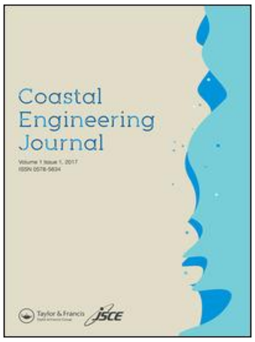

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TECHNICAL NOTE

The role of meteorological tsunamis on beach erosion in the buenos aires coast: some numerical experiments

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ABSTRACT
Meteorological tsunamis (meteotsunamis) are very similar to ordinary tsunamis but are produced by atmospheric processes. In this work, some numerical experiments are performed using XBeach numerical model investigate the role of moderate meteorological tsunamis on a sandy beach. The model was forced using tide, a moderate storm surge event, wave height data series and a meteorological tsunami event recorded in the Buenos Aires coast, Argentina. Several numerical experiments were carried out considering different time lags between the peak level of the meteotsunami event and the highest sea level (storm surge and tide). In these experiments, the volumes of moved sand were quite similar, although different erosion patterns on the beach were appreciated. Numerical experiments presented in this work constitute the first indication that the occurrence of regular meteotsunamis during moderate storm conditions could change the erosion pattern on sandy beaches in the coast of Buenos Aires.

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Meteorological tsunami; beach erosion; sandy beach profile; XBeach numerical model; Buenos Aires Province coast

1. Introduction

Meteorological tsunamis (meteotsunamis) are very similar to ordinary tsunamis, but produced by atmospheric processes and are regularly observed at sites with pronounced local resonant properties. The needed coincidence of several resonant factors significantly diminishes the possibility of occurrence for such events, and is the main reason why these phenomena are rare and restricted to specific locations (Monserrat, Vilibic´, and Rabinovich, 2006). Meteotsunamis occur frequently in the Mediterranean region, where the cases of Ciutadella Inlet (Menorca Island, Western Mediterranean) and Široka Bay (Island of First, Northern Adriatic) are examples of how destructive these waves can be (Rabinovich and Monserrat, 1996; Šepić, Vilibić, and Belušić, 2009). In addition, a well-studied meteotsunami called *Abiki* was described by Hibiya and Kajiura (1982) where maximum range (crest to trough height) reached 2.78 m at Nagasaki Bay on March 31, 1979. On the other hand, there are only a few studies that address this subject in the Atlantic coast of South America; this could be mainly due to the lack of adequate measurement in the region. In the Brazilian coast, Calliar, Franco, and Strauch (2005), based on eyewitness reports, described a possible meteotsunami event at Cassino Beach, Rio Grande do Sul. Candella (2009), using high-resolution sea level series, identified the main high frequency events and related them to possible forcing in Arraial do Cabo, Rio de Janeiro.

These longwaves (periods ranging from a 20 min to 2–3 h and heights usually lower than 0.5 m) have been frequently observed along the southeastern coast of South America (Figure 1). The spectral peaks of these waves are typically located between 1.1 and 4.7 cph (cycles per hour) during energetic events (Inman, Munk, and Balay, 1961; Dragani, 1997; Dragani, Mazio, and Nuñez, 2002). Significant coherence values showed that meteorological tsunamis can be seen as a regional phenomenon at the Buenos Aires coast. Dragani (1997) and Dragani, Mazio, and Nuñez (2002) noted that the spectral structures of atmospheric gravity waves and meteorological tsunamis were pretty similar and that the energetic transference from the atmosphere (atmospheric gravity waves) to the ocean (meteorological tsunami) was highly effective. As a result, Dragani (2007) and Pérez and Dragani (2017) concluded that atmospheric gravity waves (associated to warm and cold fronts) are the most probable forcing mechanism capable to generate meteorological tsunamis at the Buenos Aires continental shelf.

Buenos Aires is the largest and most inhabited province of Argentina (around 11% of Argentinean total area and 39% of the population) and its eastern coast extends for about 220 km between Punta Rasa and Mar del Plata (Figure 1). The beaches generally have a dissipative profile with a variable width (from 60 to 140 m), with slopes lower than 2° and with the

