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Historical assessment of extreme coastal sea state conditions in southern Brazil and their relation to erosion episodes

ARTHUR A. MACHADO[1*], LAURO J. CALLIARI[1], ELOI MELO[2] & ANTONIO H. F. KLEIN[3]

[1] *Institute of Oceanography, Federal University of Rio Grande, Av Itália Km 8, CEP: 96201-900, Rio Grande, RS, Brazil.*
[2] *Engineering School, Federal University of Rio Grande, Av. Italia Km 8, CEP 96201-900, Rio Grande, RS, Brazil.*
[3] *Department of Geosciences, Federal University of Santa Catarina, Campus Universitário Trindade, CEP 88040-970, Florianópolis, SC, Brazil.*
* *Corresponding author: oceaam@yahoo.com.br*

Abstract. Intense cyclonic weather systems in southern Brazil generate ocean storms which can, in a temporal scale varying from few hours to a day completely erode a beach profile from its maximum accretion state. Mid-latitude cyclogenesis with low pressure centers in the deep ocean and along the coast increases the intensity of the Mid-Atlantic storms causing storm surges and storm waves. Preliminary results from a hindcast of wave energy at deep water (100 m), performed with a wave model using winds from reanalysis (period 1979 - 2008), indicated a total of 40 extreme events (wave height above 6 m). These events cause maximum erosion and surge elevation on the order of 62.96m^3/m and 1.827 m respectively. Four patterns of synoptic situations capable of generating extreme events were identified. Among the 40 events, 53.66% had the trajectory of Pattern II and 26.82% were associated to Pattern III, representing both 80% of the total. Coastal erosion episodes where mostly associated with Pattern II, while Pattern III caused the highest surges. In a climate change scenario this study shows no important differences in the amount of the extreme events along the last thirty years.

Key words: storm surge, extra-tropical cyclones, wave height, NCEP/NCAR Reanalysis

Resumo. Avaliação histórica das condições extremas de mar na costa do sul do Brasil e sua relação com episódios de erosão. Sistemas meteorológicos como ciclones extratropicais de alta intensidade que ocorrem no sul do Brasil geram ondas de alta energia, que podem levar um perfil de praia de um estágio máximo acrescivo ao máximo erodido em poucas horas. A ciclogênese em médias latitudes, com centro de baixa pressão, contribui para a intensificação das tempestades do Meio do Atlântico, causando marés meteorológicas (storm surges) e ressacas (storm waves). Resultados preliminares para um estudo de energia das ondas em águas profundas (100 m), utilizando um modelo de ondas com dados de vento de reanálises (período 1979 - 2008), indicaram 40 eventos extremos (6 m de altura de onda). Alguns desses eventos geraram erosão de 62,96 m^3/m e 1,827 m de elevação do nível do mar. Foram identificados quatro padrões de situações sinóticas geradoras de alturas de ondas acima de 6m. Entre os 40 eventos, 53,66% tiveram a trajetória do Padrão II e 26,82% estavam associados ao Padrão III, ambos representando 80% do total. Episódios de erosão costeira geralmente são associados ao Padrão II. Já o Padrão III é responsável pela maior elevação do nível do mar. Diferenças significativas na quantidade de eventos extremos ao longo dos últimos 30 anos não foram observadas.

Palavras-chave: maré meteorológica, ciclone extra-tropical, altura de onda, NCEP/NCAR Reanálises

Introduction

After the accretion period which occurs between December and March, storms beginning in April start the erosion cycle of the southern Brazilian sandy beaches. Generally, erosion is caused by extreme sea state events which combine high waves and high storm surges. Since astronomical tides have higher amplitude in this region during April, and the storms can last a few days, it is not uncommon that episodes of severe erosion occur during the high water spring tide period (Calliari *et al.* 1998). These storms are mostly associated with high intensity extra-tropical cyclones that generate wind waves which can change a beach profile from its maximum accretion state to complete erosion during a period that can vary from few hours to a few days.

Regarding the occurrence of extra-tropical Cyclones in South America, Gan (1992), analyzing 10 years of data (from 1979 to 1988) has found that the majority of events happen in winter (8 events), followed by autumn (6), spring (4) and summer (3). Gan & Rao (1991) identified two cyclogenesis regions in South America: one in Argentina (42.5° S and 62.5° W) related to the baroclinic instability of the westerly winds and another in Uruguay (31.5° S and 55° W) associated with the baroclinic instability due to the presence of the Andes. Recently, a third region between 20° and in the 35°S located in southern and south-eastern Brazil was identified (Reboita *et al.* 2010).

Mid-latitude cyclogenesis with low pressure centers in the deep ocean and along the coast increases the intensity of Mid-Atlantic storms causing extreme storm surges and storm waves (Calliari *et al.* 1998). The "surge" in a specific instant is represented by the difference between the observed and the astronomical tide and can be either positive or negative causing rapid increase or decrease in sea level, respectively (Pugh 1987).

Storm surges are the major geological risk in low coastal areas. They are often associated with significant losses of life and property. Climate change, with rising sea level and changing storm tracks, will modify the regional distributions of these hazards (von Storch & Woth 2008).

The two main sources of storm surges are: changes in atmospheric pressure and the exchange of momentum between the wind and the sea surface. In general, the effects associated with atmospheric pressure is less than 10% of the total, being the wind shear stress at the sea surface the main component (Marone & Camargo1994). Additionally, sea level elevations at the shore can be further amplified by the presence of shelf waves and by the pilling up of water due to wave breaking processes at the surf zone (known as "wave set up") (Marone & Camargo 1994).

