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Weather, Hydrological and Oceanographic Conditions of the Northern Coast of the Río de la Plata Estuary during ENSO 2009–2010

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Additional information is available at the end of the chapter

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Abstract

Climatic, hydrological, and oceanographic conditions were determined during the 2009–2010 El Niño/Southern Oscillation (ENSO) on the north coast of the Río de la Plata (RdIP) estuary. The maximum monthly rainfall was observed in the middle and upper La Plata basin during September 2009 and February 2010 (“El Niño” phase, (EN)). The monthly flow of RdIP showed an increase with rainfall and significant differences between ENSO phases. The wind stress showed fluctuations in both phases, being less intense during EN, during which time maximum flow of RdIP was observed. During the EN phase, increased precipitation contributed to variations in salinity and absence of water column stratification in the north coast of RdIP. This was also associated with variations in Secchi depth, oxygen saturation, and nutrient concentrations. The spatial location of the turbidity front was associated with the flow of the RdIP and wind stress, thus conditioning the physico-chemical characteristics of the water column, mainly during EN phase.

Keywords: estuarine dynamics, river flow, physicochemical properties, ENSO, Río de la Plata

1. Introduction

“El Niño/Southern Oscillation” (ENSO) is a global phenomenon related to the ocean-atmosphere interactions in the Equatorial Pacific, with cycles consisting in a warm phase (“El Niño”), periods with neutral years (“Neutral”), and a cold phase (“La Niña”), with a 3–7 years periodicity [1, 2]. This event activates changes in the general atmospheric circulation, causing climate and hydrologic changes in continental areas, coastal areas, and tropical and extra-tropical zones of the Pacific or Atlantic Oceans [3, 4]. These modifications cause changes in the systems

physicochemical conditions at different organizational levels, impacting on the composition and abundance of benthic, planktonic, and nektonic communities [5–7].

In the La Plata basin, seasonality of the climatic elements determining the hydrologic cycles is ruled by the South Atlantic anticyclone, which is more intense in winter. The region has a warm season (October–April) with an average rainfall of 5.5 mm d^{-1} and maximum values near 9 mm d^{-1} and a cold season (May–September) with average rainfall less than 2 mm d^{-1} [8]. The alteration of the rainfall regime is one of the strongest signals of the changes caused by the ENSO event for the southern region of South America. During the warm phase, there is an increase in the spring rains, while during the cold phase, there is a decrease in rainfall [9, 10]. On the other hand, flows of the hydrological systems of the La Plata basin, including those of the main tributary rivers of the RdIP estuary (Parana and Uruguay rivers), are highly sensitive to modifications in the rainfall regime, with inter-annual and inter-decadal variability, being affected by ENSO events in their warm phase [11, 12].

Surface ocean temperature is the most analyzed oceanographic variable regarding the “El Niño” phase and its ecosystem effects in oceanic and coastal marine zones [13]. Nevertheless, estuarine zones are expected to experience a greater impact of hydrologic effects (fresh water or ocean water inputs) [14]. ENSO impacts in coastal zones include increased rainfall, hydrological changes in basins, modifications in river flow [15], and generation of inter-annual variations in fresh water discharges for estuarine systems [16, 17].

ENSO is considered in the RdIP as a large-scale atmospheric forcing effect on the discharges of the tributary rivers [15, 17], changes in salinity and nutrients [18], as well as in the location and location of turbidity or salinity fronts [19, 20]. Several studies have described the relationship between ENSO events, RdIP flow, and salinity of the estuarine system [18, 19, 21]. According to [16], surface sediments on the north coast of RdIP showed a variability in the trophic state related to the ENSO event, with differences between the phases (“El Niño” and “La Niña-Neutral”).

The aim of this study was to identify the main environmental drivers that promote modifications in the oceanographic conditions on the north coast of the RdIP, during ENSO 2009–2010. We measured the meteorological (rainfall and wind), hydrological (principal rivers flow), and oceanographic (temperature, salinity, oxygen saturation, Secchi depth, chlorophyll *a*, and total nutrients) conditions during both ENSO phases in the north coast RdIP (Montevideo coastal zone).

2. Methodology

2.1. Study area

The La Plata basin is the second largest river basin in the South America, covering an area of $3.1 \times 10^6 \text{ km}^2$; it includes five countries (Argentina, Brazil, Bolivia, Paraguay and Uruguay) with some of the most populated cities in South America including Sao Paulo, Buenos Aires, and Montevideo. The main rivers draining into the estuary of RdIP are the Parana and Uruguay rivers (**Figure 1A**).

The RdIP is an estuarine system characterized by the presence of a salt wedge, low river discharge seasonality, low tidal amplitude (< 1 m), an extensive and permanent connection to the sea, and high susceptibility to atmospheric drivers because of its large size and its shallow depth. The mean annual RdIP flow governs the salinity and has monthly to inter-annual variations of $25,000 \text{ m}^3\text{s}^{-1}$ [22–24]. In this system, several authors report biological processes [18], impacts on water quality, or presence of invasive alien species [20] associated with the spatiotemporal fluctuation of its front area [25].

The montevideo coastal zone (MCZ) is located on the north coast and middle zone of the RdIP between the mouths of the Santa Lucia River and Carrasco stream with an approximate extension of 50 km (**Figure 1B**). The largest city in Uruguay, Montevideo, covers $\approx 49\%$ of the coastal zone [26]. The MCZ is characterized by high levels of industrial and harbor activities [26, 27] but also with urban spaces for recreation (sandy beaches and rocky shores), diving, artisanal or sport fishing areas, and conservation areas (protected area Punta Yeguas and Santa Lucía Wetlands). Several studies in the MCZ identified a contamination gradient from the innermost Montevideo Bay area to the outer and adjacent coastal zone. Three contamination areas have been identified within the region: high (internal Montevideo Bay and Montevideo Harbor), medium (external Montevideo Bay and adjacent coast), and low impact (adjacent coastal zone, includes Punta Brava and Punta Yeguas) regions [27]. Montevideo Bay is 10 km^2 and has a mean depth of $\approx 5\text{m}$. In this system, nutrients (nitrogen, phosphorus), heavy metals, and hydrocarbons pollution have been associated with significant degradation of ecosystem [27–31]. These pollutants are derived from industrial activities, from “La Teja” refinery, harbor operations (i.e., navigation, bulk loading and dredging), or contributions from domestic and

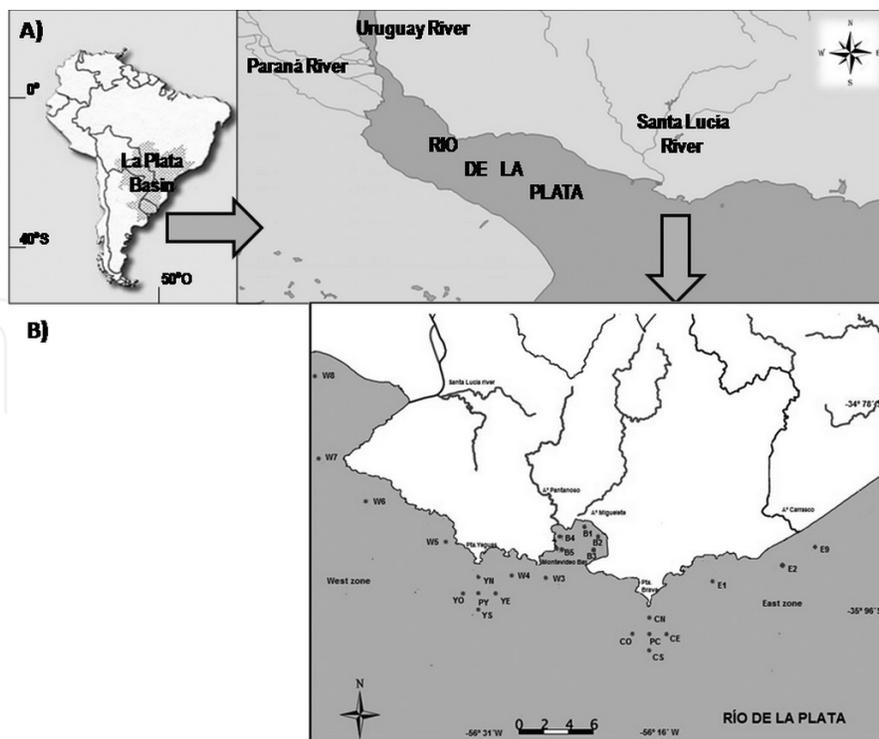


Figure 1. Location of the La Plata Basin, RdIP and Montevideo coastal zone (MCZ) with Punta Brava and sampling sites.

