In order to simplify the understanding of the set of solutions a principal component analysis was applied to the residual mass transport and to the sea surface elevation. The solution corresponding to a discharge of 20,000 m$^3$ s$^{-1}$ and without wind was removed from the transport and sea level for every wind direction before performing the analysis.

The results of this empirical orthogonal function analysis are displayed in the central and lower panels of Fig. 4, whereas the upper panels show the no-wind solution that was subtracted from the fields prior to the analysis. It can be seen in the figure that the estuary response to local wind forcing of different directions can be explained in terms of two modes of circulation. The first mode, accounting for 76% of the variance, dominates when the wind blows from directions between NNW and ESE (positive phase) or between SSE and WNW (negative phase). This mode, therefore, dominates when the wind presents a component relatively perpendicular to the river axis. The main effect of this mode is to produce an inflow of water to the estuary along the Uruguayan coast during the positive phase and, reciprocally, an outflow of water from the estuary during the negative phase. This transport is accompanied by an increase (reduction) of the sea level along the

![Fig. 4. Results of the principal components analysis performed for the model derived sea surface elevation (cm) and residual transports stream function (thousands of m$^3$ s$^{-1}$) for different wind directions. The upper panels show the model results for these variables for the no-wind case.](image-url)
The second mode, accounting for 24% of the variance, dominates when the wind blows from the northwest (positive phase) or the southeast (negative phase), that is, when the wind blows along the river axis. The effect of this mode is to produce a net inflow (outflow) of water into (out of) the estuary during the negative (positive) phase of the mode. As a result, there is an increase (reduction) of the sea level inside the estuary. This second mode accounts for two well-known extreme situations of the estuary. The negative phase, known as ‘Sudestada’, occurs when intense winds from the southeast blow over the estuary, as the result of a cyclogenesis taking place over Uruguay. Usually, the cyclone over land northward of the estuary is accompanied by an anticyclone further south over Argentina, which increases the southeastern winds (Seluchi and Saulo, 1996). During these events, which can take place several times a year (Gan and Rao, 1991), the water level rises significantly at the upper part of the estuary, often producing destructive flooding (D’Onofrio et al., 1999). The opposite situation (positive phase of the mode) is less frequent, but can be observed about once a year. It takes place when the wind blows from the northwest during several days. In these cases, the water level in the upper part of the estuary is significantly reduced (Fiore et al., 2001). These events can also be problematic because they create difficulties, or even a collapse, in the drinking water supply of the city of Buenos Aires.

These two modes, when composed with the no-wind solution (upper panels of Fig. 4), give rise to four different patterns of circulation at the Rio de la Plata estuary, related to four ranges of wind directions. The sea level and mass transport stream function related to each of those four patterns are shown in Figs. 5 and 6, respectively. The figures clearly show the extreme sensitivity of the estuary to winds blowing along the river axis. It can be seen, particularly in Fig. 5, that for winds blowing from the SE the sea level rise at the upper part of the estuary is much larger than from any other wind direction at the same wind speed. Similarly, the reduction in the water level at the upper part of the estuary is much larger for winds of the same speed blowing from the NW than for any other direction. So, the direction along the river axis is most effective to produce changes in sea level in the estuary.

The transport patterns (Fig. 6) seem to confirm the dynamical classification of the estuary proposed in the former section, now in terms of its response to winds. The circulation pattern at the upper part of the estuary displays the lower response to the winds, even though this is the region where the sea level is most affected. The exterior part of the estuary has in effect a more oceanic Ekman type response. Finally, Samborombón Bay is shown to be extremely sensitive to winds as it is very shallow and semi enclosed. This fact can be clearly appreciated in Fig. 6. Fig. 7 shows the detail of the mass transport stream function for this region for each of the 16 wind directions. It can be observed in Fig. 7 that
when the wind blows from the N a cyclonic cell develops in the northern part of the bay in front of Punta Piedras. At its southern part the circulation is anticyclonic with a net outflow from the bay. When the wind rotates to the east, the cyclonic gyre in the north is maintained even weakened and the circulation in the south breaks down in a number of small gyres with a very weak net circulation. This last kind of circulation holds for winds blowing from the ENE and E, but when the wind rotates to the ESE, the bay enters into another regime. Now the entire bay is occupied by a large cyclonic cell, except for a very small anticyclonic gyre that develops in the southernmost part of the bay, closed to Punta Rasa. As the wind keeps rotating to the west, this small anticyclonic gyre of the south grows and the large cyclonic tends to disappear; the circulation at the bay is dominated by a relatively intense transport that flows northward along the coast. As the wind acquires a W to NW direction the southernmost cell grows and occupies half of the bay meanwhile the northward circulation in the north begins to form a cell. As a result, when the wind is from the NNW, the circulation at the bay is characterized by two cells with the northernmost one cyclonic.

