



## Storm surges and coastal impacts at Mar del Plata, Argentina

Mónica M.E. Fiore<sup>a,e</sup>, Enrique E. D'Onofrio<sup>a,d</sup>, Jorge L. Pousa<sup>b,c,\*</sup>,  
Enrique J. Schnack<sup>c,f</sup>, Germán R. Bértola<sup>b,g</sup>

<sup>a</sup> Departamento de Oceanografía, Servicio de Hidrografía Naval and Escuela de Ciencias del Mar, Instituto Universitario Naval, Av. Montes de Oca 2124, C1270ABV Buenos Aires, Argentina

<sup>b</sup> Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, C1033AAJ Buenos Aires, Argentina

<sup>c</sup> Laboratorio de Oceanografía Costera, Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Calle 64, No. 3, Casilla de Correo 45, 1900 La Plata, Argentina

<sup>d</sup> Instituto de Geodesia, Facultad de Ingeniería, Universidad de Buenos Aires, Av. Las Heras 2214, C1127AAR Buenos Aires, Argentina

<sup>e</sup> Departamento de Ciencias de la Atmósfera y los Océanos, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón II, C1428EGA Buenos Aires, Argentina

<sup>f</sup> Comisión de Investigaciones Científicas de la Provincia de Buenos Aires (CIC), Calle 526 e/10 y 11, 1900 La Plata, Argentina

<sup>g</sup> Centro de Geología de Costas y del Cuaternario, Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Mar del Plata, Funes 3350, 7600 Mar del Plata, Argentina

### ARTICLE INFO

#### Article history:

Received 18 January 2008

Received in revised form

26 March 2009

Accepted 13 May 2009

Available online 28 May 2009

#### Keywords:

Storm surges

Storm index

Erosion

Sea level

Beach profiles

Argentina

Mar del Plata

### ABSTRACT

Positive storm surges (PSS) lasting for several days can raise the water level producing significant differences between the observed level and the astronomical tide. These storm events can be more severe if they coincide with a high tide or if they bracket several tidal cycles, particularly in the case of the highest astronomical tide. Besides, the abnormal sea-level elevation near the coast can cause the highest waves generated to attack the upper beach. This combination of factors can produce severe erosion, threatening sectors located along the coastline. These effects would be more serious if the storm surge height and duration increase as a result of a climatic change. The Mar del Plata (Argentina) coastline and adjacent areas are exposed to such effects. A statistical characterization of PSS based on their intensity, duration and frequency, including a surge event classification, was performed utilizing tide-gauge records over the period 1956–2005. A storm erosion potential index (SEPI) was calculated from observed levels based on hourly water level measurements. The index was related to beach profile responses to storm events. Also, a return period for extreme SEPI values was calculated. Results show an increase in the average number of positive storm surge events per decade. Considering all the events, the last decade (1996–2005) exhibits an average 7% increase compared to each one of the previous decades. A similar behavior was found for the decadal average of the heights of maximum annual positive storm surges. In this case the average height of the last two decades exceeds that of the previous decades by approximately 8 cm. The decadal average of maximum annual duration of these meteorological events shows an increase of 2 h in the last three decades. A possible explanation of the changes in frequency, height and duration of positive storm surges at Mar del Plata would seem to lie in the relative mean sea-level rise.

© 2009 Elsevier Ltd. All rights reserved.

### 1. Introduction

With a total of more than 1500 km of coastline and about 14 million people (40% of the national population), the Province of Buenos Aires is by far the most important coastal province of Argentina. Over 90% of its population lives in urban centers, the largest of which are located on the coast. Among them is Mar del

Plata, the country's most important tourist city with a population over 560,000 that doubles during summer (Fig. 1).

Up to the second decade of the 20th century the beaches of Mar del Plata presented natural characteristics with their own balance. The growth of the city and the construction of many groins and jetties have caused severe degradation and erosion ever since. Today, erosion affects not only the beaches but also threatens parts of the coastal highways that connect Mar del Plata to other adjacent littoral summer resorts. Storm surges have been responsible for the most severe erosion processes, particularly in areas of heavy human intervention, aggravated by a rise in local mean sea level (MSL) of  $1.6 \pm 0.1$  mm/year (D'Onofrio et al., 2006). The projected MSL rise for this century of 18–59 cm, as predicted by the Intergovernmental Panel on Climate Change (IPCC, 2007a),

\* Corresponding author at: Laboratorio de Oceanografía Costera, Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Calle 64, No. 3, Casilla de Correo 45, 1900 La Plata, Argentina.

E-mail addresses: [mareas@hidro.gov.ar](mailto:mareas@hidro.gov.ar) (M.M.E. Fiore), [geoduba@fi.uba.ar](mailto:geoduba@fi.uba.ar) (E.E. D'Onofrio), [jlpl@fcnym.unlp.edu.ar](mailto:jlpl@fcnym.unlp.edu.ar) (J.L. Pousa), [eschnack@netverk.com.ar](mailto:eschnack@netverk.com.ar) (E.J. Schnack), [gbertola@mdp.edu.ar](mailto:gbertola@mdp.edu.ar) (G.R. Bértola).