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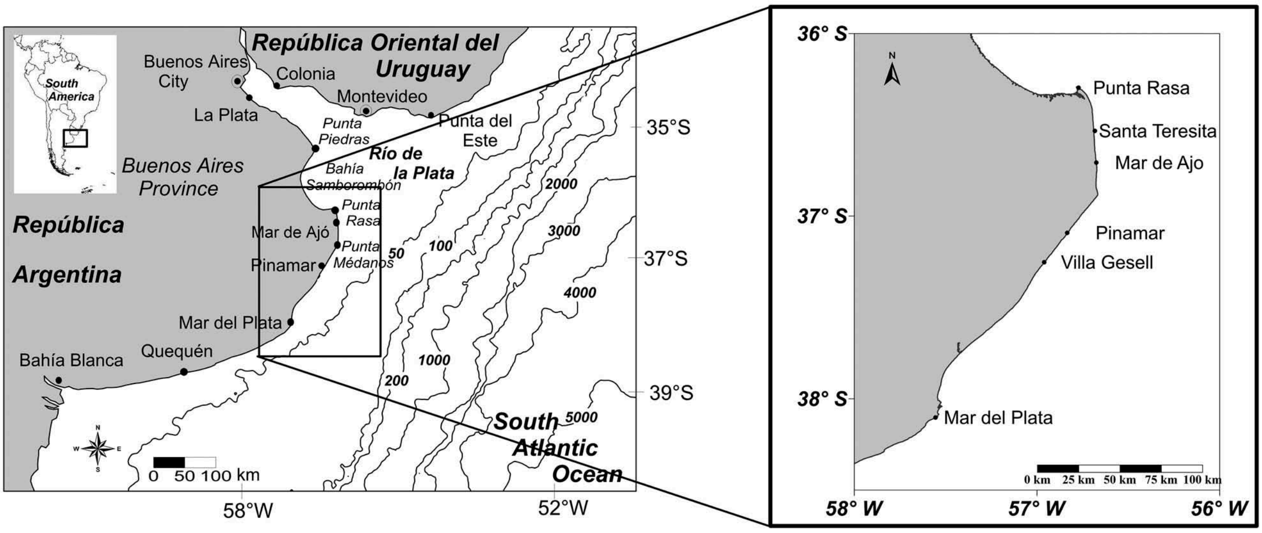

Figure 1. Buenos Aires Province coast (Argentina), on the left, and the study area, between Punta Rasa and Mar del Plata, on the right. A map of South America is included at the left upper corner.

development of sandbars (López and Marcomini, 2006). Tides in this region are mixed semidiurnal with a spring range of 1.90 and 1.88 m at Mar del Plata and Santa Teresita, respectively (SHN, 2017). The coincidence of large or even moderate high tides and large meteorologically induced surges has historically caused catastrophic floods and destruction in many coastal areas of the Buenos Aires Province (Fiore et al., 2009; Pousa et al., 2013). Dragani et al. (2014) showed that meteorological tsunamis and storm surge events can occur simultaneously and reported that meteorological tsunamis were significantly more frequent than storm surges. Storm surge events could be more destructive and hazardous if they coincide with the presence of high-amplitude meteorological tsunamis which would increase the impact of wind waves on the upper sandy beach. The combination of all these mentioned factors may enhance or modify the erosion pattern on the beach and affect some sectors of the coast which normally are not exposed. The aim of the present work is to investigate possible changes in the erosion pattern of a theoretical sandy beach profile, induced by the presence of a meteotsunami during moderate storm conditions. To that end, XBeach model, observed sea levels and wave data are used.

2. Data

Sea level records gathered every 5 min (from April 2010 to January 2013) at Mar del Plata tidal station located at the fisherman's pier (38°0′2″ S, 57° 32′ 18″ W) were available for this work. The tidal station is located in an open bay area where the mean depth is approximately 2.5 m. Except during very energetic storms, the tidal station is normally off the breaker zone, and consequently, it is not affected neither by the wave setup nor the presence of surf beats. Measurements present some few gaps but, in general terms, the record is quite complete.

Sea level data at Mar del Plata (Figure 2(a)) contain mixed mainly semi-diurnal tides (Figure 2(b)), low-frequency perturbations associated with storm surges (Figure 2(c)) and high-frequency oscillations (ranging from a few minutes to almost 2 h) related to meteorological tsunamis (Figure 2(d)). It can be seen at Figure 2(c) that storm surge activity is very frequent because storm force winds constantly blow over the continental shelf offshore of this coast (D'Onofrio, Fiore, and Pousa, 2008). Following to Dragani et al. (2014), data series (residuals) containing storm surges and meteorological tsunamis were obtained subtracting the tide from the observed sea levels. Next, residual sea levels were filtered in order to obtain the high-frequency signal (Figure 2(d)), such as was described in Dragani et al. (2014) and Pérez and Dragani (2017). The presence of active lapses between calm periods is clearly observed in Figure 2(d). This reveals the transitory character of the meteotsunamis. Three active events of meteotsunamis can be identified in this figure. The first one (from day 1 to 3) is relatively short and presents maximum amplitude of 0.15 m. A calm period (days 3–10), characterized by amplitudes lower than 0.05 m, can be appreciated after the end of the first active event. Afterward, other active event starts which lasts approximately 6 days. This is more energetic than the first one and presents maximum heights around 0.2 m. Subsequently, another calm period of 6 days long is observed between the days 16 and 22. Finally, the most energetic event with maximum heights of 0.4 m is observed from day 22. During these active events, the meteotsunamis periods are very variable ranging from 20 min to 3 h, approximately.