Therefore, our results indicate that the bay is a retention area for winds blowing from directions between the NE and E. This result is consistent with what can be inferred from the biology. This region is particularly important because it is an area of nursery for several coastal species during the spring—summer season. It was classically argued that this happens because the bay is a retention area with weak circulation. Our simulations also indicate that, even though it is not always the case, it occurs during spring and summer when the mean winds blow from the east to northeast along the estuary (Simionato et al., 2004b). Our simulation also indicates that Samborombón Bay is very sensitive to the wind direction and that the situation that favors fisheries during the warm season could change sensitively if the mean wind direction changes as a result, for example, of climate change. Fig. 7 shows that, in effect, as the wind turns from the E to the ESE, the retention pattern at the bay is lost. Results from historical data analysis seem to indicate that such a change could be already taking place. Fiore et al. (2001) analyzed hourly water levels gathered from 1905 to 2000 at the Buenos Aires Port. An increase in the annual frequency for the positive surges and a decrease for the negative ones were observed in this period. On the other hand, a positive trend was obtained for the annual extreme surge, which was explained as a consequence of a mean sea level rise rather than an increase in the intensity of the storm surges. The increase in the annual frequency for the positive surges and the decrease for the negative ones, seem to be related to an increment in the frequency of intense southeast wind events (Sudestadas) and a reduction in the frequency of the persistent northwest situations. This modification in the storm regime would have the effect of producing a mean wind with a more southeasterly component, especially during winter and spring, when the frequency of Sudestadas reaches its maximum (Gan and Rao, 1991).

Finally, as pointed out in the introduction, a kind of bimodal circulation pattern at the estuary has been reported in the literature. Our simulations suggest that in the absence of winds the normal path of the estuary flow should be a buoyant plume to the north. When the mean wind blows from directions between SSE and NNW, this pattern would be intensified (see left panels.

Fig. 6. Main residual transport stream function (thousands of m$^3$ s$^{-1}$) patterns at the Río de la Plata estuary related to wind direction.

Fig. 7 shows...
of Fig. 6). The southward path, in turn, could be a result of the wind forcing when it acts from some specific directions between NNW and SSE (see right panels Fig. 6). This could explain in turn, why this path has only been sporadically registered.

6. Summary of conclusions

In this paper the circulation patterns at the Río de la Plata and their response to the main driving forces were studied by means of process-oriented numerical simulations. The model solutions indicate that the circulation at the Río de la Plata is highly influenced by the bathymetry. In the interior part of the estuary, after discharge, the flow concentrates along the deep north and intermediate channels. As the river plume reaches the central part of the estuary, the Coriolis effect begins to be felt and the transport concentrates to the north. Even though the Arquimedes and English banks divide the flow into two branches in the exterior part of the estuary, in the absence of winds they meet again after flowing through this region.

The wind driven circulation of the estuary can be explained in terms of two modes of circulation. The first, prevailing for winds with a cross-river component, is related to an inflow-outflow of water at the exterior part of the estuary and accounts for the seasonal signal observed, for example, in the salinity field. The second mode dominates when the wind blows along the estuary axis, that is, from the SE or from the NW and has a very distinctive pattern of significant sea level increase or

Fig. 7. Residual transport stream function for Samborombón bay for 16 different wind directions.
reduction at the upper part of the estuary, respectively. This mode accounts for two extreme situations often observed with important social implications: the Sudestada and the persistent northwest wind.

Even though a kind of bimodal circulation pattern has been reported in previous papers, our simulations suggest that in the absence of winds the normal path of the estuarine flow should be a buoyant plume to the north. When the mean wind blows from directions between SSE and NNW, this pattern is intensified. The southward path observed seems to be the result of the wind forcing when it acts from directions between NNW and SSE which explains why this path has only been sporadically registered.

This set of experiments suggests that dynamically the estuary can be divided into three different regions with diverse responses to the geometry, bathymetry, the Earth’s rotation and winds. Due to its narrowness and relatively small geographical extension, the upper part of the estuary has the lowest influence of the Earth’s rotation and has essentially a fluvial regime, mostly dominated by continental runoff and bathymetry. Because of its small geographical extension and its relatively intense currents, its circulation pattern exhibits the smallest sensitivity to changes in the mean winds as well, even though the sea surface elevation has the maximum response in this area.

The second region is Samborombón Bay, isolated from the northern portion of the estuary because of its geometry and the effect of the Earth’s rotation. In the absence of winds its circulation is weak and from the south, as a result of tidal rectification. The bathymetry induces a small anticyclonic gyre on the south, whereas the northernmost part is characterized by a cyclonic one. Due to its geometry, open mouth and its shallowness, this part of the estuary is very sensitive to the wind direction. Our solutions indicate that the bay has a weak and retention circulation pattern for winds blowing from directions between the NE and E, the winds prevailing during the warm season. This favors the biota, allowing the region to become an area of nursery for several coastal species during the spring—summer. Nevertheless, our simulations also indicate that the situation that favors fisheries during the warm season could change sensitively if the mean wind direction suffers even a small shift to the south as a result, for example, of climate change. Results from historical water level data analyzed by other authors (Fiore et al., 2001) suggest that such a shift could already be taking place.

Finally, the exterior part of the estuary has more oceanic characteristics, and its circulation is not only related to discharge and bathymetry but also to rotation. The area is naturally sensitive to the winds but the response here is an oceanic Ekman type response.

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