Observations of synoptic weather conditions and sea level elevation done by Parise *et al.* (2009) showed that the highest sea level elevation events resulted from the action of SW winds which blow parallel to the main NE-SW coastline orientation in the region, a result that can be explained by the pilling up of water at the coast due to the Coriolis effect (i.e. Ekman transport). The monitoring carried out by Saraiva *et al.* (2003) from April 1997 to July 1999 on Cassino Beach indicated the highest frequency of the storm surge in autumn (65%), followed by similar values in summer and spring (15%) and lower values in winter (5%). All the storm surges observed by Saraiva *et al.* (2003) were associated with extra-tropical cyclones.

Coastal erosion has been causing substantial alterations along the coastline of the Rio Grande do Sul (RS) state in southern Brazil for quite some time. In the less occupied areas in the central littoral, coastal erosion caused habitat loss of foredune ridges and inflicted local damage to a lighthouse (Conceição lighthouse) and small beach resorts at Lagamarzinho beach (Barletta & Calliari 2003). In more developed regions of the northern littoral, such as Cidreira, Tramandaí and Imbé beaches, coastal erosion is aggravating, leading to severe loss of public and private property (Esteves *et al.* 2000, Toldo Jr. *et al.* 1993). At the southern littoral, Hermenegildo beach, located near the Uruguayan border, has had homes, roads and power lines systematically destroyed (Calliari *et al.* 1998, Esteves *et al.* 2000). Additionally, in several stretches of the RS coastline, beach erosion causes exposure of peat and muddy lagoonal outcrops leading to a decrease in the quality of beach recreation (Calliari *et al.* 1998) (Fig. 1).

In a climate change scenario, the present study aims at assessing in detail the synoptic situations that give rise to extreme sea state events in Southern Brazil and determining trends in the atmospheric patterns and path lines of meteorological systems associated with them. The erosional impact on the coastline and the storm surges caused by these extreme events are also investigated. Case studies of selected extreme events that generated strong beach erosion are also discussed in detail.

Materials and Methods

Extreme events

In the absence of sufficiently long data sets, we had to resort to numerical models to infer the occurrence of extreme events. The results used herein were extracted from a comprehensive study that is being currently carried out by the third author and are still preliminary (see Melo *et al.* 2010). In that on-going study, the wave generation model Wave Watch III (WW3) (Tolman 2002) forced with reanalysis winds from NCEP (National Centers for Environmental Prediction) was used to reconstruct sea state conditions off the southern Brazilian coast

