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ORIGINAL ARTICLE

Environmental impacts and simultaneity of positive and negative storm surges on the coast of the Province of Buenos Aires, Argentina

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Abstract The Argentine shore of the Rio de la Plata estuary and its southwards adjacent maritime front are normally affected by extratropical positive and negative storm surges that affect human activities seriously. Positive surges can raise the water level in the estuary by more than 3 m over the predicted tide; thus, flooding the coastal plain where over 13 million people live and causing extensive property damage. Sometimes, there has been loss of life too. Although less populated than the coastal plain, the maritime front has many important tourist resorts and also undergoes severe beach erosion processes and loss of property owing to positive surges. Negative surges are particularly troublesome in the Rio de la Plata because they critically affect navigation safety and drinking water supply by lowering the predicted water level in an amount that sometimes reached more than 4 m. A remarkable point is that the same storm event can simultaneously give rise to a positive surge on the maritime front and a negative one in the Rio de la Plata. The environmental impacts of positive storm surges are strongly aggravated by human intervention. At the same time, sea level rise due to global climatic change has also its influence.

Keywords Positive and negative storm surges · Simultaneity · Impacts · Province of Buenos Aires · Argentina

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Introduction

Positive and negative storm surges involve different types of hazards for human life and activities in coastal zones, and pose a variety of risks for the continuously growing coastal populations (Pugh 1987, 2005; Komar 1998; Gönnert et al. 2001; Wood 2001; Danard et al. 2003; Schnack and Pousa 2004). Positive and negative surges will be more harmful if they coincide with a high water period or a low one, respectively. The magnitude of these impacts differs between regions and also between sites within the same region, and can be aggravated by human intervention. According to Pugh (1987), negative and positive surges may be generated by the same storm at different stages of its progression, as this author illustrates with large positive surges in the North Sea often preceded by negative surges a day or so before. Specifically, Pugh (1987) refers to the well-known storm of 31 January to 1 February in the North Sea. On that occasion, strong winds from the south drove water out of the North Sea, which resulted in a negative surge. The return of this water to the North Sea, together with the surge effects of the winds from the north, reached their peak about a day later. A similar situation is numerically modeled and described by As-Salek (1997) in connection with negative surges in the Meghna estuary (Bangladesh). This author points out that (1) the main negative surge occurs before the strike of the cyclone in the Meghna estuary, (2) in a particular area the negative surges can develop even without the development of a positive surge, (3) in the areas where positive surges develop, the time difference of the peaks of the negative and positive surges are usually about 2–8 h, depending on the cyclone characteristics, and (4) the observed data supports the model outcomes.

However, the same storm event can simultaneously give rise to a positive surge at one site and to a negative surge at another site not far from the first, as will be shown below to have been the case for the coast of the Province of Buenos Aires, Argentina. In this regard, Pugh (1987) gives the example of a numerical modeling of the surge which hit the Orissa coast of India on 3 June 1982. The results of the model showed a positive surge of more than 4.5 m to the right of the track due to onshore winds (South of Chandipur), and a negative surge of less than −4 m to the left of the track, where the winds were offshore (South of Puri).

The aim of this work is to illustrate some of the environmental impacts due to positive and negative storm surges on the littoral zone of the Rio de la Plata estuary and the adjacent sandy coast of the Province of Buenos Aires, Argentina, with special emphasis on their possible simultaneous occurrence, and on how human activities have worsened these impacts.

Regional setting

The Province of Buenos Aires exhibits two well distinct littoral environments: the Rio de la Plata estuary to the north and the Atlantic front to the east and south (Fig. 1). Formed by the confluence of the Parana and Uruguay rivers, the Rio de la Plata extends to an imaginary line joining Punta Rasa (Argentina) and Punta del Este (Uruguay). With respect to the Atlantic front, this work will focus only on the eastern sandy coastline between Punta Rasa and Mar del Plata, the main tourist resort in Argentina (Fig. 1). The Rio de la Plata and the eastern sandy coastline are normally affected by extratropical positive and negative storm surges that originate either in the maritime front of the Province of Buenos Aires or in the southernmost area of the Argentine shelf (Lanfredi et al. 1998; Schnack and Pousa 2004; Pousa et al. 2007; Schnack et al. 2010). A remarkable point is that the same meteorological event can simultaneously give rise to a positive surge on the Atlantic coastline and to a negative surge in the Rio de la Plata.

Fig. 1 Location map

Estuarine setting

With an area of about 35,000 km^2 and a drainage basin of more than 3 million km^2, the Rio de la Plata runs with a general NNW–SSE direction towards the Atlantic Ocean (Fig. 1). It has a length of about 290 km and widens from 40 km at its narrowest part to 220 km at its mouth. The average depth of the estuary ranges from less than 5 m in the upper region to about 20 m at its outlet, where fresh and salt water mix. The Rio de la Plata receives a mean water discharge of 23,000 m^3/s and about 80 million t/year of terrigenous sediments. This large contribution of material forms a delta of 18,000 km^2. The estuarine environment is temperate and humid throughout the year, with little or no water deficiency. Mean annual rainfall and temperature are 1,030 mm/year and 16.5 °C (Kruse et al. 2003).

