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Short time-scale wind forced variability in the Río de la Plata Estuary and its role on ichthyoplankton retention

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Abstract

The Río de la Plata Estuary presents a strong bottom salinity front located over a submerged shoal. Apparently favored by retention processes, it is a spawning ground for several coastal fishes. This estuary is very shallow and essentially wind driven and, moreover, in time scales relevant to biota, estuarine circulation is wind dominated and highly variable. Two intriguing questions are, therefore, how this system can favor retention and what the involved mechanisms are. This paper qualitatively explores mechanisms involved in the estuary where retention is favored applying numerical simulations in which neutral particles – simulating fish eggs and early larvae – are released along the bottom frontal zone and tracked for different wind conditions. Results suggest that retentive features can be a consequence of estuarine response to natural wind variability acting over bathymetric features. For winds from most directions, particles either remain trapped near their launching position or move northeastward to southwestward along the shoal. As alternation of winds that favor along-shoal motion is the dominant feature of wind variability in the region, a retentive scenario results from prevailing wind variability. Additionally, winds that tend to export particles with a poor chance of being restored to the front are neither frequent nor persistent. Results show, therefore, that physical forcing alone might generate a retentive scenario at the inner part of this estuary. The physical retention mechanism is more effective for bottom than for surface launched particles. Wind statistics indicate that the proposed mechanism has different implications for retention along the seasons. Spring is the most favorable season, followed by summer, when particles would have a larger propensity to reach the southern area of the estuary (Samborombón Bay). Fall and winter are increasingly less favorable. All these features are consistent with patterns observed in the region in organisms having different life history traits.

Keywords: retention processes; wind variability; numerical model; Río de la Plata Estuary; bathymetric control; 60–54° W and 34–37° S

1. Introduction

Estuaries worldwide support a diverse range of marine teleosts (Cronin and Mansueti, 1971; Dando, 1984; Wallace et al., 1984; Whitfield, 1998; Potter and Hyndes, 1999). The most common life history of fishes that use those systems involves spawning of planktonic eggs in the sea, and the subsequent recruitment to estuaries as post-larvae or juveniles. Since in these systems many of those species are predominantly represented by juveniles, estuaries have frequently been referred to as nursery areas rather than as spawning grounds (McHugh, 1967; Haedrich, 1983; Claridge et al., 1986). In general, only a few species spawn within estuarine

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ecosystems (Haedrich, 1983; Dando, 1984). Among the few species that reproduce within estuaries, pelagic eggs spawners are uncommon (Dando, 1984). However, it has been documented that in the Río de la Plata Estuary (Fig. 1) several coastal fishes spawn planktonic eggs well inside the estuary. Fig. 2 presents information on ichthyoplankton distribution and reproduction sites for the whitemouth croaker (*Micropogonias furnieri*) and the Brazilian menhaden (*Brevoortia aurea*), which supports the early life history retention hypothesis. Moreover, reproductive activity has been reported in the estuary for the king weakfish (*Macrodon ancylodon*) (Militelli and Macchi, 2004), black drum (*Pogonias cromis*) (Macchi et al., 2002) and Jenyns's sprat (*Ramnogaster arcuata*) (Rodrigues, 2005).

In defining retention as staying at (or drifting towards) appropriate habitat (in terms of food supply, low predation levels, and/or physic-chemical environment) (Bakun, 1996), several authors have suggested that retention in this estuary would be a natural consequence of the theoretical circulation coupled to a salt wedge or salinity front (e.g. Mann and Lazier, 1991). That is, a convergent flow between continental and oceanic waters would retain ichthyoplankton near the head of the salt wedge preventing their exportation towards coastal waters (Acha et al., 1999; Acha and Macchi, 2000; Mianzan et al., 2001). However, neither the occurrence of retention processes in the Río de la Plata Estuary, nor the physical and/or behavioral involved mechanisms have been studied yet.

Recent papers based on numerical simulations (Simionato et al., 2004a) and ADCP current observations collected at the estuary (Simionato et al., 2005a, 2006, 2007) have shown that estuarine dynamics in the Río de la Plata region are complex, highly variable and essentially wind dominated. Those papers demonstrated that estuarine scales of variability replicate atmospheric ones, and that currents response to changes in wind direction is very fast, occurring in a lapse of around 6 h. Moreover, in the salt wedge region, wind forced variability account for 75% of the currents variance (Simionato et al., 2005a, 2006, 2007). They also revealed that, in response to winds, the estuary produces currents with a phase lag relative to wind direction that depends on its location in the estuary due to interactions with the topography and coastline. Current speed, even at the bottom layer, is significant and it is a function of wind speed and direction which, in turn, is highly variable. As a result of the described features, in time scales relevant to biota, the Río de la Plata displays weather and climate, as the atmosphere does (Simionato et al., 2006, 2007). Even though a seasonal cycle with Northeasterly (Westerly) winds prevailing in summer (winter) has been reported in the literature (Guerrero et al., 1997), atmospheric circulation over the region in synoptic to intra-seasonal scales is characterized by high variability. This is associated with several processes that include atmospheric waves coming from the South Pacific that have an influence over Argentina as frontal systems and waves moving along subtropical latitudes of the South Pacific and South American region that may result in cyclogenetic events in the vicinity of the estuary (Vera et al., 2002), so as alternating patterns of intra-seasonal variability (Nogues-Paegle and Mo, 1997). Indeed, variability in subannual scales accounts for more than 80% of meridional wind component variance and approximately 30% of the zonal one in the region (Simionato et al., 2005b). As a result of those features, winds in the region rarely blow from the same sector for more than a few days but tend, instead, to alternate their direction mainly from Northeast to Southwest and,

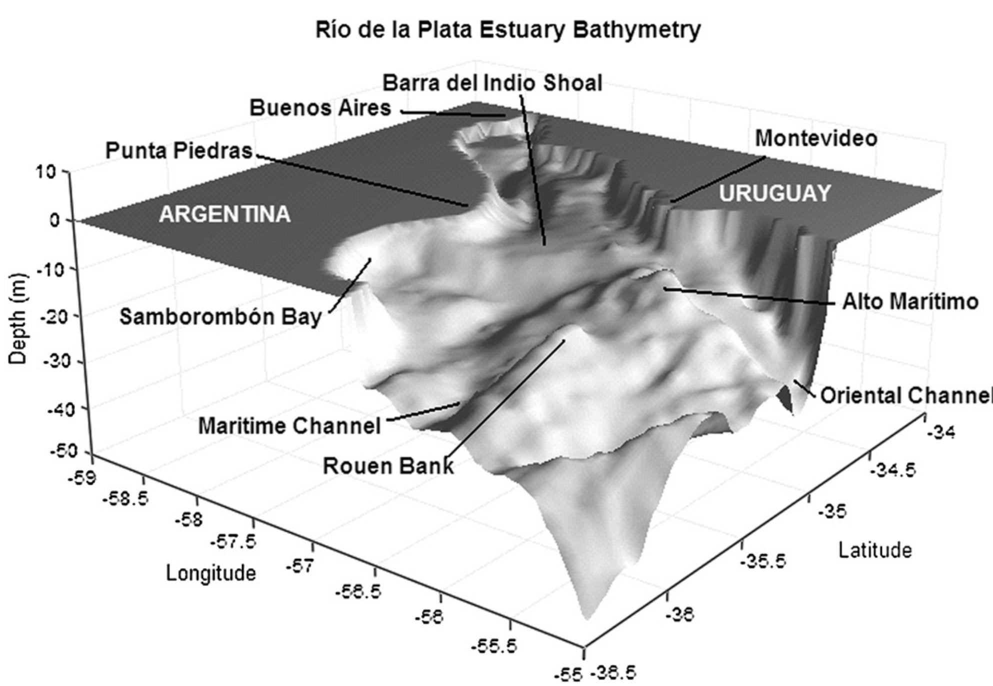

Fig. 1. Bathymetry of the Río de la Plata Estuary (in meters) and main geographical and topographical features. Note that vertical and horizontal scales are not the same.