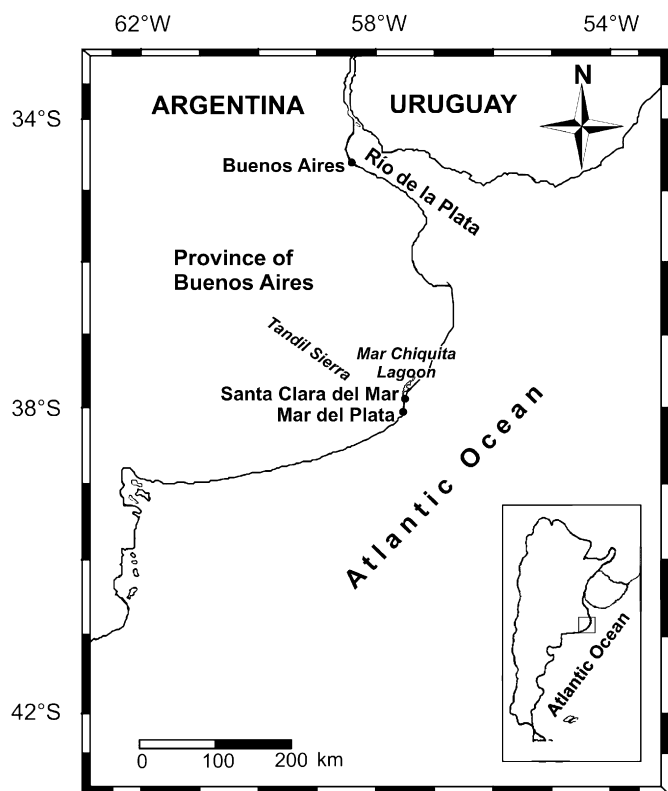


Fig. 1. Location map.

can only further aggravate beach erosion. Holgate and Woodworth (2004) found that coastal sea-level rise has accelerated over the last decade. In studying the changes in the regime of storm surges at Buenos Aires (the capital city of Argentina on the west margin of the Río de la Plata estuary), D'Onofrio et al. (2008) found that water level rise has accelerated, particularly during the period 1950–1995. However, it is worth noting that erosion is not a problem at Buenos Aires because most of its coastal fringe is protected by the harbor docks and seawalls. Instead, storm surges affect Buenos Aires mainly by piling-up the estuary waters against the coast (positive surges due to strong southeasterly winds), thus causing severe floods in the low-lying areas of the city; or by partially sweeping the waters from the coast (negative surges due to strong northwesterly winds), thus affecting navigation safety and drinking water supply.

Positive storm surges (hereafter referred to as PSS) from the south and southeast (southeasterlies), and lasting for several days, raise the water level at Mar del Plata producing significant differences between the observed levels and the astronomical tide. These storm events can be more severe if they coincide with a high tide or if they bracket several tidal cycles, particularly in the case of the highest astronomical tide. The abnormal sea-level elevation near the coast allows the upper beach to be attacked by the highest generated waves. These effects would be more serious if the storm surge height and duration would increase as a result of a climatic change.

A statistical characterization of PSS based on their height, duration and frequency, including a surge event classification, is a valuable tool in coastal protection studies. Storm surges have been classified in several ways. Allen (1981) designs a storm index based on prevailing onshore winds; Dolan and Davis (1992) classify the Atlantic Coast winter storm taking into account the storm location, tracks, fetches and wave heights. Zhang et al. (2001) show that there is a linear relation between storm surges and wave height, and that it is reasonable to use storm surges as a

substitute for storm waves to represent the strength of large storms. Zhang et al. (2001) propose a storm erosion potential index (SEPI) that includes the observed level based on hourly water level measurements. An advantage of the SEPI is that wave measurements are not necessary. Since wave measurements at Mar del Plata are insufficient, the SEPI was used in this work.

Based on hourly water levels from the Mar del Plata tide-gauge station, the main purpose of this paper was to use the SEPI for assessing and classifying the erosive potential of the PSS that affect the beaches of the city, and to relate them with changes in beach profile. A return period for extreme SEPI values was also calculated with the aim of beginning the construction of a database that allows recurrence values to be assigned to past and future events. In addition, a quantitative assessment of the changes in height, duration and frequency of PSS at Mar del Plata was performed for the period 1956–2005. These changes were evaluated in the light of the present trend in relative MSL rise. The conclusions reached for Mar del Plata were assumed to be applicable to other nearby beaches.

Due to the economical importance of the beaches of the Buenos Aires Province as tourist resorts, and because there are ongoing plans for protecting them from erosion (in fact, beach nourishment was already tried out at Mar del Plata in 1998), this work was thought as a starting point for a systematic study of storm-driven beach profile changes in other attractive beaches of the Province of Buenos Aires at a regional scale.