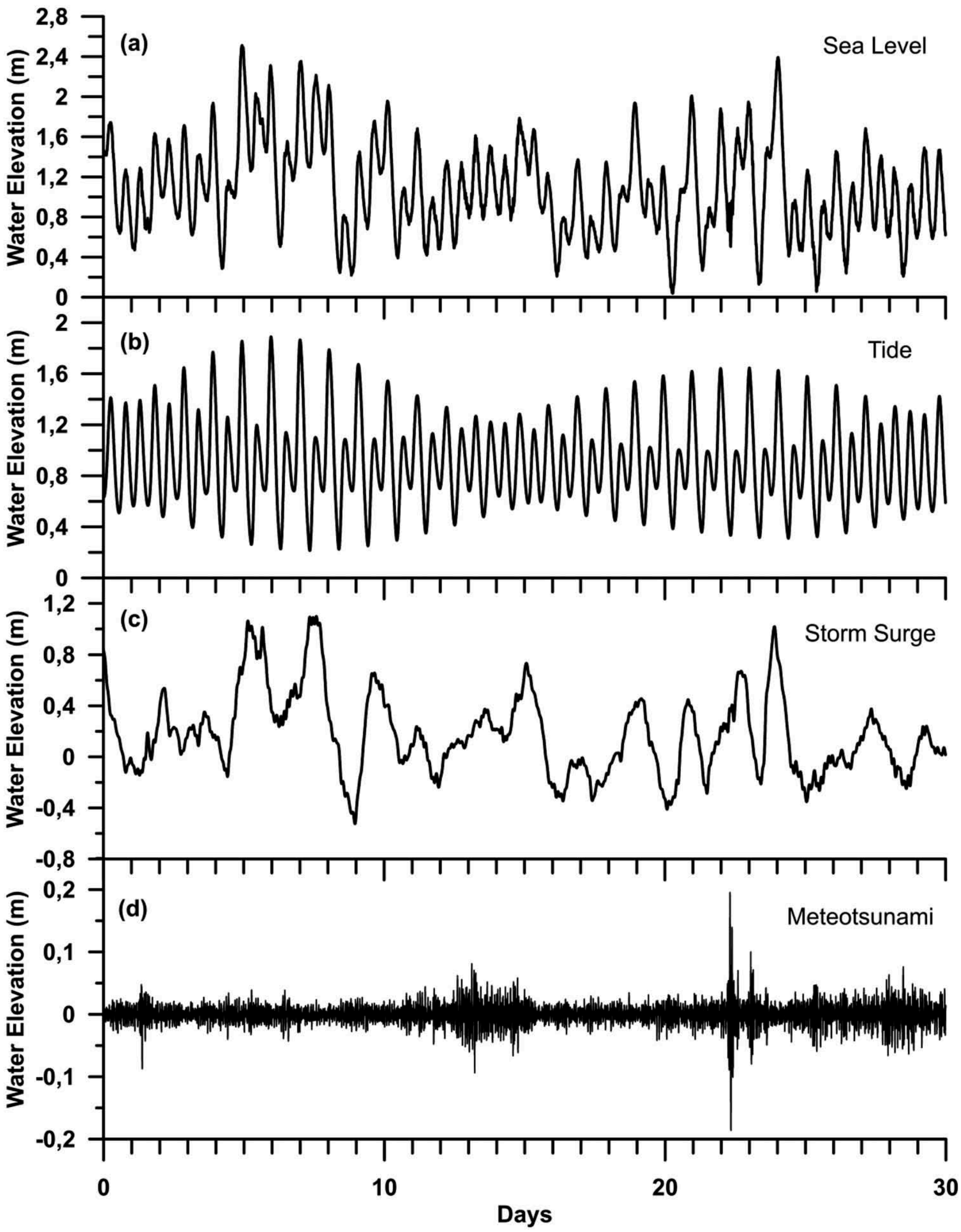

Figure 2. (a) Sea level data gathered at Mar del Plata (June 2012) contain (b) mixed mainly semidiurnal tides, (c) low-frequency perturbations associated with storm surges and (d) high-frequency oscillations (ranging from a few minutes to almost 2 h) related to meteorological tsunamis. These data series are used as basis to assemble the forcing as is shown in Figure 3.

An exhaustive analysis of meteorological tsunami and storm surge events was presented by Dragani et al. (2014). From April 2010 to January 2013, 15 energetic events of meteorological tsunamis were observed with heights higher than 0.20 m. The highest meteorological tsunami wave height was 0.36 m, and the maximum positive storm surge level reached 1.40 m. Even though meteorological tsunamis and storm surges can simultaneously occur during passages of atmospheric fronts, it is important to remark that both phenomena are completely different. Storm surges are produced by persistent and intense winds commonly blowing from the southeastern, and usually reach values higher than 1 m with periods longer than 12 h. On the other hand, meteorological tsunamis are induced by atmospheric gravity waves (associated to cold or warm fronts passages) but the amplitudes are usually lower than 0.50 m and the periods lower than 2 h. Figure 2(c) and 2(d) clearly shows the characteristics of typical storm surges and meteorological tsunamis, respectively, reordered at the Buenos Aires coast. A detailed analysis of the sea level data, which includes the date of the beginning, maximum height, maximum sea level and duration of selected meteorological tsunami and storm surge events was presented by Dragani et al. (2014). Breaker heights at Pinamar (Figure 1) were visually observed from the shore twice a day, without large gaps, from 1989 to 2013, following the guidelines given by the Littoral Environment Observation Data Collection Program (Schneider, 1981).