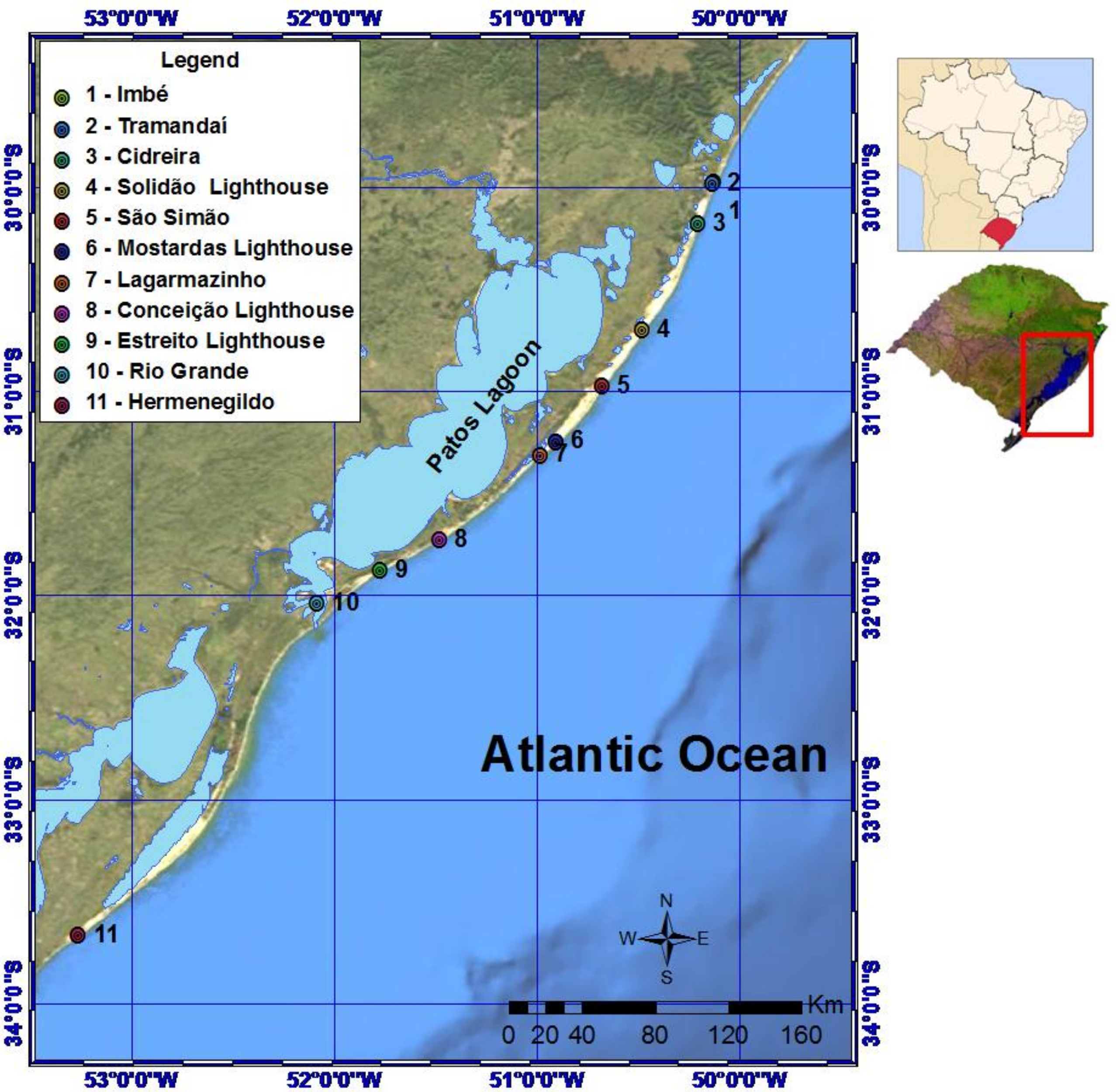

Figure 1. Study area and location of cited sites.

from 1979 to 2008. "Extreme" events were then selected based on the criteria that the reconstructed significant wave height (Hs) at a point in 100 m depth off Rio Grande city exceeded the 6 m mark. Preliminary results indicated that a total of 40 extreme events occurred in the studied period.

Synoptic scenarios associated with extreme events

The reanalysis dataset was created through the cooperative efforts of the NCEP and NCAR (National Center for Atmospheric Research) (Kalnay *et al.* 1996) to produce relatively high-resolution global analyses of atmospheric fields over a long time period. The reanalysis dataset (R-1 of NCEP / NCAR) was used to characterize atmospheric conditions that originated these 40 extreme events. To do so, meridional and zonal components of the wind and atmospheric pressure at the 995 mbar level were used. For both a spatial resolution of 2.5° x 2.5°, and a temporal resolution of 6 hours (0000, 0600, 1200, 1800 UTC) restricted between 60°S - 15°S and 90°W - 20°W was adopted. In order to better characterize the path of the systems that generated extreme events, a threshold vorticity lesser or equal than (ζ_{10}) -5 x $10^{-5}s^{-1}$ was adopted. The reanalysis dataset is available at site www.cdc.noaa.gov

Data analysis

Analysis of variance (ANOVA) was used to verify differences between the numbers of events at 3 years interval along the 30 years. Data normality was tested through the Kolmogorov-Smirnov test and the homogeneity of the same ones through the Levene test (Zar 1999).

Results and Discussion

In the period between the years of 1979 and 2008, 40 events of significant wave height (Hs) above 6 m occurred considering as reference the position of (32°54'S, 50°48'W) at 100 m water depth. The yearly mean number of events was 1.33 with a minimum of 0 events and a maximum of 4 events in the year of 1999. The standard deviation was 0.958/year.

The ANOVA result of the 10 groups joined at 3 years interval shows no significant difference in the number of extreme wave height events along the 30 years period ($F(9, 20) = 1.4815$, $p = 0.22141$ (Fig. 2A). The correlation graphic between the numbers of events and the thirty 30 years period showed a positive but weak correlation ($r = 0.30636$) (Fig. 2B).

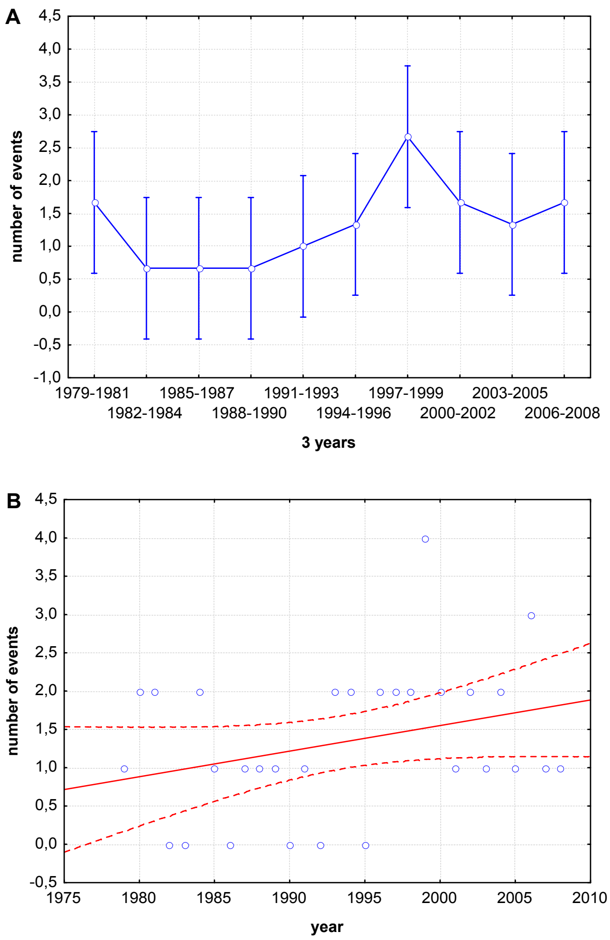

Figure 2. (A) Mean of the number of extreme events of the 10 groups, Vertical bars denote 0.95 confidence intervals, (B) Correlation of the number of extreme events over the study period, the dashed line denote 0.95 confidence intervals and the continuous line denote the regression line.

Webster *et al.* (2005) found an increase in the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature. A large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurred in the North Pacific, Indian, and Southwest Pacific Oceans, and the smallest occurred in the North Atlantic Ocean.