The coastal plain of the Rio de la Plata extends from water level to an altitude of approximately 5 m, and its width ranges from 6 to 8 km. The landscape is extremely flat, with a slope of 0.06 to 0.1. This badly drained relief, where streams and drainage divides are hardly recognized and groundwater is highly saline, is locally modified by small hills (sand levees and shelly ridges) parallel to the coastline that host fresh water in shallow aquifers. The coastal plain is composed of Holocene beach ridges, marshes and fresh-water wetlands. Landwards, the coastal plain is bounded by a terrace developed on continental sediments, mainly loess-like silts. The water table is either exposed or at a depth of 1 m, with fluctuations due to hydrometeorological causes (Ainchil et al. 2009). Due to the flatness of the terrain, the low permeability of the substrate and a shallow water table, wetlands occupy more than 50 % of the coastal plain. In many areas the old shelly beach ridge systems have been quarried for building purposes, and became water bodies working as artificial wetlands.

Changes in the water level of the estuary are due to the co-oscillating tide forced by the global tide along the shelf break. However, because of the shallowness and increasing width of the estuary, water level variations are strongly influenced by storm surges. Tides in the Rio de la Plata are mixed, predominantly semidiurnal. Average tidal range is 0.60 m at Buenos Aires (the Capital city of Argentina) and 0.79 m at Punta Rasa (SHN 2011).

Maritime setting

The eastern coast of the Province of Buenos Aires extends for about 180 km between Punta Rasa and Mar del Plata, and may be divided into two well-defined sectors: the eastern sandy barrier, extending for about 150 km between Punta Rasa and Mar Chiquita tidal inlet (Fig. 1), and the 30 km coast stretch from Mar Chiquita to Mar del Plata characterized by low cliffs. The southern beaches are typically reflective. To the north, the beaches generally have a dissipative profile with the development of sand bars. The existence of submerged linear sand ridges oriented SSE at 30° to the coastline from Punta Medanos southwards may cause temporary reflective conditions (Parker et al. 1982). The sandy barrier hosts the only natural freshwater sources for supplying the coastal inhabitants. These sources are lens-shaped reservoirs recharged by rainfall and bounded by a freshwater–brackish water interface landwards and a freshwater–salt water interface seawards (Kruse et al. 2005).

Wave energy generally increases along the coast from Punta Rasa to Mar del Plata, but at Punta Medanos larger waves are due to the linear sand ridges that concentrate wave energy (Lanfredi et al. 1992). Tides are mixed, predominantly semidiurnal. The average tidal range is 0.80 m at Mar del Plata (SHN 2011).

Materials and methods

The two longest tidal records available for the estuarine and Atlantic settings, one of them at Buenos Aires (1905–2010) and the other at Mar del Plata (1953–2009) were selected to make a quantitative analysis of the storm surges that affect the whole study area. In both cases, the basic data consisted of hourly water levels with respect to datum. The surge sample was obtained from the difference (residuals) between the observed hourly levels and the corresponding predicted tide. The predicted tide has a fixed mean water level (MWL) of 0.79 m above datum for Buenos Aires and a fixed mean sea level (MSL) of 0.91 m above datum for Mar del Plata (SHN 2011). Therefore, the residuals included a contribution from the MWL and MSL trend in the observed level. The distribution of the residuals was approximately Gaussian for both sites.

However, not every meteorological event was considered a surge. For Buenos Aires, the positive surges were obtained from the residuals considering the events that satisfied the following two criteria: (1) residual levels that never fell below 0.30 m, and (2) a highest residual value equal to or greater than 1.60 m. The last value was adopted because, when combined with a height close to the MWL during a rising semidiurnal tide, it leads to warning levels in Buenos Aires and its surroundings. Similarly, for the negative surges, the following two criteria were used: (1) residual levels that were always lower than −0.30 m, and (2) a lowest residual value equal to or less than −1.20 m. The value of −1.20 m was adopted because a height close to the MWL during a falling semidiurnal tide produces heights lower than −0.40 m during at least 6 h. The value of ±0.30 m as a threshold value for positive and negative storm surges was adopted because when the meteorological surge is negligible, the difference between the observed and the predicted tide has always been within ±10 cm. Hence, to ensure that the chosen residuals corresponded to positive or negative surges, the threshold value adopted was three times the above difference (D'Onofrio et al. 2008).

For Mar del Plata, the positive surges were defined by a period of time in which the following two criteria were simultaneously met: (1) residual levels never <0.30 m, and (2) a highest residual value equal to or >0.60 m. The threshold of 0.30 m is three times the root mean square (rms) of the differences between the observed and the predicted tide (rms = ±10 cm). This rms value is due to the presence of seiches in the tidal records. Since the distribution of the residual levels is approximately Gaussian, the criterion for a residual to be equal to or greater than two standard deviations (0.60 m) was chosen to identify the threshold for the highest residual value of each event (Zhang et al. 2001; Fiore et al. 2009).

