Journal of Coastal Research	00	0	000–000	Coconut Creek, Florida	Month 0000

Hydrography of the Inner Continental Shelf along the Southwest Buenos Aires Province, Argentina: Influence of an Estuarine Plume on Coastal Waters

Ana Laura Delgado[†‡*], **María Clara Menéndez**[†], **María Cintia Piccolo**[†‡], **and Gerardo Miguel Eduardo Perillo**[†§]

[†]Instituto Argentino de Oceanografía (IADO-CONICET)
Bahía Blanca 8000, Argentina

[‡]Departamento de Geografía y Turismo
Universidad Nacional del Sur
Bahía Blanca 8000, Argentina

[§]Departamento de Geología
Universidad Nacional del Sur
Bahía Blanca 8000, Argentina

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ABSTRACT

Delgado, A.L.; Menéndez, M.C.; Piccolo, M.C., and Perillo, G.M.E., 0000. Hydrography of the inner continental shelf along the southwest Buenos Aires Province, Argentina: Influence of an estuarine plume on coastal waters. *Journal of Coastal Research,* 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Estuarine plumes have a significant influence on the characteristics and biology of the adjacent inner shelf. In the sector occupied by the plume, several transformations occur to the sediment and nutrients exported from the continent to the oceans. The coastal zone of Pehuén Co (PC) and Monte Hermoso (MH) is located in a highly complex oceanographic and ecological regional system, which creates the basis of one of the most valuable Argentinean habitats for fishing of commercial species. In this work, the physical oceanographic characteristics of the inner shelf of the southwest Buenos Aires Province and the influence of the Bahia Blanca estuarine (BBE) waters are introduced. The *in situ* data obtained from oceanographic cruises included vertical profiles of water temperature, salinity, and turbidity. The spatial variability of the parameters was studied with a multivariate statistical analysis. Temperature and salinity presented high seasonal variability (6.1–22.9°C; 33.5–36, respectively). Maximum turbidity occurred throughout the summer (64 nephelometric turbidity units [NTU]) and showed a minimum during spring (24 NTU). The study area was characterized by a significant spatial variability, especially in terms of salinity and turbidity, while water temperature showed a more homogeneous pattern. Salinity and turbidity values decreased from PC (closer to BBE) to MH (further from BBE) stations, with the highest values located near the mouth of the BBE. The PC and MH (to a lesser extent) inner shelves are transitional environments between the estuary and the open beaches of Buenos Aires Province, creating a habitat where benthic and zooplankton estuarine and marine species are found.

ADDITIONAL INDEX WORDS: *Coastal waters, temperature, salinity, turbidity, Bahía Blanca Estuary, estuarine plume.*

INTRODUCTION

Coastal biological activities primarily depend on the physical processes acting on the inner shelf. These processes are ruled by local and regional dynamic forces, which result from interactions between land and ocean. The estuarine plumes in coastal areas are significantly influenced by land-derived discharge emanating from rivers but filtered by an associated estuary. The plume is characterized by a region with a significant salinity gradient, the extent and morphology of which depend on river discharge, tidal conditions, and wind stress (Morris *et al.*, 1995). Also, plumes are zones of interaction, where several transformations occur during the export of sediment, organic material, and nutrients from the continent to the ocean (Dagg *et al.*, 2004; Dai *et al.*, 2008). Chemical transport and biogeochemical interactions within these areas are fundamental in processes such as coastal biological production and global geochemical cycling (Morris *et al.*, 2005).

The physical oceanographic characteristics of coastal waters (*e.g.,* Barton, Lavín, and Trasviña, 2009; Bruner de Miranda *et al.*, 2011; Finolov *et al.*, 2000; Lucas *et al.*, 2005; Pearce, Lynch, and Hanson, 2006; Prego and Varela, 1998; Puillat *et al.*, 2004; Ramírez, 1983) and the influence of estuarine plumes on adjacent inner shelves have been well explored in the scientific literature worldwide. Works related to the Pearl River estuarine plume (Dai *et al.*, 2008), the Mississippi and Amazon River plumes (Dagg *et al.*, 2004; Lohrenz *et al.*, 1999), the Delaware and Chesapeake Bay systems (Houghton *et al.*, 2004; Sanders and Garvine, 2001), the Rhine River plume (Simpson and Souza, 1995), and the La Plata plume (Guerrero and Piola, 1997; Huret *et al.*, 2005; Piola, Romero, and Zajaczkovski, 2008; Piola *et al.*, 2000, 2005) are some examples. Some of the studies have been primarily devoted to the role of the plumes as drivers of nutrients, sediments, and biological species to the adjacent inner shelf waters (*e.g.,* Allen, 1997; Cloern, 1996; Lohrenz *et al.*, 1999; Morris *et al.*, 1995; Ringuet and MacKenzie, 2005; Sanders and Garvin, 2001; Yin and Harrinson, 2008). More specifically, reports on the presence of benthic, phytoplanktonic, and zooplanktonic estuarine species on nearby sandy beaches are numerous (Cowley, Whitfield, and Bell, 2001; Godefroid, Hofstaetter, and Spach, 1999; Lasiak, 1981; Sato *et al.*, 2008; Strydom, 2003; Strydom and d'Hotman, 2005). Nevertheless, there is a lack of studies concerning the influence

DOI: 10.2112/JCOASTRES-D-16-00064.1 received 12 April 2016; accepted in revision 4 June 2016; corrected proofs received 7 July 2016; published pre-print online 19 August 2016.
*Corresponding author: aldelgado@iado-conicet.gob.ar

