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Rio de la Plata estuary response to wind variability in synoptic to intraseasonal scales:
2. Currents' vertical structure and its implications for the salt wedge structure

C. G. Simionato,[1,2] V. L. Meccia,[1] R. Guerrero,[3] W. C. Dragani,[2,4,5] and M. Nuñez[1,2]

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[1] The first acoustic Doppler current profiler current data collected at two locations of the Río de la Plata salt wedge during a period of around 6 months and salinity profiles gathered at and around those locations are used to study the vertical structure of currents' response to wind variability in synoptic to intraseasonal timescales and its implications for stratification. Results indicate that the estuary rapidly responds to prevailing southwesterlies/northeasterlies with currents that decay toward the bottom with only little rotation in depth. For the less frequent southeasterlies/northwesterlies the estuary develops a strong vertical structure with a defined inversion in current direction between surface and bottom layers. These patterns derive from the estuary's geometry and bathymetry. Results have important implications for the salinity vertical structure that are verified on the analyzed profiles. First, the combination of the bathymetry and coastline with the prevailing wind variability is highly favorable to the maintenance of a salt wedge structure in this estuary. Second, weakening and eventually breakdown of stratification can only occur for intense and/or persistent southeasterly winds, which even can be very strong, are not frequent. This can explain why the Río de la Plata displays the unusual feature of being an area of spawning and a nursery for a number of coastal species that use the wedge as an essential element for their reproduction. Results show that stratification is highly affected by short-term wind variability, which is its major characteristic in the area, changing the classical concept of summer-winter seasonality as the main feature of estuarine variability.

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1. Introduction

[2] The Río de la Plata (Figure 1), located on the eastern coast of southern South America at approximately 35°S, is one of the largest estuaries of the world [*Shiklomanov*, 1998]. It has a northwest to southeast oriented funnel shape approximately 300 km long that narrows from 220 km at its mouth to 40 km at its upper end [*Balay*, 1961]. The estuarine area is 35,000 km^2 and the fluvial drainage area is 3.1×10^6 km^2. The system drains the waters of the Paraná and Uruguay rivers, which constitute the second largest basin of South America. As a result, it has a large discharge with a mean of around 25,000 m^3 s^{-1}, and maximum values as high as 50,000 m^3 s^{-1} under extreme conditions [*Jaime et al.*, 2002]. Density in the estuary is controlled by salinity, whereas changes in temperature, even important from one to other season, only display small horizontal and vertical gradients [*Guerrero et al.*, 1997].

[3] Owing to the large discharge, when it meets the ocean, the Río de la Plata estuary (Figure 1) displays a strong and active salinity front followed by a fresh water plume whose influence can be tracked as far as 23°S [*Campos et al.*, 1999]. The characteristics of the salinity front have been described by *Guerrero et al.* [1997] and *Framiñan et al.* [1999] and its dynamics in the seasonal scale have been modeled by *Simionato et al.* [2001]. These papers show that the surface salinity front presents high variability in its position in seasonal and interannual timescales. Both data and numerical simulations suggest the wind as the main forcing for the estuarine dynamics [*Framiñan and Brown*, 1996; *Simionato et al.*,

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[1] Centro de Investigaciones del Mar y la Atmósfera, Ciudad Autónoma de Buenos Aires, Argentina.

[2] Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina.

[3] Instituto Nacional de Investigación y Desarrollo Pesquero and Universidad Nacional de Mar del Plata, Mar del Plata, Argentina.

[4] Servicio de Hidrografía Naval and Escuela de Ciencias del Mar, Ciudad Autónoma de Buenos Aires, Argentina.

[5] Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.

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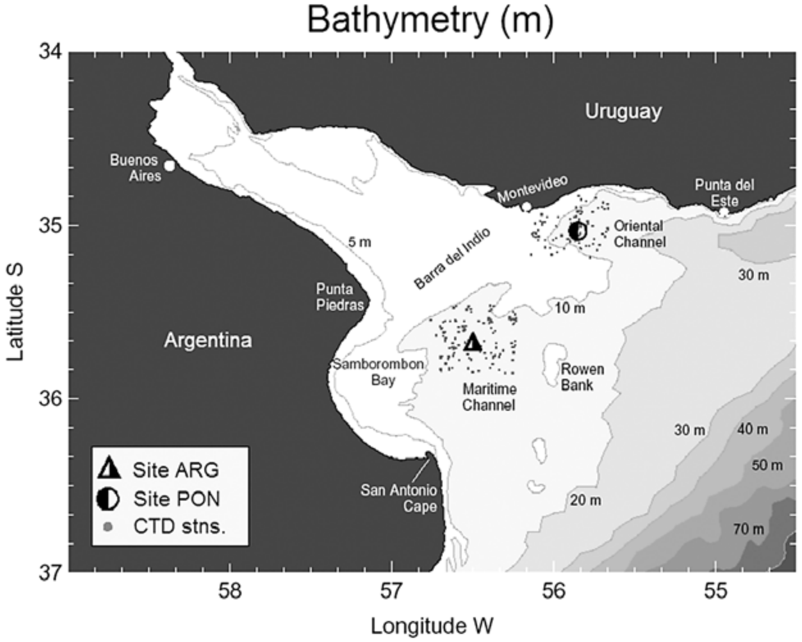

Figure 1. Bathymetry (in meters) of the study area together with the main geographical and topographical features. Locations where ADCP time series (ARG and PON) and salinity profiles were collected (small dots) are indicated. PON site also indicate Pilot station Pontón Recalada, located within a mile to the corresponding ADCP site.

2004]; given the large wind variability observed in the area [*Simionato et al.*, 2005a] large excursions can be expected to be experimented by the surface front in the synoptic timescale. The bottom salinity front, in contrast, shows a more stable position throughout the year. The shelf water intrusion to the estuary is controlled by the bathymetry; this way the bottom front remains located following a submersed shoal known as Barra del Indio (Figure 1) following, approximately, the 10 m isobath [*Guerrero et al.*, 1997]. As a result of the steadiness of the bottom front and the extension and displacement of the surface front, the estuary exhibits a time-variable salt wedge structure that is observed during most of the year. The main features of this salt wedge have been described from historical salinity and temperature observations by *Guerrero et al.* [1997] and *Framiñan et al.* [1999]. Those authors showed that both, the horizontal extension and vertical gradient of this salt wedge suffer a seasonal cycle related to the surface salinity front extension. This way, whereas the salt wedge is a semipermanent feature of the central and southern portions of the estuary, the structure can, in average, be lost during summer along the northern portion as a result of the south-westward extension of the surface salinity front.

[4] This baroclinic structure has important implications for the occurrence of internal waves [*Simionato et al.*, 2005b], modifies the coastal circulation and the mixing and convection conditions [*Piola et al.*, 2000] and is also of central importance for the coastal species that spawn and nurse in the region. In the Río de la Plata estuary, fish species as *Brevoortia aurea* and *Micropogonias furnieri* spawn pelagic eggs [*Weiss*, 1981], taking advantage of the retention properties at the head of the salt wedge [*Simionato et al.*, 2006a]. Even though those retention properties are not a unique feature of this region, spawning of pelagic eggs in estuarine systems is an uncommon event [*Acha and Macchi*, 2000]. Simultaneous biological sampling and oceanographic data show that the spawning area covers a narrow band across the estuary between Montevideo and Punta Piedras characterized by a strong halocline [*Acha et al.*, 1999]. Moreover *Neomysis americana* spawns over the area of steepest salinity gradients [*Schiariti et al.*, 2006]. Therefore the salt wedge and its structure are relevant features for the life cycle of key commercial species of the Argentinean Shelf. Nevertheless, shallowness makes this region highly sensitive to wind stress, so that disruptive wind events are known to partially to totally destroy salinity stratification [*Guerrero et al.*, 1997], exposing fish larvae and eggs to abrupt changes in salinity. A similar process has been observed in other estuaries, as, for instance, Narragansett Bay, Chesapeake Bay, Mobile Bay, York River Estuary and Escambia Bay, and is often referred to as wind induced destratification [*Weisberg*, 1976; *Blumberg and Goodrich*, 1990; *Schroeder et al.*, 1990; *Bhopal et al.*, 1998; *Scully et al.*, 2005; *Ahsan et al.*, 2005]. Those papers show that wind-induced stratification/destratification usually occurs in estuaries as a result of their response to winds blowing along the estuary axis: upstream blowing winds tend to destroy stratification whereas downstream winds tend to enhance it. Nevertheless, it is unclear that the Río de la Plata Estuary will display an identical response, given that its huge breadth in the region of the salt wedge (of more than 200 km and approximately 1 order of magnitude larger than the corresponding to the previously cited estuaries) allows for the occurrence of strong transversal currents.

[5] Even though because of the above mentioned reasons the understanding of baroclinic processes in the frontal zone of the Río de la Plata estuary is of great importance, their study has been limited by the lack of time series of direct observations. Recently, in the frame of the UNDP/GEF

Project ‘Environmental Protection of the Río de la Plata and its Maritime Front’ (FREPLATA), six month length acoustic Doppler current profiler (ADCP) current series with high vertical and temporal resolution were collected at two locations of the estuary frontal zone: the Maritime Channel, proximate to Argentinean coast, and Pontón Recalada, close to Montevideo, on the Uruguayan coast (Figure 1). Those data provide the first opportunity of exploring estuarine circulation and its variability during several months. In the first part of this contribution *Simionato et al.* [2006b] analyzed the depth averaged component of those ADCP data, accounting for approximately 50% of the total variance, and its relation to wind variability in synoptic to intraseasonal timescales. The aim of this paper is to contribute to the understanding of the vertically varying response, its relation to wind variability and the implications for the estuary’s stratification. Therefore the modifications to the vertically averaged response described by *Simionato et al.* [2006b] related to the haline structure and bathymetry are evaluated. The implications of currents response to winds on the salinity vertical structure are studied by complementing current data results with the analysis of salinity profiles collected at proximate locations. Finally, results are discussed in terms of the observed wind variability in the region.