These criteria used to deem a meteorological episode as a storm surge were also required to be met by those events that gave origin to simultaneous positive and negative surges, of which two examples are given below (May 1984 and July 2009).

Critical cases of storm episodes and their environmental impacts

General aspects

Resio and Westerink (2008) have stated that “eight of the ten largest cities in the world are located on the coast and 44 % of the world’s population lives within 150 km of the ocean. Unfortunately, coastal regions are often low lying and thus susceptible to an increase in sea-surface elevation”. As regards the regional setting, this warning is particularly true for Buenos Aires, which is one of the 20 largest cities in the world and has now a population about 3 million. If the outer suburbs are considered (the Greater Buenos Aires) the population increases to about 13 million. The Rio de la Plata shore is low lying and thus vulnerable to water surface elevations due to positive storm surges, but negative surges can also affect human activities very seriously in the estuary.

Although Mar del Plata and its surroundings have a cliffy coastal environment, a similar picture can be described for this summer resort. Southeasters raise the water level producing significant differences between the observed levels and the predicted tide. Owing to the bathymetry, concentration of wave energy normally occurs at Mar del Plata. Consequently, sea-level elevation near the coast due to southeasters allows the highest generated waves to attack the upper beach and cause severe erosion. Negative surges are much less problematic in this environment.

Simultaneity of positive and negative storm surges

Despite the general coincidence between the Mar del Plata and Buenos Aires recorded levels with respect to surge events, there can also occur marked differences between both cities. The two storm episodes of 21–23 July 2009 and 29–30 May 1984 are an example that the same storm surge can simultaneously affect both the maritime front and the estuarine zone quite differently.

The 21–23 July 2009 storm surge

On 21–23 July 2009, a severe positive storm surge and the resulting large waves affected almost the entire 5,000 km coast of Argentina. Winds reaching speeds of about 50 km/h, with gusts up to 80 km/h, piled up water along the Argentine coastline. The synoptic weather chart for the Argentine coast obtained from the reanalysis of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996) shows shore-parallel isobars extending northwards from the southern tip of Argentina and striking most of the coastline of the Province of Buenos Aires (Fig. 2). Mar del Plata was one of the most severely damaged resort cities along the coast. The maximum surge at Mar del Plata was 1.45 m at 16:45 (UTC-3) on 22 July, whereas the highest observed level was 3.07 m above datum 2 h later (Fig. 3a).

This storm event produced a very different situation at Buenos Aires and other nearby coastal sites along the west margin of the Rio de la Plata. Blowing this time from the southwest (clockwise circulation around a low in the southern hemisphere), the winds swept the estuary waters away from the coast. Thus, the same positive storm surge that battered the Atlantic coast piling up the waters along it became, at the same time, a negative storm surge in the Rio de la Plata. The residual at Buenos Aires reached −2.29 m at 19:45 (UTC-3) on 22 July, whereas the lowest observed level was −1.54 below datum at 01:45 (UTC-3) on 23 July. Figure 3b shows the observed levels at Buenos Aires from two tide gauges, together with the predicted tide. One of these gauges belongs to the SHN (Naval Hydrographic Service), and is located on the coast at the end of a pier; the other gauge is mounted at a drinking water inlet of the Buenos Aires water company (AySA, http://www.aysa.com.ar), 1,200 m offshore. The curve from the SHN tide gauge displays a constant water level for 12 h. This is because this tide gauge lacked water and remained “dry” from 22 July at 15:45 (UTC-3) to 23 July at 03:45 (UTC-3).

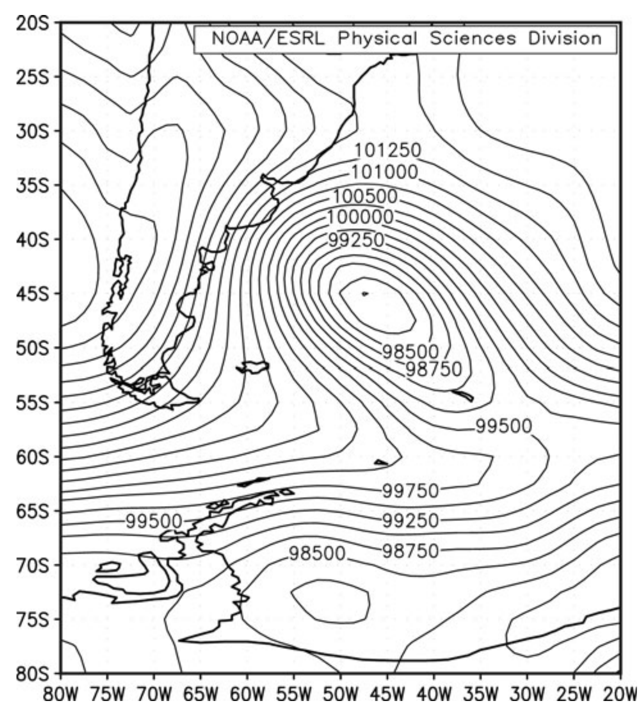

Fig. 2 Synoptic averaged weather chart for the July 2009 storm surge (from NCEP/NCAR Kalnay et al. 1996)

