Currents measurements in the coast of Montevideo, Uruguay.

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ABSTRACT: In this paper the analysis of current measurements between 2003 and 2006 in two points on Montevideo's coastal zone is presented. Two 1200 kHz broadband Acoustic Doppler Current Profilers (ADCP) were used to make the measurements. These instruments have the capability of measuring the three components of the velocity over a range of depths at the same time. These instruments were configured to make measurements during two minutes every thirty minutes. Wave direction, wave period and free surface position are obtained also in one of the ADCPs. Analysing the data the main characteristics of the currents and waves in the area were obtained. The results show that the orientation of the coast line has an important influence on the current pattern in the coastal zone.

1 INTRODUCTION

1.1 *Objective*

The main objective of this work is to present the results obtained in the preliminary analysis of currents and waves measured in the Uruguayan coastal zone between December 2003 and July 2006. Measurements were taken in the capital of the country, Montevideo, approximately 3,500 m away from the coast. The purpose was to obtain information about hydrodynamic parameters in areas where hydraulic projects are located or will be constructed in the future.

1.2 *Study Area*

Montevideo, Uruguay's capital is located in the coastal zone of the Río de la Plata River within a particularly complex area dominated by several forces and with estuarine characteristics. The flow dynamic in the Rio de la Plata and the Maritime Front is very complex due to the topographic variations of the river bed, the influence of continental flows, astronomical and meteorological tides coming from the ocean and the local winds. River level variations produced by astronomical tides are lower than those generated by the wind action and oceanic waves.

Figure 1 shows the location of the area of interest. The coastal zone of Montevideo includes several beaches, hard points, a big bay and navigation channels.

Figure 1. Study area location.

1.3 *Measurements Characteristics*

Two 1200 kHz Acoustic Doppler Current Profilers (ADCP) of the Teledyne RD Instruments Company were used in this study. This instrument is a type of sonar that measures and records water current velocities (direction and intensity) over a range of depths at the same time.

The equipment obtains the vertical profile of the current including information of module and direction but also the individual components (North, East and Vertical). Every 30 minutes a measure is obtained from the integration of the recorded information every second during two minutes. This is done in different cells distributed in the vertical direction (bins).

One of the ADCPs was installed south of Punta Brava point, at 34º 57’ 36’’ South latitude and 56º 09’ 39’’ West longitude (Figure 2). The second one was installed southwest of Punta Yeguas, another hard point located west of Punta Brava, specifically at 34º 55’ 57’’ South latitude and 56º 20’ 23’’ West longitude (Figure 2). ADCP 1 is located near the output of the city wastewater submarine outfall and ADCP 2 is located in the discharge zone of a future submarine outfall projected for the city.

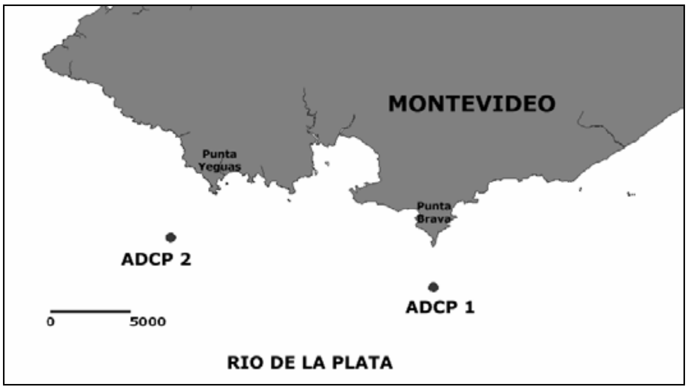

Figure 2. Acoustic Doppler Current Profilers location.

Wave direction, wave period and free surface position are obtained in the position of the ADCP 1 from the information registered with a pressure sensor installed on it. The measures are obtained every three hours from the integration of each second registered data during 20 minutes.

The ADCP 1 was programmed to collect current intensity and direction with a vertical resolution of 0.35 m and the ADCP 2 with 0.5 m. The bin closer to the bottom is the number one and is located 1.27 m above it in the ADCP 1 and 1.4 m in the ADCP 2. The amount of vertical bins in each ADCP is not fixed because it depends on the free surface elevation. In Montevideo's coast, the monthly difference average between maximum and minimum surface elevation is approximately 2 meters. The average depth around the area of the ADCP 1 is 9 m while in the ADCP 2 is 7 m.

