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RECENT ADVANCES IN THE KNOWLEDGE OF THE RÍO DE LA PLATA ESTUARY CIRCULATION, FORCINGS AND VARIABILITY

C. G. Simionato(1)(2)*, V. L. Meccia(1), W. C. Dragani(2)(3)(4), R. A. Guerrero(5) and M. Nuñez(1)(2)

(1)Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA), Argentina
(2)Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Argentina
(4)Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET), Argentina
(4)Servicio de Hidrografía Naval de la Armada Argentina y Escuela del Ciencias del Mar (ESCM-INUN)
(5)Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) and Universidad Nacional de Mar del Plata, Argentina

1. INTRODUCTION

The Río de la Plata (Figure 1), located in the eastern coast of Southern South America, approximately at 35º S, is one of the largest estuaries of the world (Shiklomanov, 1998). With an estuarine area of 35000 Km^2, a drainage area of 3.5×10^6 Km^2 (Balay, 1961). and a mean discharge of 25,000 m^{3}s^{-1} (Nagy *et al.*, 1997; Jaime *et al.*, 2002), it ranks 4th and 5th worldwide in fresh water discharge and drainage area, respectively (Framiñan *et al.*, 2000). This system substantially contributes to the nutrient, sediment, carbon and fresh water budgets of the South Atlantic Ocean (Framiñan *et al.*, 2000 and references therein), affects the hydrography of the adjacent Continental Shelf, impacts important coastal fisheries, and influences coastal dynamics as far as 23º S (Campos *et al.*, 1999; Framiñan *et al.*, 2000; Piola *et al.*, 2000). Besides its geographical extension, the estuary is of great ecological, social and economical importance for the countries on its shores. The capital cities of both countries and a number of harbors, resorts and industrial centers are located there. The estuary constitutes the main source of drinking water for the millions of inhabitants in the region, for whom it is also an important amusement zone. The estuary has important fisheries and possesses the unusual feature of being a spawning and nursery area for several coastal species (Cousseau, 1985; Boschi, 1988). Because of these reasons the estuary is being impacted by anthropogenic actions, which consequences have not been completely evaluated yet. Due to the intense discharge, when the fresh river water meets the open ocean, an intense and active salinity front followed by a fresh water plume, which influence can be tracked up to 23º S, is formed. This front is important not only for fisheries, but also modifies the coastal circulation and the mixing and convection conditions with important oceanographic implications (Campos *et al.*, 1999; Framiñan *et al.*, 2000; Piola *et al.*, 2000).

Despite of its social and oceanographic importance, not much was known about the Río de la Plata circulation, its variability and forcings a few years ago. Recently, in the context of National and International Projects -as UNDP/GEF Project "Environmental Protection of the Río de la Plata and its Maritime Front" (FREPLATA), and "Estudio de la dinámica oceánica y atmosférica del Estuario del Río de la Plata mediante un sistema de modelado numérico integral" (PROPLATA) funded by the Agencia Nacional de Promoción Científica of Argentina- important advances in our understanding of the physical oceanography of this system were done as a result of a cooperative research between scientists of Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA), Servicio de Hidrografía Naval (SHN) and Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP). This improvement is in a large extent the result of the collection, by the first time, of long term ADCP current data that allowed the study of current variability from very high frequencies to intra-seasonal time scales, and its connection to wind variability. Also, the application of numerical models contributed to the understanding of the mechanisms that control estuarine motions and the effect of their variability. As a result, our view of the behavior of this system has essentially enhanced and in many aspects has changed. In this sense, the aim of this paper is to discuss what we learned during the last few years and the main gaps that must be fulfilled in order to allow for an adequate representation of the system to permit its forecasting, management and control.

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* *Corresponding author address:* Claudia G. Simionato, Centro de Investigaciones del Mar y la Atmósfera, CIMA/CONICET-UBA, Ciudad Universitaria Pabellón II Piso 2, (C1428EHA) Buenos Aires, Argentina.
e-mail: claudias@cima.fcen.uba.ar

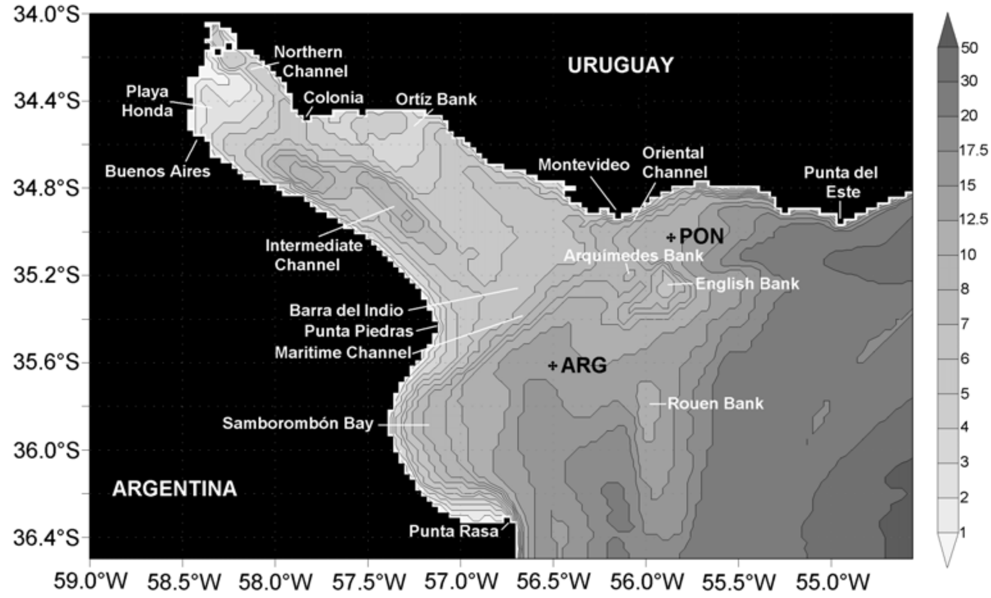

Figure 1: Bathymetry (in meters) of the study area as it derives from a 3 Km × 3 Km resolution data set together with the main geographical and topographical features. Locations where ADCP time series were collected are indicated as PON and ARG (From Simionato *et al.*, 2005a).

2. TIDAL AND WIND FORCINGS

2.1. *Tides*

A complete study of the tidal propagation in the Río de la Plata was recently presented by Simionato *et al.* (2004a). Data for the propagation of the principal lunar semidiurnal (M_2) constituent estuary were gained through a set of three one-way nested models, applying the three-dimensional primitive equation Hamburg Shelf Ocean Model (HamSOM) developed at the University of Hamburg by Backhaus (1983, 1985). As the set of models was constructed as a first step of the development of a warning and management system, they are very realistic, representing an important advance with respect to previous papers (O'Connor, 1991; Glorioso and Simpson, 1994; Veira and Lanfredi, 1996; Glorioso and Flather, 1995, 1997; Glorioso, 2000). Simulations were started with a large-scale model covering the Argentinean and Uruguayan and part of the Brazilian continental shelves. This model provides boundary conditions to a smaller scale model of the Río de la Plata and adjacent continental shelf, which in turn is used to force a small-scale high-resolution model of the Río de la Plata estuary. Model sensitivity to different boundary conditions and to model parameters was investigated. Solutions resulted neither sensitive to the two different boundary conditions tested, derived from global data assimilating models (Ray *et al.,* 1994 and Zahel, 1997), nor to lateral diffusion but to bottom friction.

Simulation results were validated using all tidal gauge data available and several currents observations resulting, in every case in a very good agreement.

Those simulations have permitted, therefore, the construction of more reliable model derived cotidal, corange (Figure 2) and tidal currents charts (Figure 3). The normal range of the tidal amplitude is around one meter on the Argentinean side, but only one third of this value on the Uruguayan side. This is not only a result of the fact that the tide is higher at the south than at the north of the estuary mouth, but also of the Coriolis effect. The wave propagates as a free external gravity wave along the estuary, with a phase velocity of $\sqrt{gH}$ (where g is the acceleration due to the gravity and H the water depth). It takes the wave approximately 12 hours to propagate from one extreme to the other one. As this period is almost similar to the period of the tide, two maximums or two minimums can co-exist at the same time within the estuary (Balay, 1961). This last feature is very clear in the simulated phases plot (Figure 2, upper right panel).

The progression of the wave, northward with the coast to the left, and the decay of the amplitude offshore are consistent with a response of Kelvin waves to the forcing at the shelf. The dynamics of the tides in terms of Kelvin waves is described by Gill (1982) and discussed for the particular case of the Río de la Plata by O'Connor (1991). The Rossby radius of deformation is an offshore amplitude decay scale; taking *H=10 m* as a representative depth of the estuary, it results $\sqrt{gH}/|f| = 115Km$ (where *f* is the Coriolis parameter), which is narrower than the size of the estuary on its outer and medium parts. This fact, added to the importance of the dissipation in shallow waters ensures that there would not be an amphidromic system inside the estuary.

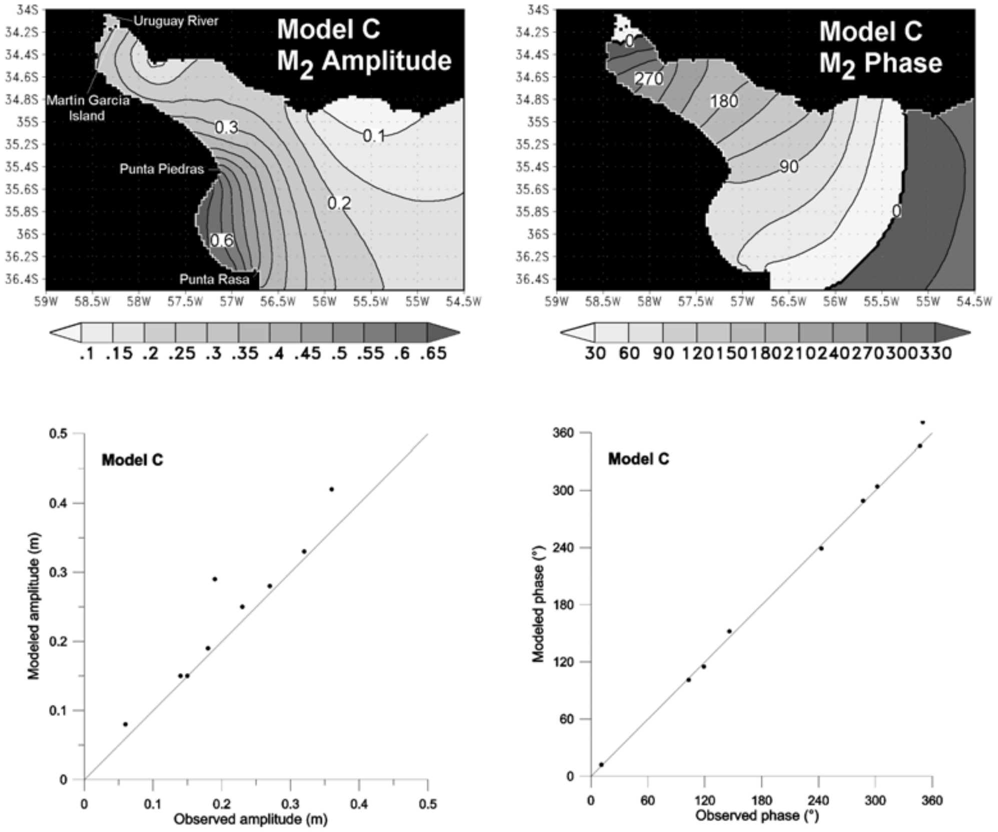

Figure 2: Upper panels: Corange (amplitudes in meters) and cotidal (phases in degrees) maps of the M_2 constituent from numerical simulations. Lower panels: Scatter plots of modeled vs. observed amplitudes and phases for model simulation; the full line indicates the perfect fit. (From Simionato, *et al.*, 2004a).

