Revista de Gestão Costeira Integrada / Journal of Integrated Coastal Zone Management, 15(1):91-107 (2015)

Revista de GESTÃO COSTEIRA Integrada — *Journal of Integrated COSTAL ZONE MANAGEMENT*

http://www.aprh.pt/rgci/pdf/rgci-555_Verocai.pdf | DOI:10.5894/rgci555

Addressing climate extremes in Coastal Management: The case of the Uruguayan coast of the Rio de la Plata System*

José E. Verocai [@, a, b]; Monica Gómez-Erache[a, c]; Gustavo J. Nagy[a]; Mario Bidegain[c, d]

Abstract

This paper deals with current storm surges (extremes) in the Uruguayan coast of the Rio de la Plata system (Argentina-Uruguay), a large (38,000 km^2) microtidal (<0.5 m) river estuary. Extremes are associated with two synoptic situations able to increase water level above mean sea level (MSL) at Montevideo (≥102 cm): the passage of cold fronts and extra-tropical cyclones over Atlantic coast. The assessment of coastal hazards and the reduction of the associated risks can be embedded within Coastal Management (ICZM). Infrastructure frequently does not comply with the legal 250 m setback. Thus, possible impacts due to inundation and flooding related to sea-level rise (SLR) and extremes respectively are high. Also, rapid-onset high river inflow often associated with El Niño events, are relevant due to the positive water level anomaly (> 10 cm) related to them. The existence of differences in the monthly distribution of both MSL and extremes occurrence suggest that both wind climate and river inflow (Q_{RP}) explain them. The most severe extremes (≥ 350 cm) at Montevideo have occurred before 1935. The frequency of events ≥200, 250 and 280 cm has slightly increased over 2003-2012, which is not attributed neither to SLR nor to increased inflow, but to wind regime changes. Two extreme events (March 1998 and August 2005) are presented which serve to enhance our understanding of the causality and timing of extremes and as analogues to developing scenarios under a changing climate. Some impacts are as follows: coastal stormwater and sewage systems become useless affecting beach quality, artisanal fisheries income is reduced, and sandy beaches and bars are eroded. Among the several obstacles to achieving a comprehensive ICZM in regards to extreme events is the lack of an effective monitoring network. This paper aims to increase awareness, research and application of the knowledge of extreme events on ICZM and risk-management in the face of SLR and flooding.

Keywords: water level, storm surges, river flow, climate adaptation, ENSO, Montevideo.

Resumo

Sobre extremos climáticos em gestão costeira: o caso do sistema de Rio de la Plata na costa do Uruguai.

Neste artigo analisam-se os extremos de maré meteorológica (elevação do nível do mar de índole meteorológica) na costa uruguaia do sistema de Rio de la Plata (Argentina-Uruguai), um grande (38.000 km^2) corpo estuarino com características de micro-maré (<0,5 m). Os extremos estão associados a duas situações sinóticas capazes de aumentar o nível de água acima do nível médio do mar (MSL) em Montevidéu (≥102 cm): a passagem de frentes frias e de ciclones extra-tropicais sobre a costa

[@] Corresponding author to whom correspondence should be addressed.

[a] Universidad de la República, Grupo de Cambio Ambiental y Gestión Costero Marina, Oceanografía y Ecología Marina, Instituto de Ecología y Ciencias Ambientales (IECA), Montevideo, Uruguay. e-mails: Verocai <otolito21@gmail.com>; Nagy <gnagy@gmail.com>; Gómez-Erache <mgomez@gmail.com>

[b] Armada Nacional, Servicio de Oceanografía, Hidrografía y Meteorología (SOHMA), Departamento de Oceanografía, Montevideo, Uruguay

[c] GEF Project "Implementing Pilot Adaptation Measures in Coastal Areas of Uruguay"

[d] Instituto Uruguayo de Meteorología (INUMET), Montevideo, Uruguay. e-mail: Bidegain: <bidegain.mario@gmail.com>

* *Submission: 16 SEP 2014; Peer review: 16 OCT 2014; Revised: 17 NOV 2014; Accepted: 23 NOV 2014; Available on-line: 25 NOV 2014*

atlântica. A avaliação de riscos costeiros e da redução dos riscos associados a tais eventos pode ser incorporado dentro de Gerenciamento Costeiro (GIZC). Com frequência, as infra-estruturas não cumprem os 250 m legais de afastamento da linha de costa. Assim, os possíveis impactos devidos a inundações relacionadas com a subida do nível do mar (SLR) e com extremos da maré meteorológica têm elevada magnitude. Além disso, há que ter em consideração as cheias fluviais relacionadas com eventos de El Niño, pois que provocam também anomalias positivas do nível de água (> 10 cm). A existência de diferenças na distribuição mensal de ambos (MSL e ocorrência de extremos de maré meteorológica) permite deduzir que tanto o vento como os fluxos fluviais (Q_{RP}) permitem explicá-las. Os maiores extremos (≥ 350 centímetros) registrados em Montevideo ocorreram antes de 1935. A freqüência de eventos ≥200, 250 e 280 centímetros aumentou ligeiramente no período 2003-2012, o que não é atribuído ao SLR nem ao aumento de fluxos fluviais, mas sim a mudanças no regime de ventos. São apresentados dois eventos extremos (Março de 1998 e Agosto de 2005) que servem para melhorar a nossa compreensão da causalidade e da temporização dos eventos extremos, constituindo bons análogos para o desenvolvimento de cenários num clima em mudança. Alguns impactos são os seguintes: sistemas costeiros de águas pluviais e de esgotos tornam-se inúteis, o que afeta a qualidade das praias, redução da pesca artesanal, e erosão das praias e bares. Entre os vários obstáculos para alcançar uma GIZC abrangente no que diz respeito a eventos extremos é a ausência de uma rede de monitoramento eficaz. Este trabalho tem como objetivo aumentar a conscientização, pesquisa e aplicação do conhecimento de eventos extremos na GIZC e da gestão de riscos perante as inundações e o aumento do nível médio do mar (SLR).

Palavras-chave: *nível da água, mare meteorological, fluxo fluvial, adaptação ao clima, ENSO, Montevideo.*

1. Introduction

This article continues a series of five papers written by the Team of Environmental Change and Coastal-Marine Management of the School of Sciences (FC-UdelaR), Uruguay for the GEF project "*Implementing Pilot Adaptation Measures to Climate Change in Coastal Areas of Uruguay",* from now on "the Project" (PRODOC, 2008). The four other works (Nagy *et al*. 2014a, 2014b, 2014c, in press), discuss the methodological evolution to cope with observed and current variability, to adapt to future climate change, and the development of alternative future scenarios to better understand and manage the coastal areas of Uruguay focused on climate threats such as episodic extreme river flows and storm surges, and gradual sea level rise (SLR).

The coast line can adopt a stable profile or shape when the processes for the input and removal of sediments are balanced. However, external factors such as storms often induce morphodynamics changes which disrupt the state of balance. Climate change and the increase of the mean sea-level (MSL) affect the transfer of sediment in complex ways; non-linear and abrupt changes can occur when certain thresholds are exceeded. If the increase of the MSL is gradual and slow, the balance can be maintained, even with morphological changes, but acceleration in the rate of increase can make it difficult to maintain, particularly where sedimentary input is limited, such as in coastal lowlands with a tendency to flood (Solomon *et al*., 2007).

According to ECLAC (2011) the 50-years return inundation level is greater in Chile, Argentina and Uruguay. The trends of coastal inundation levels in Latin America have increased to ≤ 0.5 cm over the last six decades due to SLR, waves and storm surges. The region where this increase - excluding hurricanes -was the highest (> 1cm/year) is the Rio de la Plata (Argentina-Uruguay). The impacts of coastal inundation related to storm surges are greater than those related to SLR.

As SLR accelerates, it will become increasingly necessary and useful to distinguish coastal "flooding" from "inundation" (Flick *et al*., 2012). These authors propose that the term flooding" be used when dry areas become wet temporarily and that "inundation" be used to denote the process of a dry area being permanently drowned or submerged. Thus, the former is related to episodic extremes and the latter to SLR.