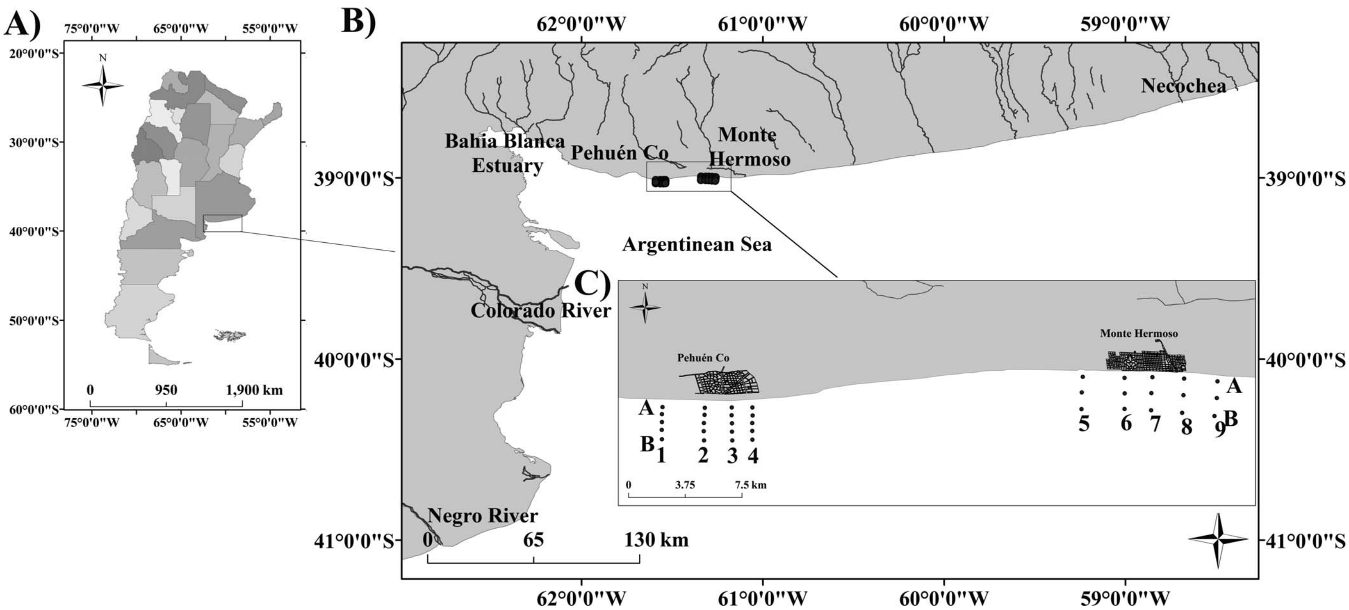

Figure 1. Location maps of the study area: (A) Argentina, (B) inner shelf of the southern part of Buenos Aires Province (El Rincon), and (C) location of the fixed measurement stations in Pehuén Co and Monte Hermoso inner shelves.

of plumes that derived from estuaries with no significant river input.

The coastal zone of Monte Hermoso (MH) and Pehuén Co (PC) is located on the inner shelf of the southwest Buenos Aires Province ("El Rincón"; Figure 1). It is a highly diverse ecosystem and home of abundant fishery resources (Carroza, Fernández Aráoz, and Pájaro, 2009). To the west of MH and PC, the Bahía Blanca Estuary (BBE) represents a turbid, shallow, and homogeneous system (Perillo and Piccolo, 1999) that is the main source of sediment for the inner shelf (Menéndez *et al.*, 2015; Perillo and Cuadrado, 1990) because it is in significant erosional stage (Perillo *et al.*, 2004). It has been hypothesized that estuarine waters influence the sediment composition of MH and PC beaches (Perillo and Cuadrado, 1990) and, further, the biological communities of this ecosystem (Carcedo, Fiori, and Bremec, 2014). The estuary is characterized by a funnel shape and numerous channels with a NW-SE direction, extensive tidal flats, low freshwater input (mean runoff from Sauce Chico River = 1.9 $m^3\ s^{-1}$ and Napostá Creek = 0.8 $m^3\ s^{-1}$; Perillo *et al.*, 2004), and continual residual fluxes (Perillo *et al.*, 2004).

Despite the importance of this coastal ecosystem, there are few studies concerning the physical characteristics of the coastal waters of the southern Buenos Aires Province, Argentina. Previous research regionally addressed the physical characteristics of the water column (Carreto *et al.*, 1995; Guerrero and Piola, 1997; Martos and Piccolo, 1988) or focused on the study of marine fronts in El Rincón (Rivas and Pisoni, 2009). Lucas *et al.* (2005) determined coastal oceanographic regimes of the northern part of the Argentinean continental shelf based on the spatial and seasonal distribution of salinity and the stratification of the water column. They characterized El Rincón zone as an area with relatively low salinity (30–33.3) and marked seasonality. In a local scale, Perillo and Cuadrado (1990) and Cuadrado, Piccolo, and Perillo (2002) hypothesized that the estuarine influence on coastal waters (relatively high saline waters and fine suspended sediment) provided by the estuarine plume is deflected towards the MH coast. Nevertheless, within this highly complex system, long-term information on the physical conditions and its actual linkage to the neighboring estuarine waters is lacking. The main objective of this paper is to advance in the current knowledge of the physical characteristics of this complex area and the influence of the particular neighboring estuarine system, to build the basis for future physical and biological studies. In this paper, the hypothesis of the influence of the BBE plume will be proven, the general characteristics of the seasonal hydrography will be presented, and further possible linkages with previous biological studies of the area will be established. The results will enhance the understanding of the ecosystem as a whole and may be useful in similar systems where inner shelf waters are influenced by plumes derived from estuaries with absence of significant riverine inputs.