industrial effluents from Pantanoso, Miguelete, and Seco streams. In the East zone, 2000 m off the coastline (Punta Brava), the submarine outflow of the sanitation system of Montevideo is located. In addition, in this zone, there are recreation areas with presence of sandy beaches, alternating with rocky shores. In the West zone (Punta Yeguas), another submarine outflow with similar characteristics in Punta Brava will be installed soon.

2.2. Weather conditions

Variability and magnitude of ENSO were determined by the Ocean Niño Index (ONI) considering the monthly anomalies of ocean surface temperature (SST) in the Niño 3.4 region (2009–2011); values were obtained from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

Total monthly precipitation to the upper zone of La Plata basin (22°00'–40°00' S and 48°00'–64°00' W) was obtained from the Global Precipitation Climate Center (GPCC; <http://gpcc.dwd.de>). The product of monitoring of precipitation on earth surface was analyzed (1.0° × 1.0°). Values are expressed as rainfall “isoareas” (mm month⁻¹), using monthly values (March 2009 and August 2011).

Wind speed and direction were collected on an hourly basis at the Punta Brava meteorological station, RdIP (34°56'S and 56°09'W; March 2009 and August 2011). We calculated the average monthly speed (\pm SD), minimum, and maximum and are expressed in m s⁻¹. We did not consider maximum wind speeds (streaks of wind) in these calculations. To determine the direction of the prevailing winds, 16 quadrants were considered, and monthly relative frequency was calculated. Wind stress (Eq. (1)) was calculated as surface force of the wind on the water column; stress values of positive or negative wind were determined by the average monthly wind direction.

$$\tau(\text{Pa}) = \beta a * CD * (V \text{ wind})^2 \quad (1)$$

where βa = air density, 1.2 kg m⁻³, CD: drag coefficient: 0.0013, and V wind: wind speed.

2.3. Hydrological conditions

The daily river flow of the Uruguay and Parana rivers was obtained from the National Water Institute (www.ina.gov.ar) for the period 2009–2011. The river flow of the RdIP was obtained by adding the daily river flow of the Uruguay and Parana rivers. Monthly averages (\pm SD) were calculated and expressed as m³ s⁻¹.

2.4. Oceanographic conditions

Eighteen oceanographic surveys comprising 25 stations (located at 2000 m of coastline, depth 3–10 m; **Figure 1B**) were conducted in the MCZ between March 2009 and July 2011. The study area was divided into the Eastern zones (E1, E2, E9, PC, CN, CE, CS, CW stations), Western zones (W3 to W8, PY, YN, YE, YS, YW stations), and Montevideo Bay (MB) (B1 to B5 stations).

Water temperature and salinity were determined *in situ* at surface and bottom waters using a multiparameter *YSI Pro plus*. During 11 surveys, oxygen saturation was determined with multiparameter in surface waters and water transparency calculated using a Secchi disk (30 cm diameter). In addition, surface water samples were collected using a Kemmerer (2L) bottle to determinate chlorophyll *a* (Chl *a*) and nutrients (total nitrogen and total phosphorous: TN, TP) concentrations.

2.5. Laboratory analysis

Chlorophyll *a* concentration was quantified by spectrophotometric analysis using GF/F filters extracted in 90% acetone [32]. Determination of TN and TP was performed according to [32, 33] with previous digestion according to [34].

2.6. Data analysis

For the analysis of the temporal variation associated with ENSO, the EN and “La Niña-Neutral” months were defined according to Oceanic Niño Index (ONI). Nonparametric analyses (U Mann-Whitney) were performed to assess temporal differences (ENSO phases) in hydrological variables (Uruguay, Parana, and RdIP flow), and spatiotemporal differences in oceanographic parameters (temperature and salinity). Nonparametric correlations (R_s , Spearman) were performed between climatic (wind stress, Niño indexes), physicochemical parameters, and river flow (RdIP, Uruguay, and Paraná). Linear relationships between river flows and average salinity were performed; both variables were transformed by $\log(x + 1)$ to fit the assumption of normality. A principal component analysis (PCA) was performed with all the physicochemical parameters (temperature, salinity, oxygen saturation, Secchi depth, Chl *a*, TN, and TP). The variables were log-transformed ($x + 1$), standardized, and Varimax type rotation was considered. We considered 99% and 95% significance levels for the different analyses. The statistical analyses were performed with the SPSS and CANOCO program [35].

3. Results and discussion

3.1. Weather conditions

The ONI showed the minimum values during October–December 2010 ($<-1.5^\circ\text{C}$) and maximum values in December 2009 and January 2010 ($<1.5^\circ\text{C}$; **Figure 2**). The 2009–2010 ONI values allowed for the identification and development of an ENSO event with an “El Niño” (EN) phase (July 2009–April 2010), a subsequent “La Niña” (LN) cold phase (June 2010–April 2011; September–December 2011), and neutral conditions (April–June 2009, April–May 2010, and May–August 2011) [2, 36].

The 2009–2010 ENSO event was classified as “moderate to strong” [37]. When comparing the maximum 2009–2010 value of this indicator (October 2009–January 2010: 1.2) with those of recent ENSO events, we found that they were smaller than those corresponding to strong events (October–January: 1982–1983: 2.1; 1997–1998: 2.3; 2015–2016: 2.2), although they were