3. Numerical model

XBeach (Roelvink et al., 2009) is an open-source numerical model developed by Deltares, together with UNESCO-IHE and TU Delft. The model is used for computation of nearshore hydrodynamics and the morphodynamical response during storm events, such as dune erosion, overwash and scour around buildings. XBeach has been calibrated and validated for storm induce beach change in different locations of the world (see, e.g., Roelvink et al., 2009; Bolle et al., 2011; Bugajny et al., 2013; Dissanayake, Brown, and Karunarathna, 2014; Muller et al., 2016). XBeach includes the hydrodynamic processes of short-wave transformation (refraction, shoaling and breaking), longwave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching. A comprehensive description of XBeach is given in Roelvink et al. (2015).

In order to assess the impact of a meteotsunami on a sandy beach profile, several simulations with XBeach model were carried out considering moderate storm conditions (i.e. including storm surge) and sea level variations produced by a meteotsunami. Required input for XBeach includes bathymetry and wave boundary condition. The model was set on 1D profile mode and it was forced in the offshore boundary with a series of stationary wind waves with normal incidence. Additionally, a time-varying water level signal (tide and storm surge) was applied to the offshore boundary. Regarding the model parameters, only the sediment grain size was specified (D_{50}), relying on the default setting for the rest of the processes and model formulation. Detail description of default values used by the XBeach could be found in Roelvink et al. (2015).

3.1. Forcing and numerical experiments

In order to evaluate the erosive impact of a meteotsunami on a theoretical sandy beach, a realistic forcing including sea level perturbation associated with tide, observed storm surge, wave heights and metotsunami was implemented. The forcing was constructed superimposing tide (computed from 123 tidal constituents) and a moderate storm surge

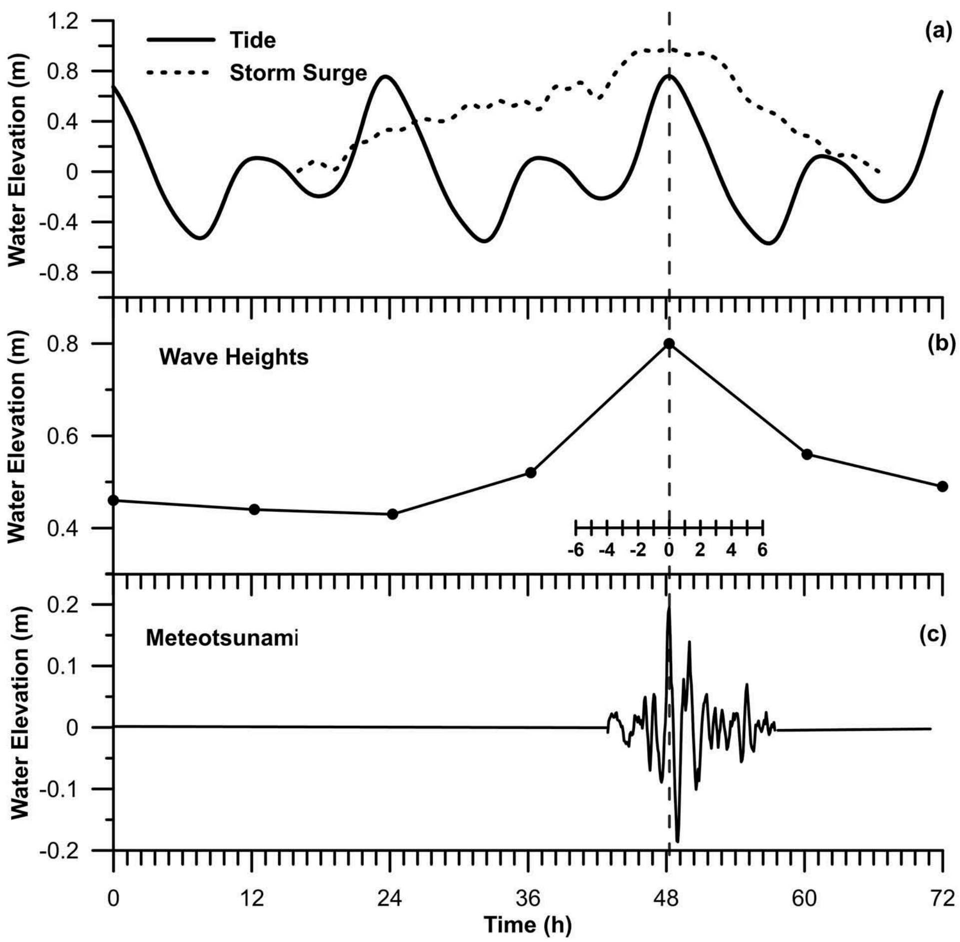

Figure 3. XBeach forcing: (a) tide and storm surge, (b) wave height and (c) meteorological tsunami. The high level tide, the maximum storm surge level and the highest breaker height were located at the time 48 h and the highest meteotsunami level was successively located at times ranged from 42 to 54 h, covering one semidiurnal cycle of the tide. Thirteen forcings were built to carry out the numerical experiments.