From the analysis of the meteorological scenarios, four patterns of synoptic situations capable of generating extreme events were identified (Fig. 3):

- PATTERN I: Cyclogenesis in the southern Argentinean coast with a displacement to the east and a trajectory between 47.5°S and 57.5°S;
- PATTERN II: Cyclogenesis in the southern Uruguayan coast with a displacement to the east and a trajectory between 28°S and 43°S;
- PATTERN III: Cyclogenesis in the southern Uruguayan coast with a displacement to the southeast and a trajectory between 32°S and 57.5°S;
- PATTERN IV: High-pressure center generating an easterly wind.

Was not observed at the study area a significant difference in the frequency of the patterns of cyclone trajectories along time. The pattern with the greatest number of extreme events was Pattern II with 22 of the 40 +1 events. Eleven (11) events were associated with Pattern III and four (4) events were associated to both Pattern I and IV. The value of 41 related to the sum of all the patterns is due to an event that occurred on 07/21/1996, in which, two parallel extra-tropical cyclones resembling Patterns I and II occurred simultaneously.

Case Studies

In this section, a selection of extreme sea state events was used to assess both, the specific meteorological scenarios associated, and the response that was observed on the coast in terms of beach erosion.

July 21th, 1996

An extreme wave height event occurred on July 21th, 1996. The meteorological scenario shows two extra-tropical cyclones parallel to each other representing Patterns I and II. Due to its eastern path and the following of a high pressure system in the rear, a long southwest wind fetch of more than 3000 km was formed over the Atlantic off the South American coast (Fig. 4).

This event caused the maximum erosion profiles recorded in 1996. At places located between Solidão and Estreito lighthouses the maximum eroded volume reached 62.96 m^3/m (Barletta & Calliari 2003) (Fig. 5).

April 18th, 1999

The meteorological scenario on this extreme event was unusual since the path of the cyclone that developed off the RS coast formed a loop without much forward motion (Fig. 6).

Severe erosion was observed at Hermenegildo beach. Prior to the storm, this beach resort had 110 beachfront houses. During the storm, 22 houses were destroyed or highly damaged. This single storm was also able to destroy the majority of coastal protection structures including 20% of all beachfront houses. However, as it was later observed, all the coastal protection structures were built on top of the foredunes without any foundation underneath them, being, in this way, susceptible to undermining. Esteves *et al.* (2000) indicated that this was the process that caused most of the structures to collapse (Fig. 7).

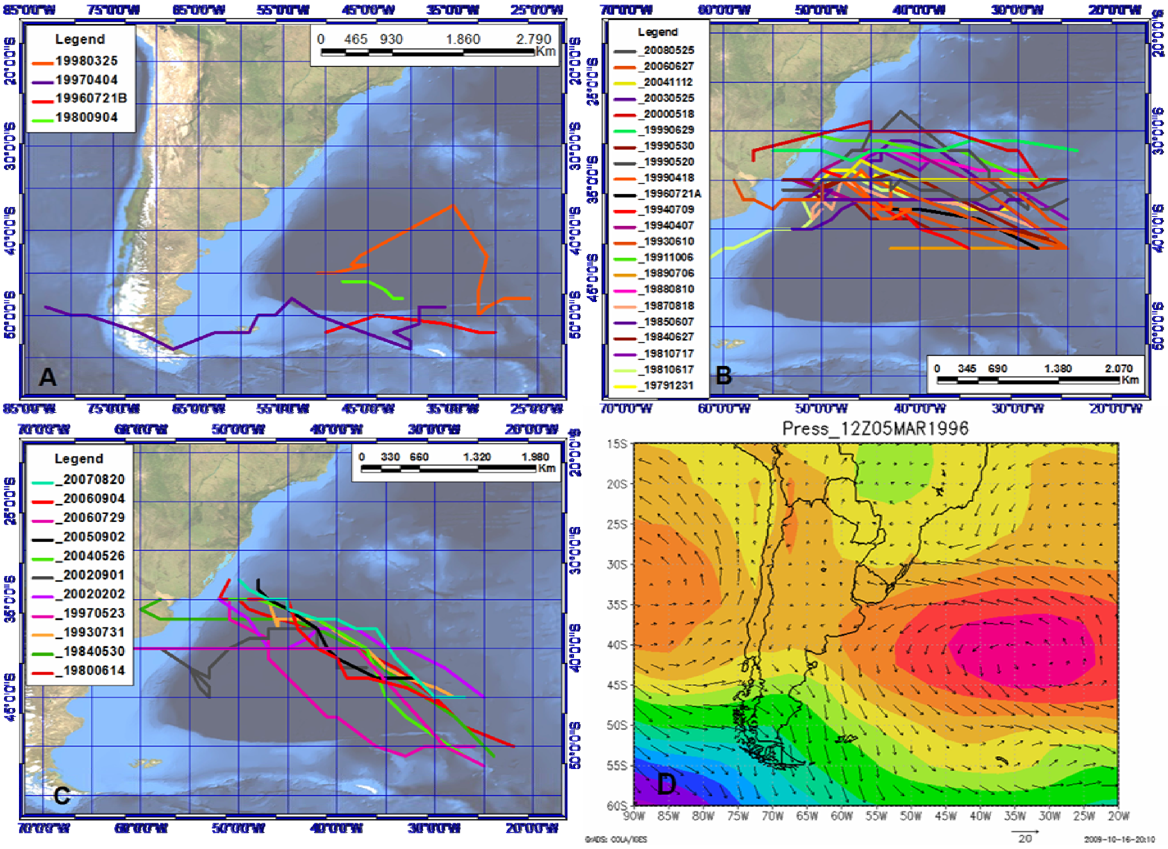

Figure 3. Path of the four synoptic situations: (A) Pattern I, (B) Pattern II, (C) Pattern III, (D) Pattern IV.

