Title: Characterization of bottom sediments in the Río de la Plata estuary

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Six oceanographic cruises at the 26 sites

CILAS - grain size distribution

Principal Components Analysis

Net sediment transport pathways
Research Highlights

Highlights

- We analyze bottom and suspended sediment samples collected in 6 cruises with 26 stations each.
- PCA is applied to the size histograms to investigate the spatial patterns of distribution.
- Sediment transport patterns information in grain-size parameters are analyzed by means of trend vectors.
- The inferred patterns are related to the geometry and the hydrodynamics of the estuary.
- A more reliable conceptual model of the bottom sediment distribution and the involved physical mechanisms is built.
Characterization of bottom sediments in the Río de la Plata estuary

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Abstract

Bottom sediments and surface water samples were collected in the Río de la Plata estuary during the FREPLATA/FFEM Experiment (2009-2010). Six repeated cruises, with 26 stations each, were performed in the intermediate and exterior estuary. Samples were processed for grain size using laser particle size analyzer, and water and organic matter contents. The aim of this work is to analyze this new data set to provide a comprehensive and objective characterization of the bottom sediments distribution in this estuary, to study their composition and to progress in the construction of a more reliable conceptual model of the involved physical mechanisms. Principal Components Analysis is applied to the bottom sediments size histograms to investigate the spatial patterns of distribution. Spatial variations in grain-size parameters contain information on possible sediment transport patterns, which were analyzed by means of trend vectors. Sediments in the upper and intermediate estuary are transported seawards and have a gradational arrangement of textures, from dominant sand at the head, silt in the intermediate estuary and clayey silt and clay at its mouth; textures become progressively more poorly sorted offshore, and the water and organic matter contents increase. The inferred patterns seem to be related to the geometry and what is known about the hydrodynamics. Along the Northern coast of the intermediate estuary, well sorted medium and fine silt predominates, whereas in the Southern coast, coarser and less sorted silt prevails. This could be due to differences in tidal currents and/or to differences in the riverine water pathways along both coasts depending on their source. Around Barra del Indio shoal, clay prevails over silt and sand, and the water and organic matter contents reach a maximum. Physicochemical flocculation processes probably become important there, and the width and the depth of the estuary also largely increase, producing a significant reduction of the currents. Immediately seawards the salt wedge, net transport reverses its direction and well sorted coarser sand dominates. This sand is much coarser than the sediment transported by the Río de la Plata tributaries, suggesting that it comes from the adjacent shelf. Around the Santa Lucía River mouth a different type of sediment is observed, consisting of poorly sorted fine silt and clay. We hypothesize that they are relict sediments. The inferred net transport suggests convergence at the Barra del Indio shoal, which is consistent with the constant growing of the banks observed in the Río de la Plata.

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1. Introduction

Between 15,000 and 20,000 million ton y\(^{-1}\) of suspended sediments reach the oceans in the entire world (Walling and Webb, 1996), 95% of them being carried by rivers (Syvitski, 2003). The amount of sediments transported by the Río de la Plata (RDP) estuary (Figure 1) has been estimated to more than 160 million tons y\(^{-1}\) (Menéndez and Sarubbi, 2007), representing more than 1% of the global estimation. Consequently, this estuary is one of the most turbid in the world, with extreme concentrations reaching more than 400 gm\(^{-3}\) (Framiñan and Brown, 1996; Moreira et al., 2013). It has been estimated that 90% (145 million ton y\(^{-1}\)) of the sediments that reach the RDP as suspended sediments are silt and clay, whereas around 10 million ton y\(^{-1}\) correspond to very fine sand (Sarubbi, 2007). Coarse sand is transported as bed load and has been estimated to 15 million ton y\(^{-1}\) (Amsler and Drago, 1988; Amsler, 1995). All those sediments mainly come from the Paraná River, the main tributary, which reaches the estuary after forming a large delta with two main branches: the Paraná Guazú to the north, and the Paraná de las Palmas to the south (Figure 1). In contrast, the second main tributary, the Uruguay River, has a much smaller sediment load (Menéndez et al., 2009). The drainage of a number of small tributaries along the Argentinean coast contribute to a minor part of the total solid discharge to the Rio.

Besides its geographical extension, the RDP is of large social, ecological and economic importance for the countries along its shores (Argentina and Uruguay). The capital cities of both countries (Buenos Aires and Montevideo) and a number of harbors, resorts and industrial centers are located on its margins and influence zone. The estuary constitutes the main source of drinking water for the millions of inhabitants in the region, for whom it is also an important recreational area.

The RDP is rich in nutrients and, therefore, has an abundant and diverse fauna. It shelters important fisheries and has the unusual feature of being both a spawning and nursery area for several coastal species (Cousseau, 1985; Boschi, 1988; Macchi et al., 1996; Acha et al., 1999; Acha and Macchi, 2000; Berasategui et al., 2004, 2006; Rodrigues, 2005). Samborombón Bay is one of the most important wetlands of Argentina and is home to a number of species of fishes, turtles, crabs and migratory birds (Lasta, 1995; Canevari et al., 1998). The fresh water plume of the RDP impacts the shelf in a distance of more than 500 km to the north (Campos et al., 1999).

Many environmental questions in the RDP and the adjacent shelf are linked to the bottom sediments distribution and their dynamics. The most significant issues include optimization of dredging operations (e.g., Cardini et al., 2002), understanding geomorphological change (e.g., Codignotto et al.,...
2012; Dragani et al., 2012), contamination (e.g., Colombo et al., 2005, 2007), benthic ecology (e.g., Gómez-Erache et al., 1999), primary productivity (e.g., Gómez-Erache et al., 2004, Huret et al., 2005) and fisheries (e.g., Jaureguizar et al., 2003a,b; 2008). Nevertheless, the subject has received relatively little attention from the scientific community, especially during the last few decades. The distribution of surficial bottom sediments in the RDP was discussed by Urien (1966; 1967; 1972), Parker et al. (1986a,b; 1987), López Laborde (1987a,b) and Parker and López Laborde (1989) on the base of data from a number of diverse sources collected mostly during the sixties and seventies. More recently, López Laborde and Nagy (1999) compiled the results of the previous papers and presented a map of the sediment distribution according to Shepard (1954) diagram. Probably due to the nature of the available data, their figure is noisy and presents several features that are difficult to interpret in the light of the most recent understanding of the estuary hydrodynamics (e.g., Simionato et al., 2004, 2006, 2007; Meccia et al., 2009, 2013).

