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WIND TIDES IN THE RIO DE LA PLATA ESTUARY: METEOROLOGICAL CONDITIONS

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ABSTRACT

Synoptic situations associated with strong southeasterly winds over the Rio de la Plata (RP) estuary are locally known as s*udestadas.* This phenomenon affects the coast of Buenos Aires city and its outskirts with floods, normally accompanied with persistent rainfall.

Storm surge levels (river level minus the astronomical tide levels) were used to identify cases associated with *sudestadas*. Although there is a local belief that most *sudestadas* are caused by cyclogenesis during winter, they actually occur during the whole year, being indeed less frequent in winter. In addition, they are not necessarily associated with cyclonic circulation. The maximum frequency of *sudestadas* is observed during summer and at the beginning of spring and autumn. This annual distribution was similar when two different water-level thresholds were used to characterize the storm surge.

The three principal components (PCs) of the atmospheric circulation field at 1000 hPa accompanying the *sudestadas* explain 75% of the variance. These patterns show that *sudestadas* are associated with either a combination of a high-pressure system to the south of the RP and relatively low pressure to the north (first and second PC modes) or a very deep low-pressure zone to the north of the river (third PC mode). These cases are associated with southeasterly winds, which produce tide waves on the RP.

Almost all the *sudestadas* associated with the third PC occur in winter and they reach on average greater peak levels than the others. These cases are associated with an intense low-pressure system north of the RP, which is typically due to the frequent cyclogenesis in that region. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: sudestada; Rio de la Plata; tide floods; storm surges

1. INTRODUCTION

The Rio de la Plata (RP) is a wide estuary formed by the confluence of the Paraná and Uruguay rivers (Figure 1). Because of the shape of the RP, which is 50 km wide at its starting location and about 300 km wide at its outlet at the Atlantic Ocean, and of its northwest–southeast course, whenever there are strong winds from the southeast, the water level rises. In these conditions, low-lying areas along the right bank are impacted by floods, including the Buenos Aires city coast and its outskirts. These situations are, in certain cases, accompanied by persistent rainfall and are locally known as s*udestadas.* Damage costs in the city of Buenos Aires, when combined with heavy rainfall, in some cases have exceeded US$250 million (Costa and Albini, 1988).

Previous synoptic studies have indicated that some of these *sudestadas* were caused by cyclogenesis centred in northeastern Argentina or Uruguay. In fact, over this region there is frequent cyclogenesis, particularly in winter (Rivero and Bischoff, 1971; Necco, 1982; Gan and Rao, 1991; Jusem and Atlas, 1991; Sinclair, 1994;

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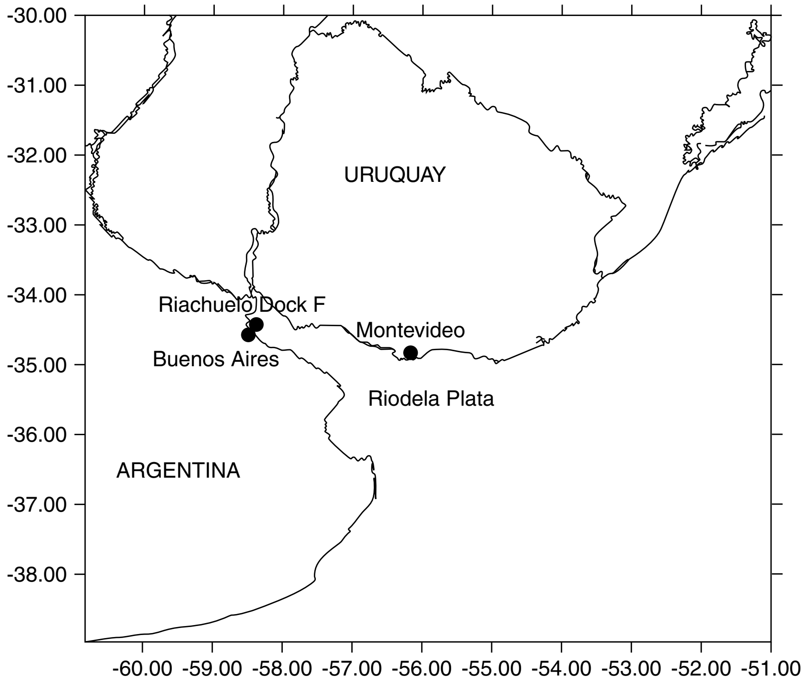

Figure 1. Geographical location of Riachuelo Dock F

Seluchi, 1995). Celemin (1984) compiled and described the *sudestadas* from 1940 to 1982 and classified their intensity according to the strength of the wind. Ciappesoni and Salio (1997) made the first systematic study of *sudestadas* and the related circulation fields in the middle troposphere for a 5 year sample (1990–94), typifying the *sudestadas* using the Celemin (1984) classification.