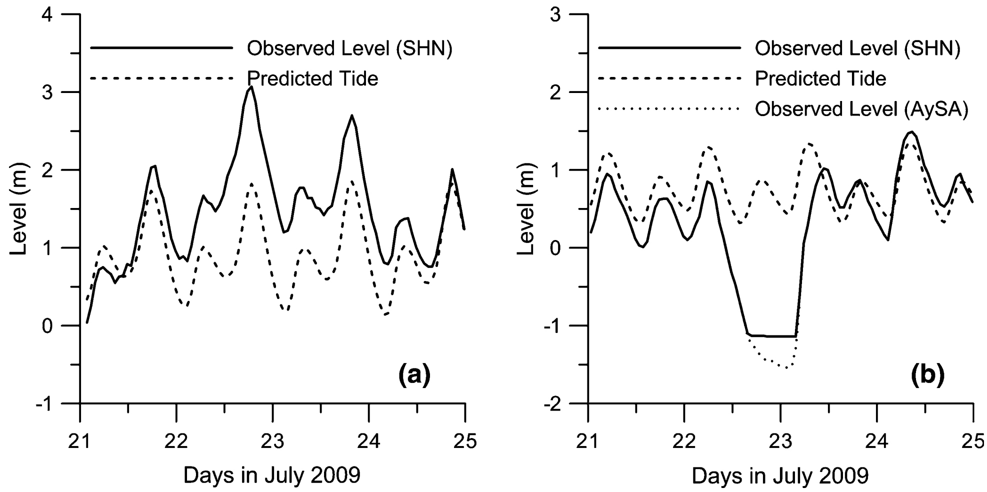

Fig. 3 The 21–25 July 2009 observed level and predicted tide at **a** Mar del Plata (SHN station) and **b** Buenos Aires (SHN and AySA stations)

The 29–30 May 1984 storm surge

On 29–30 May 1984 another severe storm surge affected the coastline of the Province of Buenos Aires, causing floods at Mar del Plata and extreme negative water levels at Buenos Aires (Fig. 4). On that occasion, the tide gauge of the Ministry of Public Works (MOSP) recorded the largest negative surge at Buenos Aires since the beginning of tide measurements in 1905. The residual was −4.61 m on 29 May at 20:00 (UTC-3), whereas the lowest observed level for this storm was −3.66 m below datum 2 h later (Fig. 5a). The SHN tide gauge lacked water and became "dry" for about 20 h. Both tidal measurements (MOSP and SHN) were made with float-operated gauges at stations located within the limits of Buenos Aires and 9 km apart. The coastline between them shows no morphological differences. At the same time, the largest positive residual for the 29 May 1984 storm at Mar del Plata was 0.67 m on 29 May at 21:00 (UTC-3), whereas the highest observed level was 1.93 m above datum on the same day from 19:00 to 20:00 (UTC-3) (Fig. 5b).

Although both storms generated positive (Mar del Plata) and negative (Buenos Aires) surges simultaneously, there is, however, a difference between their respective synoptic weather charts (Figs. 2, 4). In the May 1984 surge the isobars were not shore-parallel, as they were in the July 2009 surge. Since the tidal wave propagates northwards along the Argentine coast as a Kelvin wave, when the isobars are shore-parallel from the southern tip of Argentina northwards, the observed water levels are higher than the predicted tide at every site all along the Argentine coastline. Because of this, the observed water level at Mar del Plata in July 2009 was higher than that of May 1984. On reaching the Rio de la Plata, this over-raised tide made the 2009 low not so marked as that of 1984. For a synoptic situation that simultaneously generates a high water at Mar del Plata and a low water in the Rio de la Plata, the depth of the low water at Buenos Aires will depend on the magnitude of the positive storm surge at Mar del Plata owing to the northwards propagation of the tidal wave.

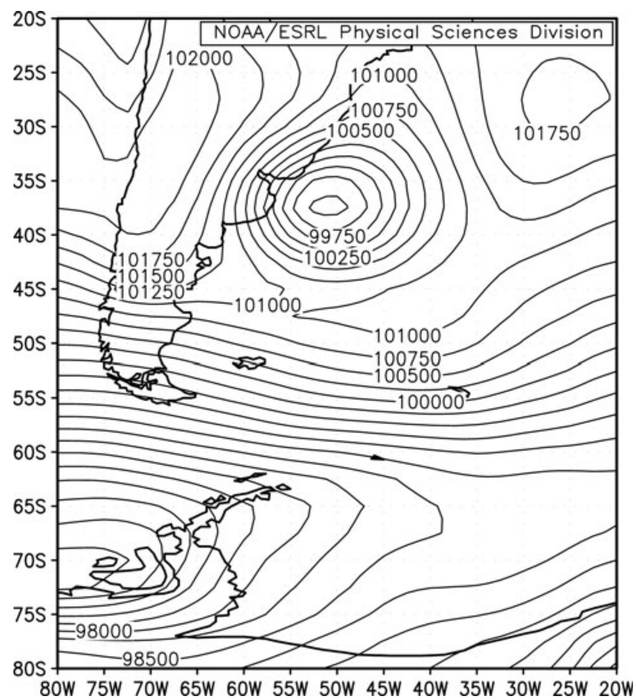

Fig. 4 Synoptic averaged weather chart for the May 1984 storm surge (from NCEP/NCAR Kalnay et al. 1996)

