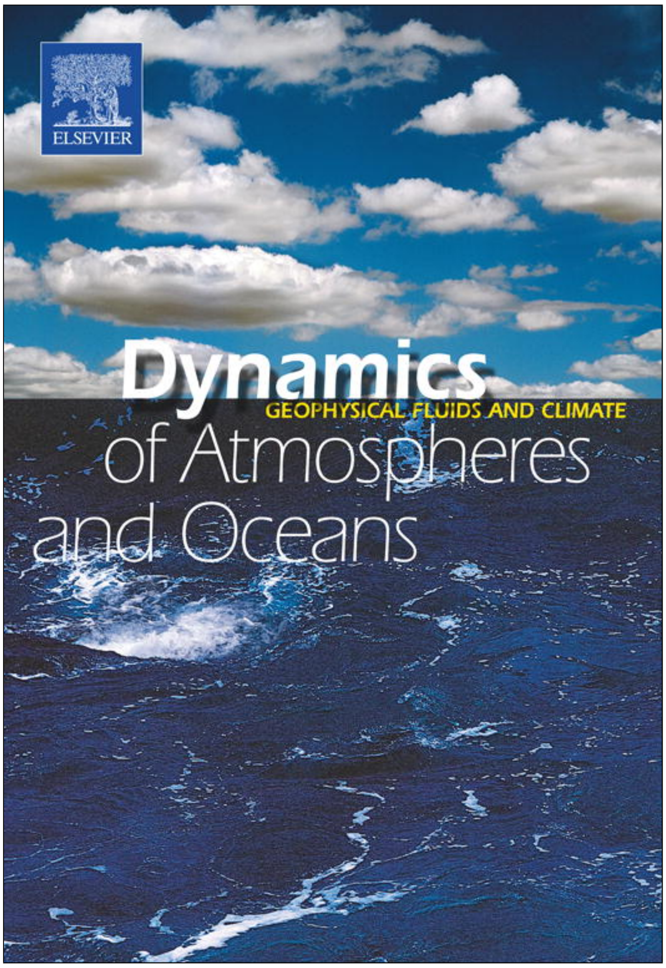
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Synoptic patterns associated with the highest wind-waves at the mouth of the Río de la Plata estuary

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A B S T R A C T

In the present paper, the highest wind waves measured at the Río de la Plata mouth were selected to characterize weather patterns associated with the most severe wave conditions in this region. This study was carried out on the basis of wave parameters data series – 14 year long – measured at the Río de la Plata mouth. From the fifteen selected energetic events, twelve were associated with the presence of cyclones located either on the continental shelf (northern 40° S) or on the Uruguayan and southern Brazilian region. On the other hand, three events were linked to the occurrence of post-frontal anticyclones and low pressure systems located in the Southwestern Atlantic Ocean. This last weather pattern is frequently associated with "cold air irruptions" in the Río de la Plata region and, up to the present, it was rarely associated with the presence of the highest waves at the Río de la Plata mouth or adjacent continental shelf. Finally, a common feature observed in almost all the selected cases was the presence of intense wind gusts. This subject is briefly described.

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1. Introduction

Several studies have been carried out on the role of extra-tropical cyclones in the generation of sea waves in the northern hemisphere (see, for example, Hadlock and Kreitzberg, 1988; Cardone et al., 1996). Even though several works were published about the variability of extratropical cyclone behavior in the Southern Hemisphere (Rivero and Bischoff, 1971; Necco, 1982; Gan and Rao, 1991; Sinclair, 1994; Seluchi, 1995; Simmonds and Keay, 2000; Wang et al., 2006), there are only a few works on the generation of sea waves in the southwestern South Atlantic Ocean. For example, da Rocha et al. (2004) studied six extra-tropical cyclones which generated wind waves higher than 5 m and caused severe damage in the southern coasts of Brazil. Further south, when strong and persistent south-easterly winds blow over the continental shelf adjacent to the Río de la Plata (RDP) estuary (Fig. 1), wind waves become very energetic and, occasionally, significant heights are higher than 4 m. During such conditions wind waves may reach as far as the southern and central Brazilian coast (Innocentini and Caetano Neto, 1996).

The RDP is a shallow and extensive estuary located on the eastern coast of South America at approximately 35° S. It has a NNW–SSE general orientation and it is formed by the confluence of two of the most important rivers of South America: the Paraná and Uruguay rivers. The estuary has a funnel shape approximately 300 km long that narrows from 220 km at its mouth to 40 km at its upper end. This system substantially contributes to the nutrient, sediment, carbon and fresh water budgets of the South Atlantic Ocean (Framiñan et al., 1999). It affects the hydrography of the adjacent continental shelf, impacts important coastal fisheries, and influences coastal dynamics up to more than 400 km north on the Brazilian shelf (Campos et al., 1999). The RDP has huge social and economical importance for the countries on its shores, Argentina and Uruguay. The most important cities and harbors, including both capitals (Buenos Aires and Montevideo, respectively) and many of the industrial centers and resorts of these countries are placed on its margins. The occurrence of large meteorologically induced surges and high wind waves has historically caused catastrophic floods in many coastal areas, threatening and claiming human lives and producing major economic and material damages.