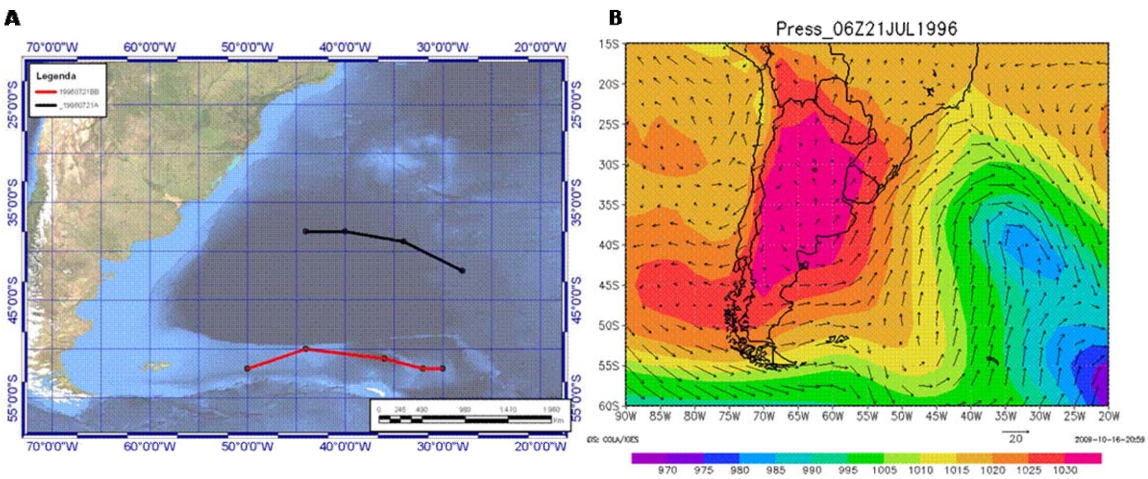

Figure 4. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

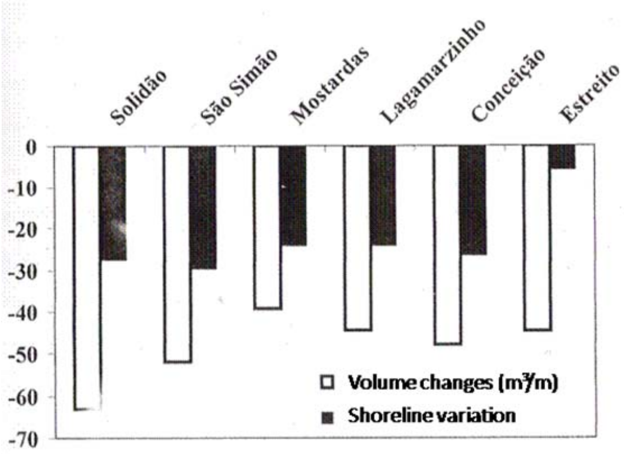

Figure 5. Shoreline (m) and volume changes (m³/m) between Estreito and Solidão lighthouses, after the storm of July 1996. Modified from Barletta & Calliari (2003).

May 25th, 2003

This event was, actually, monitored by an oceanographic buoy moored offshore Rio Grande city (Minuano buoy from the PNBOIA, Program moored at a depth of 70 m) since it caused mud deposition at Cassino beach (Calliari & Faria 2003). Buoy measurements, which did not include direction, are displayed in Table I. Maximum significant wave height came very close to the 7 m mark. The path described by the extra-tropical cyclone on this event resembled Pattern II (Figure 8A). A large low pressure center can be observed moving slowly towards the E (Fig. 8B).

September 04th, 2006

This event coincided with one of the extra-tropical cyclones studied by Parise *et al.* (2009), who shows that this particular storm caused a surge of 1.827 m. Although the surge was very high, beach erosion was low (-8.14 m^3/m) the reason being that the initial profile was already eroded by the winter storms. Regarding the meteorological scenario, it can be observed the development of a long wind fetch from S to SW (Fig. 9). The association between this wind pattern and the NE-SW orientation of the shoreline favored the extra high rise in sea level observed on the coast due to the Coriolis effect (Parise *et al.* 2009).

Table I. Wave data from the Minuano buoy (100 m depth) (Calliari & Faria 2003).

Date/Hours	Wave height (m)	Period (s)
25/05/2003- 00:00	6.9	11.6
25/05/2003- 02:00	6.7	10.7
25/05/2003- 07:00	6.9	11.6
25/05/2003- 13:00	5.6	11.1
25/05/2003- 17:00	5.6	14.2
25/05/2003- 20:00	6.9	16.0

Video-images from an ARGUS system (Holman & Stanley 2007) analyzed before and after the onset of the extra-tropical cyclone allowed the quantification of changes in beach width at Cassino during the event (Parise *et al.* 2009) Timex images from the same system display the surge reaching the dunes and the differences of the surf zone width with a third bar appearing during the storm surge (Fig. 10). Maximum values of storm surges of the order of 1 m, 1.4 m and 1.9 m in the coast of the RS have been found by Calliari *et al.* (1998), Saraiva *et al.* (2003) and Parise *et al.* (2009), respectively. During this event great part of Cassino beach was flooded when the water reached the first avenue close to the beach.