## 2. Study area

On a regional perspective, the Buenos Aires Province Atlantic coast, with nearly 1100 km length, exhibits a variety of morphological features with different exposure to waves and storms. A low-lying sandy barrier extends northward from Mar Chiquita lagoon (c. 30 km north of Mar del Plata) and cliffs cut in Late Cenozoic, poorly consolidated continental sediments mainly composed of aeolian silts, are exposed to wave action south and north of the city (Fig. 2). Coastal retreat is very rapid, at times reaching 1–2 m/year. The higher cliffs (about 25 m) are exposed on the coast south of the city. At the central Mar del Plata coast the cliffs are in more resistant lower Palaeozoic quartzites of the Tandil Sierra (Fig. 1). Here concentration of wave energy normally occurs. Several groins and jetties have been installed at Mar del Plata during the last century to protect the shore, but in many cases they operate locally and cause downdrift erosion (Fig. 3). Also, breakwaters at the entrance of the Mar del Plata harbor have accelerated erosion in the downdrift direction (northward throughout the region, and estimated between 150,000 and 200,000 m<sup>3</sup>/year by the Ministerio de Transporte, Obras Públicas y Obras Sanitarias del Gobierno de los Países Bajos (1997)). In fact, except for the harbor, all the coastal structures have been installed to protect the shore from erosion. The fluvial network is not enough to provide sand to the coastal system, nor is the sand provided by the cliffs (Schnack, 1985). Although beach replenishment was tried out at the Mar del Plata central beaches in 1998, they have undergone drastic changes in their morphodynamics ever since. Before their replenishment, these beaches had reflective to intermediate profiles and a relatively stable sedimentary balance. After the replenishment, they became dissipative but with erosive profiles. This was because the source sand used in the replenishment had a grain size finer than that of the original beach. These beaches are not in dynamical balance with the regional wave climate, and have a natural tendency to return to their original pre-replenishment morphology (Bértola, 2006).

The tide at Mar del Plata and the adjacent beaches is mixed, predominantly semidiurnal with a mean range 0.78 m (SHN, 2008).



**Fig. 2.** View of a typical erosive coast at Santa Clara del Mar, c. 15 km north of Mar del Plata. Low cliffs cut in poorly consolidated fine sediments can be observed. Cliff-top dunes have been undermined by development. Defense works between Mar del Plata and this locality have increased erosion due to the capture of the northward drifting sand (see arrow).



**Fig. 3.** Air view (1980s) of the central beaches of Mar del Plata close to a rocky headland (very hard quartzite) showing the defense works and the pattern of sediment transport to the right (northward).

D'Onofrio et al. (2006) have calculated a relative MSL rise of  $1.6 \pm 0.1$  mm/year at Mar del Plata for the period 1956–2005 by performing a linear fitting on the filtered values with a correlation coefficient of 0.92 (Fig. 4). Application of the glacial isostatic adjustment (GIA) corrections from the ICE-5G model (Peltier, 2001, 2004) gave a relative MSL rise of 2.4 and 2.5 mm/year for the VM4 and VM2 models, respectively. These model results are available for tide-gauge stations worldwide at the Permanent Service for Mean Sea Level (PSMSL) website ([www.pol.ac.uk/psmsl](http://www.pol.ac.uk/psmsl)).

### 3. Storm surge statistics

#### 3.1. Changes in frequency, height and duration

The basic data set consisted of hourly water levels from the Mar del Plata tide gauge for the period 1956–2005. The record has

an 8% of values missing from 1980 onwards. All observations are referred to a common tidal Datum that is periodically checked by accurate geodetic leveling to local benchmarks (SHN, 2008). The tidal constants were obtained through a harmonic analysis with the method of Foreman (1977). This method was applied to the period 1962–1980 because this 19-year nodal period had no gaps. The associated errors were calculated using the computational method of Pawlowicz et al. (2002).

The surge sample was obtained from the residuals between the observed hourly levels and the predicted tide. The predicted tide has a fixed MSL of 0.91 m above Datum (SHN, 2008). Therefore, the residuals included a contribution from the MSL trend in the observed tide. The distribution of the residual levels is approximately Gaussian (Fig. 5), with a positive skewness (0.41) and a standard deviation of 0.30 m. The tails contain the major surge events. The highest positive residual occurred on December 5,

1999 with 1.92 m. The lowest negative residual was  $-1.35$  m on August 19, 1959.

The PSS were obtained from the residuals and defined by a period of time in which the following two criteria are simultaneously satisfied: (1) the residual levels must not fall below the threshold value of  $0.30$  m, and (2) the highest residual value cannot be less than  $0.60$  m. The threshold of  $0.30$  m is three times

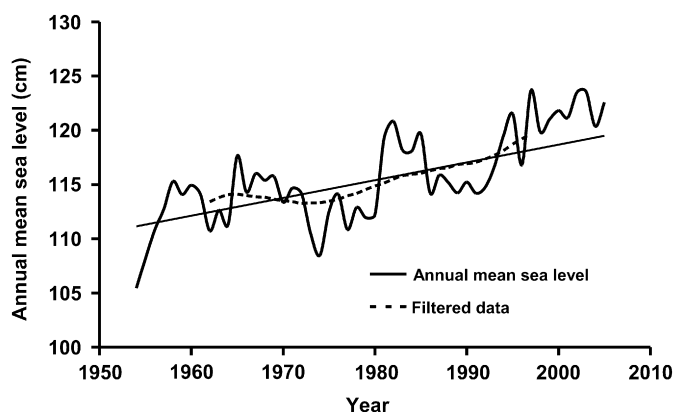


Fig. 4. Linear regression calculated from filtered data of relative annual mean sea levels at Mar del Plata for the period 1956–2005 (D'Onofrio et al., 2006).

the root-mean-square (rms) of the differences between the observed and the predicted tide ( $\text{rms} = \pm 10$  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., 1997).