Impacts

Estuarine front

Negative storm surges in the Rio de la Plata occur as a result of bad weather accompanied by strong winds blowing mainly from the NNW and N. As a general rule, the decadal trend for negative surges indicates that they are

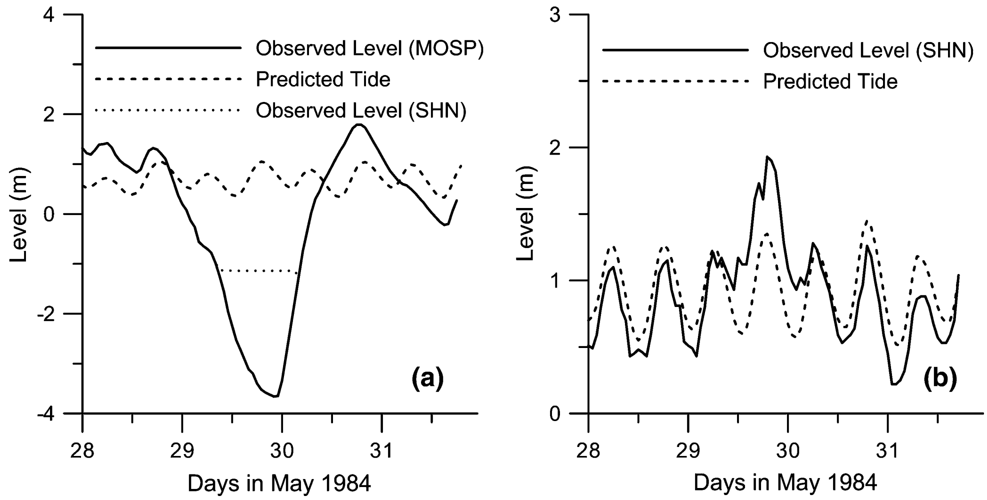

Fig. 5 The 29–30 May 1984 observed level and predicted tide at **a** Buenos Aires SHN and MOSP stations, and **b** Mar del Plata SHN station

increasingly less negative, although observed water levels have become more negative during the last 20 years. With the above criteria for deeming a meteorological event as a negative surge, the mean annual frequency of negative surges at Buenos Aires is about six events (D'Onofrio et al. 2008).

Owing to the shallowness of the estuary, a canal must be permanently dredged along the whole length of the Rio de la Plata to allow larger ships access to the ports of Buenos Aires, La Plata and those on the River Parana. The canal is about 200 km long, 200 m width and 10 m deep. Negative surges, therefore, can pose a significant risk for the navigation safety of large vessels steering with small under keel clearances. Drinking water supply to the Greater Buenos Aires is also seriously affected during negative surges. When the observed water level is −1.20 m the inlet water stations are given a warning, and are partially or totally closed at −1.50 and at −1.80 m, respectively (Campetella et al. 2007). For comparison purposes, the lowest observed level on 29 May 1984 (−3.66 m) was more than twice as negative as the closing level for water inlets. On 23 July 2009, the observed level reached a warning value of −1.54 m, and water inlets were partially closed.

Although negative surges can pose severe risks in the Rio de la Plata, positive surges are, however, more frequent and harmful. Changes in water level from tens of centimeters to more than 3 m caused by meteorological action produce extensive flooding and severe impacts along the estuary shores. Strong SE-SSE winds, which can occasionally reach the force of strong gale (75–88 km/h) at the Rio de la Plata outlet, push the estuary waters upriver thus hindering drainage into the Atlantic. During the development of these episodes, locally known as "sudestadas" (southeasters), water can penetrate several kilometers inland, reaching levels that exceed warning values and forcing coastal inhabitants to be evacuated. As storm surges travel upstream, the Coriolis force piles up the water along the Argentine shore of the estuary. Because the axis of the Rio de la Plata is approximately in the SE–NW direction, southeasters give rise to waves that can be high enough to represent a danger for small vessels steering near to their maximum safe draft. Bad weather conditions can last from several hours to 2 or 3 days. The most dramatic example of a positive surge at Buenos Aires and its surroundings occurred on April 15, 1940 when the combination of the astronomical tide and a storm surge raised the water level to 4.44 m over datum, the maximum level recorded since the beginning of systematic tidal measurements in 1905. On that occasion, the surge was 3.24 m (D'Onofrio et al. 2008). During this episode, a great part of Buenos Aires remained without energy supply, and two of its most crowded neighbor districts were totally covered by the water. The coastal plain was completely flooded and twenty-five people were killed. Using the Joint Probability Method (JPM), D'Onofrio et al. (1999) have calculated a return period of approximately 265 years for a level of 4.44 m above datum. The highest positive surge, however, occurred on November 12, 1989, with 3.48 m. It was produced by the most severe coastal cyclogenesis event in recent decades over eastern South America. Strong southeasterly gales over Buenos Aires raised the water level to 4.06 m above datum, the second maximum level since 1905. In February 1993 occurred the third maximum observed level: 3.93 m above datum. According to the above criteria for deeming a meteorological event as a positive surge, the mean annual frequency of positives surges at Buenos Aires is 7–8 events (D'Onofrio et al. 2008).