Studies done by Saraiva *et al.* (2003) and Parise *et al.* (2009) pointed out that the maximum elevation of the surge occurs mainly 24 hours after the cyclone formation (Tab. II).

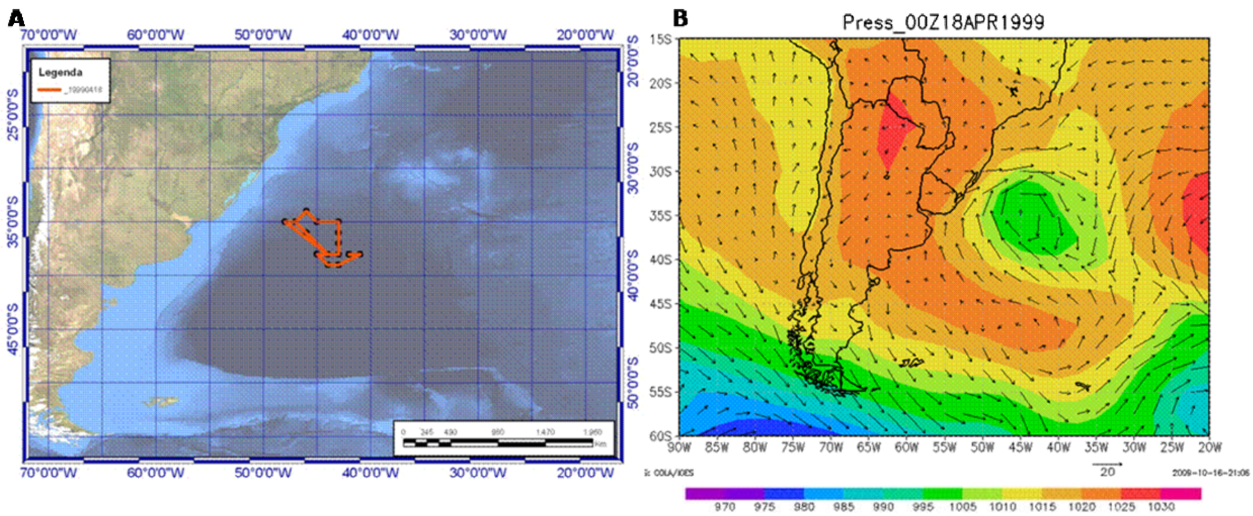

Figure 6. (A) The path in loop, (B) Synoptic situation, wind field (knots) and pressure (mbar).

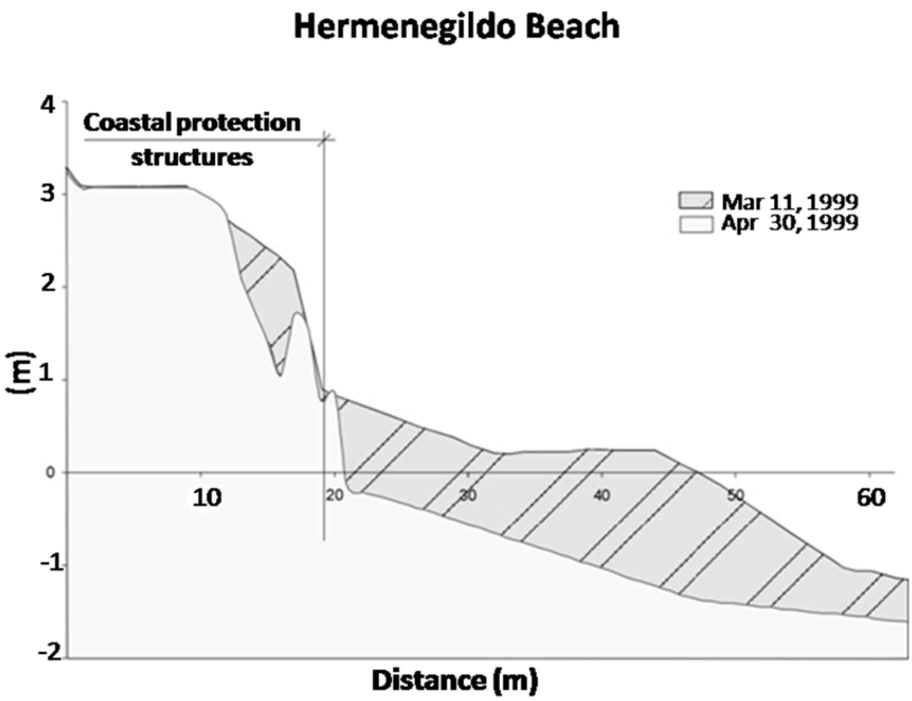

Figure 7. Beach profiles done before and after the event of 18/4/1999. Modified from Esteves *et al.* (2000).