The FREPLATA/FFEM (Environmental Protection of the Río de la Plata and its Maritime Front / French Fund for the Global Environment) Experiment was performed between November 2009 and December 2010. It consisted in building a data base of new in-situ observations in order to help understand the hydro-sedimentological processes in the estuary (Simionato et al., 2011a,b; Fossati et al., 2014) and to validate sediment dynamics numerical models. The experiment included six cruises with 26 oceanographic stations each during which, among other measurements, water and bottom sediment samples were collected in the intermediate and outer RDP. Particle size distributions (inferred from laser diffraction) as well as water and organic matter contents were derived for all samples, providing, for the first time, repeated and simultaneous measurements of those variables. The sampling strategy was meant to: 1) investigate the occurrence of possible seasonal variability in bottom and suspended sediments type and concentration; 2) investigate possible changes since previous bottom sediment maps; and 3) help interpret sediment fluxes between the bottom and the water column, making sure that the bottom was sampled at the same time as the water column.

The aim of this paper is to analyze this new data set in order to provide a more comprehensive and objective characterization of the bottom sediments distribution in the RDP, to study their composition including (for the first time) the organic matter and water contents and to progress in the construction of a more reliable conceptual model of the involved physical mechanisms. This knowledge is essential as a first step in the construction and validation of numerical models, which are needed for management and scientific purposes in this socially, economically and ecologically important region. This paper is organized as follows. In section 2 we provide a description of the most relevant features of the study area. In section 3 we describe the samples acquisition and laboratory
analysis. In section 4 we discuss the methods that are applied to analyze the data. In section 5 we present the results of diverse analyses. Finally, in section 6 we summarize and discuss the results, to build a conceptual model of the dominant sedimentological processes that occur in the different parts of the estuary, and compare our results to those of previous studies.

2. Study area

The RDP (Figure 1), located on the eastern coast of southern South America at approximately 35° S, is one of the largest estuaries in the world (Shiklomanov, 1998). It has a northwest to southeast oriented funnel shape approximately 300 km long that narrows down from 220 km at its mouth to 40 km at its upper end (Balay, 1961). The estuarine area is 35,000 km² and the fluvial drainage area is 3.1×10⁶ km² (Framiñan et al., 1999).

The RDP displays a complex geometry and bathymetry. A complete description of its morphology can be found in Ottman and Urien (1965; 1966), Urien (1966; 1967; 1972), Depetris and Griffin (1968), Parker et al. (1986a,b; 1987) and López Laborde (1987a,b). The estuary is divided into two regions by the Barra del Indio shoal, a shallow area that crosses the estuary between Punta Piedras and Montevideo (Figure 1). The upper region is mainly under fresh water influence. Seaward of this shoal is the Maritime Channel, a wide depression 12-14 m deep in the north and 20 m deep in the south. It separates Samborombón Bay to the west from a region of banks known as Alto Marítimo (with depths ranging from 6 to 8 m) and the Rouen Bank (with depths between 10 and 12 m). The Oriental Channel, the deepest zone of the estuary with depths of up to 25 m, extends along the Uruguayan coast. Samborombón Bay is a very shallow and extensive area with depths ranging from 2 to 10 m extending south of Punta Piedras and up to Punta Rasa.

The RDP drains the waters of the Paraná and Uruguay rivers, which constitute the second largest basin of South America. It exhibits a very high discharge of around 22,000 m³ s⁻¹ on average, and peak discharges as high as almost 90,000 m³ s⁻¹ and low discharges under 8,000 m³ s⁻¹ during extreme conditions, related to the El Niño - Southern Oscillation cycles (Jaime et al., 2002). Density in the estuary is controlled by salinity, whereas temperature exhibits small horizontal gradients (even though inter-annual variability may be high, Guerrero et al., 1997). Water stratification is controlled by the confluence of highly buoyant continental discharge advecting offshore, lying on denser shelf waters that intrude into the estuary as a topographically controlled salt wedge. This salt wedge is typically between 100 and 250 km long (Guerrero et al., 1997) and defines a bottom salinity front, over the
Barra del Indio shoal following the 10 m isobath (Guerrero et al., 1997). Forced by the prevailing winds (Simionato et al., 2001) both surface and bottom salinity fronts show a seasonal cycle that largely modifies the salt wedge structure from spring-summer to fall-winter (Guerrero et al., 1997). The high wind variability that characterizes the region also forces significant variability in synoptic time scales in the estuarine variables (Simionato et al., 2006a,b; 2007; Meccia et al., 2009, 2013). Over long-term time scales, a spatial overlap has been observed between the bottom salinity front and an estuarine turbidity maximum characterized by elevated turbidity and suspended sediments (Framiñán and Brown, 1996; Moreira et al., 2013).

3. Data

The samples analyzed in this paper were collected between 2009 and 2010, in the frame of the FREPLATA/FFEM Experiment, funded by the French Fund for the Global Environment (FFEM). Six oceanographic synoptic cruises spaced approximately every 2 months took place during the experiment, in November, 2009 and March, June, August, October and December, 2010. Each cruise lasted 2 to 3 days and visited the 26 sites listed in Table 1 and shown as blue dots in Figure 1. Water and bottom sediments samples were gathered using a Fly pump and a stainless steel Van Veen grab, respectively. Water from the sub-surface, at a depth of approximately 2 m was collected in 20 liter bottles, whereas bottom sediment samples were saved in sealed bags.