There are also some other studies that have dealt with floods along the Buenos Aires coast in a broader context, as in the case of D'Onofrio *et al.* (1999), who estimated the return period of floods caused by astronomical and storm tides or with the estimated impact of sea-level rise as a consequence of climate change (Lanfredi *et al.*, 1998).

This paper typifies *sudestadas* from its effects on the RP level and presents a statistical analysis of the variables that characterize *sudestadas*, namely height and duration of the storm surge. It also includes a study of the circulation patterns associated with *sudestadas*.

2. PARAMETERS AND DATA

Meteorological data used in this study were taken from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay *et al.*, 1996) for 1951–2000 in the domain 20–60 °S and 80–40 °W. The hydrological data (1951–2000), provided by the Naval Hydrographic Institute, have a gap during 1963 and 1964. For this study, the record from the tidal gauge at the Riachuelo Dock F was used ($\varphi = 34°34'$S, $\lambda = 58°23'$W; Figure 1).

The different risk levels defined by Balay (1961) are 2.50 m for alert, 2.80 m for emergency and 3.20 m for evacuation. The last two will be used as indicative to establish the thresholds for the characterization of *sudestadas.*

The level of the RP is affected by two components associated with different physical processes, i.e. the astronomical tide and the wind surge. Thus, for strong winds, the storm surge was calculated as the difference between the observed river level and the calculated astronomical tide.

Since, in the RP, storm surges depend on the intensity and persistence of the southeast wind, in the case of *sudestadas*, the rise of the water level is associated primarily with a storm surge, but in some cases is enhanced by the astronomic tide. The maximum values of the two components that define the level of the water, astronomical tide and storm surge, do not necessarily occur simultaneously. Therefore, since the warning level of the river is 2.50 m and the astronomical mean tide is approximately 0.90 m (D'Onofrio *et al*., 1999), the criterion adopted for defining a tide surge was a level of 1.60 m persisting for at least 24 h. With this criterion, a significant percentage of the cases actually exceed the 2.5 m mark. There were 297 cases in the 50 year period that satisfied the threshold in both height and duration. Hereafter, the term *sudestadas* will be restricted to these cases.

The variables used to typify the *sudestadas* statistically were the height of the storm surge, the time at which the peak storm surge occurred, the observed level of the RP obtained from the tide gauge and the duration of the *sudestadas*.

3. STATISTICAL ANALYSIS OF *SUDESTADAS* IN THE RP

The annual distribution of *sudestadas* is depicted in Figure 2. They are more frequent during summer than in winter, with two maxima in frequency, at the beginning of spring and during summer. Although not strictly similar, surface wind frequency from the east and the southeast at the Aeroparque station ($\varphi = 34°34'S$, $\lambda = 58°25'W$) on the Buenos Aires city coast, also shows a predominance from early spring to the end of summer (Table I).

Figure 3 shows the mean annual frequency of *sudestadas* for the last five decades. During the 1961–70 period, there was a reduction in absolute frequency with respect to 1951–60. However, in the following decades there was a positive trend in this frequency, going from 44 cases in 1961–70 to 79 cases in 1990–2000.

Figure 4 shows the distribution of *sudestadas*, with a mean of 1.93 m, a minimum of 1.61 m (which results from the definition of *sudestada* used here), a maximum of 3.48 m, and a standard deviation of 0.29 m. The distribution has a decreasing exponential shape with very few cases (probability of occurrence lower than 1%) of *sudestadas* higher than 3 m. Since in the 50 year period the number of *sudestadas* was 297, this 1% implies that the conditions of circulation that produce the exceptional surge storm of