Even though there are some specific works in which some noticeable storm surges were studied in relation with the weather conditions in the outer RDP (see, for instance, Escobar et al., 2004), there are only a few studies in which energetic wind wave events and the corresponding synoptic patterns were jointly analyzed in the RDP region. The waves during the synoptic evolution of a "superstorm" over eastern Argentina (from 14 to 17 May 2000) were simulated by Dragani et al. (2008) using SWAN model forced by NCEP/NCAR reanalyzed 10 m elevation winds. Numerical results showed a good agreement between observed and simulated wave heights and directions and a slight underestimation, lower than 2 s, for simulated periods. But it must be noted that the most energetic event recorded at the RDP mouth (23–24 August 2005) was only roughly simulated (the simulated heights were rather underestimated)

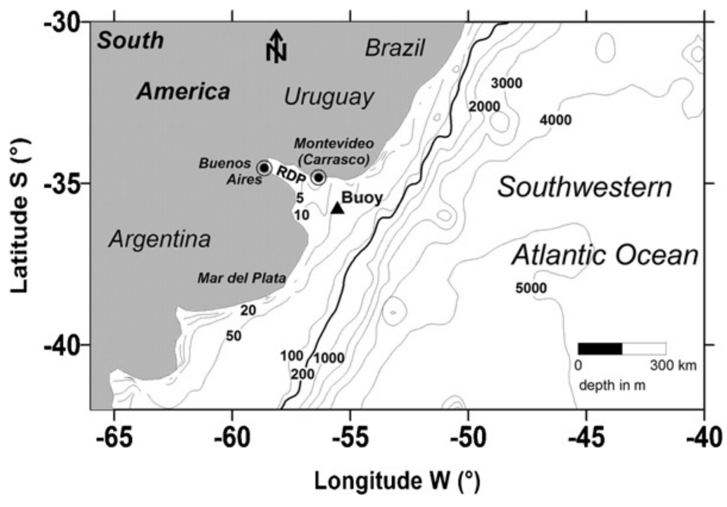

Fig. 1. Study area. Depth contours in meters. Datawell buoy position is pointed out with a triangle. RDP: Río de la Plata.

using the above mentioned numerical tool and the same atmospheric forcing (Prario, 2009). There are some recent studies in which wind wave climate and wave height trend in the RDP region were also studied implementing SWAN wave model (Dragani et al., 2008, 2010; Codignotto et al., 2012).

Nowadays the Servicio de Hidrografía Naval (SHN) of Argentina maintains a wave forecast system for the RDP and the adjacent continental shelf waters. It is based on WWIII (NOAA) model and is forced by GFS/NCEP products (http://www.smn.gov.ar/pronos/boletines_modelo_olas.php?id=10). The validation of this kind of regional wave model but, particularly, the understanding of the dynamics of the low troposphere in connection with the development of wind wave energetic events constitutes a permanent challenge to local modelers and researchers due to the scarce amount of wave measurements (Innocentini and Caetano Neto, 1996; Dragani and Romero, 2004).

In the present work, the surface pressure conditions during the most energetic wind wave events observed at the RDP mouth were selected to characterize weather patterns associated with the most severe wave conditions in this region. This study was carried out on the basis of wave parameters from data series – 14 years long – gathered at the RDP mouth. Selected highest wind wave heights and their associated weather patterns are the basis for extreme analysis of waves for marine engineering projects. This paper is organized as follows. Section 2 describes the oceanic and atmospheric datasets used in the analysis. The description of the synoptic weather patterns associated with the most energetic wind wave events is developed in Section 3 and three selected cases are illustrated in Section 4. Finally, the conclusions are presented in Section 5.

2. Data

2.1. Wave data

The unique set of long-term in situ observations of directional waves available for the region was collected between 1996 and 2009, by means of a Datawell Waverider directional wave recorder (Datawell, 1997) moored in the outer RDP estuary at 35.66° S and 55.86° W (Fig. 1). These observed data were used by Dragani et al. (2008) for the implementation and validation of SWAN (Simulating Wave Nearshore) model in the outer RDP and by Dragani et al. (2010) to study a possible wind wave climate change in the region.

The instrument was programmed to measure 20-min sea level records with a 0.5 s sampling interval every 2.66 h. The record has several gaps, one of them longer than one year (from October 2003 to November 2004), three of them eight months long (March 1998–October 1998; November 1998–June 1999; November 2008–June 2009) and other six of different duration (from two to seven months).

2.2. Wind data

Firstly, NCEP–NCAR Reanalysis I (Kalnay et al., 1996) data base (www.cdc.noaa.gov) was used in order to get a preliminary representation of the mean sea level pressure (MSLP) fields. The result of this analysis is a set of gridded data (2.5° horizontal resolution) with a temporal resolution of 6 h. Secondly, once that the highest wave events were determined and selected, the NCEP Climate Forecast System Reanalysis dataset (CFSR) (Saha, 2010) was used to represent the atmospheric circulation. This dataset is available with temporal resolution of 6 h and spatial resolution of 0.5°.

In order to study the possible role of wind gusts in wave (height) increase, observations of gusts gathered at Carrasco (International airport of Montevideo, Uruguay, 34.783° S–56.133° W) were analyzed. Even though Carrasco is located approximately 120 km northwestward from the directional wave recorder, it is the weather station located nearest to the wave buoy. In addition the meteorological data gathered in it meet all the required international standards constituting a very reliable data set. The meteorological information was obtained from the Meteorological Aerodrome Report (METAR) and from the Special Report (SPECI). METAR is an hourly weather report with a description of the meteorological elements observed at the airport. SPECI is a special aviation weather report issued when there is significant deterioration or improvement in airport weather conditions, such as

Table 1
Percentage of occurrence for significant wave heights higher than 0–3 m, for each of the eight wave directions analyzed at Datawell buoy position (1996–2009 period).

Wave directions	Hs > 0 m (%)	Hs > 1 m (%)	Hs > 2 m (%)	Hs > 3 m (%)
N	3.0	1.4	0.0	0.0
NE	2.3	1.2	0.0	0.0
E	24.9	12.9	0.9	0.1
SE	43.7	18.1	1.9	0.3
S	14.4	10.0	2.3	0.4
SW	4.9	4.0	1.1	0.1
W	3.2	2.4	0.5	0.1
NW	3.6	2.3	0.1	0.0

significant changes of surface winds, visibility and cloud base height. This information is available in http://www.wunderground.com/history/airport/.

