Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 1383-1391.

THE POTENTIAL ROLE OF WIND VARIABILITY ON PLANKTON RETENTION IN THE RÍO DE LA PLATA ESTUARY: A NUMERICAL STUDY

C. Simionato(1)(2)(*), A. Berasategui(3)(4), V. Meccia(1), H. Mianzan(3)(4) and M. Acha(3)(4)

(1) Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA, Argentina).
(2) Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Argentina.
(3) Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP), Argentina.
(4) Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

1. INTRODUCTION

Estuaries worldwide support a diverse range of marine teleosts (Cronin and Mansueti, 1971; Dando, 1984; Wallace *et al.*, 1984; Potter *et al.*, 1999; Whitfield, 1998). 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. In general, only a few species spawn within estuarine ecosystems (Haedrich, 1983; Dando, 1984) and among the species that reproduce within permanently open estuaries, the spawning of pelagic eggs is very uncommon (Dando, 1984). However, it has been documented that in the Río de la Plata estuary a great number of coastal fishes spawn planktonic eggs in the inner part of the estuary at the head of the salt wedge that characterizes the system (Macchi *et al.*, 1996; Acha *et al.*, 1999; Acha and Macchi, 2000; Militelli and Macchi, 2001; Berasategui *et al.*, 2004; Rodrigues, 2005).

As the nursery grounds of the above mentioned species are inside the estuary (mainly in Samborombon Bay and Barra del Indio Shoal) retention, defined as the stay at -or drift towards appropriate habitat (Bakun, 1996), become a necessary process in order to sustain the location of this spawning grounds (at the inner part of the estuary). Several authors have suggested that retention in this kind of estuary would be a natural consequence of the theoretical circulation coupled to a salt wedge (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 still been studied.

Recent papers have shown that the Río de la Plata dynamics is complex, highly variable and essentially wind dominated (Simionato *et al.*, 2004a; Simionato *et al.*, 2006). Those papers demonstrated that estuarine scales of variability replicate atmospheric ones, and that currents response to changes in wind direction is very fast. They also revealed that, in response to winds, the estuary produces currents with a phase lag with respect to wind direction that depends on its location in the estuary as a result of topographic rectification. Current speed, even at the bottom layer, is significant and is a function of wind direction.

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). On the other hand, atmospheric circulation over the region in synoptic to intra-seasonal scales is characterized by high variability associated to several processes (see Nogues-Paegle and Mo, 1997; Vera *et al.*, 2002; Simionato *et al.*, 2005). 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 Northerly to Southerly and, consequently, currents present a similar variable feature. A striking question is, then, whether this highly variable ecosystem can favor fish eggs and larvae retention and, if that is the fact, what are the involved mechanisms. Therefore, the aim of this paper is to explore the role of wind variability on ichthyoplankton transport patterns in the Río de la Plata estuary. For that purpose a set of process oriented numerical experiments is

[1] *Corresponding author address:* CIMA/CONICET-UBA. Ciudad Universitaria Pabellón II Piso 2. (C1428EHA) Ciudad Autónoma de Buenos Aires, Argentina. E-mail: claudias@cima.fcen.uba.ar

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.

