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Spectral variability in high frequency in sea level and atmospheric pressure on Buenos Aires Coast, Argentina

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ABSTRACT

There are some observational evidences which support that atmospheric gravity waves constitute an efficient forcing for meteorological tsunamis (meteotsunamis) along the coast of Buenos Aires, Argentina. Meteotsunamis and atmospheric gravity waves, which propagate simultaneously on the sea surface and the atmosphere, respectively, are typical examples of non-stationary geophysical signals. The variability of meteotsunamis and atmospheric gravity waves recorded at Mar del Plata was investigated in this paper. Results obtained in this work reinforce the idea of a cause (atmospheric gravity waves) effect (meteotsunami) relationship, because wavelet spectra obtained from both signals resulted quite similar. However, several very short episodes of mod-erate/low activity of atmospheric gravity waves were detected without detecting meteotsunami activity. On the other hand, it was found that atmospheric gravity wave spectral energy can appear in the wavelets as a single or multiple burst as relatively long and irregular events or as regular wave packets. Results obtained in this paper provide original spectral data about atmospheric gravity waves along the coast of Buenos Aires. This information is useful to be included in realistic numerical models in order to investigate the genesis of this complex atmosphere-ocean interaction.

Descriptors: Meteorological tsunamis; Atmospheric gravity waves; Spectral variability; Wavelet analysis; Buenos Aires coast.

RESUMO

Existem evidências observacionais que apoiam a ideia de que as ondas de gravidade atmosféricas são um forçante eficiente para os tsunamis meteorológicos (meteotsunamis) na região da costa da província de Buenos Aires, Argentina. Os meteotsunamis e as ondas de gravidade atmosférica que se propagam simultaneamente na superfície do mar e na atmosfera, respectivamente, são exemplos típicos de sinais geofísicos não estacionários. Neste trabalho investiga-se a variabilidade de meteotsunamis e de ondas de gravidade atmosférica medidas em Mar del Plata. Os resultados obtidos mostram que os ondeletas para os meteotsunamis e as ondas de gravidade são relativamente semelhantes. Isso reforça a ideia da relação causa (ondas de gravidade atmosférica) efeito (meteotsunamis) entre ambos. No entanto, vários episódios muito curtos de moderada a baixa atividade de ondas de gravidade atmosféricas foram detectados sem detectar atividade meteotsunami. Por outro lado, encontrou-se que a energia espectral das ondas de gravidade atmosférica pode aparecer nos ondeletas como uma simples ou múltipla irrupção, como eventos irregulares relativamente longos, ou como pacotes de ondas regulares. Os resultados obtidos neste trabalho proporcionam informação espectral sobre as ondas de gravidade atmosférica na região costeira da província de Buenos Aires. Esta informação poderia ser útil para incluí-la em modelos numéricos realistas, com o objetivo de investigar a gênese desta complexa interação oceano-atmosfera.

Descritores: Tsunamis meteorológicos; Ondas de gravidade atmosféricas; Variabilidade espectral; Ondeletas; Costa de Buenos Aires.

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INTRODUCTION

Meteorological tsunamis (meteotsunamis) are produced by atmospheric processes (atmospheric gravity waves, pressure jumps, squalls or frontal passage), and they are regularly observed at the same sites with pronounced local resonant properties. They 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). The necessary coincidence of several resonant factors significantly diminishes the possibility for such events to occur, which is the main reason why these phenomena are rare and restricted to specific locations (MONSERRAT et al., 2006). Meteotsunamis, with periods varying from a few minutes to almost 3 h and heights typically lower than 1 m, have been frequently observed in different tide stations between Mar de Ajo and Quequén on the southeastern coast of South America (Figure 1). INMAN et al. (1961) were the first who obtained the power spectra for meteotsunamis for a 10-day-interval of sea level records for tide gauge stations located at Mar del Plata and Quequén. Subsequently, DRAGANI et al. (2002) showed that the main spectral peaks of these waves covered almost the whole frequency band between 1 and 5 cycles per hour (cph) during energetic events. Significant coherence values estimated between Mar de Ajó and Mar del Plata (172 km apart, Figure 1) clearly showed that meteorological tsunamis at the Buenos Aires Province inner continental shelf can be seen as a regional phenomenon. In addition, maximum amplitudes detected for each event at Mar de Ajó, Pinamar, Mar del Plata and Quequén are very similar (DRAGANI et al., 2009).