Maximum speeds occur at the northernmost and southernmost tips of the Samborombón Bay, Punta Piedras and Punta Rasa, while in the interior of the Bay values are much smaller. This last region displays a rotational feature, but at the upper and central estuary the currents tend to be more unidirectional.

Tidal energy dissipation at the Argentinean Continental Shelf derived from the simulations shows that it constitutes an important amount of the globally estimated one. High-resolution simulations for the Río de la Plata estuary and the adjacent Continental Shelf have allowed the first estimations of the tidal energy flux and the energy dissipation by bottom friction at the estuary. Results indicate that M_2 energy flux to the Río de la Plata comes from the east -and not from the south as it was traditionally thought- and enters the estuary from the south-westernmost portion of its mouth. Energy flux concentrates mainly along the Argentinean coast, whereas it is very small on the Uruguayan one. Consistently, most of the dissipation takes place in the extremes of Samborombón Bay. Dissipation occurs as well along the deep channels of the middle part of the estuary as at its upper part. A secondary maximum coincident with the presence of the Rouen Bank (Figure 1) is observed at the exterior part of the estuary.

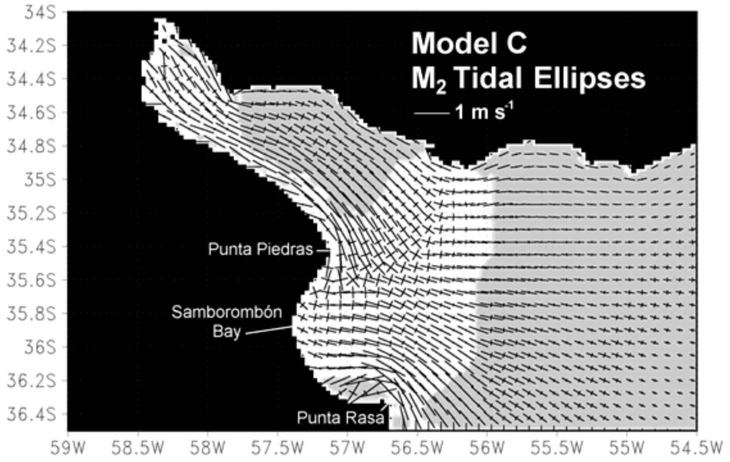

Figure 3: M$_2$ tidal current ellipses derived for the Río de la Plata. Shaded zones indicate counterclockwise rotation of the ellipses. (From Simionato *et al.*, 2004a).

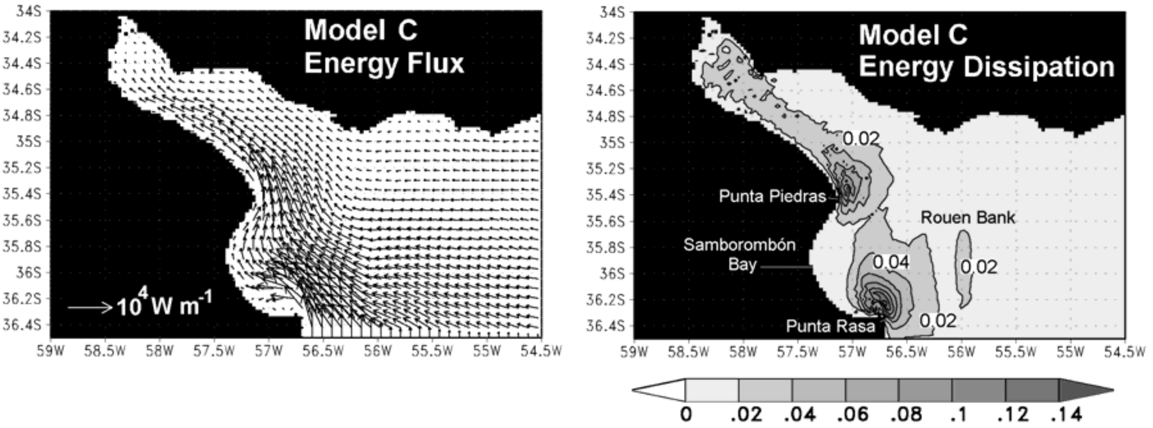

Figure 4: M2 tidal energy flux vectors in W m^{-1} (left panel) and contours of M$_2$ tidal energy dissipation by bottom friction rate in W m^{-2} (right panel) derived from Model C (From Simionato *et al.*, 2004a).

2.2. ***Winds***

A comprehensive study of surface wind variability over the Río de la Plata estuary using the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.*, 1996) data between 1948 and 1997 was presented by Simionato *et al.* (2005b). Their analysis shows that 62% and 18% of the zonal and meridional components total variance, respectively, are related to the seasonal scales while inter-annual scales account for 4% and 10.6% respectively. Nevertheless, wind variability at sub-annual scales is also important over the region, dominating the meridional component behavior. The seasonal cycle is characterized by an onshore to offshore rotation of the winds from summer to winter (Figure 5). This result is consistent with what is derived from the only direct observations available, collected at Pontón Recalada (Guerrero *et al.*, 1997). This cycle results by the superposition of an annual west-northwestward to east-southeastward dominating signal and a northwestward to southeastward semiannual one. The prevailing winds blow from the east-northeast during summer and from the west-northwest during winter (Figure 5). An important variation on both winter and summer wind speeds is observed during the last 50 years, with a displacement of the summer-winter seasonal features to earlier months. Meanwhile, transition seasons show an important change of the wind directions related to a larger influence of northern winds (Figure 6).

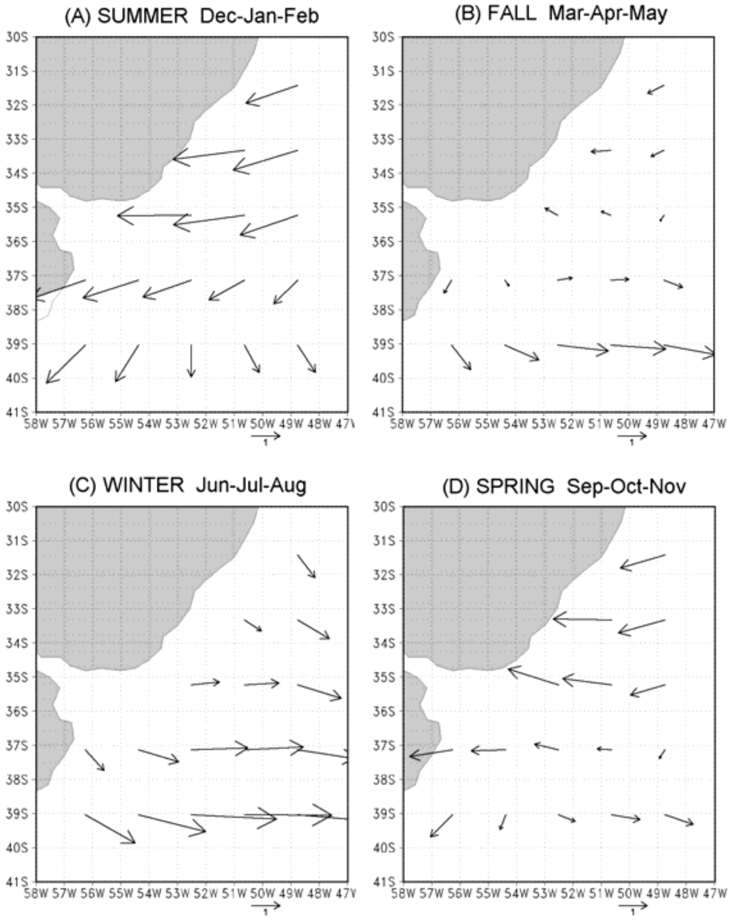

Figure 5: 50-year mean vectors of wind velocity for every season: (A) summer, (B) autumn, (C) winter and (D) spring (From Simionato *et al.*, 2005b).

On inter-annual timescales, two distinctive and important modes of variability have been found (Figure 7). The first mode seems to be a low-frequency modulation of the main seasonal pattern with periods around 2 years and it is highly anticorrelated with SST changes over the western tropical Pacific, resembling the atmospheric quasi-biennial tropical oscillation pattern identified by other authors (Kidson, 1988; Mo, 2000). Southeasterlies (northwesterlies) over Río de la Plata region are associated with negative (positive) SST anomalies over that tropical region. Consistent with that, a well defined atmospheric Rossby wave train propagating out of that tropical region and extending towards South America links both regions and it is associated with an anticyclonic (cyclonic) anomaly over the western portion of the South Atlantic and a cyclonic (anticyclonic) anomaly to the east.

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The second mode (Figure 7) is related with clockwise/counterclockwise rotations of the winds with periods between 8 and 12 years and it has almost no relationship with SST variations at tropical latitudes while it is highly correlated with SST changes at middle and high SH latitudes and particularly over the South Atlantic Ocean. Clockwise (counter-clockwise) wind rotation out off the estuary are associated with positive (negative) SST anomalies along both South Atlantic basin coasts and negative (positive) values at the inner portion. In agreement, an east-west oriented dipole is the main feature in the corresponding sea level pressure field, with an anticyclonic (cyclonic) anomaly at 40°W, 50°S and cyclonic (anticyclonic) anomaly located further east.

Non-significant signal between ENSO and changes of local annual mean winds over Río de la Plata area have been found. However, results might be different if the same study were performed on monthly average winds.