2. Data

[6] In the frame of the UNDP/GEF FREPLATA Project, current vertical profiles were measured at two locations in the Río de la Plata estuary. Initially, the project involved the simultaneous collection of data in the Maritime (Argentinean side) and Oriental (Uruguayan side) channels through the use of two RDI Acoustic Doppler Current Profilers (ADCP) of 1200 and 600 MHz, respectively. Each ADCP was located in a stainless steel mooring, which was linked to a weight of 5 ton by means of steeling cable. The weight was marked by a surface buoy. The ensemble interval was set to 10 min, with 150 pings per ensemble, and the vertical resolution to 0.5 m. The compass was calibrated before the deployment. After almost three months, during the first retrieving data task in the Uruguayan side, it was detected that the cable had been cut and, consequently, the 600 MHz ADCP had been lost. The ADCP on Argentinean side, moored at 35°40′S, 56°30′W at a depth of 17 m, is referred to as ARG in Figure 1. This instrument was recovered, data were retrieved and the instrument was deployed again, completing a total sampling period of more than 6 months. This way, two series (ARG1 and ARG2) were obtained at that location spanning the periods 4 December 2002 to 21 February 2003 and 21 February to 5 June 2003, respectively, with 31 levels each. Afterward, this instrument was moored again in September 2003 on the Uruguayan side within a mile to Pontón Recalada, at 35°02′S, 55°51′W, and pointed out as PON in Figure 1. The depth in this location is 14 m. Two series (PON1 and PON2) with a total of 24 levels each were obtained, spanning the periods 3 September to 13 November 2003 and 14 November 2003 to 26 March 2004, respectively.

[7] A careful quality control of every time series was done. A few gaps, due to larger than normal reductions in the water level, were observed in the first two levels. Immediately after and before those gaps, spurious values (differences in consecutive values larger than two standard deviations) of the speed usually appeared, which were eliminated from the records. As a result, a small number of data (less than 1%) were filled by lineal interpolation between adjacent accepted data in the first two layers.

[8] To exclusively analyze low-frequency variability, current data were filtered using a low-pass filter with a cutoff period of 30 hours. This way, high-frequency variability due to tides and internal waves [*Simionato et al.*, 2005b] was eliminated from the records. As a result, a small portion of data, equivalent to 3.15 days was lost at the beginning and ending of the records. As an example, current data for ARG2 period are shown in Figure 2 in the form of a stick diagram. For reasons of clarity only data every one meter of depth and one hour have been plotted. The first feature that emerges from Figure 2 is the high variability of the currents and their vertical structure in the scale of a few days. It can be seen in Figure 2 also that, even though in occasions there is a clear decay of currents speed with depth (as for instance around 10 April), in other cases currents at the upper and lower layers have similar speeds (as, for example around 10 March). Moreover, current direction is not always preserved along the water column, but rotation and even inversion in current direction can be observed (as for instance around 5 May). Similar features can be seen in the other time series (not shown).

[9] Temporal mean profiles and their standard deviations were calculated for the four periods observed. It was found that temporal means are very close to zero with standard deviations that exceed them by between five and ten times. This way, means are not significantly different from zero. It was also observed that mean profiles are very different from one to other observed period at the same location, suggesting that the Río de la Plata estuary is mainly wind driven.

[10] Some portable rotating-cup anemometer observations were collected at the Pilot Station Pontón Recalada station (at PON site) simultaneously with the ADCP data studied in this paper. Unfortunately, as these observations were gathered by an observer, they carry errors, they do not have constant sampling interval and there are a number of gaps with no observations at all that seriously limit the use of these data. Therefore a comparison of those observations with other three data sets was done, in order to identify a suitable source of alternative atmospheric data. Some portable rotating-cup anemometer observations are available for the observed period at Carrasco (Montevideo Airport). The second data set are 2-daily scatterometer data collected by the SeaWinds instrument on the QuikSCAT satellite (http://podaac.jpl.nasa.gov/quikscat). Finally, four daily fields of wind components at 10 m from National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses (http://www.cdc.noaa.gov) at 35.24°S–54.37°W, which is the wet point closest to the observed area, were considered. When comparing, the different characteristics of the diverse data sets must be taken into account. Pontón Recalada observations are direct and at PON site; therefore, even though they probably are not very accurate, they must be considered the best data when available. Carrasco data are also direct observations and were collected at approximately 20 nautical miles from PON; nevertheless, besides their accuracy, they have the limitation of presenting some gaps and having been gathered on land and not at the sea. Scatterometer data are instantaneous

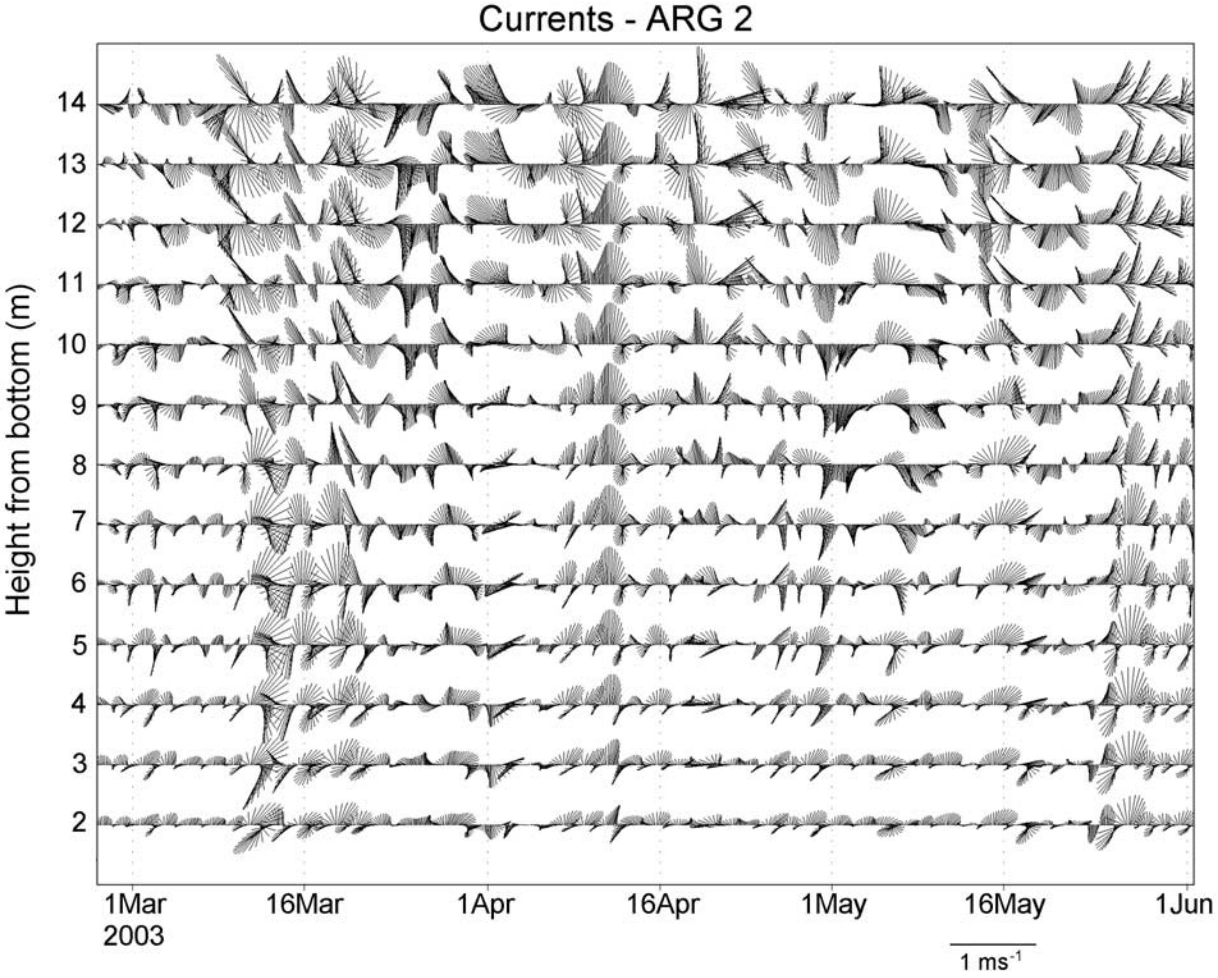

Figure 2. Stick diagram of the currents as a function of time and depth of observation for ARG2 period. Note that for reasons of clarity, only data every 1 m and 1 hour have been plotted.

observations of the backscatter of the ocean which are converted to wind speed and direction through mathematical algorithms [*Naderi et al.*, 1991; *Wu et al.*, 1994]; usually it is not considered convenient to use these data when they are very proximate to the coast. The error of the observations is of 2 m s^{-1} in speed and 20° in direction; the spatial resolution is very high, of 25 km. The sampling period is 24 hours in two passes, the ascending pass (6AM LST equator crossing) and descending pass (6PM LST equator crossing). NCEP/NCAR reanalyses are not direct observations but the result of an objective analysis combining rawinsonde observations around the world, remote observations collected via satellite born instruments and a physical numerical model [*Kalnay et al.*, 1996]. The result of this analysis is a set of gridded data with a spatial resolution of 2.5° (approximately 250 km) and a temporal resolution of 6 hours. The main advantages of these reanalyses are their physical consistency and relatively high temporal resolution. Discussions about their quality over the Southern Hemisphere are given by *Simmonds and Keay* [2000], among others, and an indirect evaluation of their performance over the Río de la Plata area is presented by *Simionato et al.* [2006c].