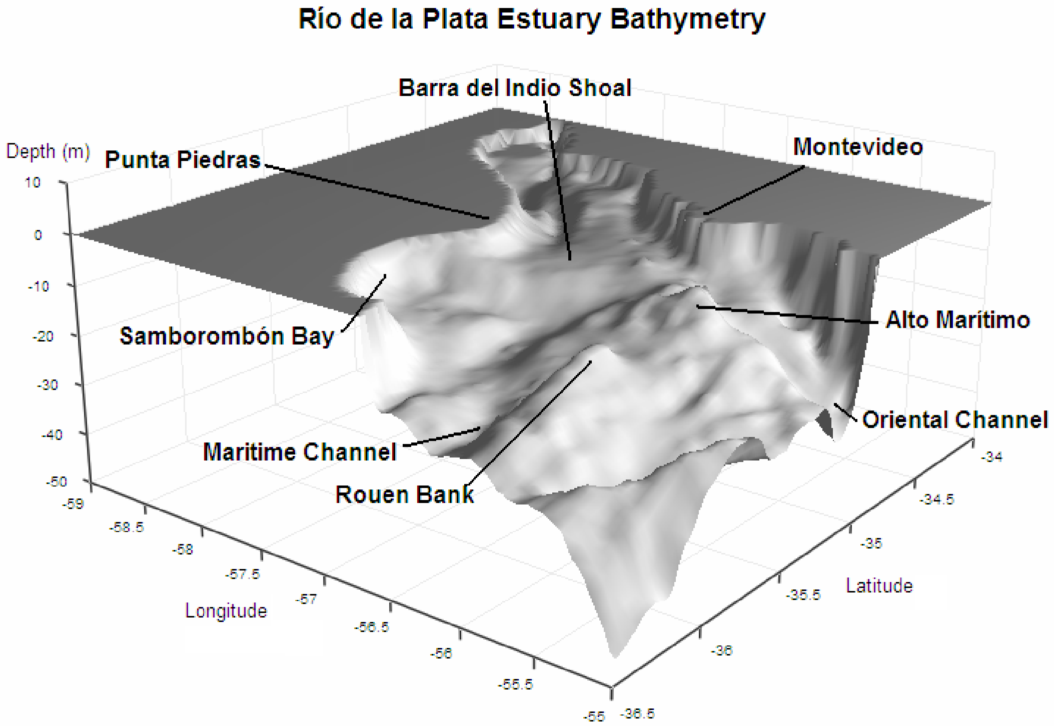

Fig. 1: Bathymetry of the Río de la Plata Estuary (in meters) and main geographical and topographical features. Note that vertical and horizontal scales are not the same.

2. STUDY AREA

The Río de la Plata (Fig. 1), located in the eastern coast of southern South America at approximately 35º S, is one of the largest estuaries of the world (Shiklomanov, 1998), draining the second basin of the continent (average 25,000 $m^3 s^{-1}$; Jaime *et al.*, 2002).

This system displays a complicated geometry and bathymetry. 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. Downstream, density is controlled by salinity. 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). Samborombón Bay, a very shallow and extensive area -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).

3. NUMERICAL MODELING

The numerical model used in this study is the Estuary, Coastal, and Ocean Model (ECOM), a three-dimensional hydrodynamic computer code (Blumberg, 1996) for application to marine and freshwater systems. It is a sigma coordinate, hydrostatic, primitive equation model derived from Princeton Ocean Model (Blumberg and Mellor, 1987) coupled with a particle tracking routine (sum of an advective deterministic component and an independent random Markovian component).

An orthogonal coordinate domain spanning the region between 58° 36'W to 50° W and 38° 30' S to 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. Highest vertical resolution was set near surface and bottom. High-resolution bathymetry data were provided by the Servicio de Hidrografía Naval of Argentina

ECOM applies a time splitting technique for computational efficiency. The external and internal time steps were set to 20 seconds and 10 minutes, respectively, in compliance with the Courant, Friedrich and Lewy (CFL) criterion. 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. Frontal zone was modeled as dependent only on salinity, following Simionato *et al.* (2001). Model was initialized with constant salinity of 33, representative of continental shelf waters, and a temperature of 10°C. A mean discharge of 25,000 m^3 s^{-1} was considered as a representative runoff for all runs. 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 reanalyzes 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 so as the salt wedge structure 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 at both, near surface and bottom (model layers 2 and 9). 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 position after a particular forcing situation.

Given the high variability in wind directions that characterizes the region (Fig. 2), simulations under real wind conditions would difficult the identification and understanding of processes that may favor retention in the area. Therefore, the modeling strategy was to develop short term simulations in which the effect of winds from 16 directions (22.5º apart) on particle advection and dispersion was studied. Simulations were done for both, winter and summer initial conditions. Wind speed was set to 6 m s^{-1}, a representative value of the mean and the mode for all seasons in the NCEP/NCAR reanalyzes climatology at 35.24° S - 54.37° W. Winds were slowly changed from their initial seasonal value during one day by applying a ramp, and particles were released after another 24 hours of simulation. Particles were tracked during a 7-days period, after what daily particle density field (number of particles per area unit) was computed for both, surface and bottom launched groups.

In order to simplify the comprehension of the numerical simulations results set, 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 (Figs. 3 and 4).