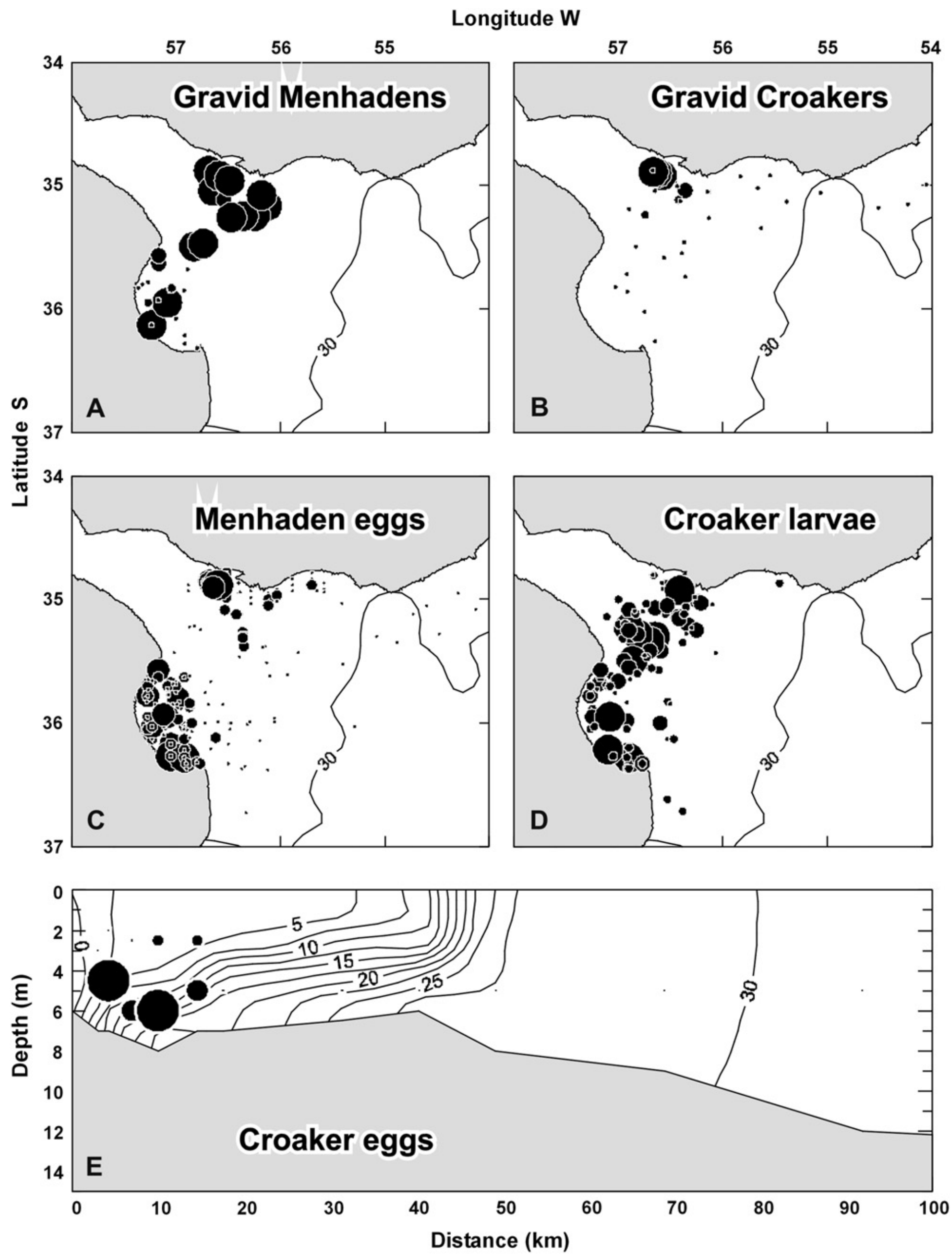

Fig. 2. Biological patterns on which the retention hypothesis was based. (A) Gravid females percentage for Brazilian menhaden (redrawn from Acha and Macchi, 2000). (B) Gravid females percentage for whitemouth croaker (redrawn from Macchi et al., 1996 and Acha et al., 1999). (C) Density of Brazilian menhaden eggs (redrawn from Acha and Macchi, 2000). (D) Density of whitemouth croaker larvae (Braverman and Acha, submitted for publication). Thirty units surface salinity contour from Guerrero et al. (1997). (E) Salinity section showing vertical distribution of whitemouth croaker eggs (redrawn from Acha et al., 1999).

consequently, currents present a similar variable feature. A striking question is, then, whether this highly variable ecosystem can favor fish eggs and larval retention and, if so, what mechanisms are involved. Therefore, the aim of this paper is to qualitatively explore the role of wind variability on ichthyoplankton retention in the Río de la Plata Estuary. For that purpose a set of process oriented numerical experiments is conducted, in which neutral particles resembling planktonic fish eggs and early larvae are released along the frontal zone of the Río de la Plata and its vicinity – spawning grounds of the above mentioned species – and tracked for different wind conditions in short time scales. Results of the numerical simulations are complemented with an analysis of local wind data statistics. As a result, a physical mechanism for particle retention is suggested and its implications for particle dispersion along the different seasons are discussed.

2. Study area

The Río de la Plata (Fig. 1), located on the eastern coast of southern South America at approximately 35° S, is one of the largest estuaries of the world (Shiklomanov, 1998). It has a northwest to southeast oriented funnel shape approximately 300-km long that narrows from 220 km at its mouth to 40 km at its upper end (Balay, 1961). The estuarine area is 35,000 km^2 and the fluvial drainage area is 3.1×10^6 km^2.

The Río de la Plata displays a complex geometry and bathymetry. A complete description of its morphology and sedimentology can be found in Ottman and Urien (1965, 1966), Urien (1966, 1967, 1972), Depetris and Griffin (1968), Parker et al. (1986a,b) and López Laborde (1987). A brief description of some morphological features relevant to the present study follows. The estuary is divided into two regions by the Barra del Indio shoal, a shallow area that crosses the river between Punta Piedras and Montevideo (Fig. 1). The upper region is mainly occupied by fresh water. Seaward of this shoal is the Maritime Channel, a wide depression with 12- to 14-m depth at the north and 20 m 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, a very shallow and extensive area with depths ranging from 2 to 10 m extending south of Punta Piedras, has been described as an important nursery ground for several coastal fishes (Lasta, 1995; Mianzan et al., 2001).

The system drains the waters of the Paraná and Uruguay rivers, which constitute the second largest basin of South America. As a result, it has a large discharge with a mean of around 25,000 $m^3\,s^{-1}$, and maximum values as high as 50,000 $m^3\,s^{-1}$ under extreme conditions (Jaime et al., 2002). Density in the estuary is controlled by salinity, whereas changes in temperature, even important from one season to another, only display small horizontal gradients (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 (Fig. 1) following the 10 m isobath (Guerrero et al., 1997). Forced by the prevailing winds (Simionato et al., 2001) both surface and a bottom salinity front show a seasonal cycle that largely modifies the salt wedge structure from spring–summer to fall–winter (Guerrero et al., 1997). Over long-term time scales, a spatial overlap has been observed between this salinity front and an Estuarine Turbidity Maximum characterized by elevated turbidity and suspended sediments (Framiñan and Brown, 1996).

3. The numerical model and setting

The numerical model used in this study is the Estuary, Coastal, and Ocean Model (ECOM), a three-dimensional hydrodynamic computer code developed by HydroQual (Blumberg, 1996) for application to marine and freshwater systems. It is a widely used sigma coordinate, hydrostatic, primitive equation model derived from Princeton Ocean Model (Blumberg and Mellor, 1987). The code includes an online particle tracking routine that calculates the displacement of particles as the sum of an advective deterministic component, and an independent random Markovian component which statistically approximates the dispersion characteristics of the environment (Dimou and Adams, 1993).

An orthogonal coordinate domain spanning the region between 58°36′–50° W and 38°30′–30° S was constructed, with variable horizontal resolution between 3.5 and 7.5 km and 10 vertical sigma levels. Finest horizontal resolution was set over the Río de la Plata Estuary and its maritime front, where grid spacing (Δx and Δy) is less than 4 km. The highest vertical resolution was set near surface and bottom. This variable grid allows for an efficient and computationally time-effective modeling framework with an adequate resolution in the areas of interest.

High-resolution bathymetry data (shown for the Río de la Plata area in Fig. 1) were provided by the Servicio de Hidrografía Naval (SHN) of Argentina and come from digitalized charts (SHN, 1986, 1992, 1999a,b). Depth was set to 200 m everywhere it is deeper than that value. This approach does not modify results in the shallow areas of interest and permits the use of a longer time-step.

ECOM applies a time splitting technique for computational efficiency in which internal (baroclinic) and external (barotropic) modes are computed separately. The external and internal time steps were set to 20 s and 10 min, respectively, in compliance with the Courant, Friedrichs and Lewy (CFL) criterion (Courant et al., 1928). Horizontal mixing coefficients of salt, temperature and momentum were parameterized using the Smagorinski (1963) formulation with the adimensional parameter (HORCON) of 0.2. Vertical mixing coefficients were parameterized using the 2.5 level closure scheme of Mellor and Yamada (1982) with a base value (UMOL) of 1×10^{-6} $m^2\,s^{-1}$.

Boundary conditions at the sea surface are wind forcing and zero salt and heat fluxes. At the bottom, momentum is balanced by a quadratic bottom stress with a bottom drag coefficient given by the ‘‘law of the wall’’; salt and heat fluxes and vertical velocity are zero. The coastal wall boundary is impenetrable, impermeable and no-slip.

