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ORIGINAL PAPER

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Abstract Meteorological tsunamis are frequently observed in different tide stations at the southeastern coast of South America. They are associated with the occurrence of atmospheric gravity waves during the passages of cold fronts over the Buenos Aires Province continental shelf. On the other hand, storm surges are also frequent in the region, and they are associated with strong and persistent southerlies, which are also frequent during cold front passages. The impact of meteorological tsunamis in coastal erosion and in the statistics of storm surge trends is discussed in this paper. For this study, fifteen meteorological tsunamis (with maximum wave heights higher than 0.20 m), seven of them simultaneous to the occurrence of storm surge events (with extreme levels higher than $|\pm 0.60\ \mathrm{m}|$), are selected from April 2010 to January 2013. The impact of meteorological tsunamis in the storm erosion potential index (SEPI) is evaluated. Not significant differences are obtained between SEPI calculated with and without filtering the meteorological tsunami signal from

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the storm surge data series. Moreover, several experiments are carried out computing SEPI from synthetic sea level data series, but very low changes (lower than 4 %) are also obtained. It is concluded that the presence of moderate meteorological tsunamis on sea level records would not enhance this index at the Buenos Aires Province coast. On the other hand, taking into account that meteorological tsunamis can reach up the 20–30 % of the storm surge height, it was concluded that the statistics of storm surge trends (and their uncertainties) should be revised for Mar del Plata data series.

Keywords Meteorological tsunamis · Storm surges · Meteorological cold front passages · Coastal erosion · Buenos Aires Province coast

1 Introduction and background

Meteorological tsunamis are very similar to ordinary tsunamis, but they are produced by atmospheric processes (atmospheric waves, pressure jumps, squalls or frontal passage), and they are regularly observed at the same sites with pronounced local resonant properties. Meteorological tsunamis are produced by the resonant superposition of internal factors (pronounced resonant properties of a specific bay or coastal areas) and external factors (strong atmospheric disturbance resonantly interacting with open-ocean waves). In general, they have a multi-resonant generation mechanism. The needed coincidence of several resonant factors significantly diminishes the possibility of occurring such events, which is the main reason why these phenomena are rare and restricted to specific locations (Monserrat et al. 2006).

Meteorological tsunamis, with periods range from a few minutes to almost 2 h and heights typically lower than 1 m, have been frequently observed in different tide stations between Mar de Ajó and Quequén on the southeastern coast of South America (Fig. 1). Dragani (1997) and Dragani et al. (2002) showed that spectral peaks of these waves covered almost the whole frequency band between 1.1 and 4.7 cycles per hour (cph) during energetic events. Significant coherence values estimated between Mar de Ajó and Mar del Plata (172 km apart, Fig. 1) clearly showed that meteorological tsunamis at the Buenos Aires Province inner continental shelf can be seen as a regional phenomenon. In general, during energetic lapses, sea level oscillations are observed firstly at Quequén and, subsequently further north, at Mar del Plata, Pinamar and Mar de Ajó, respectively. Maximum amplitudes detected for each event at the mentioned locations are very similar (Dragani et al. 2009).

With regard to the source of this long waves in the region, Balay (1955) was the first to report that long ocean waves at Buenos Aires Province coastal waters were associated with the passage of meteorological cold fronts coming from central Patagonia. Afterward, Dragani (1988) studied the possible connection between the occurrence of seismic activity in the Southern Ocean and these long ocean waves at the Buenos Aires Province coast but found practically null correlation between both phenomena. Dragani (1997) described the typical synoptic situation during the occurrence of meteorological tsunamis at coastal waters of the Buenos Aires Province. Low-level atmospheric cyclonic circulation and the passage of atmospheric fronts were always present prior to and during these events. Upper-air soundings obtained at Bahía Blanca meteorological station (Fig. 1) showed a lower pronounced tropospheric inversion that depicts an example of the state of the atmosphere