In most cases, the infrastructure in Uruguay does not comply with the 250 m setback established by the Water Code. Thus, current or possible territorial impacts due to flooding associated with SLR and/or wind storm surges are high. In view of this, sections have been identified for coastal management, in an attempt to set up a coastal management and planning unit in each section, in the light of current and applicable legislation (Medina, 2009; Medina & Gómez-Erache, 2014a, 2014b, 2014c).

This article emphasizes on the occurrence of extreme events, mainly storm surges, in the Uruguayan coast of the Río de la Plata (RdlP) river estuary from 1983-2012, regardless of the associated flooding and inundation. This period was chosen to analyze the current climate baseline, including the reported changes in hydroclimatic variables, winds, and SLR observed in the RdlP basin, river estuary, and the coastal areas of Uruguay (Escobar *et al*. 2004; Barros *et al*. 2005; Bidegain *et al*. 2005; Nagy *et al*. 2008a,b, in press).

Extreme Events and Integrated Coastal Zone Management

The assessment of coastal hazards and the mitigation of the risks in respect of those hazards can be embedded within the Integrated Coastal Zone Management (ICZM) (IOC, 2009).

Of all the impacts from climate change, the projected rise in mean sea level is one of the most significant concerns for ICZM. In addition to projected higher frequency of storm surge and inundation levels, SLR will also result in shoreline recession of unconsolidated sandy shorelines (DECCW, 2010).

ICZM is an acknowledged tool to deal with current and long-term coastal challenges, including climate change and its impacts (for instance SLR, changes in storm frequency, strength and patterns, and increased coastal erosion and flooding; Ballinger & Rhisiart, 2011).

Notwithstanding, the increasing experience in coastal management education, research, policies and actions in Uruguay, the country still has to increase current and future climate and meteorological knowledge and threats. Recently, this approach has been conducted by "The Project" which has cooperated and developed common goals related to climate adaptation with Eco-Plata Program (Gómez-Erache *et al.* 2010; Echevarría *et al.* 2013; Nagy *et al.* 2014a, c, in press).

The baseline of storm surges (1983-2012) is presented focusing on their occurrence and on examples of two events. A plausible increase in the frequency and/or intensity of extremes under projected SLR scenarios is expected to be the main threat to coastal stability until it reaches at least 20-30 cm plus, by around 2040-60 (Nagy *et al.*, 2006). Thus, a better knowledge of the occurrence, causality, timing, and impacts of storm surges is needed to planning current and near-future coastal management options.

Storm surge is defined as an increase in coastal water level caused by the effects of storms. Storm surge consists of two components: an increase in water level caused by a reduction in barometric pressure (barometric setup) and an increase in water level caused by the action of wind blowing over the sea surface (wind setup) (DECCW, 2010). The most common impacts due to storm surges are damages to the:

- Population, i.e., deaths, injuries, evacuated, temporal loss of services such as electricity and drinking water, sewage;
- Real estate and infrastructures;
- Coastal morphology, i.e., sandy beaches, barriers and dunes erosion;
- Ecosystems and biodiversity.

The goals of this article are to: i) Identify water level extremes defined as those exceeding 200 cm at Montevideo; ii) Explain the relationship between hydroclimatic variability (river inflow to the RdlP) and surface wind behavior with water level, and iii) Present two examples of observed storm surges, focused on the climatic system over the Rio de la Plata region.

2. The Rio de la Plata River Estuary and the Vulnerability of the Uruguayan Coast

The complex geophysical environment of the RdlP basin and river estuary is under stress from existing pressures such as changing hydro-climatic and wind regimes, sea-level rise, extreme events, growing population and associated increases in development over the last few decades (Barros *et al.* 2005; Nagy *et al.* 2008a, 2008b, in press). The coastal areas in Argentina and Uruguay are vulnerable to these trends over the last few decades, especially to storm surges (Escobar *et al.* 2004; Barros *et al.* 2005; Bischoff, 2005; Magrin *et al.* 2007; Nagy *et al.* 2007; 2008a, 2008b, 2013; ECLAC, 2011).

The RdlP river estuary shared by Argentina and Uruguay (Figure 1) is 290 km long, 40 to 220 km wide, has an average depth ≤10 m, and 38,000 km^2, where it mixes the continental freshwater (see Figure 1 below) from the RdlP basin (Paraná and Uruguay rivers, which supply 75 and 25% of the total river inflow (25,000 m^3/s) respectively, and the Atlantic sea waters (Nagy *et al.*, 1997, 2008a; Lappo *et al.*, 2005). Although the Uruguayan riverside of the RdlP is less exposed to winds than the Argentinean one, the shallow inner fluvial and the middle estuarine front regions suffer the effects of southern and southeastern winds which drag water into the system increasing water level by 100 to 300 cm (Balay, 1961; Escobar *et al.* 2004; Barros *et al.* 2005; Bidegain *et al.* 2005; Bischoff, 2005). Montevideo is located in the estuarine front.

The Uruguayan coast has a mixed micro-tidal regime (< 0.5 m), semidiurnal with diurnal inequality. The tide wave comes from the Atlantic Ocean, being deformed within the estuary due to the shape, banks, channels, depth, and Coriolis deflection towards Montevideo, where a strong decrease of the cross-section occurs. Thus, an increase of isoamplitudes occurs towards the inner river (upstream the estuarine front) which facilitates the occurrence of "storm surges", that is to say the positive anomaly between the astronomic tide and the observed level, which is attributed to residual effects of winds, waves, atmospheric pressure, and the flood of freshwater (Balay, 1961; Nagy *et al.*, 1997; Verocai *et al.*, 2014).

There are two typical weather development situations able to produce strong positive water level anomalies (+ 100 to 300 cm):

i) the strengthening of an extra tropical cyclone over Atlantic coast and

ii) the passage of cold fronts coming from the South.

The development of cyclones near the Argentinean-Uruguayan coast is usually associated with strong southeastern winds (35 – 50 km/h) called "Sudestadas"

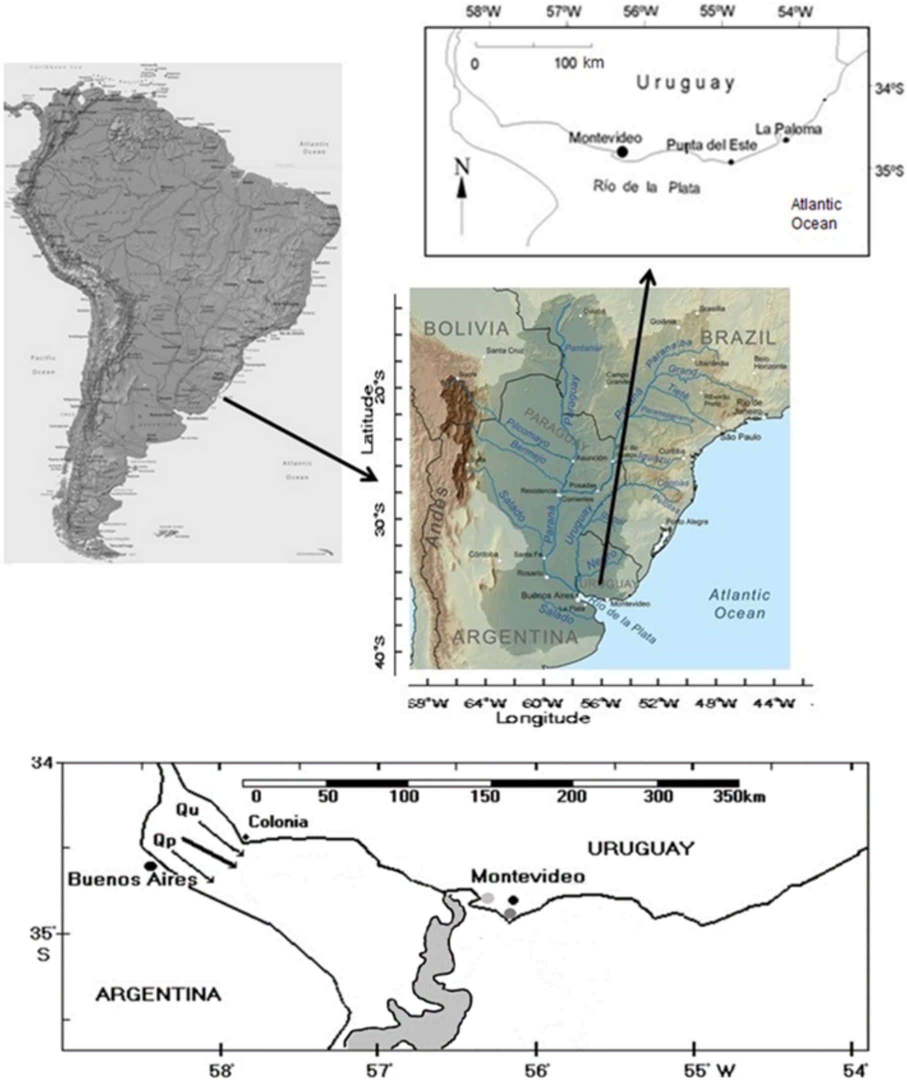


Figure 1 - Above: Rio de la Plata basin and river estuary, Southeastern South America (accordingly to Nagy *et al*., 2014a). Below: Location of the estuarine front (March 30, 2011) under typical river inflow conditions.