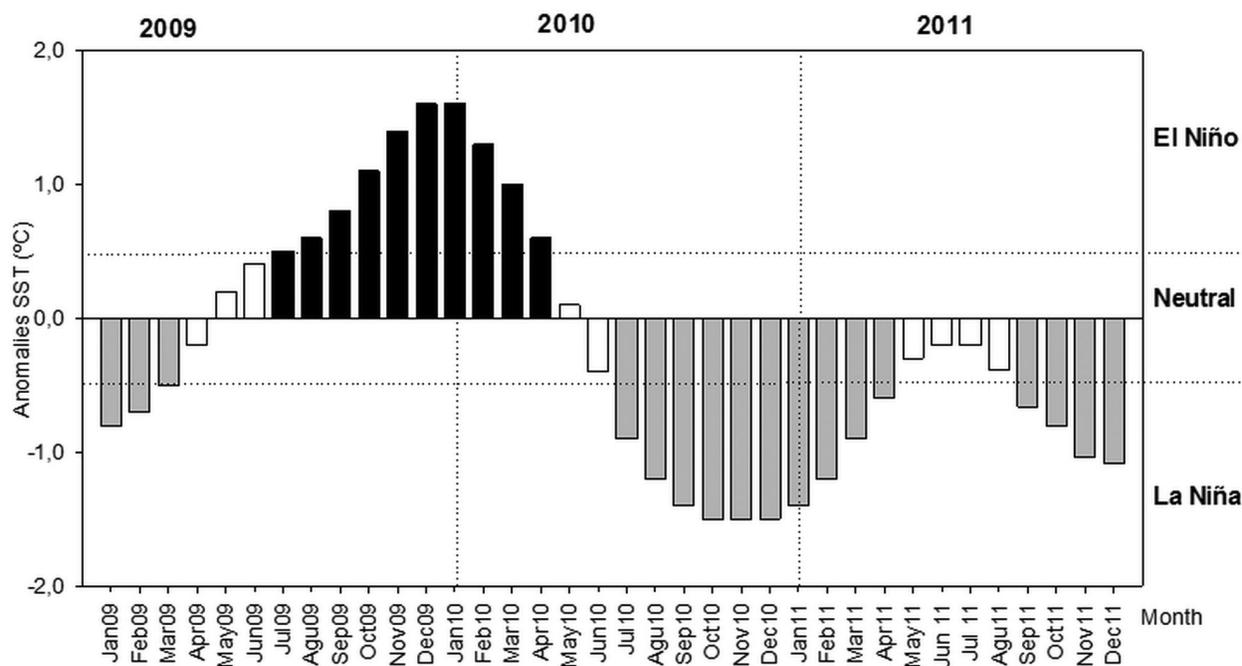


Figure 2. ONI index represented by SST anomalies (Niño 3.4 region) and ENSO 2009–2010 phases. Horizontal lines $>0.5^{\circ}\text{C}$ and <-0.5 .

similar to those of moderate events (1986–1987 and 1991–1992) [37]. Although in the range of previous moderate events, the 2009–2010 ENSO had characteristics of its own, including high SST anomalies in the Central Pacific and the fastest reported transition to the LN phase [2, 36]. The warm phase of the 2009–2010 was classified into the “WP” (warm pool) type and differs from the “Eastern Pacific” (EP) type due to the fact that SST anomalies happen in the central and not in the western zone of the Pacific Ocean [2]. It is also known as CP or WP, dateline ENSO or “El Niño Modoki” [2], and has different teleconnections and differential climatic impacts compared to the “EP” [38]. The analysis of the effects in the MCZ of the 2009–2010 ENSO, with “El Niño Modoki” characteristics, will permit the identification of variations in the behavior of meteorological variables and their impacts in the hydrologic behavior of the main hydrological systems of the La Plata basin, as well as over the RdIP estuary and its oceanographic conditions.

Total monthly precipitation for the La Plata basin during the period March 2009–August 2011 showed minimum values in April 2009 ($0\text{--}10\text{ mm month}^{-1}$) and maximum during September 2009 and February 2010 (**Figure 3**). The highest rainfall for the upper basin was reported in November 2009 (600 mm month^{-1}), while the values in February 2010 exceeded 550 mm month^{-1} . The teleconnections analyzed for the ENSO event in South America (Atlantic coast), specifically for the La Plata basin, are mainly related to their effect on rainfall variability [12]. This variability caused anomalies in surface air temperature in Argentina and southern Brazil during the “El Niño Modoki” (June–September 1979–2004), as well as higher-than-average rainfall between the months of December–February (1979–2004 period) [38]. In addition, [10] found an increase in spring rainfall during the EN warm phase. In this study, we found that the maximum rainfall values in the middle and upper basin of the Uruguay River were recorded

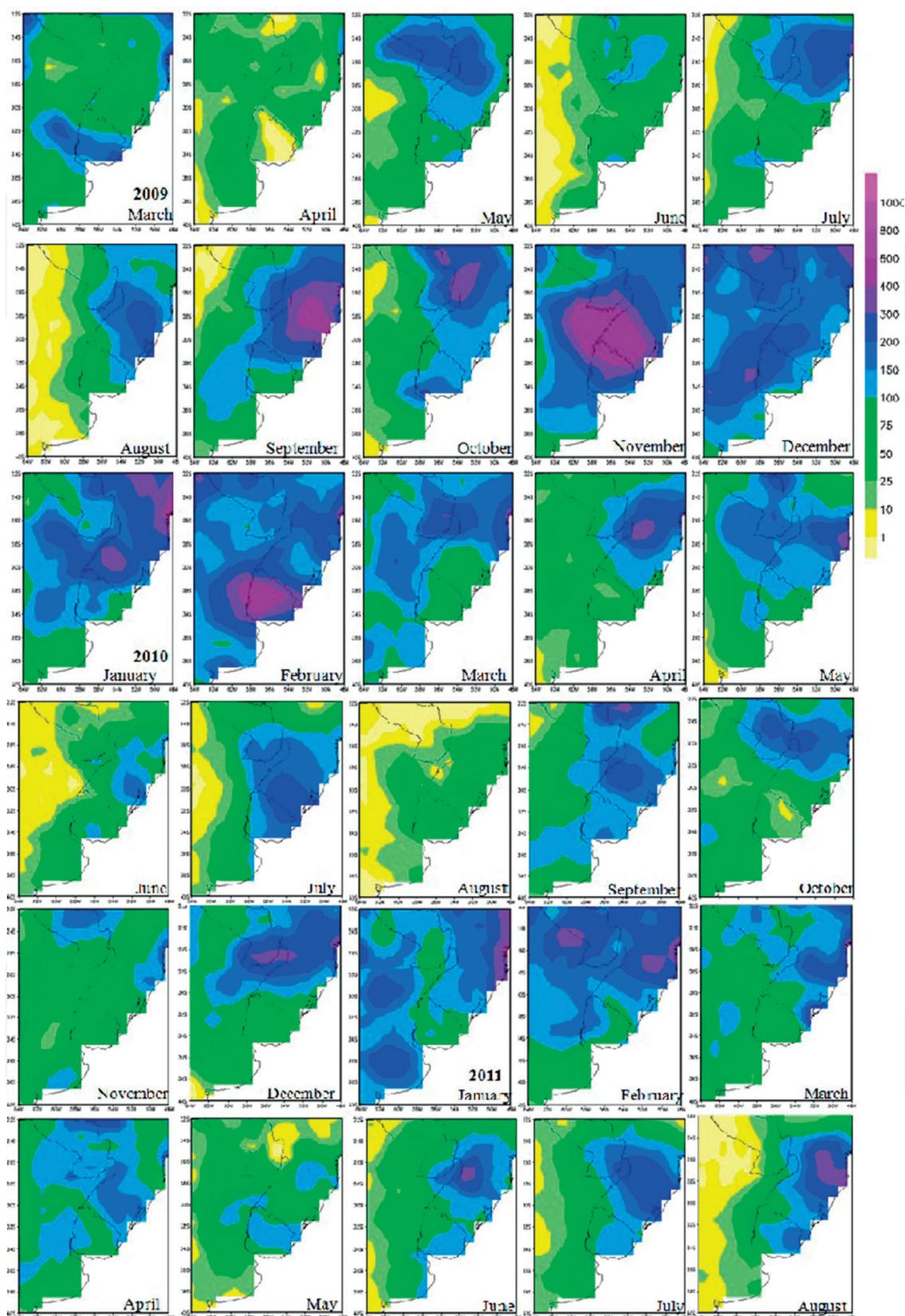


Figure 3. Total monthly precipitation (mm month^{-1}) on the surface of the earth to the region $22^{\circ}00' - 40^{\circ}00' \text{ S}$ and $48^{\circ}00' - 64^{\circ}00' \text{ W}$.

in November 2009 and December 2010, corresponding to the warm ENSO phase (EN: July 2009–April 2010) and to the spring months of the calendar year (September–December) and minimum rainfall values (April 2009 and October 2010) which corresponded to those months of Neutral and LN phase.

