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# ABOUT THE VERTICAL STRUCTURE OF CURRENTS IN THE INTERMEDIATE RIO DE LA PLATA. OBSERVATIONAL STUDY

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## ABSTRACT

The Río de la Plata is one of the most important estuarine systems of the world and the most developed basin of eastern South America. Water levels and currents have been measured at many locations of the river and a number of depth-integrated (2-D) models have been applied to determine its circulation. Nevertheless, the three-dimensional characteristics of the currents have been never analyzed neither by means of direct observations nor by means of 3-D models. In this work current data measured using an Acoustic Doppler Current Profiler are presented to show the vertical structure of currents in the intermediate Río de la Plata. In February 2-3 2000, a transect of approximately 16 Km long was repeated eleven times during 25 hours obtaining 1972 current profiles. After applying a specific processing, sinusoids with $M_2$ (12.42 hours) period was fitted to the data series using least squares fitting method. The $M_2$ amplitudes and phases of the EW and NS components of the current and both components corresponding to the mean flow (residuals) were obtained along the transversal section of the transect. Results showed that currents present strong vertical gradients not only in the phases of the semidiurnal constituent but also in the mean flux in the intermediate zone of the Río de la Plata. Although the intermediate Río de la Plata is a very shallow basin results reveal that the current from upper to bottom layers can rotate more than 90°. These results indicate that currents respond strongly to the local winds but their effects are mainly manifested at the upper layer. Finally, results indicate that 3-D baroclinic models (including temperature and salinity fields and a realistic atmospheric forcing) should be used in order to obtain a reliable and complete representation of currents especially at the intermediate and outer zone of the Río de la Plata.
**Keywords:** Intermediate Río de la Plata, acoustic Doppler current profiler, current profile, directed measurements.

## RESUMEN

El Río de la Plata es uno de los sistemas fluviales más importantes del mundo y la cuenca más desarrollada del sudeste sudamericano. Los niveles del agua y las corrientes han sido medidos en un gran número de sitios del río y, por otro lado, diversos modelos integrados en la vertical (2-D) han sido aplicados para determinar su circulación. Sin embargo, hasta el momento, las características tridimensionales de las corrientes no han sido descriptas ni mediante observaciones directas ni por medio de modelos 3-D. En este trabajo los datos de corrientes medidos con un Perfilador de Corrientes Acústico Doppler (del inglés ADCP) son presentados para mostrar la compleja estructura vertical de las corrientes en el Río de la Plata intermedio. Entre el 2 y 3 de febrero de 2000 se repitió once veces durante 25 horas una transecta de

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aproximadamente 16 Km de longitud obteniéndose un total de 1972 perfiles de corriente. Después de aplicar un procesamiento específico las series fueron ajustadas a sinusoides con periodo correspondiente a la componente de marea $M_2$ (12.42 horas) utilizando el método de mínimos cuadrados. Se obtuvo así las amplitudes y fases de las componentes EW y NS de la corriente correspondientes a la $M_2$ y las dos componentes para el flujo medio (residuos) a lo largo de la transecta estudiada. Los resultados muestran que las corrientes en la zona intermedia del Río de la Plata presentan intensos gradientes verticales no solo en las fases de las componentes semidiurnas sino también en las del flujo medio. Aunque el Río de la Plata intermedio es una cuenca muy somera los resultados revelan que las corrientes pueden variar su dirección en más de 90° entre las capas superior e inferior de la columna de agua. Estos resultados indican que las corrientes responden fuertemente a los vientos locales, pero sus efectos son principalmente manifestados en la capa superior. Finalmente, los resultados indican que para obtener una representación confiable y completa de las corrientes especialmente en las zonas intermedia y exterior del Río de la Plata deberían implementarse modelos baroclínicos 3-D que incluyan tanto los campos térmicos y salinos como así también forzantes atmosféricos realistas.
**Palabras claves:** Río de la Plata intermedio, perfilador de la corriente acústico Doppler, perfil de la corriente, mediciones directas.

## 1. INTRODUCTION

The Río de la Plata is a shallow and extensive estuary located on the eastern coast of South America at approximately 35° S. It has a NNW-SSE general orientation and is formed by the confluence of two of the most important rivers of South America. These are the Paraná and Uruguay rivers whose mean discharges are of 16000 $m^3 s^{-1}$ and 6000 $m^3 s^{-1}$ respectively (Nagy *et al.*, 1997). The Río de la Plata ranks 5th and 4th worldwide in fresh water discharge and drainage area respectively. This system substantially contributes to the nutrient, sediment, carbon and fresh water budgets of the South Atlantic Ocean (Framiñan *et al.*, 1999). It affects the hydrography of the adjacent continental shelf, impacts important coastal fisheries, and influences coastal dynamics up to more than 400 Km north on the Brazilian shelf (Campos *et al.*, 1999; Piola *et al.*, 2000).