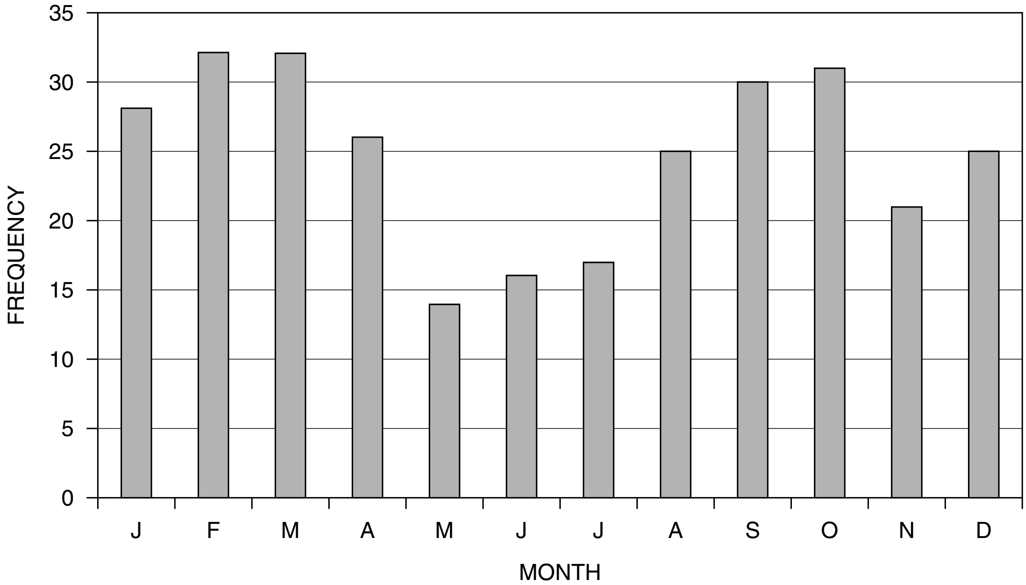

Figure 2. Annual distribution of *sudestadas* in the Rio de la Plata. Storm surge over 1.60 m

Table I. Monthly wind direction frequency at Aeroparque station ($\varphi = 34^{\circ}34'$S, $\lambda = 58^{\circ}25'$W). Period 1981–90

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
N	178	167	149	152	187	148	133	133	125	170	160	190
NE	140	132	123	124	69	68	110	98	123	113	132	150
E	241	238	189	143	100	89	136	205	225	204	217	222
SE	131	124	120	97	106	92	126	142	151	102	121	146
S	107	140	154	151	124	143	152	146	146	142	143	100
SW	51	58	72	85	116	113	93	62	66	86	55	38
W	54	50	73	103	126	138	93	80	54	63	60	45
NW	44	44	67	53	114	115	77	48	51	57	68	55
Calm	54	47	53	92	58	94	80	86	59	63	44	54

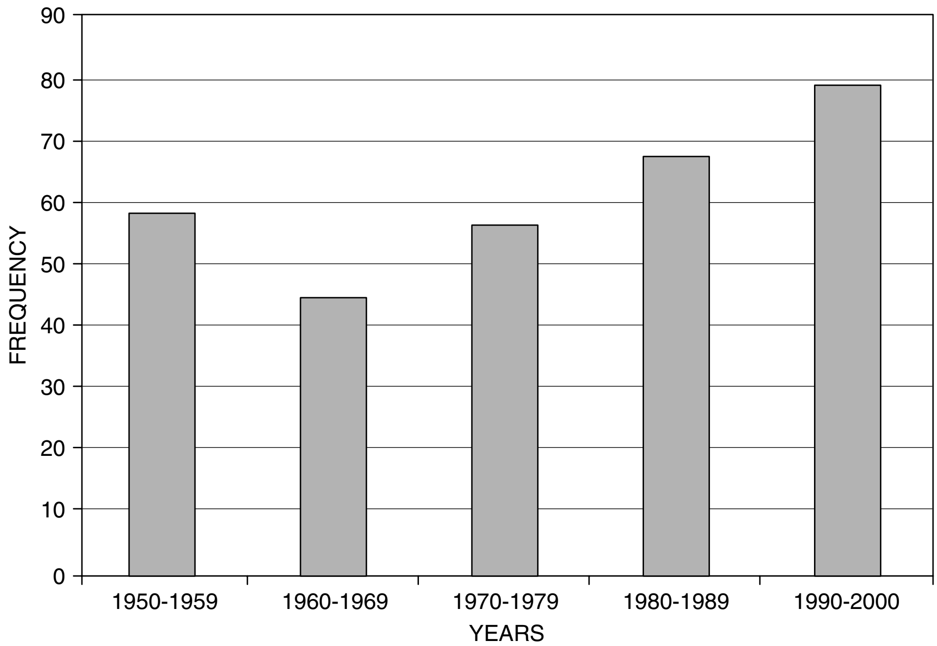

Figure 3. Decadal distribution of *sudestadas* in the Rio de la Plata. Storm surge over 1.60 m

3 m might be qualified as being of low probability (namely only three cases in 50 years); however, such conditions must be used as guidance for protection management. In addition, *sudestadas* between 2 and 3 m have a probability of occurrence not lower than 15% and, therefore, the mean frequency is almost one a year.

Figure 5 shows the empirical distribution of *sudestada* duration. It should be remembered that according to the *sudestadas* definition used here, their duration has to be longer than 24 h. The mean value was 47 h, the maximum was 175 h and the standard deviation was 22 h. As in the previous case, the distribution has a decreasing exponential shape. Durations longer than 60 h are only reached with a probability lower than 20%. Thus, approximately 80% of all the *sudestada* events registered in this period persisted for less than 2.5 days (20 to 60 h). This is the most probable range to be considered when estimating the risks associated with *sudestadas* in the RP.