3. The most energetic wind wave events at the RDP mouth

3.1. Wind waves – basic statistics

Firstly, a basic statistical description of wind wave heights was carried out using the 44,502 significant wave heights (Hs), directions and spectral peak periods (Tp) of the wave data series measured between 1996 and 2009 at the RDP mouth (Section 2.1). Directional bi-dimensional distributions of Hs and Tp were built using this data set. Table 1 shows the percentage of occurrences for the eight analyzed directions. In Table 1, the N direction (0°) includes all the cases of waves propagating with directions between 337.5° and 22.5°, the east (E) direction (45°) between 22.5° and 67.5°, and so on. The SE, E and S are the main directions of propagation, with the 43.7%, 24.9% and 14.4% of the occurrences, respectively. Frequencies for the rest of the directions were equal to or lower than 5%. Directional analysis were also carried out for Hs higher than 1–3 m, respectively and the results were included in Table 1. It can be seen that E, SE and S are also the main directions of propagation. The most frequent direction of propagation is from the SE, except for Hs higher than 2 m, where it resulted slightly higher from the S. A compass rose (Fig. 2) of Hs is also presented in order to illustrate the results shown in Table 1.

The bi-dimensional distribution for the direction with the largest number of occurrences, i.e. SE, is shown in Fig. 3. Contours indicate the number of cases of wind waves propagating from the SE, every contour delimiting a zone where the number of cases is more than the labeled value. Two relative maxima with a very large number of events, around periods of 10 s and heights of 0.8 m and periods of 5 s and heights of 1.25 m, can be clearly identified. The more energetic events, which occur very sporadically during particular atmospheric conditions, are not shown in the distributions because their Hs (>3 m) are out of the range shown in Fig. 3. Consequently the bidimensional directional distribution is only useful to represent the mean wave conditions but not the extreme events which are the subject of this work.

3.2. Selection of wave events

The histogram of significant wave heights gathered at the mouth of the RDP is presented in Fig. 4. It can be clearly appreciated that almost all the wave heights (99.82% of the cases) are lower than 3.5 m. During the period of wave data acquisition – between 1996 and 2009 – only 80 significant wave heights (cases) were higher than 3.5 m. These heights were exhaustively inspected and linked to the meteorological conditions in the region. As a result, it was concluded that all those situations corresponded to moderate or energetic atmospheric conditions. But, given that the aim of this work is to determine the weather patterns capable of developing severe wind wave conditions in the RDP mouth, the focus of this study was particularly put on the selection of the foremost severe situations, characterized by the highest wave heights. As the increasingly ordered distribution of wave heights

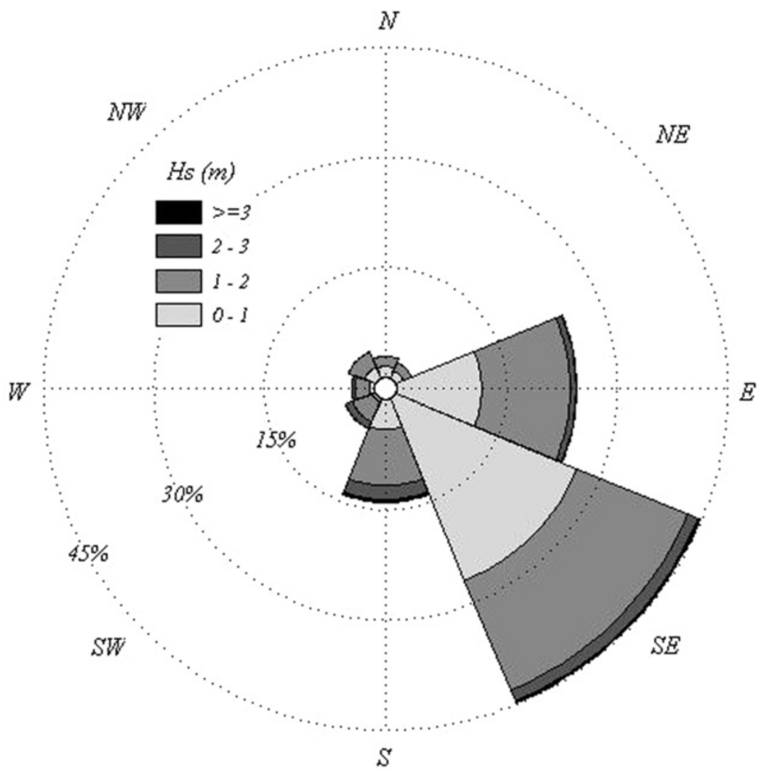

Fig. 2. Compass rose for significant wave heights for the eight main directions of wave propagation.

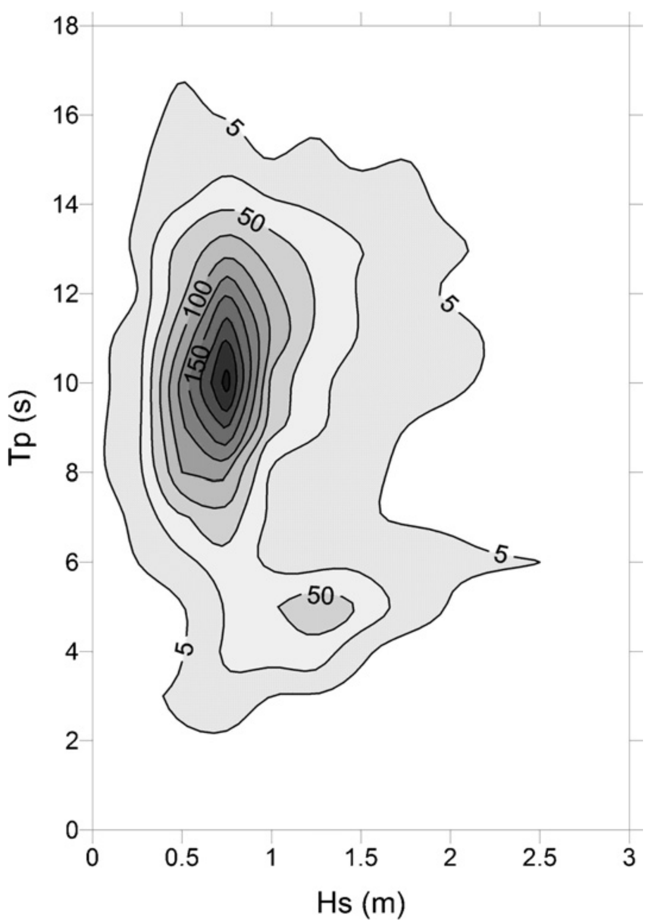

Fig. 3. Bi-dimensional distribution of significant heights and spectral peak periods. Contours indicate the frequency of wind waves propagating from the SE (1996–2009 period).