At open boundaries, boundary conditions are such that the bore triggered by the plume passes through the boundaries. For free surface elevation, the radiation condition developed by Reid and Bodine (1968) was used. Advection scheme is Smolar_r proposed by García Berdeal et al. (2002), in which the numerical diffusion introduced by upwind finite difference schemes (Smolarkiewicsz, 1984; Smolarkiewicsz and Clarke, 1986; Smolarkiewicsz and Grabowski, 1990), is corrected with an anti-diffusion velocity estimated using a recursion relationship.

Initial conditions for particles release were obtained starting model from rest and spinning it up until stabilization of the salinity frontal zone at its observed location in both summer and winter. Following Simionato et al. (2001), the frontal zone was modeled as dependent only on salinity. Model was initialized with a constant salinity of 33, representative of the Continental Shelf waters, and a temperature of 10 °C. The mean discharge of Paraná and Uruguay rivers during the last decades of the 20th century (25,000 $m^3 s^{-1}$) was considered as a representative runoff for all runs. To introduce the effect of tides in the simulation, a boundary condition that represents the evolution of M_2, by far the most important tidal constituent (D'Onofrio et al., 1999), coming from a larger scale model (Simionato et al., 2004b) was imposed to sea surface elevation. To characterize summer and winter winds, a climatology of the 1979–2001 period of National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 10 m wind components reanalyzed data (Kalnay et al., 1996) was used. Summer is defined as December–February and winter as June–August period. After 150 days of integration, simulations remarkably reproduce both bottom and surface salinity fronts (shown in Fig. 3), as well as the salt wedge structure (shown in Fig. 4) when compared to observational results (Guerrero et al., 1997).

Once the initial 'summer' and 'winter' conditions were obtained, groups of 100 particles each were launched at 12 locations along three lines parallel to the Punta Piedras–Montevideo line over the Barra del Indio Shoal, following the bottom salinity front (Fig. 3) at both near surface and bottom (model layers 2 and 9). Springtime spatial distribution of gravid females shows specimens mainly along the Barra del Indio shoal (Fig. 2), but also in the inner waters of Samborombón Bay (menhaden). Reports on vertical distribution of fish planktonic eggs (croaker and menhaden, both during the same cruise) (Acha et al., 1999; Acha and Macchi, 2000), show the eggs in the bottom layer, in a highly stratified region. So, it was worthy to launch particles at the bottom and surface layer to test for differences in retention patterns. Launching 100 particles at each location allows the study of particle spreading due to dispersive properties of the environment in addition to advection, and the identification of particles most likely positions given a particular forcing situation. Experiments were repeated increasing the number and changing the location of particles launching, but results were not sensitive to those modifications.

As mentioned in the introduction, one of the most important features of atmospheric circulation in the region is its high variability in synoptic to intra-seasonal time scales, particularly in wind direction. As a consequence, winds rarely

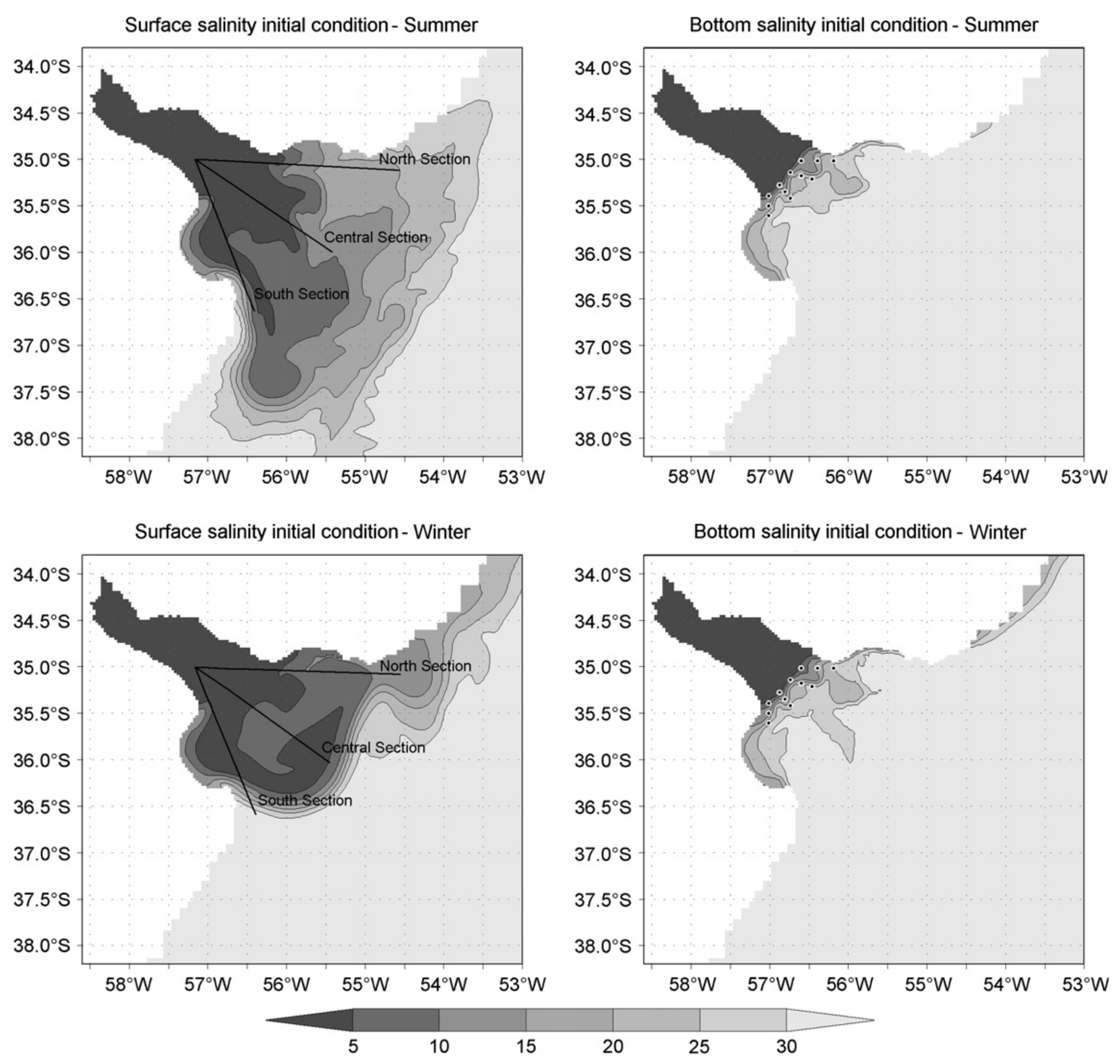

Fig. 3. Left: Surface 'summer' (up) and 'winter' (down) salinity condition on the first day of particle release; lines show the selected vertical sections shown in Fig. 4. Right: Bottom 'summer' (up) and 'winter' (down) initial salinity condition for particle release; points show the locations where groups of particles were launched both near surface and bottom.

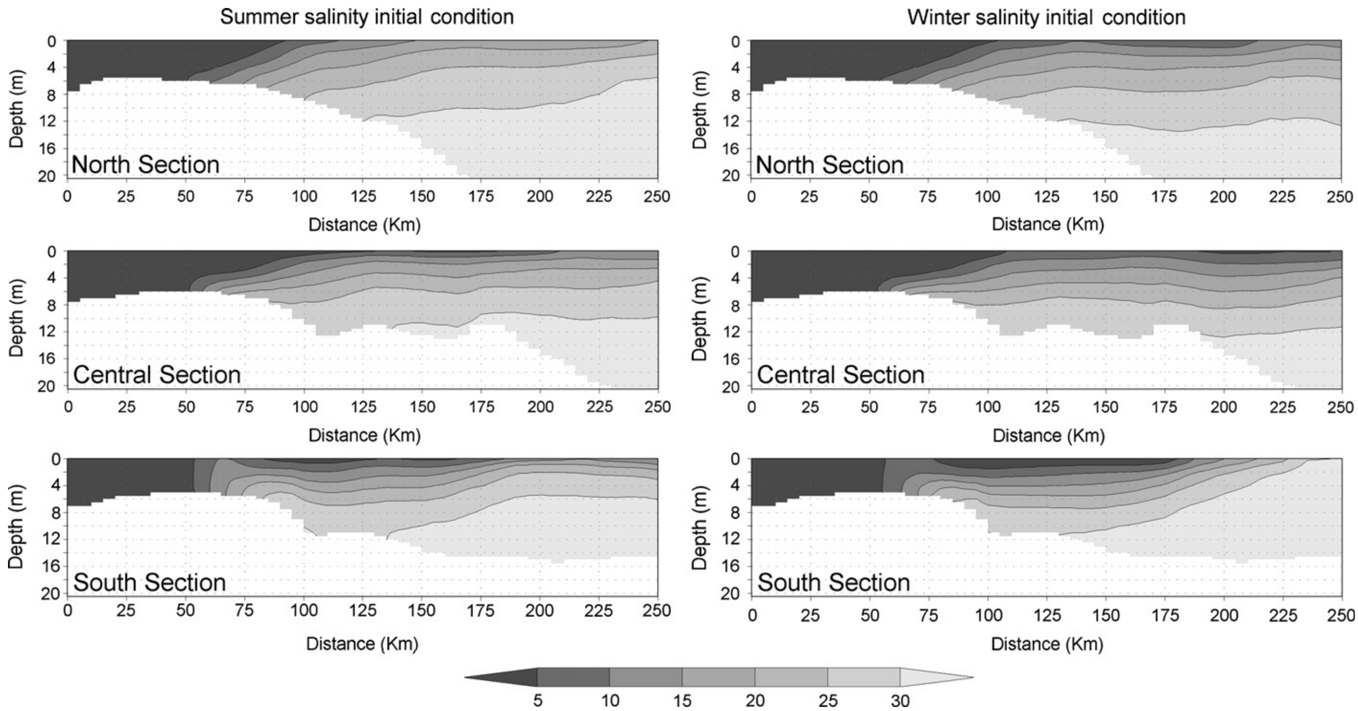

Fig. 4. Vertical salinity sections of the 'summer' (left) and 'winter' (right) salinity condition on the first day of particle release at the Northern, Central and Southern sections indicated in the left panels of Fig. 3.