The study area is located on the inner shelf of the southwestern Buenos Aires Province (El Rincón), Argentina. This area is described as a highly complex oceanographic and ecological system, influenced by large inputs of continental runoff (Negro and Colorado Rivers), local generation of high-salinity cells and winds that dominate the inner shelf dynamics (Figure 1; Lucas *et al.*, 2005). The availability of adequate food (high presence of phytoplankton and zooplankton), suitable thermal and salinity ranges, the presence of marine fronts, and the oceanic circulation that favors a retention mechanism produce an appropriate environment for successful fish larval recruitment and growth (Marrari *et al.*, 2004; Rivas and Pisoni, 2009). As a consequence, the physical and biological characteristics of El Rincón generate a rich habitat for valuable commercial species, which are very important for the local artisanal fisheries (Carroza, Fernández Aráoz, and Pájaro, 2009; Delgado *et al*., 2015).

The two coastal zones selected for this study are PC and MH, which are settled in the northeast part of El Rincón system. Both beaches are located at 15 (PC) and 43 km (MH) from the northern mouth of the BBE (Figure 1). The area has a mesotidal regime with semidiurnal tides and a mean amplitude range of 3.10 m (Figure 1; Delgado *et al*., 2012; Servicio de Hidrografía Naval, 2009). The mean significant wave height in the study area oscillates between 0.25 and 1.5 m, associated with significant wave periods between 1 and 16 seconds, with maximum heights occurring in spring and minimum heights in winter (Delgado *et al*., 2012).

This area has a temperate climate, characterized by warm summers and cold winters, as well as moderate springs and autumns. The average temperature oscillates between 14 and 20°C, and the mean annual precipitation is 650 mm (Campo de Ferreras, Capelli de Steffens, and Diez, 2004). Prevailing wind directions are from the N and NW with mean speeds that fluctuate between 22 and 24 km h^{-1} (SMN, 1992). The study area is highly influenced by El Niño–Southern Oscillation events, which are a major factor in the interannual climate variability by affecting the total amounts of precipitations (Aceituno, 1988; Delgado *et al*., 2015).

The western limit of the study area is framed by the BBE, which is a turbid, shallow, and homogeneous system, where semidiurnal tides and winds are the main factors controlling the water-turbulence processes (Figure 1; Piccolo and Perillo, 1990). This temperate estuary covers an area close to 2300 km^2, which is formed by a series of NW-SE tidal channels separated by extensive intertidal flats (Menéndez *et al*., 2015; Piccolo and Perillo, 1990). A particularity of this estuary is that the fluvial influence is low, mainly contributed by Sauce Chico River and the Napostá Grande Creek, which provide an annual mean runoff of 1.9 and 0.8 $m^3 s^{-1}$, respectively (Perillo *et al*., 2004). Water temperature varies between 24.6°C in summer and 7°C in winter (Popovich and Marcovecchio, 2008), and salinity can reach 41.89 in summer (Freije and Marcovecchio, 2004). Suspended particulate matter in the BBE varies in response to the seasons, with maximum concentrations in summer (50.7–275.2 mg L^{-1}) and minimum concentrations in winter (2–34.8 mg L^{-1}; Menéndez *et al*., 2015).

METHODS

In this section, the general characteristics of the study area are described. Also, the data sources and a comprehensive description of the applied methodological approach are provided.

Sampling *in Situ* Data

The data employed in this study were obtained between March 2010 and February 2011 from 10 oceanographic cruises. Each survey consisted of nine transects perpendicular to the coast. The selected distance between stations (St) in each transect was 500 or 1000 m, depending on the slope and depth of the site (Figure 1). The stations were located between the 1.5 m and 11 m isobaths, with a minimum distance from the coastline of 50 m and a maximum distance of 3000 m. In each station, vertical profiles of water temperature (°C), salinity, turbidity (nephelometric turbidity units [NTU]), and depth (m) with 1 s frequency were obtained with a multiparametric sonde YSI6600v2 (calibrated before each cruise). In total, 10 surveys were made, and 266 vertical profiles were obtained.

Measurements of meteorological conditions (air temperature, precipitation, and wind speed and direction) were obtained from an automatic weather station (EMAC). This station, located on the coast of MH, is equipped with sensors developed by the Instituto Argentino de Oceanografía. Meteorological parameters were sampled every 10 minutes.

Data Analysis: Statistical Methods

Simple statistics (mean and standard deviation) were calculated to determine the annual and seasonal characteristics of the coastal waters. The *in situ* surface data were interpolated with the Krigging method in Surfer 8®, in order to obtain the spatial and temporal variability maps of the parameters. To investigate the vertical structure of the water column, the first and the last transect of the surveys (1 and 9, respectively) and the stations closest and farthest from the coast (A and B, respectively) were chosen, since no significant differences were found in the parameters between all the stations. With these data, seasonal temperature-salinity (T-S) profiles were plotted.

To study the spatial variability of water temperature (°C), salinity, and turbidity (NTU), multivariate statistical analyses were performed using the PRIMER-E® software package (Clarke and Warwick, 1994). Due to the homogeneity of the parameters between the stations closest to the coast and the ones located offshore, only the extreme sites (A and B) of each transect (1 to 9) were considered for the statistical analysis. The physical variables were analyzed using the nonmetric multidimensional scaling (MDS) from a similarity triangular matrix calculated by the Euclidean distance index (with normalized data). The final stress was examined in relation to ordination dimensionality, to help select the fewest dimensions necessary to describe the data adequately. A one-way analysis of similarity (ANOSIM) was then used to evaluate the differences between groups (global test and pairwise tests).

RESULTS

The following paragraphs describe the seasonal and spatial dynamics of meteorological and oceanographic data in the inner shelf of the southern Buenos Aires Province, Argentina. The results are divided into four subsections: The meteorological data include the meteorological conditions of the sampling day. In the second and third subsections, results of the spatial and temporal distribution of parameters are presented. In the last section, the results of the statistical analysis dealing with surface parameters are described.