Samples were analyzed at the Marine Geology Laboratory of the Hydrographic Service (SHN) of Argentina for water and organic matter contents. Sediments destined for water content analysis were weighed, dried at 80° C for one week, cooled to room temperature and finally weighed. The water percentage was calculated as the difference between the weight before and after drying, divided by the initial sample weight. To determine the organic matter content, samples were dried at 60° C for one week and then triturated. They were then weighed and transferred to a small pot for ignition at 450° C during 3 hours. The burnt sediments were transferred to a drying bell (with silica gel) during 30 minutes to cool without absorbing external moisture, and finally weighed. The organic matter content was estimated as the weight difference before and after ignition.

Grain size analyzes were performed for the samples collected in cruises 2 to 6 in the Sedimentological Laboratory of the Geology Department of the University of Buenos Aires. A grain size analyzer using a laser diffraction optical system integrated with a charge-coupled device (CCD) camera (CILAS 1180) was used. This analysis allows the measurement of particles with diameters
ranging from 0.04 to 2,500 µm. The smaller particles (0.04-500 µm) were measured capturing a diffraction pattern and applying the theory of Fraunhofer or Mie, whereas the coarser particles were measured using real time Fourier transforms of the images captured by the CCD camera, which is equipped with a digital processing unit (DSP). Every sample was mechanically agitated for a few minutes to homogenize it. A representative portion of the sample was introduced into the analyzer, where the sediment was object of ultrasonic vibration during 60 seconds before the measurement. The sediment was treated with a solution of hydrogen peroxide (H₂O₂) at 20% for 2-3 weeks, until complete removal of organic matter. Then, the samples were washed with distilled water and centrifuged at 20,000 rpm during 20 minutes to completely separate the solid and liquid fractions. The liquid fraction was discarded and the solid fraction was transferred to glass jars (30 cc) and diluted with distilled water. When gravel size material was detected, usually due to the presence of bivalve and gastropod shells, the sediment was sieved with sieve #10, so that only the fraction with diameters less than 2 mm was analyzed with the CILAS particle analyzer.

4. Methods

In this work, we analyze the data described in the previous sections using different statistical methods. Given that we had six repeated observations at each of the 26 sampled locations (Figure 1), to present the mean distributions (Figures 2 and 3, first and second panels) we computed the mean and standard deviation among samples, defined as:

\[
\bar{G} = \frac{1}{6} \sum_{i} G_j 
\]

(1)

\[
\sigma_G = \frac{1}{6} \left[ \sum_{i} (G_j - \bar{G})^2 \right]^{\frac{1}{2}}
\]

(2)

where \( G \) is the variable under analysis (percentage content of sand, silt, clay, water and organic matter contents).

For every sample, the mean grain size, \( \mu \), standard deviation, \( \sigma \), and skewness, \( Sk \), were calculated using the statistic moment method (McManus, 1988):
\[
\mu = \sum_{i=1}^{n} P_i S_i \quad (3)
\]

\[
\sigma = \left[ \sum_{i=1}^{n} P_i (S_i - \mu)^2 \right]^{\frac{1}{2}} \quad (4)
\]

\[
Sk = \left[ \sum_{i=1}^{n} P_i (S_i - \mu)^{\frac{3}{2}} \right]^{\frac{1}{3}} \quad (5)
\]

where \(i\) is size class, \(P_i\) is percent of size \(S_i\), and \(n\) is the total number of size class.

The sediments were classified according to Shepard (1954). The SEDPLOT tool (http://woodshole.er.usgs.gov/software/sediment-software.html) was used to construct the Shepard’s classification scheme in the Wentworth (1922) grade scale.

We applied the Principal Components Analysis (PCA, Preisendorfer, 1988) to analyze the large number (5×26) of different CILAS grain size histograms obtained from the 5 different samples (cruises 2 to 6) collected at each of the 26 stations. The aim is to objectively extract “characteristic histograms” for different portions of the estuary and, therefore, reduce the dimensionality of the problem; this is possible because, as it will be discussed later, seasonal variability in the bottom samples is almost negligible. This type of treatment allows taking into account the relationships (represented by the correlation matrix) among all the studied histograms. The PCA creates new “characteristic histograms”, the principal components (or PCs), which are uncorrelated and are the eigenvectors of the correlation matrix. They are derived in decreasing order of importance so that, for example, the first PC accounts for as much as possible of the variance of the original data (original histograms). The percentage of the total variance accounted for each PC is interpreted as the portion “explained by” the “characteristic histogram” represented by the PC. In our case this percentage will be directly proportional to the number of samples that are represented by the mode. The most important point of PCA is that the PCs reveal groupings of histograms and/or outliers which would be difficult to find by other means and that can be associated to sedimentological processes. The user has to look at the groups of “characteristic histograms” suggested by the PCs and consider whether the components have some meaningful interpretation or are simply mathematical artifacts. The PCA analysis discussed in this paper differs from the Shepard's classification, also applied in this work, in the fact that it takes into account the shape of the grain size distribution (or histogram) and not only the fractions of silt, clay and sand. Therefore, results can provide further information about sedimentological processes. This analysis has been used by other authors with the same aim as in this work (e.g. Cheng, et al., 2004; Skene et al., 2005).
Finally, we applied grain size trend analysis to study possible sediment transport paths in the RDP. McLaren (1981) and McLaren and Bowles (1985) statistically related net sediment transport paths to spatial changes in the mean grain size ($\mu$, equation 3), the variance ($\sigma^2$, equation 4) and the skewness ($S_k$, equation 5) of the distribution. For two sampling sites $d_1$ and $d_2$, if the net transport direction is from $d_1$ to $d_2$, there are two cases of grain size changes from $d_1$ to $d_2$:

**Case 1:** $\sigma^2_2 \leq \sigma^2_1$, $\mu_2 > \mu_1$ and $S_k_2 \leq S_k_1$

**Case 2:** $\sigma^2_2 \leq \sigma^2_1$, $\mu_2 < \mu_1$ and $S_k_2 \geq S_k_1$

Gao and Collins (1991, 1992) developed a two-dimensional statistical model which derives an estimation of the net sediment transport patterns from the bottom sediment spatial distribution. The methods may be split into 3 consecutive steps. The first step consists in defining trend vectors for a grid of sampling sites, by comparing each sample with its neighbors. To identify a “neighboring” site, a characteristic distance ($D_{CR}$) representing the space-scale of sampling, is specified. If the distance between any two sites is smaller than this characteristic distance, they are considered as neighboring sites and their grain-size parameters are compared. If either a Case 1 or a Case 2 trend (described previously) is identified between the two sites, then a dimensionless “trend” vector is defined for the site with the higher variance. The direction of such a vector runs from the site with a higher variance to that with a lower value. The length of the vector is assumed, for convenience, to be unity.

Secondly, at each sampling site, there may be more than one unit-length vector. Therefore, for such a site, vectors are summed to produce a single vector:

$$\vec{R}(x, y) = \sum^n_i \vec{r}(x, y)_i$$  \hspace{1cm} (6)

where $n$ is the number of trend vectors identified for the site, $\vec{r}(x, y)$ is a trend vector, and $\vec{R}(x, y)$ is the sum of the trend vectors. Both the real transport trends and some noise are included in $\vec{R}(x, y)$, although the amount of the noise may have been reduced already due to the summing process.

The third step consists in removing the noise included in the vectors at each site. It is assumed that the various components of noise do not exhibit any ordered pattern, so that the noise may be removed by averaging the vectors of a particular sampling site with the vectors from adjoining sites. Once again, an adjoining site is assessed on the basis of the characteristic distance ($D_{CR}$) defined
previously. The averaging procedure is equivalent to the following mathematical transformation for the site at which \( \bar{R}(x,y) \) is defined:

\[
\bar{R}_{av}(x,y) = \frac{1}{k+1}[\bar{R}(x,y) + \sum_{i=1}^{k} R_i]
\]  

(7)

where \( \bar{R}_i \) is a summed trend vector obtained on the basis of equation (6) at a neighboring site, and \( k \) is the total number of such sites. The vectors \( \bar{R}_{av} \) can be defined as transport vectors; they form a residual pattern, with little influence from noise. If the residual trends have an ordered pattern in the arrangement of the transport vectors, then they should represent statistically and conceptually possible net transport paths.

Finally, the length of the characteristic vector is defined by:

\[
L = \sum_{i=1}^{N} |\bar{R}_{AV}(x,y)_i|
\]  

(8)

5. Results

5.1. Mean distribution of bottom sediments and water and organic matter contents

The samples analysis reveals that the fields of sand, silt and clay contents display low variability throughout the year and that variability does not seem to follow an obvious seasonal cycle. This low variability may be due to the fact that the samples are collected with a grab, and therefore integrate a mix of sediments deposited over a long period of time: seasonal variability could only be captured thanks to a technique allowing the sampling of the very upper bottom sediments layer. Another reason may arise from the fact that the wind forced synoptic signal is very dominant in this estuary (e.g., Simionato et al., 2006, 2007, Meccia et al., 2013). Any possible small seasonal signal therefore may not be detected with samples collected throughout only one year.

To discuss the results and to illustrate the regions with more or less variability between samples, we show the mean fields and the standard deviation between samples. This way, the mean percentage of sand (grain sizes between 62.5 and 250 \( \mu \)m), silt (grain sizes between 3.9 and 62.5 \( \mu \)m) and clay (grain sizes less than 3.9 \( \mu \)m, in the Wentworth scale classification) computed according to equation (1)
from the samples collected during the FREPLTA/FFEM Experiment are shown in the upper, central and lower left panels of Figure 2, respectively. The right panels of the figure display the standard deviation between samples (according to equation 2).

The concentration of sand (upper left panel of Figure 2) maximizes in the outer estuary, where it connects to the adjacent continental shelf. There, the percentage of sand reaches 70% and, as it will be shown below, mean grain size is around 170 µm, much coarser than for the other sampled sites. The standard deviation (upper-right panel of Figure 2) is relatively low (less than 5%) indicating low variability between samples. A low percentage (less than 10%) of very fine sands (as it will be shown below, with sizes less than 70 µm) is observed in the upper estuary and along the southern (Argentinean) coast of the intermediate estuary, with a relatively higher standard deviation (up to 7%).

Stars have been superimposed in the upper left panel of Figure 2 to indicate the regions where very coarse carbonated deposits were found in the samples (bivalves and gastropods’ shells greater than 2 mm); the size of the stars is proportional to the mean coarse sediment content. This type of shell deposits are more abundant in the northern sector of the exterior estuary, close to Montevideo, with concentrations between 10 and 40%. A lower percentage is observed to the northwest of Punta Piedras, where concentrations are less than 1%.

The mean percentage concentration of silt is shown in the central left panel of Figure 2, which shows that this grain texture is present throughout the RDP, and constitutes the most abundant sediment in the upper and intermediate estuary. In these last regions, a marked south-north gradient is observed, with an extended maximum over the Ortiz Bank where concentrations exceed 80%. Here, the standard deviation (central right panel of Figure 2) is very low, indicating low variability between samples. The orientation of the isolines dramatically changes seawards Barra del Indio shoal, where they align normally to the estuary axis. Here, the concentration rapidly decays offshore. Maximum variability among samples is observed close to Montevideo and to the north of Punta Piedras, even though values are small (less than 10%).

Finally, the lower left and right panels of Figure 2 show the mean percentage concentration and the standard deviation between samples for clay. In this case, a seawards oriented gradient is observed. The mean concentration of clay maximizes immediately downstream Barra del Indio shoal, to the east of Punta Piedras, with values higher than 40%. The standard deviation is less than 7% and maximizes along the imaginary line between Punta Piedras and Montevideo, with absolute maxima close to these locations.