Fig. 6(a) shows the annual weighted average frequencies of PSS arranged in decades from 1956. The number of hourly heights recorded in each year was used as a weight to reduce the influence of the gaps in the data. A 7% increase in the number of PSS is observed in the last decade compared to each one of the previous decades. The decadal frequency trend for PSS is  $+0.19 \pm 0.10$  events per year over the whole period.

The decadal average of annual maximum PSS in each year for the last two decades ( $1.44$  m) is larger than that corresponding to the previous decades, which are below  $1.36$  m (Fig. 6(b)). The decadal trend of the maximum PSS for the whole period is  $+0.002 \pm 0.001$  m/year.

Fig. 6(c) illustrates the mean annual duration of PSS averaged by decade from 1956. In the last three decades the average duration was  $28$  h, two hours more than for the previous decades ( $26$  h). The decadal trend is  $+0.06 \pm 0.01$  h/year. The highest duration was observed at the beginning of July 1993 with  $130$  h.

Seasonally, the winter months (June, July and August) exhibit the largest number of events (Fig. 6(d)).

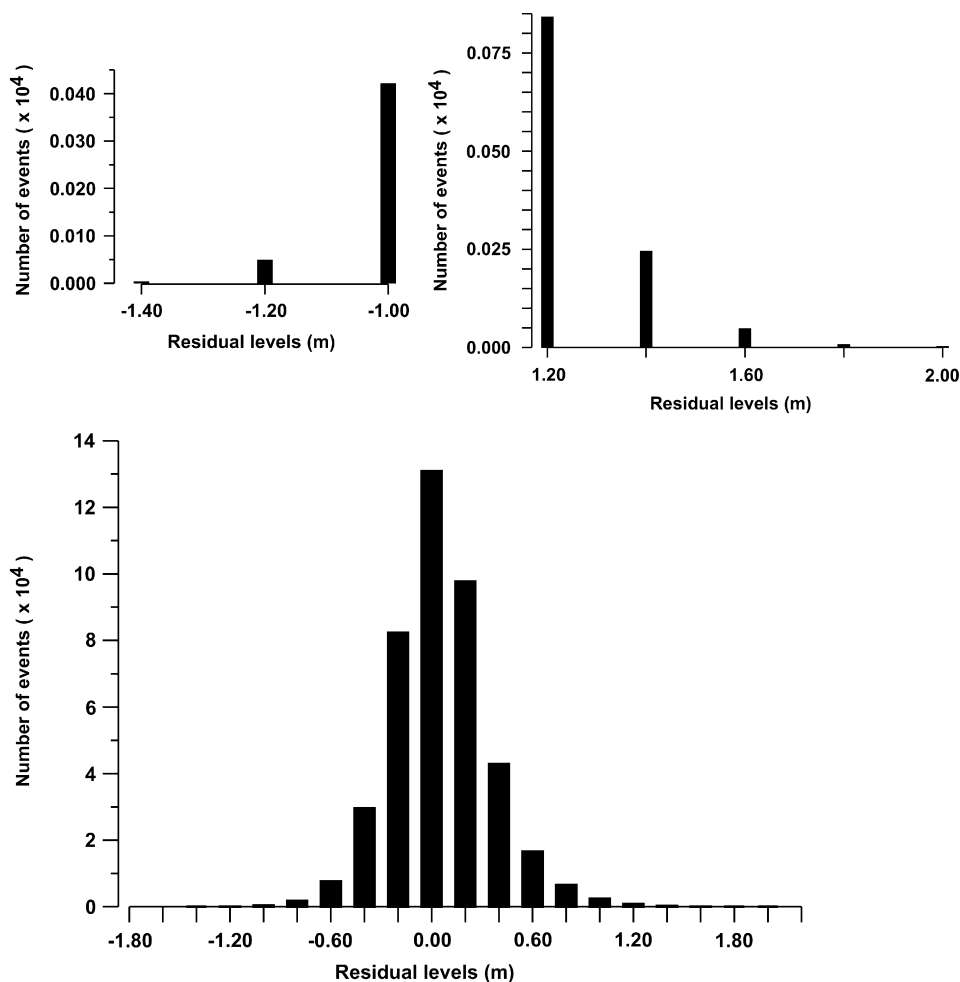


Fig. 5. Distribution of residuals (i.e. water levels minus predicted tide where the predicted tide has the same MSL). The upper part of the graph shows the tails of the residuals containing the major surge events.