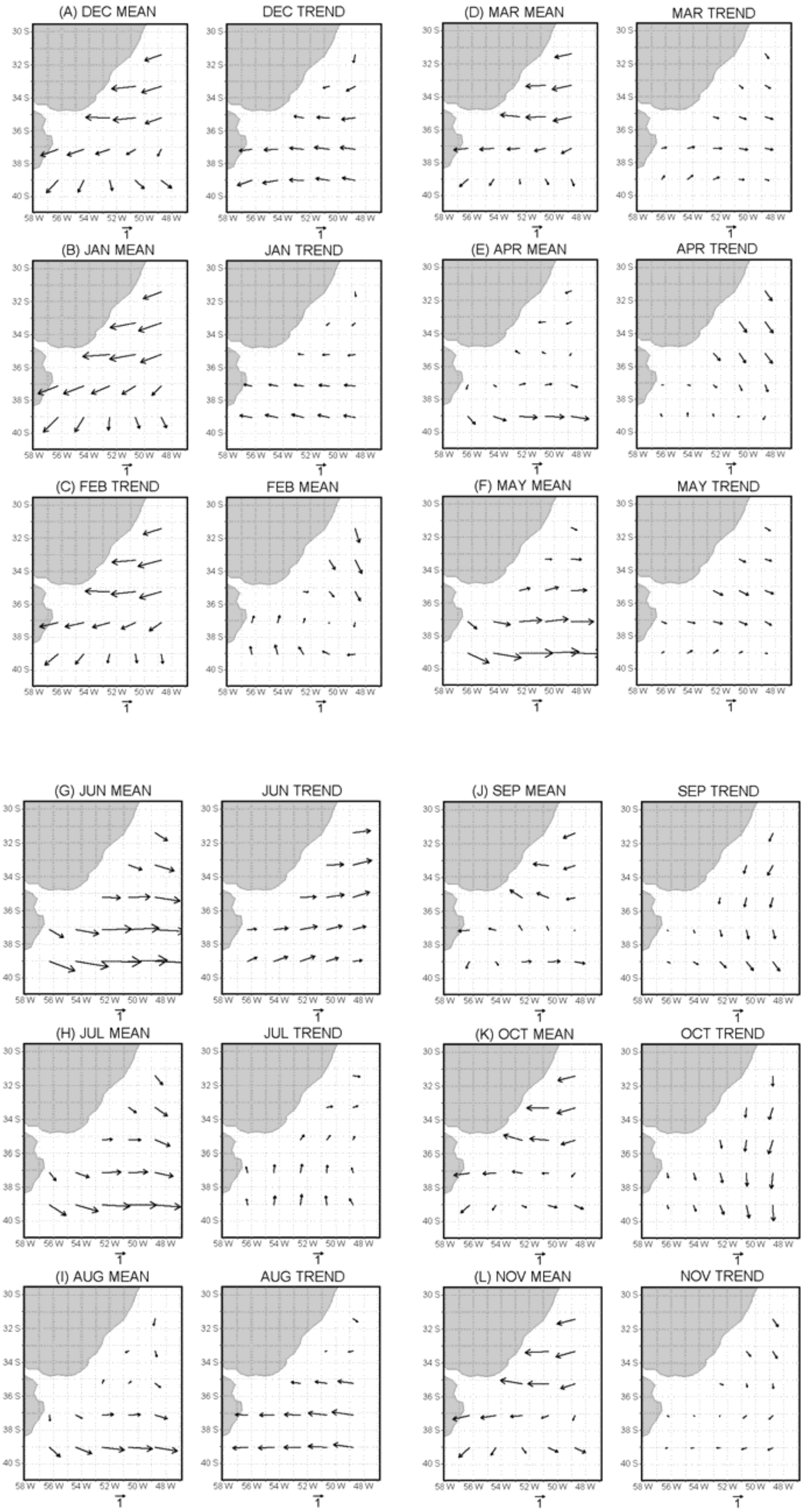

Figure 6. Surface wind climatological monthly means for each calendar month and its respective trend along the 50-year record (From Simionato *et al.*, 2005b).

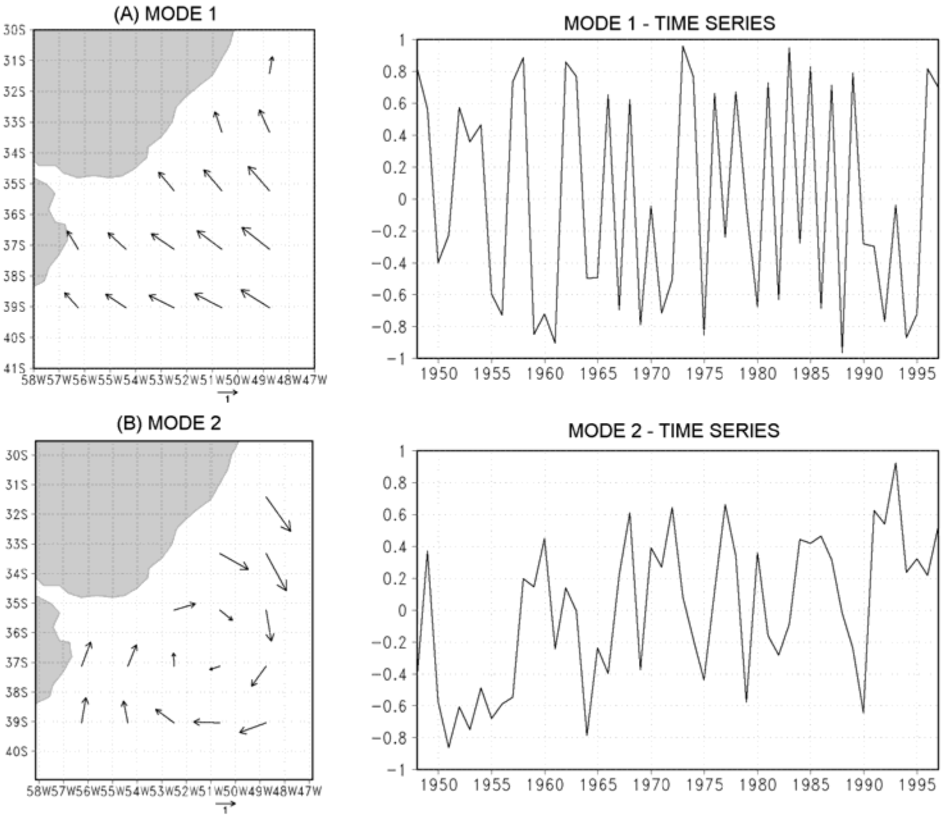

Figure 7: Leading modes of inter-annual variability for the surface winds obtained from a principal component analysis (t-mode) applied to the annual mean anomalies of the two wind components: (A,B) their spatial patterns and (C,D) the related temporal patterns (From Simionato *et al.*, 2005b).

2.3. *On the use of the NCEP/NCAR surface winds for modeling circulation in the Río de la Plata Estuary*

Atmospheric products such as the NCEP/NCAR reanalysis seem to constitute a solution for the lack of direct observations in the Río de la Plata estuary. Forcing numerical ocean models with those data allows the simulation of the estuarine system for long periods including the effect of high frequency wind variability, what in turn constitutes a powerful tool for understanding and evaluating wind forced climate variability in the region. Nevertheless, given the serious limitations of those data sets in the Southern Hemisphere, a question that must be answered before this kind of simulations is to what extent ocean models forced by a reanalysis represent the real system. Simionato *et al.* (2006a) carried out a model validation for the Rio de la Plata inner and outer estuary including adjacent shelf regions. The HAMburg Shelf Ocean Model (HamSOM) code (Backhaus, 1983, 1985) was forced with NCEP/NCAR reanalysis data to perform four hindcasts covering about one month in different seasons and five extreme events of storm surges. Three nested unilaterally coupled model domains with increasingly finer grids were used for the simulations. The role of wind forcing over the outer, large-scale shelf region was studied by both including and excluding the forcing for the outer domain. It was found that weak winds in the NCEP/NCAR reanalysis are under-estimated, and a correction factor is needed to adjust winds for different magnitudes (Figure 8). The comparison of simulated surface elevations (Figure 9 and 10) and currents (Figure 11) with observed ones yields high correlations, which improve even further when a meteorological forcing is included in the outer domain. This indicates that the Río de la Plata is sensitive to the atmospheric large scale and is consistent with the sense of propagation of coastally trapped waves, which travel northward along Argentinean coast, entering the estuary from the south. This implies an additional computational cost that could be avoided in some applications, but must be afforded if models are to be used for forecasting. The validation comprises state of the art accuracy with regards to problems where stratification plays a minor role. Numerical solutions satisfactorily reproduce both, the timing and amplitude of the observed estuarine waters response to wind, implying that the quality of the forcing is in turn good. Consequently, their simulations constitute an indirect validation of the NCEP/NCAR reanalysis 10 m winds. Even though they tend to underestimate wind speed, direction and variability seem to be properly represented, at least in the atmospheric synoptic to intra-seasonal time scales.

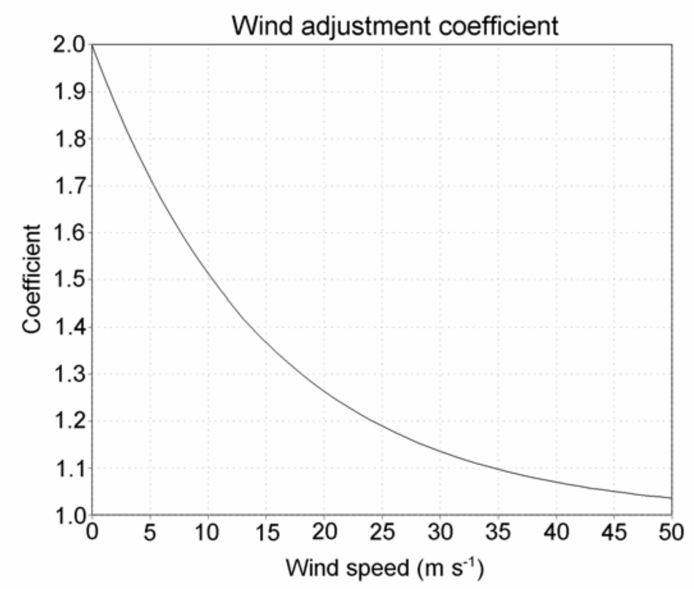

Figure 8: Coefficient suggested for NCEP/NCAR surface wind speed correction by Simionato *et al.*, 2006.