With a length of approximately 320 Km, the Río de la Plata width varies from 35 Km (La Plata-Colonia) to 220 Km (Punta Rasa-Punta del Este). Even though its total area is of about 30,212 $Km^2$ its mean depth is only 10 meters (SHN, 1999a, b). The sediment transported in huge quantities by the rivers Paraná and Uruguay is responsible for the existence of several sandbanks that constitute one of the estuary's main features. The intermediate region goes from the imaginary line that joins La Plata and Colonia to another imaginary line connecting Punta Piedras with Montevideo (figure 1).

Tidal wave has mean amplitudes of 1.10 m at Punta Rasa and 0.25 m at Punta del Este (Balay, 1961). It takes to the wave about 12 hours to travel through the river and, consequently, two high water and one low water (or vice versa) take place simultaneously with very marked diurnal inequalities. The coincidence of large or even moderately high tides and large meteorologically induced surges, has historically caused catastrophic floods in many coastal areas, threatening and claiming human lives and producing major economic and material damages (D'Onofrio, 1999).

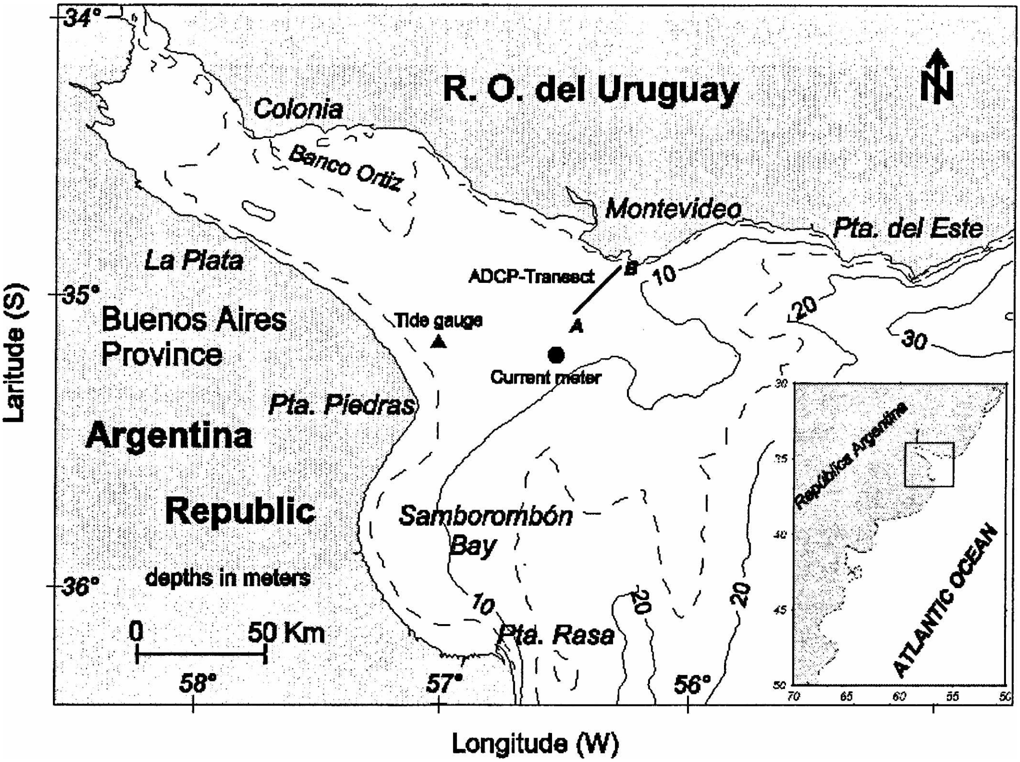


**Figure 1. Río de la Plata river showing bathymetry and the AB transect studied with acoustic Doppler current profiler (ADCP) measurements. The bathymetry is contoured at 10-m intervals. Contours of 5 and 15 m (dashed) are also included. The tide gauge station and the location of the current meter are denoted with a triangle and a circle, respectively.**

Current measurements in the Río de la Plata started at approximately 35 years ago. Since they have been intended mainly for navigation safety, the time series are of different length but usually rather short. Published data (CARP, 1989) show a hydrodynamic zoning whose limits are given by the direction and speed of the currents. Reversible currents (northwestward and southeastward in flood and ebb, respectively) flow parallel to the coast at the inner and intermediate zones but they are strongly rotatory at the outer zone on the Río de la Plata. Although the presence of Banco Ortiz constitutes a natural barrier to the flow of the Paraná river, this does not prevent the Paraná from contributing to the residual current with a significant ebb current component. The turbidity maximum is one of the major features in the estuary. It is clearly defined as a strong gradient in reflectance, a sharp change in watercolor and a strong vertical structure of currents (Framiñan and Brown, 1996; Framiñan *et al.*, 2001).