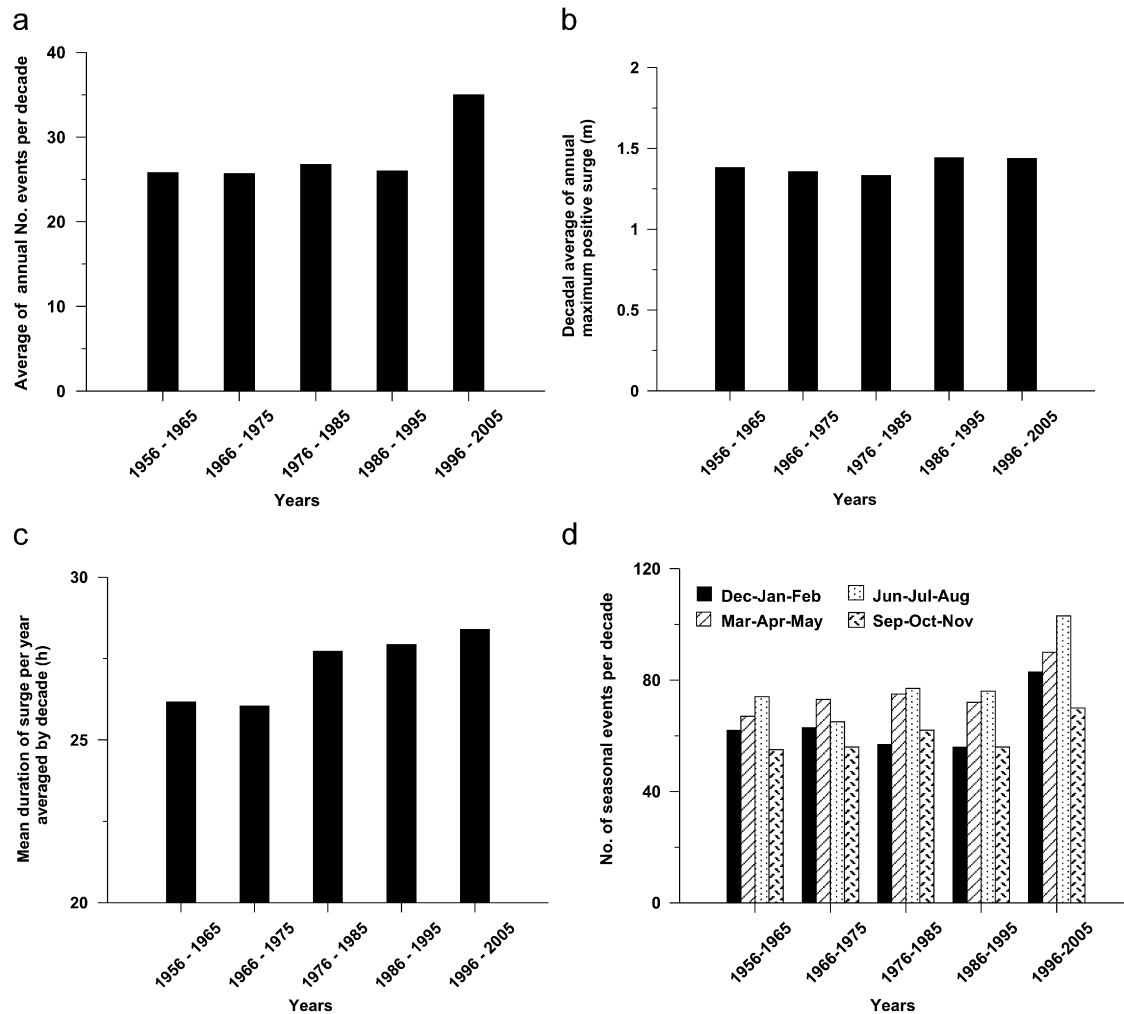


**Fig. 6.** (a) Average of annual number of PSS events per decade; (b) decadal average of annual maximum PSS events; (c) mean annual duration of PSS averaged by decade; and (d) number of seasonal PSS events per decade.

**Table 1**

The 10 maximum SEPI values from the last 20 years ranked in decreasing order, with their duration and maximum observed level attained.

| SEPI (m <sup>2</sup> h) | Month/year    | Duration (h) | Maximum observed level (m) |
|-------------------------|---------------|--------------|----------------------------|
| 22.95                   | April/1997    | 57           | 2.74                       |
| 14.33                   | June/1994     | 87           | 2.67                       |
| 11.59                   | December/1999 | 73           | 2.51                       |
| 10.11                   | March/1992    | 34           | 2.13                       |
| 8.39                    | April/2003    | 69           | 2.40                       |
| 7.94                    | June/1987     | 52           | 2.11                       |
| 7.88                    | July/1989     | 35           | 1.74                       |
| 7.86                    | January/1995  | 49           | 2.28                       |
| 6.73                    | August/1991   | 45           | 1.93                       |
| 6.64                    | July/2004     | 45           | 2.67                       |

### 3.2. Storm classification

Zhang et al. (2001) calculate the storm erosion potential index as the sum of the product of hourly values of storm surge height above two standard deviations, and water level greater than mean higher high water (MHHW) for each event, using the following equation:

$$SEPI = \sum_{t=0}^{t_D} S_{2SD}(t) S_{MHHW}(t) \Delta t$$

where  $\Delta t$  is data time interval (1 h in this paper),  $t_D$  is the integrated number of hours of storm duration,  $S_{2SD}$  is the surge height above two standard deviations of all residuals and  $S_{MHHW}$  is the difference between water level and MHHW. The MHHW at Mar del Plata for the whole period (50 years) was 1.56 m above Datum.

With the two criteria employed to define a positive surge event, 1394 such events were identified in the period 1956–2005. The SEPI was able to be defined in 1103 events, which shows that positive SEPI values were consistent with the established criteria. In the remaining events, either both conditions or any one of them were unfulfilled throughout the surge event. The largest SEPI value, 22.95 m<sup>2</sup> h, was obtained for the storm of 3–4 April 1997.