[11] Figure 3 shows the wind vectors derived from those four sources for January 2003. Beyond the differences in the sampling intervals, two characteristics emerge from Figure 3. First, it is clear that Carrasco, QuikSCAT and NCEP/NCAR data tend to underestimate the wind speed. Even though this can be expected from the NCEP/NCAR reanalyses, which represent the mean condition in a 2.5° × 2.5° box along 6 hours, and from Carrasco data, because they have been collected on land and not at sea, it is not clear to us why QuikSCAT data present the same feature. On the other hand, there is a good general consistency in the wind direction between the different series; NCEP/NCAR data, particularly, seems to better capture the main features of the observations at sea of Pontón Recalada than the other series. Other periods, when the number of atmospheric data collected in Pontón Recalada allowed for a comparison, were explored with similar results. In order to provide an objective criterion, the correlation between Pontón Recalada winds and the other series was computed when data were available over the period 2002–2004. Results are shown in Table 1 and confirm the observation that NCEP/NCAR data are the most representative, with a correlation of 0.73 (0.68) for the zonal (meridional) wind component, whereas Carrasco and QuickSCAT gave correlations of 0.60 (0.46) and 0.55 (0.55), respectively. Therefore NCEP/NCAR data set will be adopted in the present study. Wind data, available

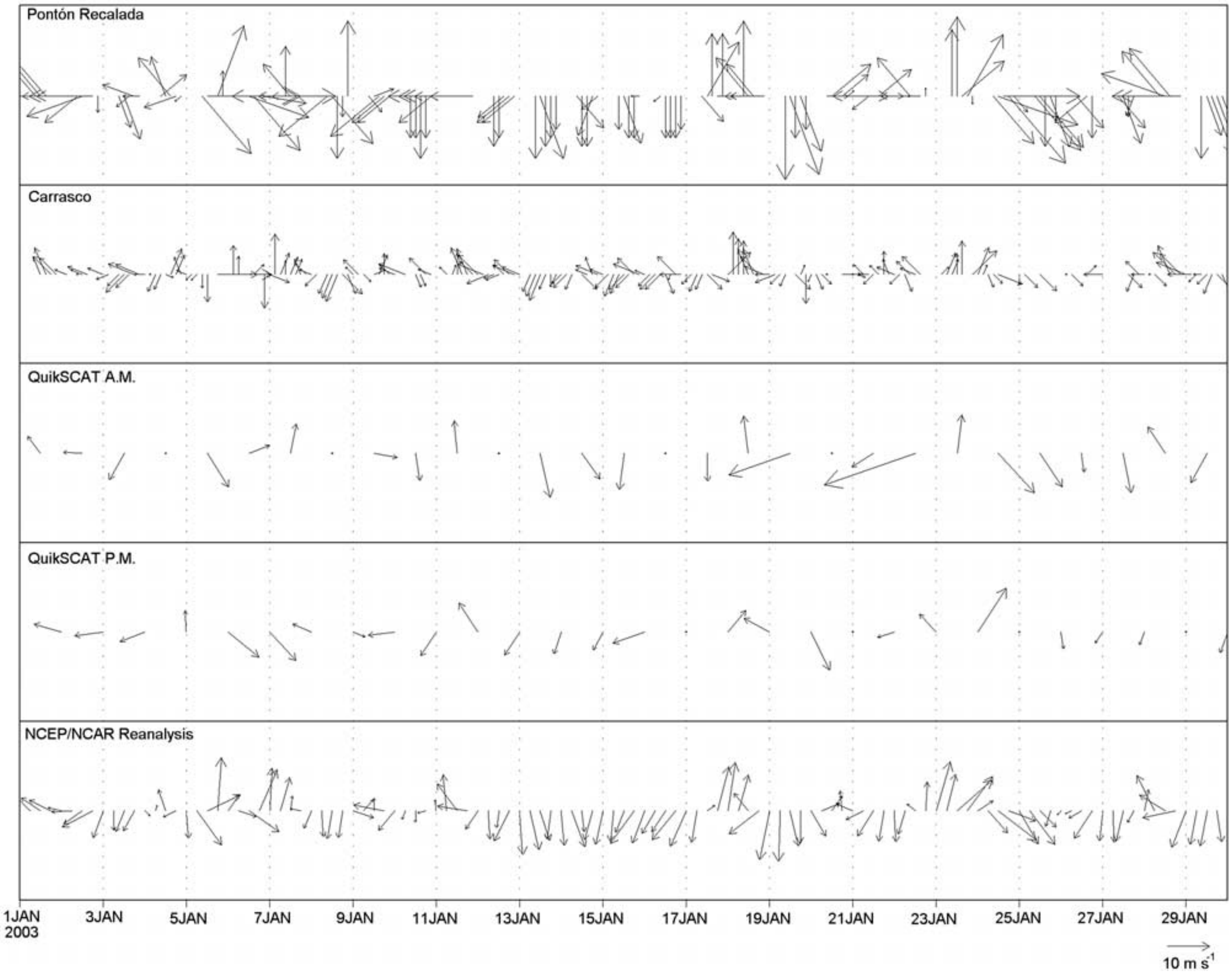

Figure 3. Wind vectors for January 2003 coming from portable rotating-cup anemometer observations collected in Pontón Recalada and Carrasco (Montevideo Airport), the nearest QuikSCAT scatterometer observation and the nearest point of the National Centers for Environmental Prediction/NCAR reanalyses.

at 0:00, 6:00, 12:00 and 18:00 GMT were linearly interpolated to the ADCP sampling period.

[12] Salinity data at and around ARG and PON sites come from conductivity-temperature depth stations collected during the last 12 years by the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) of Argentina in the frame of fisheries studies. Data corresponding to El Niño 1998 and La Niña 1999–2000 periods were excluded from the analysis as they correspond to extremely high- and low-runoff conditions, respectively. The locations of the stations used to build the composites discussed in this paper are shown as dots in Figure 1.

3. Results

3.1. ADCP Data Analysis

[13] In the first part of this contribution, *Simionato et al.* [2006b] found that wind direction has an effect on both, the direction and speed of the vertically averaged current. Wind-driven vertically averaged currents can be explained in terms of two modes, resulting of the estuary's geometry. The first one prevails for winds with a cross-river component whereas the second dominates when they blow along the estuary axis. Even though both modes give rise to vertically averaged currents which develop in a phase lag with the wind that depends on the location as a result of topographic rectification, northeasterly and southwesterly winds generate larger speeds than southeasterlies and north-

Table 1. Correlation Between 10-m Zonal (u) and Meridional (v) Wind Components Gathered at Pontón Recalada and Wind Data Collected at Carrasco (Montevideo Airport), Scatterometer (QuikSCAT) Data, and the National Centers for Environmental Prediction/NCAR Reanalyses

	Correlation Between Wind at Pontón Recalada and Other Data Sets		
	National Centers for Environmental Prediction/NCAR	Carrasco	QuikSCAT
u	0.73	0.60	0.55
v	0.68	0.46	0.55