Several streams that cross the wetland and flow into the Rio de la Plata drain an extended region of the Province of Buenos Aires plain. The low topographic gradient of the shoreline environment (10^{-4}) delays their natural flow into the Samborombon Bay. Because of this, large floods occur during wet periods and positive storm surge events. To facilitate the drainage of the plain region, a series of canals were constructed at the beginning of the twentieth century. However, the lack of a comprehensive knowledge of the behavior of this wetland environment made the canals far from being effective as regards their primary purposes. Besides, as their construction obeyed engineering criteria that disregarded the natural hydrological cycle, these canals did great damage to the ecosystem and were partially responsible for changes in the shoreline morphology and a decrease in the fresh water reserves throughout the region (Pousa et al. 2011).

Some degree of erosion due to storm surges is also present in low-lying zones along the shore and coastal plain of the Rio de la Plata. Local erosive problems have been detected on the Rio de la Plata shore, but their general trends are not well known. Sea level rise, briefly discussed below, could eventually modify the morphology of the coastal plain and marshes with the subsequent changes in the estuary shores under the form of erosion and redeposition of sediments (Braga et al. 2011).

The coastal waters of the Rio de la Plata receive significant amounts of polluted and toxic materials that are discharged daily to the estuary via small tributaries acting as open sewers [e.g. the Riachuelo (literally, small river)], or directly as untreated effluents. This is particularly evident in urban and industrial zones around Buenos Aires and La Plata. Trace metals were analyzed in suspended particles, sediments and Asiatic clams in the estuary (e.g. Cr and Cu), showing a strong anthropogenic influence near the most developed areas (Bilos et al. 1998; Colombo 2000). The discharges of crude urban and industrial effluents associated to the huge particulate load of the estuary are a major pathway for persistent organic pollutants. The muddy sediments of the Rio de la Plata shallow zone and shore are the ultimate sink of the high load of organic matter and associated organic pollutants.

The role of storm surges in pollutant's accumulation on the shore and coastal plain should be seriously considered. Oil spills, like the big one that occurred on 15 January 1999 about 20 km off the coast of Magdalena (Fig. 1) are additional environmental hazards. On that occasion a container ship and a tanker collided and 5,400 m^3 of oil were spilled on the adjacent shores. Storm surges carried inland massive amounts of hydrocarbons, causing long-term impacts on the local ecosystems that are still evident. It is said that this was the greatest oil spill that has ever occurred in a fresh water environment in the world.

Maritime front

Erosion has dominated the Buenos Aires coastline to the south of Punta Rasa, but the immediate vicinity of Punta Rasa is accretionary. Although the maritime front considered in this work has not any large cities comparable to Buenos Aires, it has many tourist resorts, among which is Mar del Plata, the main one in Argentina. This maritime front is also low-lying and, as such, severely affected by meteorological action. Positive storm surges, and their associated high-energy waves, are the most important agent for coastal erosion. During these episodes, the coastal configuration undergoes severe modifications with a marked beach profile change and a shoreline retreat. However, it must be noted that in areas that are not intervened by man, the dune-beach system tends to reestablish the profile after the storm. It is human intervention that makes the natural erosive action of storm surges irreversible. This is aggravated by the lack of fluvial sediment input. Beach sand mining for building purposes, elimination of extensive sand dunes, and unplanned urban development are responsible for erosion conditions, property loss and damage. At Mar del Plata, groins, jetties and seawalls have been constructed since the beginning of the twentieth century, particularly after the building of the harbor (1914–1919), without the utilization of basic geomorphological information, thereby partially solving local problems but increasing erosion in the downdrift direction—northwards along the whole maritime front—by trapping the transported sediments. This has increased erosion at the neighbor localities. Cliff retreat in this sector has led to the redesign of the coastal route on several occasions. Beach replenishment was tried out at the Mar del Plata central beaches in 1998, but because the sand used had a grain size finer than the original, these beaches lost their dynamical balance with the regional wave climate and have had a natural tendency to return to their original pre-replenishment morphology (Bértola 2006).

The erosion processes on the maritime front began to appear during the eighties as a direct result of increasing human activities. Although the storm episodes of May 1984 and July 2009, particularly this last one, showed clearly the consequences of these erosion processes, the two severe storm surges of February 7 and June 9, 1993 that battered the eastern sandy beach-dune system and the Rio de la Plata estuary were responsible for the drastic beach profile changes that can still be observed.

On 7 February 1993, for example, many coastal buildings that had been recklessly constructed by the sea on the eastern sandy coast collapsed because of the storm. This event destroyed many resorts and caused vertical changes in the beach profile that reached 1.40 m. In these resorts, the dune fringe had been practically destroyed by urbanization, but dune fixation by a permanent plant cover, traditionally considered a helpful practice, has also been claimed to have been responsible for some erosion. Other very strong southeasters occurred in December 2003 and in August 2005. With the above criteria for considering a meteorological event as a positive surge, the mean annual frequency of positives surges at Mar del Plata is about three events. The highest positive residual occurred on December 5, 1999 with 1.92 m (Fiore et al. 2009).