Since the installation of the instruments in December 2003 data has been registered continuously except during some periods of maintenance. The ADCP 2 broke down in 2005 so no data was collected during that year. Nevertheless the data collected in a quasi-continuous manner is the most extensive set of good quality hydrodynamic measurements in Uruguay.

2 METHODOLOGY

2.1 *Statistical Analysis*

In order to know the main hydrodynamic features in the area of study the processing and analyzing of the measured data was performed. However, it’s still necessary to do some future analysis to improve the knowledge of the coastal circulation system.

Firstly, a statistical analysis of the current measurements at different depths was performed for each ADCP. The main flow directions, mean velocity, maximum intensity and frequency distribution of velocities were calculated. The simultaneous data registered in 22 vertical bins of the ADCP 1 and in 10 bins of the ADCP 2 were considered in the analysis. That is 37,779 samples (662 days) for the ADCP 1 and 23,188 measures (483 days) for the ADCP 2.

Furthermore, the tidal current components in the surface and bottom bins were calculated for each ADCP. From these, the main characteristics of the average daily residual currents were computed.

2.2 *Vertical circulation patterns*

A preliminary analysis of the vertical current instantaneous profile has been performed. In this case two bins representatives of the bottom and the surface were selected in both ADCPs. In ADCP 1 the bin number 1 located 1.27 m above the bottom and bin number 20 located 7.92 m from the bottom have been used. In the ADCP 2 bins number 1 and 10 (1.4 m and 5.9 m from the bottom respectively) has been selected.

The principal flow components in surface and bottom were used to obtain a flow vertical profile classification. Four flow schemes were defined (Figure 3):

1 Discharge: seaward surface and bottom velocities (positives).
2 Storage: landward surface and bottom velocities (negatives).
3 Gravitational circulation: seaward flow at the surface and landward at the bottom; gravitational circulation flow.
4 Reverse: landward surface flow and seaward bottom flow; gravitational circulation opposite flow.

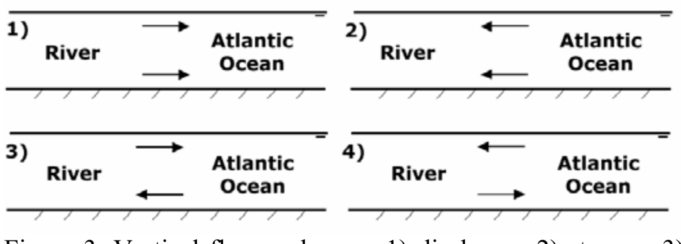

Figure 3. Vertical flows schemes: 1) discharge, 2) storage, 3) gravitational circulation and 4) reverse flow.

A second vertical circulation classification was made with the secondary velocity component. The frequency distribution was calculated for each flow scheme by analyzing the combination of the second component in surface and bottom.

In order to classify both the instantaneous and residual flow, the vertical profile classification into the four flows schemes was performed with two different databases. On classification was done using the instantaneous registered data. On the other hand, the astronomical tide component was calculated and it was removed of the currents data series. That residual data series was filtered with a 24 hours filter. Using this database the classification of the average dialy residual flow vertical pattern was obtained. By filtering the tide, the flow patterns obtained are related with the river discharge, winds and density currents.

The wind influence over residual flow patterns was also analyzed by considering the residual instantaneous currents: measured currents minus astronomical currents for each time. Wind data, intensity and direction, registered every three hours in the Punta Brava meteorological station were used. The frequency at which the surface current direction coincides with the wind direction indicating a possible wind influence over the residual flow pattern, was calculated. Only the current measures at the same time of wind data were used (every three hours).

2.3 *Waves*

The directional and scalar energy wave spectrums of each event recorded during 30 months at the ADCP 1 were processed and analyzed. Significant wave height, period and direction of propagation were calculated for 5,495 events. Previously, 466 events with a peak period of 2.9 sec (corresponding to the cut frequency of the equipment, 0.35 Hz) were eliminated due to the possible influence of base signal noise. A statistical analysis of the processed data was done in order to obtain the main characteristics of the waves.