Extreme events imply a great social and economic impact. These events can be defined as those cases that may exceed the evacuation level of 3.20 m. Since the main astronomic tide is 0.90 m, *sudestada* events with a water peak level threshold of 2.05 m are likely to surpass the 3.20 m mark in some cases. If persistence

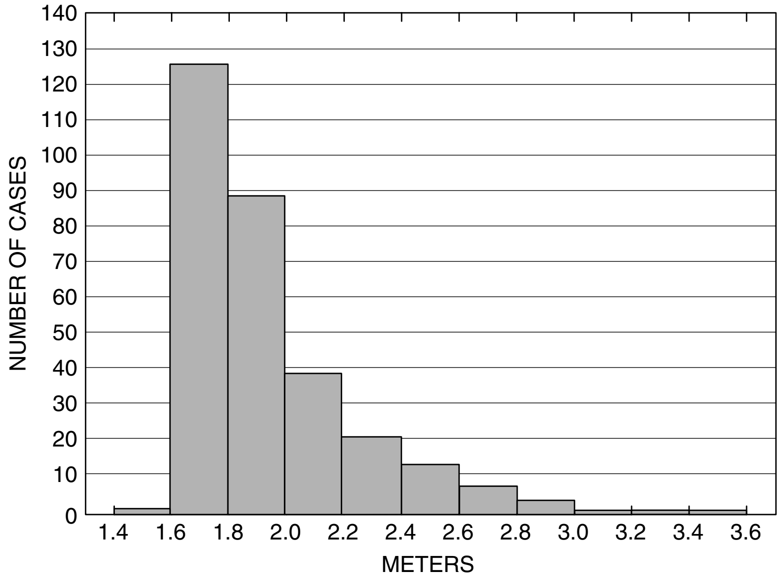

Figure 4. Distribution of storm surge height (m)

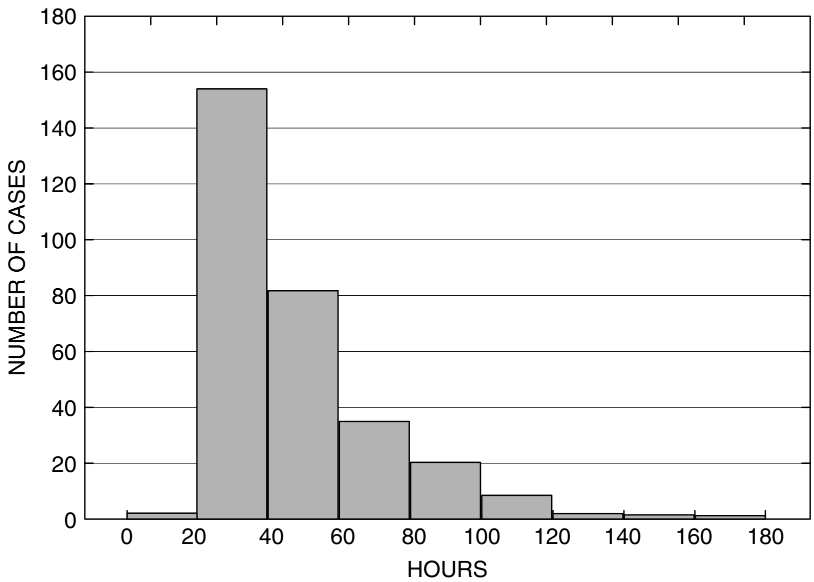

Figure 5. Distribution of *sudestadas* duration (h)

longer than 24 h is required, then only 72 *sudestadas* surpassed the 2.05 m threshold during the 50 year period.

The annual distribution of these extreme *sudestadas* is shown in Figure 6. They are more frequent at the end of summer and in spring, indicating that the annual distribution of *sudestadas* is maintained when this different threshold is taken. The frequency distribution during these *sudestada* events has the same distribution as in the case with a lower threshold. However, in their decadal frequency, the last two decades do not show a considerable increase with respect to 1950–60, as in the case of the 1.60 m threshold (Figure 7).

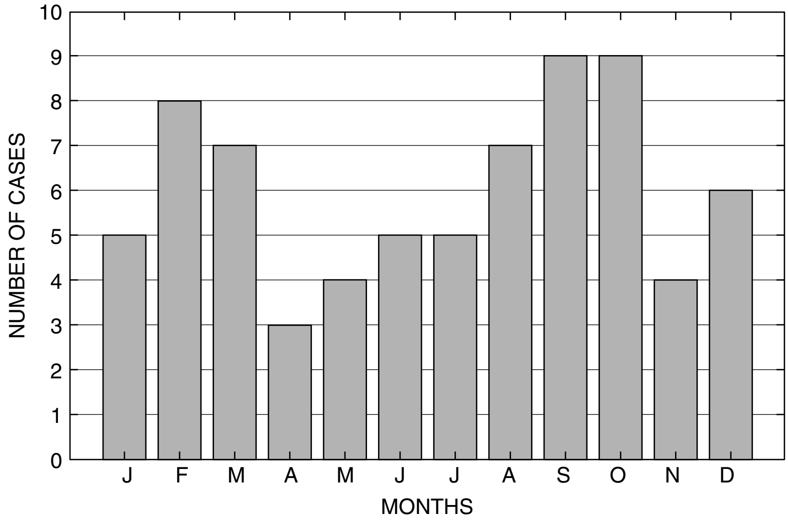

Figure 6. Annual distribution of *sudestadas* in the Rio de la Plata. Storm surge over 2.05 m