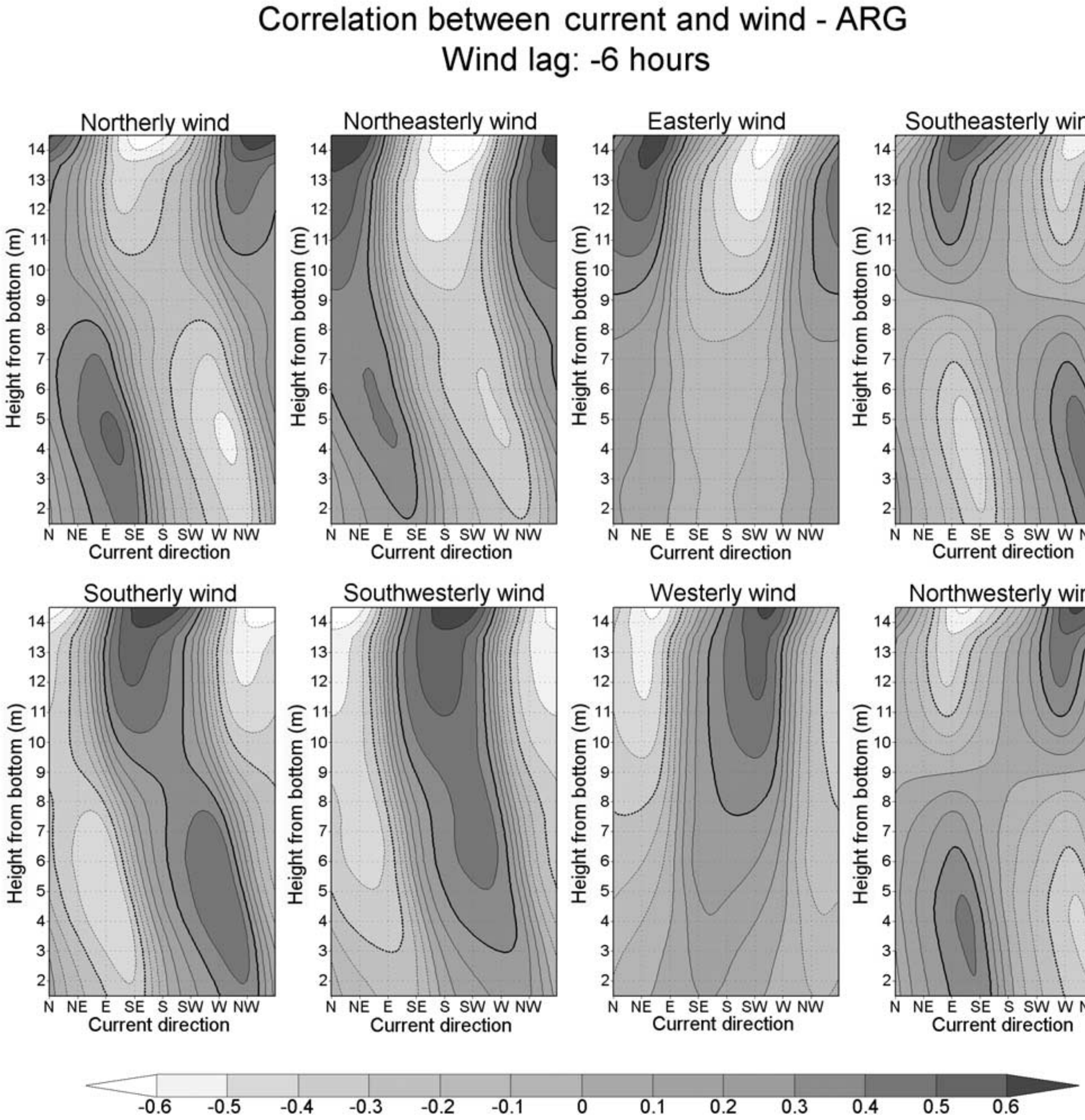

Figure 4. Isolines of correlation between currents and winds, occurring 6 hours in advance as a function of current direction and depth for north, northeast, east, southeast, south, southwest, west, and northwest wind directions for ARG. The 99% confidence level is shown as a thick line.

westerlies. This last fact suggests a connection between the blowing wind direction and the vertical current structure. To explore this matter, the statistical methodology applied by *Simionato et al.* [2006b] was extended to the total current collected at each level in ARG and PON. This way, instantaneous National Centers for Environmental Prediction/NCAR 10-m wind at the nearest wet point (35.24°S–54.37°W) and current observations were projected over 360 directions, one degree apart. Therefore 360 current time series were obtained for every level, location and observation period, and 360 wind time series were obtained for each location and observation period. Then the correlation between winds and currents projected over each of those directions was computed. Owing to the presence of noise and wind waves near surface, the two uppermost meters were eliminated and the analysis was applied to 27 and 20 levels at ARG and PON, respectively. The calculation was repeated for different time lags between currents and winds that are a multiple of the wind sampling period (6 hours) that is, 6, 12, 18 hours, etc. In all the cases it was found that correlation maximizes when currents are correlated with winds occurred 6 hours in advance, as it was found by *Simionato et al.* [2006b] for the vertically averaged signal. This indicates that the estuary response time to wind-forcing is of between 3 and 9 hours not only for the depth average current but for the total signal as well. This suggests that, probably as a result of the estuary shallowness, baroclinic

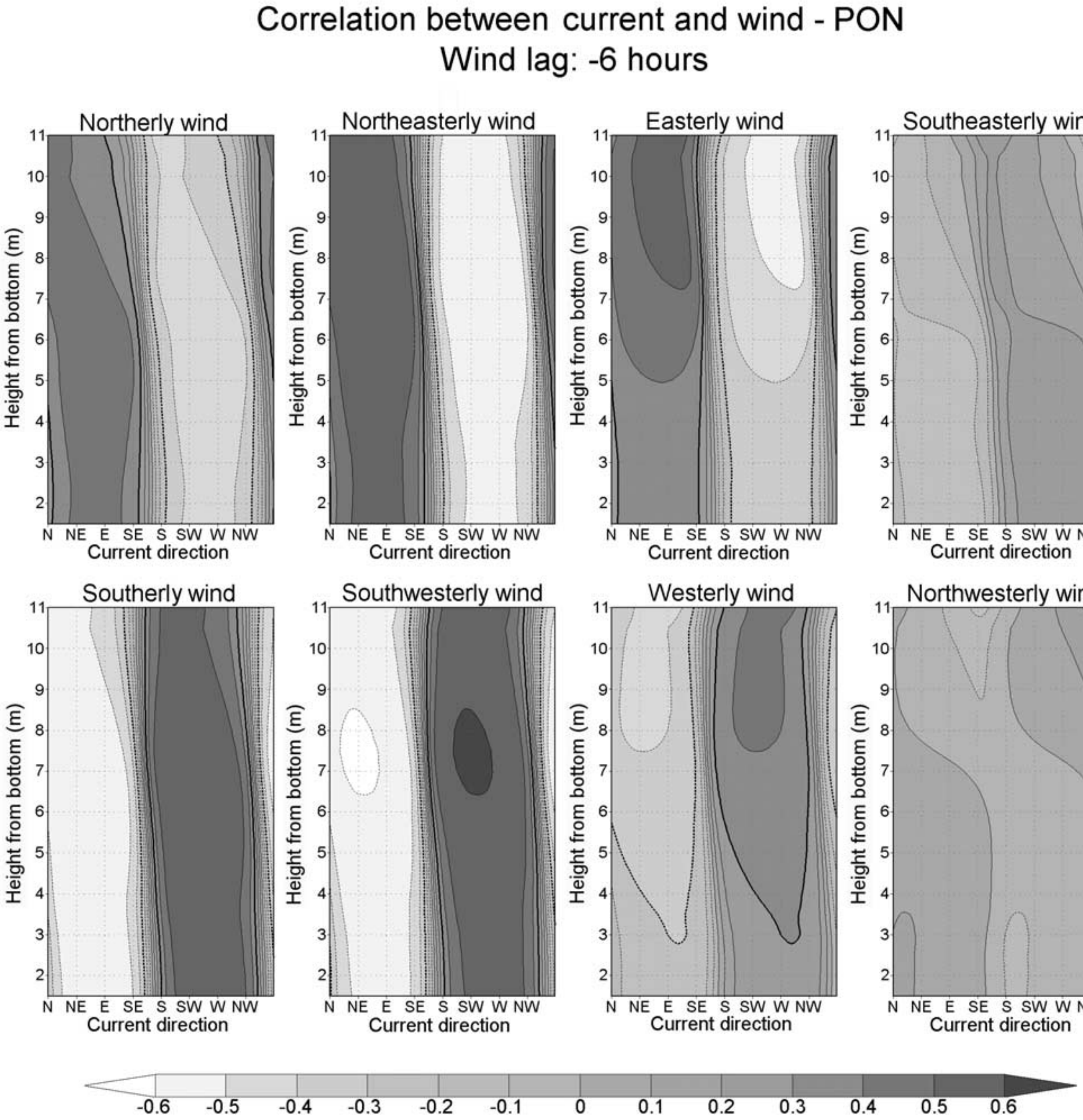

Figure 5. Isolines of correlation between currents and winds, occurring 6 hours in advance as a function of current direction and depth for north, northeast, east, southeast, south, southwest, and west wind directions for PON. The 99% confidence level is shown as a thick line.

structure does not essentially modify the estuary response time to wind changes. The correlation patterns obtained for both observation periods at each location were almost identical; therefore results will be shown for the ensemble of ARG1-ARG2 and PON1-PON2 data.

[14] Isolines of correlation between currents and winds lagged 6 hours as a function of current direction and depth, for north, northeast, east, southeast, south, southwest, west and northwest wind directions are shown in Figures 4 and 5 for ARG and PON, respectively. In Figures 4 and 5, horizontal axes represent current direction and vertical axes, height from bottom. Correlations more than 0.30, shown in Figures 4 and 5 as a thick line, are significant at the 99% confidence level. Two main features emerge from Figures 4 and 5. First, the high correlation between winds and currents at every level at each site is an indication that currents over the entire water column respond to wind changes in both locations. Second, currents vertical structure is highly dependent on wind direction.