Several modeling attempts were done for the area in order to simulate the circulation in the Río de la Plata. Molinari (1986), Albarracín (1987) and Olalde (1988) were the first in modeling the Río de la Plata tidal dynamics using a depth-integrated model (Menéndez, 1985) and a very simplified tidal forcing at the mouth of the estuary. Guarga *et al.* (1991) implemented a depth-integrated model that was forced with four tidal constituents to represent the tide at the mouth and with a simplified atmospheric forcing for studying the surge. CARP (1992) presented the first hydrodynamic model applied to the Río de la Plata where sediment transport was included. Etala *et al.* (1995) was the first who implemented a depth-integrated model in order to forecast the storm surges in the Upper Río de la Plata. The model domain was nested into other one that included the whole Argentinian continental shelf and gave the boundary conditions to the Río de la Plata model.

In a set of papers, Glorioso and Simpson (1994), Glorioso and Flather (1995, 1997) and Glorioso (2000) studied the tidal propagation in the Patagonian shelf by means of 2-D and 3-D barotropic models. Their models included marginally the Río de la Plata, but as the estuary was very close to the boundary condition, their solution for it is not very reliable. Nevertheless, there are only two papers in refereed literature (O'Connor, 1991 and Veira and Lanfredi, 1996) which were very simple approaches to the understanding of the causes of the surge and the tides characteristics, not built with the intention of being used as a forecasting tool.

2-D depth integrated numerical models are not able to represent a realistic picture of currents especially at the intermediate and outer Río de la Plata. Recently, a 3-D baroclinic model was applied by Simionato *et al.* (2001) to investigate the location of the salinity front of the Río de la Plata. River run-off, tides and mean winds for summer and winter conditions were considered in order to find out the most important factors for the observed seasonal variability of this location. The vertical structure of current was not discussed in this paper.

Vertical current profiles were measured along three 16 Km long transects aboard LH ARA "Cormorán" during Riopla II campaign in summer 2000. Both of them were made near Punta Piedras and Montevideo, respectively, in the perpendicular direction respect to the coast. The last one was located between both transects but orientated in the NW-SE direction. The objective of this field task was to survey the estuarine turbidity maximum zone of the river. Participant institutions were Old Dominion University (Center of Coastal Physical Oceanography) and Rutgers University (Institute of Marine and Coastal Sciences) from USA and the SHN from Argentina. Current data were measured using an acoustic Doppler current profiler towed along the three predetermined transects. After a preliminary inspection, it was concluded that the transect located near Montevideo was the most convenient one to be analyzed in order to describe the vertical structure of currents.

The aim of this work is to show the spatial distributions of the current in the vertical section along the selected transect. This is a descriptive study of the horizontal and vertical structure of current, which gives a preliminary view of gradients not only in the semidiurnal constituent but also in the mean flux in the intermediate zone of the Río de la Plata. In addition, data collected during Riopla II are compared with current meter data measured by Hidrovía SA and with water level measured at tidal station "Oyarvide Tower" (SHN tidal net). In section 2, field measurements and data processing are described. The vertical structures of the EW and NS components of mean flux and amplitudes and phases of both components of the main semidiurnal tidal constituent are shown in section 3. Finally, the main results and the conclusions of this work are presented in section 4.

## 2. OBSERVATION AND DATA PROCESSING

The objective of the sampling plan was to complete as many repetitions as possible of the AB transect during a 25 hours period (figure 1). This would allow for the representation of the flow conditions at different times of the tidal cycles throughout the sampling transect. The sampling strategy consisted of towing 1220-kHz RD Instruments ADCP (Acoustic Doppler current Profiler) on the starboard side of SHN LH ARA "Cormorán". The ADCP was towed looking downward along the AB transect. This transect was 16 Km long (from 56° 28'S, 35° 4'W to 56° 21.5'S, 34° 57'W, along the 040°-220° direction) and was repeated eleven times from February 2 0701 to 3 0738, 2000. The sampling path was tracked with a Global Positioning System (GPS). The ADCP sensors (four) were located approximately 0.5 m below the water surface and 15-20 m apart the ship. During this field experience heights of waves were lower than 0.5 m. The ADCP was programmed to get one current profile every 45 seconds obtaining a total amount of 1972 profiles in this transect. U (East-West) and V (North-South) components of the current were measured with 0.5-m vertical resolution and the GPS latitude and longitude of each profile were stored. The velocity measurements obtained at depths greater than the 85% of the water column were lost due to sidelobe effects because the transducer can be inclined up 30° to the vertical. This is layer of approximately 1-m depth located above the bottom. The methodology given by Joyce (1989) was considered for in situ calibration of ADCP from a moving ship.