Regarding the origin of meteotsunamis BALAY (1955) was the first that report these long ocean waves at Buenos Aires Province coastal waters were associated with the passage of meteorological cold fronts coming from central Patagonia. Subsequently, 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 Bahia Blanca meteorological station (Figure 1) showed a lower pronounced tropospheric inversion that depicts an example of the state of the atmosphere 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, 1998). Based on the occurrence of

Figure 1. Buenos Aires Province coast (Argentina). A map of South America is included at the right bottom corner.

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.

Meteotsunamis and atmospheric gravity waves, which propagate simultaneously on the sea surface and the tropospheric inversion respectively, are typical examples of non-stationary geophysical signals. Both of them were described by DRAGANI et al. (2002) implementing classic spectral analysis techniques (JENKINS; WATTS, 1969; BÅTH, 1974). However, power spectrums have shown not to be the most appropriate method to retrieve the sequence of the sea level and pressure oscillations during these events. In this sense, wavelet analysis is one of the more appropriate spectral analysis techniques to describe the variability of non-stationary sea level and atmospheric pressure data series. Wavelet transforms are used to analyze time series that contain non-stationary power at many different frequencies (TORRENCE; CAMPO, 1998). Wavelet analysis maintains time and frequency localization in a signal analysis by decomposing or transforming a one-dimensional time series into a diffuse two-dimensional time-frequency image simultaneously.

The aim of this work is to investigate the temporal variability of meteotsunamis and atmospheric gravity waves recorded at Mar del Plata using wavelet analysis technique. Meteotsunamis and atmospheric gravity waves are highly non-stationary and both signals are very noticeable in high resolution sea level and atmospheric pressure data series. There are enough evidences to support the theory that atmospheric gravity waves constitute an efficient forcing for meteotsunamis (DRAGANI, 2007). In this sense, wavelet analysis for the first available data series of simultaneous high resolution atmospheric pressure and sea level data series gathered at Buenos Aires coast is presented and discussed in this paper.

MATERIAL AND METHODS

Digital sea level records collected every 5 min at Mar del Plata tidal station located at the fisher's pier (38° 0' 2'' S, 57° 32' 18'' W) were available for this work. The tidal station is located in an open coastal area where the mean depth is approximately 2.5 m. Sea levels (tide, storm surge and meteotsunami) 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 a few gaps but, generally, the record is quite complete.

A selected sea level data series (from February 25 to March 6, 2013) is presented in Figure 2 to illustrate the different signals involved in these records. Observed sea level data (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 3 h) related to meteorological tsunamis (Figure 2.d). 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 convoluted by using a 251-weight Hamming high pass filter (HAMMING, 1977), with cutoff frequency equal to 0.5 cph, in order to obtain the high-frequency signal (Figure 2.d). A detailed statistical analysis for the whole sea level data series, which includes the beginning date, maximum height, maximum sea level and duration of detected meteorological tsunami and storm surge event was presented by DRAGANI et al. (2014).

Atmospheric pressure data series were collected every minute by a Davis weather station (barometric sensor located at 10 m level above the mean sea level) at Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP, situated 3.5 km southward Mar del Plata tidal station). Atmospheric pressure measurements present several gaps, some of them significantly long. A selected atmospheric pressure data series (from February 25 to March 6, 2013) is presented in Figure 3. Observed atmospheric pressure data series (Figure 3.a) contain the synoptic barometric contribution and very high-frequency oscillations (ranging from a few minutes to almost 3 h) related to atmospheric gravity waves (Figure 3.b). A minimum pressure value can be clearly noticed (991.5 hPa, Figure 3.a) associated to a cold front passage at Mar del Plata. Observed atmospheric pressure data series were also convoluted using the same Hamming high pass filter described before, in order to obtain the high-frequency signal (Figure 3.b). Barometric data series were re-sampled every 5 min in order to apply exactly the same mathematical technique to atmospheric pressure and sea level data series. Filtered sea level