The average monthly wind speed between March 2009 and August 2011 was $5.8 \text{ m s}^{-1} \pm 2.9$ ($n = 6722$) (2009: 6.1 ± 3.3 ; 2010: 5.6 ± 2.9 ; 2011: 5.9 ± 2.7); wind speed oscillated between 0 m s^{-1} (stills) and a maximum of 23.7 m s^{-1} in July 2009 (**Figure 4A**). The most frequent wind direction was the first quadrant (N-E) with similar annual rates of occurrence (2009: 42%, 2010: 43%, 2011: 44%); Easterly winds were the most frequent (2009: 11%, 2010: 16%, 2011: 14%; **Figure 5**). Wind stress showed minimum values during months of the EN phase (minimum September 2009: -0.076 Pa , ESE) with a peak during June–July 2009 (0.068 Pa direction N and O; **Figure 4B**). During ENSO events in the RdIP, [18] found no variations in wind speed and reported the predominance of ESE and NE winds. In addition, [20] found that during EN years, there is an increase of ESE to SE winds. In this study, we observed that in EN months (September 2009–April 2010), there was an increase in the monthly frequencies of winds in eastern direction.

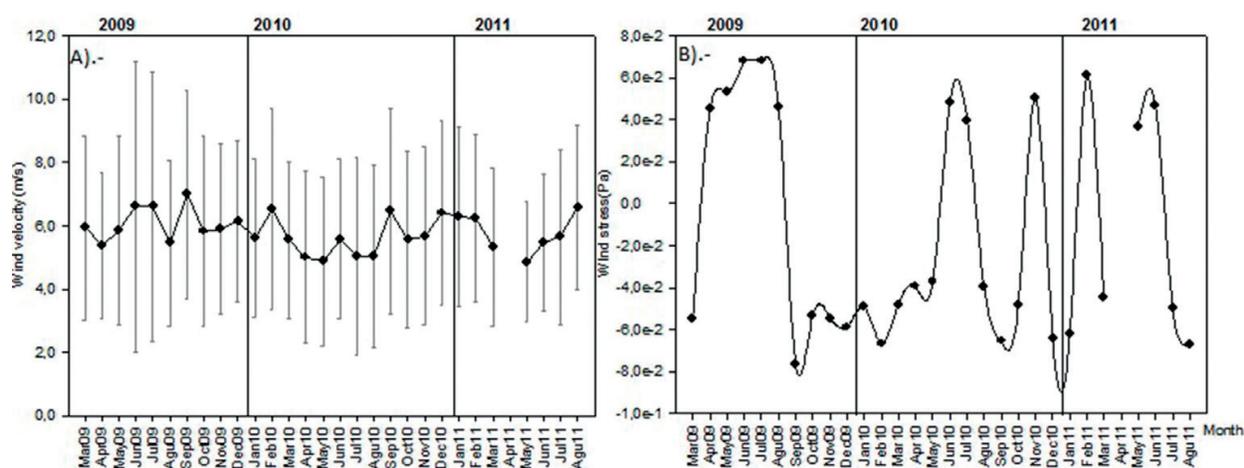


Figure 4. Average monthly wind speed (\pm SD) (m s^{-1}) (A) and wind stress (Pa) fluctuations (B) between 2009 and 2011.

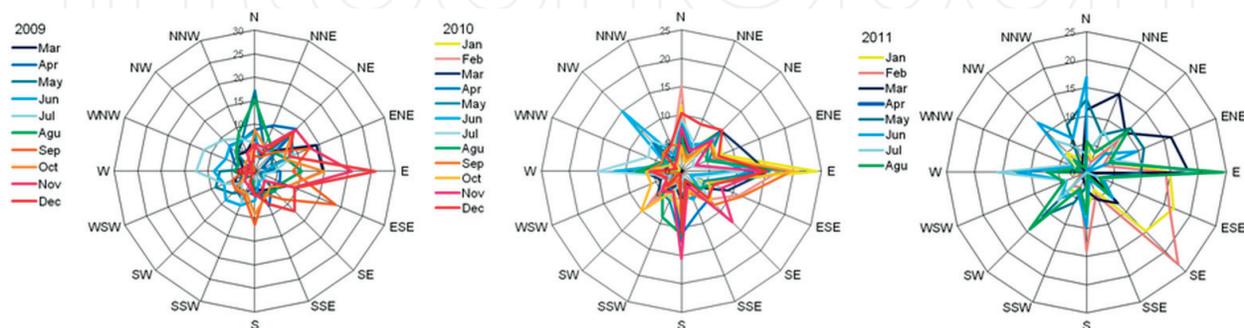


Figure 5. Monthly absolute frequencies of wind direction between 2009 and 2011 (2009: March to December, 2011: January–August).

3.2. Hydrological conditions

The average monthly flow of the RdIP, Uruguay, and Parana rivers showed an oscillation between minimum values during January and June 2009 and maximum between December 2009 and March 2010. Differences in the months of maximum discharges of the Uruguay and RdIP (December 2009) with the Parana River (March 2010) were observed (**Figure 6**).

The great rivers of the La Plata basin and tributary rivers of the RdIP are highly sensitive to rainfall variations, their flows being impacted during EN phases [11, 12]. In this study, we found strong correlations in the hydrological behavior of the Uruguay and Parana rivers in response to the increase of rainfall during the 2009 spring, coinciding with the EN warm phase. The maximum flow of the Uruguay and Parana rivers was recorded during December 2009–March 2010, and the minimum flow corresponded to those months prior to the development of the warm phase (January and July 2009). The RdIP flow had two peaks: the first in December 2009, coinciding with the maximum observed flow for the Uruguay River, and a second during the months of February–March 2010, coinciding with the maximum flow of the Parana River, previously indicated for this system by [15].

Monthly average flow of RdIP, Uruguay, and Parana rivers showed significant differences between the two ENSO phases (Mann-Whitney U: RdIP: $Z = -12.17$; Uruguay River: $Z = -11.09$; Parana River: $Z = -8.15$; $P < 0.01$). Significant associations between the flow rates of the three water systems were observed during both phases: EN: RdIP-Uruguay River ($R_s(0.025, 10) = 0.697$) and RdIP-Parana River ($R_s(0.04, 10) = 0.818$), “La Niña-Neutral”: RdIP-Uruguay River ($R_s(0.00, 21) = 0.823$) and RdIP-Parana River ($R_s(0.00, 21) = 0.970$). For the period December 2009 to March 2010, the RdIP flow exceeded $40,000 \text{ m}^3 \text{ s}^{-1}$, the greatest average flow registered in 16 years (1999–2014). Nevertheless, average values of the RdIP flow during the 2009–2010 ENSO event ($24,806 \text{ m}^3 \text{ s}^{-1}$) and its different phases (EN: $32,933 \text{ m}^3 \text{ s}^{-1}$; “La Niña-Neutral,” LNN: $22,039 \text{ m}^3 \text{ s}^{-1}$) were similar to