The positions of the current profiles were disposed forming a narrow and elongated distribution over the theoretical AB transect. After a properly rotation of the reference system the position of each profile was given by means of the distance along the transect from the initial point A and the orthogonal distance which is related to the ship's bias respect to the predefined (theoretical) transect. It was found that ship's bias was, in general, lower than 15 m but it could reach a maximum value of 30 m. Bottom depths corresponding to each profile were obtained averaging the depths given by each one of the four sensors. After rotating the reference system the profiles were irregularly spaced along the transect. A computational program was implemented in order to interpolate them and to build a regular matrix in which profiles were located even 200 meters. U and V time series were obtained for each one of the 85 (in the horizontal) by 12 (in the vertical) nodes of the transversal section along the AB transect. Each time series was formed by eleven current data with variable sampling interval ranging from 2 to 4 hours, approximately. These time series were fitted to two sinusoids with $M_2$ (12.42 hours) and $O_1$ (25.82 hours) periods using least squares fitting techniques. This procedure yields the $M_2$ and $O_1$ amplitudes and phases corresponding to U and V in addition to both components corresponding to the mean flow (residuals) at each one of the grid points of the aforementioned vertical section. Phases were referenced to the time of the initial profile (February 2 0701). The described processing methodology is based in the technique applied by Valle-Levinson and Lwiza (1995) in Chesapeake Bay.

Hourly sea level were gathered by a basic tide gauge with a floater and counterweight inside a vertical tube (UNESCO, 1985) at Oyarvide Tower. Tidal Tower is located at 35° 6'S and 57° 8'W and its position is shown in figure 1. Speed and direction of wind were also measured aboard the ARA LH "Cormorán" during the cruise. Data from a current meter installed at 35° 20'S and 56° 28'W (its position is also plotted in figure1) were considered. The instrument was an Aanderaa RCM-5 programmed with an interval sampling of 10 minutes and moored at 3 m from the bottom at 6-m depth. Data series extended from August 13 to September 6, 1996. These data were used to compute the harmonic constants (Foreman, 1977; 1978) which were compared with the results obtained from ADCP data.

## 3. RESULTS

The results of this analysis are shown in figure 2. Amplitudes of the U component of the $M_2$ constituent are quite homogeneous through the whole AB transect as seem in figure 2.a. In this figure it come out that low intensities characterize the upper layer (intensities ranging from 0 to 5 cm/sec) and slightly more intense values are observed at intermediate and bottom layers (from 5 to 15 cm/sec.). Phases of the U component of the $M_2$ constituent (figure 2.b) show that besides the low depth a strong vertical gradient is present along the first 6 Km of the transect. At the upper layer phases range from 0° and -90° and below it phases range from 0° to 90°. Between 6 and 16 Km the vertical structure of phases is fairly uniform except at the central part of the upper layer where they present a high degree of spatial variability in the gradients.

The structure of the V component amplitude associated to $M_2$ constituent (figure 2.c) is fairly similar to amplitudes shown in figure 2.a, except between 0 and 2 Km, at the upper layer, where more intense currents are appreciated (from 20 to 30 cm/sec). Phases associated to V component (figure 2.d) are quite uniform through the whole transversal section especially between 11 and 16 Km. Between 0 and 6 Km of the AB transect, phases are lower near the surface than close to the bottom. This fact implies that maximum flood and ebb associated to the $M_2$ constituent occur first at deeper layer.

According to O' Connor (1990) the $M_2$ tide propagates as a Kelvin wave along the Río de la Plata. Considering that the $M_2$ tidal amplitude near the cross-section is 0.15 m (it is supported by direct measurements) a simple calculation for the depth averaged velocity magnitude, $U_K$, can be approximate by (Pedlosky, 1979):