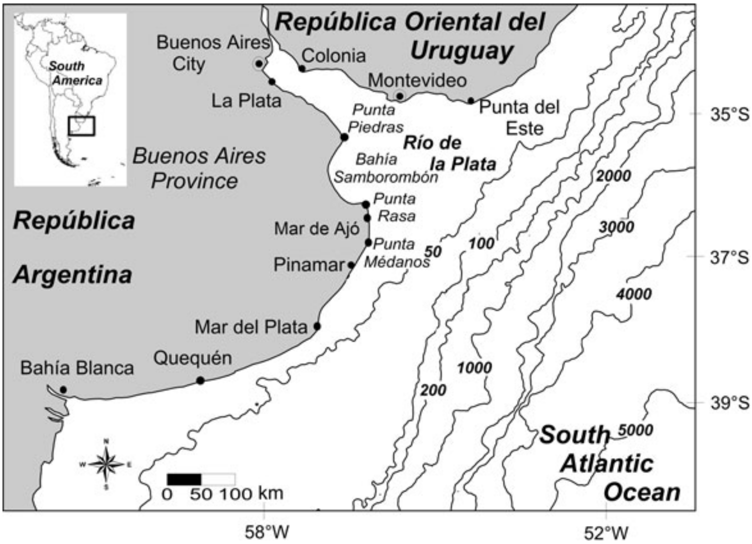

Fig. 1 Buenos Aires coastal region (Argentina) and locations, in the southwestern Atlantic Ocean. The bathymetry is labeled in meters

when a frontal surface lies overhead. This tropospheric inversion constitutes an optimal interface for the propagation of high-amplitude atmospheric gravity waves (Nuñez et al. 1999). Based on the occurrence of simultaneous atmospheric gravity waves and long ocean wave events, similarities of the spectral structures of both waving phenomena and the high effectiveness in the atmospheric-ocean energetic transference (Dragani 2007), it was concluded that atmospheric gravity waves are the most probable forcing mechanism able to generate long ocean waves (meteorological tsunamis) on the Buenos Aires Province inner continental shelf.

Tides present a mixed semi-diurnal regime and have a mean range of 0.82 and 0.83 m at Mar del Plata and Santa Teresita, respectively (SHN 2013). Meteorological conditions usually produce differences between observed sea level and astronomical tides. This anomaly is known as storm surge (positive–negative anomalies related to levels higher–lower than the predicted astronomical tide) and affects large areas of the coast over periods that may extend from some hours to several days. The action of storm surges has been clearly recognized at coastal water of the northeastern Buenos Aires Province (Campetella et al. 2007). The coincidence of large or even moderate high tides and large meteorologically induced surges has historically caused floods and damages in many coastal locations (D'Onofrio et al. 1999). Nevertheless, the action of meteorological tsunamis, which were originally reported since several decades ago in the region (Balay 1955; Inman et al. 1962), has been never taken into consideration neither from the coastal engineering point of view nor in environmental problems. They are still considered only as a scientific curiosity at the Buenos Aires Province coastal area. However, recently, it has been noted that the presence of meteorological tsunamis on sea level records could significantly affect some statistics obtained from observed records. The aim of this work is to analyze and discuss the impact of meteorological tsunamis in coastal erosion and in the statistics of extremes and trends of storm surge.

2 Data

2.1 Sea level data

Digital sea level records gathered every 5 min (from April 2010 to January 2013) at Mar del Plata tidal station of the Servicio de Hidrografía Naval of Argentina located at the fisher's pier (38.000602°S, 57.538473°W) were used in this work (Fig. 2). It is important to remark that sea level records each 5 min could be not enough for a complete spectral characterization of meteorological tsunami events because part of the energy/amplitude of the event could be missed. Sea levels were measured by a float tide gauge with a Sutron SD0001 shaft encoder, with a precision lower than ±0.003 m. The system is mounted inside a vertical tube with a little water entrance located at the lower part of it to filter high-frequency oscillations caused by wind waves (periods of several seconds). Measurements present some few gaps but, in general terms, the record is quite complete. Sea level data gathered at Mar del Plata contain mixed mainly semi-diurnal tides, sporadic low-frequency perturbations associated with storm surges and high-frequency oscillations (ranging from a few minutes to almost 2 h) related to meteorological tsunamis.