Figura 1 – Em cima: bacia e estuário do Rio de la Plata, no Sudeste da América do Sul (segundo Nagy et al., 2014a). Em baixo: localização da frente estuarina (30 de março de 2011) em condições típicas de fluxo fluvial.

in the RdlP region. These events last around 48 hours. The arrival of cold fronts originates southwest winds called "Pamperos" which duration is usually less than the one of "Sudestadas". These winds drag waters towards the inner, narrower, and shallower fluvial and frontal zones (4-10 m depth) piling-up water at both riversides. The maximum water levels vary depending on the intensity and persistence of the wind, and the simultaneous occurrence of the peak of the storm surge and the astronomic tide. Several papers explain how these winds affect water circulation (Simionatto *et al*. 2005), frontal location and displacement (Framiñan & Brown, 1996; Simionatto *et al*. 2001; Nagy *et al*. 2008a), and water level and coastal inundations (Balay, 1961; Jaime & Menéndez, 1999; Bischoff, 2005; D´Onofrio *et. al*. 1999, 2008).

These events negatively impact the aquatic environment and resources, i.e. the artisanal fishing activity (Acuña *et al*. 1992; Norbis, 1995; Nagy *et al*., 2008b, 2014b), and the coastal populations, real estate, infrastructure, and biodiversity (Volonte & Nicholls, 1995; Saizar, 1997; Nagy *et al*., 2005, 2007; ECLAC, 2011).

An estimated 70 per cent of Uruguayans live in coastal areas, 34 percent of which is urbanized, including the metropolitan area of Montevideo. Over two thirds of economic activities and income generated in Uruguay are directly or indirectly related to the coast. Also, globally relevant biodiversity sites are located in coastal areas. Consequently, coastal processes coexist alongside a variety of activities that compete for space and resources, the subsequent result being coastal degradation (Gómez-Erache *et al*., 2010).

Uruguay has been identified as one of the most exposed Latin American countries to coastal climate change (Magrin *et al*., 2007; Dasgupta *et al*., 2007) in terms of exposed population to a SLR of one meter, namely

30 per cent of the country's population. The estimated cost of climate change on coastal resources for SLR and wind-induced flooding + 0.3, 0.5 and 1,0 meter represents two, four and twelve per cent of 2008 GDP respectively (ECLAC, 2011; Nagy *et al*., in press).

Usually, ICZM in Uruguay deals with current issues, including climatic variability and extremes, and vulnerability (Nagy *et al*. 2014a, in press). Notwithstanding, there is a lack of a comprehensive study on the vulnerability, the risks, and the overall impacts of storm surges and flooding in the RdlP region. This issue is increasingly considered by the climate adaptation initiative "the Project", but it needs yet to be fully integrated by both ICZM and Emergency plans.

3. Clarifying concepts on extreme events on coastal areas

Assuming that many readers are more familiar with Integrated Coastal Management than with weather and climate extremes, and because some terms have different meanings, some definitions and concepts based on recent literature and our experience used in this paper are presented here.

A changing climate leads to changes in the frequency, intensity, spatial extent or duration of weather and climate extremes, and can result in unprecedented extremes (Field *et al*., 2012). Extreme weather includes unusual, severe or unseasonal weather phenomena at the extremes of the climatological or historical distribution (the range that has been seen in the past) on a geographical location (Solomon *et al*., 2007). Extreme weather occurs only 5 to 10 % or less (1 %) of the time. In recent years some extreme weather events have been attributed to human-induced global warming, and climate models and observed trends show that with climate change, the planet will experience more extreme weather (Hansen *et al*., 2012).

According to Stephenson (2008), meteorological events can be classified according their rarity, rapidity and severity as:

- Rare events: are those that have a low probability of occurrence. Because of the rarity of these events, human societies and ecosystems are often not well adapted to them and so suffer large amounts of damage when they do occur. Hence, despite their rarity, the large vulnerability associated with such events can often lead to large mean losses.
- Extreme events: are those that have extreme values of certain important meteorological variables. Damage is often caused by extreme values of precipitation (e.g. floods), high wind speeds (e.g. cyclones), etc. Extreme is generally defined as either taking maximum values or exceedance above pre-existing high thresholds. Such events are generally rare; for example, extreme wind speeds exceeding the 100-year return value, which have a probability of only 0.01 of occurring in any particular year.
- High-impact (severe) events: are those that can be either short-lived weather systems (e.g. severe storms) or longer-duration events such as blocking episodes that can lead to prolonged heat waves and droughts.

Extreme events have attributes such as:

- rate (probability per unit time) of occurrence
- magnitude (intensity)
- temporal duration and timing
- spatial scale (footprint)
- multivariate dependencies

Acute extremes are events that have a rapid onset and follow a short but severe course. Examples are short-lived weather systems such as tropical and extra tropical cyclones, which are generally referred to as ''windstorms'', and convective storms with extreme values of meteorological variables such as wind speed, precipitation, flash or coastal floods that can lead to devastating wind and flood damage.

Here, the use of the term extreme event refers to storm surges measured as water/sea levels at Montevideo greater than 200 cm associated with cold frontal systems passages and the strengthening of a cyclone over Atlantic coast, and strong values of wind speed. The 200 cm threshold was selected because this level is reached at least once a year since the beginning of water level records at Montevideo Harbor in 1902 (Pshennikov *et al*., 2003; Bidegain *et al*., 2005). Most years this value is exceeded several times. Thus, the operational definition is based on recurrence, regardless of flooding and damage. Usually this threshold is not associated with risks or losses. However, the sedimentary balance of sandy beaches may be affected by water levels below the threshold, usually associated with southern wind anomalies (Gutiérrez *et al*., 2013, 2015; Ortega *et al*., 2013). Also, acute rapid-onset river inflow - flash floods - or chronic climatic high precipitations in the La Plata basin, often associated with El Niño events, are relevant extreme events for the Uruguayan coast of the RdlP, due to the positive water level anomaly related to the freshwater input exceedance (Nagy *et al*., 2013).

4. Methodological approach

All the events exceeding 200 cm at Montevideo on hourly basis from 1983-2012 have been considered. Monthly and yearly frequencies were calculated for this period, computing the month of occurrence. Two case studies were selected to compare storm surges at three sites of the Uruguayan coast of the RdlP: i) Colonia (tidal freshwater upper estuary, see Figure 1 below), ii) Montevideo (brackish waters within the middle estuarine front), and iii) Punta del Este (marine lower estuary). The event of March 24-26 1998 was selected because the water level reached 300 cm (over the zero reference) and the long duration - 3 days - of the storm surge. The event of August 23-24, 2005 was selected because the water level exceeded 300 cm at Montevideo due to an extremely rapid onset and the intensity of the storm surge, associated with an extra tropical cyclone, as well as because it was the only hydro meteorological disaster in Uruguay which caused a toll of 10 deaths (Magrin *et al*., 2007). Notwithstanding, none of deaths was attributed to the storm surge but to very strong winds.