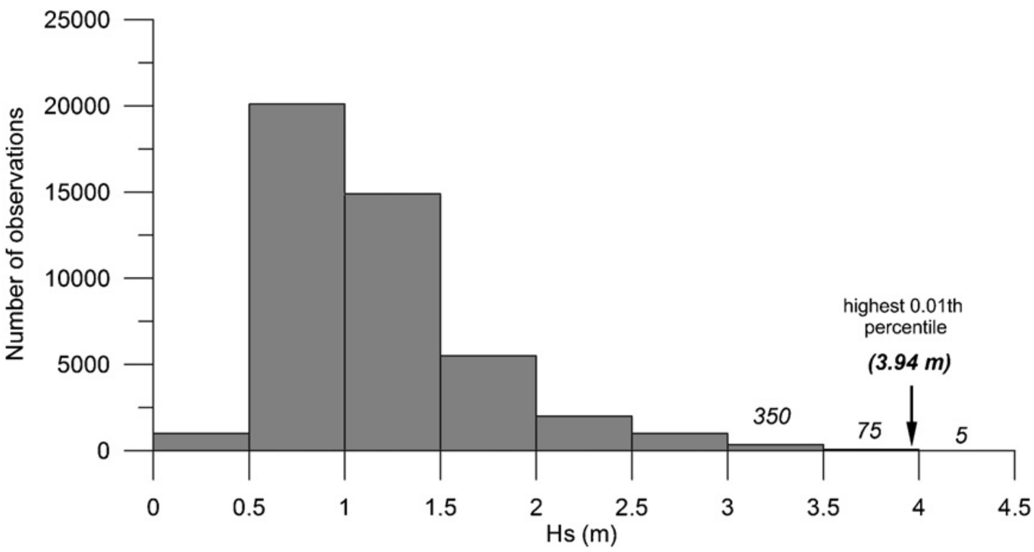

Fig. 4. Histogram of significant wave heights (1996–2009 period). The numbers of cases for the lowest bars at the end of the histogram are indicated.

(for heights higher than 3.5 m) presented a quite monotonic rising, the exact determination of the value which define the lower limit of the highest waves could not be accurately established. Finally, after several statistical trials the subsequent criterion resulted very appropriate to select a set including the more energetic wave events at the RDP mouth. If the maximum Hs of one event is higher than the Hs corresponding to the lower limit of the highest 0.01th percentile of the height distribution (3.94 m, which is indicated in Fig. 4) this event will be selected as an energetic one. Fifteen energetic events resulted from the application of this criterion. Table 2 presents the date of occurrence of the maximum wave heights and the characteristic wave parameters (Hs, Tp and direction) for each selected event. It can be seen that the highest recorded wave was 4.89 m. Eleven directions of wave propagation were between 90° and 180° and four cases between 180° and 270°. Wave periods were higher than 7 s in all the selected events.

3.3. Synoptic weather patterns associated with the highest waves

Mean sea level pressure (MSLP) and 10-m wind patterns were inspected for each selected event (Table 2). From this analysis, and considering the main similarities among them, they could be grouped

Table 2
Date of occurrence of maximum wave heights, characteristic wave parameters (Hs, Tp and direction) and associated synoptic pattern for the measured highest waves at Datawell buoy position (1996–2009 period).

Cases	Time (UTC)	Hs (m)	Tp (s)	Dir. (°)	Type
1	24/08/2005 09:39	4.89	11.9	180	I.a
2	31/01/2005 23:54	4.71	10.9	152	I.a
3	17/05/2000 01:54	4.55	10.9	101	I.b
4	07/06/1997 13:06	4.55	8.7	174	I.b
5	11/07/2000 03:03	4.39	8.7	152	I.b
6	21/10/2002 15:09	4.24	8.1	219	I.a
7	24/02/2006 14:52	4.09	8.1	135	I.b
8	30/06/2009 18:40	4.09	9.0	191	I.a
9	16/09/2001 03:09	4.09	9.1	180	II
10	20/07/1996 20:43	4.08	8.9	180	II
11	29/07/2006 12:42	3.94	11.1	163	II
12	05/11/2004 17:58	3.94	7.6	163	I.a
13	08/10/2001 22:09	3.94	11.7	96	I.b
14	22/05/1997 12:18	3.94	8.5	180	I.a
15	07/08/2003 02:16	3.94	7.2	253	I.a

in two main categories. The most common synoptic situation (twelve of fifteen cases, classified as Type I) is associated with the presence of a cyclone located on the RDP adjacent continental shelf (slightly northward of 40° S), northward of the RDP estuary or offshore the southern coast of Brazil. Another atmospheric circulation pattern, significantly less frequent than Type I, corresponds to the cold air irruptions (classified as Type II). During these last cases the circulation of the low troposphere is influenced by the presence of a post-frontal anticyclone located over the southern South America and by a cold front over the southern Brazil, while the associated cyclone is over the south-western South Atlantic Ocean, relatively far from the coast. During this weather a strong pressure gradient approximately in the E–W direction, northward 45° S, produced intense S and SW winds over almost the whole Argentinean continental shelf.