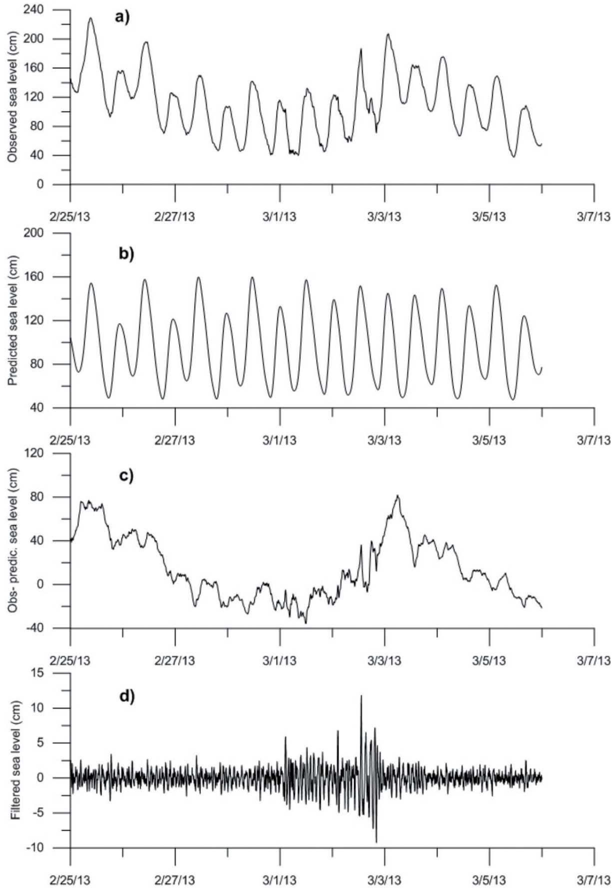

Figure 2. (a) Sea level data observed at Mar del Plata, (b) mixed mainly semi-diurnal tides, (c) low-frequency perturbations associated with storm surges and (d) high-frequency oscillations, ranging from a few minutes to almost 3 h, related to meteorological tsunamis.

data series were corrected from the inverse barometric effect, this is an increase (decrease) in barometric pressure of 1 hPa corresponds to a fall (raise) in sea level of, approximately, 0.01 m (WILSON, 1972). It was proved that this correction does not produce significant modifications on filtered sea level data series. Then, the wavelets computed from non-corrected and corrected sea level data series resulted practically identical.

RESULTS

Power spectra from filtered sea level (Figure 2.d) and atmospheric pressure (Figure 3b) are presented in Figure 4. The meteotsunami spectrum (Figure 4.a) shows the highest energetic peak placed at 0.47 cph (2.1 h), and secondary spectral peaks at 0.70 and 0.92 cph (1.4 and 1.08 h). Several weaker spectral peaks are located from 1 cph to higher frequencies. The atmospheric gravity wave spectrum (Figure 4.b) shows the highest energetic peaks located at 0.44 cph (2.23 h) and 0.66 cph (1.53 h).Three intense peaks, two of them located between 0.5 and 0.6 cph and one at 0.82 cph (1.21 h), are also appreciated. Three moderate peaks are placed around 1 cph and one at 1.67 cph (0.6 h). Several weaker spectral peaks can be observed from 2 cph to higher frequencies. Both power spectra seem fairly similar to each other, but they are unable to explain the temporal variability of both signals. In addition, traditional spectral analysis is not the more appropriate spectral analysis technique to describe the variability of non-stationary sea level and atmospheric data series because spectral contributions corresponding to energetic and no energetic lapses are averaged. Classical spectra analysis is frequently used to analyze separately energetic events (active lapses) and periods of calm (background) of sea level and atmospheric pressure and, consequently, the periods of increasing or decreasing of the activity between