[15] To appreciate those characteristics directly from the observations, mean current profiles for winds blowing from 45° wide sectors centered at north, northeast, east, southeast, south, southwest, west and northwest were calculated from data at each site. The resulting composites for winds speeds of between 8 and 10 m s^{-1} are shown in Figures 6 and 7 for ARG and PON, respectively. Composites were constructed

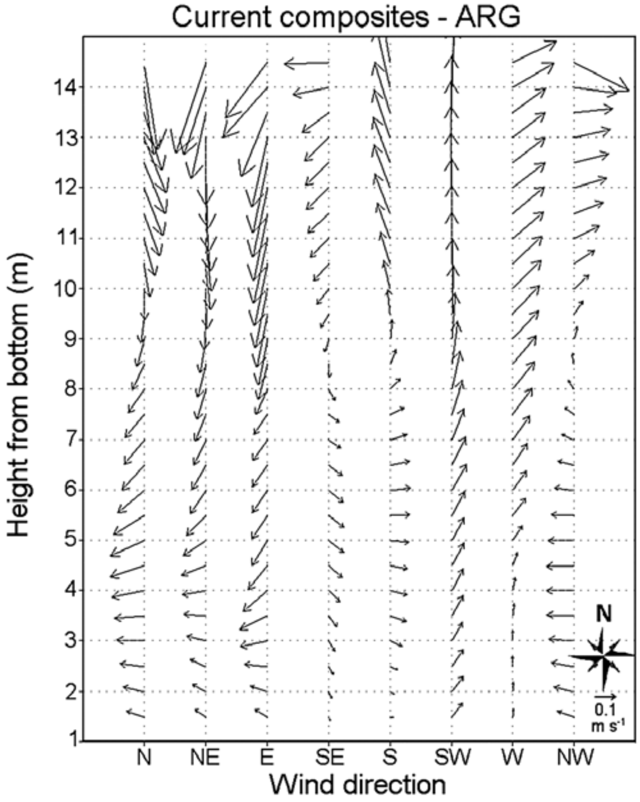

Figure 6. Composites of current profiles for north, northeast, east, southeast, south, southwest, and west wind directions for winds with speeds of between 8 and 10 m s^{-1} for ARG.

for different wind speed ranges, but results showed that even though current speed increases as the wind one does, the vertical current structure is always preserved. It can be observed in Figures 6 and 7 that, in general, maximum currents occur near surface and decay toward the bottom. Nevertheless, even though vertical structure is merely manifested as a weakening of currents with depth for some wind directions, for others an inversion of current direction between surface and bottom layers is observed. That inversion becomes more evident as wind direction acquires a dominant component parallel to the estuary axis, reaching the maximum vertical structure for southeasterly and northwesterly winds. Even though this feature is clearly observable in ARG (Figure 6), it is weaker in PON (Figure 7).

[16] To simplify the interpretation of the former results a Principal Components (EOF) analysis was applied to the composites of current profiles of Figures 6 and 7 in order to extract patterns of vertical structure for different wind directions. Results are shown in Figures 8 and 9 for ARG and PON, respectively, where the left panels show the modes (factor scores) and the right panels show the correlation between each mode and the blowing wind direction (factor loadings). EOF analysis reveals that estuary response to changes in wind direction can be explained, in both cases, in terms of two modes (left plots of Figures 8 and 9). These modes have a structure of correlation to wind direction (right plots of Figures 8 and 9) which is almost identical to that found for the vertically averaged currents from these data [*Simionato et al.*, 2006b] and numerical simulations [*Simionato et al.*, 2004]. The first mode, accounting for 55% (54%) of the variance in ARG (PON), is related in both locations, in its positive (negative) phase to southerly southwesterly (northerly northeasterly) winds. This mode produces currents with a vertical structure which has maximum values at upper layers and decay toward the bottom with a slight rotation in lower layers probably due to bottom friction. In effect, the rotation direction is anticyclonic (counterclockwise in the Southern Hemisphere) from the bottom, what is consistent with the bottom Ekman spiral. Mode 1 is associated to northward-northwestward (southward-southeastward) currents in ARG and northeastward-eastward (southwestward-westward) currents in PON in its positive (negative) phase over almost the entire water column. Second mode, accounting for 38% (25%) of the variance in ARG (PON) is associated, in both locations, in its positive (negative) phase, to northwesterly (southeasterly) winds. This mode produces a defined vertical structure with an inversion between surface and bottom currents. It is associated, in its positive (negative) phase, to eastward (westward) currents in ARG and southeastward (northwestward) currents in PON in upper layers and opposite currents in lower layers. The vertical structure related to this mode results stronger in ARG, where surface and bottom current speeds are similar, than in PON. This difference is probably a consequence of the difference in the mean stratification observed in both locations. Whereas ARG is located in a

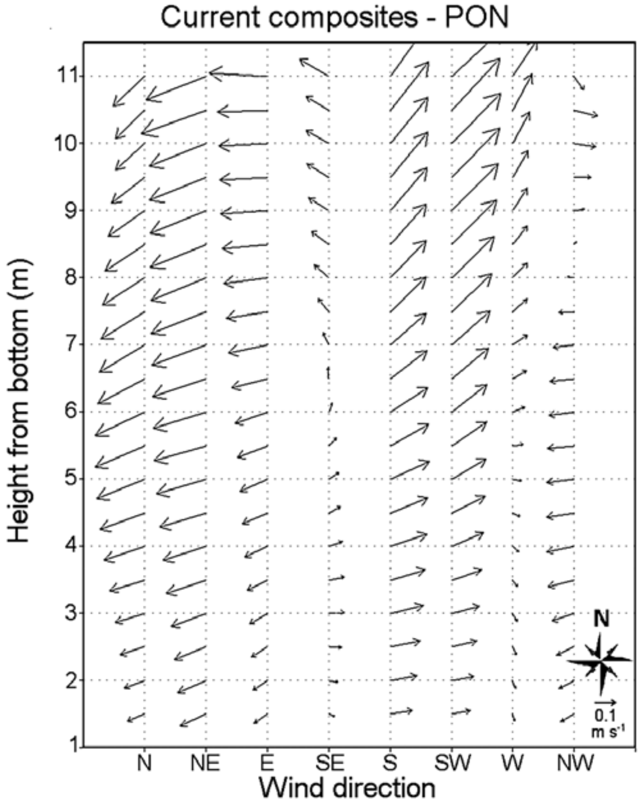

Figure 7. Composites of current profiles for north, northeast, east, southeast, south, southwest, west wind directions for winds with speeds of between 8 and 10 m s^{-1} for PON.

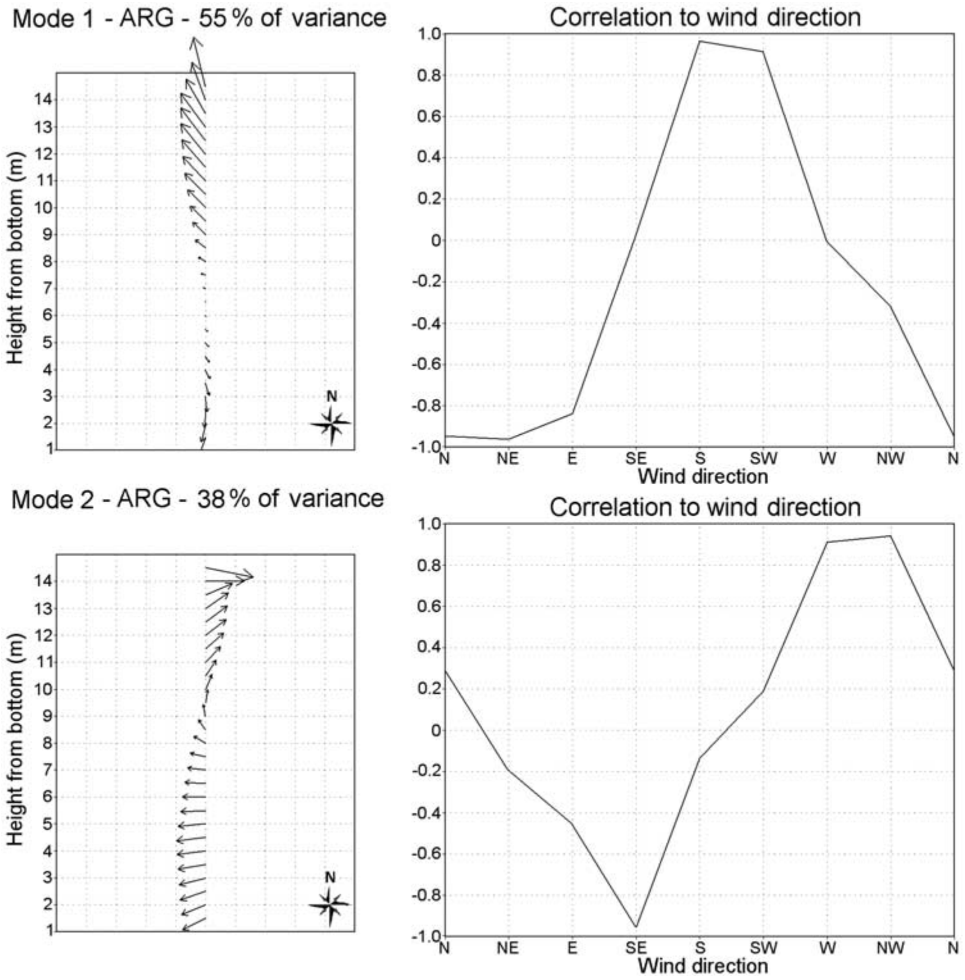

Figure 8. Principal components analysis results for the current composites profile of ARG. (left) Modes and (right) correlation of the corresponding mode to wind direction.

region where stratification is strong during most of the year, PON is situated in an area where it is usually weaker [*Guerrero et al.*, 1997] (see Figure 10).