blow from the same direction for more than a few days. This feature can be seen in the wind vectors stick diagrams from NCEP/NCAR reanalyzes at 35.24° S–54.37° W (Fig. 5) for the four seasons of a typical year (1995). It can also be observed in Fig. 5 that wind variability on short time scales is mainly related to changes from a dominant Northerly component to a prevailing Southerly one, over a temporal scale of around 2 to 3 days, whereas persistent events with dominant Easterly or Westerly components are less frequent. Simulations under real wind conditions made the identification and understanding of processes that may favor retention in the area, which are the aim of this paper, complicate. Therefore, the modeling strategy was to develop short-term simulations in which the effect of winds from 16 directions (22.5° apart) on particle advection and dispersion was analyzed. Simulations were done for both winter and summer initial conditions. Wind speed was set to 6 m s^{-1}, a value that represents the mean and the mode for all seasons in the NCEP/NCAR reanalyzes climatology at 35.24° S–54.37° W. Wind speed and direction were gradually changed from their initial seasonal value during one day by applying a linear ramp, and particles were released after 24 h of simulation. Particles were tracked during a 7-day period, after which the daily particle density field (number of particles per area unit) was computed for both surface and bottom launched groups.

4. Results

4.1. Numerical simulations

In order to simplify the interpretation of the numerical simulations results, a Principal Components (Empirical Orthogonal Functions – EOF) analysis was applied to the daily particle density field independently for both summer and winter simulations, and for particles launched in surface and bottom layers. That analysis helps to identify common dispersion patterns resulting from the different modeled wind directions. EOF results for summer initial conditions after 3 days of simulation for bottom and surface released particles are shown in Figs. 6 and 7, respectively. In those figures, the maps display the modes (characteristic particle density fields) and the inner discs, the associated loadings (which represent the correlation between the mode and the numerical solutions for each wind direction). For both bottom and surface released particles it was found that four modes account for approximately 75% of the total variance. They, in turn, define four different spatial particle density fields mainly correlated to winds blowing from four different sectors. The first field (upper left panels of Figs. 6 and 7) is related to Southeasterly to West–Southwesterly (clockwise) winds for bottom particles and with Southeasterly to Southwesterly winds for surface particles. Particle density fields associated with the first mode are similar for both bottom and surface released groups, displaying a tendency for particles to move northeastward, following bathymetry, with relatively little dispersion. Particles released in the southernmost portion of the front display a slight upstream-the-estuary motion. Nevertheless, it can be appreciated that more dispersion was seen for surface than for bottom-released particles. This feature is especially noticeable for particles released along the northernmost line, whereas those launched at the southernmost one exhibit a more homogeneous pattern for different launching depths. Given that ECOM applies sigma coordinate in the vertical, even though particles were released at the same model layer, their initial depth can differ from one

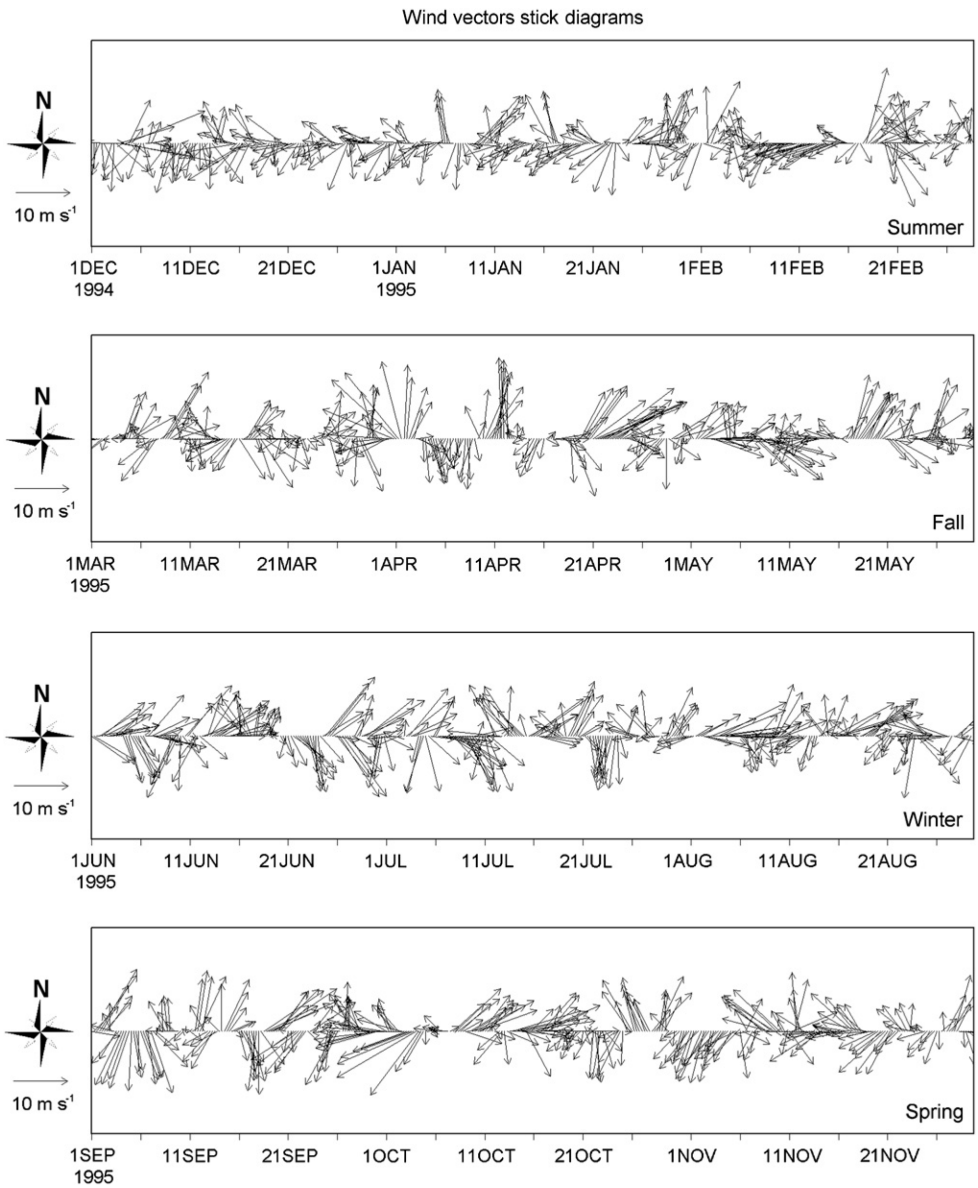

Fig. 5. Four-daily wind vectors stick diagrams for the four seasons of 1995 from the NCEP/NCAR reanalysis at 35.24° S–54.37° W.

point to an other. This way, whereas northernmost launching locations are relatively deep, the southernmost ones are much shallower and, therefore, more directly influenced by winds. This can explain, in part, the above mentioned differences found between particles launched at different locations. The second mode (upper right panels of Figs. 6 and 7) is related to Northerly to East–Northeasterly (clockwise) winds for bottom particles and to North–Northwesterly to Northeasterly winds for surface particles. Even though the characteristic particle density field associated with mode 2 is similar for both bottom and surface launched particles – displaying a tendency for them to move southwestward, following bathymetry and, in occasions, entering Samborombón Bay – more dispersion is again observed for surface than for bottom groups.