Meteorological Data

Meteorological conditions during the sampling days are shown in Figure 2. Maximum daily mean air temperature oscillated between 28°C in summer and 7°C in autumn-winter

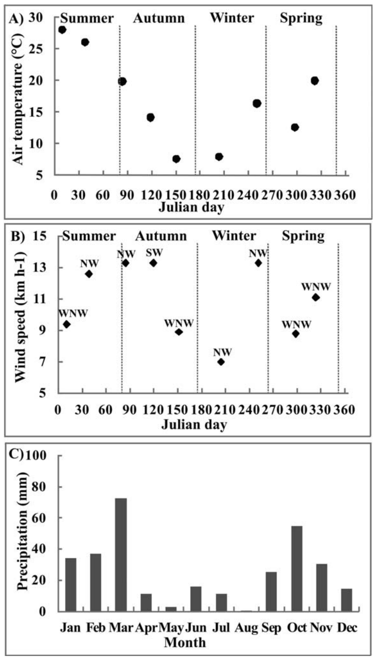

Figure 2. Meteorological conditions on the cruise measurement days obtained from an automatic weather station (EMAC) in Monte Hermoso: (A) daily mean air temperature (°C), (B) daily mean wind speed (km h^{-1}) and direction, and (C) monthly total amount of precipitation (mm).

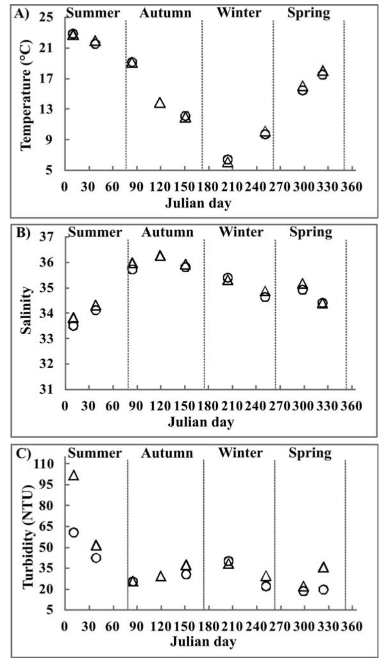

Figure 3. Monthly mean values of oceanographic parameters in the study area between March 2010 and February 2011: (A) sea-surface temperature (°C), (B) salinity, and (C) turbidity for Pehuén Co (triangles) and Monte Hermoso (circles) stations. Julian day 1 corresponds to 1 January 2010.

(Figure 2A). It is important to notice that cruises were only possible with good weather conditions (wind speed < 20 km h^{-1} and N direction), and so no significant variability will be found in the wind data. The NW continental winds dominated most of the studied period (90%), with the exception of the April cruise, when the predominant direction was from the SW. Mean daily wind speed varied between 6.0 (July) and 13.3 km h^{-1} (April; Figure 2B). During the study period, precipitation was characterized by a strong seasonal variability (Figure 2C). Monthly maximum records were detected in March (72.6 mm) and October (55 mm) and seasonally in summer (143 mm). Autumn was the driest period, with a total precipitation of 30 mm.

Temporal and Spatial Variability of the Surface Parameters

Mean sea-surface temperature (SST) was 15.6°C, with a thermal amplitude of 16.6°C. The lowest values were registered in July (6.1 ± 0.5°C in PC; 6.4 ± 0.1°C in MH), and the highest temperatures were recorded in January (22.7 ± 0.3°C in PC; 22.9 ± 0.2°C in MH; Figure 3A). During summer, high SST was observed near the coast along both beaches, reaching values up to 23.4°C in PC in January (Figures 3A–4). In both locations, the SST decreased offshore and in a W-E direction, observing the minimum values at the MH east stations (22.1°C; Figure 4). In autumn, mean SST was 15.3 ± 0.3°C. Isotherms were distributed relatively parallel to the coastline, with minimum temperatures near the coast and at the west stations (15.3°C). Maximum temperatures were registered offshore and to the east of both beaches. In winter (mean 8.1°C), minimum SST values were registered near the coast, with an increase of values towards offshore. PC waters were characterized by higher spatial variability (±0.5°C) than MH waters (±0.1°C). During spring, SST oscillated between 15.2°C in October (MH) and 18.2°C in November (PC). Higher SST was registered in PC and over the coastline (17.3°C), and minimum values were registered in MH (16.4°C).

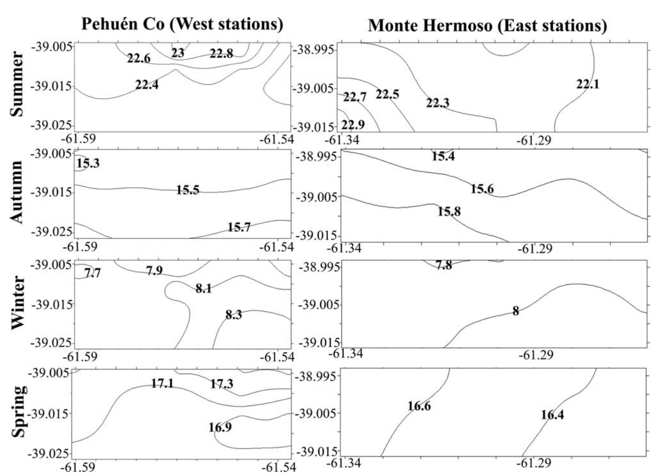

Figure 4. Spatial and seasonal distribution maps of sea-surface temperature (°C) along the southwest Buenos Aires Province inner shelf (Pehuén Co and Monte Hermoso) between March 2010 and February 2011.