$$U_K = \sqrt{g/H}\,\eta = 21 cm/\sec. \qquad (1)$$

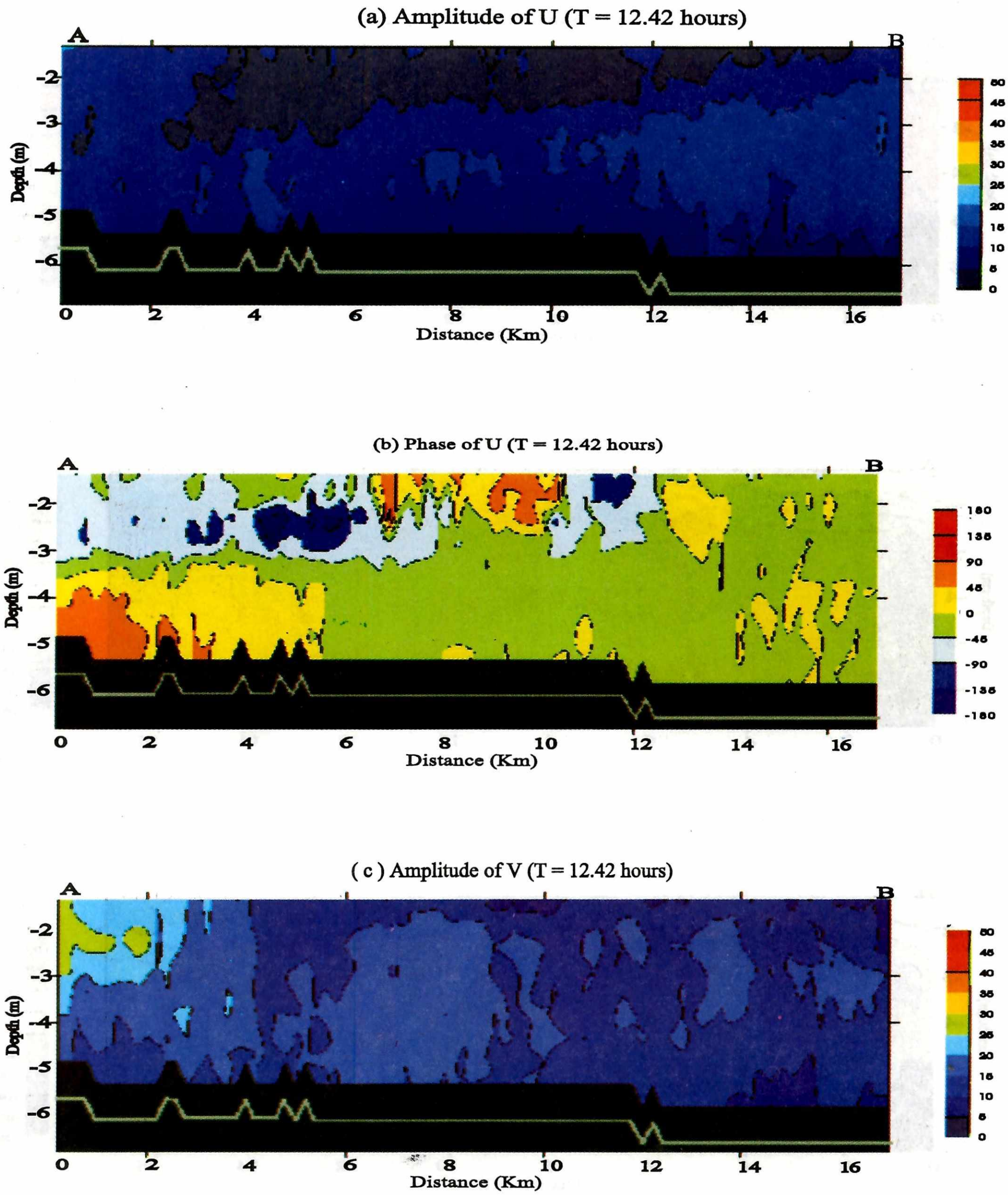


Figure 2. (a) Amplitude (centimeters per seconds) of the east-west component of the $M_2$ tidal currents. Contour interval is 5 cm/sec. (b) Phase lag of the east-west component of the $M_2$ tidal currents. Contour interval is 45°. (c) Amplitude (centimeters per seconds) of the north-south component of the $M_2$ tidal currents. Contour interval is 5 cm/sec.