Firstly, tidal signal was properly filtered from the observed data series. Predicted sea levels computed every 5 min (D'Onofrio et al. 2012) were obtained from 123 tidal constituents resulting from harmonic analysis (Foreman 1977) of a complete hourly sea level data series gathered between 1956 and 2006 at Mar del Plata. Data series (residuals) containing storm surges and meteorological tsunamis were obtained subtracting predicted sea levels from observed sea levels. The very slight sea level trend (approximately 1.53 mm/year; Fiore et al. 2008) was not taken into account in this study because the selected period (April 2010–January 2013) is short and its effect can be reasonably disregarded. A selected lapse of observed sea level data and predicted tide is shown in Fig. 3a where the predominantly semi-diurnal astronomical tide, the high frequencies associated with meteorological tsunamis and the low frequencies associated with storm surges can be clearly seen. Secondly, residual sea levels (observed sea level minus tide) were convoluted by means of a 251-weight Hamming high pass filter (Hamming 1977), with cutoff

Fig. 2 Mar del Plata tidal station, at Buenos Aires coast. (*Source* Google Earth)

frequency equal to 0.5 cph, to separate storm surge from meteorological tsunamis. A selected lapse with the simultaneous presence of a storm surge and a meteorological tsunami can be appreciated in Fig. 3b where the interference between both phenomena is clearly observed. It can be seen that the meteorological tsunami distorts the storm surge not only in the times of occurrence of the highest and lowest levels but also in the levels. Filtered sea level (meteorological tsunami) records at Mar del Plata (from 12/24 00:00 to 12/28 00:00 UTC 2012) are presented in Fig. 3c. It can be appreciated that large oscillations started at 12/24/2012 15:00 and the maximum observed amplitude was 0.30 m. This energetic event lasted for approximately 36 h. From the analysis of the whole sea level data records (April 2010–January 2013), fifteen energetic events of meteorological tsunamis with maximum wave heights higher than 0.20 m are obtained. Dates of the beginning, durations and maximum heights for each selected event are presented at Table 1. In addition, dates of the beginning, durations and extreme sea levels (positive or negative) for each selected storm surge event are also presented at Table 1, where an event was selected if the maximum (minimum) sea level water (without tide and meteorological tsunami) was higher (lower) than |±0.60 m|.

2.2 Meteorological data

NCEP-NCAR reanalysis I (Kalnay et al. 1996) database (www.cdc.noaa.gov) was used in order to get a representation of the mean sea level pressure (MSLP) fields for the fifteen selected events of meteorological tsunamis. The result of this analysis is a set of gridded data (2.5° horizontal resolution) with a temporal resolution of 6 h. In all the inspected