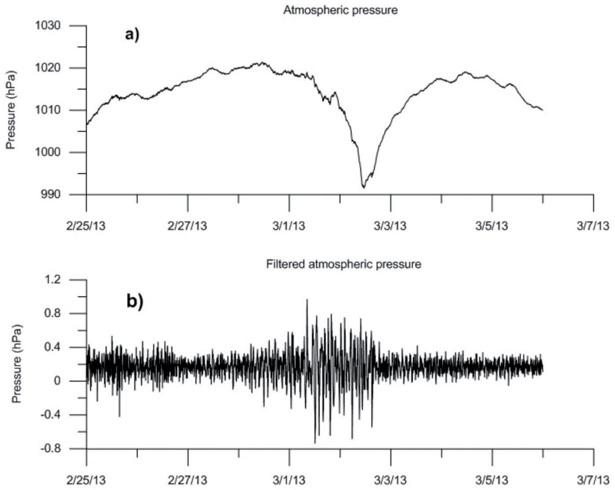

Figure 3. (a) Atmospheric pressure observed at Mar del Plata and (b) high-frequency oscillations, ranging from a few minutes to almost 3 h, related to atmospheric gravity waves.

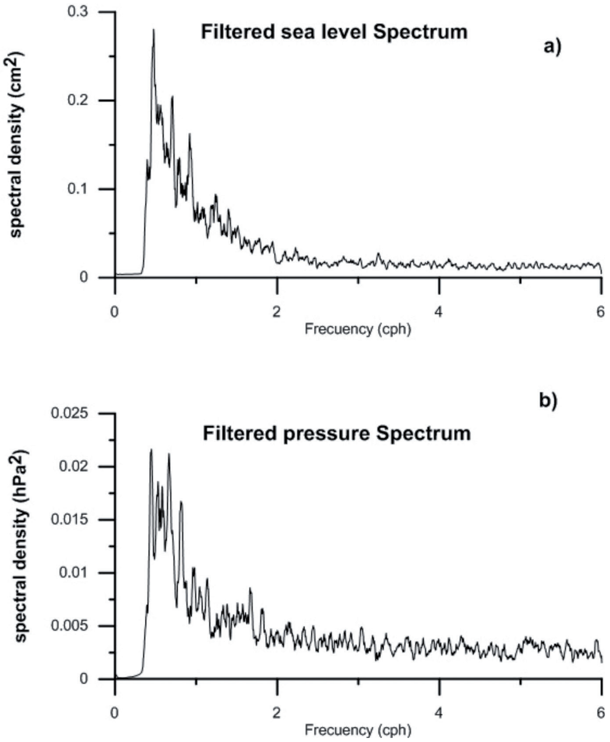

Figure 4. Filtered (a) sea level and (b) atmospheric pressure spectra obtained from data series presented en Fig. 2 and 3, respectively.

both states are not usually considered or described. For this specific subject, wavelet analysis is considered as one of the more appropriate spectral analysis techniques to describe the variability of non-stationary data series.

Three relatively long data series (~1 month) of simultaneous sea level and atmospheric pressure data series were selected to analyze the activity of meteotsunamis and atmospheric gravity waves. Filtered sea level and atmospheric pressure transforms using Morlet Wavelet (TORRENCE; COMPO, 1998) for the three selected active events are presented in Figures 5 to 10. The sea level wavelet power spectrum (Figure 5) for the first selected period (from February 20 to March 21, 2013) shows three active lapses with distinctive features. At the beginning, a short episode located around February 24, with higher spectral peaks located at periods of 50-80 min, can be observed. After that, a longer period of irregular and high activity (between March 1 and March 4) is clearly manifested. Spectral energy gradually increases, in March 1-2 spectral energy is broadly distributed between 50 and 160 min and, subsequently, a noticeable reduction of the energy can be appreciated. Finally, a relatively longer event of moderate and irregular activity (from March 6 to 13) is observed in Figure 5.b. Spectral energy is irregularly distributed between 30 and 150 min. The atmospheric pressure wavelet power spectrum (Figure 6) also shows three active lapses which occur simultaneously to the sea level events, with spectral characteristics very similar to the described before, for the first selected period.