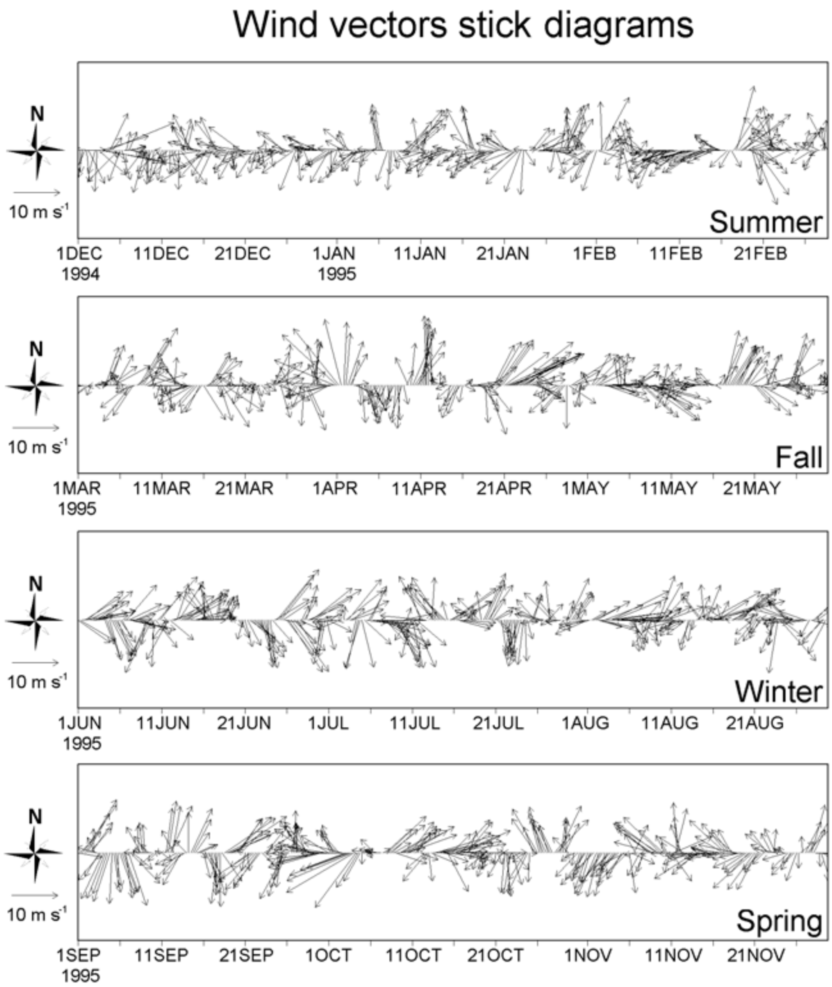

Fig. 2: 4-daily wind vectors stick diagrams for the four seasons of 1995 from NCEP/NCAR reanalyzes at 35.24° S - 54.37° W.

4. RESULTS AND DISCUSSION

EOF 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 coast line (Figs. 3 and 4). 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 particles, upstream motion is inhibited by the shoal in the lower layers and the continental discharge in the upper ones, resulting in preservation of most of them in the