event (50 h long) which reached a maximum level of 0.97 m (Figure 3(a)). In addition, a selected data series of wave heights normally incident with respect to the coast were transformed (shoaling) from the breaking point depth to the deepest point of the profile (8 m depth) to build the wave boundary condition (Figure 3(b)). Finally, a meteorological tsunami event (14.5 h long), characterized by a maximum height of 0.36 m (crest to trough height), was added to build the forcing (Figure 3(c)). Considering the amplitude of sea level variations due to different forcings (Figure 3 (a) and (c)), it is easy to conclude that the contribution of meteotsunamis will be, in general, far less than the effect of the tide and the storm surge. The single difference among every numerical experiment was the lag between the time of the highest level reached by the meteotsunami and the time of the highest sea levels reached by the storm surge and tide. The high level tide, the maximum storm surge level and the highest breaker height were located at the time 48 h and the highest meteotsunami level was successively located at times ranged from 42 to 54 h, covering one semidiurnal cycle of the tide (Figure 3(b) and 4).

Available beach profiles at the Buenos Aires coast between Punta Rasa and Mar del Plata present fairly high spatial and temporal variability (Parker, Perillo, and Violante, 1978a; 1978b; Perillo, 1979). Then, it is rather difficult to choose a single measured beach profile which can be considered as representative of the Buenos Aires coastal area. In order to obtain a profile inclusive of most beach features, several locations (between Punta Rasa and Villa Gesell) and time (summer, winter, pre or pos storm) were included. An initial profile was synthesized averaging available short observed beach profiles from the dune to the surf zone (Figure 1). From the surf zone to the closure depth, an extrapolation was made using the equilibrium beach profile formula given by $h = A\,x^{2/3}$, where h is the still depth, x the cross-shore axis and A is the profile scale factor which is function of the energy dissipation and indirectly of the grain size (Dean and Dalrymple, 2004). Uniform mean diameter (d_{50}) of 0.19 mm (fine sand) was set for carrying out numerical experiments. This value was selected from the analysis of sediment grain size distributions of sand samples collected at the surf zone between Punta Rasa and Villa Gesell (Figure 1). Consequently, a synthesized profile referred to mean sea level, extending from the back dune to 8 m depth (approximately 420 m offshore) with regular spatial resolution of 5 m was used as initial condition in all numerical experiments. It is important to highlight that was not possible to carry out satisfactory calibration and validation of XBeach model in the region. Although beach profiles measured from 1974 to 1976 are probably the best ever obtained in the region, there are not simultaneous full beach profiles, high resolution sea level data and reliable wave data observations.