An important element to analyze is the cyclone tracks because the direction of the wind in the outer RDP will depend on it. An eastward movement of the cyclone enhances the occurrence of south-easterlies (Type I.b, Table 2, five cases) but, on the contrary, a typical south-eastward displacement of the cyclone (Gan and Rao, 1991) is associated with southerlies and/or south-westerlies at the RDP mouth (Type I.a, Table 2, seven cases). A common feature observed in the fifteen selected cases is the occurrence of wind gusts with intensities higher than 20 m s^{-1} and with maximum values that can reach up to 60 m s^{-1}. This latter intensity was recorded during the event of highest waves (August 2005) which was associated with an explosive cyclone which caused severe material damages on the Uruguayan coast (Possia et al., 2011). It is necessary to highlight that wind gust data were not collected at the wave buoy but they were recorded at Carrasco Airport (Montevideo, Uruguay) located 120 km from the buoy. Wind data gathered at the weather stations located in Buenos Aires and Mar del Plata cities were inspected too. In both locations wind gusts were also recorded during the selected events and, consequently, this fact constitute evidence that gusts are present in the whole RDP area during severe weather conditions. As a first approximation it was assumed that wind gusts recorded in Carrasco are representative of gusts at the location of the buoy.

4. Case study

Three selected and documented cases are described to illustrate the three synoptic patterns mentioned above (Type I, a and b, and Type II). All temporal references mentioned in this paper correspond to Coordinated Universal Time (UTC).

4.1. Type I.a: 23–24, August 2005

On August 23–24, 2005 (the first event listed in Table 2) a deep and intense cyclone developed over the RDP producing strong winds and gusts causing severe damage over the Uruguayan coast (Possia et al., 2011). At the beginning of this event (09:00, August 23) the cyclone was located over SW Uruguay and NE of province of Buenos Aires, with a minimum pressure of 1002 hPa. Later (21:00, August 23) the cyclone moved southeastward, intensified and deepened 10 hPa. MSLP and 10-m wind fields (03:00, August 24) are shown in Fig. 5 where an intense pressure gradient is observed over the outer RDP. The maximum wave height of this event was measured 3 h later (Table 2).

Fig. 6 displays the data series of wind intensity and gusts recorded at Carrasco and the wave heights measured at the buoy. This figure shows an intense and persistent wind – from 18:00, 23 to 06:00, 24, August – with intensities greater than 15 m s^{-1} and a maximum intensity of 33 m s^{-1} (21:40 23, August). During the same period, gust intensity was higher than 17 m s^{-1} reaching uncommon peaks between 40 and 60 m s^{-1}. After the occurrence of the strongest wind gusts, wave heights began to increase reaching the maximum significant height recorded at the RDP mouth (4.89 m, 24 August 2005). Wave height persisted over 4 m for almost half a day, from 02:00 to 13:30 August 24, 2005 (Fig. 6). Firstly, when the cyclone was approximately located at 34° S–56° W, the wind and waves propagated from the SSE/SE. But later, when the cyclone moved slightly southeastward and the gusts began, the wind rotated to the W/SW, even so, the waves did not present significant changes in the direction of propagation.

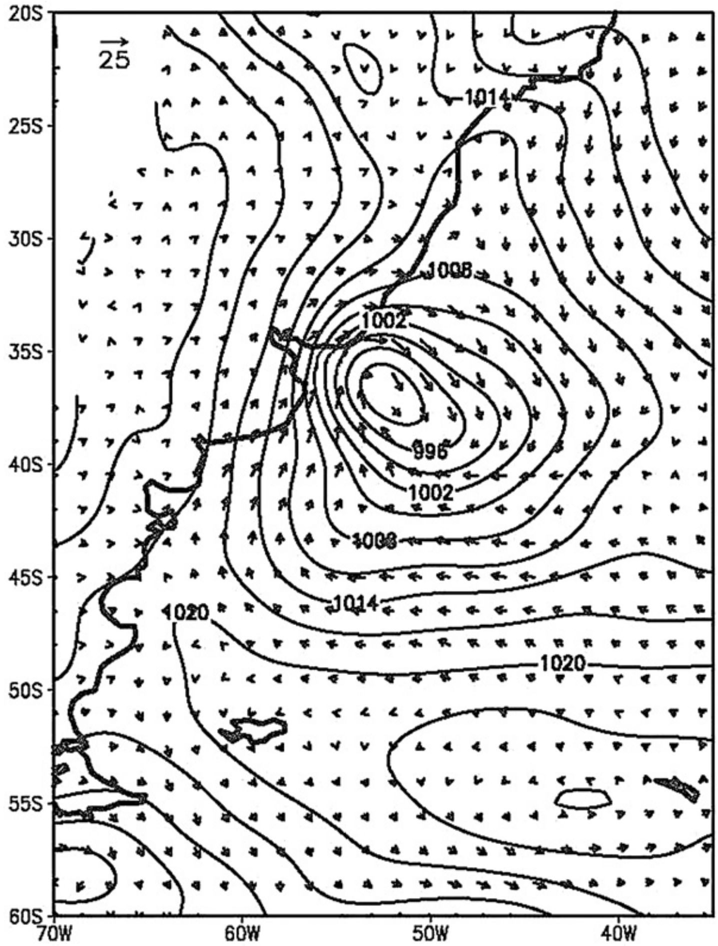

Fig. 5. Synoptic situation corresponding to 06:00 UTC, August 24, 2005. Mean sea level pressure (hPa) and 10-m wind (m s^{-1}).