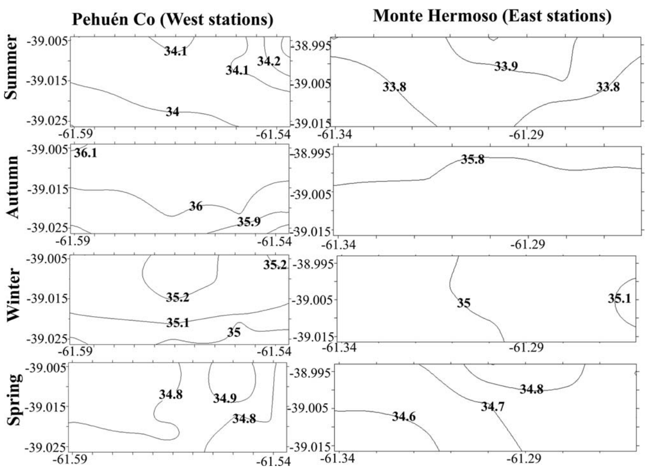

Figure 5. Spatial and seasonal distribution maps of sea-surface salinity along the southwest Buenos Aires Province inner shelf (Pehuén Co and Monte Hermoso) between March 2010 and February 2011.

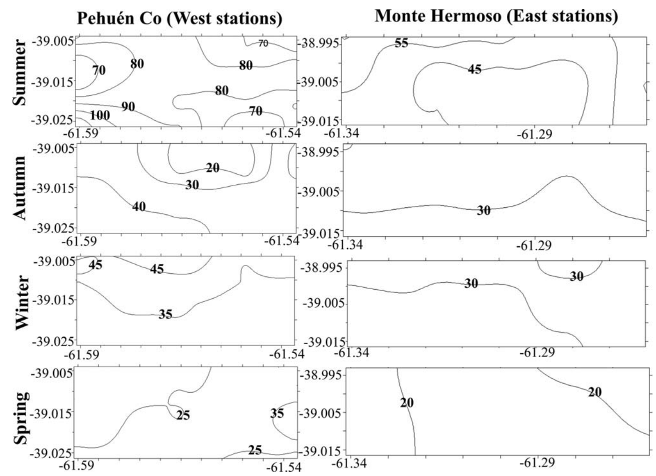

Figure 6. Spatial and seasonal distribution maps of sea-surface turbidity (NTU) along the southwest Buenos Aires Province inner shelf (Pehuén Co and Monte Hermoso) between March 2010 and February 2011.

Sea-surface salinity oscillated between 33.4 and 35.8 in MH and between 33.6 and 36.7 in PC. The highest salinity values were registered during autumn, meanwhile the lowest ones were observed in summer. The study area was characterized by a significant spatial variability in salinity, reaching a gradient up to 0.7 (February) between both beaches (Figure 3B). January presented lower salinity values than February, with maximum values of 31.8 (PC) and 31.7 (MH). Isohalines were generally parallel to the coastline, with maximum concentrations on the coast, diminishing offshore (Figure 5). In autumn, salinity values oscillated between 35.7 (MH) and 36.7 (PC). Although the isohalines did not show a general pattern, maximum salinity was observed near the coastline, diminishing offshore. In winter, salinity oscillated between 34.6 (September) and 35.5 (July). In PC, maximum values were observed onshore and minimum ones offshore. On the contrary, in MH, the isohalines were perpendicular to the coast, with maximum concentrations at the eastern stations. During spring, salinity presented high spatial variability in the study area (1.1), with maximum concentrations near the coastline (35.4 in PC and 35.2 in MH). In November, the values diminished, reaching 34.4 in PC and 34.3 in MH.

Turbidity presented a steep variability throughout the year, with mean values ranging between 30 and 102 NTU in PC and between 26 and 61 NTU in MH. PC always showed higher values and greater spatial variability than MH, which was more homogeneous (Figure 3C). The highest turbidity was observed during summer, reaching 120 NTU in PC and 80 NTU in MH. In both cases, higher values were observed near the coast (Figure 6). Turbidity decreased in autumn, with higher values in PC than in MH, mainly at the western stations. The mean turbidity in both beaches oscillated between 20 and 80 NTU. During winter, turbidity varied between 20 and 52 NTU. October was the month with lowest values, with maximum values in PC (30 NTU). During spring, the clearest waters were observed, with values that oscillated between 17 (MH) and 52 (PC).

Vertical Distribution of Temperature, Salinity, and Turbidity

The vertical distribution of temperature and salinity clearly represented the typical vertical homogeneity of the water column all year-round (Figure 7), with no development of a seasonal thermocline or halocline. Temperature amplitude between surface and bottom varied between 0 and 1°C, while salinity amplitude ranged between 0 and 0.6.

In all cases, temperature was always higher at the surface than near the bottom, but with variable magnitude: Summer and spring presented variations closer to 0.4°C, while in autumn, variability was lower than 0.1°C. During summer, the salinity of the water column varied between 0.1 and 0.2. In the stations closer to BBE (St1), higher salinity was observed on the bottom, contrary to farther profiles (St9), since higher salinity values were registered on the surface. In winter, on west stations, higher salinity values were found at the bottom (>0.2).