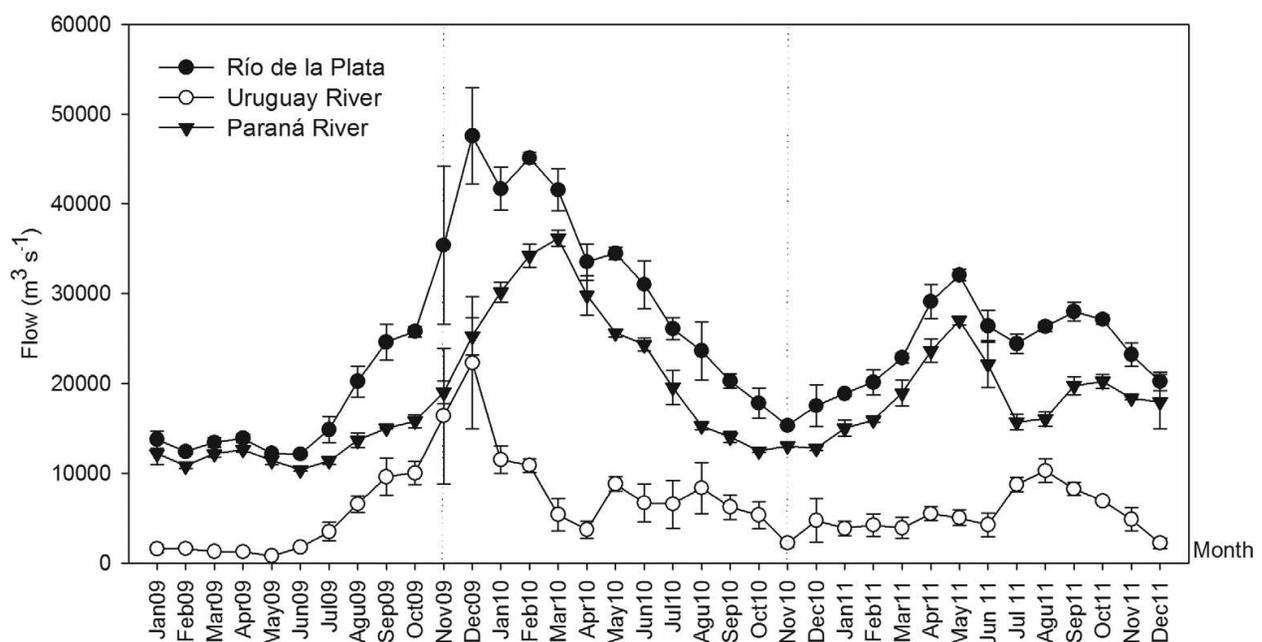


Figure 6. Monthly average flow (\pm SD) ($\text{m}^3 \text{ s}^{-1}$) of RdIP, Uruguay and Parana rivers between 2009 and 2011.

other ENSO events previously registered for the RdIP (1961, 2008: $24,700 \text{ m}^3 \text{ s}^{-1}$ and 1998, 2008: $24,000 \text{ m}^3 \text{ s}^{-1}$; [19, 20]). Average flow of the Uruguay River during low ($3000\text{--}4000 \text{ m}^3 \text{ s}^{-1}$) or high ($< 7000 \text{ m}^3 \text{ s}^{-1}$) discharge periods is lower than the ones found for LNN (Q Uruguay River = $5238 \text{ m}^3 \text{ s}^{-1}$) and EN (Q Uruguay River = $9970 \text{ m}^3 \text{ s}^{-1}$) in this study, although they fall into the range reported for ENSO events, characterized by their high variability ($1000\text{--}20000 \text{ m}^3 \text{ s}^{-1}$; [19, 20]). On the other hand, the average discharge of the Parana River for the 1884–1975 period ($17,000 \text{ m}^3 \text{ s}^{-1}$) ranged between 8000 and $22,000 \text{ m}^3 \text{ s}^{-1}$ [39], falling within the range of the flow found in this study.

3.3. Oceanographic conditions

The average water temperature (surface-bottom) displayed a seasonal pattern with minimum temperatures in winter (July 2010: $10.4 \pm 0.2^\circ\text{C}$ and July 2011: $10.6 \pm 0.6^\circ\text{C}$) and maximum in summer (January 2010: $25.9 \pm 1.1^\circ\text{C}$; **Figure 7**). No significant differences between surface and bottom or between areas of the study were detected ($P > 0.05$). The average salinity ranged between minimum values during July 2010 (0.6 ± 0.5) and maximum values in March 2009 and January 2011 (21.2 ± 6.1 , 22.3 ± 8.8 , respectively). Salinity values in surface and bottom waters showed no significant differences for most of the study; however, differences were found at the beginning (March and July 2009, Mann-Whitney U: $Z = -3.46$ and $Z = -2.57$; $P < 0.01$) and at the end of the study period (June and July 2011; Mann-Whitney U: $Z = -2.95$ and $Z = -3.06$; $P < 0.01$). During the warm phase, the MCZ comprised brackish water with oligo to mesohaline conditions (maximum salinity: 15) and a temperature range between 15 and 28°C ; in the cold-neutral phase, the water column salinity was highly variable (rank salinity: 0.1 to 33), with temperatures between 10 and 29°C . In July 2009, salinities were higher (15–30 range), although average water temperatures were lower than that during the EN phase (**Figure 7**).

Water temperature demonstrated greater temporal than spatial variation, with the lack of any differences between different depths or sampling study zones. Minimum and maximum values corresponded to winter and summer, respectively, and were associated with environmental

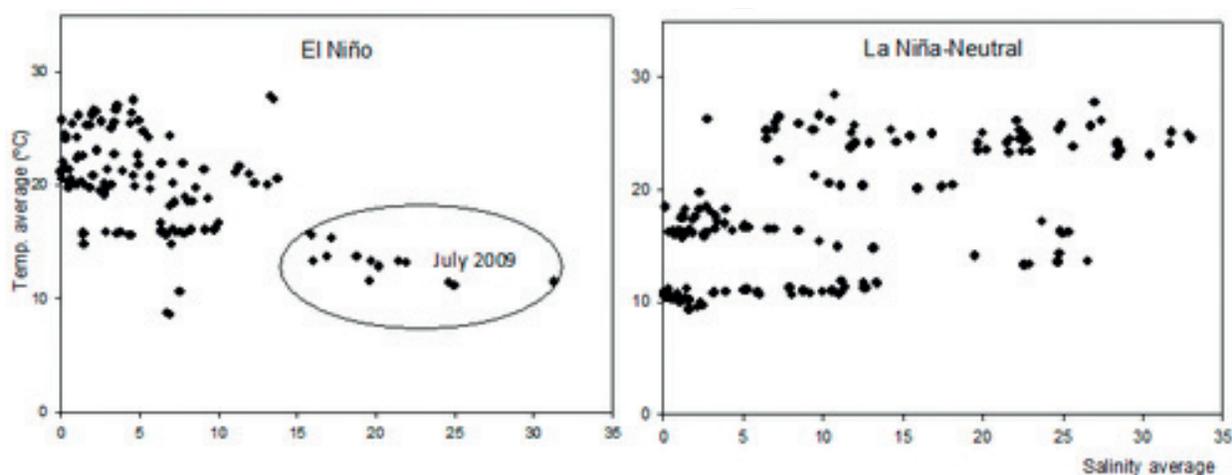


Figure 7. T-S diagrams (temperature and salinity average) during ENSO phases.

factors. Similar results were found in long time series in MCZ, and the seasonal patterns are consistent with previous studies for the middle RdIP [22, 24, 25, 39]. Reduced variation coefficients were found in summer (February 2010: 1%), which increased in July 2009 (16%). During this investigation, the average water temperature in July 2009 was $12.4 \pm 2.1^\circ\text{C}$ higher ($10.7 \pm 0.5^\circ\text{C}$) than during the other winter months study period (July 10, June and July 11). These results suggest an increase in temperature in the months prior to the development of EN over the MCZ. In this regard, [21] found a variability, related with years of pre- ENSO events in winter (April–October), in the anomalies of ocean surface air temperature (SST) in eight points of the South-West Atlantic region. The EN phase is characterized by negative anomalies in the SST in the Brazil Current, while during LN phase, cold anomalies were recorded in the Brazil Current and warm ones in the Malvinas Current. In the RdIP estuary, the influence of ocean bodies over adjacent coastal waters can be observed: sub-Antarctic cold waters between autumn and late spring and subtropical waters between late spring and autumn [40]. The anomalous records of July 2009 could be related to the LN phase prior to the effect of the EN event in the coastal zone of the RdIP.