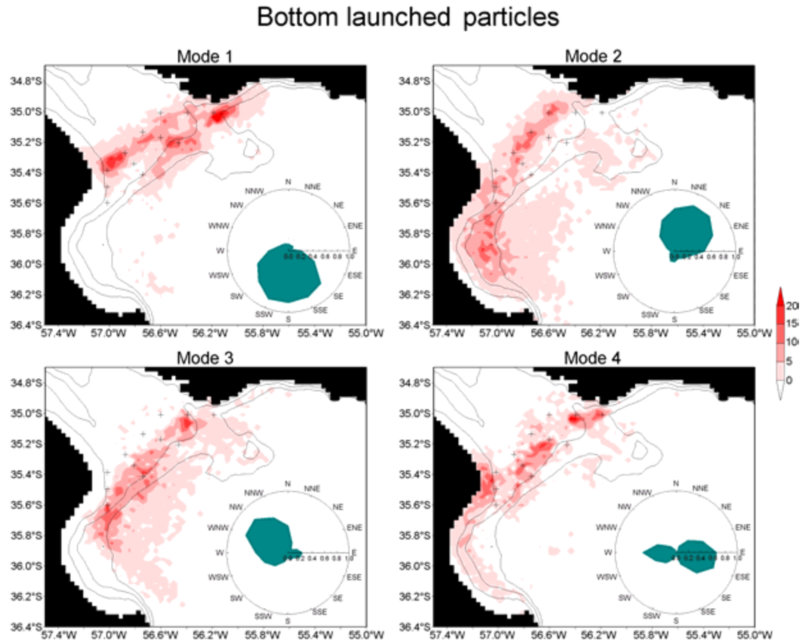

Fig. 3: Results of numerical solutions EOF analysis for bottom launched particles. Maps show the modes or characteristic particle density fields. Lines representing the 5, 7.5 and 10 m isobaths have been superimposed. The inner panels show the associated loadings which represent the correlation between each mode and numerical solutions for every wind direction. + indicates particles launching positions.

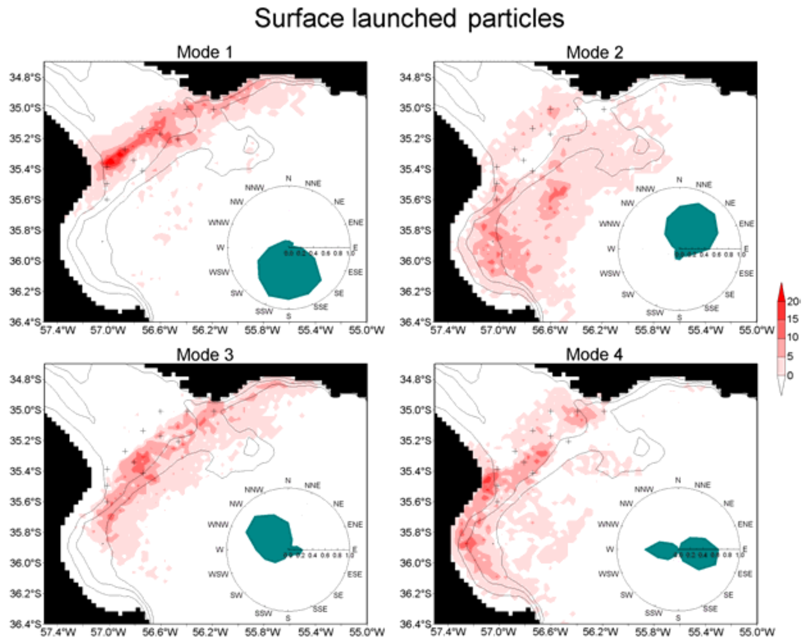

Fig. 4: Results of numerical solutions EOF analysis for surface launched particles. Maps show the modes or characteristic particle density fields Lines representing the 5, 7.5 and 10 m isobaths have been superimposed to the graphs. The inner panels show the associated loadings which represent the correlation between each mode and numerical solutions for every wind direction.+ indicates particles launching positions.

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 wind directions the majority of particles launched over the bottom salinity front would either remain trapped in the proximity of their initial position or move in north-eastward/southwestward direction along the Barra del Indio shoal. When particles have northeastward to southwestward preferential motion along the shoal, they can be moved out the bottom frontal zone, either northward to the Uruguayan coast or southward into Samborombón Bay. Nevertheless, additional similar numerical experiments (not shown) in which particles were launched at those areas, indicate that they have a high probability of being restituted to the frontal zone as wind direction reverses. Moreover, Samborombón Bay displayed a similar feature to the bottom frontal zone, in which particle motion is essentially bathymetrically controlled and, therefore, tends to develop along the coast, with associated wind directions slightly displaced to North-South for Modes 1 and 2, and East-West for Modes 3 and 4.

This way, only under persistent winds with a northwest dominant component, particles would be exported out from the frontal zone with a poor chance of being restituted to that area. When those facts are considered together with observed wind variability in the relevant time scales, an indication of the reasons why the bottom frontal zone of the Río de la Plata might display retentive features even in presence of high wind variability becomes evident and could explain (at least in part) why this area functions as spawning ground. In effect, as illustrated by Fig. 2, wind direction in the region mainly tends to vary, in synoptic to intra-seasonal scales, from a dominant Northerly component to a prevailing Southerly one. This feature would maintain particles, particularly 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; Fig. 5-. Moreover, persistent Northwesterly winds -that would export particles out of the area- are neither frequent nor strong or persistent (Figs. 5 and 6), 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 might generate by itself a retentive scenario at the inner part of this estuary. Retentive features would be the result of the estuarine system response to natural wind variability acting over bathymetric features more than a consequence of the salt wedge structure.