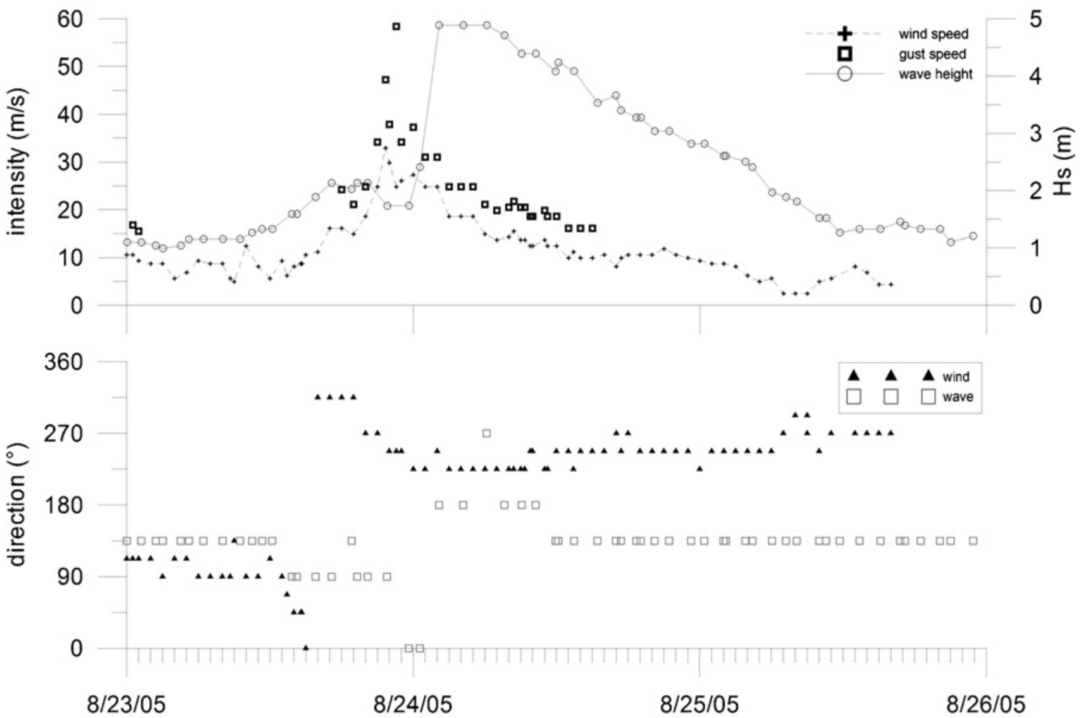

Fig. 6. Series of observed wind intensity, speed gust and significant wave height (upper panel) and wave and wind directions (lower panel).

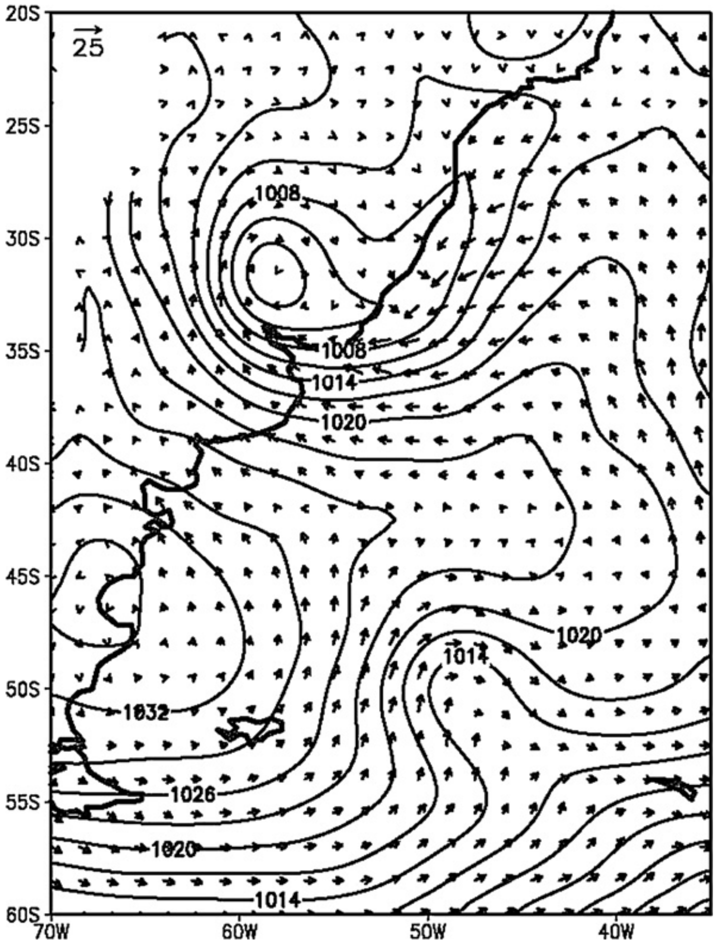

Fig. 7. Synoptic situation corresponding to 00:00 UTC, May 17, 2000. Mean sea level pressure (hPa) and 10-m wind (m s^{-1}).

This event was, probably, the most energetic wave episode recorded at the RDP mouth. At 19:20 August, 23, Recalada Pontoon (more than 100 m long), moored in the outer RDP at 35°06.5′ S–55°57.8′ W was disengaged by the intense winds and strong gusts, moved 30 km east-northeastward and finally stranded 20 km off the Uruguayan coast, at 34°57′S–055°41′W.

4.2. Type I.b: 15–17, May 2000

A well known meteorological event called "the superstorm of the Río de la Plata" (Possia et al., 2003) occurred on May, 15–17, 2000 and is herein discussed as a case study of Type I.b (Table 2). The cyclone began to develop on the northeastern of Argentina on May, 15 15:00. Then the cyclone moved firstly southwards to the NW of Uruguay, the atmospheric pressure reached minimum values and the storm acquired its maximum strength (Fig. 7). Finally, the unusual northeastward movement of this cyclone was probably due to the interaction with another low pressure system located eastward, at the middle of southwestern South Atlantic Ocean.