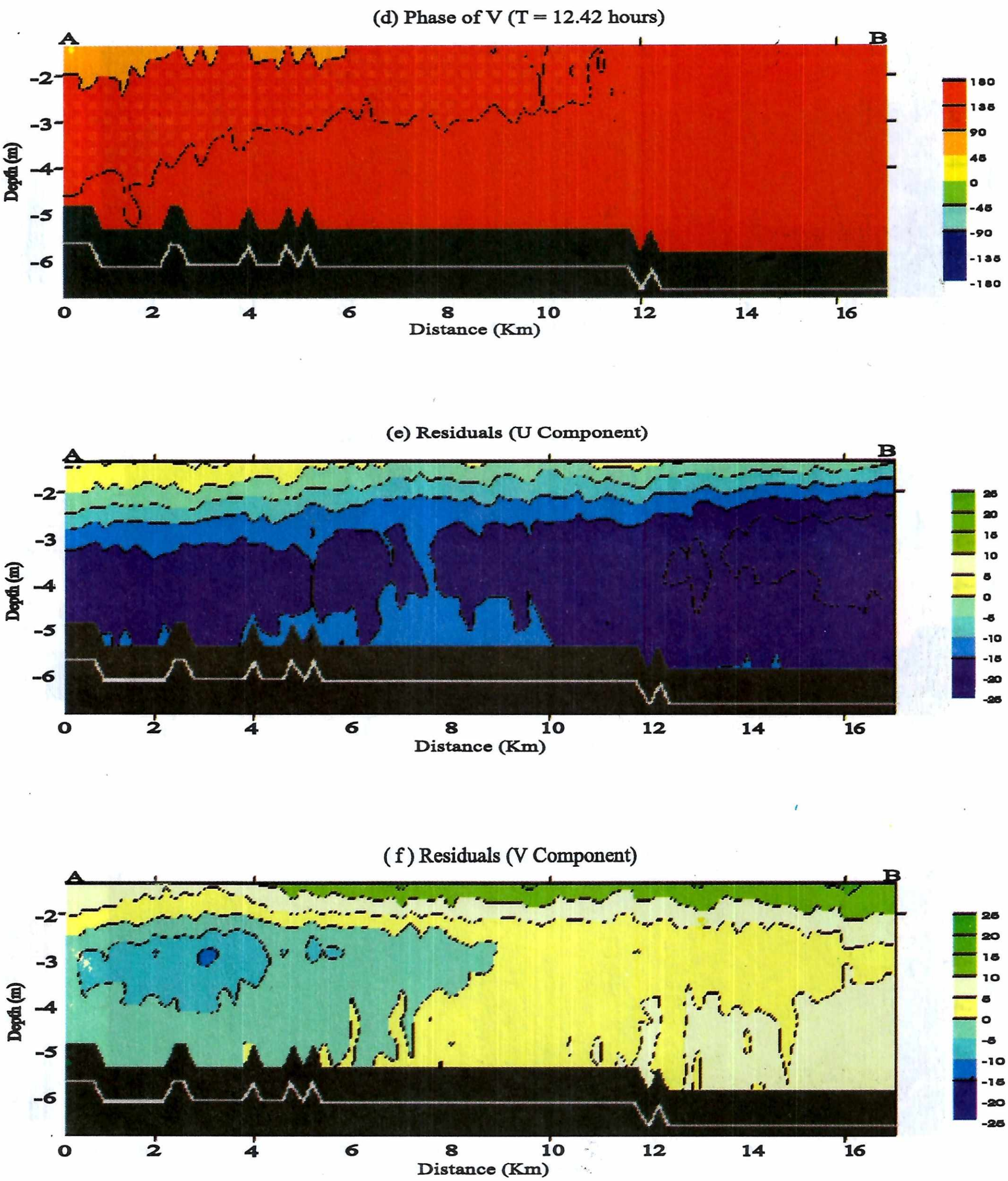


**Figure 2. (d) Phase lag of the north-south component of the $M_2$ tidal currents. Contour interval is 45°. (e) Speed (centimeters per seconds) of the east-west component of the residual currents. Contour interval is 5 cm/sec. (f) Speed (centimeters per seconds) of the north-south component of the residual currents. Contour interval is 5 cm/sec. The continuous grayish line shows the true bottom. The layer above the true bottom (approximately 1-m depth) can not be resolved by the ADCP measurements.**

where g is the acceleration due to the gravity, H (=5 m) the mean depth and $\eta$ (=0.15 m) the wave amplitude. This result is in accordance with the measurements taken near the point A. On the other hand, semidiurnal amplitudes calculated from this analysis compare well to those obtained from harmonic analysis from current data derived from a longer record measured in a point located southwestward the AB transect (figure 1). Amplitudes of 19.8 cm/sec and 21.2 cm/sec were obtained for U and V, respectively. A very good accordance is achieved for the V components but U component appears to be slightly higher than amplitudes obtained from our analysis.

Even though amplitudes and phases of the U and V components of the $O_1$ constituent have been calculated, both of them seem to be poorly resolved because time series processed are only 25 hours long, that is, slightly shorter than the $O_1$ period. Consequently, the results corresponding to the main diurnal constituent are not included in this work.

Distribution of the U component corresponding to the residuals (a rough estimation of the mean flow) shows a very strong vertical speed gradient (figure 2.e). At the upper layer the speed is very low. Between 0 and 7 Km current flows eastward (0-10 cm/sec) and at the rest of the upper section eastward and westward flows are alternated. Below 2-m depth currents present westward flow and the speed increases towards the bottom. Distribution of the V component of the residuals (figure 2.f) shows a very sharp vertical gradient between 0 and 4 Km. Here speed ranges from 10 cm/sec at the surface to −15 cm/sec at around 3-m depth. At the northeastern part (from 9 Km to B point) the whole water column flows northward with the speed increasing upward.