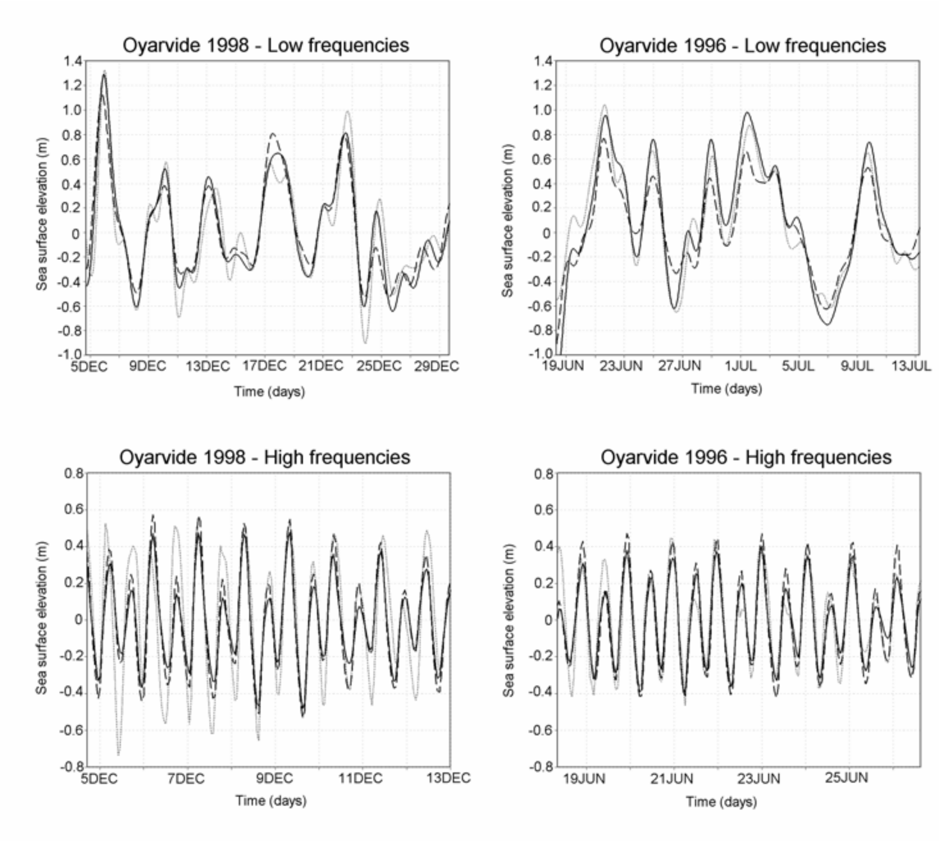

Figure 9: Comparison between observed (grey line) and simulated sea level in Oyarvide station during June, 1996 (right panels) and December, 1998 (left panels) when wind forcing is included (solid black line) and not included (dashed black line) in the remote shelf. Upper (lower) panels correspond to variability in periods higher (lower) than 28 hours. Note that 25 days are shown for low frequencies but, for reasons of clarity of display, only 8 days are given for the higher ones (From Simionato *et al.*, 2006a).

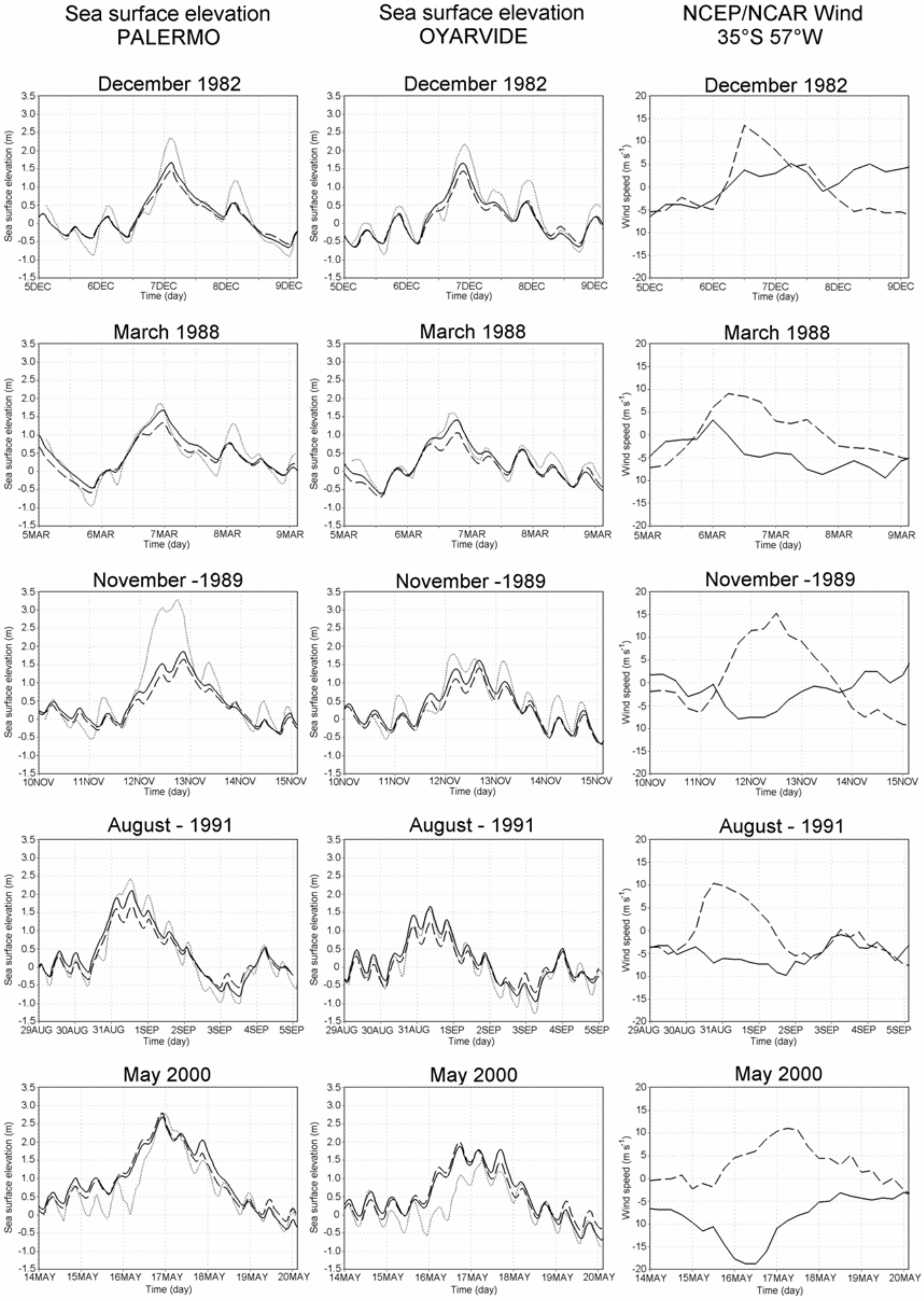

Figure 10: Left and central panels: Comparison between observed (grey line) and simulated sea level when wind forcing is included (solid black line) and not included (dashed black line) in the remote shelf for the five severe storm surges simulated in Palermo (left) and Oyarvide (central) stations. Right panel: NCEP/NCAR zonal (solid line) and meridional (dashed line) wind speed at 10 meters at 35º S, 57º W (From Simionato *et al.*, 2006a).

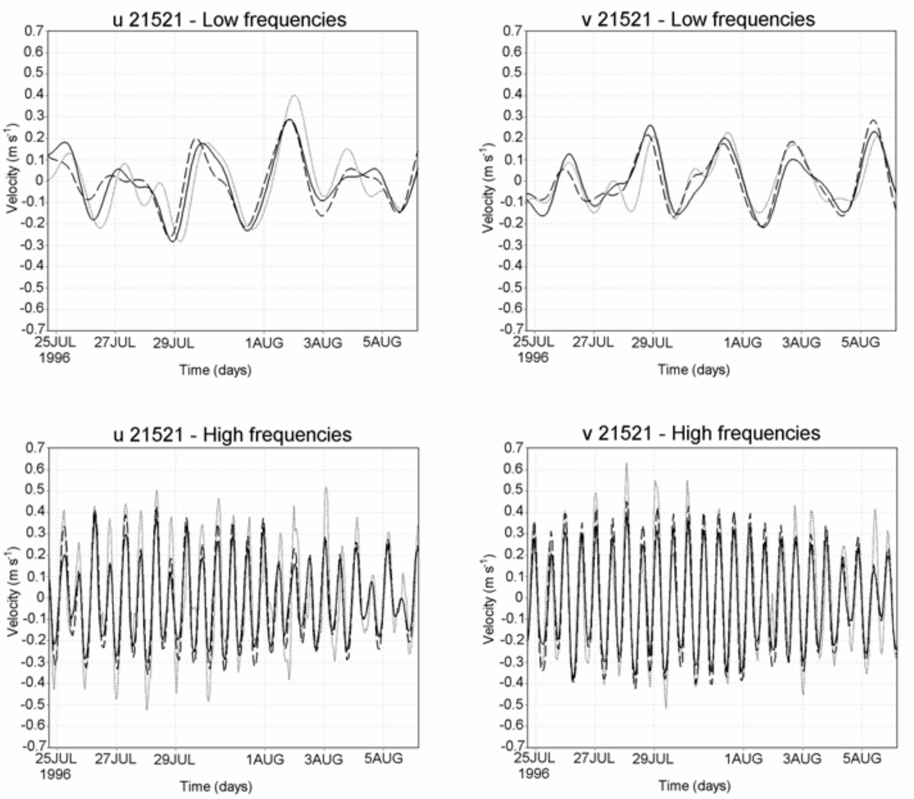

Figure 11: Comparison between observed (grey line) and simulated zonal (left panels) and meridional (right panels) current in Hidrovía 21-521 station during July-August 1996 when wind forcing is included (solid black line) and not included (dashed black line) in the remote shelf. Upper (lower) panels correspond to variability in periods higher (lower) than 28 hours (From Simionato *et al.*, 2006a).

3. SEASONAL VARIABILITY OF THE SURFACE SALINITY FRONT

Analysis of hydrographic data collected during the last 30 years (Guerrero *et al.*, 1997) show that the surface salinity front exhibits an intense variability in the seasonal scale. It was hypothesized that it is controlled by the balance between onshore and offshore winds, the river discharge and the Coriolis force. Data indicate the occurrence of two clearly different periods. During fall-winter, a NNE drift of estuary waters along the Uruguayan coast is observed; it has been related (Guerrero *et al.*, 1997) to a balance between onshore and offshore winds and a maximum in the continental drainage. Reciprocally, during spring-summer the presence of fresh water along the Argentinean coast up to 37° S and the penetration of Shelf waters up to Punta del Este (Uruguay), has been attributed to onshore dominant winds and a minimum in the runoff.

Simionato *et al.* (2001) studied the influence of the main driving forces that have been proposed to be responsible of the surface salinity front variability by means of process oriented numerical experiments. They applied the 3-D baroclinic primitive equations HamSOM model (Backhaus, 1983, 1985), and analyzed the isolated and combined effect of the different forcings under realistic bathymetry and coastline. Despite the idealistic conditions, the simulations are able to capture the most outstanding features of the observed variability (Figure 12).