Retention along the bottom salinity front implies that larvae are kept over a zone of high micro and mesozooplankton biomass (Mianzan *et al.*, 2001; Kogan, 2005; Berasategui *et al.*, 2006), the Estuarine Turbidity Maximum. Moreover the high levels of turbidity of this area are thought to reduce visual predation over fish larvae and juveniles creating a predation refuge (Chesney, 1989). Therefore, retention within this structure appears to be an important life history strategy that promotes ichthyoplankton survival.

5. ACKNOWLEDGMENTS

This paper is a contribution to the ANPCYT PICT 2002 07-12246 ‘Estudio de la dinámica oceánica y atmosférica del estuario del Río de la Plata mediante un sistema de modelado numérico integral’, and partially supported by the following grants: UBA X264, Fundación Antorchas 13900-13, CONICET PIP 5009 and FONCyT (07-09424 and 07-13659). We also wish to thank A. Schiariti for his constructive comments and critical reading of the manuscript

Fig. 5: Monthly wind direction histograms from the 1979-2001 period of the NCEP/NCAR reanalyzes at 35.24° S - 54.37° W. Histograms bars were colored by wind directions related to each of the described motion modes for bottom launched particles.

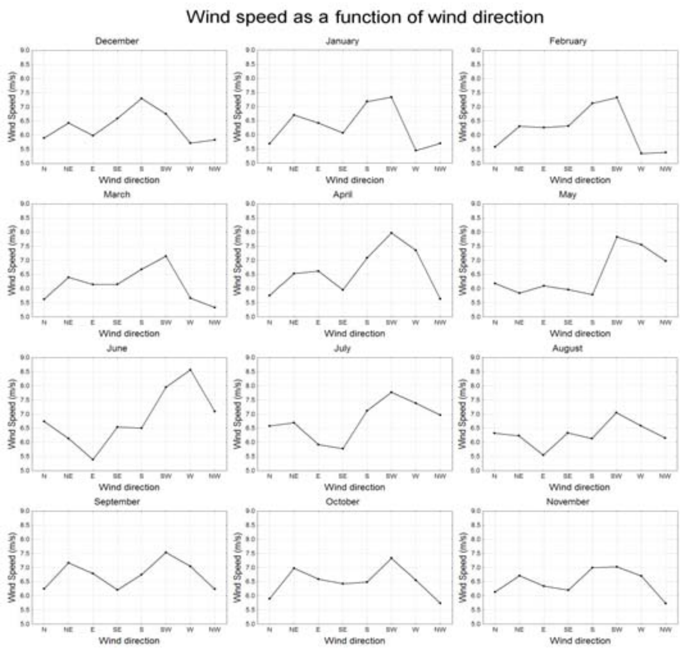

Fig. 6: Mean wind speed as a function of wind direction for every month from the 1979-2001 period of the NCEP/NCAR reanalyzes at 35.24° S - 54.37° W.

6. REFERENCES

Acha, E.M. and Macchi G.J. (2000) Spawning of Brazilian menhaden, *Brevoortia aurea*, in the Río de la Plata Estuary off Argentina and Uruguay. Fishery Bulletin **98**: 227-235.

Acha, E.M., Mianzan, H.W., Lasta, C.A. and R.A. Guerrero (1999) Estuarine spawning of the whitemouth croaker *Micropogonias furnieri* (Pisces: Sciaenidae) in the Río de la Plata, Argentina. *Mar. and Freshwater Res.* **50**: 57-65.

Bakun, A. (1996) *Patterns in the Ocean: Ocean Processes and Marine Population Dynamics*. San Diego-La Paz: University of California Sea Grant in cooperation with Centro de Investigaciones Biológicas de Noroeste Baja California Sur, 323pp.

Berasategui, A.D., Acha, E.M. and N.C., Fernandez Araoz (2004) Spatial patterns of ichthyoplankton assemblages in the Río de la Plata Estuary (Argentina-Uruguay). *Est. Coast. Shelf Scie.***60**: 599-610.