Multivariate Analysis: Spatial Distribution of Parameters

The MDS plot showed the ordination of stations into three major groups, corresponding mainly to spatial variability (Figure 8A). Based on this plot, group 1 (G1) included the two stations that are located closer to the mouth of the BBE. G2 grouped PC stations together, and G3 consisted of MH samples, the most distant from the BBE (Figure 8A). It is important to highlight that in the MDS plot, MH stations seemed to be more similar ("homogeneous") to each other than those sampled in PC. One-way ANOSIM showed significant differences in physical variables among spatial groups (ANOSIM global $R = 0.862$; $p < 0.001$). Pairwise tests showed significant differences between G1 and G2 ($R = 0.948$; $p < 0.05$), G1 and G3 ($R = 1$; $p < 0.05$), and also between G2 and G3 ($R = 0.798$; $p < 0.001$). The study area was characterized by a significant spatial variability, especially in terms of salinity and turbidity (Figure 7B). Water temperature showed a more homogeneous pattern, with

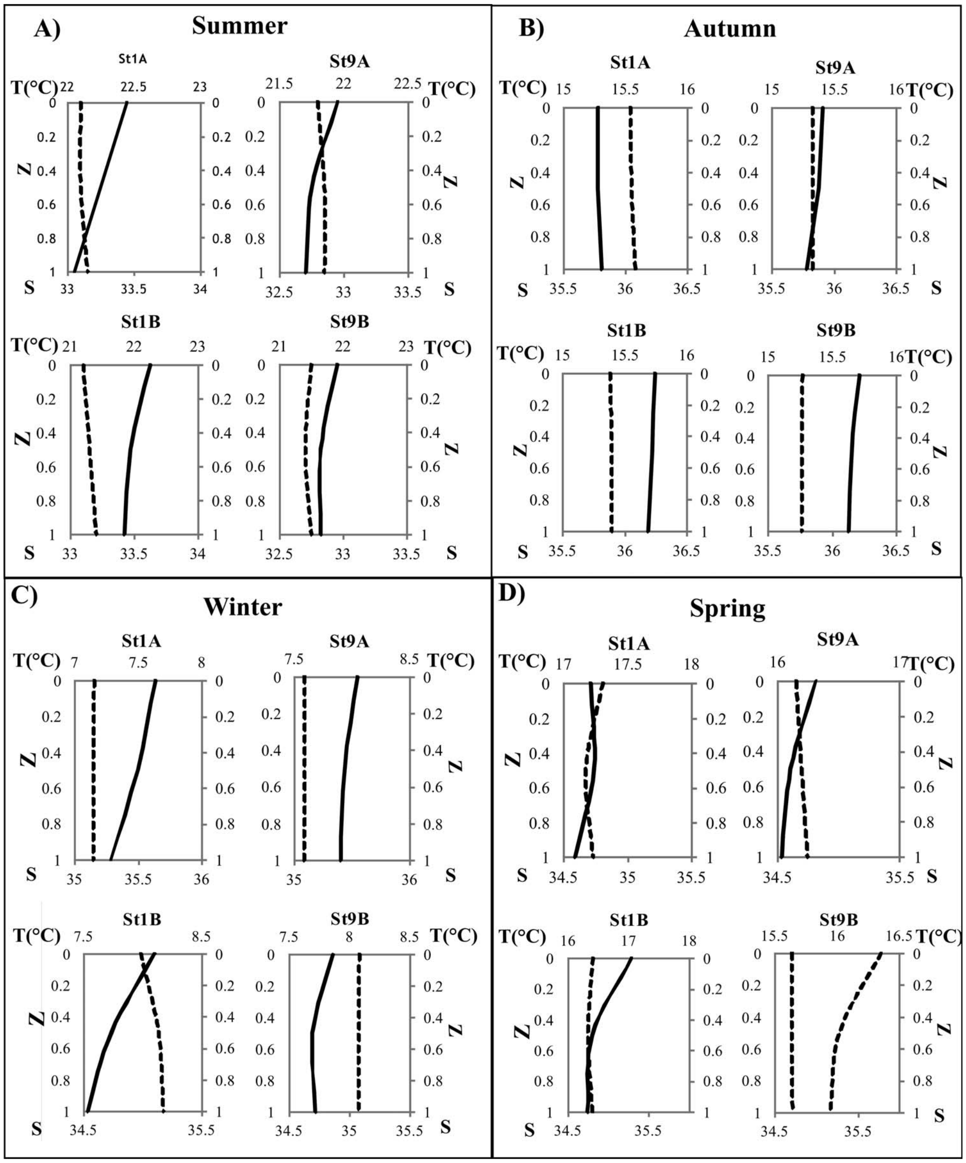

Figure 7. Vertical seasonal distribution of temperature (°C) and salinity (T-S plots) in the study area between March 2010 and February 2011 in (A) summer, (B) autumn, (C) winter, and (D) spring. Stations 1A and 1B represent the west profiles (Pehuen Co) of the study area, closer and farther from the coastline, respectively. Stations 9A and 9B represent the east profiles of the study area (Monte Hermoso), closer and farther from the coastline, respectively. Abbreviations: Z = normalized depth, T = temperature (°C), S = salinity, St = station.

similar values between MDS groups (Figure 8B). Salinity values clearly decreased from PC to MH stations (G1 to G3), with the highest values located near the mouth of the BBE (G1; Figure 8C). A similar pattern was observed in turbidity, with higher concentrations in PC than MH stations (Figure 8D).

DISCUSSION

In this section, the main results related to the seasonal variability of water temperature are discussed: salinity and turbidity in the inner shelf of the southwest Buenos Aires Province. Also, the influence of the BBE plume on the study area will be analyzed.