It must be considered that residuals have been obtained from records of 25-hours long. Consequently, meteorological effects (especially wind stress) could not be properly filtered and then they would be included in results shown in figures 2.e and 2.f. Figure 3 shows that wind blew predominantly from N during the first 6 hours of this cruise and then it rotated towards S with a variable intensity range from 7 to 16 knots. Probably, this could explain why residual currents present a predominantly northward flow especially close to the coast and the highest speed close to the surface (figures 2.e and 2.f). In the intermediate zone of the Río de la Plata mean flow associated to freshwater discharge was calculated from data (CARP, 1989) resulting a value of 10 cm/sec. But it is only a rough estimation. An accurate value of mean flow can be only obtained by means of a very long data series, which is not available in the zone. In addition, freshwater discharge effect could not be discriminate from records of 25 hours long measured along the AB transect.

In order to give a more comprehensive representation of the vertical structure of current, the north and east components of the residual and the $M_2$ current were composed to give the current vectors in two point of the transect. Isometric view of currents profiles (observed from the southwest) for two points located 3.2 Km (left panels) and 14.0 Km (right panels) from point A, along the AB transect for flood (upper panels) and ebb (bottom panels) conditions are displayed in figure 4. Current profiles are very alike during flood condition (upper panels) in both locations: currents flow northward in upper layers and turn leftward almost 100° with the depth. In contraposition, current profiles are pretty different between both locations during ebb condition (bottom panels). Currents in the upper layer of both locations flow almost in opposite direction: south-southeastward close to point A and northward 14.0 Km from A. It can be explained because U component of the residual current (figure 2.e) and U and V $M_2$ phases (figures 2.b and 2.d) present significant horizontal gradient in the upper layer between A and B. Below the upper layers, currents are more alike in both locations and present a predominantly westward flow.

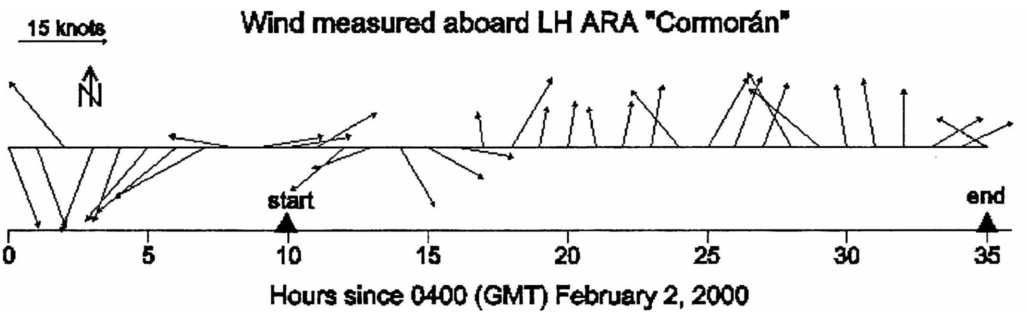


**Figure 3. Wind conditions before and during the sampling period. Start and end times of the measurements are noted by triangles.**

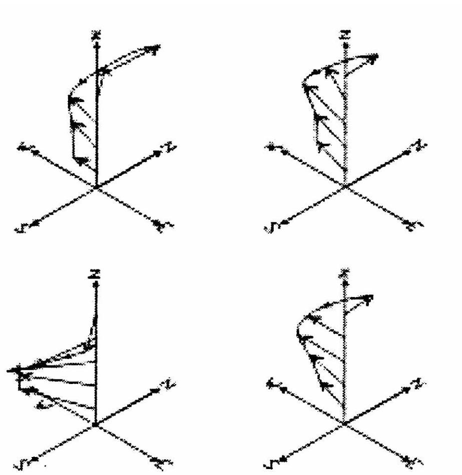

**Figure 4. Isometric view of currents profiles (observed from the southwest) for points located 3.2 Km (left panels) and 14.0 Km (right panels) from point A, along the AB transect (Figure 1). Flood (upper panels) and ebb (bottom panels) conditions are displayed. Residuals and $M_2$ tidal constituents were considered to compose the profiles. Current vectors are plotted even 1 m in depth, beginning from 1.33 m below the water level. A curve passing through the extreme of each vector (adjusted using spline method) is used to give the sense of the rotation of the current with the depth.**

Wind blowing over the Río de la Plata from S or SE direction produces an increasing of water level whose effect are well known along the Buenos Aires coast (D'Onofrio *et al.*, 1999). During the ADCP measurements wind coming from south raised the water level more than half meter from the expected astronomical prediction (SHN, 2000). Figure 5 shows expected (tide) and measured water level at Oyarvide Tower. It can be seen that at the end of the ADCP measurements water level reached a height 1-m higher than the predicted tide. In general, an increasing of the sea level due to the wind (surge) is associated with a northward flow of the current. This effect can be noted in figure 2 f where values higher than 15 cm/sec can be appreciated in the top of the water column.