3 WAVES ANALYSIS

3.1 *Height and Period*

Significant wave height distribution obtained from ADCP 1 data is presented in Figure 4. The results show that the significant wave height is less than 0.6 m in 70% of the cases and only 1% of the measured waves exceed a significant height of 1.49 m. The 5% of the analyzed waves have a significant height higher than 1.12 m.

The wave period distribution is shown in Figure 5. There is data accumulation in the short waves period corresponding to the 'sea' type waves with periods between 3 and 5 seconds. The results also indicate that the sea waves have more occurrence probability than the long waves ('swell' type wave).

The wave direction distribution obtained from ADCP 1 data is shown in Figure 6. Approximately 80% of the data belongs to the second quadrant (East to South) with 35.4% of waves coming from the Southeast direction.

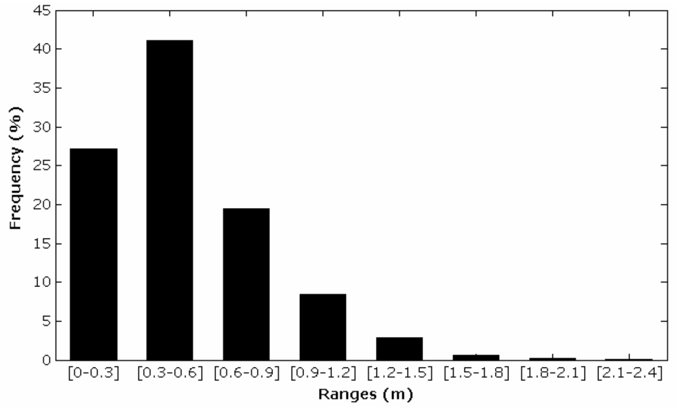

Figure 4. Significant wave height distribution.

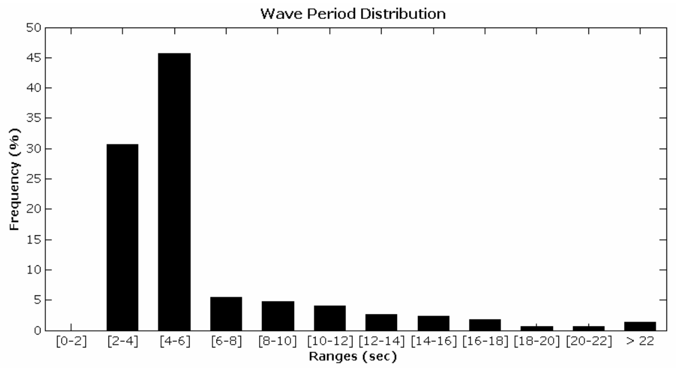

Figure 5. Wave peak period distribution.

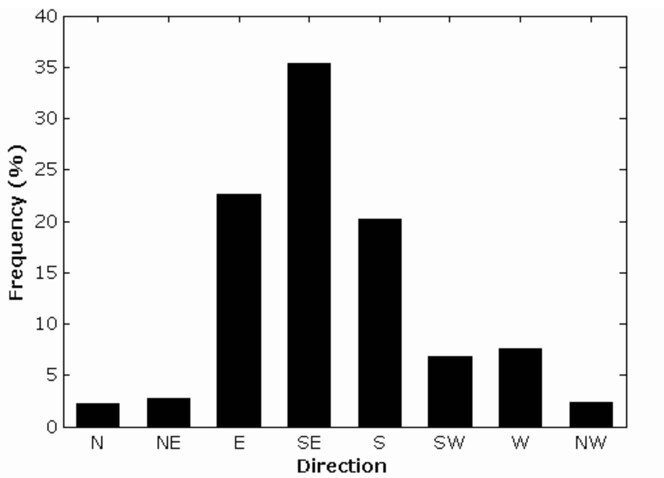

Figure 6. Wave direction distribution.

A combined analysis of peak period, significant wave height and wave direction shows that most of the short waves (sea waves) have a significant height between 0.3 and 0.6 m and a period between 4 and 6 sec. The major part of the swell type waves have a significant height lower than 0.3 m. In both types of waves the predominant direction is Southeast.

Data dispersion can be observed in Figure 7. The graph presents the significant height vs. peak period for all data set. It is possible to identify the two types of waves mentioned above: the sea type waves with short period and high significant height and the swell type waves with long periods and significant height lower than 0.6 m.