The sea level wavelet power spectrum (Figure 7) for the second selected period (from March 23 to April 30, 2013) shows two meteotsunamis events. The first one takes place between March 25 and 27, spectral energy is broadly distributed between almost 30 and 135 min, approximately. A period of relative calm is presented in the middle part of this event, from March 25th 18:00 to March 26th 12:00. This temporal variability in the spectral power is very common in this kind of phenomenon. Subsequently, a short energetic lapse can be observed on April 6-7, where sea level heights (distance between trough to crest) of almost 0.30 m can be observed (Figure 5.a). In contraposition, the atmospheric pressure wavelet power spectrum for this period (Figure 8) shows not only activity for the above described lapses but also several very short episodes of moderate or low activity of atmospheric gravity waves which do not impact on the sea level.

The sea level wavelet power spectrum (Figure 9) for the third selected period (from May 28 to June 30, 2013) presents irregular activity of meteotsunamis from May 28 to June 19 at 12:00. Spectral energy can be seen unevenly distributed between 40 and 150 min and energetic lapses are alternated by short periods of calm. After June 20 the meteotsunami activity significantly decreases. The atmospheric pressure wavelet power spectrum (Figure 10) presents spectral characteristics very similar to the before described for the sea level. It can be seen that atmospheric gravity waves activity is clearly also intermittent.

DRAGANI et al. (2002) presented several evidences that suggest that meteotsunamis could be forced by atmospheric gravity waves associated to frontal passages at the Buenos Aires coast. In the present work, results obtained from the first long data series of simultaneous sea level and atmospheric pressure measured at Mar del Plata confirm this suggestion. As was showed previously, atmospheric gravity waves can appear as a burst, as

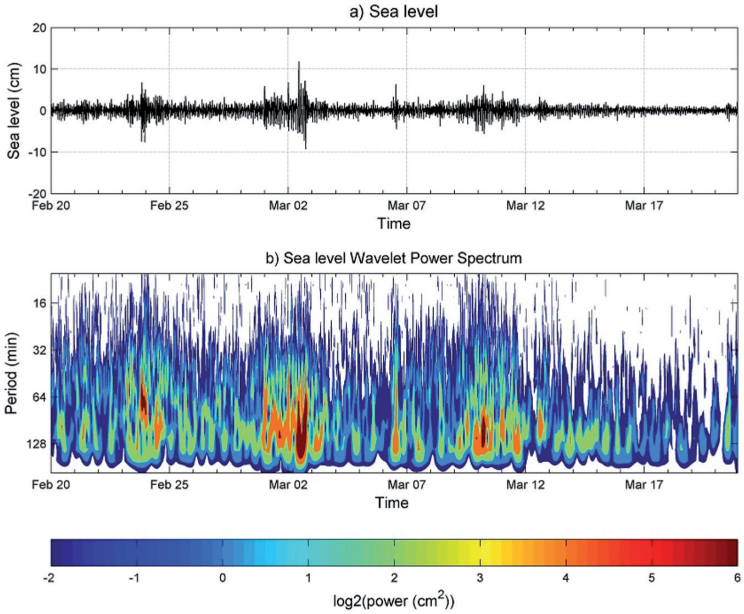

Figure 5. (a) First selected sea level data series, from February 20 to March 21, 2013 and (b) wavelet spectrum