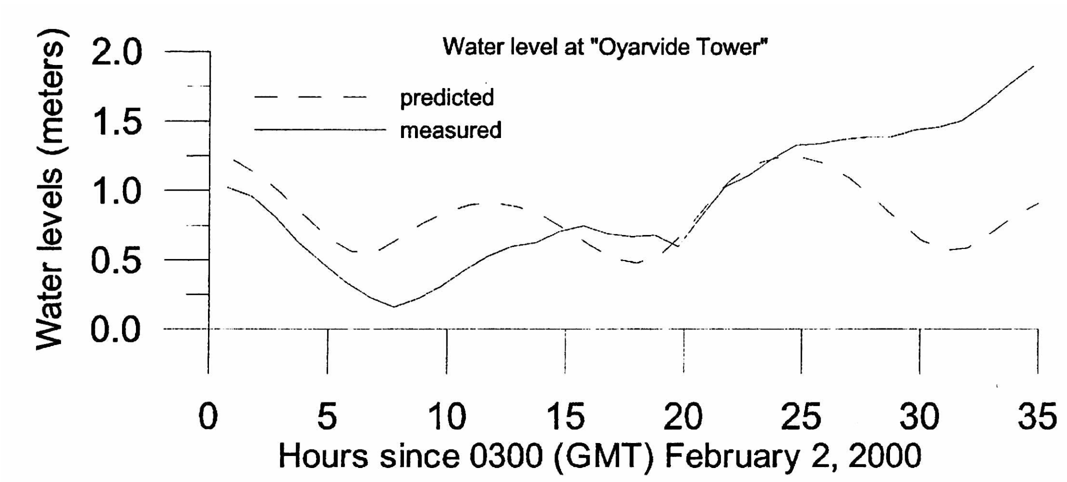


**Figure 5. Observed sea levels gathered in "Oyarvide Tower" (solid) and predicted tide (meters).**

## 4. DISCUSSION AND CONCLUSION

Results presented in this work reveal that the vertical structure of the currents in the intermediate Río de la Plata display a very complex pattern. Amplitudes of the U and V components of the $M_2$ constituent are weak and pretty homogeneous throughout the analyzed transversal section. In contraposition, distributions of phases reveal a strong vertical gradient especially for the east-west component. This distribution shows that maximum flood and ebb occurs first at the deepest layers - in general phases are greater near the bottom than the at the upper layer - especially at the southwestern part of the AB transect. Intensity of currents obtained along the AB transect are consistent with theoretical estimations obtained from a simplified expression resulting from the Kelvin wave theory. V component amplitudes match well with those resulting from the harmonic analysis of current data measured in a point located further southwestern of the point A and U component amplitudes result to be slightly lower.

With regard to the residuals (a rough estimation of the mean current) it was shown that water column is mainly dominated by the wind stress especially at the northeastern part of the AB transect (close to the coast). In contraposition, at the offshore part of the AB transect the V component shows southward flow (opposite to the wind direction). This inversion in the current direction clearly reveals the presence of the turbidity front in the study area (Framiñan and Brown, 1996; Guerrero *et al.*, 1997; Framiñan *et al.*, 2001). It was also discussed that freshwater discharge could not be discriminate from the analyzed data.

It should be noted that results shown in this work are only representative of the day in which measurements were done and, consequently, they must not be neither generalized nor extrapolated to other locations of the river. These results are only presented in order to emphasize the very complex vertical structure of the currents associated to the semidiurnal and mean flow in the Río de la Plata. In several cases (section 1) the Río de la Plata was modeled using 2-D models. These are hydrodynamic depth-integrated models, which do not give any information about the vertical structure of the currents. Therefore their results should be only considered as a rough approximation of the mean circulation.

In order to get a more realistic picture of the dynamics of the Río de la Plata the 3-D baroclinic primitive equation HamSOM model (Backhaus (1983; 1985) is being implemented at the estuary. This model was applied to many shelf seas worldwide (see, for example, Backhaus and Hainbucher, 1987; Stronach *et al.*, 1993; Simionato *et al.*, 2001). It is the first 3-D baroclinic numerical model specifically applied to the Río de la Plata to study the vertical structure of currents, salinity and temperature at the intermediate and outer region of the estuary. Nevertheless, it is clear that a more extensive program of field measurements is needed for testing and verification purposes. In this sense, ADCP and drifters measurements will be collected in the context of the UNDP/GEF project "Environmental Protection of the Río de la Plata and its Maritime Front". These measurements will be very valuable to further validation of model results.

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