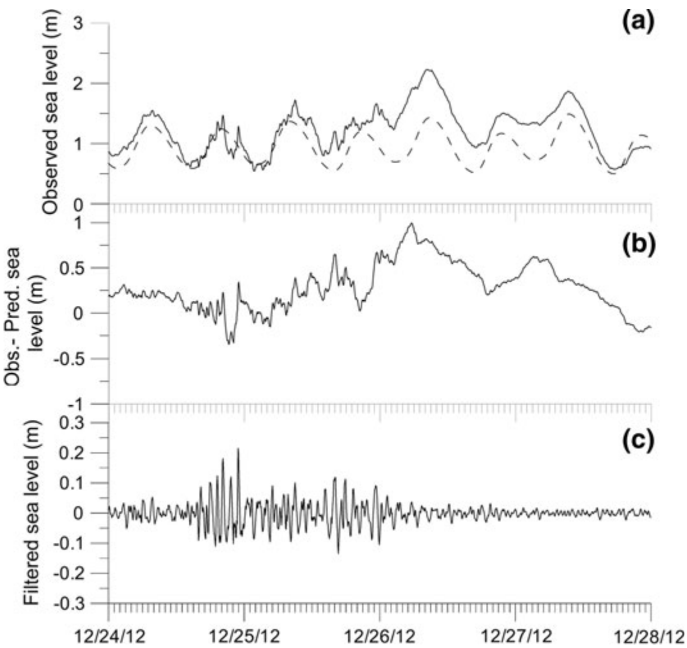

Fig. 3 **a** Observed (*solid line*) and predicted (*dashed line*) sea level (m), **b** storm surge and meteorological tsunami and **c** filtered sea level (meteorological tsunami) recorded at Mar del Plata (*period* December, 24–28, 2012)

Table 1 Date of the beginning, maximum height (Hmax), maximum sea level (SLmax) and duration of selected meteorological tsunami and storm surge events at Mar del Plata

Meteorological tsunamis (Hmax > 0.20 m)			Storm surges (SLmax > |±0.60 m|)		
Date (start)	Hmax (m)	Duration (h)	Date (start)	SLmax (m)	Duration (h)
11/03/2010 10:39	0.23	10.58	NR		
12/07/2010 22:59	0.23	27.75	12/08/2010 06:24	0.63	14.00
01/14/2011 00:19	0.27	24.58	NR		
01/28/2011 01:24	0.26	25.25	NR		
04/13/2011 07:04	0.20	37.08	04/14/2011 05:39	1.18	21.92
06/18/2011 19:04	0.26	53.08	NR		
11/09/2011 02:44	0.25	31.42	11/10/2011 09:54	0.61	11.42
11/27/2011 15:59	0.23	17.58	NR		
01/09/2012 23:29	0.32	33.25	NR		
03/09/2012 15:14	0.36	34.50	03/10/2012 14:29	0.64	17.08
07/16/2012 08:34	0.24	25.50	NR		
07/18/2012 06:54	0.21	38.92	07/18/2012 15:04	−0.66	10.58
08/12/2012 00:54	0.20	30.92	NR		
12/16/2012 15:49	0.28	32.25	12/17/2012 10:14	0.84	23.25
12/24/2012 14:59	0.30	36.42	12/25/2012 22:24	0.97	39.91

NR no recorded

cases, the synoptic situation was associated with the presence of a cyclone located southward the Río de la Plata estuary or at the north of the Patagonian continental shelf (slightly northward of 40°S) and with the noticeable presence of an atmospheric cold front coming from the south/southwestern. Synoptic situations corresponding to two selected events are shown (Figs. 4, 5) in order to illustrate these atmospheric features.

On December 24–25, 2012 (filtered sea level record was presented in Fig. 3c), an intense cyclone, with a minimum pressure of 996 hPa, can be appreciated over Buenos Aires Province continental shelf. This meteorological system produced strong southerlies on the western and northerlies on the eastern side of the cold front (Fig. 4). Maximum meteorological tsunami wave height reached 0.30 m and maximum storm surge level 0.97 m. On March 9–10, 2012 (the highest meteorological tsunami amplitude recorded during the analyzed period, Table 1), a cyclone, with a minimum pressure of 1003.5 hPa, can be seen at the north Patagonian adjacent continental shelf (Fig. 5). A cold front is clearly present in the region. Maximum meteorological tsunami wave height was 0.36 m, and maximum positive storm surge level was 0.64 m.