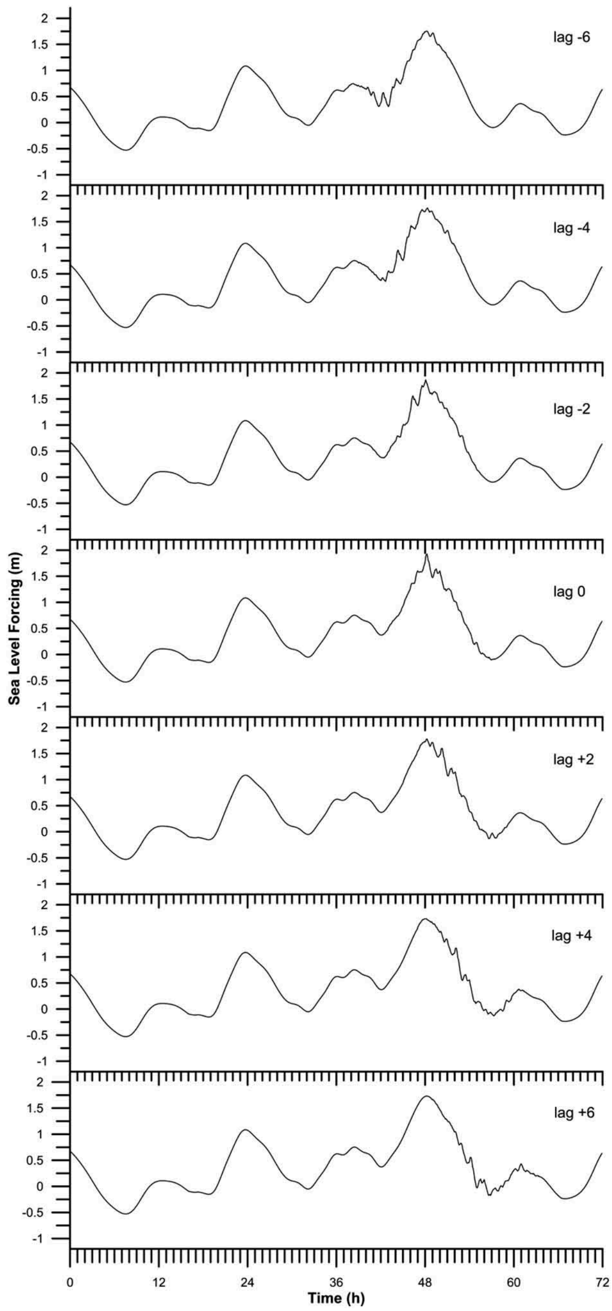

Figure 4. XBEACH sea level forcing: The high level tide and the maximum storm surge level were located at the time 48 h and the highest meteotsunami level was successively located at times lagged from −6 to + 6 h with respect to 48 h. Only even lags are shown.

Then, a set of numerical experiments are presented and discussed in the section below. The main aim of these numerical experiments is to quantify the role of a realistic meteotsunami on the beach erosion pattern during moderate conditions of tide, surge and waves. The first numerical experiment (control run) was carried out without including the meteotsunami data series in the forcing. In this case, the forcing was implemented with tide, storm surge and wave data series where the three maximum values were synchronized at the same instant (48 h). Initial and final profiles resulting from the control run are presented in Figure 5(a). Erosion on the beach (between 50 and 90 m) and two underwater bars, the main one (0.12 m height) located around 130 m and a narrower one at 100 m can be clearly appreciated in this figure. The difference between the final and the initial profiles is presented in Figure 5(b). The grayish area denotes the eroded zone on the beach.

4. Results and discussion

Several scenarios under multiple (moderate) tide, surge and wave conditions were considered and analyzed, but only a selected set of results is presented and particularly discussed. In the present section, 13 numerical experiments (where meteotsunami sea level perturbations were added with different lags in the forcing) were selected to show the impact of this atmospherically induced perturbation on the initial beach profile. The impact of each different forcing was quantified by means of the amount of sand redistributed on the beach (m^3/m^2, i.e. the volume of sand relocated on an elongated area of unitary width disposed along the whole profile) for every numerical experiment of 72 h of duration (Table 1). For a given numerical experiment, the erosion on the beach was quantified by means of the difference between the computed volumes of sand (m^3/m^2) with respect to the control run. The reallocated volume of sand corresponding to the control run was 1.25 $m^3/m^{2.}$ Positive differences (or percentages) presented in Table 1 indicate that the inclusion of the meteotsunami in the forcing (with a given lag) is more erosive than the forcing corresponding to the control run (that is, without meteotsunami).

Table 1 summarizes the numerical results. All experiments (and the control run) correspond to the same time (72 h) are presented in Figure 6. The volume of reallocated sand ranged from a null value (0%, lags −6 and ±5) to 1.34 m^3/m^2 (+7.2%, lags ±2) which is indicating that the relative position of the maximum height reached by the meteotsunami can modify the erosion on the beach profile. This issue is clearly evidenced when results corresponding to the lags +1 and +2 are compared. Numerical experiment corresponding to lag +1 (the meteotsunami peak occurs 1 h delayed) moved 1.26 m^3/m^2 of sand (almost the same amount of sand moved in the control run) but, when the meteotsunami peak occurs 2 h delayed, the amount of reallocated sand reached a maximum value of 1.34 m^3/m^2 (i.e. 7.2% more than the sediment moved in the control run). The most noticeable movement of sand resulted for the lags ± 2h. In both cases the volume of moved sand was 1.34 m^3/m^2