Cross correlations (r Pearson) between the monthly Paraná and Uruguay rivers inflows (measured at the basin about 500 km to the northwest of Montevideo) to the RdlP and monthly freshwater/sea levels at Colonia (220 couples of data) and Montevideo (530 couples of data) were calculated. The selection of a monthly time window is due to the lag between river flows and their arrival into the RdlP, estimated as varying from 1 week for very high discharges to 2 months for very low discharges (Nagy, 2000). Thus, all moon phases were taken into account and a 5% error is accepted. More than 1000 couples of data were recorded for southern and southeastern winds and water level at Montevideo. Also, water/sea level at Colonia and Montevideo were related to the river inflow to the RdlP (Q_{RP}: Paraná River + Uruguay River) on monthly average basis.

5. Results

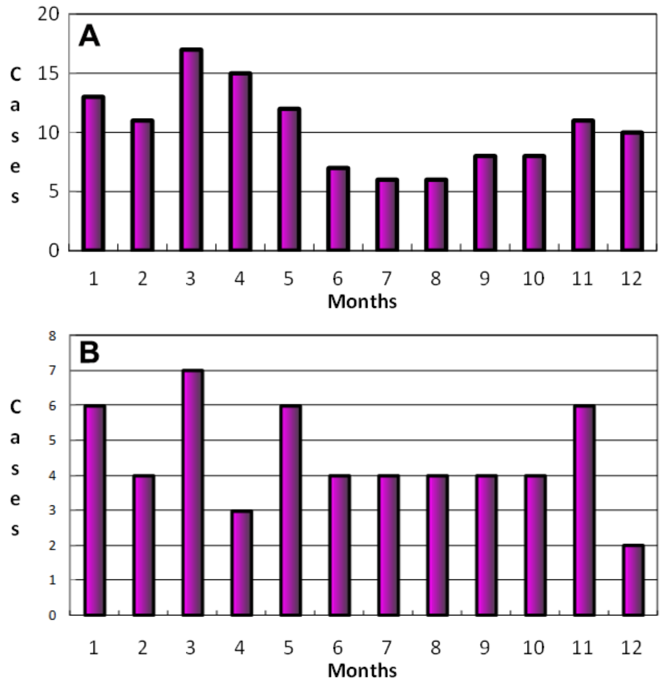
Wind, river flow and water/sea levels

The number of events exceeding 200, 250, 280, and 300 cm at Montevideo from 1983 – 2012 were 356 (11,4/year), 52 (1,7/year), 17 (0,56/year), and 6 (0,19/year), respectively (Table 1).

The monthly distribution of events from 1983-2012 is unequal (Figure 2 and Table 2). The months with greater occurrence of extreme events were January, February, March, April, May, June, August (the highest ones) and November, whereas the ones with lower occurrence were July (austral winter), October and December. Extremes up to 260-280 cm occurred all over the year, whereas those greater than 300 cm occurred only in 5 months (January, February, April, June and August).

Figure 2 - Monthly distribution of storm surges from 1983-2012. A) storm surges ≥200 cm and B) storm surges above 250 cm.

Figura 2 –Distribuição mensal das marés meteorológicas entre 1983 e 2012. A) marés meteorológicas ≥200 cm; B) marés meteorológicas superiors a 250 cm



A slight increase of extreme events was observed over the last decade 2003-2012. The maximum level achieved was 320 cm, which is well below the three historical maxima of 430 cm in 1923 (July), 400 cm in 1914 (April), and 350 cm in 1935 (November). According to ECLAC (2011) and based on larger spatial scales than the ones used here, coastal inundations in the RdlP show no marked seasonality.

Table 2 shows the percentage (%) of occurrence of storm surges (i.e. > 200 or 280 cm) for each month.

Table 1 - Decadal frequency of storm surges higher than 200 cm, 250 cm and 280 cm at Montevideo, from 1983 to 2012.

Tabela 1 - Frequência decadal de marés meteorológicas maiores do que 200 cm,250 cm e 280 cm, em Montevidéu, entre 1983 e 2012.

Decade	N° of events (≥200cm)	N° of events (≥250cm)	N° of events (≥280cm)
1983 – 1992	115	13	1
1993 – 2002	104	19	6
2003 – 2012	137	20	10

Table 2 - Percentage (%) of occurrence of storm surges greater than a given freshwater/sea level (i.e. > 200 or 280 cm) for each month (January= 1; December= 12) from 1983-2012. The highest monthly occurrences are highlighted as follows: Higher monthly occurrence (dark grey), second higher occurrence (grey), and third higher monthly occurrence (light gray).

Tabela 2 - Percentual (%) de ocorrência de marés meteorológicas maiores do que um dado nível de água doce / mar (ou seja, > 200 ou 280 cm) para cada mês (janeiro = 1; dezembro = 12) entre 1983 e 2012. As maiores ocorrências mensais estão realçadas da forma seguinte: maior ocorrência mensal (cinza escuro), segunda maior ocorrência (cinza), e terceira ocorrência mensal mais elevada (cinza claro).

Months	Level 200	Level 220	Level 240	Level 260	Level 280	Level 300
1	8,3	9,6	11,9	16,7	17,7	14,3
2	10,8	10,1	8,3	5,6	11,7	28,6
3	9,1	10,1	8,3	5,6	5,9	0,0
4	10,2	10,1	9,5	8,3	11,7	14,3
5	9,4	6,9	9,5	11,1	17,7	0,0
6	6,6	8,5	9,5	11,1	5,9	14,3
7	7,2	6,9	3,6	2,8	0,0	0,0
8	7,5	6,9	8,3	11,1	11,7	28,6
9	9,1	9,0	6,0	8,3	11,7	0,0
10	5,5	5,3	7,1	2,8	0,0	0,0
11	7,7	8,5	10,7	11,1	5,9	0,0
12	8,6	8,0	7,1	5,6	0,0	0,0

All the correlations (r Pearson) between river flow (River Uruguay-Q_U or the accumulated of Rivers Uruguay and Paraná-Q_{RP}) against sea level at Montevideo were significant (r= p<0.05). The highest correlations were found for both Qu and Q_{RP} at yearly time-scale. The distribution of data is concentrated around the mean water level for Colonia (73 cm.) and Q_{RP} (22,500 m^3/s). The lowest values at Colonia, < 60 cm were never observed for high Q_{RP} > 40,000 m^3/s. A positive relationship between river inflow and water level was observed at Colonia (Table 3) and Montevideo respectively (Figure 3), showing that river flow is a climatic forcing of water/sea level.

The unequal monthly distribution of sea-level at Montevideo is related to prevailing winds (Nagy *et al.*, 1997) and river inflow, especially the Paraná River (Q_P), the main input of freshwater (75% on average to the RdlP). The latter is shown in Figure 4, where a good agreement is found with this river. When the agreement is lower, this is due to low Q_P and wind effect, i.e. during December-January, or the periodic Uruguay River floods, during May-June and September-November.

The relationship between winds and sea level at Montevideo shows that southern and southeastern winds have a positive and significant correlation when a strong positive level anomaly occurs (Figure 5).

Table 4 summarizes the causes and the magnitude of water/sea level fluctuations at Montevideo around the current mean sea level (MSL) of ≥102 cm. The permanency of water levels higher than MSL is approximately 50%, whereas it is less than 3, 1 and 0,5% for water levels higher than 200, 260 and 280 cm respectively. Most positive deviations are attributable to non-tidal or residual oscillations due to southern winds, low sea-level pressure (SLP), and high river flow.

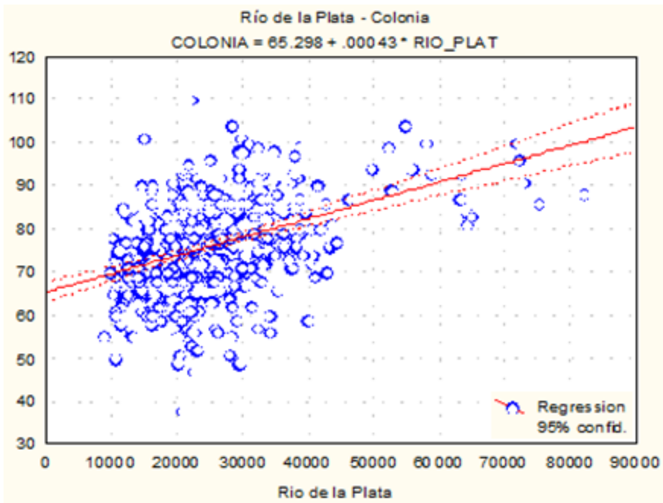


Figure 3 - Observed monthly Rio de la Plata inflow (m^3/s) and water level at Colonia. Dispersion and linear regression, with 95% confidence level limits of data adjusted for the correlation (lag 0) are shown.