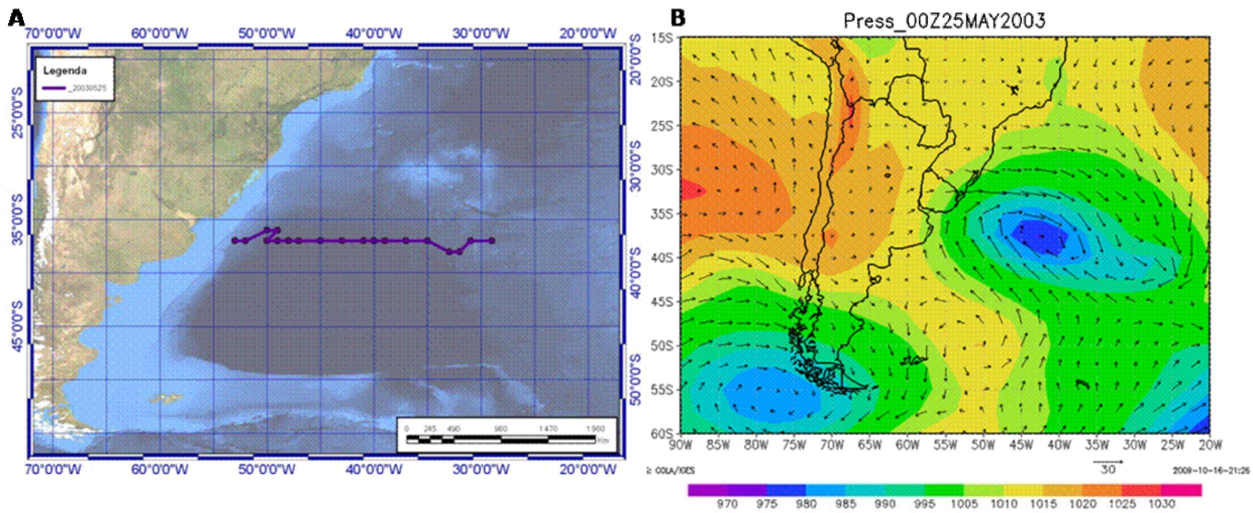

Figure 8. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

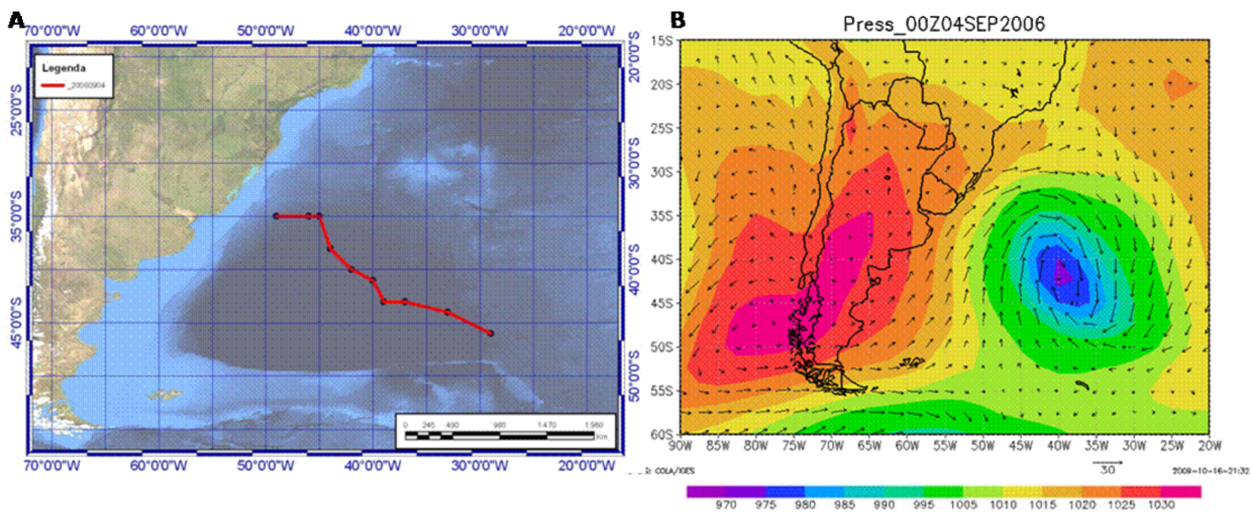

Figure 9. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

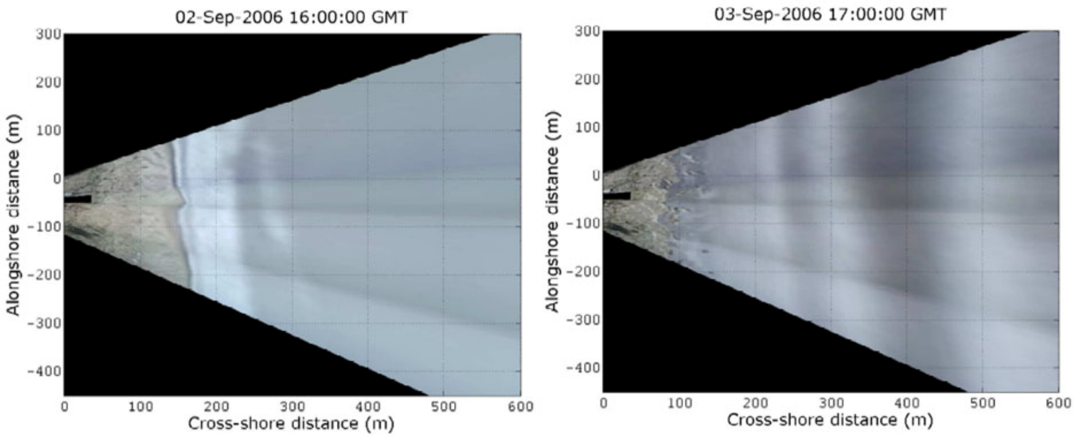

Figure 10. Timex images of the Argus system installed at Cassino beach, during a normal surf-zone (left) and during the storm surge (right). LOG-FURG/2007 - http://www.praia.log.furg.br/