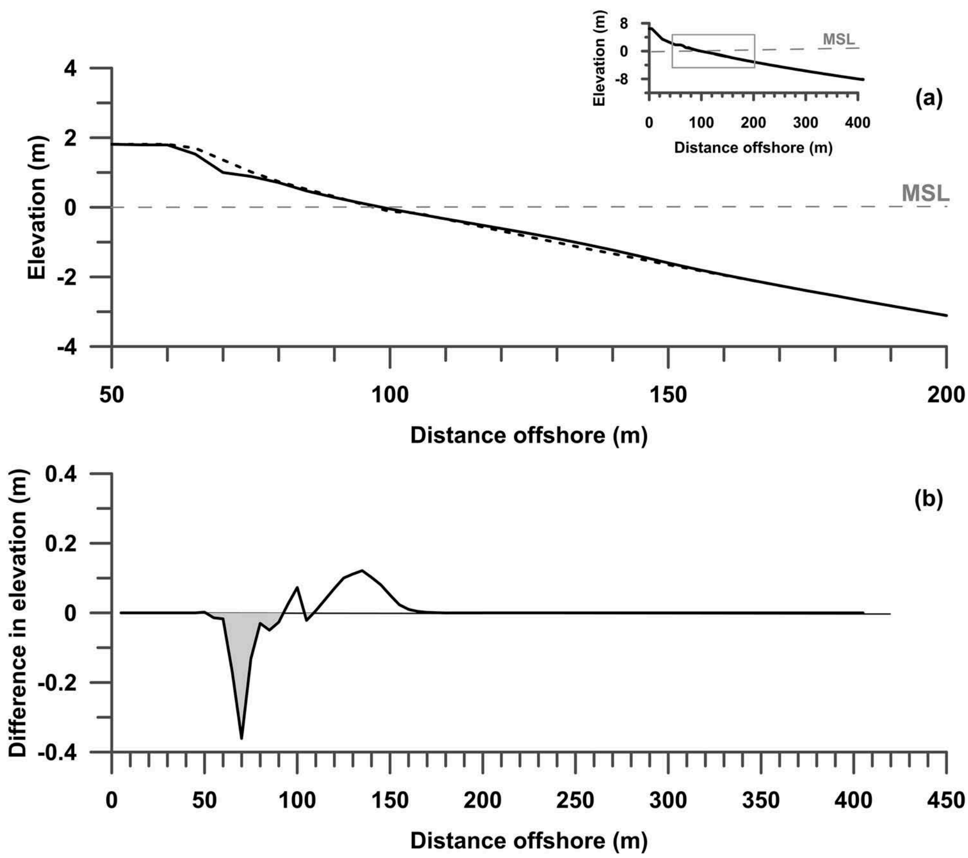

Figure 5. (a) Initial (dashed line) and final (solid line) profiles resulting from the control run, detail of the profiles between 50 and 200 m. (b) Difference between the final and the initial profiles, erosion on the beach (between 50 and 90 m) and two underwater bars, the main bar located around 140 m and the other bar at 100 m can be clearly appreciated. Grayish area denotes the eroded zone on the beach.

Table 1. Numerical results corresponding to different experiment from lag −6 to +6 h. Amount of sand redistributed on the beach (m^3/m^2 and percentages) and differences (percentages) between computed volumes with respect to the control run.

Lag (h)	Volume (m^3/m^2)	Volume (%)	Difference with control (%)
−6	1.25	93	0
−5	1.25	93	0
−4	1.29	96	3.2
−3	1.30	97	4
−2	1.34	100	7.2
−1	1.32	99	5.6
0	1.28	96	2.4
+ 1	1.26	94	0.8
+ 2	1.34	100	7.2
+ 3	1.30	97	4
+ 4	1.29	96	3.2
+ 5	1.25	93	0
+ 6	1.26	94	0.8
Control	1.25	93	–

(7.2% more than the control run). Numerical experiments corresponding to lags ±6, ±5 and +1 showed volumes of sand very similar to the control run (lower than +1%, approximately). In addition, it can be appreciated a clear symmetry between results corresponding to positive and negative lags (±2, ±3, ±4, ±5, ±6). The only exception corresponds to lags ±1, where the volumes of moved sand are different, 1.32 and 1.26 m^3/m^2, respectively.

A selection of results is presented in Figure 6 to illustrate the variability of the experiments when the meteotsunami data series is located at different times in the forcing. For space reason, only numerical results corresponding to even lags are portrayed in this figure. First, it can be noted that simulated beach profiles show an eroded beach and two sub-aqueous sandy bars. In all cases, it can be seen a broad sandy bar located between 110 and 160 m, approximately, which presents the maximal height (0.15–0.18 m) at 135 m. In addition, a lower (0.10 m height) and narrower sandy bar can be appreciated between 90 and 105 m. In general, the erosion on the beach is appreciated between 50 and 80 m, approximately. Although different erosion pattern is obtained for each numerical experiment depending on the lag. A sharp and deep eroded area, located between 60 and 75 m (with a minimal elevation around −0.42/−0.45 m) can be observed in Figure 6 for the lags: ±6 and ±4. In these cases, the differences of moved sand with respect to the control run are lower than 3.2%. A less sharp eroded area located between 55 and 80 m, with a minimal elevation of around −0.38 m, can be observed for lags ±2 h (Figure 6). In both beach profiles, the volume of sand moved was 1.34 m^3/m^2 (7.2% more than the control run). Finally, a wider and blunt eroded sector, located between 50 and 80 m, is produced in the numerical simulation corresponding to lag 0. In this case, the volume of moved sand was 1.28 m^3/m^2 (2.4% more than the control run).