The first two modes, therefore, are associated with winds with a Southerly (Northerly) dominant component and tend to produce a northeastward (southwestward) particle motion. Particles drift following bathymetric features, along the arc defined by the Samborombón Bay coast, the Barra del Indio shoal and the Uruguayan coast. Positions of particle groups launched along the central line (Fig. 3, right panels) after 1, 2 and 3 days of simulation are shown in Figs. 8 and 9 for bottom and surface released particles, respectively. Those groups are representative of the general behavior of the total of the particles launched. Each figure was built using simulation results for the wind forcing direction that better correlates to the associated mode and, therefore, displays a 'particle dispersion pattern' related to wind blowing from the corresponding sector. In addition to allowing for a better visualization of the above mentioned particle dispersion characteristics, Figs. 8 and 9 permit the differentiation of zones where motions tend to be faster or slower and to better visualize particles most likely path under persistent wind conditions. It can be seen, for example, that for winds with a Southerly dominant

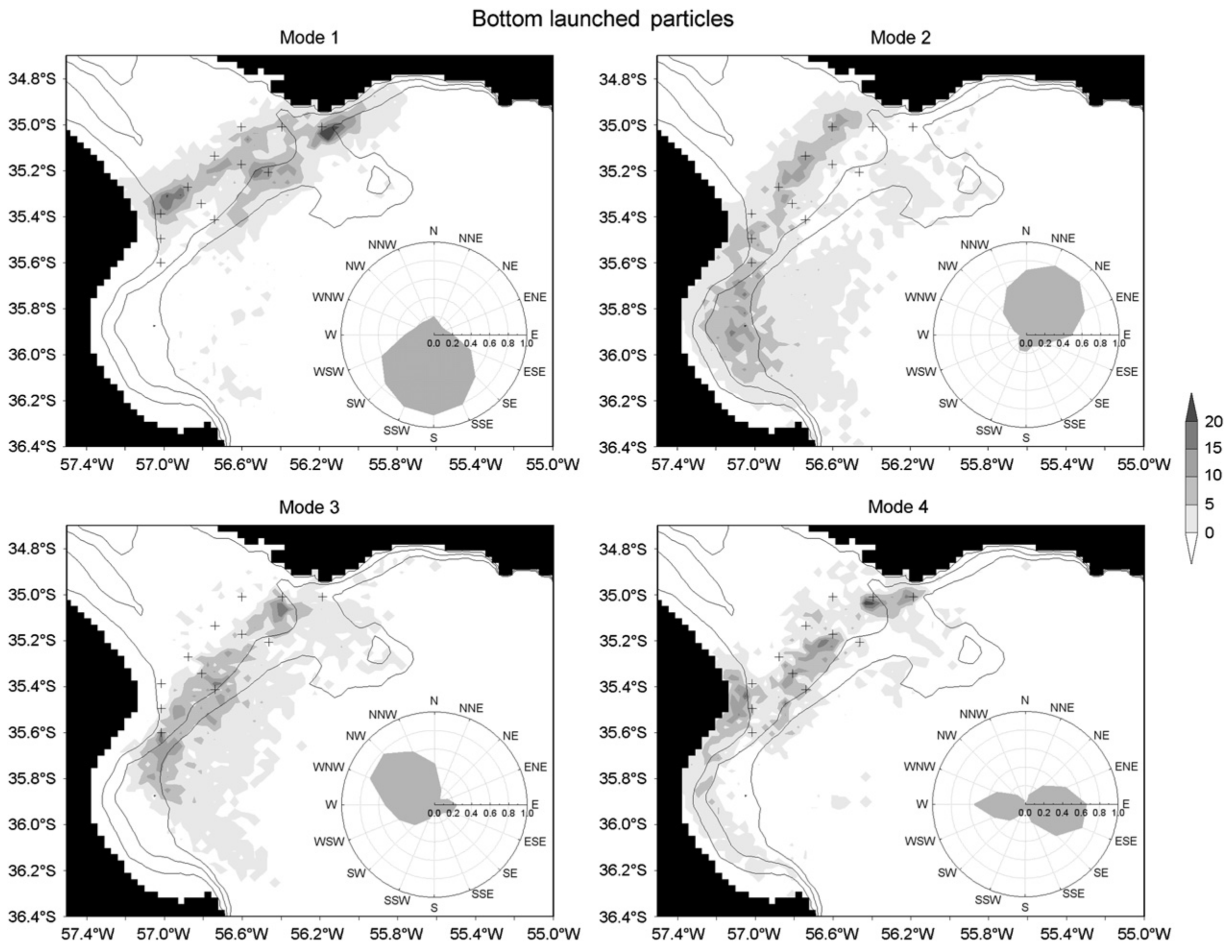

Fig. 6. Results of numerical model solutions EOF analysis for bottom launched particles. Maps show the modes or characteristic particle density fields (number of particles per area unit). Lines representing the 5, 7.5 and 10 m isobaths have been superimposed. The inner discs show the associated loadings representing the correlation between each mode and numerical solutions for every wind direction. The symbol '+' indicates particles launching positions.

component, particles launched in the southernmost portion of the front tend to disperse less than particles released in the northernmost one, whereas the reciprocal is observed for winds with a Northerly dominant component. It can also be appreciated that, as winds persist from the same sector, dispersion patterns following bathymetry are preserved, although particles are more dispersed. This behavior is even preserved after a much longer number of days (not shown). That is an indication that modes are robust and indeed represent the system behavior.

The third and fourth modes (lower panels of Figs. 6 and 7) are, as expected, orthogonal to the first two and, therefore represent the response to winds with a Westerly (for mode 3) and Easterly (for mode 4) dominant component. These modes are related to a southeastward–northwestward oriented motion of particles, respectively, that is, perpendicularly to bathymetry. As a result of those modes, for Westerly to Northwesterly (clockwise) winds, particles would tend to move downstream, and for Easterly to Southeasterly winds, particles would tend to move upstream. As shown in Figs. 8 and 9, this is indeed the case for mode 3, related to West–Northwesterly to North–Northwesterly (clockwise) winds for bottom particles, and West–Southwesterly to Northwesterly winds for surface particles. Nevertheless, as seen in Fig. 8 (lowermost panels), for Easterly to Southeasterly winds (mode 4) bottom particles cannot penetrate upstream but remain trapped, except for those released at the southernmost portion of the front, where estuary is in general much shallower (see Fig. 1). This suggests that trapping may be bathymetrically controlled, as a result of the presence of the Barra del Indio shoal, rather than due to the occurrence of the salinity front. Surface particles (lowermost panels of Fig. 9) for those wind directions do not penetrate the estuary either, but instead tend to move southwestward, following bathymetric features and moving into Samborombón Bay. This behavior is probably a result of the continental freshwater output linked to the upper layers. Finally, Figs. 8 and 9 indicate that particles released in the northernmost portion of the front tend to display a more retentive pattern than those launched in the south for most of wind directions, suggesting that the first region could be more favorable to biota as far as retention is concerned.

Results of the analysis for winter initial conditions (not shown) do not differ from the above discussed summer ones, indicating that for mean runoff conditions, particle dispersion characteristics are dominated by wind variability.