Seasonal Variability of Surface Parameters: Water Temperature, Salinity, and Turbidity

The inner shelf of the southwest of Buenos Aires Province (Argentina) is characterized by temperate (15°C), high saline (35), and turbid (37 NTU) waters, with pronounced seasonal variability and homogeneity of the water column all year-round. Accordingly, previous works associated the homogeneity of El Rincón inner shelf waters to the constant winds and tidal currents typical of the study area (Lucas *et al*., 2005; Martos and Piccolo, 1988; Perillo, 1994). Water temperature in this study presented high seasonal variability and thermal amplitude (July: 6.1°C to January: 22.9°C; and 16.6°C,

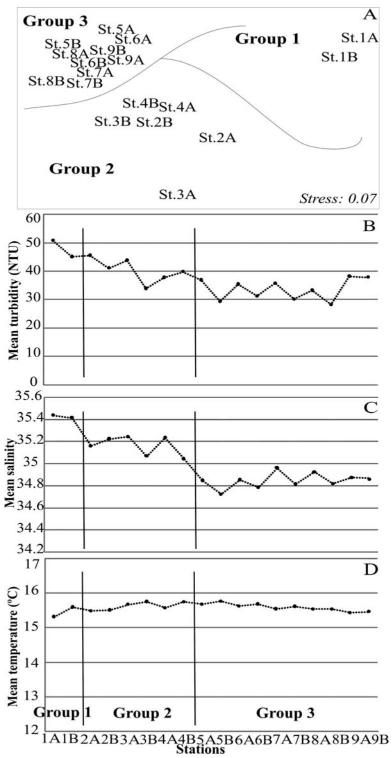

Figure 8. Results of the multivariate statistical analysis (MDS) representing the spatial behavior of the studied variables (temperature [°C], salinity, and turbidity [NTU]) along the inner shelf of southwest Buenos Aires Province, Argentina. (A) MDS plot showing the stations groups observed in the study area. The main groups shown in the MDS are separated by filled lines. (B, C, D) Mean values of turbidity (NTU), salinity, and water temperature (°C) during the sampling period (March 2010–February 2011). St. = station.

respectively). This parameter is coupled with shallow depth effects (1.5 m $> h <$ 12 m) and the influence of the BBE plume (Delgado *et al.*, 2014). On one hand, the sea temperature rapidly responds to the air temperature variations (7–28°C), evidencing a strong heat exchange between the sea and the atmosphere, which is typical of shallow coastal waters (Beigt, Piccolo, and Perillo, 2003; Piccolo, 2009). Further, the atmosphere-sea interaction could be assumed by the heating and cooling processes, which occurred first at the coastal stations ($d < 2$ m) and later at the offshore stations of the study area (see Figure 3). In addition to this, western stations (PC, St1) presented higher thermal amplitude than eastern stations (MH, St9; Figure 8). In this regard, it has been reported that water temperature in the inner and outer BBE are also characterized by a wide thermal amplitude (7–25°C, 7–24°C, respectively; Table 1; Delgado *et al.*, 2014). Dissimilarly, in comparable coastal open waters (*e.g.,* Necochea), temperature seasonal variation is considerably less pronounced, with values ranging between 10°C in winter (Lucas *et al.*, 2005) and 19–20°C in summer (Delgado *et al.*, 2014). Thus, it is assumed that waters coming from the estuary by littoral drift are influencing the thermal conditions of PC and MH coastal waters.

Water mean salinity (35) in the study area is high for typical coastal waters (Perillo and Piccolo, 2011). This phenomenon could be explained by regional and local processes. In a regional scale (El Rincón), 90% of the freshwater input into the system relies on the discharges of the Negro and Colorado Rivers (Lucas *et al.*, 2005). Thus, changes in the total annual discharges, mainly due to rainfall variability, are the cause of major interannual salinity changes in the whole region (Lucas *et al.*, 2005). In accord with results presented by Delgado *et al.* (2015), the decrease of rainfall in 2007–08 generated a reduction in the main freshwater inputs (Colorado and Negro Rivers) and, consequently, an increase of salinity in 2009. The drought continued until 2010, increasing water salinity along the entire inner shelf, and in the study area. From a local approach, the BBE is considered to be a source of saline waters because of the presence of a 30 km^2 salt flat (Salitral de la Vidriera), the relative low input of the Sauce Grande River (2 $m^3 s^{-1}$; Piccolo and Perillo, 1990), and the restricted water circulation, which is associated to evaporation processes that are enhanced by the constant continental winds (Piccolo and Perillo, 1990). In dry years, salinity values up to 41.89 (Freije and Marcovecchio, 2004) have been reported. Furthermore, in the study area, higher salinities were found in the stations located closer to the BBE (G1 $>$ 35.4) compared to those located farther from the BBE (34.7 $<$ G3 $<$ 34.9), evidencing the influence of the estuarine waters on the adjacent inner shelf (Figure 8).

Salinity seasonal variability was pronounced during the study period, with maximum values in autumn (36) and minimum values in summer (33.5; Figure 3). Similarly, Lucas *et al.* (2005) registered lower salinities in El Rincón in spring-summer (33–33.5) and higher values in autumn-winter (33.8–34). The seasonal behavior is associated with the estuarine signal of the Negro and Colorado Rivers, the maximum extension of which is found in spring-summer and minimum in autumn-winter, coupled to the higher and lower discharges of the rivers, respectively (Lucas *et al.*, 2005). Further, the northern advection of the high-saline San Matías Gulf waters is extended towards the inner shelf of the southern part of Buenos Aires Province, particularly in winter (Lucas *et al.*, 2005; Rivas and Pisoni, 2009), increasing the winter salinity values. Also, a tight relationship was found between local precipitation and salinity seasonal variability; higher (lower) salinities values were observed when lower (higher) precipitation amounts were registered (autumn-summer, respectively; Figures 2 and 3).