Figure 3 shows the mean percentage concentration and standard deviation between samples of the water (Figure 3a and b) and organic matter (Figure 3c and d) contents. Both distributions resemble
those of the clay, reflecting the degree of consolidation of bottom sediments. Given that the size of the clay is very small, it is more difficult for this type of sediment to reach consolidation; the water content therefore maximizes where the concentration of that texture is the greatest. The maximum water content variability between samples was observed in the northern exterior estuary close to Montevideo (Figure 3b), in the area related to the wind-forced displacement of the RDP freshwater plume (Simionato et al., 2001; Meccia et al., 2013).

Both the concentration of organic matter in the bottom sediments samples and the standard deviation between samples (Figure 3c and d) maximize in a broad area seawards the Barra del Indio shoal, coinciding with the area where the water content is larger. It has been observed that in this area turbidity rapidly decays towards the sea (Framiñan and Brown, 1996; Moreira et al., 2013).

5.2. Bottom sediment diameter and degree of sorting

Figure 3 also shows the mean (Figure 3e), mode (Figure 3f) and standard deviation (Figure 3g) of the bottom sediments size. This figure was built after applying an arithmetic mean to the five CILAS distributions available at each of the 26 stations, and normalizing the distributions obtained so that the total is 100%. The Figure 3h, shows the degree of sorting defined as the ratio between the standard deviation (equation 4) and mean grain size (equation 3) (Skene et al., 2005).

Figure 3e and f reveals that the mean and the mode present a similar pattern, with a minimum at the Barra del Indio area, between Punta Piedras and Montevideo. Fine silt and clay with diameters less than 15 µm are present in the bottom sediments in this region, and standard deviation also reaches a minimum, with values less than 15 µm. The sediment size increases both upstream and downstream the Barra del Indio shoal. Coarser sediments (sand with $d_{50}\sim170$ µm) dominate at the exterior part of the RDP; this sediment is characteristic of the maritime zone (Ottman and Urien, 1966). Upstream the Barra del Indio shoal, sediment size does not only increase, but also a small north-south gradient is observed, with a secondary maximum along the Argentinean coast of the intermediate RDP. The mean diameter there is of around 40 µm, which corresponds to coarse silt. The standard deviation (Figure 3g) shows a distribution that resembles that of the mode, so that maximum values are observed where the grain size is larger.

The degree of sorting (Figure 3h) shows a marked gradient in the direction of the estuary axis, with maximum values (corresponding to poorly sorted sediment) over the Barra del Indio shoal and decreasing values upstream and downstream that area. The absolute minimum occurs in the maritime zone, where well sorted sand is present (Figure 2). Sorting values decrease from the Barra del Indio...
region toward the inner estuary, indicating that sediments are better sorted, with more similar sediment sizes. In general, sediments are poorer sorted along the Argentinean coast than along the Uruguayan coast.

5.3. Sediment’s distribution according to Shepard’s classification

The right panel of Figure 4 displays the Shepard classification scheme (without considering shell deposits) calculated for the RDP, whereas the left panel shows a schematic distribution map for the different types of bottom sediments over the estuary, according to that classification. The Shepard scheme (right panel of Figure 4) shows that sediments classified as “sand” are only present in site number 19 (yellow in the left panel of Figure 4), located in the exterior RDP, and seem to not have the same origin as the sediments observed in the rest of the estuary. “Sandy silt” is observed in sites 2, 5 and 6 (dark brown in the left panel of Figure 4), corresponding to the Argentinean coast of the upper and intermediate estuary. Sediments classified as “silt” are observed in the northern intermediate estuary, over and downstream the Ortiz Bank in sites 1 (close to Buenos Aires harbor), 3, 4, 7, 8, 9, 11 and 12, (dark green in the left panel of Figure 4). Sediments classified as “clayey silt” are present over and seawards Barra del Indio shoal in sites 10, 13, 14, 15, 16, 17, 18, 20, 21, 22, 23 and 26 (light green in the left panel of Figure 4).

5.4. Principal components analysis of the bottom sediments distribution

PCA was applied to the $5 \times 26 = 130$ histograms resulting of the CILAS grain size analysis on the samples collected during cruises 2 to 6 at each of the 26 stations. The aim of this analysis was to reduce the dimensionality of the problem, and to investigate whether spatial patterns of homogeneity and significant relationships between stations could be derived, taking into account the (small) variability between samples gathered at each site. The results of the analysis are summarized in figures 5 and 6. Figure 5 schematically shows the areas where each of the derived PCs dominate, identifying five different regions of the estuary.

The first PC (Factor 1) accounts for 70% of the total variance of the histograms. Grain size distributions of sites 1, 4, 7, 8, 9, 11 and 12 (dark green in Figure 5) are negatively correlated with this PC with a maximum loading (or correlation) of -0.99 with the sample collected at site 9 during the third cruise. This last station is located to the north of the intermediate estuary, close to the Uruguayan coast.
and halfway between Colonia and Montevideo. Grain size distributions of stations 13, 14, 15, 16, 17, 18, 20, 21, 22, 23 and 26 (light green in Figure 5) are positively correlated to Factor 1. The highest correlation between the mode and the histograms is observed for site 20 (located to the southeast of Punta Piedras), with a maximum of +0.94 for the sample collected during the second cruise.

The second PC (Factor 2) accounts for 20% of the total variance of the set of histograms. The highest positive loading occurs for site 10 (with a maximum of +0.88 for the sample collected during the fourth cruise), but this mode also correlates well with observations gathered at the stations 24 and 25, and partly, 23 (orange in Figure 5). These four sites are located along the northern coast of the intermediate RDP, close to the Santa Lucía River mouth. Factor 2 is negatively correlated with grain size distributions of sites 2, 3, 5 and 6 (dark brown in Figure 5); the highest loading is observed for site 2 (with a maximum of -0.97 during the fourth cruise). These sites are located along the southern coast of the upper intermediate estuary.