Salinity is the main physicochemical variable of the water column, or “master parameter” of the RdIP, operating as regulator of biogeochemical, ecological, and sedimentological processes [18, 20, 22, 24, 41]. During most of the months of the EN (October 2009–July 2010) and LNN (September 2010–February 2011), we observed a mixed water column with no salinity stratification. Nevertheless, in the months prior to the EN (March and July 2009) and in LNN months (June and July 2011), the water column within MCZ was stratified. Vertical mixing of the water column in the study area may be generated by the predominant winds (speed and direction) [24] or by the fresh water inputs from the Uruguay and Parana rivers [18, 24, 40]. We identified the flow as the predominant driver, over wind stress, of the extension of the discharge plume of the RdIP during the EN months; this effect may also explain the lack of stratification along coast north of the RdIP during EN phase.

According to studies performed with long time series (1935–1975 Montevideo Bay; 1971–1991 Punta Brava), salinity in MCZ shows annual variations, with minimum monthly average values in autumn-winter and maximum ones in summer; minimum salinity values may occur throughout all the year, particularly in February, May, June, August, October, and December, although they have not been registered in January and rarely in July [40]. The minimum average salinity values were found during July 2010; however, according to [40], this month rarely displays such minimum salinity values. In addition, the mean salinity was 5.0 ± 4.6 higher during EN phase and even higher (12.7 ± 9.8) in LNN months. According to the inverse relationship between salinity and RdIP flow, the anomalous values are related to the ENSO 2009–2010 event, to the minimum salinity values during the EN months (October 2009–July 2010) and to the maximum values during LNN, respectively, which are associated with maximum and minimum values of the RdIP flow.

The first two components of PCA accounted for 67.5% of the total variance of the spatiotemporal variability. Principal component 1 (38.6%) showed a positive correlation with salinity (0.736), Secchi depth (0.798), and oxygen saturation (0.589), interpreted as gradient of hydrological variability. Principal component 2 (28.9%) showed a positive correlation with temperature

(0.882) and Chl *a* (0.826), interpreted as gradient of seasonal variability. Associated with axis 1, stations of the EN phase with lower salinity and water transparency (Secchi depth) and higher nutrient (TN and TP) were located. The stations of the LNN phase are located to the right of axis 1 and are characterized by higher values of oxygen saturation, water transparency, and salinity. Associated with axis 2, stations with higher (upper) or lower (lower) temperature values and Chl *a* concentrations are observed (**Figure 8**).

The location and presence of the turbidity front is one of the environmental features regulating ecological processes in the RdIP [19, 24, 25]. The influence of ENSO events on this feature have been poorly studied [24]. Our results agree with those of [40], who found that the turbidity front was related to the salinity and discharge flow of the RdIP. In this study, we showed the relationship between the RdIP flow and the spatial location of the turbidity front that conditioned the physicochemical characteristics of the water column of the MCZ, mainly during the EN phase. In **Figure 9**, we show satellite images (MODIS) of the RdIP where different locations of the turbidity front are depicted. Before the development of the EN phase (February 2009), the turbidity front was located west of the MCZ. During the EN phase (July 2009–April 2010), the turbidity front was located adjacent to the MCZ, while during the LNN (October 2010–January 2011), the front was again west of the MCZ, with less turbid waters in the MCZ. The monthly average Secchi depth was directly correlated with salinity, thus reflecting the occurrence of low turbidity waters in the MCZ during the low discharge flows of the RdIP. In addition, the PCA showed an arrangement of the

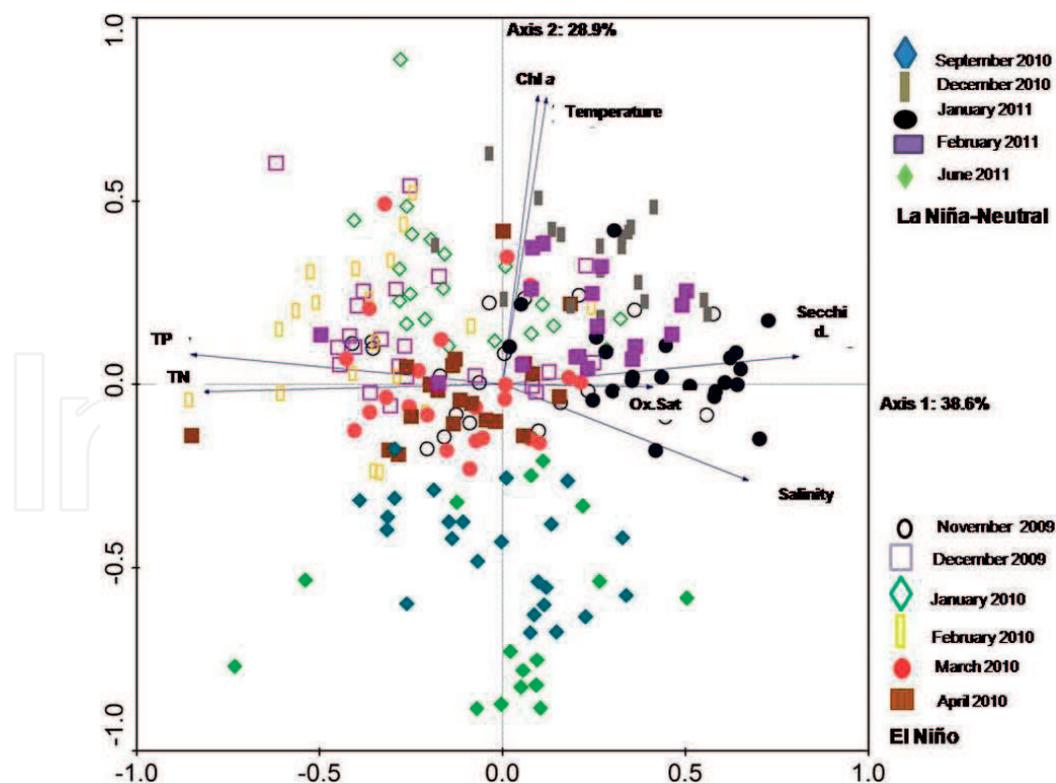


Figure 8. Principal component analysis diagram of physicochemical parameters classified according to ENSO phases (“El Niño” and “La Niña-Neutral”). TN (Total nitrogenous), TP (Total phosphorus), Ox. Sat. (oxygen saturation), Secchi d. (Secchi depth), Chl *a* (chlorophyll *a*).