Berasategui, A.D., Menu Marque, S., Gómez-Erache, M., Ramírez, F.C., Mianzan, H.W. and Acha, E.M. (2006) Copepod assemblages in a highly complex hydrographic region. *Est. Coast. Shelf Scie.* **66**: 483-492.

Blumberg, A. F. (1996) An Estuarine and Coastal Ocean Version of POM. *Proceedings of Princeton Ocean Model Users meeting (POM96)*, Princeton, NJ.

Blumberg, A. F. and Mellor, G. L. (1987) A description of a three-dimensional coastal ocean circulation model, In *Three-Dimensional Coastal Ocean Model, Coastal Estuarine Sciences*. N. S. Heaps (ed.) Washington D. C.: AGU, pp.1-16

Chesney, J.R. (1989) Estimation the food requirements of stripped bass larvae *Morone saxalitilis*: effects of light, turbidity and turbulence. *Mar. Ecol. Prog. Ser.* **53**: 191-200.

Cronin, L.E. and Mansueti, A.J. (1971) The biology of the estuary. In *A Symposium on the Biological Significance of Estuaries.* P.A. Douglas and R.H.B. Stroud (eds) Washington D.C.: Sport Fishing Institute, pp. 24-39

Dando, P.R. (1984) Reproduction in estuarine fishes, In *Fish Reproduction: Strategies and Tactics*. G.W. Potts and R. J. Wootton (eds) London: Academic Press, pp. 155-170.

D'Onofrio, E., Fiore, M. and Romero, S. (1999) Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. *Cont. Shelf Res.* **19**: 1681-1693.

García Berdeal I., Hickey, B. M. and Kawase, M. (2002) Influence of Wind Stress and Ambient Flow on a High Discharge River Plume. *J. Geophys. Res.* **107(C9)** 3130, doi:10.1029/2001JC000932.

Guerrero, R.A., Acha, E.M., Framiñan, M.B. and Lasta, C.A. (1997) Physical oceanography of the Río de la Plata Estuary, Argentina. *Cont. Shelf. Res.* **17(7)**: 727-742.

Haedrich, R.L. (1983) Estuarine fishes In: *Ecosystems of the World. Estuaries and Enclosed Seas.* B.H. Ketchum (ed.) Oxford: Elsevier Scientific Publishing Co. vol. 26, pp. 183-207.

Jaime, P., Menéndez, A., Uriburu Quirno, M. and Torchio, J. (2002) Análisis del régimen hidrológico de los ríos Paraná y Uruguay. *Inf. LHA 05-216-02*. Buenos Aires: Instituto Nacional del Agua 140 pp.

Kalnay, E. *et al.* (1996) The NCEP/NCAR 40-Year reanalysis project. *Bull. Amer. Met. Soc.* **77**: 437-471.

Kogan, M. (2005) Estudio de la composición específica, abundancia y distribución espacial del microzooplancton (protozoos y micrometazoos) en el estuario del Río de la Plata. PhD Thesis, University of Buenos Aires, Argentina, 174 pp.

Lasta, C.A. (1995) La Bahía Samborombón: zona de desove y cría de peces. PhD Thesis, National University of La Plata, Argentina.

Macchi, G.J., Acha, E.M. and Lasta, C.A. (1996) Desove y fecundidad de la corvina rubia (*Micropogonias furnieri*, Desmarest, 1826) en el estuario del Río de la Plata, Argentina. *Bol. Inst. Esp. Oceanogr.* **12**: 99-113.

Mann, K.H. and Lazier, J.R.N. (1991) *Dynamics of Marine Ecosystems: Biological-Physical Interactions in the Oceans.* Boston: Blackwell Science, 466 pp.

Mellor, G.L. and Yamada, T. (1982) Development of a turbulent closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.* **20**: 851-875.

Mianzan, H., Lasta, C., Acha, E. M., Guerrero, R. A., Macchi, G. and Bremec, C. (2001) The Río de la Plata estuary: Argentina-Uruguay, In: *Ecological Studies. Coastal Marine Ecosystems of Latin America*. U. Seelinger and B. Kjerfve (eds) Berlín Heidelberg: Springer-Verlag, vol. 144.