[17] Our results indicate, therefore, that the Río de la Plata estuary responds with vertically decaying currents for winds with a dominant component perpendicular to the estuary axis and with currents that reverse their direction from surface to bottom for winds with a prevailing direction parallel to the estuary axis. Those structures seem to be connected to estuary's geometry and bathymetry. For winds with a dominant component perpendicular to the estuary axis, wind forced transport in the salinity frontal zone tends to follow bathymetric features, producing a net northeastward or southwestward transport along the Barra del Indio shoal and coast lines [*Simionato et al.*, 2004, 2006a, 2006b]. Therefore the flow is not inhibited by bathymetric obstacles. For southeasterly (northwesterly) winds, surface waters are pushed upstream (downstream) toward (from) the upper part of the estuary [*Simionato et al.*, 2004]. This mass transport must be compensated by a net outflow (inflow) of bottom waters downstream (upstream) the estuary, what gives rise to the observed inversion in currents. Also note that the minimum response in the vertically averaged currents found by *Simionato et al.* [2006b] for southeasterly northwesterly winds can be explained, according to Figures 8 and 9, in terms of the maximum vertical structure in the wind forced currents. For these wind directions, the estuary develops opposite currents in upper and lower layers, giving rise to weak mean vertical currents.

3.2. Implications for the Salt Wedge Structure

[18] The above discussed results for currents have obvious implications for the vertical density structure, as stated in the introduction, controlled by salinity, related to the salt wedge. Whereas winds perpendicular to the estuary axis produce currents that decay toward the bottom, therefore tending to extend the surface fresh water plume with only a small change in bottom conditions, winds parallel to the estuary axis generate an inversion in currents, tending to modify vertical shear, and therefore vertical mixing, with a direct effect on stratification either enhancing or weakening it.

[19] To verify those conclusions, composites of vertical salinity profiles at and around ARG and PON for winds blowing from different directions were constructed. For that, National Centers for Environmental Prediction/NCAR 10-m wind data at the nearest wet point (lagged 6 hours in advance respect to salinity data) were assigned to the set of observations available in a box with a side of approximately

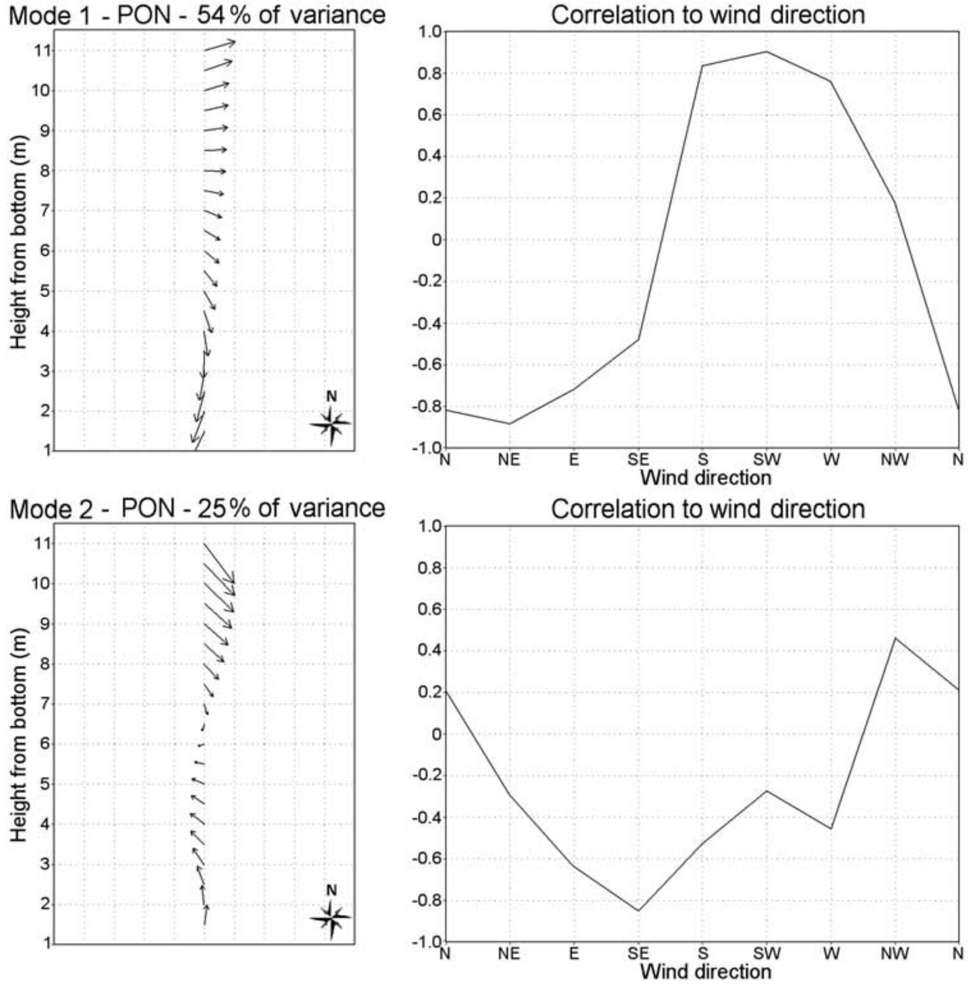

Figure 9. Principal components analysis results for the current composites profile of PON. (left) Modes and (right) correlation of the corresponding mode to wind direction.

36 km (20 miles) around ARG and PON (Figure 1), and profiles were averaged for the different wind sectors. Given that salinity observations are relatively scarce, data could not be separated by wind speed. Nevertheless, cases when wind speed was weaker than 2 m s^{-1} were considered as calm conditions and, therefore, not included in the average.

[20] Results for 45° wide sectors centered at northeast, southeast, southwest and northwest wind directions are shown in Figure 10 for ARG (Figure 10, top) and PON (Figure 10, bottom). It can be observed in Figure 10 that for northeasterly winds, a strong salt wedge structure develops in ARG whereas a weaker vertical structure occurs in PON. Those features can be explained in terms of our previous results for currents. Northeasterly winds produce southeastward (southwestward) currents that decay toward the bottom in ARG (PON). This implies penetration of fresh (salty) waters in upper layers in ARG (PON) and little displacement of water at bottom in both locations. Consequently, a strong vertical salinity structure develops in ARG whereas the opposite results in PON. Inverse results would occur for southwesterly winds; that is, a penetration of relatively salty water in ARG and fresh water in PON in upper layers with small displacements in bottom waters. The result is a weaker (stronger) salt wedge structure in ARG (PON) as it is observed in Figure 10. The estuary response for northwesterly and southeasterly winds is highly dependent on depth with an inversion in current direction between surface and bottom layers in both locations. Northwesterly winds generate eastward (southeastward) currents in upper layers in ARG (PON) and from the opposite directions in lower layers. This produces penetration of fresh water near surface and salty water near bottom and, consequently, an intensification of the salt wedge structure in both locations. Finally, southeasterly winds produce the reciprocal currents in upper and lower layers and, consequently, a weakening of the salt wedge structure in both locations. This way, southeasterly winds are the only which can act weakening the stratification. Those last features can be observed in the salinity composites showed in Figure 10.

[21] Even though the available observations do not allow for an estimation of the timescale of the salinity field response to winds, the fact that changes can be observed in the composites, built with data collected for different wind speeds and persistence and in presence of a very large synoptic atmospheric variability, suggests that that scale is very short, probably of only a few hours. It must be taken into account that the use of composites could smear out existing time lags, in particular if they are not constant but

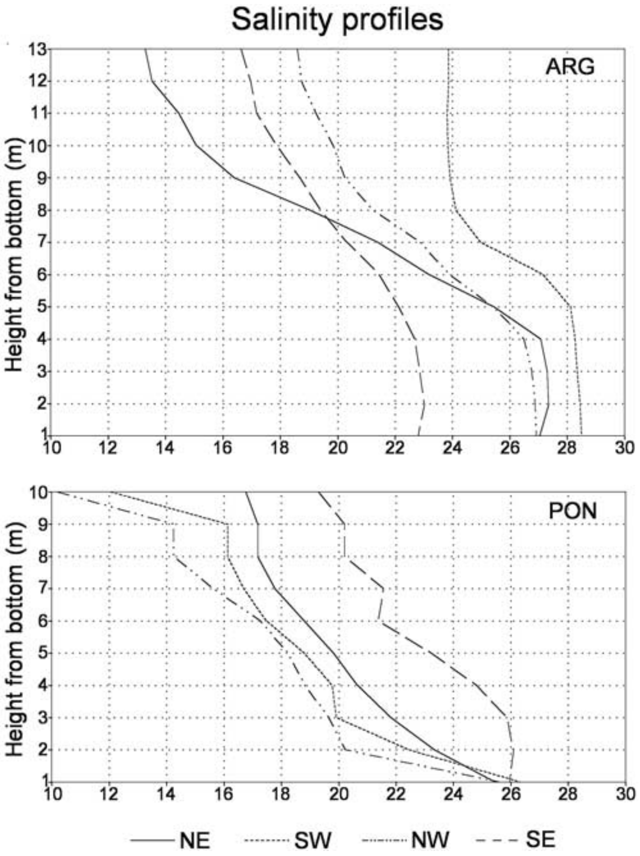

Figure 10. Composites of vertical salinity profiles in the vicinity of (top) ARG and (bottom) PON for winds blowing from the northeast, southeast, southwest, and northwest directions.

depend on other parameters like wind speed or direction. Unfortunately the number of profiles is not large enough to allow for a proper study of the salinity field response as a function of both, wind direction and speed. Nevertheless, a visual evaluation of the available profiles shows no indication that thresholds occur for any wind directions, and a response is observed for every wind speed which, in turn, seems to be larger as wind speed increases.