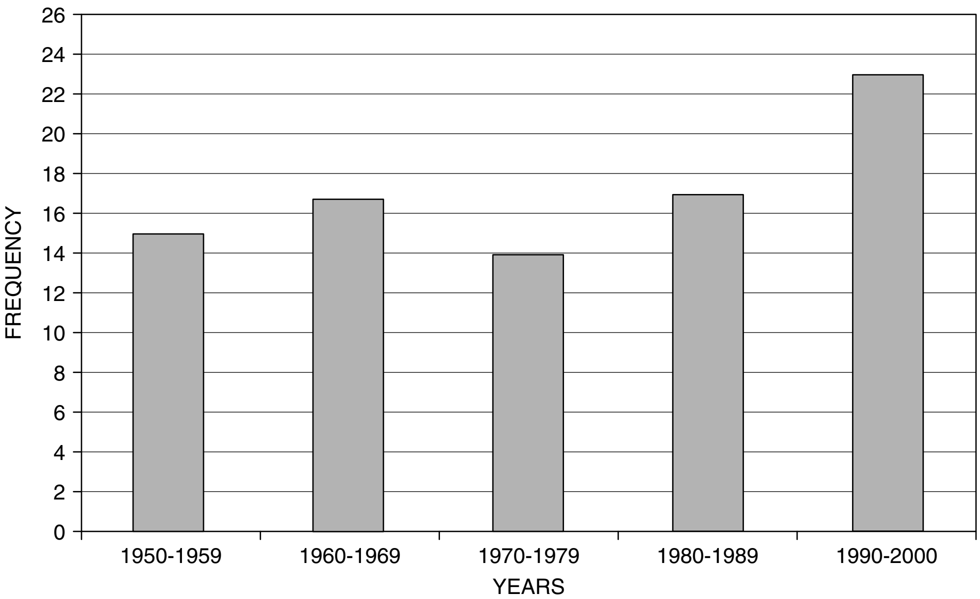

Figure 7. Decadal distribution of *sudestadas* in the Rio de la Plata. Storm surge over 2.05 m

4. LOW-LEVEL ATMOSPHERIC CIRCULATION AND *SUDESTADAS*

4.1. Event classification

Synoptic situations were associated with the *sudestada* definition given in Section 2. Since river level data were available at every 1 h, *sudestada* peaks can be identified with an hourly resolution. On the other hand, NCEP–NCAR reanalysis is only available every 6 h (00Z, 06Z, 12Z and 18Z). Therefore, the geopotential height at 1000 hPa from the reanalysis time that was closest to the hour of the *sudestada* peak was selected to be associated with the *sudestada* event.

4.2. Mean 1000 hPa geopotential height fields

The geopotential field at 1000 hPa is closely related to sea-level pressure, and hence it permits one to visualize the surface wind field. The mean 1000 hPa geopotential height pattern of the *sudestada* cases (Figure 8, left) shows a high centre to the south of the RP at 40 °S. With this geopotential pattern, there are moderate southeasterly winds over the RP estuary, which cause the water level rise over the RP estuary. On the other hand, the mean 1000 hPa geopotential height pattern of the total sample (Figure 8, right), with and without *sudestadas*, suggests westerly or calm winds over the RP and the neighbouring ocean. According to this, the circulation pattern associated with *sudestadas* is anomalous when compared to the mean circulation pattern.

The mean geopotential fields at 1000 hPa associated with the *sudestadas* of each decade all have similar features (figures not shown). However, there is an intensification of the meridional gradient of geopotential over the RP estuary during the last two decades. This is consistent with a positive trend in the frequency and the eventual intensity of the *sudestadas* (Figure 3).

4.3. Variability of the 1000 hPa geopotential height fields associated with sudestadas

In order to assess the predominant patterns of the 1000 hPa geopotential height fields associated with *sudestadas* and their variability, principal component analysis (PCA) was used in T-mode with the correlation matrix as input (Green, 1978; Richman, 1986). The mathematical approach and some relevant properties of this methodology can be found in Richman (1986). Varimax rotation retaining three principal components (PCs) was applied to isolate signals from noise. To select the numbers of components, the eigenvalue 1.0 rule was used (Richmann *et al*., 1992).