The study area waters were also characterized by high turbidity values with pronounced spatial and seasonal variability. On a spatial scale, higher mean values were found in the stations closer to BBE (St1 44-50 NTU) compared to those located farther from the estuary mouth (St9: 28–38 NTU), and on stations closer to the coast compared to those offshore. Therefore, it is believed that the main source of turbidity in the study area is the BBE, which has been reported to act as a source of sediment offshore, mainly in summer months (Menéndez *et al.*, 2015). It is important to highlight that the estuary is in an erosional state, which results in the turbidity of the water column all year-round, and, since the sediments are mainly fine (silt and clay), they are transported in suspension

Table 1. *Seasonal hydrography data (temperature [°C], salinity, and suspended particulate matter, SPM [mg L^{-1}]) of the Bahía Blanca Estuary based on previous studies.*

Parameter	Summer	Autumn	Winter	Spring	Reference
Temperature (°C)	25	16	7.3	16.5	Popovich and Marcovecchio (2008); Piccolo and Perillo (1990); Menéndez *et al.* (2015)
Salinity	29–37	28–34	32	29–32	Popovich and Marcovecchio (2008); Piccolo and Perillo (1990); Menéndez *et al.* (2015)
SPM (mg L^{-1})	50–275	100–110	2–35	70	Menéndez *et al.* (2015)

throughout the estuary (Perillo and Piccolo, 1999). Moreover, Perillo and Cuadrado (1990) addressed the presence of the water plume of BBE near MH beach with high concentration of suspended matter all year-round. They further demonstrated that the suspended sediment mineralogy was similar to that of the estuarine suspended sediments. In this study, seasonal distribution indicated that maximum turbidity occurs throughout summer (64 NTU), and minimum values occur during spring (24 NTU; Figure 3). Accordingly, in the BBE, it has been reported that suspended particulate matter varies also in response to the seasons, with maximum concentrations in summer (50.7–275.2 mg L^{-1}) and minimum ones in winter (2–34.8 mg L^{-1}; Menéndez *et al.*, 2015; Table 1).

Influence of the BBE Plume on the Adjacent Continental Shelf

The spatial and temporal variabilities of the sea-surface temperature, salinity, and turbidity observed during this study reinforce the hypothesis of the influence of the BBE waters on the adjacent inner continental shelf. The PC coastal area was more strongly affected by the plume, meanwhile MH showed more similarities to the open beaches (*e.g.,* Necochea). Statistical analysis also corroborated this observation and highlighted the fact that waters coming from BBE are characterized by high salinity and turbidity values and are warmer (cooler) in summer (winter) as well. The results obtained confirm previous assumptions in the study area related to the influence of the BBE on coastal waters (*e.g.,* Carcedo, Fiori, and Bremec, 2014; Carcedo *et al.*, 2015; Perillo and Cuadrado, 1990). From the physical point of view, the W-E gradient in the measured variables shows the degree of dilution of the estuarine plume by the inner shelf waters. However, it was also demonstrated that the high water temperatures on both beaches, as well as the turbid waters, are due to the plume of the estuary. Without the plume, the touristic development of both resorts could not have been possible, since the natural waters of the inner shelf, specifically during the summer months, are below 17°C (Martos and Piccolo, 1988), as originally suggested by Piccolo and Perillo (1990) and later partly corroborated by Cuadrado, Piccolo, and Perillo (2002).

On the other hand, from the biological perspective, Carcedo, Fiori, and Bremec (2014) also speculated about this in an ecological study related to the macrobenthic community in the surf zones of PC and MH. The presence of nonresident, typically estuarine species in the benthic community evidenced some kind of connection between both ecosystems (Carcedo, Fiori, and Bremec, 2014, p. 333). Those authors discussed that this phenomenon could be due to "the export of warm waters from the BBE, a process that would give rise not only to higher temperatures but also to a high load of suspended sediment and some invertebrates." Furthermore, it was supposed that the proximity of these beaches to the BBE could mitigate the habitat challenges, enhancing the density of organisms (Carcedo *et al.*, 2015). The influence of the BBE has been mentioned as a crucial factor structuring the intertidal macrobenthic community in the southwest part of Buenos Aires Province (Carcedo *et al.*, 2015). Reinforcing the connection between both environments, the surf zone zooplankton community in MH was characterized by both estuarine species and others typical of inner shelf waters (M.C. Menéndez, *personal observation*). Similar findings have been observed in other surf zone beaches worldwide (*e.g.,* Cowley, Whitfield, and Bell, 2001; Lasiak, 1981; Strydom, 2003; Strydom and d'Hotman, 2005). In all of these studies, surf zone and nearshore catches exhibited a degree of coupling with adjacent estuarine environments (Strydom, 2003). Aggregations of estuarine-associated ichthyoplankton in the inshore zone have been related to physical and environmental factors of the exported waters (Cowley, Whitfield, and Bell, 2001).

CONCLUSIONS

In this study, the hydrography of PC and MH coastal waters is presented for the very first time. The coastal zone of PC and MH is located in a highly complex oceanographic and ecological regional system, influenced by large inputs of continental runoffs, an estuarine plume, and local meteorological forcing. Further, the occurrence of dry/wet periods influences the seasonal and annual rainfall, acting as the major source of interannual salinity variations of the water column. The study area is highly affected by the BBE plume, and as consequence, it is vulnerable to seasonal and interannual dynamics of the estuary. Thus, the PC and MH (to a lesser extent) inner shelves are considered to be a transitional environment between the estuary and the open beaches of Buenos Aires Province, creating a habitat where benthic and zooplankton estuarine and marine species are found. These conditions may also affect the presence and the abundances of fish species in the study area. As a consequence, it is recommended to consider these characteristics for further studies and planning of the uses of natural resources.

ACKNOWLEDGMENTS

Partial support for this research was provided by grants from the Agencia Nacional de Promoción Científica y Tecnológica (ANPCYT, PICT 2012-0356) and Universidad Nacional del Sur (UNS, PGI 24/H103). The authors wish to thank the crew of the Instituto Argentino de Oceanografía boat *IADO IV* for their help during the oceanographic cruises. The authors would also like to thank the anonymous reviewers for their constructive observations, which have improved the quality of this paper.

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