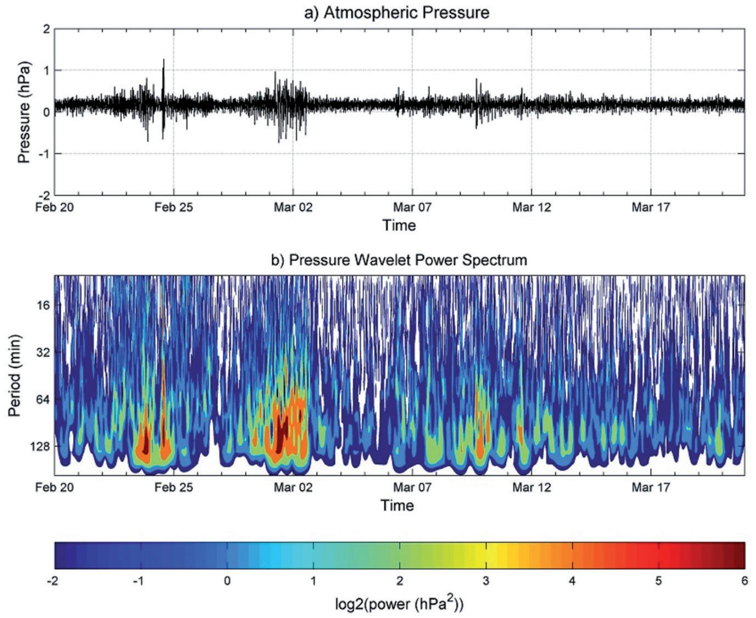

Figure 6. (a) First selected atmospheric pressure data series, from February 20 to March 21, 2013 and (b) wavelet spectrum

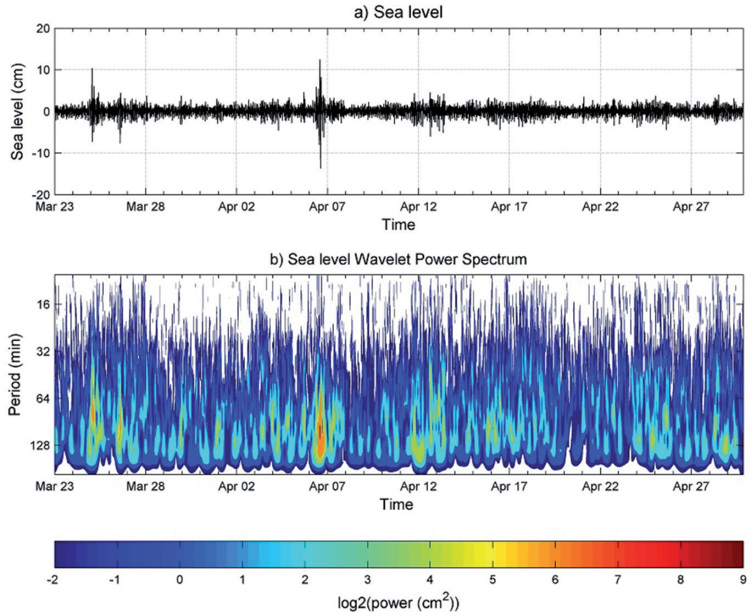

Figure 7. (a) Second selected sea level data series, from March 23 to April30, 2013 and (b) wavelet spectrum.

multiple bursts, as relatively long and irregular events or as regular wave packets but always with associated spectral energy distributed from 20 min to almost 3 h. Periods of calm of variable length, characterized by relative low energy levels, are usually present between energetic events. The spectral structure and the temporal variability of meteotsunami and atmospheric gravity wave energy are not exactly the same but they are fairly compatible. Wavelet spectra of atmospheric gravity waves present more events than the meteotsunami spectra. A selective energy transference from the atmosphere to the ocean, in some measure constrained by the characteristic

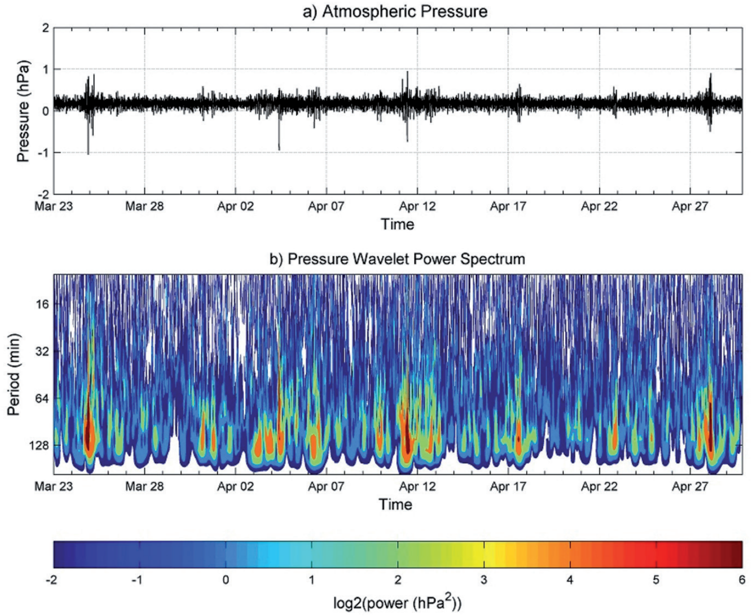

Figure 8. (a) Second selected atmospheric pressure data series, from March 23 to April 30, 2013 and (b) wavelet spectrum.