2.3 Geophysical data

The southeastern coast of South America (Fig. 6) has been traditionally considered to have low hazard probabilities of being affected by tsunamis. The main reason is the emplacement in a stable, tectonically inactive and passive continental margin (Mouzo 1982). However, some geological, topographical and oceanographic aspects of the Antarctic and surrounding regions should be reviewed as they could favor the occurrence of destructive events or contribute to increase damage. The Scotia Arc, located between the southernmost extreme of South America and the Antarctic Peninsula, is a highly dynamic convergent

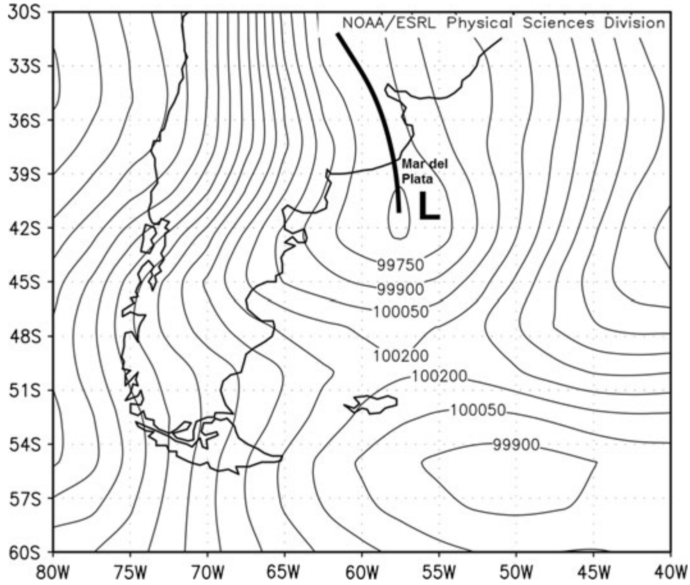

Fig. 4 Synoptic situation corresponding to 06:00 UTC, December 25, 2012. Mean sea level pressure (Pa). Surface cold front is indicated with *solid heavy line*

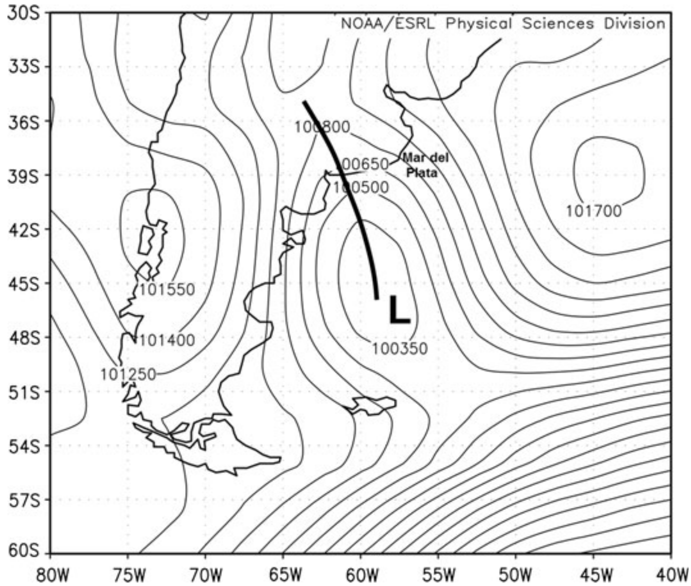

Fig. 5 Synoptic situation corresponding to 06:00 UTC, March 10, 2012. Mean sea level pressure (Pa). Surface cold front is indicated with *solid heavy line*

margin with frequent occurrence of earthquakes and volcanic eruptions (USGS-NEIC 2013). Considering the regional geotectonic setting, the configuration and the relative geographical position of Argentine coasts, the vulnerability to long ocean waves originated by submarine events such as earthquakes, volcanic eruptions and submarine landslides in the Scotia Arc and surroundings cannot be rejected. The seismic activity in the South Atlantic Ocean was inspected from the USGS-NEIC database for the studied period. Taking into consideration that no seismic activity with magnitude higher than 7 was recorded in the region (Fig. 6) from April 2010 to January 2013, the low possibility that some of the selected high-frequency sea level oscillations lapses (meteorological tsunamis events, Table 1) could have been generated by seismic activity was rejected. It is important to highlight that the unique tsunami detected at the Buenos Aires Province continental shelf—at the present—was generated as a response to the magnitude 9.3 earthquake centered off the west coast of northern Sumatra (3.3071N, 95.9471E) on December 26, 2004, at 00:59 UTC (Dragani et al. 2006; Dragani et al. 2008; Dragani et al. 2011). Maximum wave height observed at Mar del Plata station, almost 1 day after the occurrence of this earthquake, was 0.15 m.