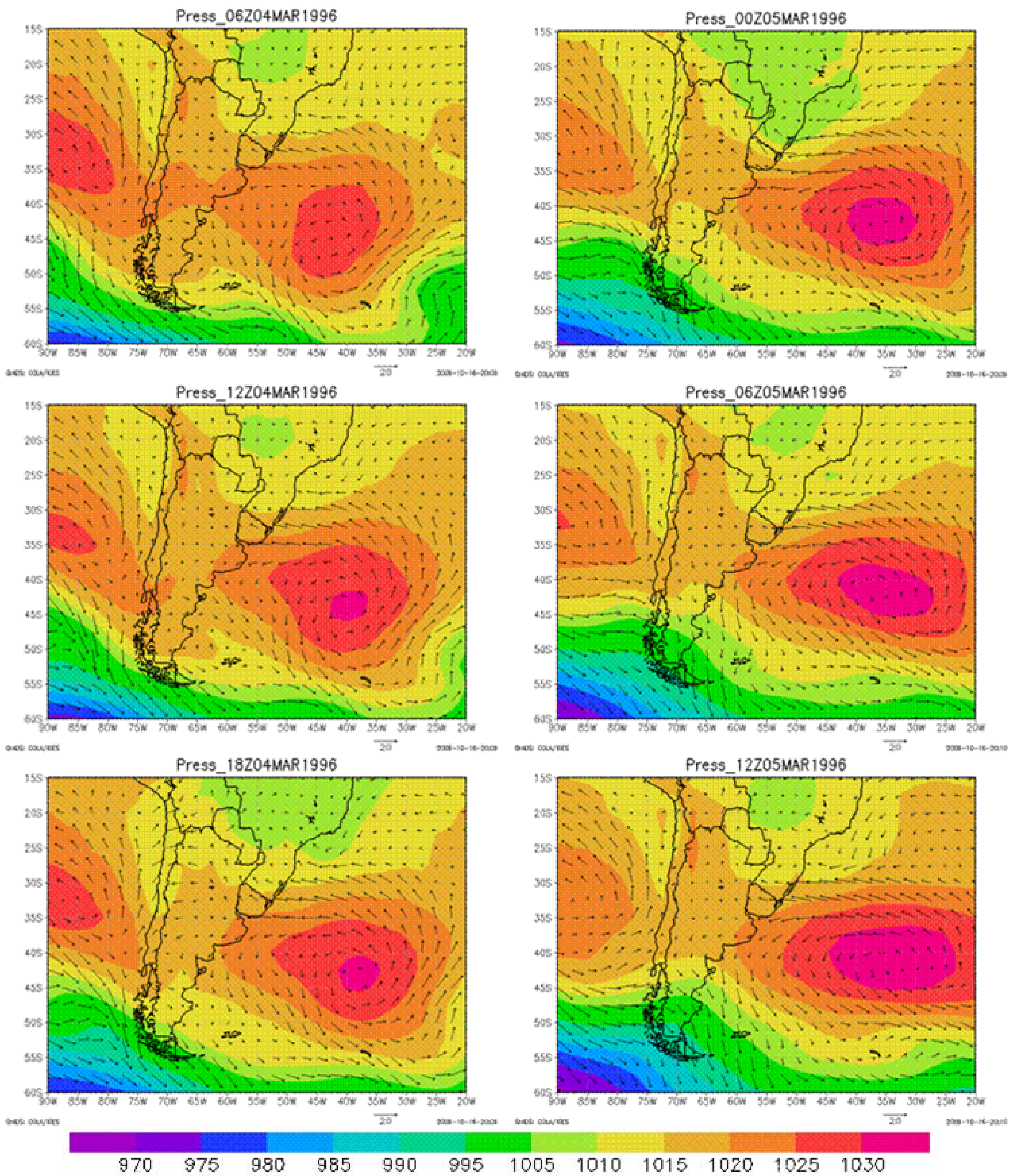

Figure 11. Synoptic situation of the of high pressure center (anticyclone) moving toward the east. Wind (knots) and pressure (mbar)

Table II. Time interval between the formation of the cyclone and the maximum surge elevation.

MONITORING	6h	24h	36h	48h
1997 to 1999 (Saraiva *et al.* 2003)	10%	45%	10%	30%
2006 to 2007 (Paris *et al.* 2009)	9%	39%	26%	26%

Special Cases

Among the 40 extreme wave height events, four were generated by strong easterly winds associated with large anticyclonic system, which also displays the path of the high-pressure center between March 04 and 05 of 1996. This event generated waves from the east quadrant as indicated by the wind field shown in figure 11.

Conclusion

This study shows no important differences in the amount of extreme events along the last thirty years. The mean number of events obtained was 1.33 per year. To these events data of wind velocity and vorticity, atmospheric pressure and sea level elevation were added. Effects of extreme events on the coast caused maximum erosion and surge elevation on the order of 62.96m³/m and 1.827 m, respectively.

Among the 40 events studied, 22 (53.66%) had the trajectory of Pattern II with Cyclogenesis to the south of the Uruguayan coast with a path to the east and a trajectory between 28°S and 43°S. Cyclones associated with Pattern III, represented 26.82% (11 events). Those two types represent 80% of the total extreme events. The relationship between the coastal erosion and these extreme events is clear, as observed from Parise *et al.* (2009), being the cyclones associated with Pattern II the most erosive ones, whereas those associated with Pattern III the ones that cause highest surges.

The reanalysis dataset of NCEP proved very useful in this type of analysis, because although the spacing of the data 2.5 degrees, cyclones and anticyclones studied have diameters above 1000 km, thus presenting a good answer to the synoptic situation that caused each extreme event studied.

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