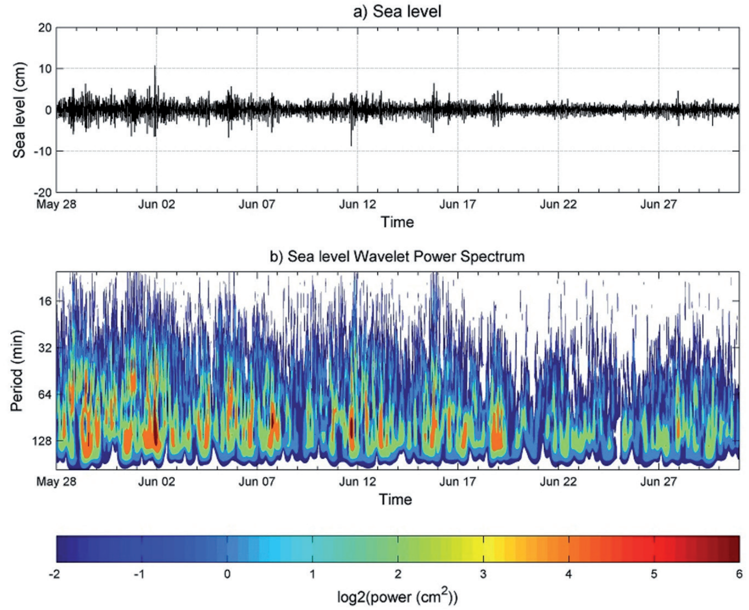

Figure 9. (a) Third selected sea level data series, from May 28 to June 30, 2013 and (b) wavelet spectrum.

of the forcing (for example, direction and speed of the cold front or amplitude and celerity of the atmospheric gravity waves) could be the explanation of the spectral differences. An appropriate inference of these atmospheric parameters would be crucial to implement realistic pressure patterns of atmospheric gravity waves to simulate meteorological tsunamis by using of numerical models (DRAGANI, 2007). In this sense, results obtained in this paper give new information about the spectral structure of the atmospheric gravity waves at Buenos Aires coastal area.

Interactions between atmospheric gravity waves and meteotsunamis were reported and analyzed in different sites

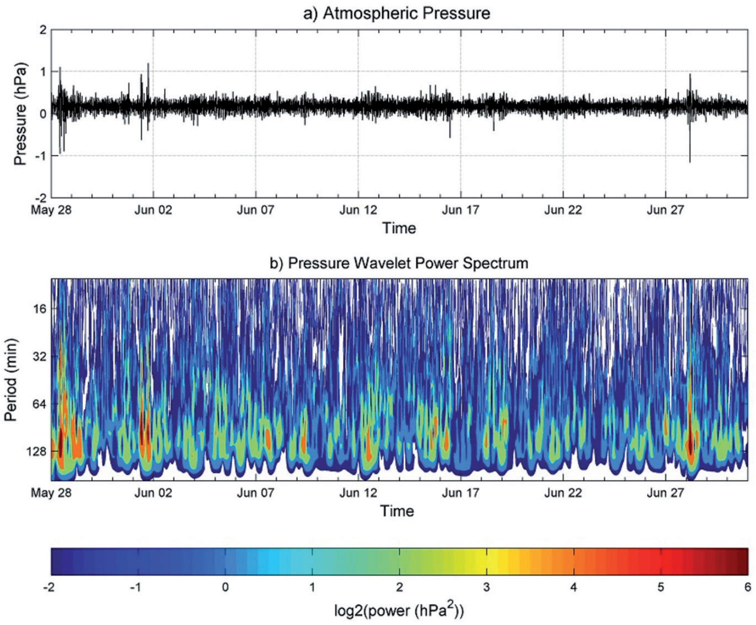

Figure 10. (a) Third selected atmospheric pressure data series, from May 28 to June 30, 2013 and (b) wavelet spectrum.