Beach replenishment was tried out at Playa Grande, immediately north of the Mar del Plata harbor, in 1998 thus enlarging the beach in about 200 m. However, in July 1999 the beach had already receded about 100 m. Eight storms of different intensity were recorded between July 1999 and March 2000, the SEPI varying between 1.40 and 11.59 m<sup>2</sup> h. The last value corresponds to the storm of December 5, 1999, the seventh most important storm in the whole period (1956–2005). A marked decrease in the vertical dimension of the beach profile due to storm events took place during the period October 1999–March 2000, in which the December 5 storm occurred.

Table 1 shows the 10 maximum SEPI values from the last two decades ranked in decreasing order, with their duration and

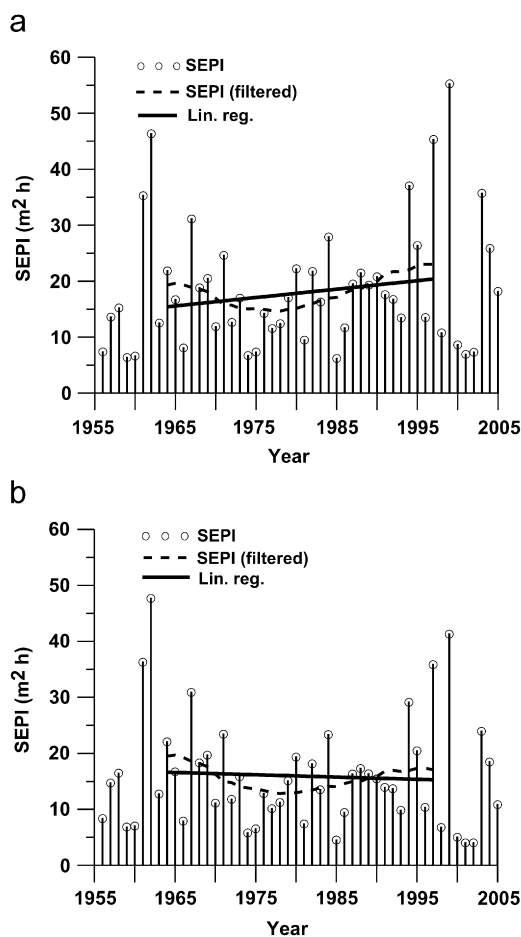


Fig. 7. Long-term behavior of the SEPI for the period 1956–2005: (a) with relative MSL trend included and (b) without relative MSL trend.

maximum observed level attained. All these storm surges changed the beach profile in a short time interval. It is seen that neither the duration nor the maximum height attained become automatically ranked in decreasing order. Therefore, neither of these parameters, taken either separately or together, allows a potential storm erosion scale to be constructed as the SEPI does.

### 3.3. Long-term behavior

To analyze the long-term behavior of the SEPI for the period 1956–2005, the individual hourly SEPI values were added together for each year to obtain a time series of total annual SEPI values that could represent the stormy character of any particular year (Fig. 7(a)). To calculate the trend of the total annual SEPI values, the time series of Fig. 7(a) was low-pass filtered leaving variability of period 13 years and longer (Hamming, 1977; Harris, 1978; Lanfredi et al., 1998). The linear regression calculated from filtered data was  $+0.15 \pm 0.04 \text{ m}^2 \text{ h/year}$  (Fig. 7(a)). A different approach to this analysis consists in subtracting the relative MSL trend for Mar del Plata (Section 2) from the observed hourly water levels (Fig. 7(b)). This trend was removed so that the first level of 1956 remained constant (Graff, 1981). The PSS events were then recalculated keeping the same criteria as before, and a new annual filtered series of total SEPI values was obtained. The trend for this new filtered series is  $-0.04 \pm 0.02 \text{ m}^2 \text{ h/year}$  (Fig. 7(b)). As this value is close to zero, the relative MSL rise would seem to be the main cause of the positive trend in Fig. 7(a). It is possible that if there were not some missing observed hourly water levels since

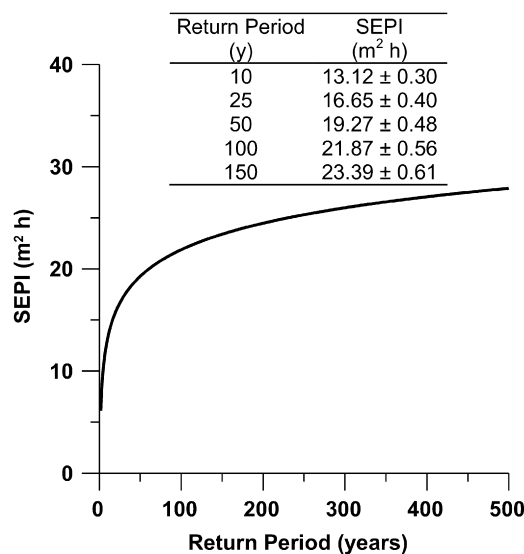


Fig. 8. Return period of extreme maximum annual SEPI values.