Finally, Factor 3 accounts for 5% of the total variance; this mode is negatively correlated to grain size distribution of site 19 (with a maximum of -0.98 for the sample collected during the fifth cruise), located at the exterior RDP (yellow in Figure 5).

This way, the PCA analysis reduced the 130 samples to 5 characteristic histograms describing the bottom sediment of the estuary. In order to show real histograms and not (mathematical) modes, Figure 6 shows the characteristic grain size distributions for the five regions identified from the PCA, represented by the histogram with the largest correlation to the modes:

- The positive phase of Factor 1 (Figure 6a), represented by site 20 cruise 2, corresponds to a region where sediments are typically “clayey silt” (mixed sediment, 53.75% of silt and 46.25% of clay, very poorly sorted) with very fine silts and clays (less than 5 µm). Hereinafter we will refer to this area as “Barra del Indio region” (light green in Figure 5).

- The negative phase of Factor 1 is represented by site 9 cruise 3 (Figure 6b). It is a zone where sediments are typically “silt” (similar size sediment, 0.56% of sand, 85.52% of silt and 13.92% clay, well sorted) with medium and fine silts, with diameters of 10 to 30 µm. In what follows, we will refer to this region as “Northern coast of the intermediate RDP” (dark green in Figure 5).

- The positive phase of Factor 2 is represented by site 10 cruise 4 (Figure 6c), where typical sediments are “clayey silt” (more mixed sediment, 0.70% of grave, 68.40% of silt and 30.89% of clay, poorly sorted). The grain size distribution indicates that the sediments are medium and fine silt (diameters up to 30 µm) with a percentage of clay (diameters of 0.1 to 0.4 µm). This
zone has more silt than the area associated to the positive phase of Factor 1 (Figure 6b). We will refer to this area as “Santa Lucía region” (orange in Figure 5).

- The negative phase of Factor 2 (Figure 6d), represented by site 2 cruise 4, is characterized by “sandy silt” (mixed sediments, 19.24% of sand, 71.39% of silt and 9.37% of clay, poorly sorted). We will refer to the region as “Southern coast of the intermediate RDP” (dark brown in Figure 5). Grain size distribution for this area shows mean diameters of 30 to 60 µm for the coarse silts and, up to 80 µm for the very fine sands; sediments here are coarser than in the previously mentioned areas.

- Finally, the negative phase of Factor 3 (Figure 6e), represented by site 19 cruise 5, is characterized by “sand” (94.01% of sand, 3.08% of silt and 2.91% of clay, well sorted) with medium and fine sands. The mean grain diameter for this region is about 200 µm, the largest in the estuary. We will refer to this area as “Exterior RDP” (yellow in Figure 5).

5.5. Suspended sediments distribution for the identified main zones of the Río de la Plata

To complement the study of the bottom sediments grain size distribution, we also analyzed the suspended sediments grain size distribution (water samples were collected at the same stations as bed samples). Results (Figure 7) show that over the five areas previously characterized, the grain size distribution of the suspended sediments presents thinner particles than the bottom sediments; the histograms displayed by Figure 7 correspond to the same sites and cruises that those of Figure 6. The following can be observed:

- Over the “Barra del Indio” region (Figure 7a) suspended sediments correspond to 30.20% of silt and 69.80% of clay, “silty clay” in the Shepard classification. Compared to the bottom sediments (Figure 6a), there is less silt and more clay in suspension than in the bottom. This is consistent with the nature of the sediments: the thinner particles remain in suspension, whereas the coarser ones settle to the bottom.

- In the “Northern coast of the intermediate RDP” region (Figure 7b), the Shepard’s classification of the suspended sediments (0.87% of sand, 85.87% of silts and 13.26% of clays) is “silt”, similar to the bottom sediments (Figure 6b). The grain size distributions differ in the presence of finer silts, with diameters between 5 and 15 µm, in the suspended sediments.

- The “Santa Lucía” area (Figure 7c) is characterized “silt” type suspended sediments according to Shepard’s classification, whereas the bottom sediments were classified as “clayey silts”. This
is due to the fact that there is more silt and less clay in the suspended sediments (87.10% of silt and 12.90% of clay). The grain size histograms for the suspended and bottom sediments samples are, therefore, different. The diameter of the suspended particles goes up to 20 µm and there is a lower percentage of coarse clay (around 1 µm) than in the bottom sediments.

- For the “Southern coast of the intermediate RDP” region (Figure 7d) the Shepard’s classification identifies “silt”, whereas the bottom sediments are “sandy silt”. The grain size distribution of the suspended sediments shows less sand (only 0.23%) and more silt and clay (82.52% and 17.25%, respectively). Figure 7d shows that the mean diameter of the suspended sediments (ranging from 5 to 20 µm) is thinner than for the bottom ones and with a larger percentage of fine sediment (clays with diameters around 0.3 µm).

- Finally, in the “Exterior RDP” region (Figure 7e) the analysis reveals a completely different grain size distribution between the suspended and bottom sediments. Suspended sediments have a very low percentage of sand (0.48%) and abundant silt and clay (67.20% and 32.32%, respectively). They correspond to “clayey silt” in the Shepard’s classification, very different from the “sandy” region identified for the bottom samples. Bottom sediments (diameters between 100 to 200 µm) are much coarser than the suspended ones (diameters from 0.8 to 20 µm), which must have a different origin and have been obviously advected there.

5.6. Net sediment transport pathways

The data set of computed grain-size parameters was used for a trend analysis to determine statistically possible net sediment transport pathways. To define the trend and transport vectors, the characteristic distance $D_{CR}$ has been chosen to 60 km, slightly larger than the maximum sampling interval for this particular investigation (~45 km). Therefore, any two samples with a distance less than 60 km were compared. Transport vectors were derived according to equations (6) and (7). The identified residual grain-size trends (Figure 8) show a highly ordered pattern, with a characteristic (non dimensional) vector length ($L$), estimated according to equation (8), of 1.35.