3 Results

In order to study situations in which meteorological tsunamis and storm surges were simultaneously observed, events with filtered sea level oscillations higher than 0.10 m and (positive or negative) storm surges higher than $|\pm 0.30|$ m were preliminarily selected. Adopting these criteria, 186 active lapses of meteorological tsunamis and 125 of storm surges were obtained. Mean wave height (computed as the average of the mean wave

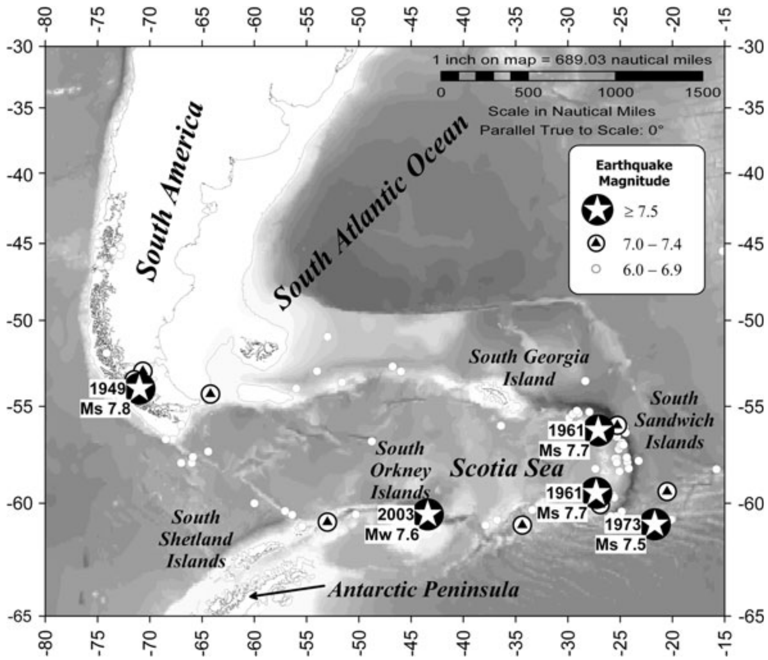

Fig. 6 Southwestern Atlantic Ocean and Antarctic Peninsula region. Locations of earthquakes which occurred in this area are pointed out with *white stars*, *black triangles* or *white circles* for earthquakes whose magnitudes were equal or higher than 7.5, ranged from 7.0 to 7.4 or from 6.0 to 6.9, respectively. Adapted from Dragani et al. (2008)

heights corresponding to each event selected) and mean duration for selected lapses of meteorological tsunami were 0.13 m and 27 h, respectively, and the maximum and minimum durations were 83 and 2 h, respectively. The duration of each event was calculated as the time in which the amplitude remained, in general, larger than the adopted threshold (0.10 m in this case). But it must be remarked that the amplitude may change significantly during a meteorological tsunami event and then amplitudes could be a little lower than the adopted criteria during brief periods. With regard to the storm surges, mean, maximum and minimum durations were 27, 184 and 7 h, respectively. Subsequently, in order to obtain a set of more energetic events, a more restrictive criterion was adopted for the selection. A subset of events in which the maximum wave heights were higher than 0.20 m and the storm surge extreme levels higher than |±0.60 m| were selected and are presented in Table 1. Maximum and minimum durations for the fifteen selected energetic meteorological tsunamis events were 53.08 and 10.58 h, respectively, and maximum and minimum durations for the seven selected intense storm surges lapses were 39.91 and 10.58 h, respectively.