4. Discussion in Terms of the Observed Wind Variability in Synoptic to Intraseasonal Timescales

[22] The atmospheric general circulation in the Río de la Plata region is controlled by the influence of the quasipermanent South Atlantic high-pressure system. Southwestward circulation, associated with this high, advects warm and moist air from subtropical regions over the estuary [*Minetti and Vargas*, 1990]. On the other hand, cold systems coming from the south drive cold air masses over the area with a dominant periodicity of around 4 days [*Vera et al.*, 2002]. As a result, an alternation of winds from the northeast to the southwest in a scale of a few days is the dominant feature of wind variability in the area. This fact is illustrated in Figure 11, where National Centers for Environmental Prediction/NCAR 10-m wind vectors are shown for the periods when data were collected; winds for other periods show similar features. In order to eliminate very high frequency variability a 5 elements moving average filter was applied to data. The northeast-southwest alternation is modulated in intraseasonal timescales by an alternating pattern of variability that links the precipitation anomalies over eastern Argentina and southeastern Brazil [*Nogués-Paegle and Mo*, 1997], which is associated with northeast to southwest changes in the surface winds in the region of our study [*Liebmann et al.*, 2004].

[23] Additionally, the Río de la Plata is located in one of the most cyclogenetic regions of the world, associated to waves that move along subtropical latitudes of the South Pacific and South American regions, exhibiting maximum variability in periods of 10–12 days, and interact with subtropical air masses over northeastern Argentina, Uruguay and southern Brazil [*Vera et al.*, 2002]. Approximately 8 cyclones per year occur, with higher frequency in summer. When they develop over Uruguay, they can originate very strong southeasterly winds, with speeds that can easily exceed 15 m s^{-1} [*Seluchi*, 1995; *Seluchi and Saulo*, 1996]. Those storms, known as "Sudestadas" produce floods in the upper estuary [*D'Onofrio et al.*, 1999] and have a frequency of occurrence of around 2 to 3 events per year [*Escobar et al.*, 2004].

[24] Figure 12 shows isolines of the frequency of occurrence (in % of time) of northwesterlies (Figure 12, top left), northeasterlies (Figure 12, top right), southwesterlies (Figure 12, bottom left) and southeasterlies (Figure 12, bottom right) for the different months of the year and for different wind speeds as calculated from the 50 years of National Centers for Environmental Prediction/NCAR data spanning the period 1955–2004. Note that contour interval is not regular, but a logarithmic scale has been used. The first feature that emerges from Figure 12 is that wind speed is usually moderate in the area, with values of between 5 and 7 m s^{-1} prevailing for every direction and month of the year. Nevertheless, when analyzing Figure 12 it must be taken into account that reanalyses tend to underestimate wind speeds, especially the weak ones (see section 2 and *Simionato et al.* [2006c]); therefore, in nature, speeds are probably larger than those shown in Figure 12. Second, the predominance of southwesterlies and northeasterlies along most of the year is evident in Figure 12, with a seasonal cycle associated to a larger frequency of winds from the west sector in winter and from the northeast in summer. Finally, it is evident in Figure 12 that winds from the northwest and southeast are neither frequent nor strong in the area.

[25] An evaluation of the results of previous section in terms of the discussed natural wind variability has interesting connotations with regards to the salt wedge structure observed in the Río de la Plata estuary. Our results indicate that even though stratification is a natural consequence of the intense continental discharge and bathymetry, prevailing winds, which alternate from northeasterlies to southwesterlies (see Figures 11 and 12), favor it, as they allow for an extension of the surface salinity front with little displacement of the bottom one intensifying the vertical salinity gradient. Moreover, northwesterly winds even relatively less frequent in the region (Figure 12, top left) intensify the vertical salinity structure as well. Finally, probably the most interesting implication of our analysis is that stratification can be destroyed only by persistent or

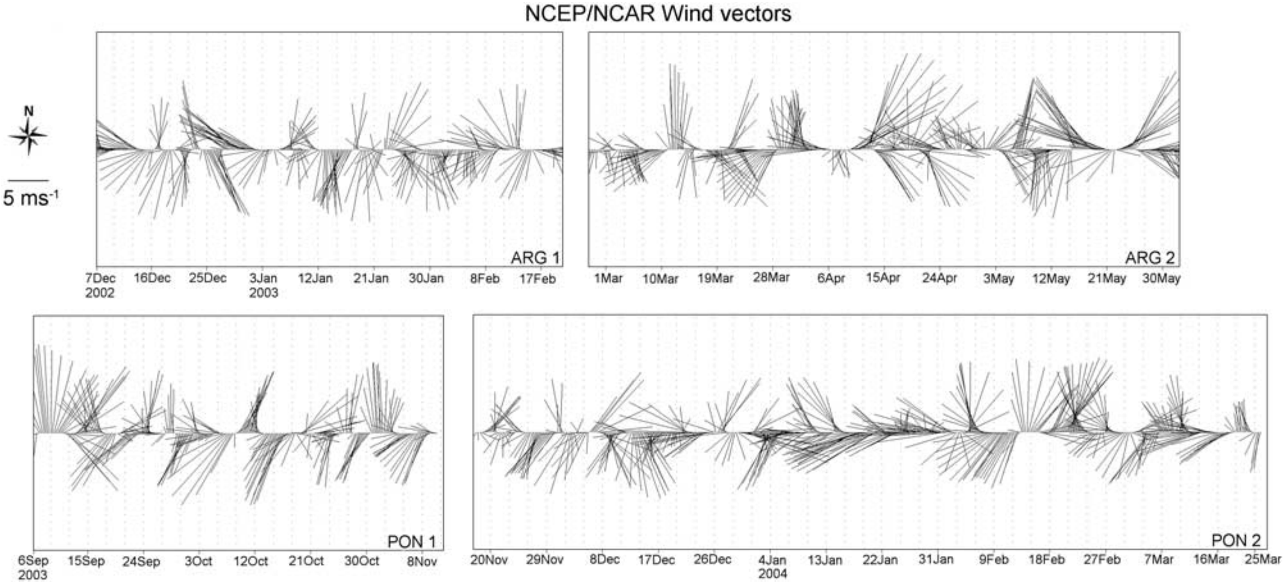

Figure 11. National Centers for Environmental Prediction/NCAR wind vectors for the periods when data were collected. A five-elements moving average filter was applied to wind data.

intense southeasterly winds which, even though can be very strong are not frequent (Figure 12, bottom right). Therefore local winds tend to favor the occurrence of a marked halocline at this estuary during most of the time. In fact, historical observations [*Guerrero et al.*, 1997] show that the most significant feature of seasonal salinity means is the occurrence of a salt wedge. Nevertheless, our results suggest that even though seasonal variability observed in salinity mean fields has been related to the mean winds occurring in summer and winter [*Guerrero et al.*, 1997; *Simionato et al.*, 2001], it is more likely the result of the most frequent wind conditions along those seasons. In effect, the formerly discussed results indicate that the estuary rapidly responds to wind variability in synoptic scale (which peaks at periods of around 4 days) in both, currents and salinity fields; in such a variable system, the seasonal means are accompanied by a very large dispersion. According to our results, conditions classically though as characteristic of "summer" or "winter" more probably take place during any season with high variability. On the other hand, as shown in Figure 12 the most frequent winds in summer and winter are those related to the seasonal means, that is, northeasterlies and westerlies, respectively. This, in turn, would generate a larger frequency of the characteristic summer and winter salinity patterns during those seasons, dominating the means.

[26] Finally, data show that breakdowns of the salinity structure have only been observed for easterly/southeasterly winds with speeds more than 10 m s^{-1} (R. A. Guerrero, unpublished data, 1993). In particular, *Guerrero et al.* [1997] showed data from a synoptic campaign performed in April 1993 when southeasterly to east-southeasterly winds of 10–14 m s^{-1} blew during 60 hours; in this situation the halocline broke down by wind-induced vertical mixing. This way, the break down of the vertical structure in the Río de la Plata would only occur in association to strong cyclogenetic events, which only take place a few times every year.

5. Summary of Conclusions and Final Remarks

[27] In this paper vertical profiles of ADCP currents collected at two locations of the Río de la Plata estuary salt wedge and salinity profiles gathered at and around those locations were used to evaluate the impact of wind variability in short timescales on that baroclinic structure. Data indicate that owing to the estuary shallowness, currents rapidly respond to wind changes at every level with a response time of between 3 and 9 hours. Currents vertical structure is highly dependent on wind direction and can be explained in terms of two modes whose structure of correlation to wind is similar to that found for the vertically averaged component. At both studied locations the estuary responds with vertically decaying currents for winds with a dominant component perpendicular to the estuary axis and with a marked inversion in current direction between upper and lower levels for winds with a dominant component along the estuary axis. This feature seems to be in a large extent a consequence of the estuary's geometry and bathymetry. For winds with a dominant component perpendicular to the estuary axis the flow is not inhibited by bathymetry. Instead, for winds parallel to the estuary axis the presence of the coast at the inner estuary demands a compensation of the inflow (outflow) at upper layers by an outflow (inflow) at the lower ones, originating the observed inversion in currents.