Figura 3 - Fluxos mensais observados em Rio de la Plata (m^3/s) e níveis da água em Colonia. Representou-se a dispersão e regressão lineares com 95% de intervalo de confiança dos dados ajustados à correlação (lag 0).

Table 3 - Cross correlations between monthly and yearly river discharges (Uruguay River and RdlP) and freshwater level at Colonia and sea-level at Montevideo for lags 0 and -1 (month/year). All correlations are significant ($p<0.05$).

Tabela 3 - Correlações cruzadas entre as descargas fluviais mensais e anuais (Rio Uruguai e RdlP), níveis de água doce em Colonia e do nível do mar em Montevidéu para defasagens 0 e -1 (mês / ano). Todas as correlações são significativas (p <0,05).

	Montevideo (0)	Montevideo (-1)	Colonia (0)	Colonia (-1)
Monthly River Uruguay	0.09	0.10	0.24	0.15
Monthly RdlP	0.22	0.23	0.34	0.25
Yearly river Uruguay	0.39	0.05	0.48	0.07
Yearly RdlP	0.42	0.20	0.47	0.16

Table 4 - Causes and magnitude of sea level fluctuations at Montevideo.

Tabela 4 - Causas e magnitude das flutuações do nível do mar em Montevidéu.

Cause	Level and approximate fluctuation (cm)
Current MSL	≥102
Typical yearly fluctuations	40 to 200
Tidal oscillation	+/- 30 to 40
Residual oscillations	Typically from 100 to 200 cm and up to 350 cm
River inflow	+/- 0 to 25
Barometric setup	+/- 0-30
Wind setup	+/- 0-300

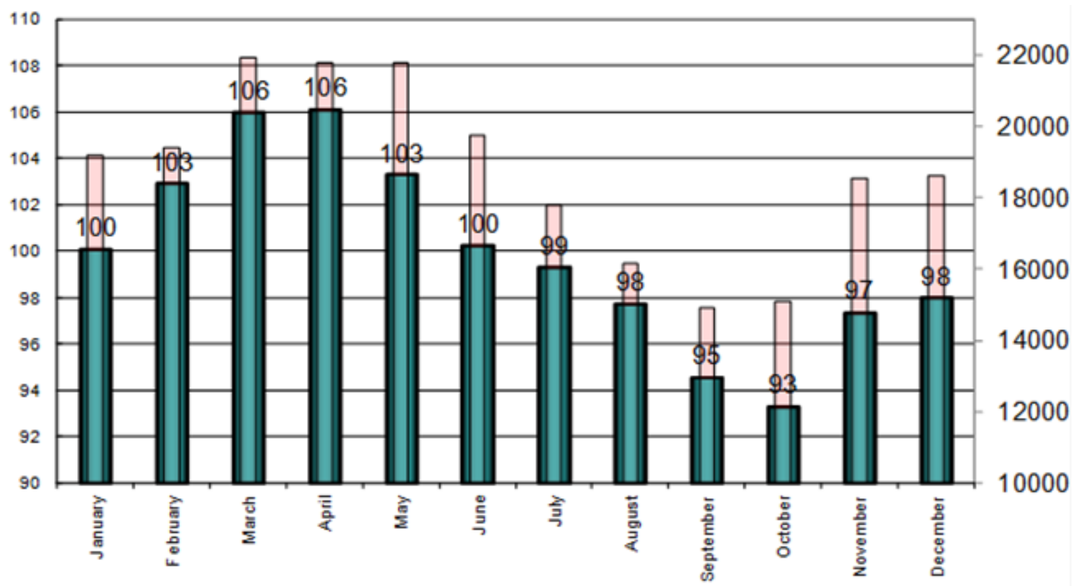


Figure 4 - Monthly Paraná River flow (light bar, right axis, m^3/s) and sea level at Montevideo (green bar, left axis, cm) since 1961.

Figura 4 - Fluxos mensais do Rio Paraná (barras mais claras, eixo da direita, m^3/s) e níveis do mar em Montevideo (barra verde, eixo esquerdo, cm) desde 1961.

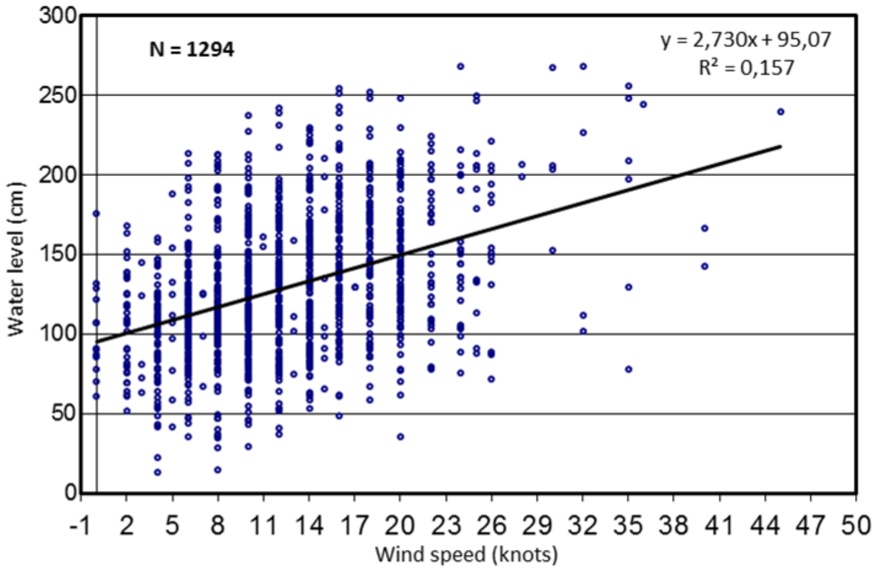


Figure 5 - Relationship between southeastern (SE) winds and sea-level at Montevideo. Dispersion and linear regression of 1294 couples of wind-water level data are shown. Water level for zero SE wind is very close to current mean sea-level (≥ 102 cm) and the interception wind speed 200 cm occurs around 38 knots (19 m/s).

Figura 5 - Relação entre ventos do sudeste (SE) e do nível do mar em Montevidéu, com base na dispersão e regressão linear de 1.294 pares de dados de nível de vento-água. O nível de água para vento zero de SE está muito perto do nível médio do mar atual (≥ 102 cm) e a intercepção do vento com 200 cm ocorre a cerca de 38 nós (19 m/s).

Case Studies

Herein the analysis is focused on the synoptic timescale of two extreme storm surges which serve as analogues useful for developing scenarios of extreme events under a changing climate. These events are March 24-26, 1998 and August 23-24, 2005.

Case 1: March 24-26, 1998

From March 24-26, 1998 water-level exceeded 300 cm during several hours (Figure 6) because of strong Southwestern and Southern southwestern winds reaching gusts > 40 knots (> 20 m/s) by March 24 which affected the Uruguayan coast from Montevideo to Punta del Este. Freshwater inputs (Q_{RP}) before this event were well above (52,000 m^3/s) than usual for March, the 1998 average (47,341 m^3/s) and the long-term (1961-2008) average (24,608 m^3/s) which was associated with the strong El Niño 1997-98 event (Figure 7). Yearly 1998 sea-level average was around 10 cm above the 1971-2003 trend-line (Bidegain *et al*., 2005; Nagy *et al*., 2005).