Wavelet analysis is one of the more appropriate spectral analysis techniques to describe the variability of non-stationary sea level data series. Wavelet transforms (Torrence and Compo 1998) were applied on the selected energetic lapses (Table 1), but for space reasons, only the wavelet power spectrum (Fig. 7) corresponding to the event of December, 24–28, 2012 (Fig. 3c), is presented in this work. At the beginning, a short and weak episode located around the day 23 12:00, with spectral energy centered on 0.75 cph, can be observed in Fig. 7. After that, a longer and stronger period of irregular activity (between day 24 21:00 and 26 01:00) is clearly evident. Spectral energy is distributed between 0.5 and 1.5 cph, approximately. After the day 26 01:00, the spectral energy shows a noticeable reduction. It should be remarked that the analyzed power spectrum, corresponding to the event of December 24–28, 2012, can be considered as representative of the other events selected.

4 Discussion

From the inspection of the Table 1, it can be seen that, even though meteorological tsunamis and storm surge events can occur simultaneously, this is not always the case. For

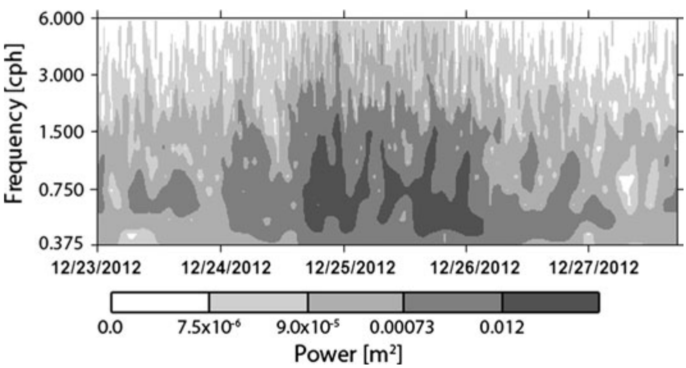

Fig. 7 Mar del Plata wavelet power spectrum. Levels of color palette from *white* to *dark gray* have been chosen so that 75, 50, 25 and 5 % of the wavelet power is above each level, respectively (Torrence and Compo 1998)

the analyzed period (from April 2010 to January 2013), meteorological tsunamis are pretty more frequent than storm surges. In the Buenos Aires Province, inner continental shelf meteorological tsunamis are generated by fluctuations of the atmospheric pressure associated with the propagation of atmospheric gravity waves which are very energetic during the passage of atmospheric cold front. The effectiveness of this generator mechanism was proved by Dragani (2007) by means of numerical simulations. On the other hand, storm surges occur during events characterized by persistent and strong southerlies, which can be also associated with frontal passages (Figs. 4, 5).

It is well known that positive storm surges can raise the water level producing significant differences between the observed level and the astronomical tide, and these events can be more severe if they coincide with a high tide and, specially, with the highest astronomical tide. However, storm surge events could be even more destructive and hazardous if they coincide with the presence of high-amplitude meteorological tsunamis. In this regard, it is important to highlight that the most conspicuous meteorological tsunami occurred on March 28, 1970, when a sea level oscillation of 1.62 m height (a little lower than the maximum tidal range at Mar del Plata, 1.70 m; SHN 2013) and 33-min period was recorded at Mar del Plata (Fig. 2, in Dragani et al. 2002). These sea level perturbations, present during strong and persistent southerlies and/or atmospheric cold front passages, can also increase the impact of wind waves on the upper sandy beach. The combination of all these mentioned factors could produce severe erosion on the beach, threatening sectors located along the Buenos Aires Province coast.