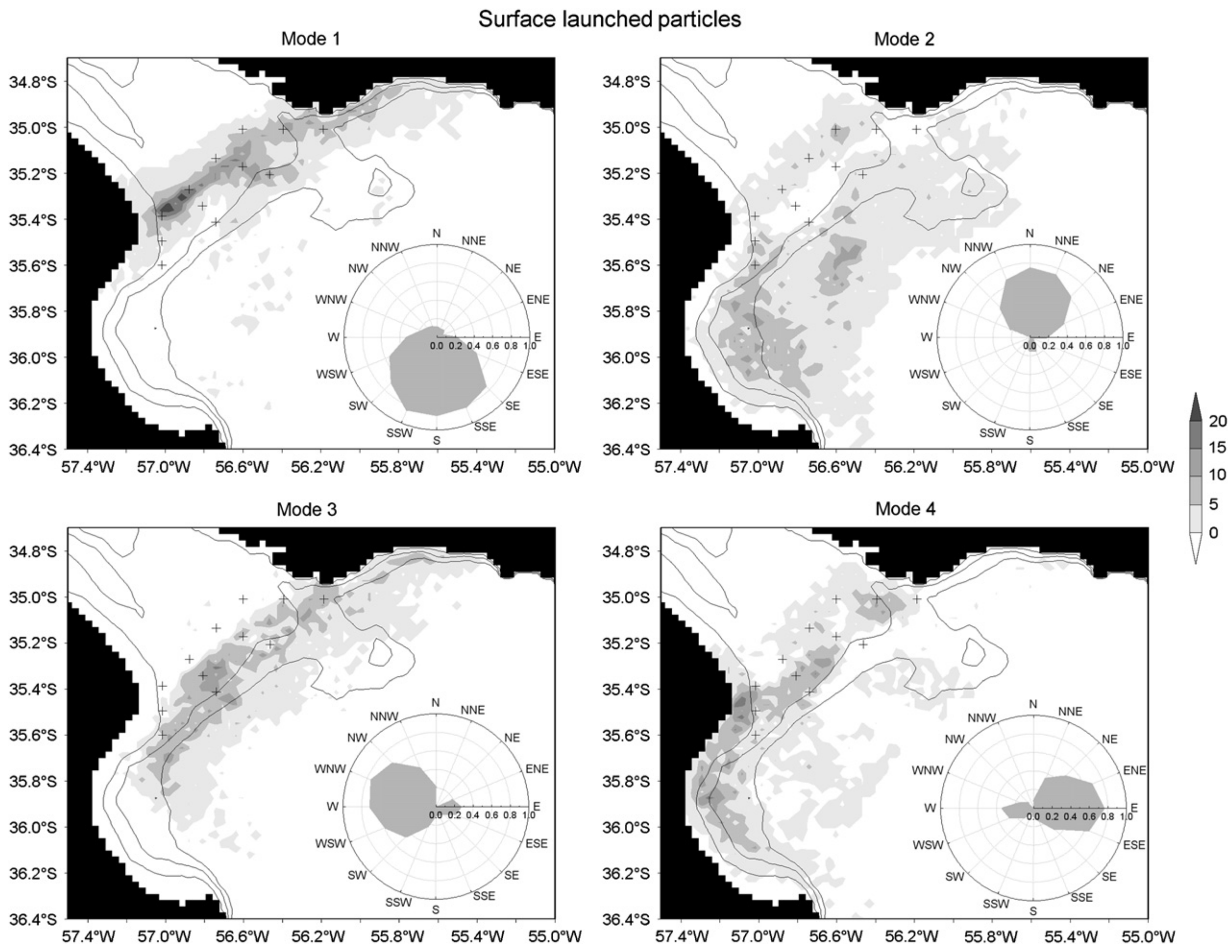

Fig. 7. Same as Fig. 6 for surface launched particles.

4.2. Wind statistics

In order to analyze our results in the context of the observed wind variability in the region along the year a statistics of the NCEP/NCAR 10-m winds at 35.24° S–54.37° W was done. Monthly wind direction histograms are shown in Fig. 10 where histogram bars were grayed by wind directions relative to each of the described dispersion modes for bottom launched particles. Light grey bars are associated to mode 1, dark grey bars to mode 2, black bars to mode 3, and white bars to mode 4. For simplicity, the figure has been confined to the eight most important wind directions. To complement the analysis, Fig. 11 shows the mean wind speed as a function of wind direction for every month. Figures show that during October–March (the austral spring/summer period) the most frequent wind directions are Northerly and Southerly, in that order, that is, those associated with modes 2 and 1, respectively. In that period wind direction related to mode 3 (Westerly) is both the weakest and less frequent. During the rest of the year (fall/winter) wind directions associated with modes 1 and 2 are the most frequent, but Westerly/Northwesterly winds increase both their frequency of occurrence and mean speed. This way, the main seasonal change in wind is an increase of West–Northwesterly winds in both frequency of occurrence and mean speed during fall/winter.

5. Discussion and conclusions

Results indicate that the preferential motion of particles launched along the bottom salinity front of the Río de la Plata – simulating fish eggs and early larvae – is mainly driven by blowing wind direction. This motion can be explained in terms of four modes, which essentially produce two orthogonal dispersion patterns associated with the coexisting bottom bathymetry and coastline. The first pattern, occurring for winds with a Southerly (Northerly) dominant component is related to a preferential northeastward (southwestward) particles motion along the Barra del Indio shoal. The second pattern, associated to winds with a dominant Westerly (Easterly) component is connected to a downstream (upstream) preferential particle motion across the shoal. Nevertheless, for most of the particles, upstream motion is inhibited by the shoal in lower layers and the continental discharge in upper ones, resulting in preservation of most of them in the vicinity of their launching position – especially for particles released near the bottom – whereas remaining particles show, in general, a displacement towards Samborombón Bay. Therefore, according to our results, for most of wind directions, in short time scales, the majority of particles launched over the bottom salinity front would either remain trapped in the proximity of their initial position or move in northeastward/southwestward direction along the Barra del

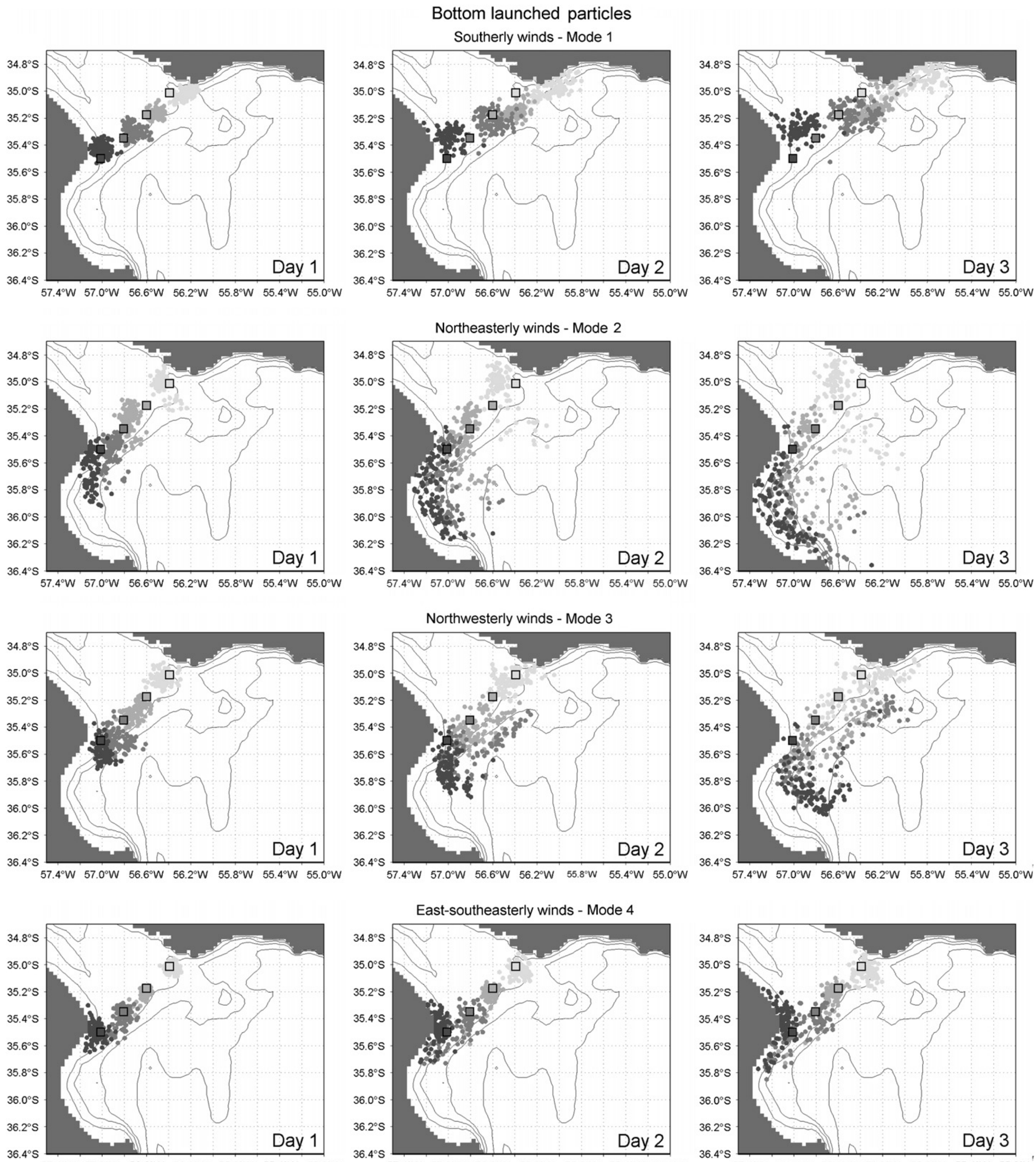

Fig. 8. Positions of particle groups launched at the bottom of the central line (Fig. 4) after 1, 2 and 3 days of simulation, for wind directions representative of modes 1, 2, 3 and 4. Squares and grey levels represent particles initial positions. Lines representing the 5, 7.5 and 10 m isobaths have been superimposed.