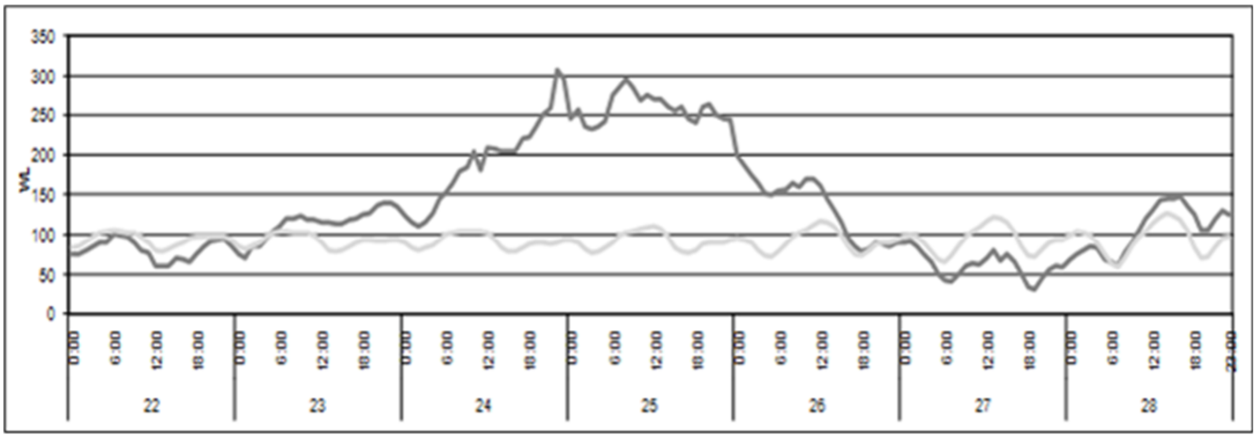


Figure 6 - Water level (WL) at Montevideo: forecasted (clear grey) and observed (dark grey) for the period March 22-28, 1998. The storm surge (residue > 200 cm) develops by the end of March 24 and astronomical spring-tides are observed from March 25.

Figura 6 - Nível de água (WL) em Montevideo: previsão (cinza claro) e observado (cinza escuro) para o período de 22-28 março de 1998. A sobreelevação (resíduo > 200 cm) desenvolve-se até ao final de 24 de Março e as maré vivas astronómicas são observadas a partir de 25 de março.

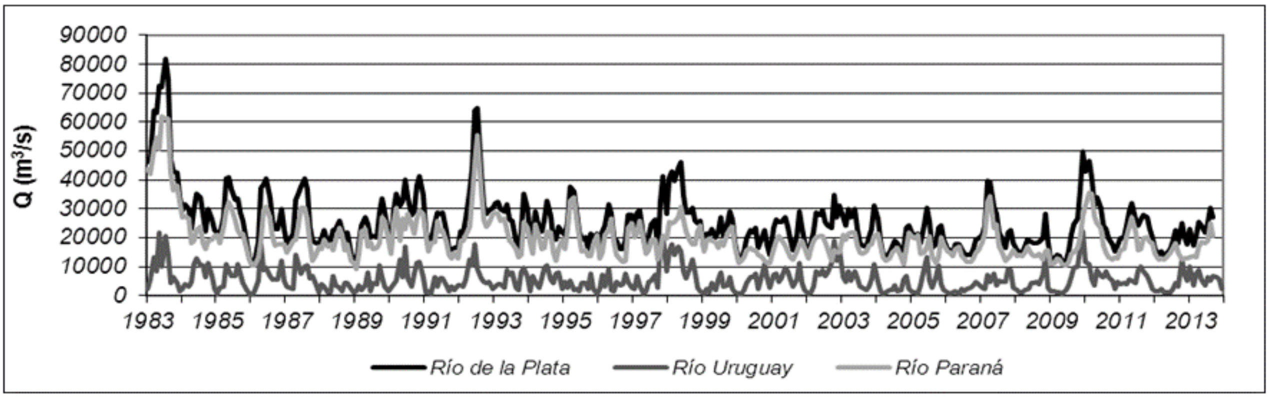


Figure 7 - Monthly River flows of the Paraná and Uruguay Rivers, and their combined inflow to the Rio de la Plata from 1983-2013. Part of the observed variability is ENSO-related, especially the extremes: La Niña low discharge and El Niño high discharge (i.e. 1997-98). Source: Instituto Nacional del Agua y el Ambiente, INAA, Argentina.

Figura 7 - Caudais fluviais mensais dos rios Paraná e Uruguai, e fluxos combinados debitados para o Rio de la Plata no período 1983-2013. Parte da variabilidade observada está relacionada com a ENSO, especialmente os extremos: La Niña - baixa descarga; El Niño - alta descarga (ou seja, 1997-1998). Fonte: Instituto Nacional del Agua y el Ambiente, INAA, Argentina

The forecasted astronomical high tides were greater than 100 cm over the zero reference at Montevideo (about 30 cm above MSL), which accounted for at least + 20 cm. The wind-induced sea-level increase happened to coincide with high astronomical tides and very high El Niño-related River flows. This case is an excellent analogy for likely near future threats due to the combination of natural variability and increased climatic pressures.

At Colonia, freshwater level reached a maximum of 225 cm on March 25, and the predicted astronomical high-tide was near 100 cm, thus a storm surge ≥ 125 cm. At Punta del Este sea-level showed two peaks ≥ 200 cm recorded on March 25 (separated by the astronomical low tide). When comparing the three sites, the storm surges, that is to say the observed minus forecasted water/sea level, was greater at Montevideo and lower at Colonia.

An estimate of the impacts is not available, but at Montevideo, the addition of strong winds, storm surge, and heavy rains impacted the coastal infrastructure and maintenance works of the seawall (BPL, 2009).

Case 2: August 23-24, 2005

From August 23-24, 2005 the passage of a low pressure system or extra tropical cyclone with winds exceeding 170 km/h (up to 190-200 km/h) impacted the RP (Figure 8), particularly the Uruguayan riverside (Magrin *et al*., 2007; Possia *et al*., 2011). Freshwater inputs (Q_{RP}) before this event were below average.

The death toll was 10 and the physical losses were the highest ever recorded in Uruguay. For instance, at Montevideo 30% of homes suffered electrical shutdowns for 2 days at least and the supply of drinking water was affected at several locations. All the harbors,

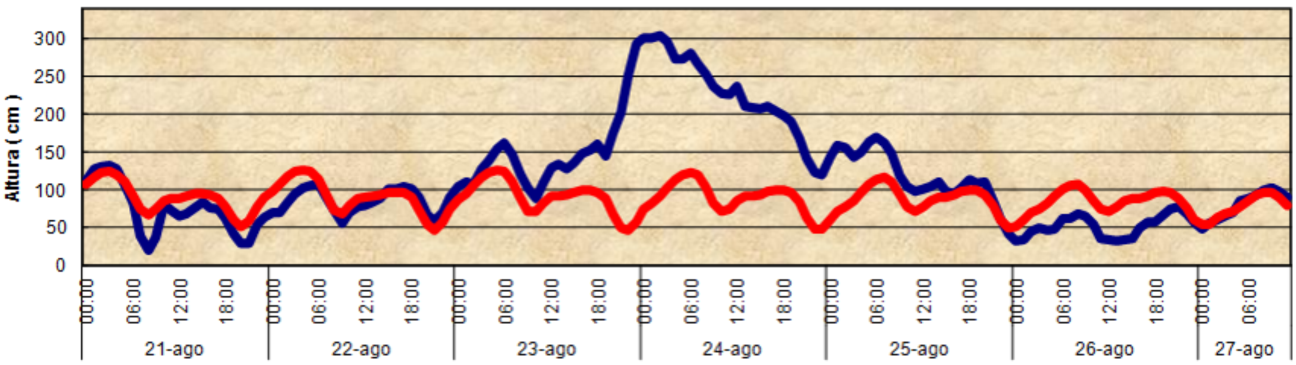


Figure 8 - Storm surge of August 23, 2005. Predicted heights (red line) and observed heights (blue line). The difference between the both is due to the barometric and wind set-up.

Figura 8 – Sobreelevação de 23 de agosto de 2005. Linha vermelha: alturas previstas; Linha azul: alturas observadas. A diferença entre os dois é devida ao vento barométrico e à distância de atuação.

especially Montevideo, suffered physical losses, including damaged and sunk ships, and the services were affected for several days. The eastern coast of the RdlP, close to Punta del Este, suffered the loss of at least 160,000 tons of sand and the dunes retreated 3-5 meters. The quantified losses exceeded U$S 37 million (BPL, 2009), which seems to be highly underestimated.

Synoptic situation: August 23, 2005.