The irreversible erosion pattern established by human action in the sandy coastal environment seriously threatens local inhabitants by putting the lens-shaped coastal aquifers in grave danger of being encroached by saltwater, or polluted by some other agents. Fed by the rapid infiltration of water surplus from rainfall, these aquifers are 5 to 15 m thick, with a permeability of 20 m/day, an effective porosity of 10 % and a very small runoff (Carretero and Kruse 2010). However, because the zones where the summer resorts are located have grown in a rather chaotic way, the areas of the pristine dunes have shrunk, thus reducing the infiltration and recharge of the aquifers and increasing runoff. Carretero and Kruse (2010), for example, have found a marked retreat of the piezometric lines in the area of Punta Rasa. Although there are not yet severe seawater encroachment problems within the area, it has been shown that the quality of the fresh water stored in the lens-shaped aquifers has deteriorated at several sites because of groundwater exploitation. Pumping activities alter the equilibrium between fresh water and salt water, favoring seawater infiltration towards the dune barrier. Sea level uplift due to storm surges has produced a salinization process because of seawater intrusion into those sectors of the original dune barrier that have been either destroyed or seriously damaged by human action (Pousa et al. 2007).

Although much less problematic than in the Rio de la Plata, negative surges in the maritime environment may have an influence on coastal sediment transport (Burlace 1986). The lowest negative residual at Mar del Plata was −1.35 m on 19 August 1959 (Fiore et al. 2009). At times, the sole astronomical tide at Parque Camet (about 5 km northwards downtown Mar del Plata) is responsible for the uncovering of a shallow water area where the outdated sewage outfall of the city discharges wastewater into the sea (Scagliola et al. 2006; Comino et al. 2008; Corral et al. 2008; Elias and Vallarino 2009). Negative surges can only aggravate this problem. According to these investigators, Mar del Plata has now only a pre-treatment sewage plant that grinds raw material, filters and retains a small part of these solids. All the rest is disposed into the sea at a rate of 2.8 m^3/s most of the year, but that reaches 3.5 m^3/s during summer. This has posed a very serious sanitary problem to bathing people. Elias and Vallarino (2009) state that even at 10 km south of Parque Camet the concentration of Enterococci exceeds in more than three times the acceptable density values for recreational marine water (fixed by the Environmental Protection Agency at a maximum of 104 Colony Forming Units of enterococci per 100 ml of marine water). Although negative surges leave exposed the discharge area of the sewage outfall where large biogenic, reef-like formations of seaworms thrive, positive surges, instead, play a significant role in keeping these shallow water areas relatively clean in spite of the large amounts of wastewater and pollutants disposed by the city's sewage outfall. However, this self-cleaning capacity of the sea has a limit, and Mar del Plata seems to have passed it. The consequence is a contaminated coastal environment. This is why a new sewage outfall is now under construction. With a length of nearly 4,000 m, it will dispose wastewater offshore at a depth between 13 and 15 m.

Beyond human intervention, sea level rise due to global climatic change can further aggravate the impacts of storm surges on the estuary and the adjacent maritime front by further worsening flooding episodes, wave action and erosion processes. To calculate the secular MWL trend for Buenos Aires (1905–2010) and MSL trend for Mar del Plata (1953–2009), a low-pas, 17-element numerical filter was designed from the Kaiser–Bessel window (Hamming 1977; Harris 1978). This filter was used to attenuate contributions from the astronomical tide that range from 8 to 19 years (Godin 1972). Linear regressions from filtered data threw positive water level trends of 1.62 ± 0.01 mm/year for Buenos Aires and 1.72 ± 0.01 mm/year for Mar del Plata (Fig. 6).

Dealing with the impacts

Dealing with the impacts of positive and negative storm surges in the study area is not an easy task at all. Although a given possible solution might be technically feasible, the costs involved could be unaffordable. To begin with, any improvement in the weather forecasting and warning systems will, of course, be welcome. About 1965, it was proposed to construct a 'polder' (like those in Holland) all along the Rio de la Plata to protect the estuary shores against sea level rise and positive storm surges. This project received many criticisms about its consequences on the coastal environment and was then abandoned. Towards the end of the last century, three measures were taken to prevent some low-lying parts of Buenos Aires from flooding; namely (1) the elevation of the Riachuelo's banks to 1.5 m above the historical flooding level, (2) the installation of an additional 7-km storm sewer to aid controlling and conveying the total water flux towards seven pumping stations, (3) the restoration of 4 km of seawalls. Some embankments and seawalls have also been built at a few locations along the estuary shore as a defense against flooding. Strict norms for lowland use planning are inescapable to decrease the continuous need for getting many people away from places were floods occur. As stated above, negative surges in the estuary are a serious risk for shipping, harbor operations