The 3-D baroclinic numerical experiments indicate that most of the seasonality of the surface salinity front is due to the winds seasonal variation, meanwhile the change of the river discharge exhibits a much smaller influence. The tides play an important role on producing mixing and extending the influence of the fresh water plume to the north. The winter condition is mainly explained by the Coriolis effect, which deflects the fresh water plume to the north along the coast, whereas winds play a minor role. During this season offshore winds are only slightly more frequent than onshore ones; therefore, they have a small but positive effect on the plume extension to the ocean. During the summer, even though the amount of the river discharge is large enough to produce a similar picture to the one observed during the winter, the predominant easterly winds inhibit the plume extension and force the fresh waters to the west along the Uruguayan coast, and southwest on the Argentinean side. Even though historical data do not exhibit an intense seasonal variation on the river outflow, except during the last part of 20th Century, simulation results compare better to data when this variation is included into the simulation. This last is probably due to the fact that most of the observations were taken during that period. In these experiments, the influence of the exterior mean condition was analyzed; results suggest that the system-analyzed variability is quite independent from it, indicating that exterior conditions do not play a significant role in the definition of the frontal position.

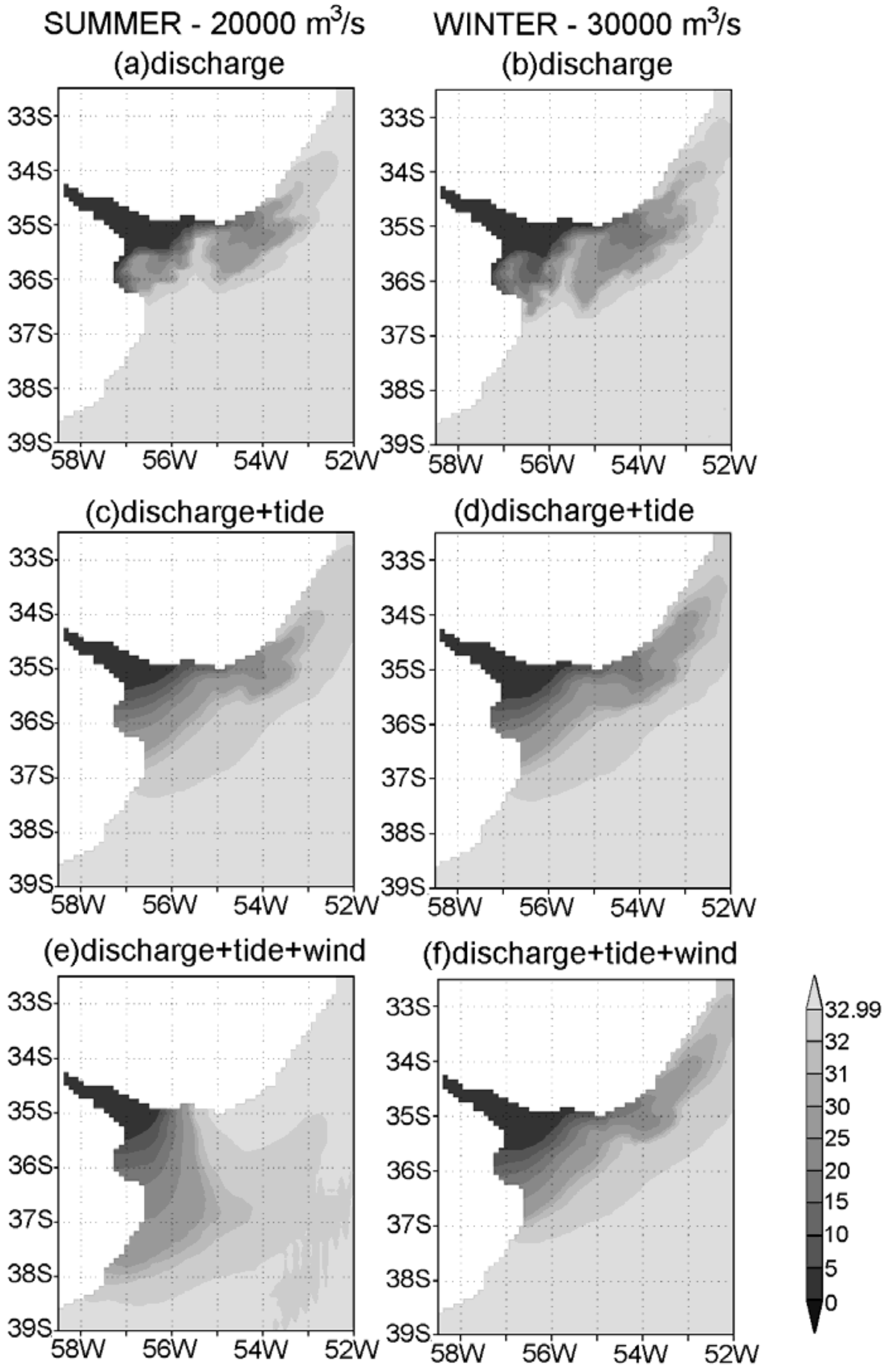

Figure 12: Results of the three sets of experiments forced with river runoff (upper panel), runoff and tides (central panel) and also winds (lower panel); the figures display the first layer simulated salinity. Note that contour intervals are not regular (From Simionato *et al.*, 2001).

4. BAROTROPIC CIRCULATION

Not much was known up to recent times about the Río de la Plata circulation. Due to the lack of comprehensive current meter measurements, most of what is affirmed about the system currents had 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 by those means.

Based on this kind 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 Brandhorst *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 the Samborombón Bay the saline water movement is quite restricted due to its shallowness. The influence of the water plume in the north had been inferred or suggested by several other papers (Hubold, 1980; Carreto *et al.*, 1986; Lusquiños and Figueroa, 1982; Nagy *et al.*, 1997; 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 had been reported in literature. The most often registered path, and also the most accepted one, was to the north, along the deeper channels of the upper part of the estuary. This path is consistent with a buoyant plume that spreads on the Southern Hemisphere deviated to the left by the Earth's rotation. The low salinity along the southern coast had been explained in terms of a more complex tidal regime and mixing processes associated with the shallowness of the Samborombón Bay. Nevertheless no clear explanation of the patterns that generate this bimodal discharge pattern had been proposed, neither the frequency of occurrence had been established.

Recently, in the frame of the FREPLATA project, six months length ADCP current series with high vertical and temporal resolution were collected at two locations of the estuary: the Maritime Channel, proximate to Argentinean coast (shown in Figure 1 as ARG), and Pontón Recalada, close to Montevideo, on the Uruguayan coast (shown in Figure 1 as PON). Those data provided the first opportunity of exploring the estuarine circulation and its variability during several months. The analysis of those data (Simionato *et al.*, 2006b) together with the application of numerical models in process oriented simulations (Simionato *et al.*, 2004b) have allowed the understanding of the circulation patterns in the estuary and their connection to wind variability in synoptic to intra-seasonal time scales.

Numerical simulations (Simionato *et al.*, 2004b) indicate that, in absence of winds, the circulation at the Río de la Plata (Figure 13) is highly influenced by the bathymetry. In the interior part of the estuary, after discharged, 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 (Figure 1) divide the flow into two branches in the exterior part of the estuary, in absence of winds they meet again after flowing through this region. Under weak winds, the circulation associated to the Samborombón Bay is very weak. The model produces for this area two low transport circulation cells. The larger scale one is cyclonic (clockwise) and occupies most of 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 southernmost extreme of the bay. The penetration of continental shelf colder waters around this cape has been inferred from SST satellite data (Lasta *et al.,* 1996; Framiñan *et al.,* 2000). Even though it has been suggested that the circulation in this bay is inhibited by its shallowness and dominated by the tides (Urien, 1967, 1972), simulations demonstrate that in absence of winds, the weak 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. Solutions also show that, even though an increase (reduction) in the runoff -as observed during winter (summer)- enhances (reduces) transport, it does not essentially modify the described circulation pattern.

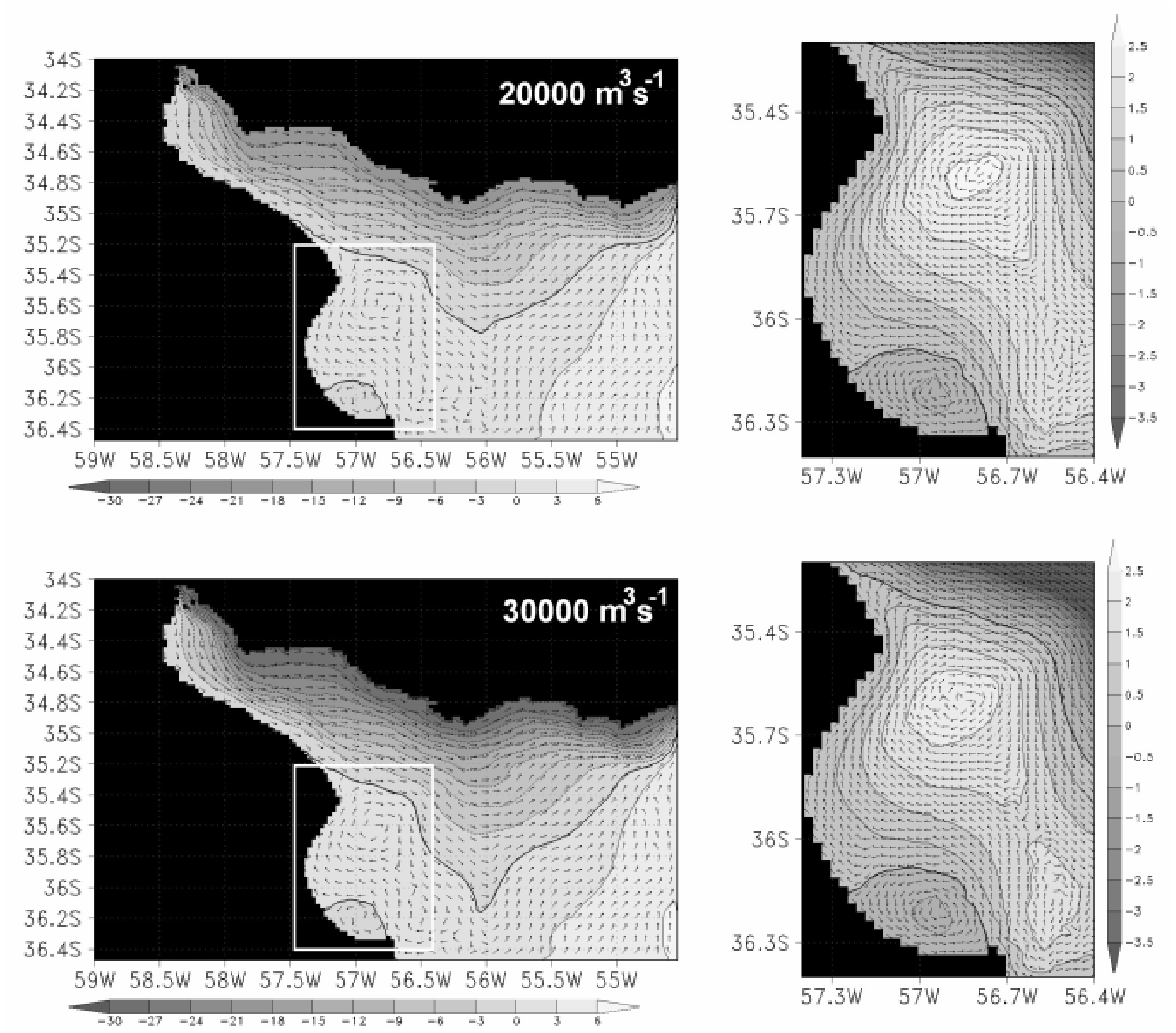

Figure 13: Model derived residual transport stream function (m^3s^{-1}) at the Río de la Plata (left) and a detail of Samborombón Bay (right). Upper panel: summer (20000 m^3s^{-1}) runoff condition. Lower panel: winter (30000 m^3s^{-1}) runoff condition (From Simionato *et al.*, 2004b).