The evolution of horizontal pressure fields gradients at sea level is a good estimate of the hourly mean surface wind velocities. A strong low atmospheric pressure or extra tropical cyclone developed on August 22 over Argentina, which is usual in the region, especially during austral autumn and spring time. However, the atmospheric perturbation developed in August 2005 was rare due to its intensity. A cold atmospheric frontal system displaced over southern Uruguay on August 23, whereas another warm front evolved over the Atlantic Ocean at 39° south. After the passage of the cold one, a high pressure system entered the RdlP from the southwest. The surface pressure field (0600 Z) on August 23 showed the entrance of a low pressure ≤ 1002 hPa (Figure 9).

Thus, a strong pressure gradient was observed to the southwest of the low pressure center, eastern and southeastern winds blown over the Argentinean Riverside, and eastern winds blown over the RdlP increasing water level at the Argentinean coast, together with strong precipitations (138 mm on August 23, for a monthly climatic normal 1961-90 = 70 mm). This precipitation was a daily record for August and the fourth daily maximum since 1882 (Bidegain *et al*. 2006). The atmospheric pressure decreased to < 993 hPa over the RdlP (1800 Z) whereas an anticyclone (1018 hPa) developed to the West over Argentina and southeastern winds blown over the RdlP.

Finally, the atmospheric field pressure over the Atlantic ocean was < 992 (0000 Z, August 24), high pressure achieved 1018 hPa over Argentina, southwestern winds blown over the RdlP, the gradient pressure increased from the Atlantic, and very strong winds blown over the Uruguayan coast near Montevideo (gusts over 170 km/h reaching 190-200 km/h). Water level reached 316 cm.

The lag between the observed storm surge at La Paloma (200 km to the East of Montevideo) and Montevideo from 1988-2008 showed the best cross correlation is 4,30-5,00 hours. Thus, when storm surges associated with eastern and southeastern winds develop, the in-

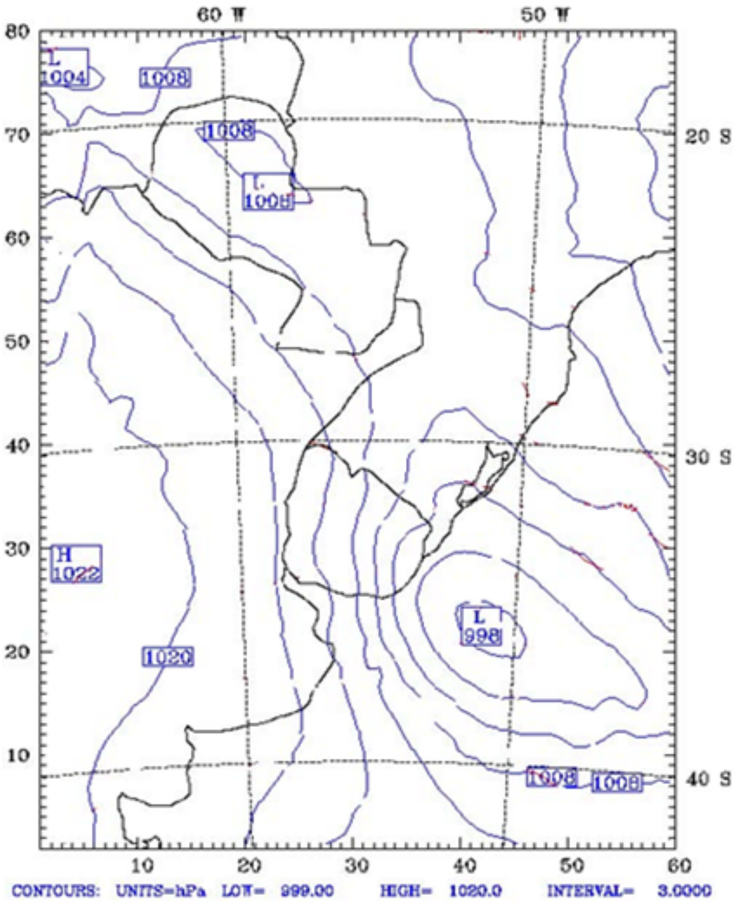


Figure 9 - Sea Level Pressure forecast for 00 Z August 24, 2005.

Figura 9 - Previsão de pressão atmosférica ao nível do mar para 00 Z 24 de agosto de 2005.

crease in sea level is first observed at La Paloma (LP), then at Punta del Este (2 hours after LP), Montevideo (4-5 hours after LP) and Colonia (6-9 hours after LP).

6. Discussion

The analysis and monitoring of wave climate, wind and tides system, and the sedimentary transfer process over time are essential for the implementation of coastal climate change adaptation measures (EcoPlata, 2000; Gómez-Erache, 2012, 2013). Unfortunately, the public institutions and local governments in charge of monitoring, forecasting, early warning system, emergency management, and/or climate adaptation lack an effective coordination of actions to reduce vulnerability, risks, and damages. In this regard, the occurrence of 356, 52 and 17 events exceeding 200, 250 and 280 cm (11,4, 1,7 and 0,56 /year) respectively at Montevideo, that is to say 109, 159 and 189 cm above the historical reference (91 cm) and 97, 147, and 177 cm above the current MSL (≥102 cm) respectively, are useful indicators of risk and are relevant to understand the coast line evolution.

Due to the small tidal amplitude (< 0.5 m), the coast line should not be highly resilient to extremes within the range 200-250 cm. The distribution of the events exceeding 200, 250 and 280 cm was not uniform over the last three decades, reaching 13,7, 2 and < 1 events/year respectively over 2003-2012. This slight increase could be attributed to both the increase in southern winds and/or river inflow. Even if precipitations over the RdlP basin and river discharges have increased since early 1970s (García & Vargas, 1998; Barros *et al*., 2005), showing strong interannual fluctuations partly associated with ENSO variability (Barros *et al*., 2005; Nagy *et al*., 2002; 2008a), the yearly river inflow average stabilized over the last decade - not the variability -, whereas the frequency of southeastern winds increased (Bidegain *et al*., 2011; Nagy *et al*., 2013; Gutierrez *et al*., 2013; Ortega *et al*., 2013). Furthermore, the acceleration of SLR from 1971-2002 (Nagy *et al*., 2005; Magrin *et al*., 2007) almost stopped since 2004 which was attributed to less river inflow (Nagy *et al*., 2013, 2014a, b). The influence of river flow and ENSO-related variability on SLR in the Uruguayan coast is explained by the local effect of a great river (Nicholls *et al*., 2011) such as the RdlP tributaries (Nagy *et al*., 2014a). Thus, it is plausible that during El Niño years, the positive anomalies of both freshwater inflow and southeastern winds lead to water/sea-level increases.

Also, the higher frequency of extreme water levels from February-April can be partly associated with high Q_{RP} during March and April, which are the third and first higher recorded monthly Q_{RP} over the last 52 years (26,798 and 27,846 m^3/s respectively). Southern and southeastern winds exert a strong effect raising water level because they drag water, block or decrease river discharge, generate extraordinary high-tides, waves, and residual currents stronger than normal.

If the events are grouped by season, 29,5% and 20,9% occurred during Summer and Winter respectively (see Figure 2). However, Q_{RP} is above the average in July, below the average in August, and well below in September. Thus, river flow is not a driver in July but it may be in September.

Monthly occurrence of severe extremes > 280 cm from 1983-2012 (< 0,5% of permanency) suggests risks are concentrated in February and August and in a less degree in January and April. This occurrence has increased over the last three decades from only 1 to 6 and 10. Extremes ≥ 300 cm have been only 6 and those events >320 cm have not occurred from 1983-2012. Notwithstanding, they were relatively frequent before 1935 (i.e., July 1923, April 1914 and November 1935). Two of these maxima occurred in July and November, which would not be expected from the current climatology. This observed seasonal pattern of storm surges is in disagreement with the lack of seasonality of coastal inundations reported by ECLAC (2011) which may be attributed to the large scale of their study.

From the two case studies (March 1998 and August 2005), the former occurred during the peak of local impacts of the ENSO warm phase 1997-98, a strong El Niño event which caused strong positive anomalies in river discharges and wind regime changes. Thus, the water/sea level was increased depending on the site, more at the tidal river region (Colonia) and less at the marine one (Punta del Este).