of the world. For instance, VILIBIĆ and MIHANOVIĆ (2003) studied resonant oscillations in the Split harbor (Adriatic Sea) implementing wavelet spectra. Theyfound that large amount of energy is placed both on air and sea pressure data series. Nevertheless, it was found that the peak connected with sea-level oscillations is somehow wider in time (almost three times). The spectral evolution showed that the sea-level energy rise together with the air pressure energy. THOMSON et al. (2009) analyzed in details events of 13 July 2007 and 26 February 2008 in the North America west coast. Analysis of coincident 1-min sea level data and high frequency atmospheric pressure data confirms that the events originated with atmospheric pressure jumps and trains of atmospheric gravity waves with amplitudes of 1.5–3 hPa. PELLIKKA et al. (2014) analyzed four case studies of exceptional wave events of meteorological origin, observed on the Finnish coast in the summers of 2010 and 2011. They used high-resolution sea-level measurements and confirmed that the sea level oscillations coincide with sudden jumps in surface air pressure at coastal observation stations, related to the passage of squall lines or gust fronts. These fronts propagate above the sea at a resonant speed, allowing efficient energy transfer between the atmospheric disturbance and the sea wave that it generates. ŠEPIĆ et al. (2015) studied atmosphere induced long ocean waves in the Mediterranean and Black Seas generated by high-altitude atmospheric forcing by using spectral wavelet analysis. They analyzed simultaneous pairs of 3-h cut-off, high-pass filtered time series of air pressure and sea level recorded at coastal locations on the Balearic Islands (Spain), in the Adriatic Sea (Croatia), and in Sicily (Italy). ŠEPIĆ et al. (2015) showed that the passage of pronounced atmospheric disturbances is roughly concurrent with the onset of strong sea level oscillations. In addition they reported that although the linkages between enhanced sea level oscillations and intensified atmospheric disturbances are highly non-linear, the time series are clearly indicative of a cause and effect relationship. Recently, ŠEPIĆ et al. (2016) examined a two-day period of remarkable meteotsunami activity in the Adriatic Sea. To examine temporal variations of the observed water-level and air pressure oscillations in the frequency domain they used a multiple-filter method (DZIENOWSKI et al., 1969), which is similar to wavelet analysis. They concluded that meteotsunamis occurring at various parts of the coast were generated by different atmospheric air pressure disturbances and that the sea surface response was strongly dependent on details of atmospheric forcing.

Results obtained in this paper reaffirm previous presumption given by DRAGANI el al. (2002) which supports that meteotsunamis could be forced by atmospheric gravity waves at the Buenos Aires coast. First long data series of simultaneous sea level and atmospheric pressure measured at Mar del Plata confirm the possibility of a cause (atmospheric gravity waves) and effect (meteotsunami) relationship. Even though atmospheric gravity wave and meteotsunami wavelet spectra are quite similar (as in time as in frequency), there were several very short episodes of moderate/low activity of atmospheric gravity waves detected which did not produce activity on the sea level. It was suggested that a delicate energy transference mechanism from the atmosphere to the ocean could play a significant role to explain some of the identified differences between sea level and atmospheric pressure wavelets spectra. This particular topic should be investigated implementing comprehensive numerical simulations with a realistic atmospheric forcing. In this sense, this paper constitute a contribution to the elucidation of this subject because it provides new information about the spectral structure of the atmospheric forcing. The variability in the duration of the atmospheric gravity events was clearly depicted by using of wavelet spectra. It revealed that spectral energy can appear as a single or multiple burst, as relatively long and irregular events or as regular wave packets. It is important to highlight that the measurement of atmospheric pressure every minute is very unusual at the Buenos Aires coast. High resolution barometric data series analyzed in this work are in effect the only atmospheric pressure data series available in this coastal area. Consequently, at the present, the spatial variability of the atmospheric gravity waves cannot be studied by means of direct observations of atmospheric pressure at the Buenos Aires coastal region.

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