Indio shoal. When particles have northeastward–southwestward preferential motion along the shoal, they can be moved out the bottom frontal zone, either northward to the Uruguayan coast or along the front southward into Samborombón Bay. Nevertheless, additional similar numerical experiments (not shown) in which particles were launched at those areas indicate that they have a very high probability of being restored to the Barra del Indio region as wind direction reverses. Moreover,

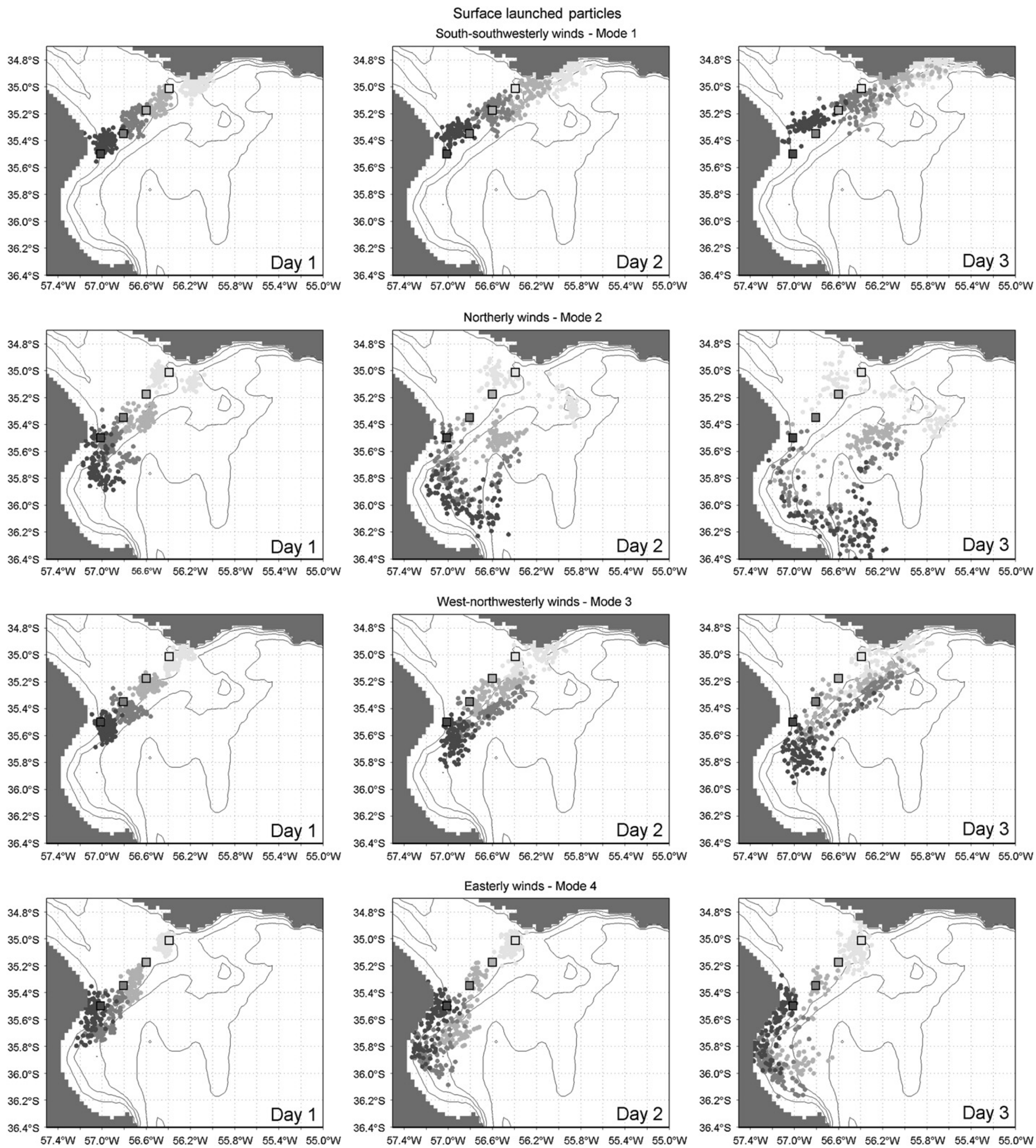

Fig. 9. Same as Fig. 8 for surface launched particles.

Samborombón Bay displayed a similar feature to the Barra del Indio zone, in which particle motion is essentially bathymetrically controlled and, therefore, tends to develop along the coast, with associated wind directions slightly displaced to South–North for modes 1 and 2, and West–East for modes 3 and 4.

Only under persistent winds with a Northwesterly dominant component, would particles be exported out from the frontal zone with a poor chance of being restored to that area. When those facts are considered together with observed wind variability in short time scales, an indication of the reasons why the bottom frontal zone of the Río de la Plata might

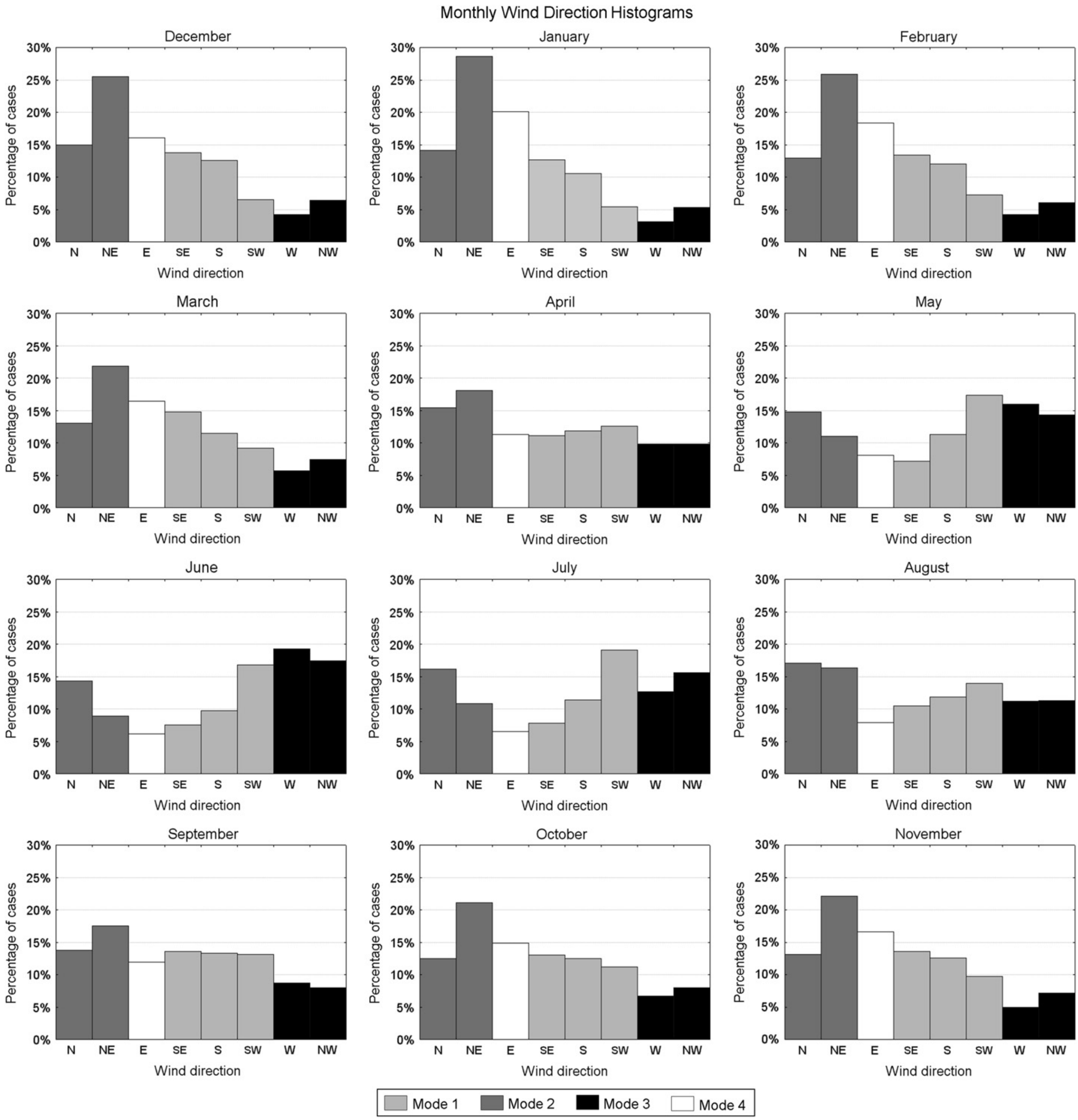

Fig. 10. Monthly wind direction histograms for the 1979–2001 period of the NCEP/NCAR reanalyzes at 35.24° S–54.37° W. Histogram bars were colored by wind directions related to each of the described motion modes for bottom launched particles.

display retentive features even in presence of high wind variability becomes evident and could explain (at least in part) why this area functions as a spawning ground for fishes. Indeed, as illustrated by Fig. 5, wind direction in the region mainly tends to vary, in a scale of a few days, from a dominant Northerly component to a prevailing Southerly one. This feature would maintain particles, especially those released near the bottom, moving alternatively northeastward to southwestward and vice versa along the Barra del Indio shoal during most of the time – from about 60% in Winter to 75% in Spring as shown by wind statistics (Fig. 10). Spatial distribution of fish eggs and larvae (Fig. 2C, D) support this interpretation. A good visual correlation does exist between eggs and larvae, and particles distribution as a combination of modes 1 and 2. Moreover, persistent Northwesterly winds that would export particles out of the area are neither frequent nor strong