Previous works (Bidegain *et al*., 2005; Nagy *et al*., 2005, 2013) have stated that during extreme anomalies associated with strong El Niño events, sea level at Montevideo fluctuates around 110 cm and plus. During the event of August 2005 (almost neutral ENSO) river flows below the average did not account for an increase in water level. Nevertheless, the 300 cm level was reached at both case studies.

During the event of August 2005 sea-level rose 171 cm sharply in 10 hours (see Figure 8) and lasted 23 hours to back to the initial level. Wind velocities were stronger on the previous day, August 23. Southern winds gusts exceeded 170 Km/h, with a maximum in the range 190-200 km (Possia *et al*. 2011). A one day lag between southern wind velocities and water level increase has been frequently observed, but it is not discussed here.

This event was a clear evidence of the lack of preparedness of Uruguay against extreme events. The death toll was 10, which is considered a hydro meteorological disaster according to the United Nations International Strategy for Disaster Reduction (UNISDR) criteria.

Despite the availability of abundant physical information and the improvement over the last few years (since 2009-11), there is no proper coordination between public institutions in charge of the survey, prognosis and early warning of extreme events in coastal areas. The expected impacts of storm surges were classified and an associated risk was assigned according to their probability of occurrence and to the consequent sea level at Montevideo (Table 5).

Three questions emerge in regards to these coastal extreme events:

i) What would have happened on August 2005 if river flows had been twice or three times greater?

ii) Was the event of 1998 so strong mainly because the coincidence of very high river inflow and maximum spring-tide?

iii) What would be the impact if events in the range 350-430 cm occur again?

When storm surges occur at Montevideo, even the more frequent ones, in the range 200-250 cm, sewage outfalls are assisted by hydraulic pumps to redirect surplus water to overflow channels, and when water level exceeds 250 cm, they become useless and sewage is dispersed in the coastal waters and beaches, contaminating them with fecal coliforms. Since these events are more frequent during the austral summer (see Figure 2 and Table 2), beach quality and tourism are impacted during 24-48 hours because the beaches are closed to bath (Nagy *et al*., 2014b).

Existing coastal gravity drainage, storm water infrastructure and sewerage systems may become gradually affected over time as the mean sea level and/or storm surges increase. Some of the common impacts are as follows:

- The maritime channel signalization buoys can be released from its anchorage, displaced, or may suffer light disconnection, becoming useless and even a threat for navigation instead of an aid.
- The artisanal fisheries located at Pajas Blancas to the west of Montevideo, which exploit the croaker *Micropogonias furnieri* during the spawning period from October to March, are affected by southern winds (Norbis, 1995; Nagy *et al.,* 2008b, 2014b), and during an extreme event, the currents and waves drag their fishing nets. Thus, besides the economic and environmental impacts, fishermen's lives are at risk because they try to recover their nets before the storm becomes very strong.
- The sandy beaches, dunes and bars are highly vulnerable and threaten by both storm surges and SLR (Panario & Gutiérrez, 2006; Gutierrez *et al*., 2013, 2015; Ortega *et al*., 2013; Nagy *et al*., 2014a). Storm surges ≥ 260-280 cm at Montevideo are able to flood most sandy beaches and bars.

Table 5 - Water/Sea Level (cm), consequences, and probability of occurrence of storm surges (> 200 cm). The extreme coastal events painted in light gray were observed in this study (modified from Verocai *et al*., 2014).

Tabela 5 - Nível da água / do mar (cm), consequências e probabilidade de ocorrência de sobreelevações (> 200 cm). Os eventos extremos costeiros destacados em cinza claro foram observados neste estudo (modificado de Verocai et al., 2014).

	Sea Level (cm)	**IMPACTS**			
		Slightly harmful (>200)	**Moderately harmful (>250)**	**Highly Harmful (>300)**	**Extremely Harmful (>350)**
PROBABILITY	High: 1 each 1 month	Moderate Risk	High Risk	Very high Risk	Intolerable Risk
	Medium: 1 each 6 months	Tolerable Risk	Moderate Risk	High Risk	Very high Risk
	Low: 1 each 5 years	Trivial Risk	Tolerable Risk	Moderate Risk	High Risk
	Very Low: 1 each > 30 years	Negligible Risk	Trivial Risk	Tolerable Risk	Moderate Risk

7. Conclusions

Main findings

Sea level rise (SLR) and storm surges are not strongly present in Uruguay's public agenda. The main reasons for this are that

i) SLR does not represent a serious risk for human settlement and infrastructure (yet);

ii) the occurrence of storm surges which cause moderate to high impacts, i.e., > 250 and > 280 cm, and particularly > 300 cm are not very frequent; and

iii) those events able to harm many coastal services and built environment, i.e., > 350 cm, have not occurred over the last eight decades.

Notwithstanding, the high number of events > 200 cm and mainly those reaching > 250 and > 280 cm observed during the studied period (1983-2012) impact the coastal services, morphology, ecosystem resources, and even the infrastructure and housing. Thus, there is a need to include storm surges in coastal management, climate adaptation and risk-management initiatives, plans and programs.

Case studies

Two case studies of storm surges which serve as analogues useful for developing scenarios of extreme events under a changing climate were presented. These examples show evidence supporting a plausible alternative scenario of extreme wind storm, very high river discharge, spring high tide, and increasing SLR which could favour the occurrence of water levels ≥ 300 cm reaching ≥ 350 cm. The latter could be accepted as a rough estimation impact threshold based on observed impacts (i.e., > 400 cm in July 1923), and the recent ones (i.e., 300-320 cm). A scenario including SLR and/or − SLP + wind + river induced flooding - 20-30 cm and plus could reach this threshold at any time over the next few decades.

Application of the knowledge on extreme events on ICZM and Early Warning Systems

The coastal threats described in this paper call for coastal management and planning which take into account the vulnerability of major systems and sectors in the face of climate change, SLR and wind-induced flooding. Emphasis is put on the plausible occurrence of extreme events greater (i.e., > 320-350 cm) than those usual over the last 30 years (i.e., 280-320 cm), under slow and gradual SLR, and especially strong El Niño years, when increased river flows and southeastern winds increase the magnitude and impact of flooding.

One of the obstacles to achieving a comprehensive integrated coastal management in Uruguay and particularly in regards to climatic and meteorological threats is the deficit of an effective and integrated hydrological, meteorological and oceanographic, monitoring network. The three of them exist, are not coordinated yet, resulting ineffective to prevent an eventual long (i.e., > 12 hours) > 320-350 cm event.

The occurrence of extremes greater than 280 and 300 cm from 1983-2012 shows that risks are concentrated in February, August, and less in January and April. Nevertheless, the historical maximum occurred in July 1923, which would not to be expected under current climate patterns.

The public institutions and local governments in charge of monitoring, forecasting, modelling, early warning system (EWS), and emergency management lack an effective coordination of actions to reduce vulnerability, risks, and damages. Despite a significant progress over the last few years (since 2009-11), there is a less than ideal coordination between monitoring, preparedness, alert, and reactive phases in order to face extremes greater than those usual.

Recommendations

A few easy, low cost and viable useful improvements are to:

- Enhance coordination of all public institutions in charge of observing and monitoring climatic, hydrological, and oceanographic variables, as well as those in charge of preparedness, disaster management, and EWS, such as the National System of Response to Climate Change and Variability (SNRCC).
- Concentrate monitoring and EWS efforts when the first signals are forecasted and observed, some of which have been identified in this article, including the analysis of past extreme weather causality, statistical occurrence, climatic forecasts, SST 3.4 evolution, modeling, hydrologic observations, and/or weather forecasts.
- Improve the tactics and procedures to achieving effective preparedness for coastal extreme events based on past experience and failures. In this regard, a more detailed analysis of the causality and impacts of events > 280 cm over the last 30 years should serve to better understanding and simulate the extraordinary extremes > 350 cm which occurred before 1935. The frequency and permanency of events > 280 cm, which have increased over the last three decades should be closely followed as an indicator of change, impact and risk.
- To update the estimation of potential economic, human and environmental impacts associated with a long (> 12 hours) > 350 cm storm surge at Montevideo useful to be incorporated in coastal zone use, infrastructure, regulations and governance.

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