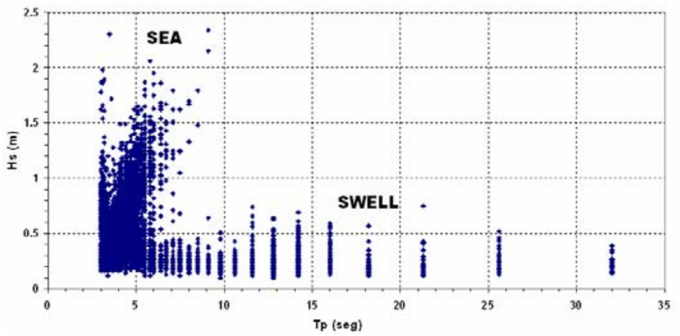

Figure 7. Significan height vs Peak period.

In the whole measured period the maximum significant height registered was 2.34 m corresponding to a Southern wave with 9.1 sec of period (31 January 2005 at 15:30 hour).

4 CURRENT ANALYSIS

4.1 *ADCP 1*

4.1.1 *Intensity and Direction*

Figure 8 presents the directional distribution of occurrence frequency, average intensity and maximum intensity in the vertical profile computed using the ADCP 1 current data.

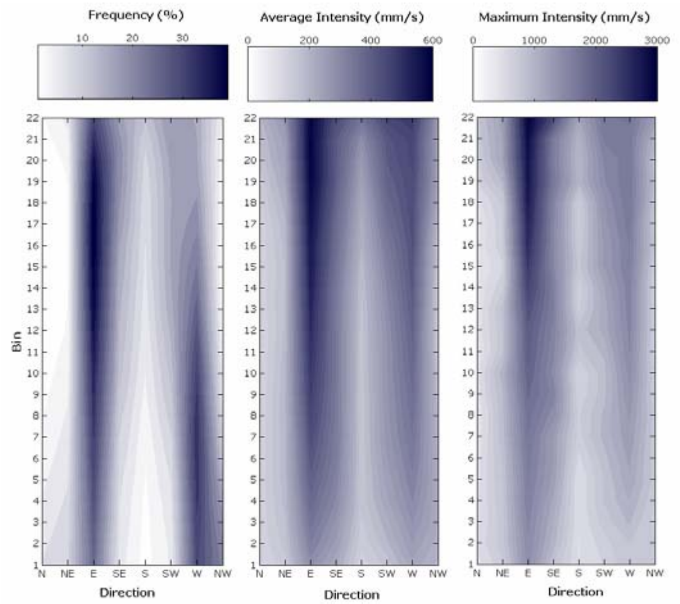

Figure 8. Directional distribution vertical profile of velocity frequency, velocity average intensity and velocity maximum intensity in ADCP 1.

Throughout the vertical profile the flow has an East and West predominant directions although the occurrence percentage is changing along it. The Northwest flow is also important at the bottom. Near the surface the West flow frequency decreases and the Southwest and Southeast flow directions increases. The greatest average and maximum intensities are observed in the East and West directions for all depths. The intensity of currents increases to the surface reaching average values of 0.6 m/sec in the East and maximum values greater than 2.0 m/sec in the East and Southeast directions.

4.1.2 *Astronomical Tide and Residual Components*

As expected in a microtidal zone, the astronomical tide component of the current measured at the surface and bottom is small. Approximately, the astronomical tide component is a 30% of the measurements intensity. The residual average daily velocity field has a slightly different spatial distribution than the instantaneous measured velocity field (Figure 9). At the bottom the direction of the residual flow is mainly west and northwest while at the surface the east direction is the most predominant. Throughout the vertical profile the greatest average residual intensities are to the East, 0.2 m/sec at the bottom and 0.5 m/sec at surface.