Table 2

Main features of PSS events and their impacts at Mar del Plata and Buenos Aires.

|                                                             | Mar del Plata<br>1956–2005                    | Buenos Aires 1954–2003                                      |
|-------------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|
| Range of the decadal average of annual number of PSS        | 25.7–35                                       | 48–97                                                       |
| Range of the decadal average of annual maximum PSS          | 1.3–1.4 m                                     | 2.3–2.4 m                                                   |
| Range of the decadal average of mean annual duration of PSS | 26–28.4 h                                     | 43–53.3 h                                                   |
| Main PSS impacts                                            | Coastal erosion.<br>Changes in beach profiles | Hindrance of storm sewers and flooding of low-lying sectors |

1980 onwards, the trend in Fig. 7(b) would be even closer to zero. The relative MSL rise boosted the storm effects.

### 3.4. Return period of extreme maximum annual SEPI values

The time series of extreme maximum annual SEPI values for Mar del Plata (1956–2005) exhibits a linear trend of  $+0.02 \pm 0.01 \text{ m}^2 \text{ h/year}$ . This trend was removed so that the last level of 2005 remained constant, thus analyzing the remaining events as if they were truly random (Graff, 1981). The probability density function for maximum annual SEPI values has been obtained applying the generalized extreme value (GEV) distribution proposed by Jenkinson (1955). The best fit to these data set obtained by the maximum likelihood method indicated that Fisher–Tippet Type I was the adequate distribution. The return periods of extreme maximum annual SEPI were calculated following the method of Kite (1978) (Fig. 8). The table in Fig. 8 shows the SEPI values for the most common return periods used in coastal engineering. The SEPI value for the storm event of 3–4 April, 1997 ( $22.95 \text{ m}^2 \text{ h}$ ) at Mar del Plata has a return period of about 140 years.

## 4. Concluding remarks

In general the results show an increase in the average of the number of PSS events per decade. Considering all the events, the

last decade (1996–2005) exhibits an average 7% increase compared to each one of the previous decades. Seasonal distribution shows that winter months (June, July and August) exhibit the greatest number of events. A similar behavior was found for the decadal average of maximum annual PSS events; in this case the average height of the last two decades exceeds that of the previous decades by approximately 8 cm. The mean annual duration of PSS averaged by decade shows an increase of 2 h in the last three decades.

Similar results for the PSS trends were found for the Buenos Aires harbor (D'Onofrio et al., 2008). However, there are marked differences between Mar del Plata and Buenos Aires. Table 2 shows a comparison of the main features of past PSS events and their impacts at both sites for almost the same period.

In each case, the range of the variations for Buenos Aires has upper and lower limits higher than those for Mar del Plata. For example, the number of PSS events averaged by decade for Buenos Aires is 2.4 times greater than that for Mar del Plata. With respect to the decadal average of maximum heights and durations it can be seen that they are 1 m higher and 21 h longer, respectively, at Buenos Aires than at Mar del Plata. It must be taken into account that the Buenos Aires harbor is within the Río de la Plata estuary, one of the largest estuaries in the world, with a mean depth of about 10 m (Balay, 1961). The NNW-SSE orientation and funnel-like shape of the estuary favors the action of strong southeasterly winds that push the waters upriver. Mar del Plata, on the other hand, is at the open South Atlantic Ocean.

In the overall it can be seen an increase in the decadal average number of PSS events for Mar del Plata, as well as in their decadal duration, particularly in the last decade. A possible explanation of the changes in frequency, height and duration of PSS at Mar del Plata (and also at Buenos Aires) seem to lie in the relative MSL rise. Both the relative MSL rise and the PSS parameters show an increasing trend. According to the IPCC AR4 Report (IPCC, 2007b), changes in extreme sea levels can, in many cases, be driven by changes in mean sea level.

There is, however, a matter that should be mentioned here. Some evidence suggests a southward shift of the South Atlantic high during the last decades of the twentieth century (Camilloni, 2005), as well as a southward shift of the regional atmospheric circulation over the southeastern portion of South America (Barros et al., 2000). It is therefore possible that changes in the wind regime over the southwest Atlantic could drive an increasing tendency of the PSS characteristics as much as (or even more than) the relative MSL rise does.

Positive storm surge impacts at Mar del Plata and Buenos Aires are different. Although most of the coastal fringe of Buenos Aires has different structures (such as seawalls and the docks of the harbor) that protect it from erosion, water level rise due to PSS becomes a hydraulic barrier at the outlet of the main storm sewers making the water come back to the city and flood the low-lying sectors. On the other hand, coastal erosion is the main PSS impact at Mar del Plata and other near summer resorts.

Quantification of the erosive potential effects of PSS at Mar del Plata can be achieved by applying the SEPI approach to the available time series of hourly sea levels. The probability density function for extreme SEPI values gives the needed information for different return periods. A recurrence value can be assigned to each of the 1103 detected events at Mar del Plata, which gives the possibility of constructing a database with historic and future storms events for this city. Because of the economic importance of the zone this database will be a powerful tool in coastal planning and protection at the institutional level. The extension of the SEPI analysis to beaches north and south of Mar del Plata is now being carried out.