The correlation matrix was constructed with the 297 geopotential height fields at 1000 hPa associated with *sudestadas* of the 1950–2000 period. Figure 9 (left panels) shows the first three PCs associated with the principal circulation modes in the atmosphere when a *sudestada* occurs in the RP and the explained variance for each mode. The cases that had a correlation coefficient equal to or higher than 0.7 between geopotential at 1000 hPa and a PC were composited (Figure 9, right panels). Hereafter, these fields will be called the associated pattern with their respective PC

PC1, which explains 33.4% of the variance (upper left panel in Figure 9), shows a pattern with anticyclonic circulation to the south of the RP and, therefore, has associated southeasterly winds over the RP estuary and neighbouring ocean. The pattern is typical of post-frontal anticyclones, likely entering the continent around

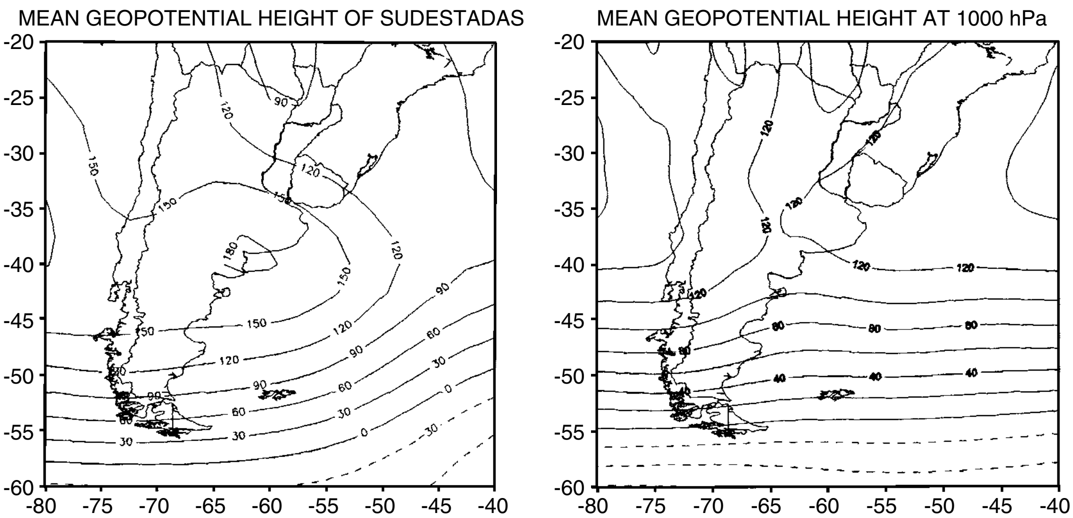

Figure 8. Mean 1000 hPa geopotential height fields associated with *sudestadas* (left). Mean 1000 hPa geopotential height of the total sample (right)