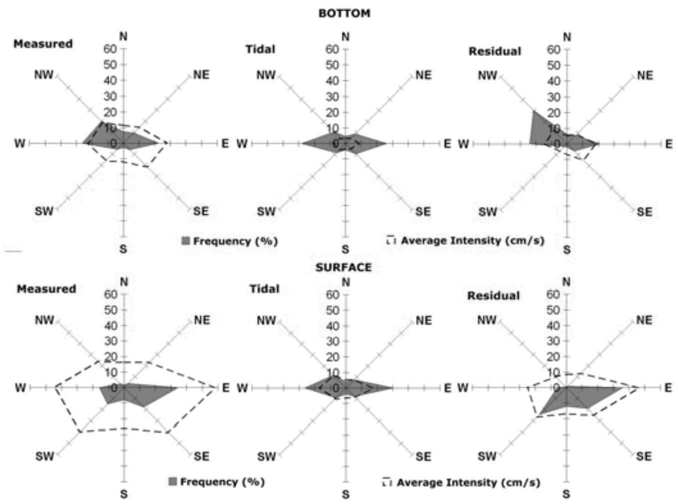

Figure 9. Bottom and surface directional distribution of occurrence frequency and average intensity for: measured data, astronomical tide components and residual flow components. ADCP 1.

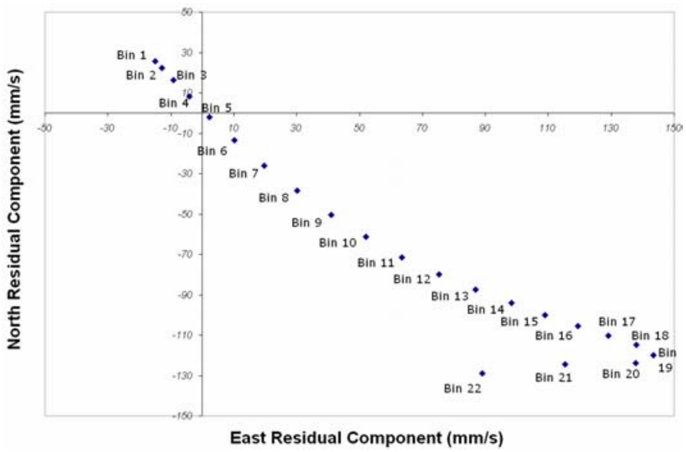

Figure 10. Residual velocity variation with depth in ADCP 1.

The residual velocity components obtained for all the analyzed period (662 days) show a varying net flux according to depth (Figure 10). At bin number one (1.27 m above the bottom) the net flux direction is Northwest. The net flux direction remains the same until bin number 4 (2.32 m) with a decreasing intensity. From bin number 5 the net flux changes toward Southeast and the intensity increases as it approaches the surface. The greatest net flux is reached at bin number 19 (7.57 m) and in the last layers the direction varies smoothly towards the South.

4.2 *ADCP 2*

4.2.1 *Intensity and Direction*

Figure 11 presents the directional distribution of occurrence frequency, average intensity and maximum intensity in the vertical profile computed from ADCP 2 current data. The Southeast and Northwest directions are identified as predominant flow directions throughout the vertical profile. Also West and North directions have high occurrence frequencies at the bottom. At the surface the Northeast flow decreases while the Eastward flow increases. Throughout the profile the Southeast and Northwest currents have the highest average and maximum intensities. The greatest average intensity is 0.42 m/sec towards the Southeast and the highest recorded in the area reached 1.7 m/sec towards the Southeast.

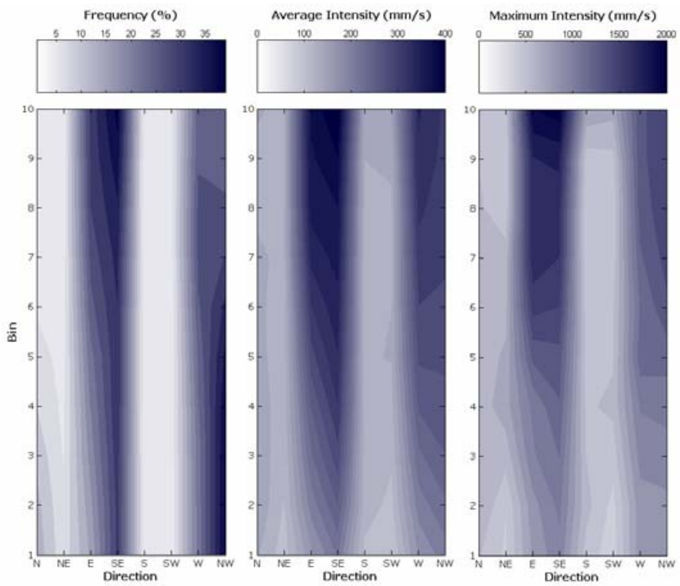

Figure 11. Directional distribution vertical profile of velocity frequency, velocity average intensity and velocity maximum intensity in ADCP 2.