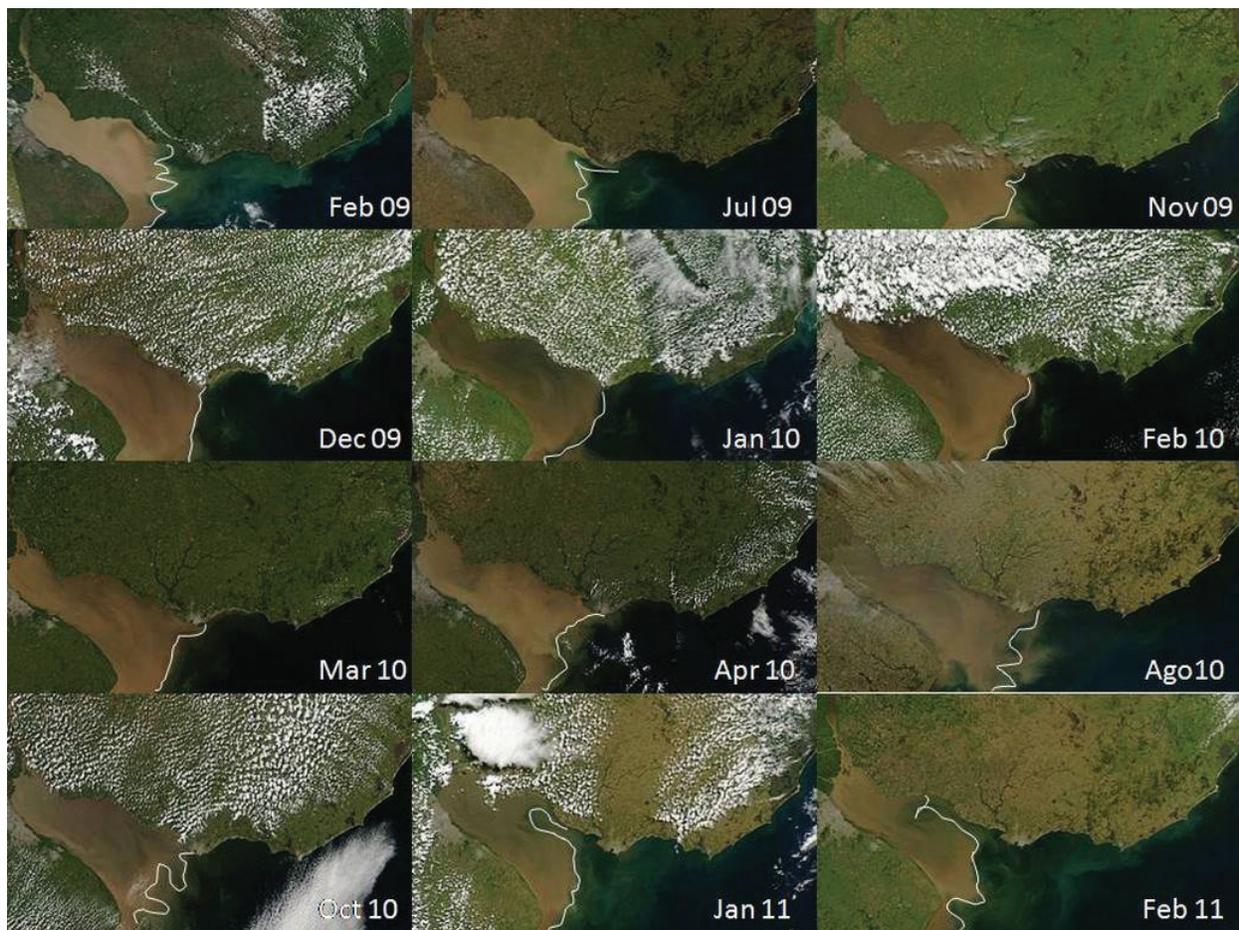


Figure 9. Turbidity front position (white line) during the study period. Images MODIS (AERONET-CEILAP-BA-Subset-Aqua-1 km-true-color). From: http://lance.modaps.eosdis.nasa.gov/imagery/subsets/?subset=AERONET_CEILAP-BA.terra.1km (accessed in July 2016).

sampling stations according to the hydrological behavior and seasonal variation. Coastal zones influenced by river discharges show gradients in nutrient concentrations related with changes in salinity [42]. Both TN and TP concentrations were positively associated with the RdIP and Parana flows and negatively associated with salinity and Secchi depth. In addition, the stations with the highest nutrient concentrations were associated to the axis 1 of the PCA, which represents the hydrological variability of the system. These results suggest that an increase in the RdIP flow promotes an increase of nutrient availability in the MCZ, particularly during the EN phase.

On the other hand, high Chl *a* concentrations and temperature associated with PCA axis 2 are interpreted as a seasonal variation of biomass phytoplankton related to temperature. In [28], phytoplankton Chl *a* usually displays a concentration peak by the end of summer and the beginning of autumn, showing a unimodal trend in the seasonal pattern. There are few studies of the RdIP regarding the seasonal patterns in total chlorophyll concentration; nevertheless, recent studies have demonstrated that salinity, depth, and light availability, which attain maximum values in spring, are the main variables controlling the biomass and composition of the phytoplankton community in the RdIP [43].

3.4. Weather, hydrological, and oceanographic interactions

Significant correlations between Niño indexes (Niño 3.4 > Niño 4 > Niño 1 + 2 > Niño 3) and flows of RdIP, Uruguay, and Parana rivers were only found during EN event (n = 10; **Table 1**).

During the “EN” phase, we observed significant correlations between the RdIP and Uruguay River flow and the different Niño indexes (Niño 1 + 2, Niño 3, Niño 3.4, and Niño 4), where Niño 3.4 showed the highest correlation coefficients. Similar correlation coefficients ($r = 0.51$) were observed between Niño 3.4 and the Uruguay River flow [19]. The associations found in this study with the RdIP and Uruguay River flow were higher than those of the above

	Q RdIP	Q Uruguay river	Q Paraná river
Niño 1 + 2	-0.685 (P = 0.029*)	NS	-0.842 (P = 0.002**)
Niño 3	NS	0.673 (P = 0.033*)	NS
Niño 3.4	0.888 (P = 0.001**)	0.912 (P = 0.000**)	0.578 (P = 0.080 MS)
Niño 4	0.806 (P = 0.005**)	0.782 (P = 0.008**)	0.648 (P = 0.043*)

P = * 0.05; ** <0.01; MS: marginally significant; NS: not significant.

Table 1. Correlations (Rs) between Niño indicators and flow (Q) of RdIP, Uruguay and Parana rivers.

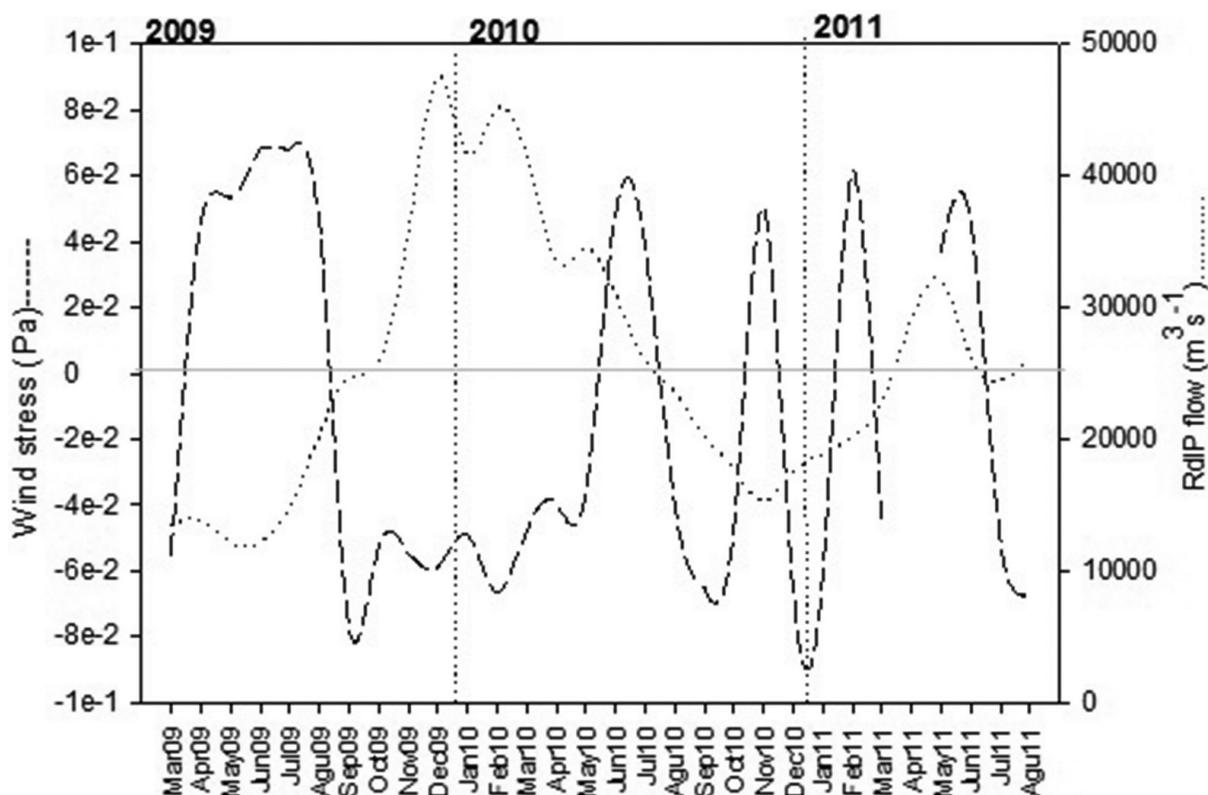


Figure 10. Wind stress fluctuations (Pa) (dashed lines) and RdIP flow ($\text{m}^3 \text{s}^{-1}$).