Militelli, M.I. and Macchi, G.J. (2001) Reproducción de la pescadilla real, *Macrodon ancylodon*, del área rioplatense. *IV J. Nac. de Cs. Mar* 11-15 de Septiembre, Puerto Madryn, Argentina, p. 92.

Nogues-Paegle, J., and Mo K.C. (1997) Alternating wet and dry conditions over South America during summer. *Mon. Wea. Rev*. **125**: 279-291.

Potter, I.C. and Hyndes, G.A. (1999) Characteristics of the ichthyofaunas of southwestern Australian estuaries, including comparisons with holartic estuaries and estuaries elsewhere in temperate Australia. A review. *Austr. J. of Ecol.* **2:** 395-421.

Reid, R.O. and Bodine, B.R. (1968) Numerical model for storm surges in Galveston Bay. *J. of the Waterways and Harbors Division* **94**: 33–57.

Rodrigues, K.A. (2005) Biología reproductiva de la saraquita, *Ramnogaster arcuata* del estuario del Río de la Plata. MS Thesis, University of Mar del Plata, 40 pp.

Seluchi, M.E. and Saulo, A.C. (1996) Possible mechanisms yielding an explosive coastal cyclogenesis over South America: experiments using a limited area model. *Australian Met. Mag.* **47**: 309-320.

Shiklomanov, I.A. (1998) *A summary of the monograph world water resources. A new appraisal and assessment for the 21st Century*. UNEP: Society and Cultural Organization.

Simionato, C.G., Nuñez, M. N. and Engel, M. (2001) The Salinity Front of the Río de la Plata: a numerical case study for winter and summer conditions. *Geophys. Res. Lett.* **28**: 2641-2644.

Simionato, C.G., Dragani, W., Meccia, V. and Nuñez, M. (2004a) A numerical study of the barotropic circulation of the Río de La Plata Estuary: sensitivity to bathymetry, earth rotation and low frequency wind variability. *Est. Coast. and Shelf Scie.* **61**: 261-273.

Simionato, C.G., Dragani, W., Nuñez, M.N. and Engel, M. (2004b) A set of 3-D nested models for tidal propagation from the Argentinean Continental Shelf to the Río de la Plata Estuary -Part I M2. *J. Coastal. Res.* **20**: 893-912.

Simionato, C., Vera, C. and Siegismund, F. (2005) Surface wind variability on seasonal and interannual scales over Río de la Plata area. *J. Coastal Res.* **21**: 770-783.

Simionato, C.G., Meccia, V. Dragani, W., Guerrero, R. and Nuñez, M. (2006) The Río de la Plata Estuary response to wind variability in synoptic to intra-seasonal time scales. Part 1: Barotropic Response. Submitted to *J. Geophys. Res*.

Sinclair, M. (1988) *Marine populations: an essay on population regulation and speciation*. Seattle: University of Washington Press, 252 pp.

Smagorinski, J. (1963) General Circulation Experiments with the Primitive Equations. I. The Basic Experiment. *Mon. Weather Rev.* **91**: 99 p.

Smolarkiewicsz, P.K. (1984) A fully multidimensional positive definite advection transport algorithm with small implicit diffusion. *J. Comput. Phys.* **54**: 325-362.

Smolarkiewicsz, P.K. and Clarke, T.L. (1986) The multidimensional positive definite advection transport algorithm: Further development and applications. *J. Comput. Phys,* **67**: 396-438.

Smolarkiewicsz, P.K. and Grabowski, W.W. (1990) The multidimensional positive definite advection transport algorithm: Nonoscillatory opinion. *J. Comput. Phys.* **86**: 355-375.

Vera, C.S., Vigliarolo, P.K. and. Berbery, E.H (2002) Cold season synoptic scale waves over subtropical South America. *Mon. Wea. Rev.* **130**: 684-699.

Wallace, J.H., Kok, H.M., Beckley, L.E., Bennett, B., Blaber, S.J.M. and Whitfield, A.K. (1984) South African estuaries and their importance to fishes. *South African J. Sci.* **80**: 203-207.

Whitfield, A.K. (1998) Biology and Ecology of fishes in Southern African estuaries. *Ichthyological Monographs of the J.L.B. Smith Institute of Ichthyology* **2**