4.2.2 *Astronomical Tide and Residual Components*

Figure 12 shows the occurrence frequency and average intensity roses for measured current, astronomical tide components and residual flow components in ADCP 2. The predominant tidal flow directions are the Northwest and the Southeast with average intensities smaller than 0.14 m/sec at bottom and 0.24 m/sec at surface. The residual flow has a spatial distribution different to the astronomical components and measured flow. The residual flow at bottom is mainly towards the Northwest. The residual flow at the surface is mainly towards the East and Southeast with average intensities of 0.2 m/sec in both directions.

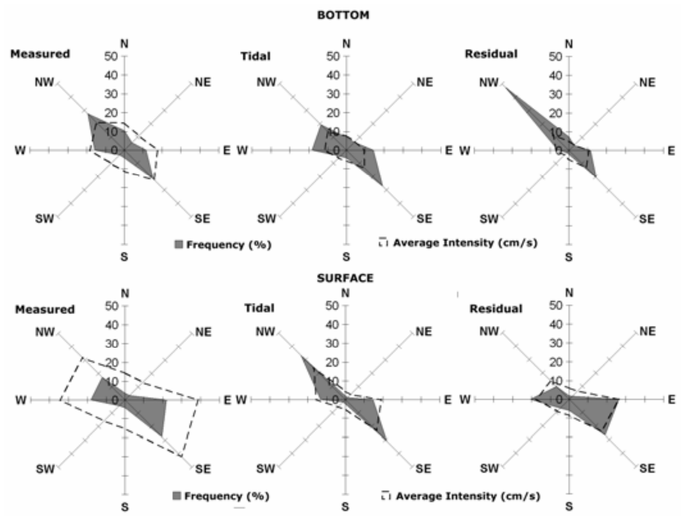

Figure 12. Bottom and surface directional distribution of occurrence frequency and average intensity for: measured data, astronomical tide components and residual flow components. ADCP 2.

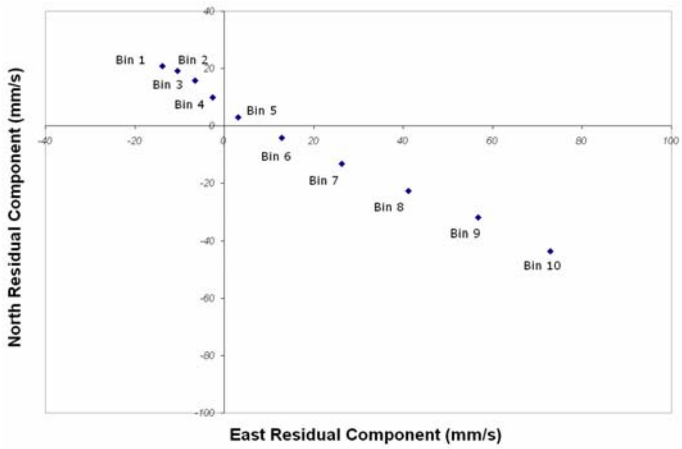

Figure 13. Residual velocity variation with depth in ADCP 2.

The average current vector computed for each bin shows the net flux behaviour in the area of the ADCP 2 measuring station. There is a change of the net flux alignment from Northwest to Southeast from bottom to the surface (Figure 13). The net flux intensity decreased until the bin number 5 and then it begins to rise again, reaching the maximum in the bin number 10 (5.9 m above the bottom).

5 VERTICAL CIRCULATION PATTERNS

5.1 *ADCP 1*

Results obtained from the simultaneous analysis of vertical flow patterns for the Punta Brava area (Table 1) show that the most common patterns are discharge (39%) and storage (35%). This means that almost 75% of the time the current at the bottom and surface have the same predominant direction. The gravitational circulation flow is observed on 22% of the analyzed period, while the reverse flow occurs only 4% of the time. The most frequent discharge flow pattern (44%) is a surface flow towards the SE quadrant and a bottom flow in the NE quadrant. The SW flow at the surface and NW flow at the bottom are the most frequent in the storage flow pattern (63%).