The statistical net sediment transport patterns, represented by the grain-size trends, reveal several distinct characteristics. Firstly, in most of the RDP the sediment transport is suggested to be towards the southeast, that is, seawards. This is the case for every sampled point, with the exception of station 19, for which the model suggests upstream transport. A slight upstream transport is computed for station 18, but the associated vector length is very small, almost negligible. This different behavior agrees with the PCA analysis which clearly identified station 19 as an outlier: this station exhibits a
grain size distribution which is not characteristic of the sediments transported by the RDP estuary, and that seems to be originated from the adjacent shelf. Figure 8 also reveals that the statistical net sediment transport increases from the estuary head to the intermediate RDP, and then it decreases again up to the Barra del Indio shoal. This suggests a convergence in this last area.

The transport divergence suggested by Figure 8 between stations 1, 2 and 3 and those located immediately downstream seems to be a mathematical artifact due to the fact that only a few measurements were done in the upper estuary, more than a real feature.

6. Discussion and conclusions

The characterization of the bottom sediments and the statistical net sediment transport pathways of the RDP discussed in the previous sections allow making inferences about the sedimentological processes that take place in the different parts of the estuary. All along the upper and intermediate estuary, up to Barra del Indio shoal, sediments are transported to the southeast, *i.e.*, seawards (Figure 8). Bottom sediments have a gradational arrangement of textures, from sand at the head, silt in the intermediate estuary and clayey silt and clay at the mouth (figures 2, 4 and 5). The textures become progressively less sorted (Figure 3h), and the water and organic matter contents also increase towards the estuary mouth (Figure 3a and c). In the region seawards the salt wedge (and the Barra del Indio shoal), well sorted coarser sand dominates. The derived transport and the gradational arrangement of textures seem to be related to the geometry and what is known about the hydrodynamics of the estuary.

Fine sands carried by the RDP main tributaries are deposited at the estuary head (not sampled during the FREPLATA/FFEM experiment), forming the Paraná River Delta and Playa Honda (Brea *et al*. 1999). The fine sands are kept in suspension within the tributary rivers thanks to the high level of turbulence they encounter, but they quickly settle to the bottom when the width and depth of the estuary increase, which leads to a decrease in the currents speed (Brea *et al*. 1999; Simionato *et al*., 2004; Moreira *et al*., 2013). Coarser sands transported by bed load also settle in this region (deposits are estimated to reach 15 million ton y⁻¹, Amsler and Drago, 1988; Amsler, 1995). This mechanism permits a rapid seaward progress of the Paraná River delta. At the present growing rate, the delta could reach Buenos Aires city by the end of this century (Sarubbi, 2007). Most of the sand is therefore deposited within the delta and its front, which explains why the sediments transported beyond include a relatively small percentage of sand, and mainly consist in silt and clay.

In the intermediate RDP, silt (with percentages more than 70%) predominates over clay and
sand, and in the area of the bottom salinity front (following approximately the Barra del Indio shoal) bottom sediments are composed by almost equal parts of fine silt and clay with diameters less than 5 µm (figures 2, 5 and 6). The progressive dominance of these much finer sediments may be due to the fact that clay, smaller and lighter than the silt, can remain in suspension for a longer time and travel farther away from the source. However, our analysis indicates the occurrence of different types of bottom sediments mixtures in the northern and southern portions of the intermediate RDP (figures 4 and 5). The northern coast is characterized by well sorted sediments including more than 85% silts, with sizes between 10 and 30 µm (figures 5 and 6b). The southern coast, instead, is characterized by coarser and less sorted sediments, with diameters between 30 and 60 µm (figures 5 and 6d). Here, even though more than 70% of the bottom sediments are silt, the percentage of sand reaches almost 20%. The difference between these two regions might also be due, at least in part, to the hydrodynamics. Tidal currents are indeed much stronger along the southern coast of the estuary than along its northern coast (Simionato et al., 2004). It has been suggested that this could drive higher concentrations of suspended sediments along the Argentinean coast (Moreira et al., 2013). We hypothesize that this also might inhibit the deposition of sands (or resuspend them) which could therefore be transported further downstream. Along the northern coast, over the shallow Ortiz bank region, tidal currents are weaker and silts might therefore be able to more easily settle. Another process explaining the different textures observed along the northern and southern coasts of the RDP might be the different circulation pathways for the fresh water coming from the various tributaries: the Uruguay and Paraná Guazú river (the mightiest branch of the Paraná) waters flow along the northern estuary, whereas the waters of the other branch of the Paraná (Paraná de las Palmas) follow the southern coast (Simionato et al., 2009). Right before it converges to the RDP estuary, the Paraná de las Palmas receives the waters of the Luján River. This last is a minor tributary with a much lower runoff, but which drains waters and sediments from the Pampas and which influence is obvious in other properties of the southern portion of the RDP, as the conductivity (Simionato et al., 2009).

At and immediately seawards the Barra del Indio shoal, in the region of the estuary’s salt wedge, the clay percentage in the bottom sediments rises to more than 45% (figures 2 and 6a) and the water and organic matter contents reach a maximum (Figure 3a and c). The presence of finer and cohesive sediments might be due to physicochemical flocculation processes, which are supposed to become important in this region (Ayup, 1986, 1987) leading to the deposition of the clay. The estuary depth and width also markedly increase in this region, leading to a significant reduction of the currents and favoring deposition. Being finer, the sediments of this region are much less consolidated and the water content is therefore higher (Figure 3a). In this area, on the other hand, the suspended sediments
diameter becomes much smaller and their concentration decays (figures 2 and 7a). This is accompanied by an increase in the number of living organisms, as revealed by the organic matter concentration in the bottom sediments (Figure 3c). The RDP estuary presents two sources of organic matter: phytoplankton and plant detritus (Acha et al., 2008). In the Barra del Indio region a high density of the copepods *Acartia tonsa* -up to 8,000 ind m\(^{-3}\) - and mysid *Neomysis americana* -up to 2,520 ind m\(^{-3}\) - has been observed (Mianzan et al., 2001; Schiariti et al., 2006). They are omnivorous and could take advantage of the abundance of organic matter in the detritic form (Acha et al., 2008).