Zhang et al. (2001) calculated the storm erosion potential index (SEPI) 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 for each event. Subsequently, Fiore et al. (2009) calculated this index from observed levels based on hourly water level measurements at Mar del Plata. In this work, the storm surge signal was obtained from the residuals between the observed hourly levels and the predicted tide. Consequently, Fiore et al. (2009) used sea level measurements without filtering the meteorological tsunami oscillation. In order to evaluate the effect of the meteorological tsunami perturbation on SEPI, in the present work, this index was calculated using filtered storm surge data series (removing the meteorological tsunami signal), but not significant changes (lower than 2 %) were obtained. Some experiments were carried out computing SEPI on synthetic sea level records built by means of the (mobile) addition of the highest storm surge (14/4/2011) and the highest meteorological tsunami (9/3/2012) events (Table 1). Several experiments were designed positioning the instant of the maximum meteorological tsunami height in different moments of the storm surge data series, but very low changes (lower than 4 %) resulted in the values of SEPI. Consequently, considering these results, it is concluded that the presence of moderate meteorological tsunamis on sea level records would not enhance the erosive processes at the Buenos Aires coast at least, from the SEPI point of view.

Trends in height or extreme value of storm surges are usually determined from statistical analyses of hourly water levels. In general, positive and negative surges are determined from the residuals between observed levels and the predicted tide (D'Onofrio et al. 2008), but meteorological tsunamis are not considered in this analysis because they cannot be filtered from historical hourly sea level data. Taking into account that the positive or negative fluctuation of the meteorological tsunami can reach up the 20–30 % of the maximum (positive or negative) mean storm surge, its effect on the residuals (observed sea level minus predicted tide) could be highly significant and, consequently, could distort the statistics based on hourly sea level data. For instance, if the maximum elevation of the meteorological tsunami fell on the maximum positive (minimum negative) storm surge height, it would be significantly improved (diminished), but, on the other hand, if the minimum elevation of the meteorological tsunami fell on the maximum positive (minimum negative) storm surge height, it would be significantly reduced (enlarged). Consequently, the computed uncertainties on positive and negative storm surge height trends should be revised at least, at the Buenos Aires coastal area.

5 Conclusions

In this paper, it was seen that meteorological tsunamis were more frequently detected than storm surges for the period of study at Buenos Aires coastal region and sometimes both phenomena were simultaneously recorded at Mar del Plata. This occurs when atmospheric cold fronts and persistent strong southerlies are presented at the same time. The aim of this work was to discuss the effect of meteorological tsunamis in coastal erosion (during storm surge events) and the possible uncertainties in the computed trends of positive and negative storm surge extremes. In this study, simultaneous events in which maximum meteorological tsunami wave heights higher than 0.20 m and storm surge extreme levels higher than $|\pm 0.60|$ were selected and analyzed. Fifteen meteorological tsunamis, seven of them simultaneous to the occurrence of storm surge events, were selected. The impact of the meteorological tsunami in the SEPI was calculated. In the previous studies, SEPI was calculated at Mar del Plata from observed hourly water level measurements but without filtering the meteorological tsunami. In the present work, SEPI was calculated using filtered storm surge data series (from April 2010 to January 2013), but not significant differences (lower than 2 %) were obtained. Several sensitive experiments were carried out computing SEPI from synthetic sea level records, but very low changes (lower than 4 %) in the SEPI were also obtained. Consequently, the presence of moderate meteorological tsunamis on sea level records would not modify this index at the Buenos Aires Province coast. Trends in the extreme values of storm surges are usually determined from statistical analyses of hourly water levels. But the presence of meteorological tsunamis has not been considered because it cannot be subtracted from historical hourly sea level data. Taking into account that the oscillation of meteorological tsunamis can be up the 30 % of the storm surge extreme, it is highly possible that the statistics built on hourly sea level data can be a little distorted. Consequently, the statistics of extremes (and specially their uncertainties) of positive and negative storm surge trends should be reviewed at the Buenos Aires Province coastal area.

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