Although the numerical simulations showed that the relocated volumes were similar with respect to

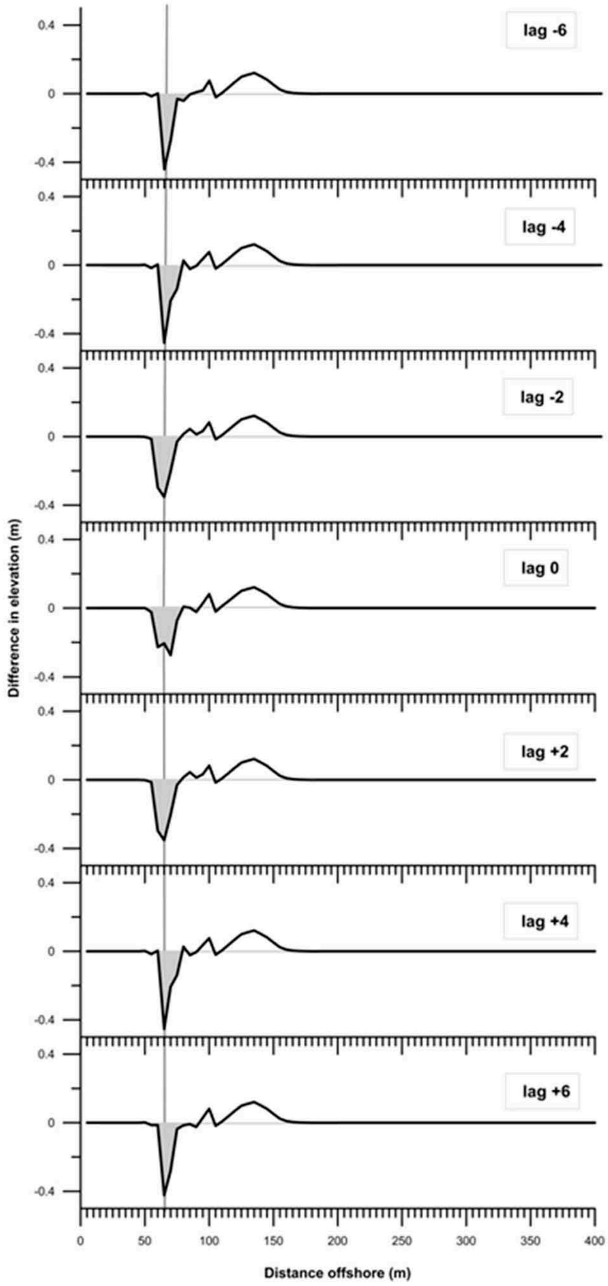

Figure 6. Difference between final and initial profiles for selected lags. Grayish area denotes the eroded zone on the beach. It can be appreciated that numerical results corresponding to lags −6, −2, +2, +4 and +6 present a similar pattern, that is, a moderated eroded beach and a subaqueous sandy bar. On the contrary, significant differences can be appreciated when simulated profiles corresponding to lag −4 and 0 are compared. Vertical gray line is added as reference.

the control run (Table 1), moderate differences in the erosion patterns on the beach profile were obtained when the meteotsunami is included in the forcing. In the control run, the eroded area is produced between 50 and 90 m on the profile (Figure 5). It can be seen that the erosion is weak and produces a small deepening (lower than 0.10 m) between 50–60 and 80–90 m. Between 60 and 80 m, the erosion pattern is very sharp, reaching a maximum depth of almost 0.40 m located at 70 m on the profile.

Numerical results corresponding to the lags ±2 (Figure 6) displays an erosion pattern slightly different. Erosion is produced between 55 and 80 m. The erosion pattern is less sharp than the corresponding to the control run, the maximum erosion is located at 65 m and three subaqueous sandy bars are produced when the meteotsunami is included in the forcing.

Numerical experiments described in the present work show that longwaves associated to a meteotsunami – superimposed to a moderate storm surge and tide – can change the erosive pattern on the sandy beach, but they do not constitute an erosive force as wind waves. When a meteotsunami event is present, waves (wind) can affect a wider sector of the beach which would not be reached. Meteotsunami impact on the Buenos Aires beaches is far to be comparable to the damages produced by meteotsunamis recorded in other places of the world. For instance, Šepić et al. (2015) reported that the chain of meteotsunamis in the Mediterranean and the Black Sea regions (June 23–27, 2014) significantly affected the coast of countries from Spain to Ukraine. Finally, there is no observational evidence which supports that meteorological tsunamis are able to break on the beach to produce direct erosion at the coast of Buenos Aires, as the case of destructive long ocean waves associated to typical tsunamis.

5. Conclusions

The role of a moderate meteorological tsunami on a sandy beach profile during regular storm conditions was studied by means of the XBeach numerical model. The forcing was constructed superimposing tide, a moderate storm surge event, wave height data series representative of an ordinary wind wave condition and a regular meteorological tsunami event. Meteotsunami data series were located at different times along the tidal cycle to generate a set numerical experiments. Even though the volumes of relocated sand were quite similar (ranged from 1.25 to 1.34 m^3/m^2), different erosion patterns on the beach were obtained depending on the lags between the instants of occurrence of the meteotsunami peak and the wave data series, storm surge and tide maxima. Then, these results constitute the first indication that the occurrence of regular meteotsunamis during moderate storm conditions could change the erosion pattern on sandy beaches in the coast of Buenos Aires. Unfortunately, the lack of simultaneous pre and post full storm beach profiles, high-resolution sea level data and wave observations precludes advancing in the calibration and validation of XBeach model in order to reach a better understanding of this subject in the study region.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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