Finally, in the exterior estuary, seawards the bottom salinity front area (at the region of the salt wedge), coarse sand with grain size between 170 and 200 µm dominates (figures 2, 5 and 6e). This sand is much coarser than the sand transported by the RDP (Figure 7), indicating that it must come from a different source (presumably the shelf). The absence of typical RDP sediments in this region (Figure 6) also suggests that the offshore limit of the significant RDP sediment deposits, forming the submerged delta, occurs just upstream in association with the salt wedge and the flocculation region. This hypothesis is supported by the net transport vector analysis (Figure 8).

Our analyses also reveal the presence of a different bottom sediment texture along the northern coast of the estuary, in the area around the Santa Lucía River mouth (figures 5 and 6c). Here the bottom sediments are poorly mixed and composed by fine silt (almost 70%) and clay (around 30%). The particular composition of these sediments, which greatly differs from the suspended sediments characteristics in this area (Figure 7c) suggests that the bottom sediments are relict.

Parker et al. (1987; hereinafter referred as PAR) made an interpretation of the grain size observations available for that time and a synthesis of various geological and oceanographic arguments to develop a first hypothesis for the processes associated to the sediments transport and dispersion in the RDP. Their Figure 3 (provided as supplementary material), which schematically shows their conclusions regarding the genetic association of the sediments, closely resembles our Figure 5, based on an objective statistical analysis of a homogeneous set of observations. Their hypothesis about the processes that determine the observed patterns are also mostly consistent with those that derive from our results. According to PAR, the upper RDP estuary is divided into two parts, one to the north and other to the south, the first one influenced by the Uruguay and the Paraná Guazú rivers, and the second one influenced by the Paraná de las Palmas and Luján rivers. Upstream the Santa Lucía River mouth and along the Uruguayan coast of the estuary, PAR suggest the presence of relict mud. Seawards those three regions, over the Barra del Indio shoal region, PAR suggest the flocculation of clays. Finally, relict sands are identified in the exterior RDP. In this sense, our study supports most of PAR conclusions and provides further evidence about other possible mechanisms influencing the bottom
sediments texture in the RDP.

Our results do not only contribute to a better understanding of the sedimentological processes in this important estuary, but will also help the construction and validation of numerical models, which are needed for management and scientific purposes. Those studies, including future sediments and biogeochemical modeling are envisaged as a continuation of this research.

Acknowledgments

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Figure captions

Figure 1. Study area, bathymetry and geographical references. Blue dots indicate the 26 sites where samples were collected during the six oceanographic cruises of the FREPLATA/FFEM Experiment. The latitude and longitude of every sampling site is shown in Table 1.

Figure 2. Mean (left panel) and standard deviation between samples (right panel) of the percentage concentration of sand (upper panel), silt (middle panel) and clay (lower panel), estimated from the bottom sediments samples gathered during the six cruises of the FREPLATA/FFEM Experiment. Green stars in the upper left panel represent the mean percentage of gravel.

Figure 3. Mean percentage and standard deviation between samples of the water content (panels a and b), organic matter (panels c and d), mean (e) and mode grain size (f), standard deviation (g), and degree of sorting (h) of the bottom sediments size, computed from the bottom sediments samples gathered during the six cruises of the FREPLATA/FFEM Experiment.

Figure 4. Schematic distribution of the characteristic bottom sediments (left) according to the Shepard (1954) classification scheme (right), computed from the bottom sediments samples gathered during the six cruises of the FREPLATA/FFEM Experiment.

Figure 5. Schematic distribution of the areas where data well correlate to the different factors derived of the PCA analyzes applied to the grain size histograms derived from the CILAS analysis of the bottom sediments samples gathered during the six cruises of the FREPLATA/FFEM Experiment.

Figure 6. Grain size distribution of the bottom sediment samples for: a) Factor 1 positive, site 20 - cruise 2, “Barra del Indio region” (light green in Figure 5); b) Factor 1 negative, site 9 - cruise 4, “Northern coast of the Intermediate RDP” (dark green in Figure 5); c) Factor 2 positive site 10 - cruise 4, “Santa Lucía region” (orange in Figure 5); d) Factor 2 negative, site 2 - cruise 4, “Southern coast of the Intermediate RDP” (dark brown in Figure 5); and e) Factor 3 negative, site 19 - cruise 4, “Exterior RDP” (yellow in Figure 5).

Figure 7. Grain size distribution of the suspended sediment samples for: a) “Barra del Indio region” (light green in Figure 5), site 20 - cruise 2, b) “Northern coast of the intermediate RDP” (dark green in Figure 5), site 9 - cruise 4, c) “Santa Lucía region” (orange in Figure 5), site 10 - cruise 4, d) “Southern coast of the Intermediate RDP” (brown in Figure 5), site 2 - cruise 4, and e) “Exterior RDP” (yellow in Figure 5), site 19 - cruise 4.

Figure 8. Distribution of statistical net transport vectors in the Río de la Plata estuary.
### Table 1: Number, geographical location (latitude and longitude) and depth (m) of the *in-situ* sampling sites shown as blue dots in Figure 1.

<table>
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<th>Longitude</th>
<th>Depth (m)</th>
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Figure 05

- Sandy silt (coarse silt and very fine sand) - Factor loading 2 negative.
- Silt (medium and fine silt) - Factor 1 negative.
- Clayey silt (very fine silt and clay) - Factor 1 positive.
- Clayey silt (medium and fine silt and clay) - Factor 2 positive.
- Sand (medium and fine sand) - Factor 3 negative.
Figure 07
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