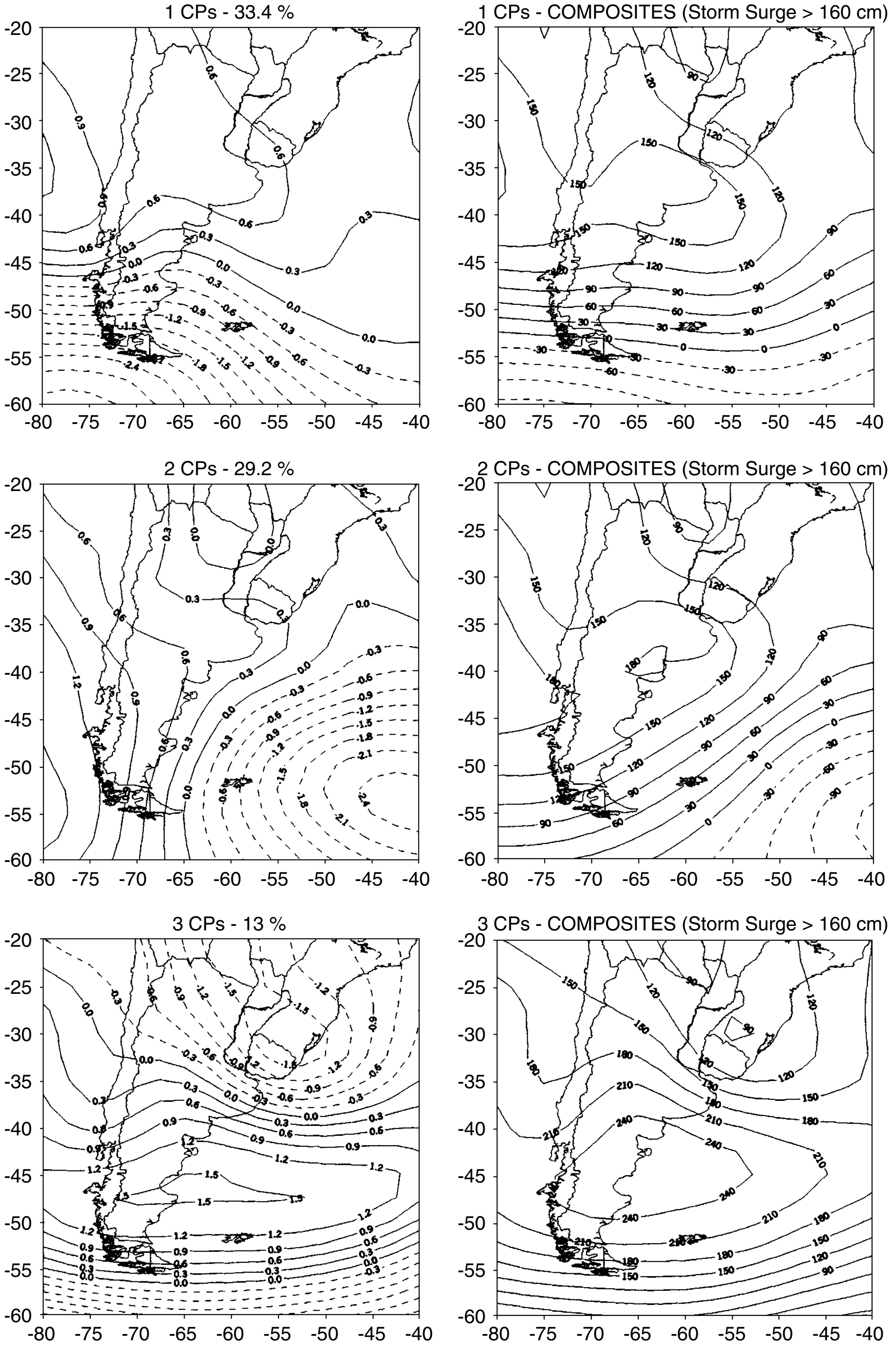

Figure 9. PCs (left) and composite 1000 hPa height fields (right)

35 °S. Figure 9 (upper right panel) shows the composition of cases associated with this pattern. It shows a low-pressure region extending from the northwest to the southeast, from Paraguay to the South Atlantic Ocean, suggesting that this field is associated with the cold fronts that usually progress over the region from southwest to northeast.

PC2, which explains 29.2% of the variance (Figure 9 centre left panel), has a pattern corresponding to an intense high system entering over the continent and a deep low system in the South Atlantic Ocean centred at approximately 55 °S, 45 °W. This pattern suggests a strong intrusion of cold air over the whole of southern Argentina, producing southerly–southeasterly surface winds over the RP estuary.

Finally, PC3 explains 13% of the variance (Figure 9, bottom left panel) and has a pattern consistent with a well-defined low-pressure system over Uruguay and southern Brazil that is usually observed over this region during cyclogenesis. This field also shows a strong anticyclone over the Argentine Patagonia with its centre at about 47 °S. The coupling of these two intense systems (extra-tropical cyclone over northeastern Argentina and high pressure in the south of the country) implies strong southeasterly winds over the RP.

The meridional gradient of geopotential at 1000 hPa in the composite of cases associated with PC3 is considerably higher than in those of the composites associated with the other two PCs. Consistent with this fact, the mean heights of the *sudestada*s associated with PC3 are higher than those of the other two PCs (Table II). As might be expected, the three sets of cases have almost the same mean value for the astronomical component, but different values in the storm surge component.

The number of cases that are associated with the first three PCs is 210 out of 297 *sudestadas* (Table II). This is about 70% of the cases, which is a value near the 75% of the variance explained by the first three modes. The cases associated with PC3 are 18, which is only 8.5% of the *sudestadas*. This means that cyclogenesis, which was believed to be the synoptic situation that caused *sudestadas, only* produces a small percentage of them, although certainly with a higher mean peak in the river level.

Figure 10 shows the annual distribution of *sudestadas* associated with each of the three PCs of the geopotential height at 1000 hPa. Mode 1 (Figure 10, upper panel) predominates during the summer and in September and November; mode 2 (Figure 10, central panel) has three peaks, in January, autumn and spring. These two modes determine the annual storm surge frequency variation along the year depicted in Figure 2, with two maxima: one in summer and the other in early spring.

Although *sudestadas* associated with PC1 and PC2 take place during the whole year, with some predominance in certain months, *sudestadas* associated with the PC3 occur from May to October, with a maximum frequency during August and September and a few events in summer. This fact is related to the lowest frequency of cyclogenesis during the summer over this region due to the significant decrease in baroclinicity with respect to the other seasons (Rivero and Bischoff, 1971; Necco, 1982).