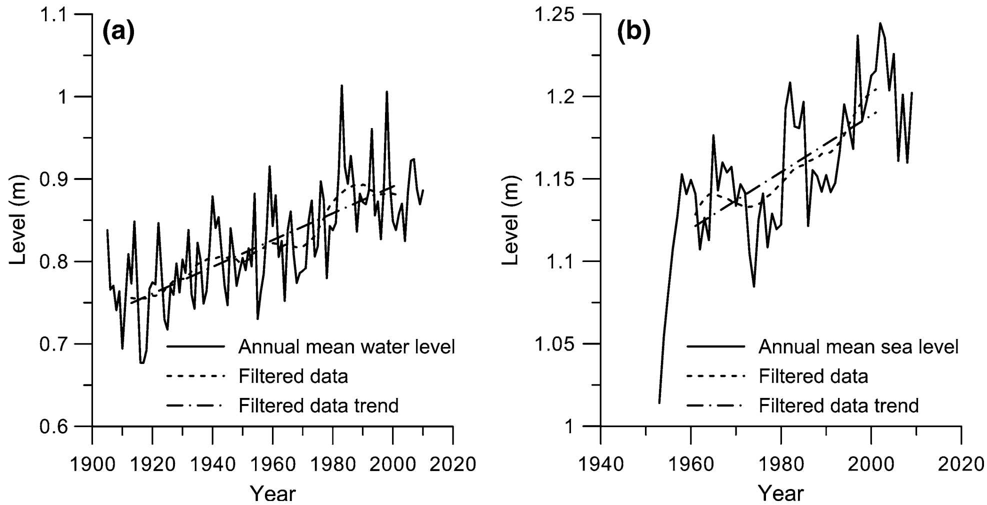

Fig. 6 Linear regression calculated from filtered data of the annual mean levels for **a** Buenos Aires (1905–2010) and **b** Mar del Plata (1953–2009)

and drinking water supply. The dredging of the access canal down the Rio de la Plata to more than 10 m would seem to be an adequate measure. As regards drinking water supply, the search for other alternative sources looks reasonable. These sources might include an increase in the production of wells in the Great Buenos Aires, or the conveying of water from the River Parana. Because of the occurrence of negative surges the local water company has provided the water intakes in the Rio de la Plata with tide gauges. Strict watching of navigation in the estuary should always be exercised to avoid accidents and fuel spills with disastrous consequences, as was the case of the collision between a tanker and a container ship on 15 January 1999. At the maritime front, instead, the main problems posed by positive surges are beach erosion, destruction of coastal structures, and seawater encroachment of coastal aquifers. The conflicts between pollution, recreation, and coastal protection were, are, and will surely continue to be significant in the larger summer resorts of the Province of Buenos Aires. For instance, groins, jetties and seawalls have been built at Mar del Plata, but they are not a suitable solution. Beach replenishment is now receiving an increasing attention. An improved urban planning and a better groundwater management should be adopted to reduce the risk of saltwater encroachment of coastal aquifers threatened by positive surges. The new and longer sewage outfall under construction at Mar del Plata will solve the problem of the present disposal areas that become exposed when negative surges occur.

Conclusions

The Rio de la Plata estuary shores and the adjacent Atlantic front between Punta Rasa and Mar del Plata host a large population and a variety of human activities. The whole area is normally affected by positive and negative storm surges. Positive surges can be the cause of disastrous floods along the Rio de la Plata estuary shores, and of severe beach erosion, destruction of coastal structures, and salt water encroachment of coastal aquifers down the Atlantic front. Although negative surges can also affect the entire area with hazardous consequences, they are most dangerous in the estuary because they can represent a serious threat for navigation safety and drinking water supply to Buenos Aires and its surroundings. Extreme positive and negative meteorological residuals, such as those of 12 November 1989 (+3.48 m) and 29 May 1984 (−4.61 m) in Buenos Aires speak for themselves. Sometimes, however, due to clockwise circulation about a low in the southern hemisphere, a positive surge in the Atlantic front becomes simultaneously a negative surge in the Rio de la Plata. That occurred, for example, on 29–30 May 1984 and on 21–23 July 2009. As in the case of separate positive and negative surges, severe though rather different, environmental impacts resulted from these particular phenomena. Like the two faces of the same coin, while the Atlantic front underwent strong beach erosion and destruction of coastal structures, the estuary waters were swept away by the southwest winds, thus affecting navigation all along the estuary, harbor operations and drinking water supply. Human activities have very often worsened these impacts. In the Atlantic front, for example, beach sand mining, dune removal, coastal structures built without adequate geomorphological information, unplanned urban development and unsuitable sewage disposal have aggravated the consequences of storm surges. In the Rio de la Plata estuary, instead, the construction of drainage canals disregarding the behavior of this wetland environment, and the daily discharge of large amounts of polluted and toxic materials via small tributaries acting as open sewers, are the main causes that exacerbate the hazardous effects of surges. The entire area has been subjected to a permanent reckless management for decades. This must change through judicious measures, as otherwise mismanagement can result in irreversible consequences for the environment and the coastal dwellers. All this should be considered within the frame of the relative sea level rise that affects the whole study area.

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