A persistent and intense wind, greater than 11 m s^{-1} blew during 22 h (beginning at 04:00 16 May), with a maximum value of 16 m s^{-1} (May, 16 20:00), recorded at Carrasco (Fig. 8). Gust intensity was greater than 15 m s^{-1} with a maximum intensity of almost 30 m s^{-1} (May, 16 18:00). The cyclone remains quasi-stationary during the period of occurrence of the most intense winds (Possia et al., 2003), as can be inferred by the persistent easterly/southeasterly wind in Fig. 8, producing the phenomenon of "Sudestada" which raised the water level (storm surge) to 3.52 m at Buenos Aires Port in the upper RDP (Fig. 1).

Wave heights and gusts rose simultaneously during this event, reaching maximum values at practically the same time. The highest waves remained over 4 m during 18 h (Fig. 8). Wind and wave

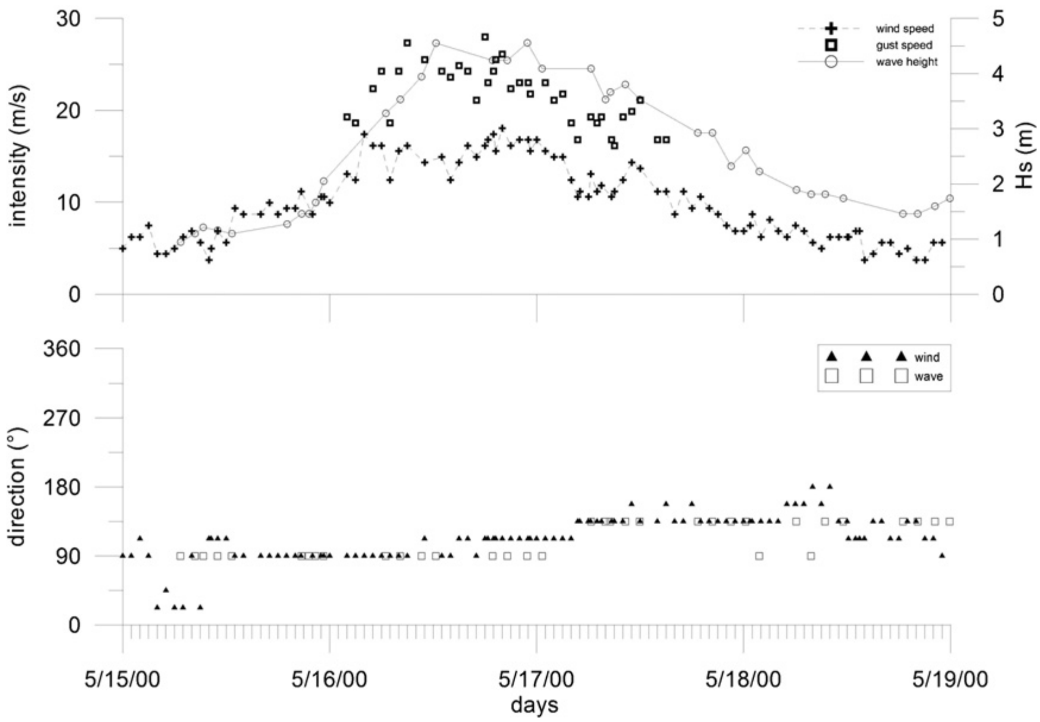

Fig. 8. Series of observed wind intensity, speed gust and significant wave height (upper panel) and wave and wind directions (lower panel).

directions were quite similar (90–135°) which is consistent with a weather condition characterized by cyclone development north of 35° S.

4.3. *Type II: 20–22, July 1996*

The third type of atmospheric circulation pattern during highest waves is associated with cold air irruptions which are documented by Garreaud (1999, 2000). It is characterized by a large post-frontal anticyclone located in the southern region of South America. During this type of episode the cold front is approximately disposed along the southern part of Brazil and the associated low pressure system is placed off-shore, at the Southwestern South Atlantic Ocean. A clear example of a typical cold air irruption is shown in Fig. 9 (15:00, July 20, 1996, event number 10, Table 2). A noticeable zonal atmospheric pressure gradient, approximately disposed along 35° S, produced intense SSW winds during the whole event (July, 20–22). Maximum wave height (4.08 m) was recorded at 17:43, July 20 (Fig. 10). Persistent winds (almost 15 m s^{-1}) blew during 10 h and a maximum gust of 22 m s^{-1} was recorded at 13:00, July 20. At the beginning and ending stages of this event, wave direction was from the SE but, during the period of wave developing, they propagated from the S (from 17:00 to 24:00, July, 20, approximately).

As mentioned in the introduction, the most energetic event recorded (23–24 August, 2005) was only roughly represented (the simulated heights were rather underestimated) in a numerical simulation using SWAN model forced by NCEP/NCAR (Prario, 2009). The possible cause of this underestimation may be explained from, at least, two points of view. With regard to the first one, the validation of regional wave models at the RDP mouth and adjacent continental shelf constitute a permanent challenge to regional ocean modelers due to the scarce amount of wave measurements in the region (Innocentini and Caetano Neto, 1996; Dragani and Romero, 2004) and the lack of a well validated and reliable high resolution atmospheric numerical model to provide a realistic wind forcing for the oceanic computational domain. The second reason is related to the wind wave generation process. The role of the wind intensity, duration and fetch in the wave generation (CERC, 1984) is well known, but, on the other hand, the role of wind gusts is rather uncertain in this complex generation mechanism.