Table II. Statistical parameters of the variables analysed for each of the three PCs

	N	Mean	Minimum	Maximum
PC1				
Height (m)	107	253.0	202	403
Storm surge (m)	107	189.6	161	348
Duration (h)	107	40.2	25	113
PC2				
Height (m)	85	251.0	202	366
Storm surge (m)	85	189.0	161	295
Duration (h)	85	50.9	25	175
PC3				
Height (m)	18	285.1	215	350
Storm surge (m)	18	226.1	164	304
Duration (h)	18	70.1	37	108

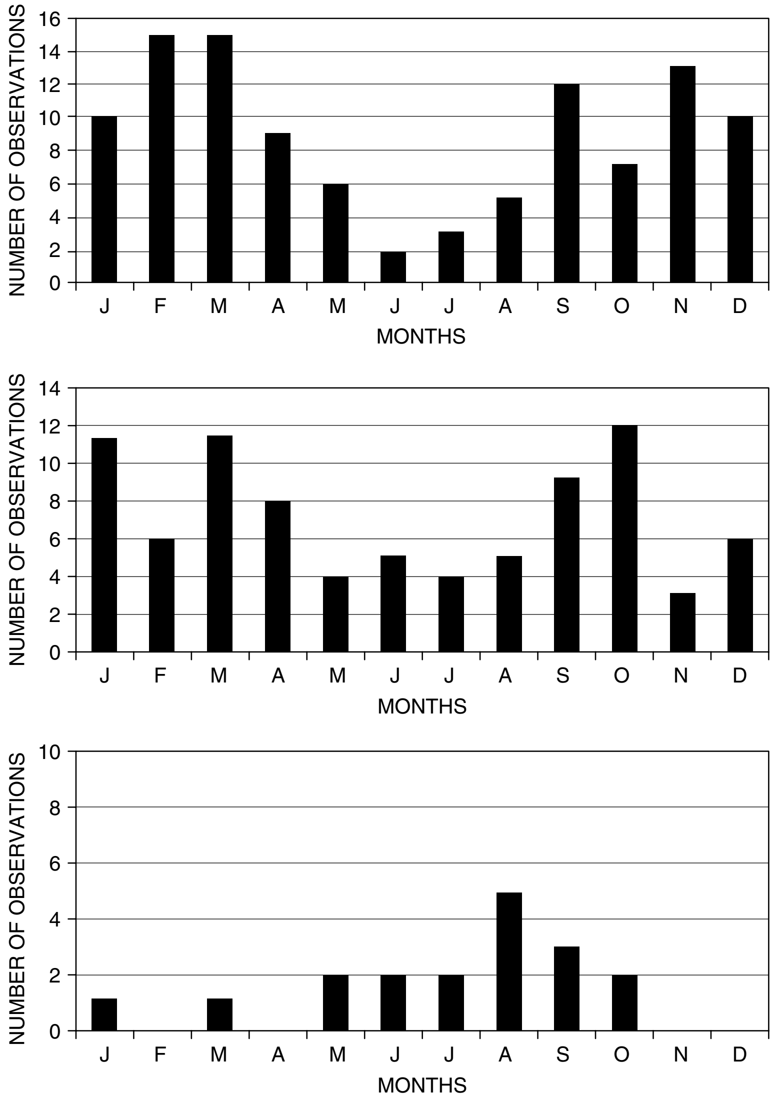

Figure 10. Annual distribution of *sudestadas*. Storm surge over 1.60 m. Mode 1 (top), mode 2 (centre) and mode 3 (bottom)

5. CONCLUSIONS

There are different patterns of the low-level atmospheric circulation that can cause *sudestadas*. Three of them account for 70% of the cases and more than 60% are associated with an anticyclonic circulation centred to the south of the RP estuary. Actually, most of the *sudestadas* are basically associated with both high pressure to the south of the RP and a relative or a very deep low-pressure zone to the north that causes winds from the southeast sector, and thus produce an upsurge of the sea level and a strong swell on the coast of the RP estuary. These low-level atmospheric circulation fields that force *sudestadas* are considerably anomalous with respect to the mean and prevailing conditions over the region. In other words, *sudestadas* are a consequence of extreme anomalies of the low-level atmospheric circulation.

Sudestadas occur during the whole year, but are least frequent in winter. However, those that do occur in winter have an intense and considerably developed low-pressure system in the northeast of Argentina or Uruguay characteristic of cyclogenesis, and they reach higher peak levels than the others on average.

The storm surge height distribution has a decreasing exponential shape, and shows that storm surges with a peak height higher than 3 m have probabilities near to 1%. Although this percentage implies only three cases in 50 years, this level must, however, be taken as guidance for protection management. *Sudestadas* exceeding 60 h have a probability not higher than 20%. This implies that most *sudestadas* persist for only 1 to 3 days; therefore, although their impact can be acute, they are relatively brief, thus moderating the adverse social and economic effects.

The storm surge frequency variability through the year shows common features when two different thresholds (1.60 and 2.05 m) are used to define them, suggesting similar properties for different threshold levels.

Interdecadal variability of the frequency of *sudestadas* shows no trends from 1950 to 1970 and a positive one after that. The beginning of this trend in around 1970–80 was similar to what has been observed in other climate and hydrological variables of the region (García and Vargas, 1998; Barros *et al*., 2000; Bischoff *et al*., 2000)

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