[28] The occurrence of different vertical current structures for different wind directions has implications for the vertical salinity structure that, consistently, can be observed in the in situ vertical salinity profiles analyzed. Northeasterly (southwesterly) winds produce a change in the salinity field consistent with an extension toward the southern (northern) coast of the surface front and an enhancement of the

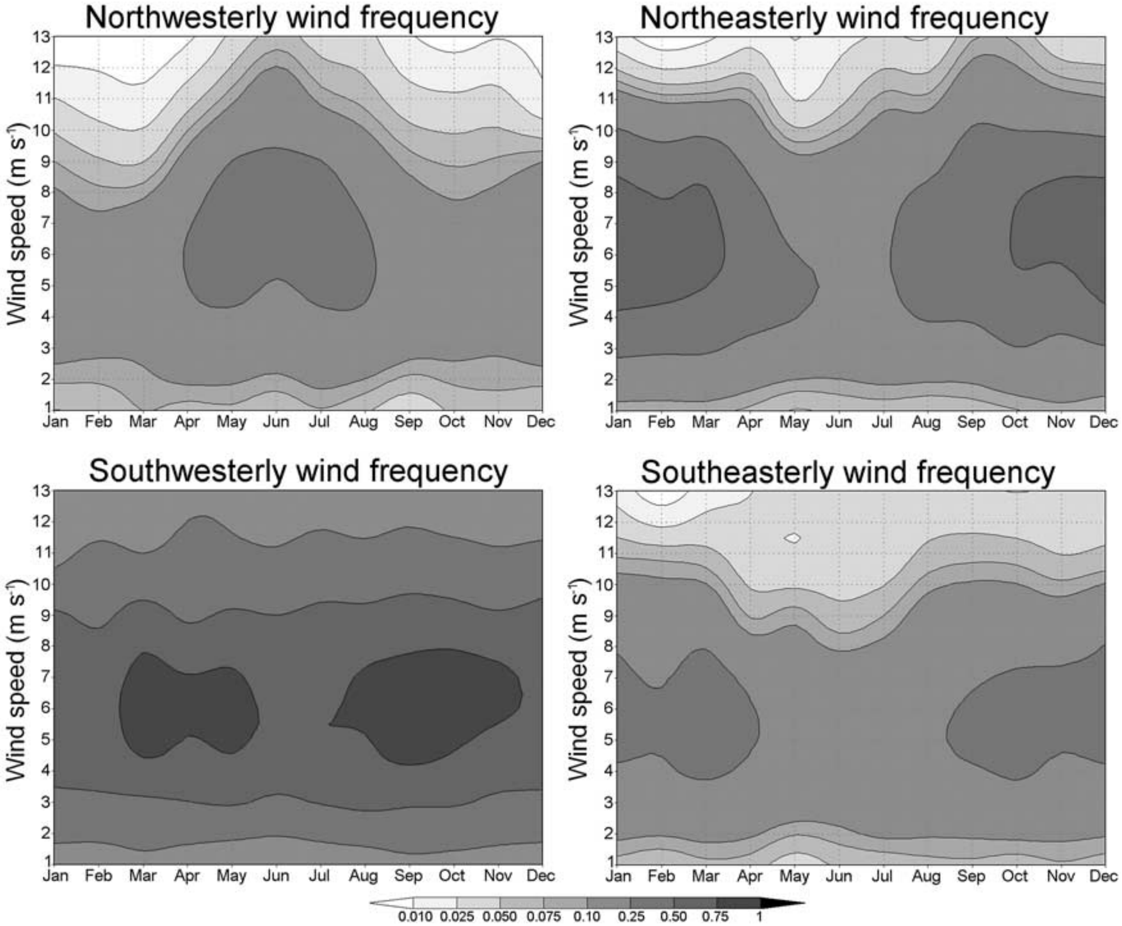

Figure 12. Isolines of the frequency of occurrence (in % of time) of (top left) northwesterlies, (top right) northeasterlies, (bottom left) southwesterlies, and (bottom right) southeasterlies for the different months of the year and for different wind speeds from the 50 years of National Centers for Environmental Prediction/NCAR data spanning the period 1955–2004. Note that contour interval is not regular, but a logarithmic scale has been used.

stratification along that coast. When wind blows parallel to the estuary axis, the occurrence of an inversion in currents direction between upper and lower layers either enhance or weaken the vertical salinity structure. Weakening, and eventually breakdown of stratification can only occur as a consequence of persistent and/or intense southeasterly winds. The fact that the described features can be observed in composites of salinity profiles, collected for different wind speeds and for diverse persistence conditions in this highly variable system, implies that the response of the salinity field is also fast, probably taking place in only a few hours.

[29] As an alternation of winds from northeasterlies to southwesterlies is the dominating feature of surface wind variability in synoptic to intraseasonal scales in the region, winds are in general favorable to the maintenance of a salt wedge in this estuary. Even though northwesterly winds are commonly neither strong nor persistent in the region, their effect is also an intensification of stratification. Moreover, strong southeasterly winds that can destroy the vertical structure are not frequent, but occur only a few times per year in association with cyclogenetic events. Therefore the combination of the estuary geometry and the prevailing wind variability makes the system itself efficient in maintaining the salinity structure that a number of fish species use for their reproduction and that is the base of a rich ecosystem that houses crabs, turtles and birds [*Boschi*, 1988; *Lasta*, 1995]. Moreover, the most significant mixing events producing exchanges of water, sediments, nutrients and other properties between the estuary and the ocean are limited to occur along a few days of the year, when cyclogenetic storms develop over the area producing strong southeasterly winds. On the other hand, our results imply that the fresh water plume of the Río de la Plata estuary would impact the continental shelf in the form of alternating pulses toward the northeast or to the southwest associated to wind events from those directions.

[30] The fact that stratification is highly affected by short-term variability indicates that the reported ‘‘seasonal cycle’’ can be explained not as a result of the mean winds for that season but as a consequence that summer (winter) is characterized by a higher frequency of winds from the northeast (west-southwest) sector. Actually, conditions classically though as characteristic of ‘summer’ or ‘winter’ can take place during any season with high variability.

[31] A similar response to upstream/downstream winds has been observed in other estuaries. For instance, *Weisberg* [1976], *Scully et al.* [2005] and *Ahsan et al.* [2005] found that wind forced signal in Narragansett Bay, the York River estuary and Escambia Bay, respectively, is mostly related to winds blowing along the estuary axis. Down-estuary winds enhance the vertical shear, which interacts with the along-channel density gradient to increase vertical stratification whereas up-estuary winds tend to reduce, or even reverse the vertical shear, reducing vertical stratification. Nevertheless, the enormous breadth of the Río de la Plata allows for the occurrence of another wind-forced mode of circulation related to cross-river winds in which lateral currents dominate and that has not been previously reported in other estuary. In fact, in what concerns circulation, the Río de la Plata behaves more as a semienclosed basin than as a typical estuary. At the Río de la Plata two modes can occur: one related to winds in the direction of the mouth and another one, associated to winds perpendicular to it. Because of the observed wind variability, this second mode dominates during most of the time and gives particular features to this estuary, as for instance, the displacement of the surface salinity front from the northern to the southern coast that originates the reported seasonal cycle and introduces variability in the vertical structure over those coasts.

[32] Even though this and the other previous papers related to the matter tend to attribute wind direction dependencies to local geometry and bathymetry, the coastline orientation outside the estuary and hence the effects of the coastal ocean response to winds may also be important [*Wang and Elliott*, 1978; *Wang*, 1979]. We find a significant correlation between currents and local winds but, given that processes that originate atmospheric variability in the area (the semipermanent anticyclone, Rossby waves coming from the south and cyclogenesis) have a very large scale, they probably introduce a remote signal intensifying estuarine response. In fact, in a recent paper, *Simionato et al.* [2006c] demonstrate that remote effects can have an important influence in the strength of the response of the Río de la Plata to winds. Nevertheless, those effects cannot be studied with the data considered in the present paper.

[33] A remaining question is whether gravitational convection occurs or not in the Río de la Plata estuary. It was found that temporal means are different from one to other observed period, very close to zero and with standard deviations that exceed them by between five and ten times. On the other hand, the statistical methodology applied (EOF) could not separate a significant signal occurring for all wind directions. Evidently gravitational circulation is very small compared to the wind forced signal that dominates in this estuary. Therefore a much larger observation period would be necessary to filter out the synoptic, intraseasonal and seasonal wind forced variability in order to properly discriminate gravitational convection.

[34] Finally, the compilation and analysis of the available historical data in terms of short-term wind variability would be a valuable continuation of this study that is envisaged for the near future. Nevertheless, the collection of simultaneous current, salinity and wind observations is fundamental to better understand the processes that take place in this estuary and to fully verify the conclusions of this paper, so as to evaluate the associated timescales. In the mean time, numerical models could help in estimating the response timescales of the salinity field to changes in winds and the scales of restitution of the salt wedge structure after a break down produced by local cyclones.

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W. C. Dragani, Servicio de Hidrografía Naval, ESCM-INUN de la Armada Argentina, Av. Montes de Oca 2124 (C1270ABV), Ciudad Autónoma de Buenos Aires, Argentina. (dragani@hidro.gov.ar)

R. Guerrero, INIDEP, Universidad Nacional de Mar del Plata, Paseo V. Ocampo No. 1, CC 175 (B7602HSA), Mar del Plata, Argentina. (raul.guerrero@inidep.edu.ar)

V. L. Meccia, M. Nuñez, and C. G. Simionato, Centro de Investigaciones del Mar y la Atmósfera, CIMA/CONICET-UBA, Ciudad Universitaria Pabellón II Piso 2 (C1428EHA), Buenos Aires, Argentina. (virna@cima.fcen.uba.ar; mnunez@cima.fcen.uba.ar; claudias@cima.fcen.uba.ar)