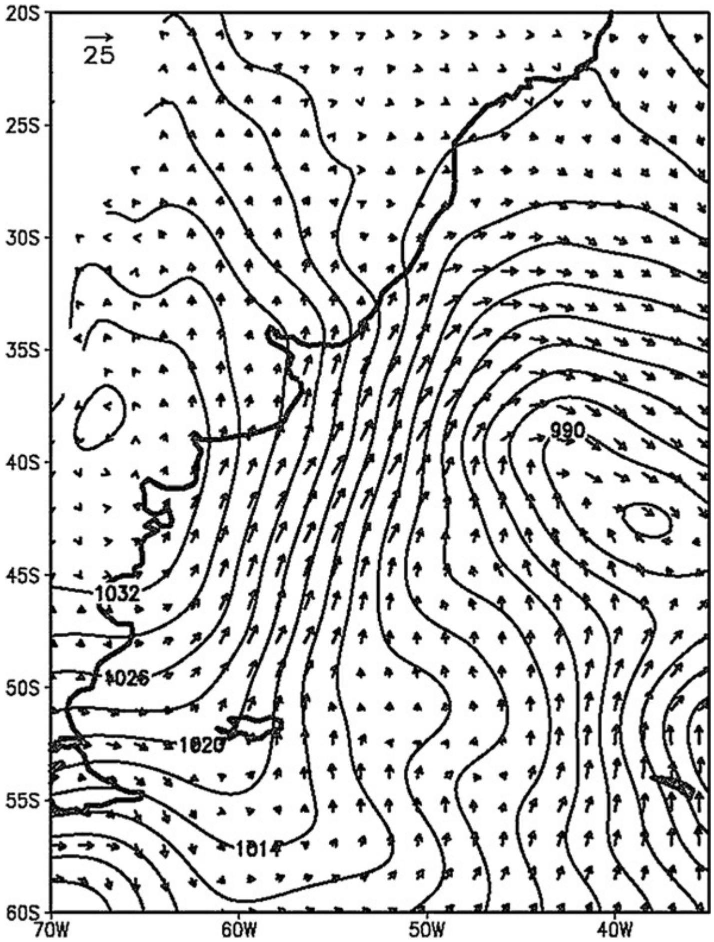

Fig. 9. Synoptic situation corresponding to 18:00 UTC, July 20, 1996. Mean sea level pressure (hPa) and 10-m wind (m s^{-1}).

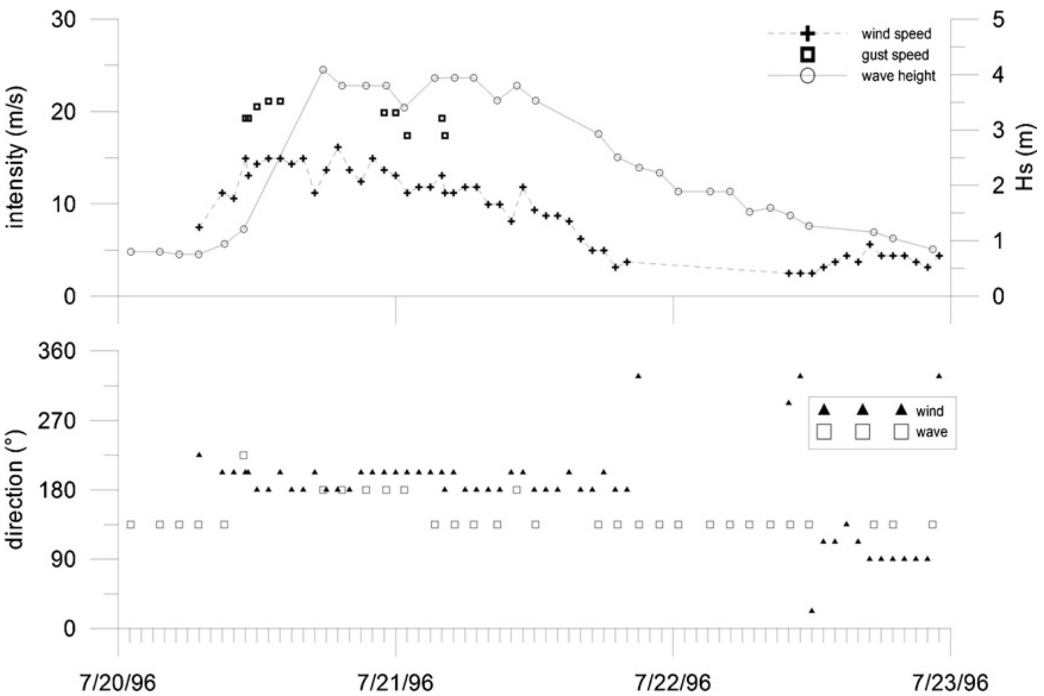

Fig. 10. Series of observed wind intensity, speed gust and significant wave height (upper panel) and wave and wind directions (lower panel).

5. Conclusions

The most severe sea conditions in continental shelf waters adjacent to the RDP estuary from 14 year long data series of wave parameters (1996–2009) were analyzed in this paper. The selection criterion considered the maximum wave heights of the energetic episodes fell into the 0.01th percentile of distribution of Hs. Fifteen events satisfied this criterion with waves up to 3.94 m. Strong surface winds responsible for the highest sea waves were associated with two well different atmospheric circulation patterns. Twelve events were related to the presence of cyclones located either in the continental shelf (northward 40° S) or in the Uruguayan and southern Brazil regions. It was noted that waves predominantly propagate from the SE during events of the Type I.b and from SW during events of the Type I.a. On the other hand, only three events were linked to the occurrence of post-frontal anticyclones and low pressure systems located in the Southwestern Atlantic Ocean. This last pattern is usually associated with "cold air irruptions" in the RDP region. This paper constitutes the first reference in which this particular synoptic situation is connected to highest waves at the mouth of the RDP. A particular study about this subject should be carried out since, even though not all cold air irruptions may be capable of generating energetic sea, it is evident that the duration of the intense wind during these events could play a significant role in the wave development. In addition, it is important to highlight that there is no evidence about swell heights higher than 4 m at the RDP mouth. The highest waves are typically associated to strong local wind which responds to the regional synoptic pattern.

A common feature observed in all of the selected cases was the presence of wind gusts. It seems to be clear that gusts are very important in wave development at the mouth of the RDP. This fact could explain the considerable wave height underestimation observed in some particular wave simulations carried out in the outer RDP (Prario, 2009).

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