Both, data and models indicate that the estuary is extremely sensitive to wind variability, even in very short time scales. Wind driven barotropic currents can be explained in terms of two modes, resulting of estuary's geometry (figures 14 and 15). The first one, 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, that is, from the SE or from the NW and has a very distinctive pattern of significant sea level increase or 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 western wind. These two modes, when composed with the no-wind solution (upper panels of Figure 14), give rise to four different patterns of circulation at the Río 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 Figure 16. This figure clearly shows the extreme sensitivity of the estuary to winds blowing along the river axis. It can be seen 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.

Numerical experiments suggests that dynamically the estuary can be divided into three different regions with diverse responses to the geometry, bathymetry, Earth 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 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.

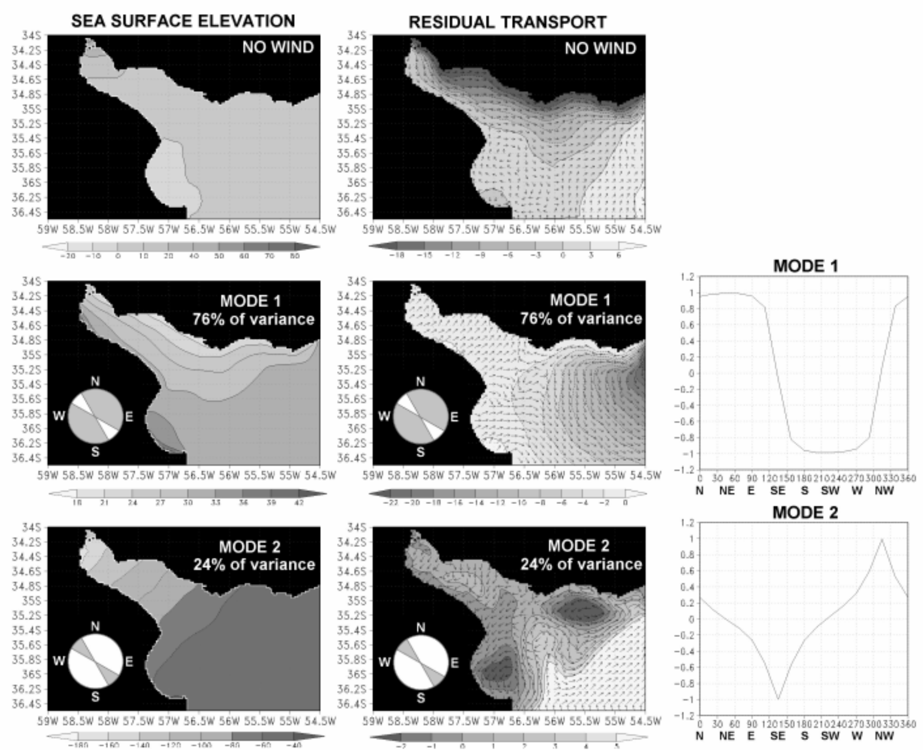

Figure 14: Modes of circulation and sea surface elevation of the Río de la Plata derived from numerical simulations. Upper panels illustrate the numerical solution under a no wind condition. Central an lower panels show the two modes (maps) and their corresponding correlation to wind direction (From Simionato *et al.*, 2004b).

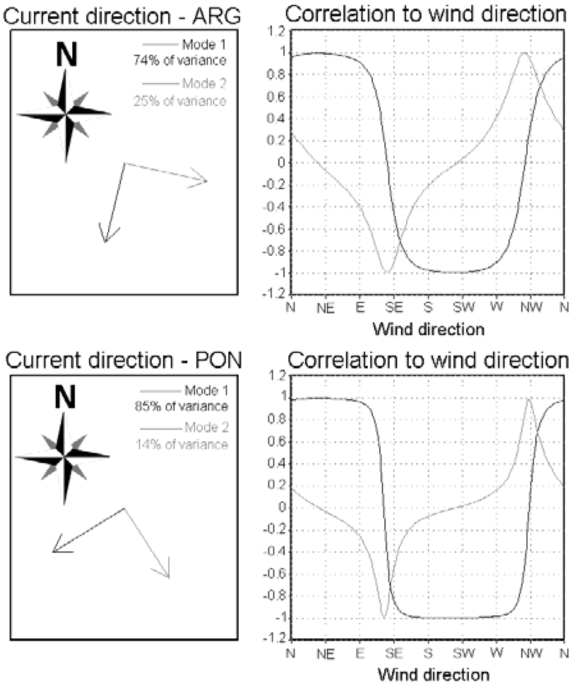

Figure 15: Modes of circulation of the Río de la Plata at the locations indicated as ARG and PON in Figure 1, derived from ADCP direct observations (left panels) and their corresponding correlation to wind direction (right panels). From Simionato *et al.*, 2006b.

The second region is the Samborombón Bay, isolated from the northern portion of the estuary because of its geometry and the effect of the Earth rotation. In 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. Numerical 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, 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, for example, a result of climate change. Results from historical water level data analyzed by other authors (Fiore *et al.*, 2001) suggest that such a shift could be already 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 is also to rotation. The area is naturally sensitive to the winds but the response here is an oceanic Ekman kind one.

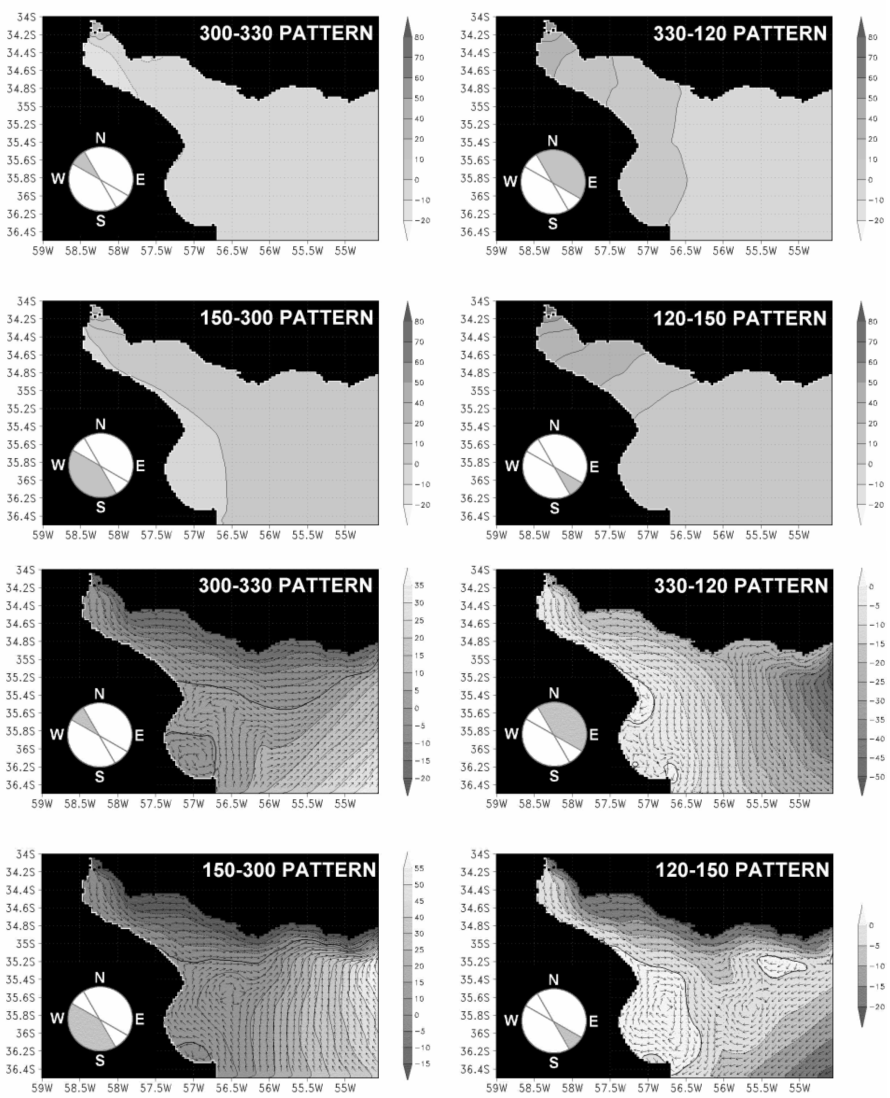

Figure 16: Upper panels: Main sea surface elevation (cm) patterns at the Río de la Plata estuary related to wind direction. Lower panels: Main residual transport stream function (m^3s^{-1}) patterns at the Río de la Plata estuary related to wind direction (From Simionato *et al.*, 2004b).

ADCP observations indicate that even though both modes imply that barotropic currents develop in a phase lag with the wind that depends on the location as a results of topographic rectification, northeasterly and southwesterly winds -Mode 1- generate stronger currents than southeasterly and northwesterly winds -Mode 2- (Figure 17). Barotropic response to winds occurs in a lapse of around 6 hours and an equilibrium regime is reached for processes with temporal scales more than 4 days.