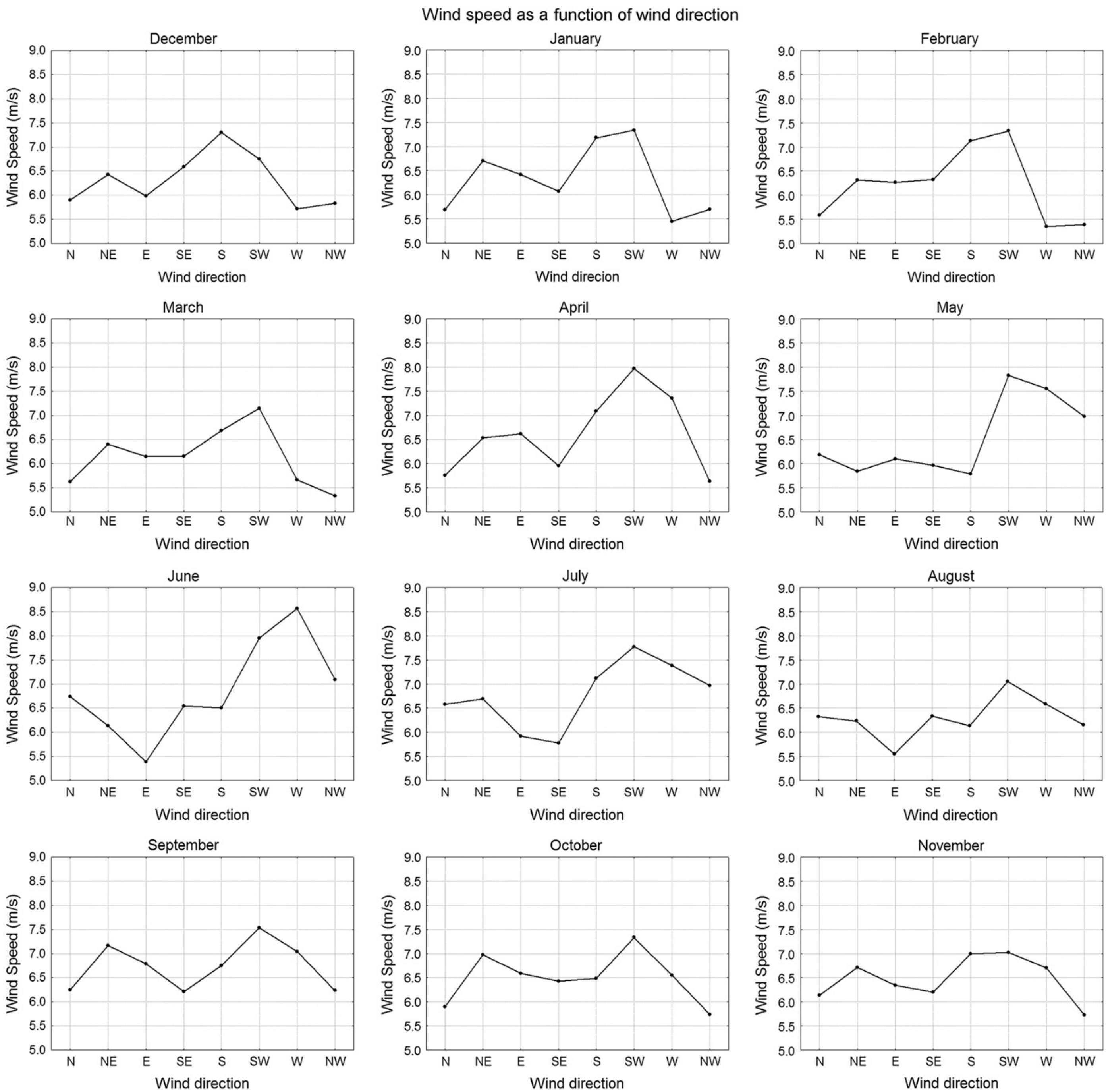

Fig. 11. Mean wind speed as a function of wind direction for every month calculated from the 1979–2001 period of the NCEP/NCAR reanalyzes at 35.24° S–54.37° W.

or persistent (except from May to July, Figs. 10 and 11), and Easterly/Southeasterly winds, which often occur in association to local cyclogenesis and can be very strong (Seluchi and Saulo, 1996), tend to retain particles in the area. This way, even though larval fish retention has been postulated to be an interaction between water dynamics and behavioral traits (e.g. Sinclair, 1988), our results show that physical forcing alone might generate a retentive scenario at the inner part of this estuary. Retentive patterns in the Río de la Plata would be the result of the estuarine system response to natural wind variability in short time scales acting over bathymetric features, rather than a consequence of the salt wedge structure alone. It is interesting to note that mean (summer or winter) winds cannot explain the retention; indeed, our results indicate that if wind persisted blowing from the same direction for a large number of days, particles would be exported out of the system. Excepting for the eggs, we have no information on vertical distribution during the early life history of fishes. Though active swimming of small, feeble larvae cannot be hypothesized to control horizontal position, vertical movement coupled to a two-layered circulation pattern (characteristic of stratified estuaries) would help in maintaining larvae inside the estuary (e.g. Weinstein et al., 1980). That is, some larval behavioral traits that improve retention cannot be discarded.

Retention along the bottom salinity front implies that larvae are kept over a zone of high micro and mesozooplankton biomass, that constitutes their main food source (Mianzan et al., 2001; Kogan, 2005; Berasategui et al., 2006). Therefore, retention within this structure appears to be an important life history strategy that promotes ichthyoplankton survival.

The above proposed mechanism could additionally explain distinctive features of the life history of fishes that utilize the Río de la Plata Estuary to concentrate their spawning activities, so as *Micropogonias furnieri*, *Brevoortia aurea* and *Macrodon ancylodon*. In fact, wind statistics for the different months (Fig. 10) reveal that natural atmospheric variability generates diverse retentive characteristics over the seasons. Winds would be the most favorable for eggs and larvae retention during Austral spring, coinciding with the main spawning season of *M. furnieri*, whose nursery areas are located in Samborombón Bay, along the Barra del Indio Shoal and the Uruguayan coast (Jaureguizar et al., 2003; Lagos and Acha, 2003). During that season, winds that favor particle motion along the shoal prevail, whereas Northwesterly winds – exporting particles out of the estuary – are neither frequent nor strong (Fig. 10). Summer would display a higher tendency for particles to be displaced to Samborombón Bay than spring, due to a relative increment of the Northeasterlies frequency. Finally, winter would be the least favorable season in terms of retention, since both frequency and speed of Northwesterly winds increase (Fig. 10). This is also consistent with the fact that only one species (*Ramnogaster arcuata*) have been detected spawning during that period (Rodrigues, 2005).

Simulations also indicate that the proposed retention mechanism is more effective for bottom than for surface launched particles (Figs. 6–9). This is in agreement with the observed spawning pattern of *Micropogonias furnieri* and *Brevoortia aurea* whose adults release planktonic eggs at the tip of the salt wedge, below the halocline (Fig. 2E) (Macchi et al., 1996; Acha et al., 1999; Acha and Macchi, 2000). In this sense, it is relevant to note that our study does not consider particle buoyancy properties; as a result in our simulations particles are allowed for an upward/downward displacement either due to vertical advection or dispersion. It is possible that eggs in Nature, with density higher than the surface water (Hempel, 1979) have a tendency to remain in lower layers, and display even more retentive features than those shown by our simulations. An evaluation of the efficiency of the proposed mechanism, that is a quantification of the retentive properties of the estuary, is still necessary. Previous works based on particle dispersion modeling have quantified retention by setting pre-defined retention areas (Stevenik et al., 2003; Paris et al., 2005) or calculating the distance traveled from release location (Lett et al., 2006). The main limitation for this kind of applications in our region is the lack of information: a detailed study on the influence of buoyancy over transport patterns would require to include aspects of the egg shape, size and density for the different fish species in the model equations. Nevertheless, our motivation for this study has been to understand physical retention properties in the very large and shallow Río de la Plata Estuary (which is essentially wind driven) in the presence of high wind variability. Consequently, modeling strategy was designed with the aim of providing clear qualitative arguments about the involved processes. Our conclusions can be expanded to understand processes concerned in the spatial patterns of other organisms that also concentrate along this frontal interface. For example, persistent assemblages of tintinnids (Kogan, 2005) and copepods (Berasategui et al., 2006) were recurrently found in association with the bottom salinity front over Barra del Indio shoal. Moreover, Giberto et al. (2004) have shown that distributional patterns of the scallop *Mactra isabelleana* (having planktonic larvae), as well as the mysid *Neomysis americana* (Schiariti et al., 2006), show the highest abundances all along the bottom salinity front (from Samborombón Bay to the Uruguayan coast). The conceptual model proposed in this paper, describing retention mechanisms in this front, could help better explain this persistent pattern exhibited by organisms having different life history traits.

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