mentioned authors. During ENSO events, joint monitoring of the Niño 3.4 index and the RdIP and the Uruguay River flow would allow the assessment of the temporal variability in hydrology of the system, promoting the generation of early warnings of floods or maximum water levels in both systems.

The wind stress and flow of the RdIP showed in phase and out of phase fluctuations (*sensu* [23]) (**Figure 10**). Wind stress and RdIP flow ($R_s(0.021, 29) = -0.41$) and Uruguay River flow ($R_s(0.001, 29) = -0.50$) showed significant inverse correlations. Minimum continuous stress values were observed during September 2009 and April 2010, coinciding with peak flows of RdIP, while maximum values of stress (May and August 2009) coincided with the RdIP minimum flows.

Flow (RdIP, Uruguay and Parana rivers) and average salinity showed inverse linear relationships with higher coefficients recorded during the EN phase than during "LNN" phase (**Figure 11**).

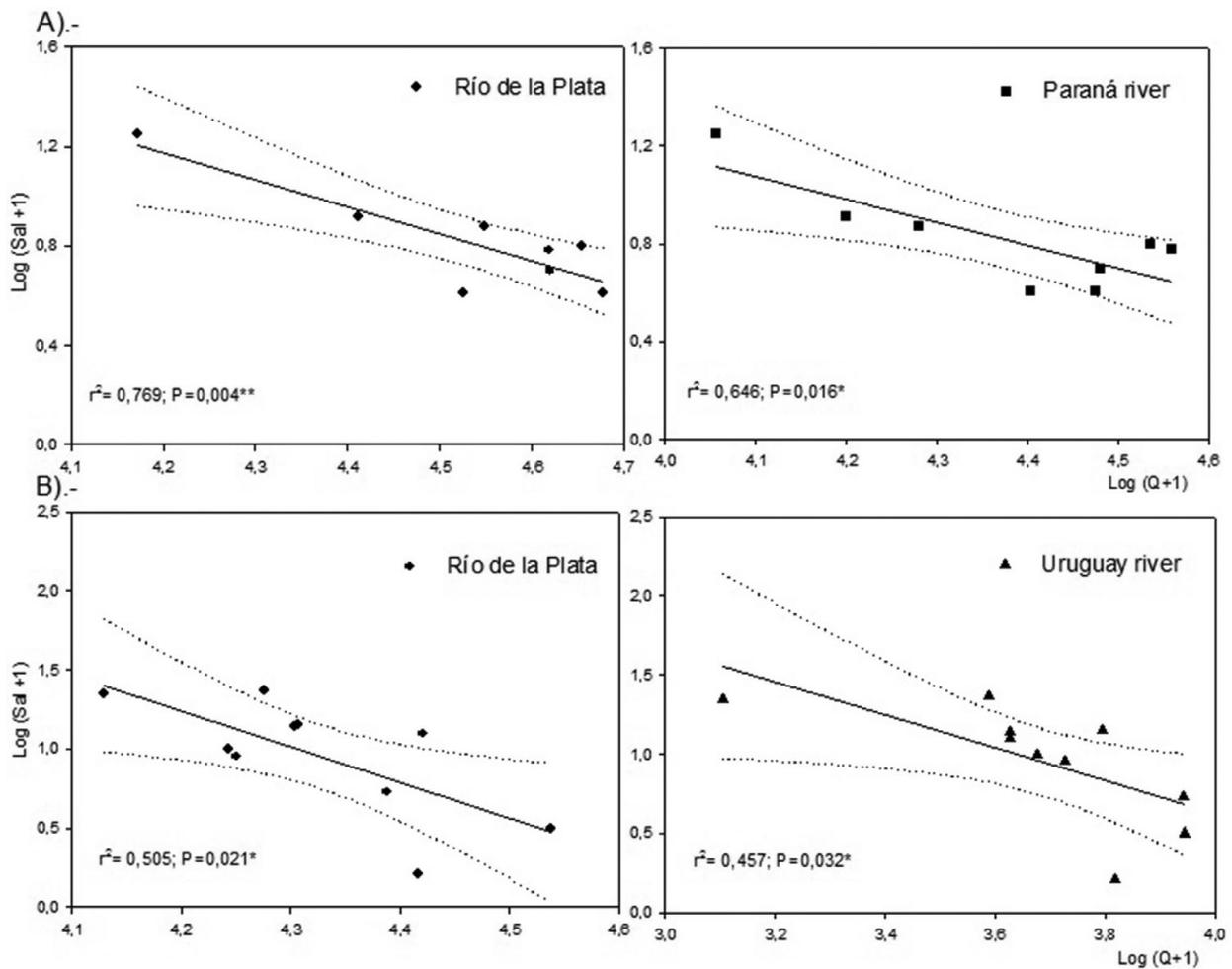


Figure 11. Inverse linear relationships between MCZ average salinity and RdIP, Uruguay and Parana rivers flow. (A) "El Niño," n = 8; (B) "La Niña-Neutral," n = 10.

Wind stress and discharge levels are the main processes responsible for extending the estuarine discharge plume of the RdIP over the Atlantic continental shelf [23]. In this system, the E-ESE-E wind direction promotes the inflow of ocean water into the estuary, while W-WNW winds promote discharge of affluent rivers (Parana and Uruguay rivers), increasing or reducing average salinity and the upriver or downriver displacement of the saline front [18, 19]. During high discharge periods ($Q_{RdIP} < 30,000 \text{ m}^3 \text{ s}^{-1}$), which are largely associated to ENSO events (5 in 7 between 1959 and 1990), only the event in 1992 presented wind stress conditions favorable for the dispersion of the river plume into the internal zone of the RdIP. In the remaining events, the wind strength opposite to the penetration of the plume was negligible [23]. During September 2009–May 2010 (EN phase), we observed “out of phase” fluctuations between the RdIP flow and wind stress, while during “LNN” fluctuations were mostly of the “in phase” type (*sensu lato* [23]). According to [23], high flows in the Uruguay and Parana rivers combined with minimum wind stress promote optimal conditions for the discharge and penetration of RdIP waters into the Uruguayan and Argentinean coastal zone. Similar results were observed for the RdIP discharge plume over the continental shelf [44]. In this study, we recorded a predominance of flow over wind stress as the main driver for the extension of the plume discharge over the north coast of the RdIP estuary during EN phase.

4. Conclusions

During the 2009–2010 ENSO event, in the EN phase, there is an increase in rainfall from spring 2009, promoting an increase in the flows of the main tributary rivers to the RdIP estuary. During EN phase, the RdIP flow and wind stress are the principal drivers of oceanographic condition at the north coast of RdIP.

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