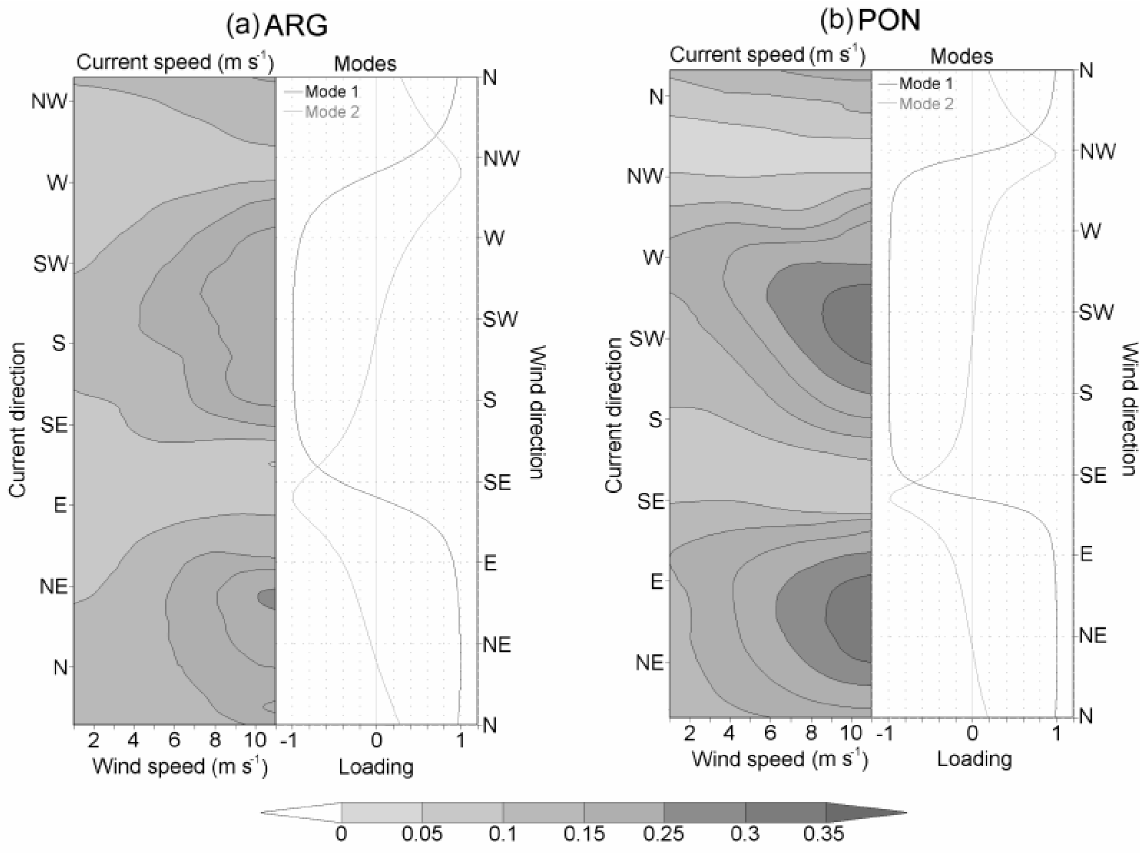

Figure 17: Barotropic current speed (m s^{-1}) as a function of wind speed (m s^{-1}) and current direction for the ADCP data collected at the locations indicated as ARG (a) and PON (b) in Figure 1, together with correlation between Modes 1 and 2 and wind direction (From Simionato *et al.*, 2006b).

The temporal scale of estuarine variability replicates the wind ones, with activity in bands around 2-8, 10-12 and 18-25 days. (Figure 18) Therefore, estuary reaches an equilibrium regime with most of atmospheric processes from synoptic to intra-seasonal scales. Intra-seasonal variability can be significant and even act in the same direction than the synoptic one. Therefore, intra-seasonal modulation can have significant effects on estuarine circulation.

Those features of estuarine barotropic response imply that its variability is characterized by the atmospheric one, from synoptic to intra-seasonal time scales presenting, consequently, ‘weather’ and ‘climate’ as the atmosphere does. In that sense, even though seasonal variability observed in salinity mean fields has been related to the mean winds occurring in summer and winter new results suggest that it is probably the result of the most frequent wind conditions along those seasons. It is likely that conditions up to the moment understood as characteristic of ‘summer’ or ‘winter’ take place during any season with high variability.

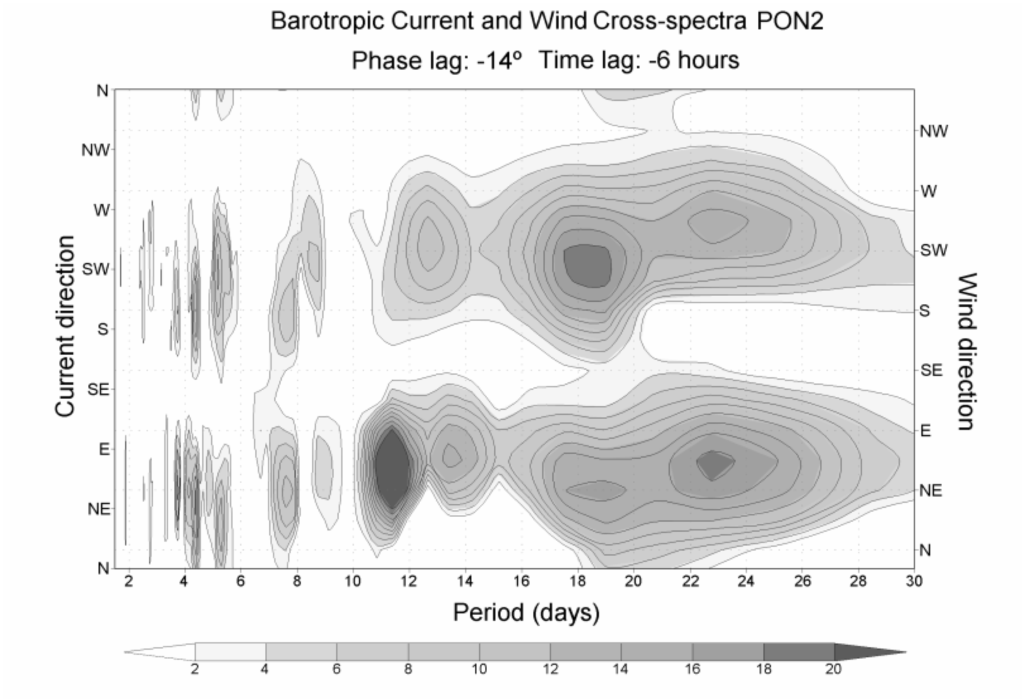

Figure 18: Cross-spectra between the wind and the current lagged -14º and -6 hours for PON2; only contours of spectral covariance for which coherence between variables was greater than 0.7 have been drawn (From Simionato *et al.*, 2006b).

5. INTERNAL WAVES

Simionato *et al.* (2005a) explored the long period, high vertical and temporal resolution ADCP velocity time series collected in the Río de la Plata estuary salinity front (Figure 1) for periods less than 30 hours. ARG series correspond to summer and autumn seasons whereas the PON to spring and summer. Series were analyzed for their barotropic and baroclinic components. Barotropic component shows characteristics for both, the tidal and mean currents, which are consistent with what is known about the circulation in the estuary.

The baroclinic component of the currents provides the first observational evidence of the occurrence of internal waves in the frontal zone of the Río de la Plata estuary. Results indicate that these baroclinic oscillations can account for as much as half of the total velocity variance in periods lower than 30 hours, with related speeds of around 0.5 m s^{-1} (Figure 19).

Differences in the wave's periods are observed from the northernmost to the southernmost location of observation (Figure 20). In the first case, essentially zonal oscillations with semidiurnal period and oscillations with a dominant meridional component and diurnal period are observed. Whereas the first one could be related to the dominant semidiurnal tide in the area, the second one seems to be atmospherically forced by land/sea breeze. In the southernmost location, oscillations of similar amplitude in the zonal and meridional currents were observed with periods around the inertial and diurnal ones. Some of the inertial oscillations detected could result of wind relaxation, whereas oscillations in the diurnal band seem to be, as in the other location, forced by the land/sea breeze.

Internal wave activity in the diurnal band is less frequent in the northernmost location than in the southernmost one. This fact can be attributed to less frequent favorable stratification conditions for internal wave generation in that area, at least during summer.

Observations indicate that internal wave activity in the southernmost location was weaker, the observed year, during fall than throughout the summer (Figure 21). This could be a typical feature given that during autumn both, the number of storms mixing the water column and destroying the thermohaline structure increases, and appropriate conditions for breeze are less frequent. The fact that these conditions are even more marked during winter suggests that internal wave activity in the 24 hours band probably presents a seasonal cycle in the area.

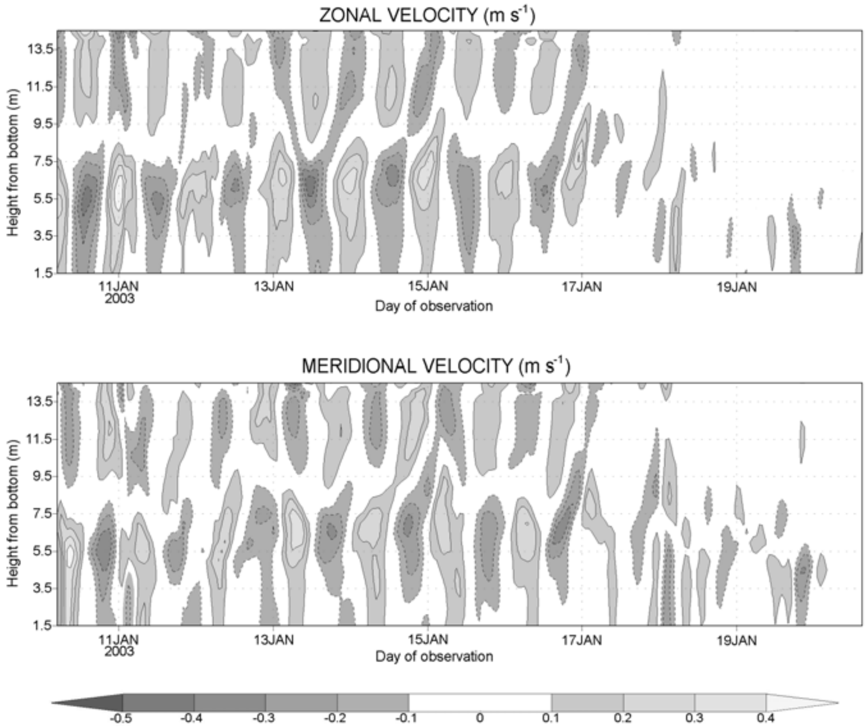

Figure 19: *z-t* Hovmöller diagrams for the zonal (upper panel) and meridional (lower panel) current component in ARG (Figure 1) between January, 30th and February 6th, 2003, showing evidence for the occurrence of internal waves. Contour interval is 0.1 m s^{-1} and only speeds larger that 0.1 m s^{-1} have been contoured (From Simionato *et al.*, 2005a).