Table 1. Vertical Flow schemes distribution for ADCP 1.

Flow type	Quadrant		Frequency	
	Surface	Bottom	Relative	Absolute
Discharge: 39%				
	S-E	N-E	44 %	17 %
	S-E	S-E	36 %	14 %
	N-E	S-E	11 %	4 %
	N-E	N-E	9 %	4 %
Storage: 35 %				
	S-W	N-W	63 %	22 %
	S-W	S-W	14 %	5 %
	N-W	N-W	14 %	5 %
	N-W	S-W	9 %	3 %
Gravitational circulation: 22 %				
	S-E	N-W	45 %	10 %
	S-E	S-W	27 %	6 %
	N-E	S-W	16 %	3 %
	N-E	N-W	12 %	2 %
Reverse : 4 %				
	S-W	N-E	55 %	2 %
	S-W	S-E	19 %	1 %
	N-W	N-E	16 %	1 %
	N-W	S-E	10 %	0 %

The results obtained with the wind influence over the vertical circulation patterns analysis show that the reverse flow pattern is the most wind-influenced vertical pattern. Discharge and gravitational circulation type flows don't show a relationship with the winds. Among the storage flow pattern, the analysis shows a wind influence to the pattern with surface flow toward WS quadrant and bottom flow in SW or NW quadrant.

The vertical pattern time distribution computed for the residual flow is similar to the instantaneous flow: 37% of discharge, 36% of storage flow, 25% of gravitational circulation and 2% of reverse flow. The main quadrant structures identified for the instantaneous flow are maintained also.

5.2 *ADCP 2*

Results obtained show that the most common patterns are discharge and storage type flow with a frequency of 39% and 37%, respectively. That means the surface and bottom currents have the same mainly direction 76% of the time. A gravitational circulation flow vertical pattern (partially mixed estuary characteristic flow) ocurrs 18% of the time and the inverse flow 7% of the time. The most frequent discharge flow pattern has a surface and bottom currents towards the SE (75%). The flow opposite to that (bottom and surface current towards the NW) is the most frequent storage flow pattern type in the zone.

The vertical pattern time distribution computed for the residual flow is similar to the instantaneous flow: 37% of discharge, 37% of storage flow, 23% of gravitational circulation and 3% of reverse flow.

6 DISCUSSION

The main circulation patterns have been identified with the analysis of high quality vertical currents data profiles measured in Montevideo's coastal zone.

The behaviour of instantaneous flow shows that most of the time the vertical flow patterns correspond to a discharge or an storage type, i.e, the surface and bottom currents are not opposite. However, the gravitational circulation type flow is observed in several periods of time. In order to identify the influence of continental discharge, winds, salinity gradients, storms, etc, on the vertical flow patterns a more complex analysis should be performed.

Furthermore, the net flow analysis over a long periods of time can identify a large scale gravitational circulation flow pattern. The observed net flux has a non uniform vertical current distribution with a seaward flow in the surface layers and a landward flow at the bottom. This behaviour is associated with the estuarine classical water movement, a salty denser water entrance at the bottom combined with a fresher water outlet through the superficial layers.

The results show an influence of the coastline orientation on the flow patterns spatial behaviour in these two points of the coast of Montevideo. In Punta Yeguas the storage and discharge vertical flow patterns are symmetrical, with a preferential direction parallel to the adjacent coast direction. In Punta Brava the morphology is more complex and there is a localized contraction. This generates the deviation towards the Southwest of the storage flow (coastline direction at Punta Brava east) and a surface flow deviation towards the Southeast in the discharge type flow.

Finally, the results show that the current intensity in Punta Brava (ADCP 1) is larger than in Punta Yeguas (ADCP 2). Comparing the average values, it can be concluded that currents in Punta Brava are about 15% to 20% higher than in Punta Yeguas.

The characterization of waves in Montevideo's coastal zone was obtained with the measured waves in the ADCP 1. Approximately 35.4% of the waves are from the Southeast direction. The sea and swell height distribution were computed. The 5% of the analyzed waves have a significant height higher than 1.12 m.

In the future, additional data analysis will be made in order to improve the understanding of the water movement in this coastal zone.

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