## Acknowledgments

This research was funded by the Comisión de Investigaciones Científicas de la Provincia de Buenos Aires (CIC), to which the authors are gratefully acknowledged. It is also part of the “Study of the ocean tides on the Argentine coast” Project (Hydrographic Plan 206-PHID, Naval Hydrographic Service, Argentina), and of the I014 Project (Science and Technological Division, University of Buenos Aires (UBACYT) 2008–2010).

## References

- Allen, J.R., 1981. Beach erosion as function of variations in the sediment budget, Sandy Hook, New Jersey, USA. *Earth Surface and Landforms* 6, 139–150.
- Balay, M.A., 1961. El Río de la Plata entre la atmósfera y el mar. Servicio de Hidrografía Naval, Armada Argentina, Buenos Aires, Argentina.
- Barros, V.R., Castañeda, M.E., Doyle, M.E., 2000. Recent precipitation trends in southern South America east of the Andes: an indication of climatic variability. In: Smolka, P.P., Volkheimer, W. (Eds.), *Southern Hemisphere Paleo- and Neoclimates*. Springer, Berlin, pp. 187–206.
- Bértola, G., 2006. Morfodinámica de playas del sudeste de la Provincia de Buenos Aires (1983 a 2004). *Latin American Journal of Sedimentology and Basin Analysis* 13 (1), 31–57.
- Camilloni, I., 2005. Tendencias climáticas. In: Barros, V., Menéndez, A., Nagy, G. (Eds.), *El Cambio Climático en el Río de la Plata*. Chapter 2, 13–19. CIMA-CONICET, Buenos Aires.
- Dolan, R., Davis, R.E., 1992. An intensity scale for Atlantic coast northeast storms. *Journal of Coastal Research* 8, 352–364.
- D'Onofrio, E. E., Fiore, M.M.E., Mediavilla, D., 2006. Evolución de las ondas de tormenta en Mar del Plata durante el período 1956–2005. Resúmenes VI Jornadas Nacionales de Ciencias del Mar y XVI Coloquio de Oceanografía IAPSO, 4 al 8 de diciembre de 2006. Puerto Madryn, Argentina, p. 164.
- D'Onofrio, E.E., Fiore, M.M.E., Pousa, J.L., 2008. Changes in the regime of storm surges at Buenos Aires, Argentina. *Journal of Coastal Research* 24 (1A), 260–265.
- Foreman, M.G.G., 1977. Manual for tidal heights analysis and predictions. Pacific Marine Science Report, Institute of Ocean Sciences, Patricia Bay, Sidney, Canada, 77–10, p. 97.
- Graff, J., 1981. An investigation of the frequency distributions of annual sea level maxima at ports around Great Britain. *Estuarine, Coastal and Shelf Science* 12, 389–449.
- Hamming, R.W., 1977. *Digital Filters*. Prentice Hall, Englewood Cliffs, New Jersey.
- Harris, F.J., 1978. *Digital Filters, Signal Processing Series*. Prentice Hall, Englewood Cliffs, New Jersey.
- Holgate, S.J., Woodworth, P.L., 2004. Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters* 31, L07305.
- IPCC (Intergovernmental Panel on Climate Change), 2007a. *The Physical Basis-Summary for Policymakers*, <<http://www.ipcc.ch/SPM2feb07.pdf>>.
- IPCC (Intergovernmental Panel on Climate Change), 2007b. Bindoff, N.L., Willbrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D., Unnikrishnan, A. Observations: oceanic climate change and sea level. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. <[http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1\\_Print\\_Ch05.pdf](http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_Ch05.pdf)>.
- Jenkinson, A.F., 1955. The frequency distribution of the annual maximum (or minimum) values of meteorological elements. *Quarterly Journal of the Royal Meteorological Society* 81, 158–172.
- Kite, G.W., 1978. *Frequency and Risk Analyses in Hydrology*. Water Resources Publications, Fort Collins, Colorado, USA.
- Landfredi, N.W., Pousa, J.L., D'Onofrio, E.E., 1998. Sea-level rise and related potential hazards on the Argentine coast. *Journal of Coastal Research* 14 (1), 47–60.
- Ministerio de Transporte, Obras Públicas y Obras Sanitarias del Gobierno de los Países Bajos, 1997. Estudio del puerto y la costa de Mar del Plata. Informe Interno de la Municipalidad de General Pueyrredón. 142 pp, unpublished.
- Pawlowicz, R., Beardsley, B., Lentz, S., 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T\_TIDE. *Computers and Geosciences* 28, 929–937.
- Peltier, W.R., 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), *Sea Level Rise-History and Consequences*. Academic Press, San Diego, CA, pp. 65–95.
- Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and grace. *Annual Review of Earth and Planetary Science* 32, 111–149.
- Schnack, E.J., 1985. Argentina. In: Bird, E., Schwartz, M. (Eds.), *The World's Coastlines*. Van Nostrand-Reinhold Co., NY, pp. 69–78.
- SHN (Servicio de Hidrografía Naval, Armada Argentina), 2008. *Tablas de Marea*, H-610, Buenos Aires.
- Zhang, K., Douglas, B.C., Leatherman, S.P., 1997. US East Coast storm surges provide unique climate record. *EOS* 78 (37), 389.
- Zhang, K., Douglas, B.C., Leatherman, S.P., 2001. Beach erosion potential for severe nor'easters. *Journal of Coastal Research* 17 (2), 309–321.