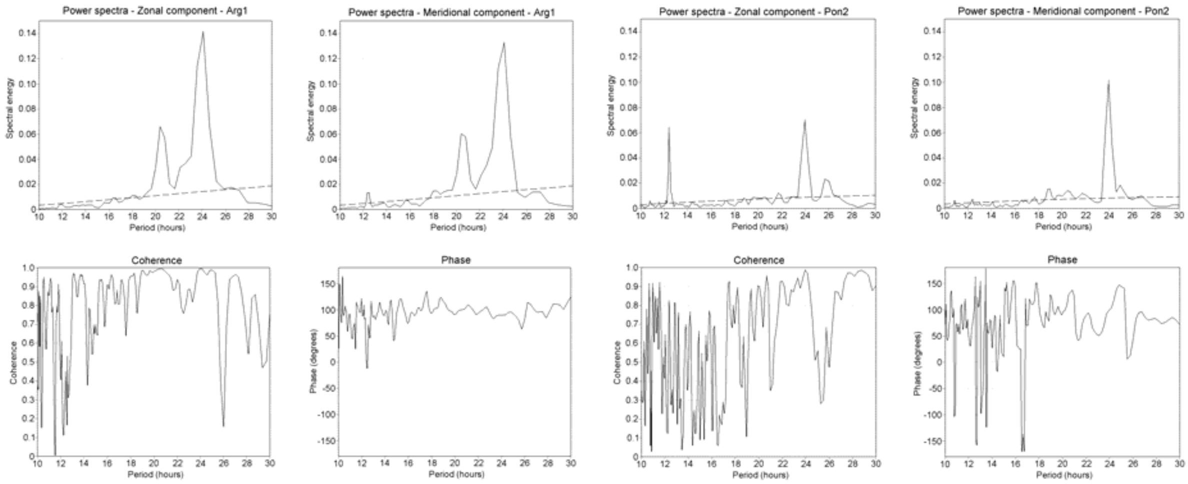

Figure 20: Upper panels: power spectra of the time series related to the modes 1 (associated to internal waves) resulting from the Principal Components analysis of the zonal (left) and meridional (right) current components in ARG and PON; dashed line indicates the 99% confidence level. Lower panels: coherence (left) and phase lag (right) derived from a cross-spectral analysis between u and v modes time series (From Simionato *et al.*, 2005a).

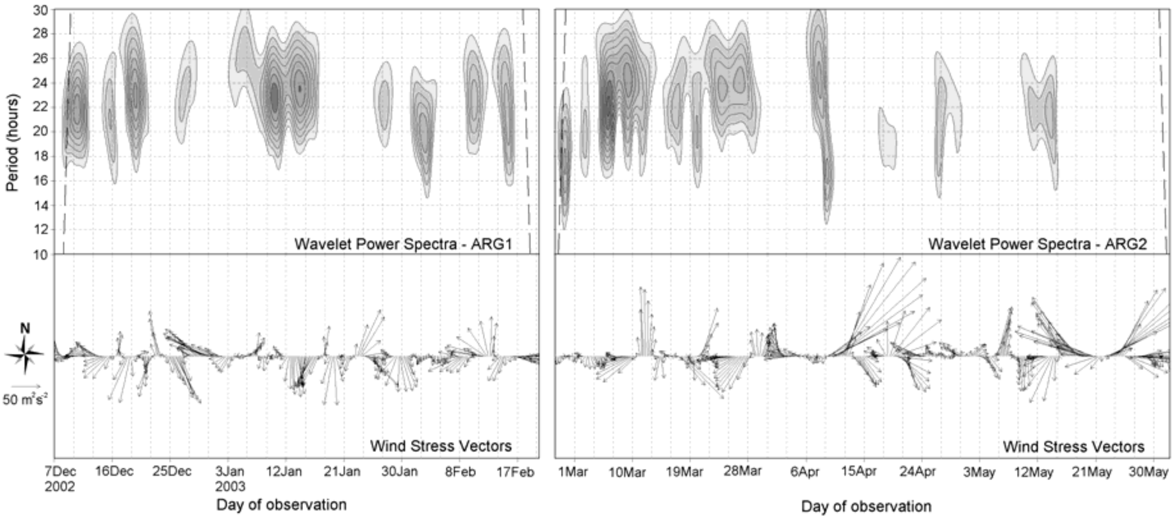

Figure 21: Upper panel: amplitude scaleograms of the zonal velocity component modes 1 (associated to internal waves) time series in ARG1 and ARG2. Only contours significant to a 99% confidence level have been plotted. Vertical lines at the beginning and ending of the plots define the cone of influence. Lower panel: wind stress vectors as derived from the NCEP/NCAR reanalyzes with a 6 hours temporal resolution (From Simionato *et al.*, 2005a).

6. SUMMARY AND FINAL REMARKS

The collection, by the first time, of long term ADCP current data and the application of numerical models contributed to a significant improvement in our understanding of the physical processes that occur at the Río de la Plata Estuary. As a result, our knowledge of the behavior of this system has essentially enhanced. In particular:

- More reliable cotidal and corange charts have been built, providing information about tidal features in areas where observations are not available.
- The first maps of tidal ellipses have become available for the region, so as the first study of tidal energy flux and dissipation.
- Seasonal to inter-annual wind variability has been studied and the connections of this variability to processes occurring in remote regions have been identified.
- It has been proved that the available atmospheric data bases allow for a proper representation of estuarine variability, what constitutes a powerful tool for studying climate variability.
- It has been demonstrated that processes in the remote Patagonian shelf impact estuarine circulation and sea level.
- Processes responsible for the observed seasonal variability in the estuarine circulation, affecting the salinity front, have been isolated and explained.
- The flow patterns of estuary and their connection to bathymetrical features and forcing have been understood, allowing also for a better dynamical classification of the different estuarine zones.
- Wind forced variability has not only been understood, but it was also found that it is much more important than was ever though.
- Intense internal wave activity was discovered to occur in the estuary salt wedge, accounting for almost %50 of the variance in the tidal frequency band.
- State of the arts 3-D baroclinic numerical models have been by the first time implemented and properly validated for the region.

As a result of this cooperative research, our view of the estuary and its dynamics has changed. Whereas only a few years ago the system was thought as a quite steady one, where most of the variability was related to the tide and at most characterized by a wind forced seasonal cycle, now we understand that it is a much more dynamic and complicated zone. Tides account for only one fourth of the variance in the salinity frontal zone, whereas the other 75% is wind forced. 25% of the total variance is related to internal waves, at least in spring/summer, and 50% to wind forced current in trans-tidal frequencies. The estuary responds to winds generating internal waves almost instantaneously, develops barotropic currents in a period of between 3 and 9 hours and reaches the equilibrium with winds for processes with time scales more than 4 days. Moreover, preliminary studies the baroclinic component of the current and its effects on the salt wedge structure indicate that those processes are also wind dominated. Those features of estuarine response imply that its variability replicates the atmospheric one presenting, consequently, ‘weather’ and ‘climate’ as the atmosphere does. These results also imply that important changes can occur in the estuarine circulation and density structure as a result of atmospheric variability, either natural or of anthropogenic origin, with potential impact on the people living in the hinterlands and the biota.

The fact that processes in the remote shelf impact estuarine circulation also changes our view of the needs for a proper representation of the Río de la Plata estuary. Any forecasting system in the future will require the consideration of a very large domain including the whole continental shelf, what substantially increases the computational cost.

The way in which tidal currents are measured in the region must be reviewed. Classically, tidal currents in the Río de la Plata have been observed using a single level instrument. If the area where current observations are collected is active in terms of internal waves, the so obtained results can be completely misleading. Therefore, simultaneous measurements of the density structure and the use of multilevel current meters are recommended.

Even though an important progress has been done in our knowledge of the estuarine dynamics and forcings many gaps must still be fulfilled to fully understand this complicated system and permit its adequate forecasting, management and control. In what follows, some of the most important issues that in our view should be faced in the next future will be discussed.

Firstly, it is clear that an open to the community operational forecasting system is necessary. Even though the lack of real-time salinity and temperature observations will seriously limit the development of a baroclinic forecasting model, we are at present in condition to build a barotropic one, what would allow for a good prediction of levels and currents in the upper estuary. This task is being faced currently as a cooperative work between the Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA) and the Servicio de Hidrografía Naval (SHN) in the context of the ANPCyT-PICT PROPLATA project.

The installation of an oceanic buoy is foreseen as a result of a cooperative project between FREPLATA and IFREMER (France). Atmospheric and oceanic data collected by such a buoy would be valuable for the study of both, atmospheric and oceanic processes in the region, constituting as well an important step towards the operational baroclinic forecasting. Nevertheless, the construction of such a forecasting system would require the collection of more *in-situ* real-time observations so as the assimilation of satellite data. In this sense, a better understanding of the processes at the front in every scale is also needed.

The study of wind waves is another important gap in the estuary. Even though wind waves are of central importance for sediment transport, coastal processes and construction, their study has been seriously limited by the lack of direct observations. A wave climate for the Río de la Plata is not available yet. At present the implementation of Simulating WAves Nearshore (SWAN) model is being started as a result of a cooperative research between CIMA and SHN in the context of the PROPLATA project with encouraging preliminary results.

A better study of the atmospheric forcing is also needed. The fact that estuarine processes are mainly wind driven implies that our understanding of the system will always be limited by our comprehension of the atmosphere. More studies of surface wind variability including land-sea breeze, synoptic and intra-seasonal variability so as climate variability and change are fundamental. In this sense, the collection of atmospheric observations in the estuary is crucial. Four meteorological stations will be placed in coastal locations of the estuary in the context of PROPLATA. Data are currently being collected at Pontón Recalada by the SHN. Nevertheless, the lack of data in the outer estuary is still a serious limitation. In this sense, the installation of the oceanic buoy would be extremely helpful.

Even progress towards the understanding of the impacts of the climate change on the estuary have been done in the context of the AIACC LA2G ‘Impacts of Global Change on coastal areas of the Río de la Plata’ project, more effort is still needed to fully asses this issue, so as to the knowledge and understanding of climate natural variability.

Finally, as many fish species spawn and nurse in the estuary, the understanding of the physical processes that favor and condition those animals is ecologically and economically important. Facing this issue requires interdisciplinary cooperative work among scientist from different institutions that should be encouraged. In this sense, efforts are being done between CIMA and Instituto Nacional de

Investigación y Desarrollo Pesquero (INIDEP) with very encouraging preliminary results.

Acknowledgments

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